Abstract
This paper describes a new approach to modelling geological structures, using a grid of pillars in 3D. This method allows the creation of faults, horizons and zones within a single 3D grid. The construction of the grid is performed step by step, using the original data directly, as seismic interpretation and well picks.

The key benefit of this method is that faults and geological horizons are modelled within the same framework, ensuring consistency whilst retaining control over interpolation and extrapolation of data.

The result is that structural models can be generated much faster than previously possible and rapidly updated as new data becomes available. The approach has been tested and proven in the commercial modelling software package, Petrel.

Step 1: Fault Modelling

The purpose of the fault modelling is to generate a realistic description of faulting which can be incorporated into a 3D grid. The modelling results in a wire frame structure with groups of pillars describing the faults. This structure is used in the next step.

A pillar is a 3 dimensional line or a curve limited by an upper and lower level. The pillars can be one of the following geometries, depending on the number of control points used to define them:

- Vertical pillar (straight line)
- Linear pillar (straight line, inclined)
- Listric pillar (Spline curve with 3 points)
- Curved pillar (Spline curve with 5 points)
- Other types pillars can be added later

Pillars are grouped together to form fault planes. It is possible for pillars to be part of two separate fault planes, thus joining faults together and allowing the generation of branching and crossing faults. In this way the pillars can describe a huge network of faults whilst still providing a realistic description of the relationships between individual faults.

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The user creates the fault model interactively in the 3D window. New pillars can be made by picking on any objects in the 3D space, e.g. seismic data, interpreted surfaces, interpreted seismic lines or well top picks. The shape of each pillar (i.e. the number of control points used to describe it) can be changed at any time during editing and the nodes and pillars themselves can be moved interactively in 3D.

In order to understand the methodology, it is important to note that data from horizons and zones is not required during the building of the fault model.

**Step 2: Gridding**

Gridding is done in order to incorporate the faults into a single 3D skeleton grid, which can be used for structural modelling.

The skeleton grid consists of pillars sorted in a 2 dimensional matrix (rows & columns). This is a non-physical notation and refers to the way the data is organised, not the physical position of the pillars. Since the pillars are unconstrained in the X, Y and Z-directions, the grid is irregular in all 3 dimensions.

The fault model defines the skeleton grid layout. Users may also input trends by defining the orientation given to parts of faults or arbitrary lines. The orientation can be set as arbitrary (default), I direction or J direction. A fault set with an orientation in the I direction will be a part of a row in the skeleton grid whilst J directions be a part of column. Arbitrary faults will sometimes follow the I-direction and sometimes the J-direction, depending on their geometry and the grid layout.

The grid is limited by a boundary. This boundary is normally a 2 dimensional curve between faults where the faults pass outside the area to be modelled. The curve will be connected to the middle control point of the pillar. If there are no faults going out of the field, the boundary can be given by a closed 2 dimensional curve. Parts of the grid falling outside the boundary will not have any pillars.

This figure shows a small skeleton grid, containing 3 rows and 3 columns of pillars. The notation I and J correspond to the direction of the grid nodes and is a non-physical notation. The pillars maintain their real position in 3D.

The layout if the grid is constructed using a 2D projection of the middle control point of the pillars describing the fault model. The algorithm tries to make the I and J grid lines perpendicular to each other and the 2 dimensional area of each grid cell is as equal as possible. The grid lines in one direction are not allowed to intersect each other. The user is able to control the grid resolution, the density of the grid lines in certain areas, and the grid line smoothness by a number of user settings.
The figure below shows how the faults are incorporated into the grid. The figure is a 2D projection of the middle control point of the pillars describing the fault model. The faults are shown as red (orientated along the J direction), green (orientated along the I direction) and thick white (Arbitrary direction). The cyan line forms a part of the boundary. The stippled green and red lines are trends, which are used to direct the grid lines along a particular orientation. The figure to the right demonstrates the use of zig-zaged faults, suitable for flow simulation, while the left shows smooth faults. Note how the grid lines follow the faults.

Pillars generated during fault modelling are resampled into the skeleton grid at the resolution specified by the user. This process is aimed at changing the geometry of the fault pillars as little as possible. Fault information such as name and the connections between the faults are also maintained in the grid generated. This information is stored with the pillars forming the fault, and is used in order to model faults correctly. The original fault model has now been incorporated in the grid and is no longer required, other than for regeneration of new grids with alternative user inputs.

By changing the user input e.g. grid resolution and the handling of faults, separate grids suitable for geological modelling or flow simulation can be generated from the same fault model.

**Step 3: Vertical Layering**

The vertical layering will be done in 3 main steps. The steps are:

1. Model primary horizons.
2. Geological zonation.
3. Generate final fine scale resolution.
During vertical layering, geological horizons are added into the skeleton grid, to form a complete geological description. The Z coordinate of each horizon at each of the existing pillars is described by adding a horizon node to each pillar. The exact 3D position of a horizon node, \((x, y, z)\) is calculated from the Z coordinate and the geometry of the pillar itself.

For each geological horizon, non-faulted pillars have one horizon node, while faulted pillars have 2 horizon nodes, one for footwall and one for hanging wall. If the pillar is at the junction of a branched fault it will have 3 horizon nodes whilst pillars at crossing faults will have 4 horizon nodes. This information has been generated during the gridding process.

![This figure shows a main fault with a branch. The logical layout of the horizon nodes is drawn. The blue points are the horizon nodes for the pillar that is connected to both faults.](image)

Both the horizon nodes and the pillar geometry can be edited interactively after they have been generated.

