Simulation of subseismic faults in Havana using displacement densities, and finding positions of faults in wells

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Contents

1 Introduction

This is a report on the project "Well sampling and improved intensity modelling in Havana", sponsored by Norsk Hydro, and performed at the Norwegian Computing center by Petter Mostad and Anne-Lise Hektoen during the spring and summer of 1999. The project was focused on programming some new features into the Havana program, and resulted in a code release and a short summary report. A full report on the project has now been produced, in the form of this document. Note that some additional adjustments of the program were done in connection with the writing of this report.

2 Summary

This project has had two quite separate parts. The first part has to do with computing intersections between (stochastically generated) faults and well paths. Previously, the general version of Havana had no way of outputing such intersections. The new module made available to Hydro does such computations, while also outputing data like fault dip, strike and displacement for each intersection.

The second part of the project concerns the use of intensity maps to guide the placement and orientation of faults in Havana. The previous way to use intensities in the simulation of new faults involved only the center points of the faults, and it has not given very satisfactory results when the intensity varies strongly. In the new feature, an intensity map derived from each fault realization is compared with a target density map, and this is used to produce realizations with densities close to the target density. The density is computed from each realization by taking into account for each fault the entire fault plane and the displacement across it. In a similar way, it is now possible to input maps describing preferred orientations for the faults. At each point, several preferred orientations may be given.

Below are some more technical descriptions of the changes made, from the point of view of a user of the program.

2.1 Well intersections with faults

A new module, activated with the Havana command

```
ACTION GetWellIntersections \
```

has been written. It is only available to Hydro, through the Hydro version of the Havana home page (http://www.nr.no/auth/havana_hydro). It contains the following keywords:

```
INPUT_HAVANA_FAULTS
INPUT_RMS_FAULTS
INPUT_WELL_PATHS
OUTPUT_WELL_INTERSECTIONS
```

Basically, the module computes the intersections between fault patterns and well paths. Data like fault dip, strike and displacement is output for each intersection.

2.2 Fault density modelling

A number of new commands have been added to the module in Havana simulating faults, in order to improve fault modelling based on density maps. Specifically, the commands

```
DISPLACEMENT_INTENSITY
DISPLACEMENT_INTENSITY_GRID
OUTPUT_DISPLACEMENT_INTENSITY
DISPLACEMENT_INTENSITY_PARAMETERS
```

have been added. A 3D field of positive values may be read in with the command DISPLACEMENT_INTENSITY. These values are then sampled into a grid specified with the DISPLACEMENT_INTENSITY_GRID command and this becomes a “target density”. Then, when faults are simulated, the density of displacement is computed on the same grid, and compared to the target density. (The target density is normalized, so that the sum of the target density and the sum of the simulated density over the grid is the same). An error is computed, and fault realizations minimizing this error are preferred. The result may be checked by looking at the resulting fault density using the OUTPUT_DISPLACEMENT_INTENSITY command.

The density of displacement is computed in the following way: In each grid cell, a sum is taken over all fault planes intersecting the cell. The value for each fault is the displacement of the fault in the cell.

In connection with the improved intensity modelling, an improvement in the possibilities of modelling spatial variability of fault strike and fault dip has been included. A command

```
ORIENTATION_GROUPS
```

has been added, making it possible to simulate simultaneously several groups of faults with independently controlled strikes and dips. This should be useful when using the displacement intensity modelling in connection with strain modelling, which may predict two different orientations at every point.

3 Model

In this section, we will describe the stochastic model and the simulation algorithm used in the simulation conditioned on displacement density. The central idea is that sum of the the “displacement effect” of the faults are compared with a target displacement density field, and that the faults are moved around so as this sum is not too different from the target field.

When simulating faults, it is always possible to use a set of fixed faults in the start. Of these, the elliptic ones will count towards the displacement target, exactly as the non-fixed simulated faults. So in a way, the effect of these will be subtracted from the target density before the rest of the faults are simulated. For simplicity, we assume below there are no fixed faults.

Note that well observations of faults result in faults corresponding to the observations being simulated before the rest of the faults. Again for simplicity, we assume below there are no such faults. (The displacement effects of these faults would count towards the target density, just as for fixed elliptical faults).

The displacement intensity field will be used not only for comparison with the displacement effect of the faults, but also to place the center points of the faults, just as with the RELATIVE_INTENSITY command. However, the displacement intensity comparison has effect only on mother faults; the children are clustered around the mothers using the usual parameters. Thus, when using displacement intensity, it is recommended to use only mother faults (i.e., the parameter for the number of families should be set much larger than the total number of faults).

