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Integrating Faulting and Locally Varying Anisotropy

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Geostatistical modeling of reservoir properties is common in the assessment of expected reservoir flow. Typically, static properties such as porosity, saturation and permeability are modeled with geostatistical techniques to quantify the level of uncertainty in reservoir characterization. Lately, practitioners have become concerned that purely statistical techniques do not sufficiently integrate all geological knowledge available; rather statistical assumptions such as Gaussianity and simplistic assumptions on geometry such as global directions of anisotropy or simple stratigraphic coordinates, dominate. The proposed methodology can incorporate complex information regarding deposit geometry in the form of locally varying anisotropy (LVA) to generate numerical property models that better reflect the level of geological knowledge available. Specifically, surfaces from seismic data, geological interpretations and dip meter data can be used to assess local orientations of continuity in the deposit and generate an appropriate LVA field. This work presents a novel technique for integrating faulting and LVA information in a single numerical modeling step.

Introduction

Multiple surfaces representing local orientations from seismic data and faulting from either seismic or geological interpretations can be of first order importance when assessing reservoir response. Numerical models that conform to these features are required. Stratigraphic coordinates can be used to conform property models to two surfaces (top and bottom), but cannot easily consider a single domain with multiple surfaces that may fold back on themselves. Using LVA, any number of intermediate and bounding surfaces can be honored. LVA is considered in this work following the technique presented in Boisvert and Deutsch (2011). In addition to LVA, multiple faults at various dips are difficult to incorporate directly into coordinate transformations. Coordinate systems can be modified to consider vertical faulting, but the proposed methodology is effective in 3D, with a large number of faults and with various dips. A novel technique is proposed for incorporating faulting by modifying the shortest path calculation to use offsets based on fault displacement.

Consider a simplistic example (Figure 1) of a deposit that conforms to a top, bottom and intermediate surface and contains a single vertical fault. The intermediate surface would likely be imaged from a combination of seismic data and detailed geological interpretation. With this knowledge, an LVA field that represents the orientation of anisotropy can be generated (Figure 1). The LVA field defines the local orientation and magnitude of continuity (the ‘major direction of continuity’ in geostatistical terminology). The vertical fault (east=60m) is integrated into the property model by joining blocks along the fault in the calculation of the shortest path with the Dijkstra algorithm. In short, the distance between a block on one side of the fault and a block on the opposite side separated by the appropriate offset is negligible (Figure 2); in Figure 3 the distance A-C is the summation of segments 1+2+3, segment 2 would have an anisotropic distance of ~0m. The anisotropic distance A-B (without fault) is effectively the same as the anisotropic distance A-C (with fault). Geologically this is appropriate as it is typically assumed that at the time of deposition A and C were in close proximity and should be highly correlated. Further details on the use of the shortest path in numerical modeling can be found in Boisvert and Deutsch (2011).

The anisotropic distance (Figure 3) is used in the kriging system of equations to estimate (kriging) or simulate (SGS), with a small modification to ensure positive definiteness (Boisvert and Deutsch, 2011). Figure 3 indicates how LVA is incorporated into modeling; along the major directions of continuity the anisotropic distances are shorter, resulting in a higher correlation in the kriging system of equations, thus ‘smearing’ the grades along the orientation of the LVA field defined in Figure 1. Estimation using ordinary kriging with and without faulting shows reasonable reproduction of the three surfaces and the fault (Figure 4). The abrupt end to the high valued zone in the center is due to the lack of high grades in the left and right wells. The identical data and LVA fields are used in both the faulted and non-faulted scenarios with everything east of 60m shifted upwards by 20m. Simulated realizations using SGS could be generated to better characterize reservoir heterogeneity.

