GEOMAPPER: A VISUAL BASIC SOFTWARE FOR RECONSTRUCTION AND RENDERING OF 3D SOLID GEOLOGIC MODELS

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ABSTARCT

Reconstruction and visualization of the three-dimensional process models has been recently advanced underpinned with the rapid advances in computer technology and numerical computation algorithms. These modeling approaches has proved promising in predicting geologic, tectonic, and hydrologic processes needed for environmental planning of land-use, hazard mitigation, and sustainable resource management. However, these models require densely distributed data points that are often sparse and scarce. The present work introduces prototype 3D geologic modeling tools developed to assist in constructing 3D models from traditional geologic maps stored as GIS layers taking information depicted on these maps or from drilled-well charts as the source base data. The process-oriented algorithm integrates a successive sequence of geologic events and a logical model. The logical model describes the inter-relationships between the geologic units and its defining boundaries and their 3D surface data represented by the topography. The tools implemented can produce and visualize models ranging from the simple layered sedimentation/erosion to the complexly structured faulted geologic units, based on scattered data, surfaces, 3D grids, and the geologic entity/boundary hierarchy. An interactive lighting technique was implemented to enhance surface details of the model. The tools were encoded into a Visual Basic (VB) program with Arabic and English graphical user interfaces (GUI). The software implemented functions are estimating the continuous surface boundaries using optimal approximation techniques, importing data from other GIS packages like GRASS GIS and ARC GIS, logical model building, interactive setting the visualization and lighting positions, contouring, and outputting the results to bitmapped image format. Outputs include 2D and perspective 3D geologic views, user-defined cross-sections, structure contours, and continuous dip surfaces. Mathematical formulae used for the implemented tools are described. The software was successfully tested and proved promising using fault and landslide data.

Keywords: 3D geologic model, Logical modeling, Model Visualization, GIS, Visual Basic.

1. Introduction

Efficient representation and interaction with three-dimensional (3D) geological models is a topic of high interest for a range of environmental, hazard and resource exploration studies (hydrocarbon, groundwater, geothermal, or mineral resources). Data availability, structure, and representation techniques are crucial for the model usability. Pure statistical techniques are of common use for building very sophisticated 3D geologic models in areas where extensive drilling and 3D geophysical mapping provide a wealth of observation data. These techniques ignore constraints derived from geological knowledge when building model geometries. In many cases, poor outcrops, the expense of acquiring data at depth, and the geological complexity, typically impose constraints on the number and type of field observations that can be recorded in practice. Boundary representation (B-rep) and in particular the Triangular Irregular Networks (TINs) data structure has been extensively used for the 3D solid geologic modeling (Bak and Mill, 1989; Lemon and Jones, 2003; Wu, 2005). However, for further analysis and integration of the model products in geographic information system environments, TINs have a very limited use, and the regular grid structure is an efficient alternative. Therefore, an approach is needed which incorporates data scarcity and the gridded boundary structure, that maintain the logical geologic objects' relationships in 3D geologic modeling practices.

In the present work, as an initial effort, we are developing an interactive graphical modeling environment that could facilitate the construction and rendering of real world 3D geologic models from the scarce observation data available on geologic maps or gathered during field surveys or from boreholes. The modeling mathematical background, implemented features, and examples of fault and landslide 3D solid models are introduced in the next sections.

2. THREE-DIMENSIONAL SOLID MODELING APPROACH

A geologic model, in the developed methodology, is defined as a set of 3D spatial geologic entities represented by their B-rep gridded interfaces (depositional, erosinal, structural, unconformities, and other interfaces) and logical rules that govern their behavior in a geo-referenced system. Boundary surfaces defining various geologic entities can be optimally approximated through integrating location (x, y, z) and orientation data (dip and strike). The orientation data either noted on geologic maps or collected from drill holes can be used to constrain the geometry of the entities at depth. Once all boundary surfaces have been defined in this way, they are assembled into a 3D volume structure according to "logical rules" that specify the underlying and overlying relationships of different geologic entities relative to boundary surfaces. A geologic function can be then defined uniquely to assign a geologic entity to every point in the 3D space and the spatial 3D distribution of entities can be visualized on an objective surface. Properties are then assigned to different entities. A key to the intelligible and complete computer representation of the geological knowledge therefore is the careful representation of the geologic boundaries and their relationships to the different entities.