With the assumptions above, we are ready to describe in more detail the model and method for fault simulation. We assume that we would like to simulate the position, displacement, size, orientation, and truncation pattern of a set of n faults: $F_1, \ldots, F_n$. At the core of the method is a displacement intensity grid. This grid is completely regular and aligned to the grid used in the intensity map. The default grid uses 50 cells in the x- and y-directions, and one cell in the z-direction. The sizes of the cells are set so that the grid covers the simulation volume.

First, the intensities input with the DISPLACEMENT_INTENSITY command are read into the regular intensity grid. Those cells where there is no intensity information are set as “undefined”, and are not used in later calculations. In other words, if a fault is later placed partially or totally in such undefined cells, it will have little or no effect on the fitting with the target displacement intensity field. A consequence may be an edge effect (see Section 4.1). For the defined cells $C_1, \ldots, C_k$ we get a target intensity value $T_1, \ldots, T_k$ in each of them.

Assume we have a set of (possibly truncating) elliptic faults $F_1, \ldots, F_n$. For a fault F_i and a cell C_j, we define $D(F_i, C_j)$ to be zero if the fault plane of F_i does not intersect C_j, and otherwise we set it equal to the local displacement of the fault at the projection to the fault plane of the center point of the cell. We then would like to somehow compare the values $\sum_{i=1}^{n} D(F_i, C_j)$ for $j = 1, \ldots, k$ to the values T_j for $j = 1, \ldots, k$. For this to make sense, we first normalize the target values T_j by multiplying all of them by

$$\left(\sum_{j=1}^{k} \sum_{i=1}^{n} D(F_i, C_j) \right) / \left(\sum_{j=1}^{k} T_k \right)$$

where $F_1, \ldots, F_n$ is the initial fault realization.

We can now describe the probability distribution we simulate from as

$$\begin{aligned} \pi(F_1, \ldots, F_n) &= \left(\prod_{i=1}^{n} \pi(F_i) \right) \operatorname{tr}(F_1, \ldots, F_n) \\ & \quad \exp \left(K^{-1} \sum_{j=1}^{k} \left(\sum_{i=1}^{n} D(F_i, C_j) - T_j \right)^2 \right). \end{aligned}$$

Here, $\pi(F_i)$ denotes the distribution where the position, displacement, size, and orientation of each individual fault is described with the standard parameters of the Havana simulation model. The details of these distributions may be found in the manual. Further, $\operatorname{tr}(F_1, \ldots, F_n)$ denotes the distribution for the truncation, also described in the manual. It is however the last term that concerns us here. The constant K determines how strongly one will condition on meeting the target displacement density information. The constant may be set using the DISPLACEMENT_INTENSITY_PARAMETERS command of Havana. We see that the conditioning is based on minimizing a sum of squared errors.

A smoothing function has also been implemented. If it is active, the effect of a fault F (i.e., the values of $D(F, C_j)$ for $j = 1, \ldots, k$) will be smoothed before they are used in the calculations above. Specifically, after smoothing, the new value of $D(F, C_j)$ will be the arithmetic average of the old values of $D(F, C_s)$ for all C_s in a square of size $2m + 1$ around C_j. The parameter m is by default 0, but can be set with the DISPLACEMENT_INTENSITY_PARAMETERS command.

The algorithm employed is a very simple MCMC algorithm. At each iteration, a random fault in the set is selected, and its properties are changed according to the distribution $\pi(F_i)$. The rest of the distribution above is then used in an acceptance criterion.

4 Examples

This section contains two simple examples, using the new commands and features of Havana implemented in the project.

4.1 Simulating subseismic faults using displacement densities

In the Havana manual, Example 2 shows how one may simulate a set of subseismic faults using the RELATIVE_INTENSITY keyword. Example 2 also shows how one may instead use the the DISPLACEMENT_INTENSITY keyword (using the file "simulate_b.model" instead of the file "simulate.model"). All the model files and data files used for this example are available from the Havana home page.