The 3D model itself maintains information and status about each of the horizons and zones. Therefore any of the 3 steps used to create vertical layering can be rerun at any time, this facilitates changing or update the model when new data input is available.

**Step 3.1: Model primary horizons**

Primary horizons are made directly from the seismic interpretation or from point data, surfaces, or lines data as contours. Several data source can be combined and applied to different fault compartments. The horizons can be adjusted to match well picks.

The algorithm behind this includes both local interpolation and global interpolation/extrapolation (1). During local interpolation, the horizon node will get its elevation from either the input points closest to the pillar or from a number of points within a user specified distance from the pillar. Using the second option this distance is used to form a 3 dimensional cylinder or a pipe around the pillar, which follows the pillar geometry. All points inside the cylinder will be used for the local interpolation.

Various interpolation algorithms can be used in the local interpolation. The simplest is the moving average algorithm, where the elevation is weighted by the inverse square of its distance to the pillar (2). Another method is gradient estimation with the least square method (3).

If the input is a surface, an intersection algorithm between the pillar and the surface finds the elevation of the horizon node. Pillars that don’t have any neighbouring points or surface intersection are left to the global interpolation and extrapolation.

Pillar on the faults are treated differently. Since data close to faults are normally not correct, the user can choose the offset from fault within which local interpolation should not be applied. This can of course also be set to zero such that data close to the fault is honoured. The fault itself
forms a barrier for point searching, such that data on one side of the fault is not used during interpolation for horizon nodes on the opposite side.

The global interpolation/extrapolation is done on horizon nodes, which have not been defined during the local interpolation. The algorithm tries to minimize the entire curvature on the horizon (3), by solving a partial differential equation over all unknown horizon nodes. Using the information along the faulted pillars, the algorithm sets the boundary condition at the horizon nodes on or close to the faults to avoid interpolating across the faults.

Well picks are honoured by determining the error at each location, and calculating a residual surface. The modelled horizon is then adjusted using this residual surface. During the building of horizons, the user can specify the relationship between them. This is then used to determine the most appropriate method for dealing with any crossing horizons which must be truncated. All horizons are normally generated in one single operation but this can also be done one by one. The user must generate at least one horizon before proceeding to the next step.

Modelling of primary horizons is normally done in the time domain, because seismic data (the most common input) is normally in time. The entire model can then be depth converted prior to geological zonation. Depth conversion of the 3D grid is not discussed in this paper.

**Step 3.2: Geological zonation**

In the geological zonation the volume between the primary horizon is divided into several zones (intervals between horizon), separated by new secondary horizons. The secondary horizons are here stored in the grid exactly as for the primary horizons.

The user can specify the thickness of the zones by giving:

- **Isochore**: Surface representing the vertical thickness of the zones.
- **Isopacks**: Surface representing the stratigraphic thickness of the zone.
- Constant value, as an absolute number or percentage of the total thickness.
- No specific value, use the well picks to determine the thickness.

The user decides whether to start the zonation from top or from base. The algorithm can also build above the top of primary horizons or below the base of primary horizons. Thickness can be measured by one of the three different methods shown below; vertical thickness, stratigraphic thickness and vertical thickness along pillars. Two figures are shown because the angle between the pillar and the direction perpendicular to the horizon can differ.

![Diagram of geological zonation](image)

If there are well picks available, the secondary horizon is corrected in the same way as the primary horizons. If the user has thickness data for all the zones and is building between two
primary horizons, the sum of the thicknesses may not match the thickness between the two primary horizons. In this case volume correction is used and the thickness of the zones is adjusted automatically. This volume correction can be divided up between the all zones or just a few user defined zones.

**Step 3.3: Generate final fine scale resolution**

The fine layering is inserted between the existing horizons in the model. This simply adds new horizon nodes between the existing horizon nodes in the grid. There are various ways of doing this:

- Add layer from base or top of the zone using constant thickness
- Add layer by proportional thickness using a specified number of layers. It can be specified a relation between the new layers, for instance 1,4,1,2 means the first and third is one unit thick, the second 4 units thick and the fourth 2 units thick.
- Add layer from base or top of the zone using a dipping surface. This surface is a template surface with a dip indicating the dip of the layers at deposit time.

Again the algorithm allows the user to select the way in which thickness is measured; see the figure in the Geological zonation section.

**Conclusion**

With previous methods, 3D grids are constructed in one single operation. The method described in this paper involves constructing the geological model step by step, using the original data directly, as seismic interpretation and well picks. The steps are:

**Step 1** - Fault modelling  
**Step 2** - Gridding  
**Step 3** - Vertical layering, which is divided into:

- **Step 3.1** – Model primary horizons.  
- **Step 3.2** – Geological zonation.  
- **Step 3.3** – Generation of the final fine scale resolution.

Modelling geology directly on a 3D grid of pillars has many benefits:

- Faults, horizons and zones are in one single model, which ensures consistency within the data.  
- Fault are described and modelled realistically, with full control over interpolation and extrapolation around the faulted area.  
- Consistent layering, crossing horizons can not occur.  
- Cells are organized in rows, columns and layers, which makes them ready for facies and petrophysical modelling and flow simulation.

Proof of the benefits of this approach is demonstrated in Petrel, a piece of commercial geological modelling software. Using this method, the time taken to construct a 3D structural grid has been reduced by 10-100 times and rapid updates are possible as new data becomes available. This has provided significant benefits to end users.
References


(3) For Minimum Curvature, see: