A Topologically-based Framework for Simulating Complex Geological Processes

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Abstract

Earth scientists acquire and interpret a variety of data in an attempt to define the best description of subsurface geological structures, or an earth model, as the data permit. The generation of numerical meshes derived from an earth model is a necessary critical step to provide specific data representations such as finite difference grids or finite element meshes, including the model geometry and associated physical properties for simulation applications.

The construction of geological, or earth, models has been a challenge not only due to the scarcity of subsurface data but also because of the geometrical complexity of geological structures. Since typical geological structures (e.g., fractures, faults, salt domes) evolve with time due to various physical processes such as compaction, we use a topological framework to create and maintain earth models that allow the geometry to be modified during simulations and with new interpretations.

In this paper we describe a framework used to create a reference model defining a spatial partition, which is used to represent multi-material objects. Multi-resolution and multi-structure meshes can be associated as attributes to each cell of the reference model, making it possible to have a flexible mesh management environment for numerical simulations.

Typical applications in geosciences are reservoir simulation, basin-wide heat and fluid transfer, and propagation of seismic waves. Because these applications may require significant computational resources, we use this framework to provide critical adjacency information for the spatial domain decomposition used in parallel computing. Application of these techniques is not restricted to geosciences. They can also be applied to engineering fields that involve large deformations, such as car crash or ballistic simulations.

The simulation of complex geological processes such as the evolution of sedimentary basins and multiphase fluid flow within sediments is an important component of the decision-making process in the oil industry. In oil exploration and production, critical decisions are made based on the results of simulations and interpretations of subsurface earth models.

Keywords: geometric and topological representations; multi-resolution models; conceptual design techniques; engineering analysis, including FE mesh generation.

I. Introduction

The simulation of complex geological processes such as the evolution of sedimentary basins and multiphase fluid flow within sediments is important for decision-making process in the oil industry. In oil exploration and production, critical decisions are made based on the results of reservoir-scale or basin-wide simulations. The quality of these simulations is directly dependent on the accuracy of subsurface earth models.

The drilling of a wildcat well can cost between $ 5 to 50 million USD. The worldwide success rate of these wells is on average less than 10%. In known petroleum reservoirs, an average of 40% is recovered or produced, whereas about 35% of the oil is usually left in place due to rock-fluid interaction forces. The remaining 25% can be potentially recovered and may represent a sizable increase of assets for oil companies if new technologies are made available to identify and produce these resources.

One of the major causes of the relatively poor performance in exploration and production is the limited knowledge of the physical and geometrical characteristics of earth models. The construction of earth models is a phenomenal problem not only due to the scarcity of data but because of the geometrical complexity of geological structures. The major sources of data on subsurface comes from wells and from interpretation of the acoustic response to seismic waves. This data is very patchy (e.g., Figure 1) in nature and provides a limited amount of information for building the earth model "puzzle".

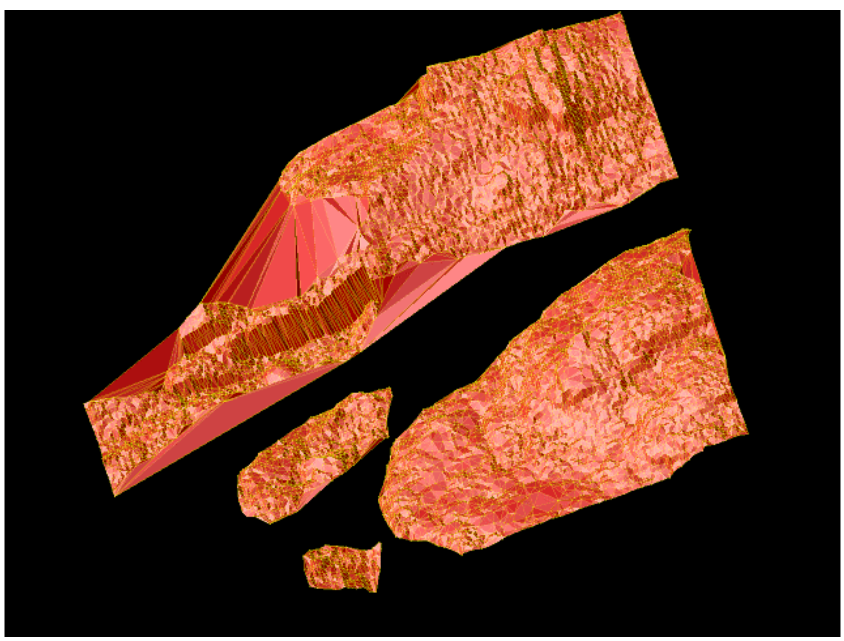

Figure 1 - Typical geological surface derived from data interpretation in the Mahogany Field area, Gulf of Mexico. Earth models are normally built by integrating incrementally various surfaces that are in general patchy in nature (data courtesy of Western Atlas International).

Traditionally, the geological interpretation of seismic data results in a set of curves and surfaces, which are used to construct a consistent earth model. This model can then be used to generate discrete meshes for several kinds of numerical simulations, such as a reservoir simulation, the propagation of acoustic waves, or large-scale fluid and heat flow within saturated porous sediments (e.g., Mello and Karner, 1996; He et al., 1998).

Because of the unique nature of geological data, commercial CAD systems generally designed for mechanical or architectural markets are not appropriate to build 3-D earth models. In addition, geological surfaces are frequently inconsistent with each other due to the uncertainties in their generation. Hence, it is frequently necessary to use pre- and post-processing tools to correct inconsistencies in order to produce a coherent 3-D earth model. Various commercially available geological interpretation systems do not enforce model consistency because they regard earth models as just a collection of 2-D surfaces embedded in 3-D space, which are used to generate 3-D raster earth models when a voxel representation is required.

Geological "CAD" systems such as gOcad and Pyramid (Wiggins et al., 1993) have been designed to build truly 3-D earth models. However, the design of these systems was also oriented toward specific tasks in the industry. These systems are appropriate for building static earth models, but this is a limitation if one wants to use these systems to model dynamic geological structures that evolve through time.

The simulation of rock deformation through time can be used to determine if the geometry of a potential reservoir has been appropriate to retain oil in the past. A geometry that does not define a trap for hydrocarbon instead allows migrating oil to be lost, going straight to the earth surface or to the sea (e.g., gas seeps in the Gulf of Mexico). Numerical simulations of generation, migration and accumulation of hydrocarbons are currently used to assess the exploration risk associated with new prospects.

We have designed a framework to build dynamic 3-D earth models. The main characteristic of this framework is that the model topology and geometry are kept separated. This characteristic is very important because many rock deformations are topologically invariant in time and can be described by geometrical changes. Topological changes occur in few distinct events, and Mello and Henderson (1997) have described techniques to minimize significantly topological changes during simulations.

In this paper we give an overview of our topologically based framework that allows the creation of 3-D earth models and management of geological attributes, including multi-resolution meshes, either structured or unstructured.

II. Topologically-based Framework

The high-level architecture of our modeling framework is shown in Figure 2. This is a layered architectural pattern (Buschmann et al., 1996) in which each layer has a distinct role in the framework. In the base of the framework, we use a topological representation based on the Radial Edge Data Structure - REDS (Weiler, 1988; Martha, 1989), which is used to represent complex non-manifold topologies.