The model file for doing the simulation ("simulate_b.model") looks like this:

```
! The maximum number of iterations before termination:
NUMBER_OF_ITERATIONS 20000 \

! The simulation volume is here defined by a top and bottom surface:
SIMULATION_VOLUME
        horizons/munin_top.s
        horizons/munin_bot.s \

! The target displacement intensity of (mother) faults:
DISPLACEMENT_INTENSITY
        MultiSurface
        horizons/intens.s
        horizons/intens.s
\

! The final displacement intensity, and the target displacement
! intensity, measured on regular grids, are output to given files:
OUTPUT_DISPLACEMENT_INTENSITY outdisp.dat targetdisp.dat \

!The number of new faults to be simulated:
NUMBER_OF_FAULTS         100 \

! Parameters or maps specifying the range and strength of the fractal
! dimensions (range in m, fractal_dimension is the slope of
! the line from log(n) vs log(displacement), usually between 1-4)
DISPLACEMENT             Range 7.5 30 FractalDimension 2.0 \

! Parameters specifying the relationship between displacement(d)
! and length(l). The relationship is l = (d/c1)^(1/p), where
! p and c1 are parameters. p=1.1 and c1=0.01 below, 0.05 is
! the stochastic uncertainty.
```

```
FAULT_DISPLACEMENT_LENGTH 1.1 0.01 0.05 \

! Parameters specifying the relationship between height and length.
! h = l/c2
! c2 sigma2
FAULT_LENGTH_HEIGHT       2.0 0.1 \

! Parameters specifying the relationship between height, length and
! reverse drag. r = c3 * sqrt(h * l)
! c3 sigma3
FAULT_AVERAGE_REVERSEDRAG 0.4 0.1 \

! The expected number of families:
NUMBER_OF_FAMILIES        200 \

! Two possible strike directions, with half probability each:
ORIENTATION_GROUPS 0.5 0.5 \

! Parameters and maps specifying the distributions of
! strike for mother faults. As specified in the
! ORIENTATION_GROUPS command, there
! are two groups of parameters. All values in degrees.
STRIKE
Gaussian
Expectation
Constant 60.0
Stdev
Constant 10.0
;
Gaussian
Expectation
Constant 150.0
Stdev
Constant 10.0
\

! Parameters and maps specifying the distribution of dip
! for mother faults. All values in degrees.
DIP     ProbDownEast 0.7 ProbNormal 1.0
        Expectation Constant 80.0 Stdev Constant 5.0 \

! Parameters specifying the location of children faults around the
! mother faults. The three numbers are the standard deviations of
! the normal distribution of child fault center point around the
! mother fault; along and relatively to the length, height and
! reverse drag of the mother fault.
CHILDREN_PARAMETERS       0.9 0.3 0.7 \

! The strike of the child faults are determined from a normal
```

```
! distribution with the mother strike as the expected value and
! the value below as the standard deviance. (In degrees.)
CHILDREN_STRIKE          10.0 \

! The dip of the child faults are determined from a normal
! distribution with the mother dip as the expected value and
! the value below as the standard deviance. (In degrees.)
CHILDREN_DIP             2.5 \

! When two fault planes have a relative intersection of more than
! this number, the first will truncate the second.
FAULT_TRUNCATION         0.01 \

!Write out the result so far:
OUTPUT_HAVANA_FAULTS     hfdir \

! File with the different faults in a readable format:
FAULTS_STATISTICS statistics.dat \
```

The main point here is the use of the command

```
DISPLACEMENT_INTENSITY
        MultiSurface
        horizons/intens.s
        horizons/intens.s
\
```

which guides the positions of the faults. The intensity map “intens.s” is illustrated in Figure 1. There is an area of high intensity in the middle, surrounded by quite low intensities. Havana then converts this intensity map to an internal regular intensity grid, illustrated in Figure 2. Using this intensity grid as a targed, the faults shown in Figure 3 are simulated with the model file above. As a control, we can see that the intensity grid for these faults (Figure 4) is fairly similar to the target intensity grid of Figure 3.

We see in Figure 3 that almost all the simulated faults are contained in the area with high intensity. However, there are also some other faults, mainly at the edge of the simulation volume. This is an edge effect resulting from using an intensity map with the same lateral extension as the maps defining the simulation volume. It is only the part of a fault actually inside the volume where the intensity is defined that is used when the program judges how well the fault fits the intensity field. So a fault only slightly touching the intensity field in a low intensity area is judged to fit fairly well. To avoid this edge effect, the intensity field should extend well beyond the simulation box in the lateral direction.

Clearly, many parameters can be varied in the simulation above. For example, we could use smoothing, by including the command

```
DISPLACEMENT_INTENSITY_PARAMETERS 2 \
```

The effect is that the faults are placed much more evenly around the reservoir, although one may still see the area of higher intensity in the realization (see Figure 5).