2.1. BOUNDARY REPRESENTATION (B-REP)

There are several computational algorithms designed to fit a surface to position and orientation data; many are unsuitable for our purpose since they typically require all of the relevant data to be *on* the surface being fitted; we have noted that some of our data – which we must take into account – may be *above* or *below* the geology contact surface that we want to generate. Further, most available tools for representing complex geologic surfaces and volumes are not designed for producing optimal grids for analysis and rendering. Even with a complete understanding of stratigraphy, material properties, boundary conditions, the task of incorporating data into a numerical model can be difficult and time consuming. Shiono, 1987 has developed a constrained approximation technique for automating finite element optimal grid generation that maintains the geometric integrity of geologic structure and stratigraphy. The approximation method produces boundaries that respect simultaneously the scattered elevation or depth information defining the geological boundary position as well as strike and dip data that guide the subsurface orientation of the geological surface. A plenty of such kind of data are already depicted on geologic maps, cross-section, or collected during field surveys or from drill-holes. The algorithm iteratively minimizes the least squared error until an optimal approximation of the sampled observations is reached. More on the mathematical basis behind this approach can be found in Masoud *et al.*, 2008.

The constrained optimization method (Shiono *et al.*, 1987) fits a smooth surface honoring all of the observation data for building the boundaries. Three sorts of field data can be used: equality data (when the relative position of the geologic boundary coincides with the sample data), inequality data (when the relative position of the geologic boundary is above or below sample data), and inclination data (strike and dip of boundary and bedding parallel to boundary). Data determining each boundary surface *f(x, y) are* given in the following format:

$$\text{location } (x_k, y_k, z_k), \text{ index } I_k, \text{ strike } \xi_k, \text{ dip } \eta_k \quad (k = I,...,N),$$

where I_k is an index of the spatial relationship between the outcrop (x_k, y_k, z_k) and the surface $f(x, y)$. The variable $I_k = -1$, 0, and + 1 when the kth outcrop is below, exactly on, and above the surface, respectively. These data provide constraints that the surface $f(x, y)$ should satisfy as follows:

$$f(x_k, y_k) \geq z_k \; (I_k = -1),\; f(x_k, y_k) = z_k \; (I_k = 0),\; f(x_k, y_k) \leq z_k \; (I_k = +1),$$
$$f_x(x_k, y_k) = -\cos \xi_k \tan \eta_k ,\; f_y(x_k, y_k) = \sin \xi_k \tan \eta_k.$$

The residual sum of squares can be evaluated by $\Phi_H(f)$ and $\Phi_D(f)$ as follows:

$$\begin{aligned} \Phi_H(f) &= \sum [f(x_k, y_k) - z_k]^2 && (\text{sum for } I_k = 0) \\ &+\sum [\min \{0, f(x_k, y_k) - z_k\}]^2 && (\text{sum for } I_k = -1) \\ &+\sum [\max \{0, f(x_k, y_k) - z_k\}]^2 && (\text{sum for } I_k = +1), \end{aligned} \tag{2.1}$$

$$\Phi_D(f) = \sum [\{f_x(x_k, y_k) + \cos \xi_k \tan \eta_k\}^2 + f_y(x_k, y_k) - \sin \xi_k \tan \eta_k\}^2]. \tag{2.2}$$

The smoothness can be evaluated by

$$J(f. = m_1 \int [fx^2 + fy^2]\, dxdy + m_2 \int [(fxx)^2 + 2(fxy)^2 + (fyy)^2]\, dxdy$$

(2.3)

The smoothest surface should minimize:

$$\Omega(f;\alpha) = J(f) + \alpha\left[\Phi_H(f) + \gamma\,\Phi_D(f)\right], \qquad (2.4)$$

where α and γ are constants to control the relative weights of $\Phi_H(f)$ and $\Phi_D(f)$, respectively.

When we approximate $f(x, y)$ by discrete values $f = (f_{11}, \ldots, f_{nm})$ on an n x m grid, the smoothness $J(f)$ *is* evaluated in a quadratic form of f. Then we can obtain the optimal solution f^* through successive approximation of $f^{(k)}$, which minimizes $\Omega(f;\alpha_k)$ for the increasing sequence $\{\alpha_k \mid \alpha_1 < \alpha_2 < \ldots \alpha_k\}$.

Equality and inequality data are automatically selected because the variable l_k can be assigned using the logical rules describing relations between geologic entities and boundaries. Further, inclination data can be selected using the parallelism data in the input, as previously described. Therefore, we can determine all boundary surfaces $S_1, S_2, \ldots, S_{n-1}$ automatically.