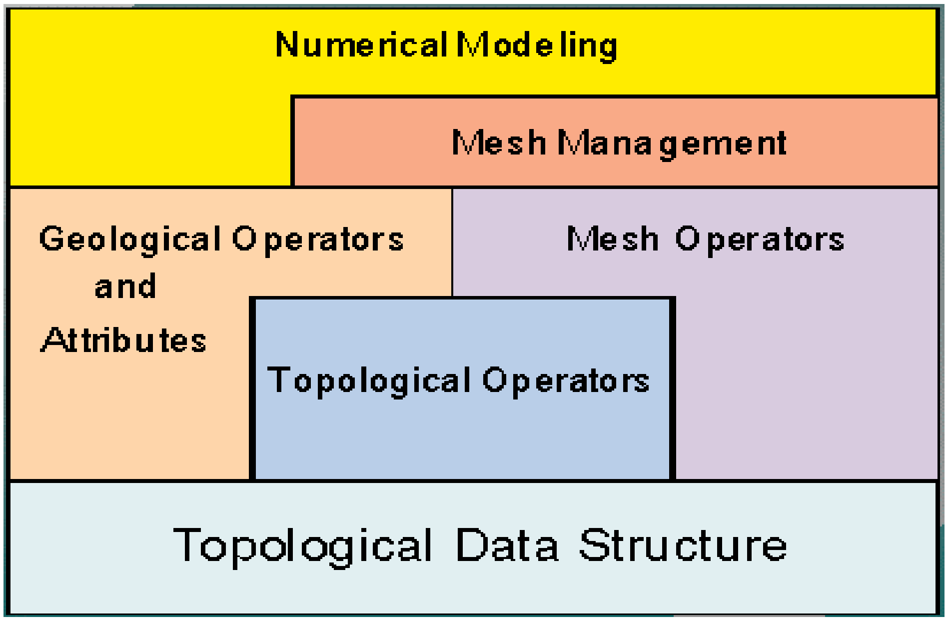

Figure 2 - Architecture of our modeling framework.

We implemented the REDS and its topological operators using C++, and this implementation is very compact, having less than 50 classes. The REDS is the component that stores the topological and geometrical representation of an earth model. Geological attributes and high-level operators have been designed to mimic geological processes and to process input surfaces defining geological objects. The MultiMesh Toolkit - MMT (Figure 3) is the layer that generates and manages numerical meshes associated with earth model cells. It is important to note that meshes are treated as attributes of geological entities such as blocks, horizons, layers and faults. Hence, a mesh is not the model, but only one possible realization of a model or a sub-region of the model. This paradigm is very powerful for simulation of evolving processes where the geometry is changing with time and therefore some degree of re-meshing is frequently necessary. In addition, this paradigm can also be used to integrate legacy simulation applications, such as geostochastic, reservoir and forward seismic simulations. This latter use is very important to increase the productivity of multidisciplinary projects. In these projects, significant resources are normally necessary to translate the numerical mesh representations among applications that use distinct numerical techniques (e.g., finite differences, finite volume or finite elements).

Using MMT, the meshing operators can provide multiple mesh representations with multiple resolutions of a given earth model. These meshing operators are used to re-mesh specific regions of the model that have undergone excessive deformation and to transfer information among meshes. One particularly important application of these operators is in the area of reservoir characterization, where it is commonly necessary to downsize geological grids to a resolution such that the flow simulation can be executed on available computers (Lagendijk et al., 1997). Operations between coarse and fine resolution grids are greatly facilitated within this framework.

This framework has also allowed us to manipulate voxel representations of the earth with great flexibility. For example, we treat 3-D seismic images as regular grid attributes of the earth model. Because our framework has explicit information about the geometry of geological objects in the model, we can for example easily select only the seismic voxels of a particular reservoir object. This technique has been successfully applied to perform time-lapse seismic analysis in the Gulf of Mexico (He et al., 1998).

The explicit adjacency information that our framework provides can be also used to perform geologically based domain decomposition for parallel computing. This kind of decomposition has the potential to provide unique information for load balancing, given that some problems have more computation restricted to some specific areas of the model such as high-permeability faults or actively deforming areas.

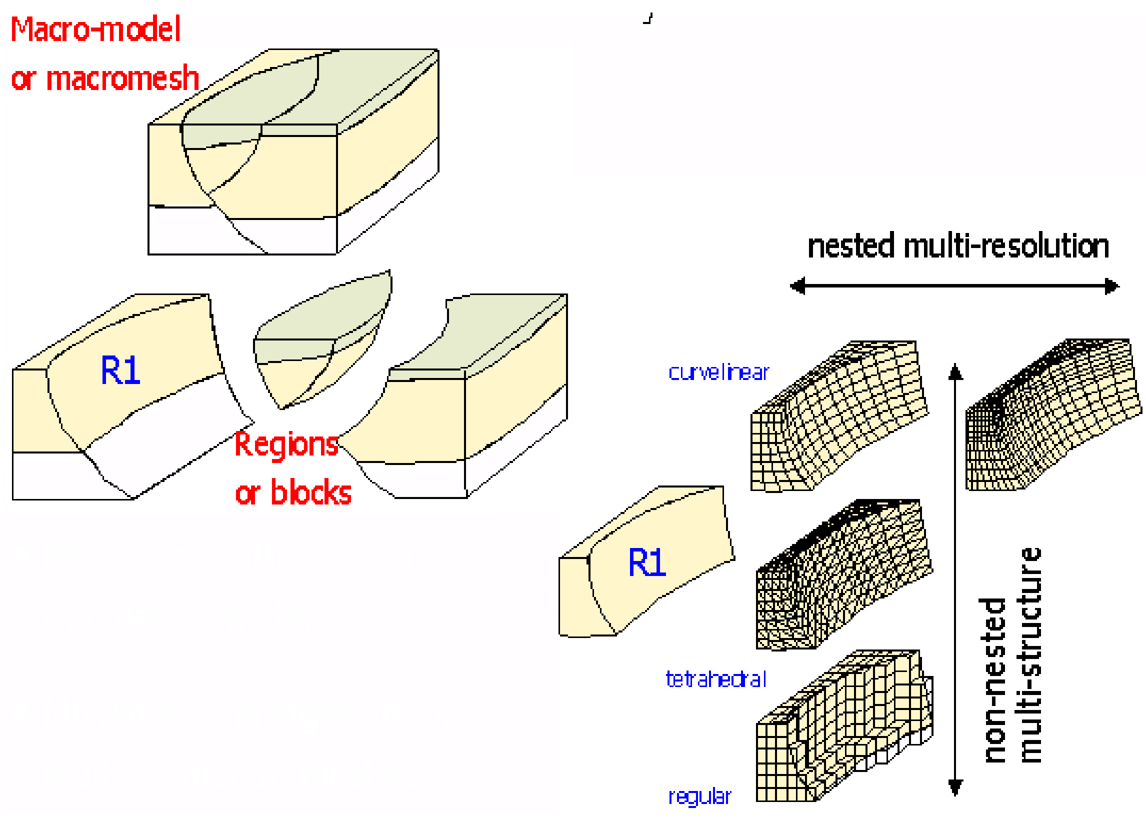

Figure 3 - MultiMesh toolkit concepts. See text for details.

III. Building an Evolving Earth Model

A typical object-based earth model is created from surfaces that define the geometry of geological objects such as horizons and faults. A horizon is normally the interface between geological layers with distinct geological properties. Faults represent discontinuities caused by the sliding of fractured rock. Geometrically, there are no restrictions on the positioning of surfaces in the 3-D space, and they do intersect each other. These geological surfaces are usually supplied by a set of planar polygons or regular 2-D grids.

The input polygonal surfaces are read, and each of its defining polygons is inserted incrementally as described in Cavalcanti et al. (1997). To ensure that the planar intersection engine of the framework will work properly, non-planar polygons (within a given tolerance), if present, are automatically triangulated.

When rectilinear gridded surfaces are provided, a decimation filter is normally applied to compress and reduce the redundancy in the object geometrical information. In the decimation, a specified tolerance controls the number and the quality of triangles defining the original gridded surface.

The process of incrementally adding polygons defines the spatial partition of the earth model and generates the set of faces bounding a geological object. To improve the execution time for the spatial localization of the face set in the model that can potentially intersect the incoming polygon, we use a dynamic index structure, R^*-tree (Beckman et al., 1990). A face may be present in multiple input surfaces (if the defining polygons have a tangent overlap). To keep track of the face-surface relationship, each face has an attribute index that points to its respective entry in the model attribute table, which contains all the surface attributes such as type, name, age and so forth.

In principle, the order of inserting faces is irrelevant and the result is deterministic. In practice, the result is tolerance-dependent. After all the surfaces are input, if the model is not bounded, a bounding box is added to delimit a closed region of interest encompassing all surfaces.

Following the model creation, it can be saved in several formats with various degrees of trade-offs between file size and explicit connectivity information. The most complete format is virtually a map of the model internal representation in the computer memory onto the disk, mapping directly the topology and geometry of the model. The framework can also export other popular 3-D formats including VRML, gOcad and PLG.