4.2 Finding intersections between wells and faults

We end with a simple examle illustrating how we may compute intersections between faults and wells using the "GetWellIntersections" module. Running the fault simulation of the previous section produced a directory called "hfdir" containing faults. We now run Havana on a model file containing

```
LEVEL_OF_INFORMATION       2 \
ACTION                     GetWellIntersections \
INPUT_FAULTS               hfdir \
INPUT_WELL_PATHS           A1 a1data.dat
                           A2 a2data.dat \
OUTPUT_WELL_INTERSECTIONS intersections.dat \
```

This instructs Havana to find the intersections between the faults in "hfdir" and the wells A1 and A2, whose paths are described in files a1data.dat and a2data.dat, respectively. The file "a1data.dat" contains

```
50
462000 6581000 2000
462200 6581300 2500
463000 6583000 2700
```

and the file "a2data.dat" contains

```
50
462000 6581000 2000
461800 6580500 2500
461000 6579500 2500
```

The output file looks like

```
A1  462257 6.58142e+06 2514.35 2801.97 2.47901 154.515 82.146 N
A1  462665 6.58229e+06 2616.18 3764.01 4.42116 151.127 85.266 N
A1  462454 6.58184e+06 2563.41 3265.54 8.5433 74.1577 81.9803 N
A1  462748 6.58246e+06 2636.94 3960.15 6.14661 60.9668 76.8318 N
A1  462365 6.58165e+06 2541.36 3057.18 0.374798 253.231 79.1135 N
A2  461602 6.58025e+06 2500 3102.57 11.8621 51.6611 70.4634 N
```

More details can be found in the Havana manual.

5 Possible further work on subseismic pattern simulation

Although Havana now implements several methods for producing clustering fault patterns, it is safe to say that no final solution for subseismic fault pattern simulation has been reached. First of all, some issues with the displacement density method described in this report could be looked at, for examle

- The “smoothing” parameter may help produce a better fit to the intensity field, but it may also lead to larger faults “repulsing” smaller faults, contrary to what is seen in nature.
- One should look at other smoothing functions. It may also be possible to do the smoothing in a way that makes much faster iterations possible.
- The relationship between 2D and 3D intensity fields should be investigated further.

But a more fundamental change could be to change the way the displacement intensity field is computed from the fault realization. It should be possible to compute a strain field from the fault realization using the parametric descriptions of the faults, and fitting this strain intensity to a target intensity (derived from the seismic faults) may very well give better results than the current method.

Appendix: Excerpts from the Havana manual

For easy reference, we have collected below some parts of the Havana reference manual relating the this project. In the next section, we list the five keywords added in the simulation module of Havana in connection with the project. Then, we describe the Havana module where one may compute well intersections with faults. Finally, som relevant file formats for well data are described.

A Simulation of subseismic faults

Below is a description of the four new Havana commands which may be used to simulate faults based on a displacement intensity field, and the new command which may be used to simulate different families of faults with different orientations.

A.1 DISPLACEMENT_INTENSITY

Optional.

Description: Specifies a trend function for the displacement intensity of simulated mother faults. This command is an alternative to the commands RELATIVE_INTENSITY and REPULSION.

Arguments: One A **MultiSurface** trend function. For a description of its format, see the Havana manual.

Example:

```
DISPLACEMENT_INTENSITY
   MultiSurface
      munin_top.s
      munin_bot.s
      munin_displ_intensity.s
      munin_displ_intensity.s \
```

A.2 DISPLACEMENT_INTENSITY_GRID

Optional.

Description: Specifies number of simulation box gridcells nx, ny, nz in x-, y- and z- direction respectively for the displacement intensity grid. The default numbers are: $nx = 50$, $ny = 50$ and $nz = 1$. Only used if command DISPLACEMENT_INTENSITY is specified. Note that the number of gridcells will influence the execution time of the Metropolis algorithm heavily.

Arguments: Tree. Integers.

Example:

```
DISPLACEMENT_INTENSITY_GRID  100 100 1 \
```

A.3 OUTPUT_DISPLACEMENT_INTENSITY

Optional.

Description: When the DISPLACEMENT_INTENSITY command is used, one may use the OUTPUT_DISPLACEMENT_INTENSITY command to output the displacement intensity of the realization produced by the simulation. One may also output the target displacement intensity, for comparison. This target intensity is computed by the program from the input in the DISPLACEMENT_INTENSITY command. Both intensities are output on a simple grid format:

```
nx ny nz
for (i=0; i< nx*ny*nz; i++)
  grid[i]
```

This is the grid used internally in the program when it is trying to match the target intensity.

Arguments: One or two. The first argument is the name of the file where the result intensity will be written out. If there is a second argument, it should also be a file name, and the target intensity will be written out there.

Examples:

```
          OUTPUT_DISPLACEMENT_INTENSITY
simDisplIntensity.dat \
          OUTPUT_DISPLACEMENT_INTENSITY
simDisplIntensity.dat targetIntensity.dat \
```

A.4 DISPLACEMENT_INTENSITY_PARAMETERS

Optional.

Description: One may use this command to change from their default settings some of the parameters used in the displacement intensity simulation. Specifically, the first argument is the number of blocks (in the displacement intensity grid) used when smoothing the displacement intensity before matching it with the target density. The default value is 0. The second (and optional) argument is the constant used in the error estimation of the simulation. The default value is 1. A larger value will give realizations which match the target density less well, but the convergence of the iteration will be faster. A smaller (but positive) argument will make the program try harder to match the exact target density, but the convergence will be slower.

Arguments: One or two. The first is the number of grid cells used in smoothing, while the second is the constant used in the error computations when matching a simulated displacement density with the target density.

Examples:

```
          DISPLACEMENT_INTENSITY_PARAMETERS 4 \
          DISPLACEMENT_INTENSITY_PARAMETERS 0 10 \
```

A.5 ORIENTATION_GROUPS

Optional.

Description: The strike, dip, and "dip down east" parameters of a fault are collectively described as the "orientation" of the fault in this manual. One may specify several distinct groups of faults and then control the orientation of the faults in each group separately. In each group, the orientation may in fact vary across the reservoir.

To use more than one group of faults in this sense, one must use the command ORIENTATION_GROUPS. It specifies the probability for *mother* *faults* to belong to the different groups. Orientation parameters for each of the groups must be specified in the STRIKE and DIP commands.

Arguments: Positive decimal numbers specifying the probability of each of the orientation groups. HAVANA normalizes the specified values to probabilities. The number of values will give the number of orientation groups.

Examples:

```
ORIENTATION_GROUPS  0.3 0.7 \
```

B Computing intersections between well paths and faults

Below is a description of the Havana module which Hydro may use to compute intersections between wells and faults. The way to start the module is to use

```
ACTION GetWellIntersections \
```

and the keywords are as described below.

B.1 INPUT_FAULTS

Necessary.

Description: Reads one or more files or directories containing fault information. Four types of faults may be read in:

- Havana Faults, i.e, directories written out by Havana using an OUTPUT_HAVANA_FAULTS keyword.
- Irap RMS fault directories.
- Files containing deterministic descriptions of elliptic faults. The format is similar to (but not identical to) the output generated by the FAULT_STATISTICS command of the Simulate module.
- Parametric faults directories.

(However, this module cannot currently handle PFM faults, and they will be removed with a warning). The order of the faults in the combined list will be given by the order the fault sets are listed in the input command. No truncations will be generated between faults in different groups.

Arguments: One or more. Each argument should be either the name of a directory of faults on Havana format, an Irap RMS fault directory, a file containing elliptic faults, or a directory containing parametric faults.

Examples:

```
INPUT_FAULTS hfdir \

INPUT_FAULTS Bigfaults hfdir \
```

B.2 INPUT_WELL_PATHS

Required

Description: This command is used to specify the wells. For each well, the name of the well must be given, together with the name of a file specifying the well path. The format for this file is given in Section C.1.

Arguments: A list of pairs of arguments. Each pair consists of the name of the well and the name of the file containing the well specification.

Example:

```
INPUT_WELL_PATHS
   A1 wellpathA1.dat
   A2 wellpathA2.dat \
```

B.3 OUTPUT_WELL_INTERSECTIONS

Required

Description: The output file generated by this command will contain the intersections computed by the program. The format of the file is given in Section C.2.

Arguments: One. The name of a file that will contain the output.

Example:

```
OUTPUT_WELL_INTERSECTIONS out.dat \
```

C Well data files

We have collected below some file formats currently used in HAVANA for inputing and outputing well data.

C.1 Input of well paths

This file describes a single well path. It starts with a single positive number, indicating the "Kelly Bushing" of the well, i.e., the number of meters above sea level where the well begins. Then follows a number of lines, each specifying the (x,y,z) coordinates of a point on the well path. The z coordinate is positive, indicating depth below sea level. The well path starts directly above the first given point (at the height given by the Kelly Bushing), ends at the last given point, and is linear between any pair of consecutive points.