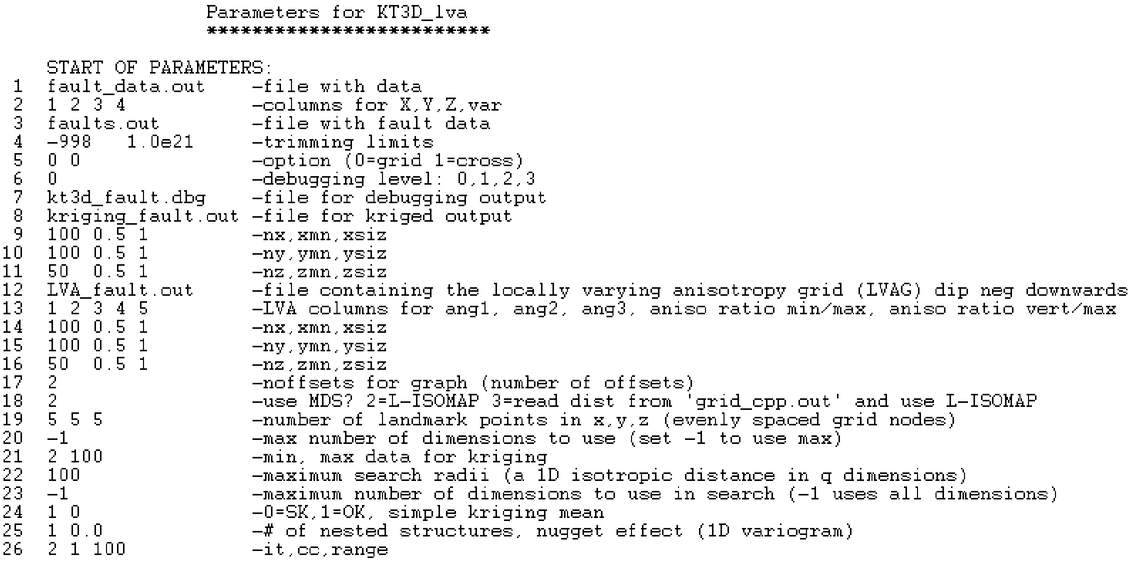
Defining a Fracture/Fault

A plane upon which to offset nodes is defined by a normal vector, n=[a, b, c], as well as one point on the plane p=(x1, y1, z1), Figure 2; this is sufficient to fully define the plane upon which translation of nodes occurs. The user must also supply the offset along which the nodes are translated; this offset is defined by a vector that must lie in the plane. For example, in Figure 4, the offset would be x=0 y=20 z=0.

A number of details are important when defining faulting. The ordering of the faults is important and controls truncation (Figure 6). The first fault in the fault definition file (see below for complete parameter definition) is never truncated. Successive faults are always truncated by all intersecting faults that precede its order in the file (Figure 7). Moreover, when truncating a fault there are two possibilities, the fault above the truncation point can be kept or below. As discussed previously, a fault is defined by a vector and a point; the point defining the fault to be truncated is used to determine which segment of the fault to keep, the side of the fault containing the point defining it as a fault is kept. For example, in Figure 8, the point defining fault 3 is to the west of fault 2, thus the segment of fault 3 to the west of fault 2 is kept.

Program

The parameter file for KT3D_lva.exe is detailed below:

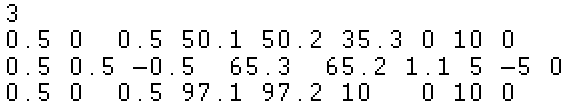


```
                 Parameters for KT3D_lva
                 *************************

    START OF PARAMETERS:
 1  fault_data.out    -file with data
 2  1 2 3 4           -columns for X,Y,Z,var
 3  faults.out        -file with fault data
 4  -998   1.0e21     -trimming limits
 5  0 0               -option (0=grid 1=cross)
 6  0                 -debugging level: 0,1,2,3
 7  kt3d_fault.dbg    -file for debugging output
 8  kriging_fault.out -file for kriged output
 9  100 0.5 1         -nx,xmn,xsiz
10  100 0.5 1         -ny,ymn,ysiz
11  50  0.5 1         -nz,zmn,zsiz
12  LVA_fault.out     -file containing the locally varying anisotropy grid (LVAG) dip neg downwards
13  1 2 3 4 5         -LVA columns for ang1, ang2, ang3, aniso ratio min/max, aniso ratio vert/max
14  100 0.5 1         -nx,xmn,xsiz
15  100 0.5 1         -ny,ymn,ysiz
16  50  0.5 1         -nz,zmn,zsiz
17  2                 -noffsets for graph (number of offsets)
18  2                 -use MDS? 2=L-ISOMAP 3=read dist from 'grid_cpp.out' and use L-ISOMAP
19  5 5 5             -number of landmark points in x,y,z (evenly spaced grid nodes)
20  -1                -max number of dimensions to use (set -1 to use max)
21  2 100             -min, max data for kriging
22  100               -maximum search radii (a 1D isotropic distance in q dimensions)
23  -1                -maximum number of dimensions to use in search (-1 uses all dimensions)
24  1 0               -0=SK,1=OK, simple kriging mean
25  1 0.0             -# of nested structures, nugget effect (1D variogram)
26  2 1 100           -it,cc,range
```

Lines 1,2,4-26 are identical to previous versions of KT3D_LVA, see previous CCG reports for guidance on parameter selection. Line 3 is the only addition to this version of the program and provides fault information for offsetting nodes. Faults are defined by a point and normal vector as well as an offset. The fault file format begins with the number of faults, then one line for each fault. The ordering of faulting controls truncation.

An example fault file follows:



```
3
0.5 0   0.5 50.1 50.2 35.3 0 10 0
0.5 0.5 -0.5  65.3  65.2 1.1 5 -5 0
0.5 0   0.5 97.1 97.2 10   0 10 0
```

There are a total of 3 faults. The first three values define the normal vector for the fault (Figure 5). The second thee values define the point required to locate the fault (Figure 5). The final three values define the vector offset that is used to translate along the fault.

3D example

A 3D example is shown with three faults as defined above (Figure 8). Note that incorporating faulting with LVA is straightforward; however, fault lengths have not been considered. Each fault is assumed to traverse the domain. Rules for the generation of the graph would be required to determine the behavior at the ends of faults.

Conclusions

The proposed methodology can be used to incorporate multiple surfaces that represent orientations of continuity for the variable of interest, typically determined from seismic data or a geological understanding of the domain. Moreover, any number of faults can be integrated with LVA in a single modeling step. The main difficulty in implementing the proposed methodology is the generation of the LVA field (Figure 1) and modeling of the faulting including offset orientation and magnitude. With these input parameters known, modeling (kriging or SGS) is straightforward.

References

Boisvert and Deutsch. 2011. Programs for kriging and sequential Gaussian simulation with locally varying anisotropy using non-Euclidean distances. Computers and Geosciences. Volume 37. 495-510.

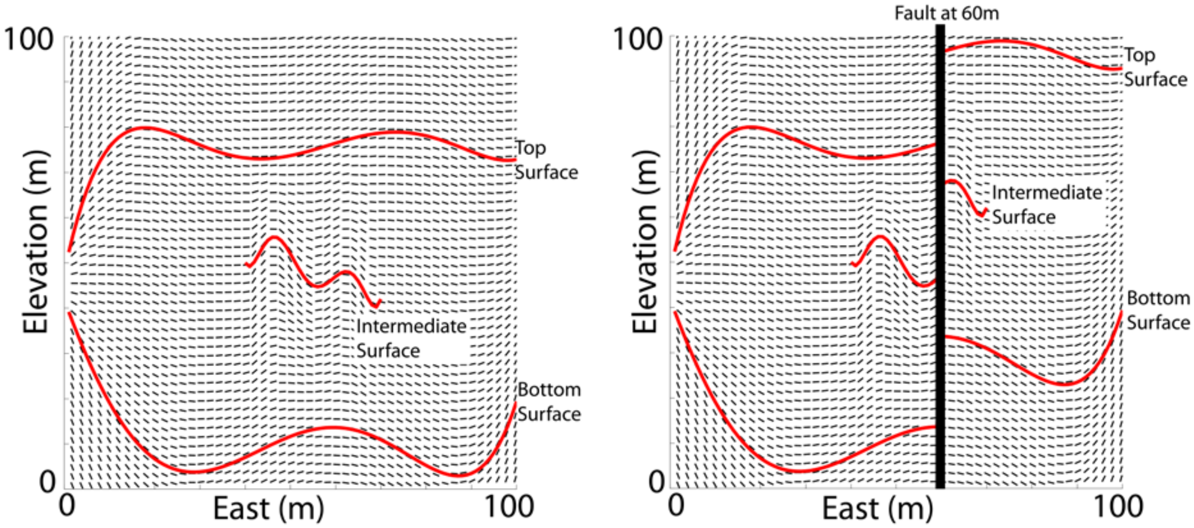


Figure 1: LVA field and surfaces used for the synthetic example. Short black lines represent the orientation of the locally varying anisotropy (i.e. the local direction of maximum continuity). Left: no fault. Right: fault at east=60m. Magnitude of anisotropy is a constant 100:1 ratio.

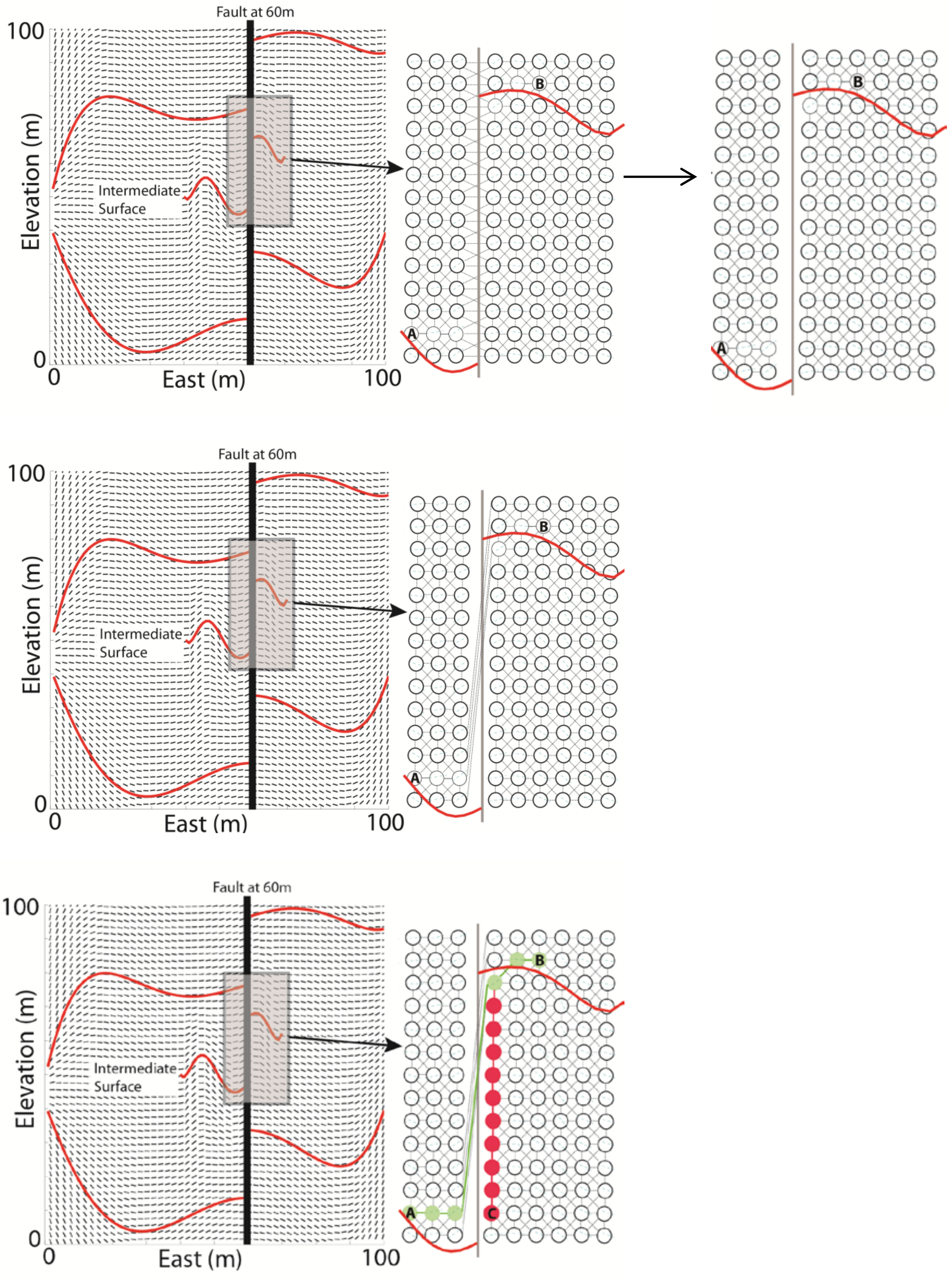


Figure 2: Methodology for fault incorporation. Above: Step 1 – Break all edges connecting nodes across the fault. Middle: Step 2: Add edges connecting nodes across the fault as per the desired fault offset. These edges have a negligible distance. Below: Step 3: the distance between points can be calculated. Path A-B (green) would have a short distance, whereas A-C would traverse a larger distance.