Figure 4 represents the entire Gulf of Mexico basin and is an example of one of the largest earth models we have built. This model was built from 8 input surfaces and it has 7 regions, 40743 faces, 32783 vertices and requires approximately 19.5 MB of memory to store its topology and geometry.

IV. Processing operators

Unfortunately, input surfaces are many times incomplete, noisy and frequently they do not define closed geological objects. This stems from the uncertainty in the interpretation process. The most common problems are holes in the surface and lack of closure among surfaces. The holes occur because of lack of data, and closure problems are associated with mismatches between surface boundaries and appear as gaps (when a surface is too short), or rims (when a surface is too long).

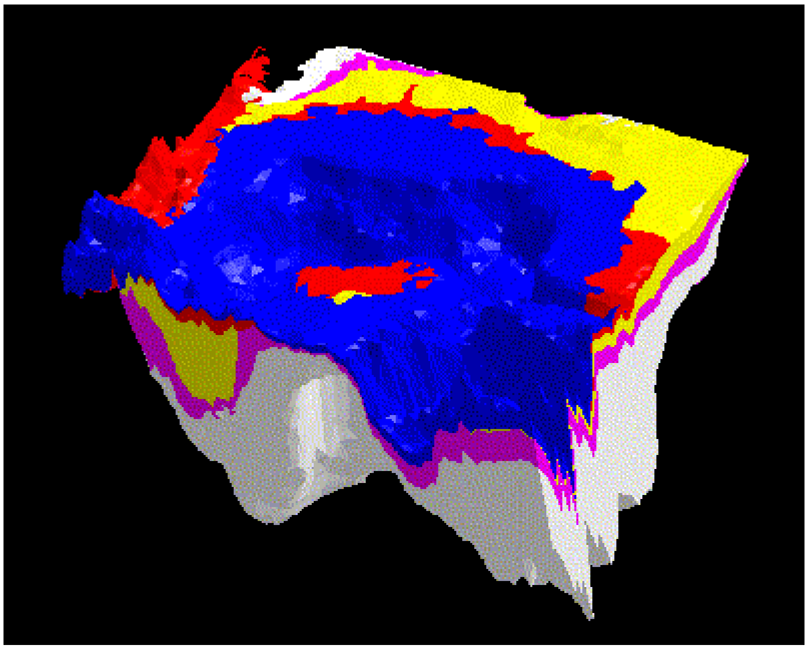

Figure 4 - Earth model of the entire Gulf of Mexico basin

Geometrical "noise" can induce the creation of a quite large number of very small regions. These spurious small regions should be eliminated, since they overwhelm the model with unusable information.

To address these issues related to geological data, we have designed a number of high-level operators that can dramatically improve the productivity in the creation of high-quality earth models. In the next sections, we briefly describe the most important high-level operators. Notice that they are implemented on top of the low-level topological operators described by Weiler (1988).

IV.1 Pave hole operator

In order to close holes in a given surface, or shell, of the model we find its lamina edges. A lamina edge is an edge that has just one face incident to it, and hence, lamina edges bound dangling faces. A series of closed cycles of lamina edges define the boundaries of holes and the external boundary of a surface. The pave hole operator lists the lamina edge cycles and allows a face to be glued on one of them thereby closing it. The selection of the holes to be paved is normally done interactively, enforcing the closure of holes only in selected places. Figure 5 displays a typical result of this operation.

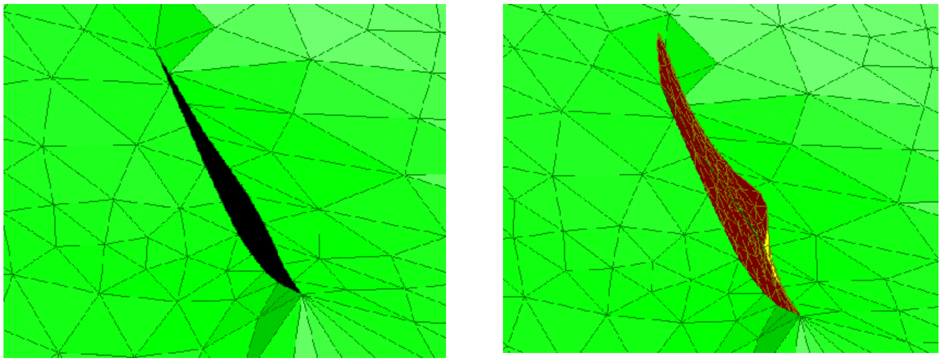

Figure 5 - A surface hole before and after the hole paving operation.