Example:

```
50
460000 6580000 3000
461000 6581000 3200
```

C.2 Output of well intersections

This format is currently only available to Hydro.

This file specifies the intersections between a set of faults and a set of wells. Each line in the file specifies one intersection. The items on each line are as follows:

- The name of the well intersecting the fault.
- The x coordinate of the intersection point.
- The y coordinate of the intersection point.
- The z coordinate of the intersection point.
- The measured depth of the intersection point.
- The throw at the intersection point.
- The dip azimuth at the intersection point.
- The dip at the intersection point.
- N if the fault is normal, R if the fault is reverse.

Example:

```
A1 460000 6580000 3000 3250 4.5 45.3 80.2 N
A1 460010 6580010 3010 3265 3.4 47.3 85.3 N
```

See Section B.3 for usage of such files.

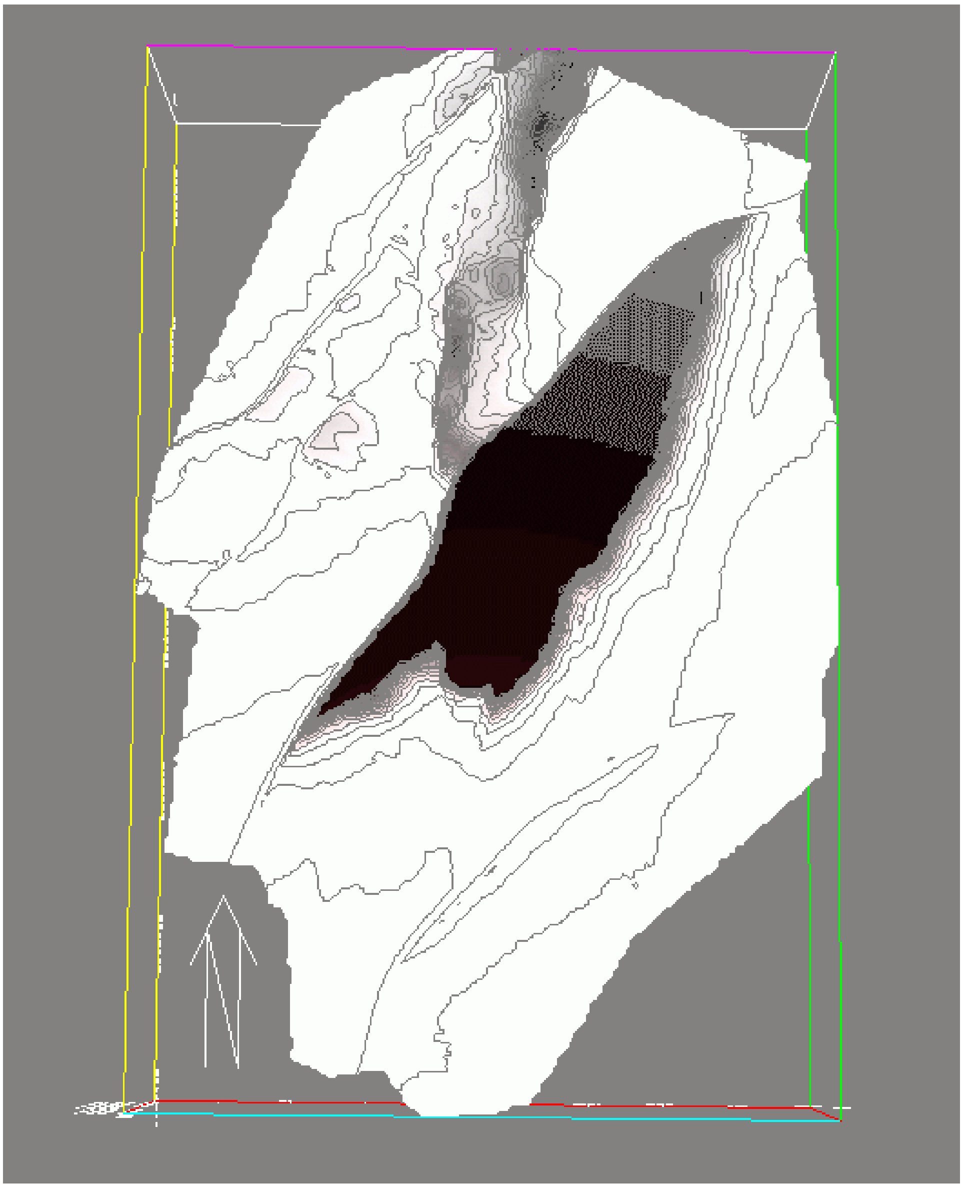

Figure 1: The intensity map input.