2.2. LOGICAL MODELING

In nature, the Earth's topographic surface is a boundary between the atmosphere/hydrosphere *open space* (*α*) and the lower 3D *geologic space* Ω consisting of various geologic entities separated by discontinuity boundary surfaces. Since topographic surface is well defined by the digital elevation models, thus defining that any point $f(x, y)$ to belong to the open space or to the geologic space can be easily judged. Based on this, the function $f(x, y)$ that assigns every point in the 3D geologic space a geologic entity can be defined uniquely once the boundary surfaces constituting various entities are well defined. This can be set by a logical model that establishes hierarchical relationships assigning (+), (–), or (*), for entities located in direct contact above, below, or unrelated to their boundary surfaces, respectively. Examples of various geologic settings and their corresponding logical models are described in the following sections.

2.3. RECONSTRUCTION OF 3D GEOLOGIC MODELS

When a boundary surface (S_{event}) defined by $z = s(x, y)$ resulting from discontinuity geologic event like sedimentation (*s*), erosion (*e*), faulting (*f*), divides its surrounding geologic space (*G*) into upper S^{+}_{event} and lower S^{-}_{event} subspaces, then we will have the following relationship:

$$S^{-}_{event} \cup S^{+}_{event} = G \qquad (2.5)$$

where S^{-}_{event} and S^{+}_{event} can be given by:

$$S^{-}_{event} = \{(x, y, z) \mid z < s(x, y)\}, \text{ and } S^{+}_{event} = \{(x, y, z) \mid z > s(x, y) \qquad (2.6)$$

The subscript *event* refers to any geologic event and can be substituted by *e* (erosion), *s* (sedimentation), *f* (faulting), etc. Therefore, any geologic entity can be easily defined by intersecting the 3D subspaces confined to two successive boundary surfaces. Once entities are defined by the corresponding confining boundaries, their solid models can be reconstructed. This process or event-based formulation is true and applicable for any single or complex geologic events (Fig. 3).

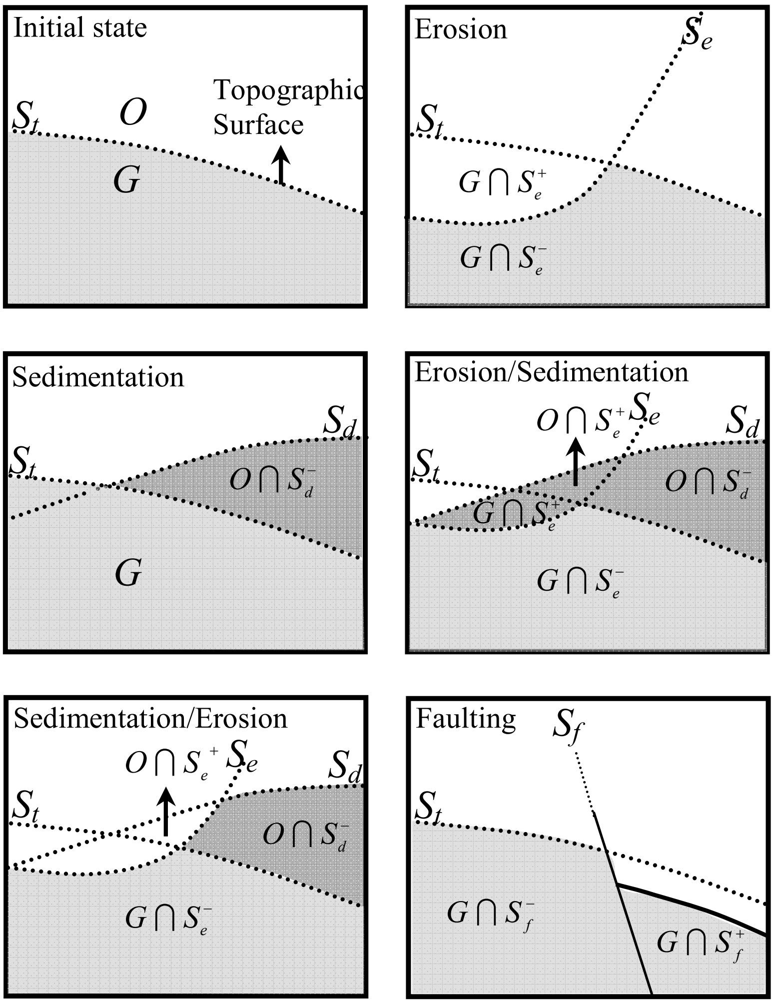
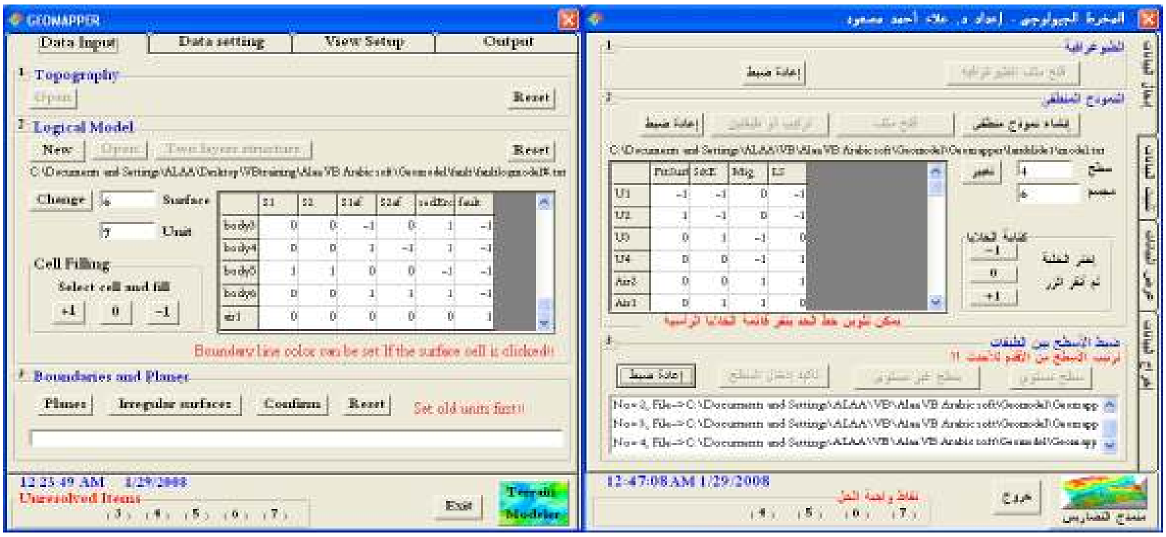