IV. 2 Regularize region operator

Regularization is the process of deleting all dangling faces in selected regions of the earth model. It is normally used to remove excess rims generated by the intersection of mismatched surfaces (Figure 6). This operation is based on the fact that a dangling face in the rim is adjacent to just one region as opposed to desired faces which are on the interface between two regions.

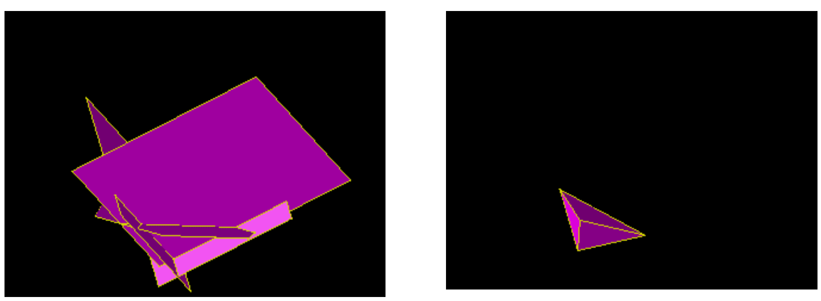

Figure 6 - A simple tetrahedral region before and after regularization.

IV.3 Extract interface operator

An interface is a set of faces adjacent to two distinct regions. The ability to extract adjacency between regions of the earth model is useful in the parallelization algorithms using unstructured meshes since the interaction between the two regions occurs through their common interface. In addition, this operation is necessary to merge adjacent regions of the model, where the interface is simply removed as described in the next section.

IV.4 Merge region operator

The merge region operation removes the interface between two adjacent regions. This operation is necessary to join regions or parts of a geological object that are supposed to be continuous. Discontinuous geological objects can be unwittingly created by inaccurate geometry of the input surfaces. Selection of the regions to be merged can be done interactively or automatically using the adjacency and attribute information.

IV.5 Small region aggregation operator

This operation is used extensively when the surfaces have geometrical noise that creates numerous small, spurious regions in the model. Regions with a volume smaller than a fraction of the model volume can be automatically aggregated to larger adjacent regions with similar attributes (Figure 7). In the process of aggregation, the interface between the region to be killed and an adjacent region is deleted.

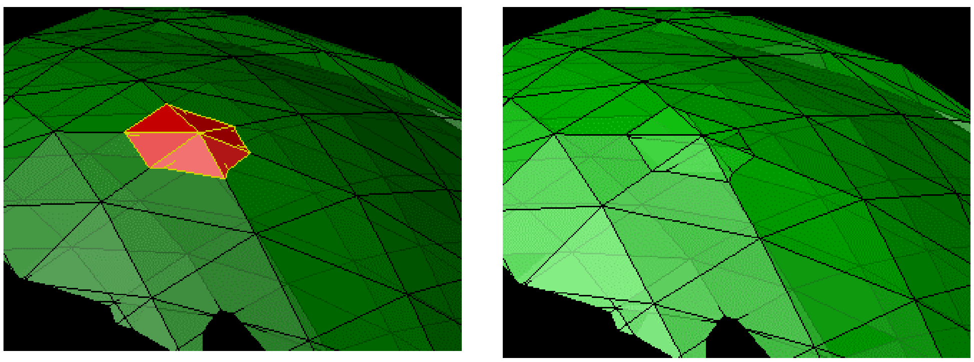

Figure 7 - A small region (red) before and after its aggregation to a salt dome.

The Gulf of Mexico model (Figure 4) was initially generated with 3034 regions due to geometrical noise. All small, spurious regions were eliminated upon application of the operator thereby leaving only the relevant 7 regions expected initially.