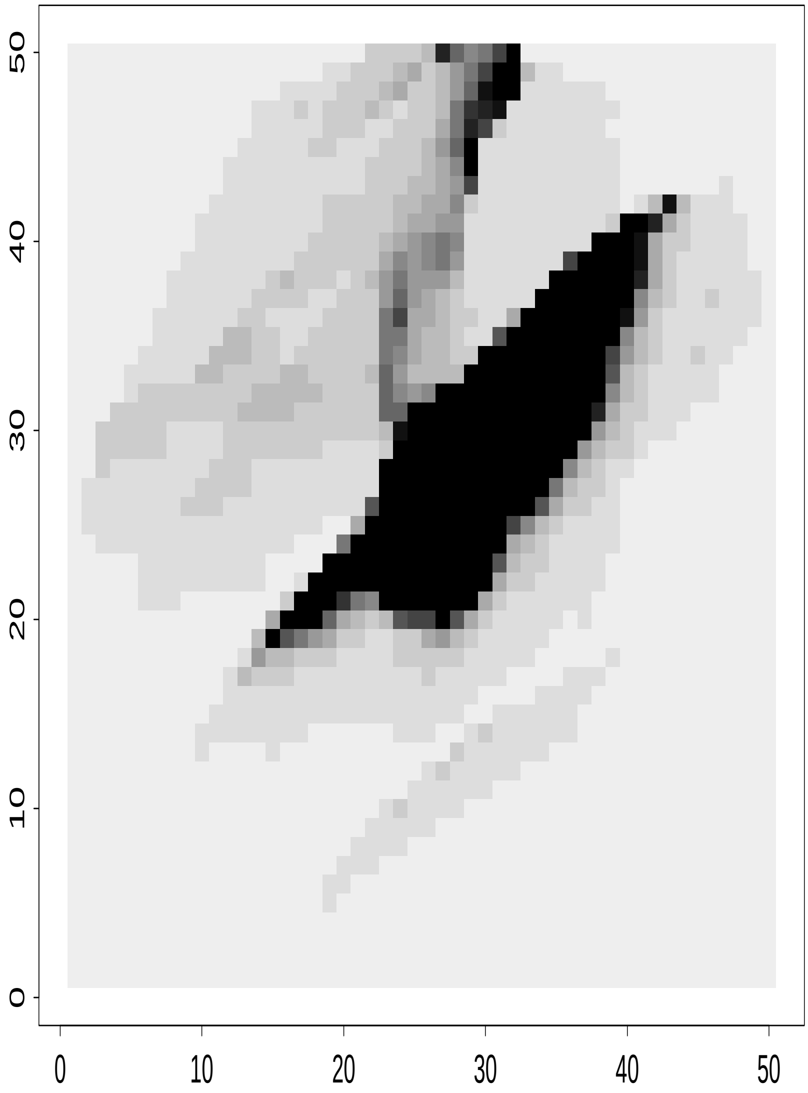

Figure 2: The target density on the internal regular grid

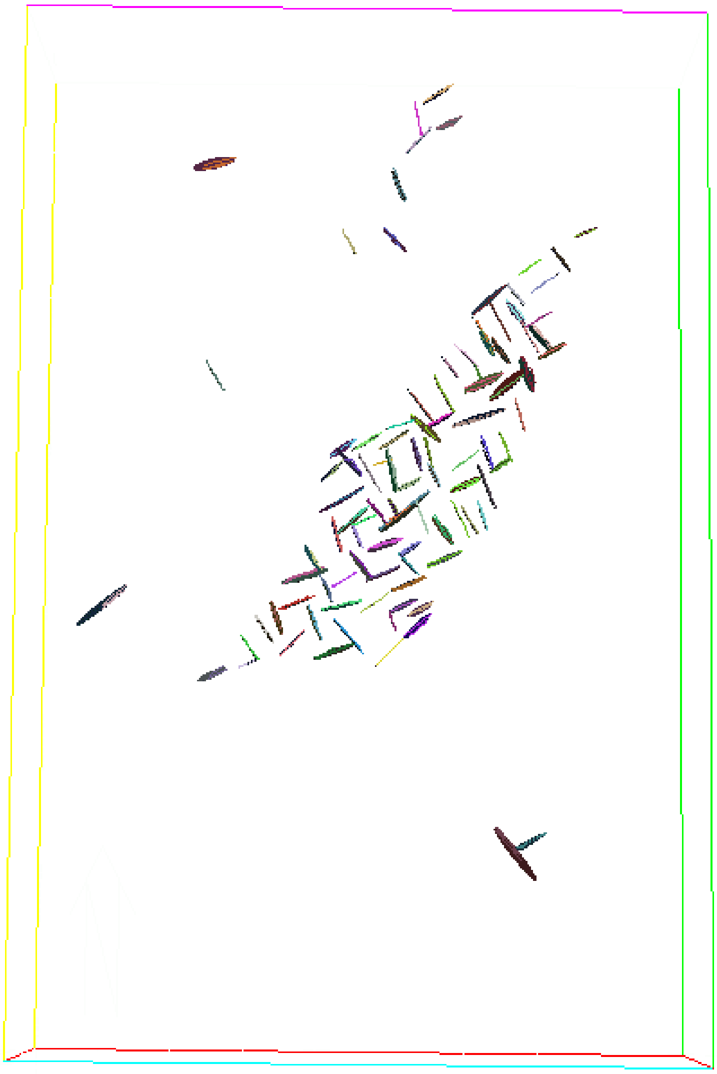

Figure 3: The simulated fault pattern