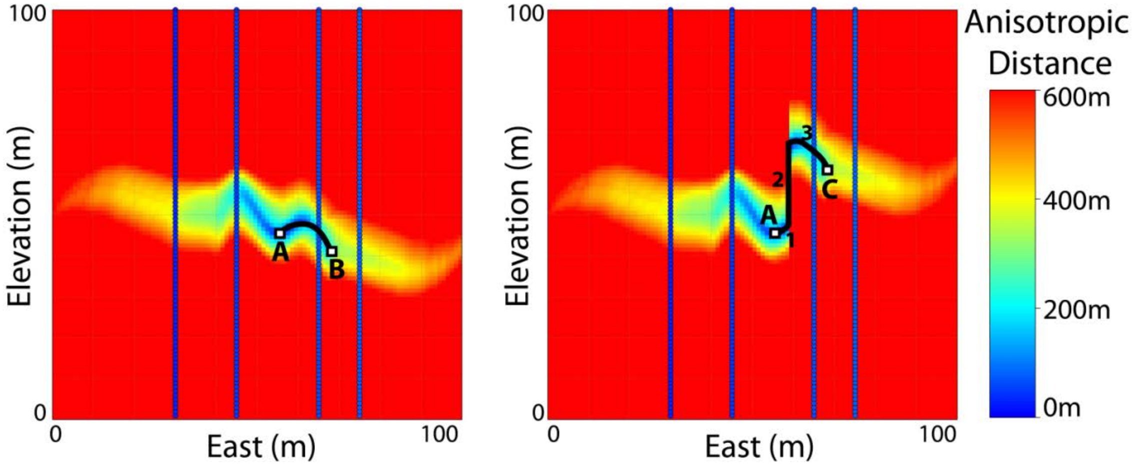


Figure 3: Anisotropic shortest distance from A to all other blocks following the LVA field in Figure 1. The shortest path between A-B and A-C is indicated. Path A-C would be the summation of segments 1+2+3 with line segment 2 having an effective anisotropic distance of ~0m.

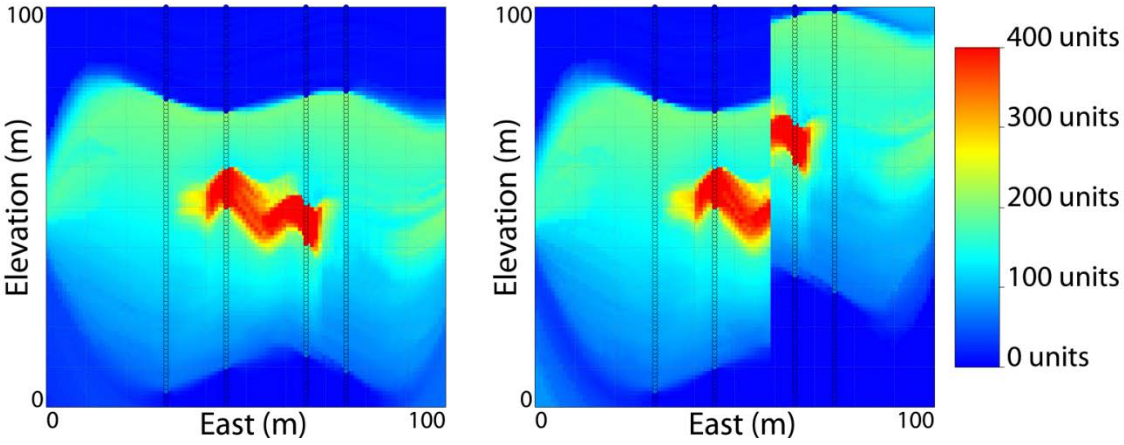


Figure 4: Ordinary kriging result using LVA. Left: no fault. Right: vertical fault at 60m east. Variable units not specified.

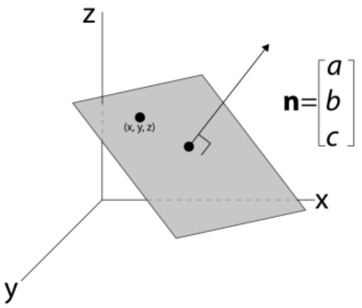


Figure 5: Plane definition with a normal vector and point.

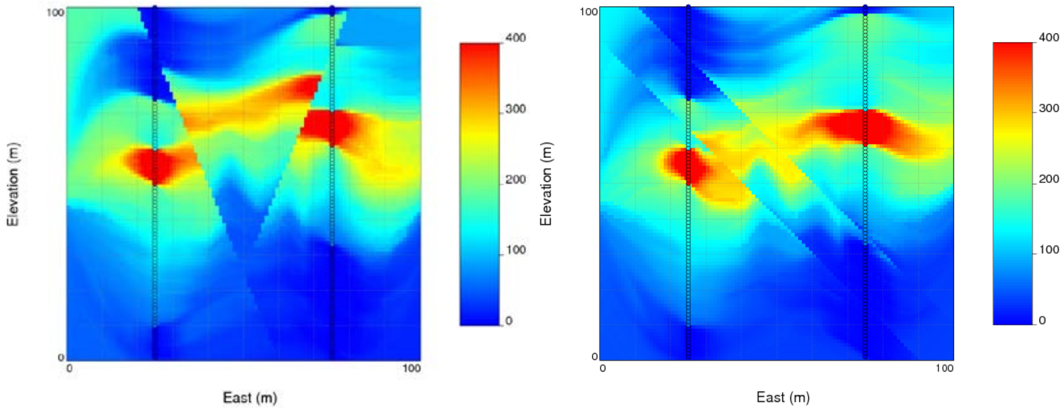


Figure 6: Left: the right fault is truncated by the left fault. Left: parallel faults

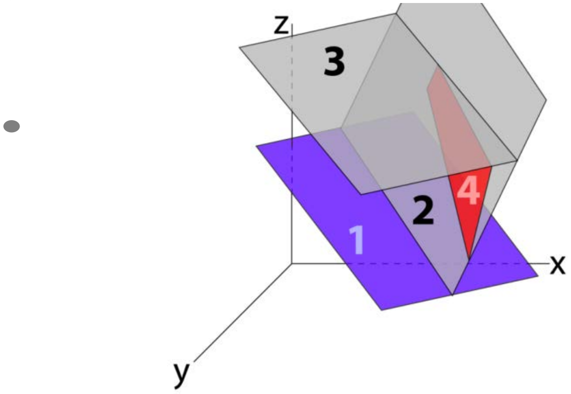


Figure 7: Defining multiple faults with truncation. The point defining fault 3 is shown.

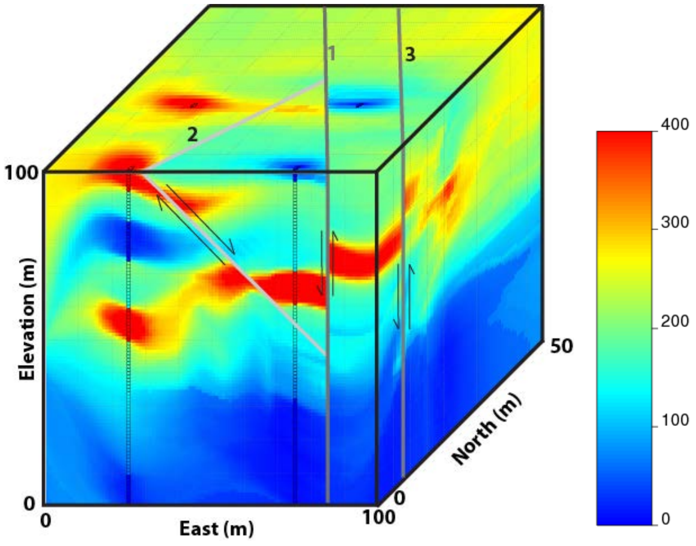


Figure 8: Three faults in three dimensions. Fault ordering for truncation is 1, 2, 3.