IV.6 Extracting 2-D and 2.5-D cross sections

For geologists and modelers, the extraction of 2-D planar cross-sections of an earth model is a very useful operation, either for visualization purposes or for simulation since several algorithms used in the oil industry still require 2-D models. A 2.5-D model is a 2-D model with constant thickness in the third dimension. The 2.5-D model is useful to test new 3-D algorithms versus 2-D solutions. To extract a cross-section, a plane that cuts the model must be defined. This cutting plane is normally defined by three values that must be supplied: a point in the model, the plane strike direction and the dip angle. In our framework, this operation is easily accomplished by using the framework intersection engine to define the faces that represent a 2-D map of the 3-D geological objects on the cutting plane (Figure 8). These faces are not inserted in the earth model because they are not part of any of the geological objects.

V. Meshing operators

Meshing operators are used to create an alternative realization of the model. These operators are used for numerical solution of partial differential equations and for interpolation purposes. Meshing operators are hierarchical in nature, and most of the meshing operations start on cells of lower dimension (1-D), moving to higher dimensions (3-D) hierarchically. The higher dimension meshes are constrained by the lower dimensional ones previously generated. Next we describe the most important meshing operators we have implemented so far.

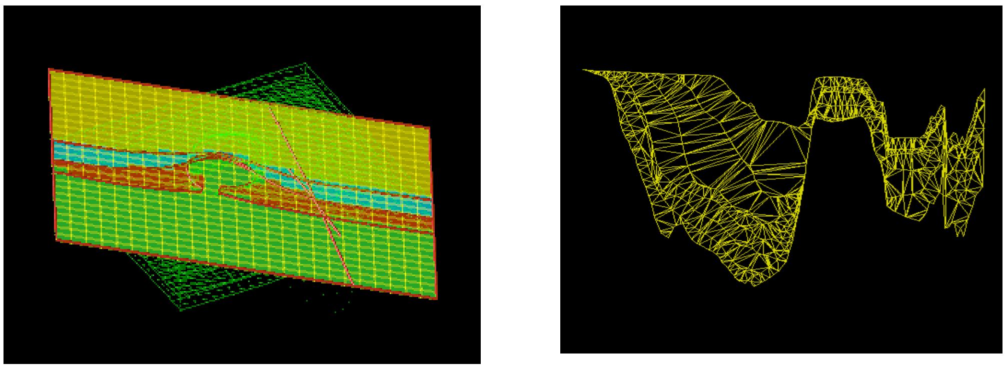

Figure 8- A) 2.5-D regularly gridded cross-section of a salt dome and B) triangulated cross-section of the Gulf of Mexico model displayed in Figure 4.

V.1 Rectilinear mesh operator

We take full advantage of the explicit adjacency information stored in our framework to efficiently generate regular meshes. Given an arbitrary mesh-bounding box in the space of the earth model, we sample the geological objects by shooting rays at specified intervals that define a rectilinear mesh. This process is analogous to the scan-line algorithm used in computer graphics for visible-surface determination (see Foley et al., 1995). The intersection points between a ray and the model surface faces are sorted along the ray path in one of the coordinate directions. Then samples representing grid cells are generated along the ray path. For efficiency, the R*tree is used to locate quickly the model faces along the shooting ray. In Figure 8a, a 2-D gridded cross-section generated by this operator is displayed.

V.1 Triangulation operator

This operator triangulates any set of polygonal faces of the model. This operator is very useful to generate initial triangulated surfaces either (1) for further refinement in cross-sections (Figure 8b) or (2) for creating triangulated bounding surfaces that will constrain the tetrahedralization of regions in the model. To triangulate a set of faces we used Delaunay triangulation techniques as described by Shewchuk (1997).

V.3 Tetrahedralization operator

This operator uses the 3-D Delaunay approach to generate initial tetrahedral meshes (Figure 9). We use a flip-based algorithm (Joe, 1989 and Joe, 1991) that has proven to be very robust for our models.