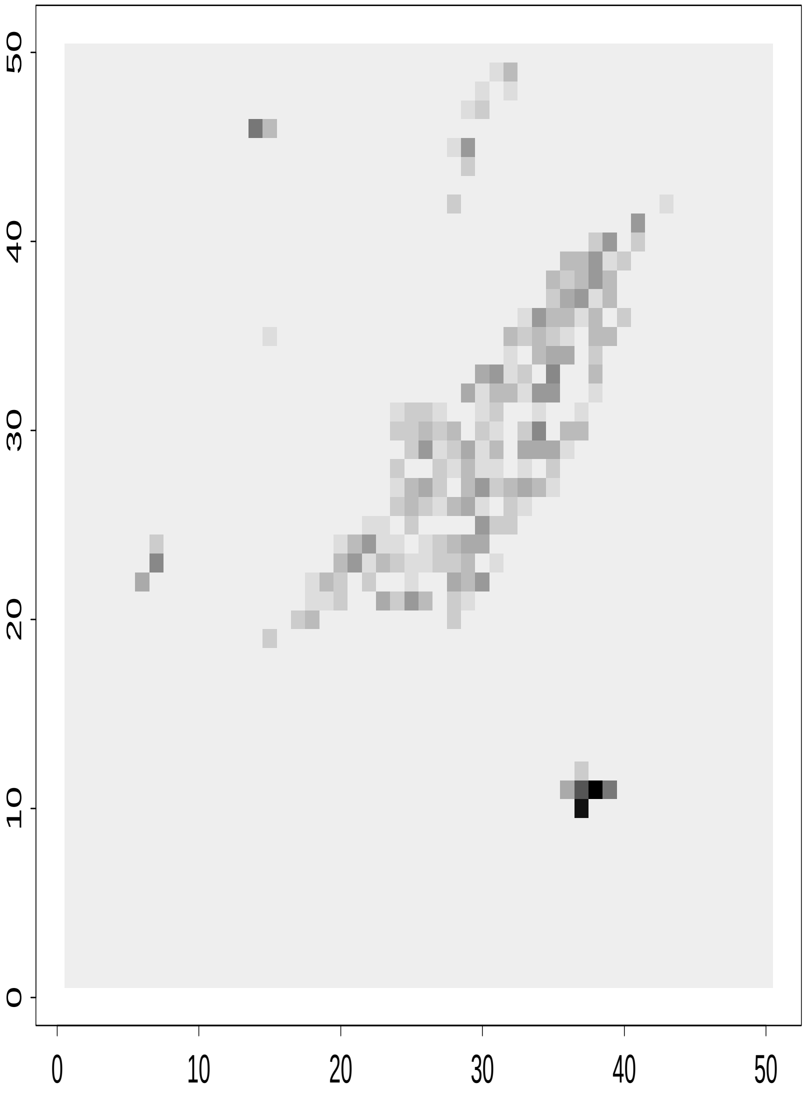

Figure 4: The result density on the internal regular grid

Figure 5: A simulated fault pattern with smoothing