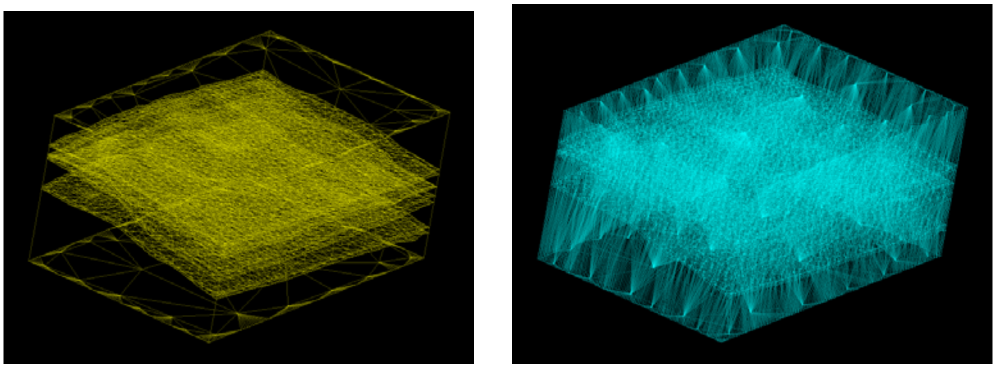

Figure 9 - Macromodel and tetrahedral mesh of a set of stacked reservoirs

V.4 Mesh extraction and merge operators

These operators manipulate voxel representations of an earth model using explicit information about the geometry of geological objects in the model. In Figure 10, an example is shown on which we extract the seismic voxels of three reservoir objects.

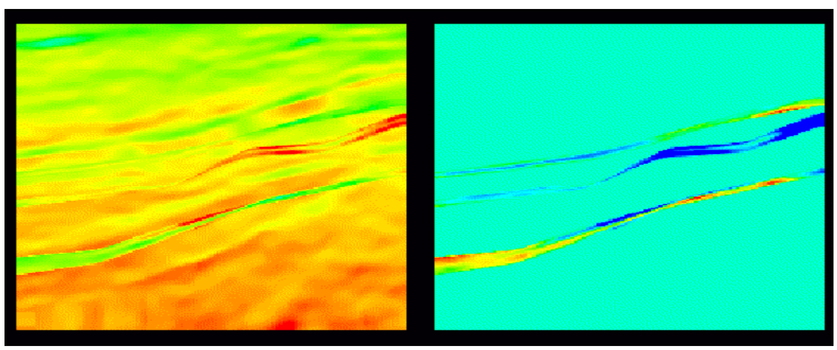

Figure 10 - Extraction of three reservoirs from 3-D seismic data.

VI. An application: heat and fluid transfer surrounding an evolving salt dome

In Figure 11, one application of our modeling framework is shown. In this application, we calculate the temperature and pressure field surrounding an evolving salt dome using finite element methods. Note the deflection of the fluid path around the low-permeability salt and thereby moving the fluid away from reaching the reservoir (in green).

VII. Acknowledgments

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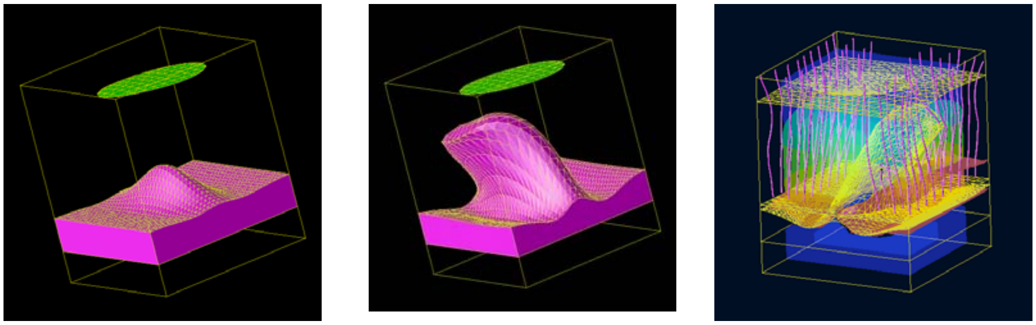

Figure 11 - (a) and (b) Two stages of a salt dome (magenta) evolution and (c) the pressure field and associated streak lines of fluid flow surrounding the dome.

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