Fig. 3: Concept of event-based definition of geologic entities and surface boundaries (a) Initial state where the space Ω is divided into open (*O*) and geologic (*G*) spaces by a topographic surface (S_t). (b) Erosion, (c) Sedimentation, (d) Erosion followed by sedimentation, (e) Sedimentation followed by erosion, and (f) Faulting.

3. GEOMAPPER IMPLEMENTATION

A set of software tools named GEOMAPPER was developed for modeling boundary surfaces, building logical models, construction of the 3D solid geologic models, and for visualization. In order to take its full advantage of graphical interaction and editing techniques, Visual Basic *Graphic user-interface* (GUI) under Microsoft Windows environment was appraised to design the software. This was also for its wide use and the user-friendly interface that could play a crucial role in the overall usability of the tools and impact the user’s productivity. A task-oriented main four panels are developed included model input, data setting, view setup, and output that can support a.

Input data includes topographic surface, geologic boundaries, and logical models (Fig. 4). Topographic data are either DEMs imported from the commonly used formats such as ARC and GRASS GIS ascii data or generated together with geologic boundaries from scattered irregularly-spaced location and orientation data picked up from maps or from field surveys using GEOSURFER (Masoud, 2008). The tools enable the user to read logical models from text files, to set simple two layer structure model, or interactively setup a new complex logical models based on the geologic history of events like deposition/erosion, faulting, landsliding, or any alternated combination of these events. Boundary surfaces are read from grid files if irregular or can be set interactively for regular planes representing simple bedding and faulting planes. Simple regular dipping planes can be set using a point of exposure (x, y, z) and the heading/angle of dipping.



C:\Documents and Settings\ALAA\Desktop\VBtraining\Alaa VB Arabic soft\Geomodel\fault\faultlogmodel8.txt

Surface: 6

Unit: 7

	S1	S2	S1af	S2af	sedEro	fault
body3	0	0	-1	0	1	-1
body4	0	0	1	-1	1	-1
body5	1	1	0	0	-1	-1
body6	0	0	1	1	1	-1
air1	0	0	0	0	0	1

Boundary line color can be set If the surface cell is clicked!!

Set old units first!!

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Unresolved Items

(3) (4) (5) (6) (7)

C:\Documents and Settings\ALAA\VB\Alaa VB Arabic soft\Geomodel\Geomapper\landslide1\model.txt

	FtrSurf	SdE	Mig	LS
U1	-1	-1	0	-1
U2	1	-1	0	-1
U3	0	1	-1	0
U4	0	0	-1	1
Air2	0	0	1	1
Air1	0	1	1	0

No=2, File->C:\Documents and Settings\ALAA\VB\Alaa VB Arabic soft\Geomodel\Geomapp

No=3, File->C:\Documents and Settings\ALAA\VB\Alaa VB Arabic soft\Geomodel\Geomapp

No=4, File->C:\Documents and Settings\ALAA\VB\Alaa VB Arabic soft\Geomodel\Geomapp

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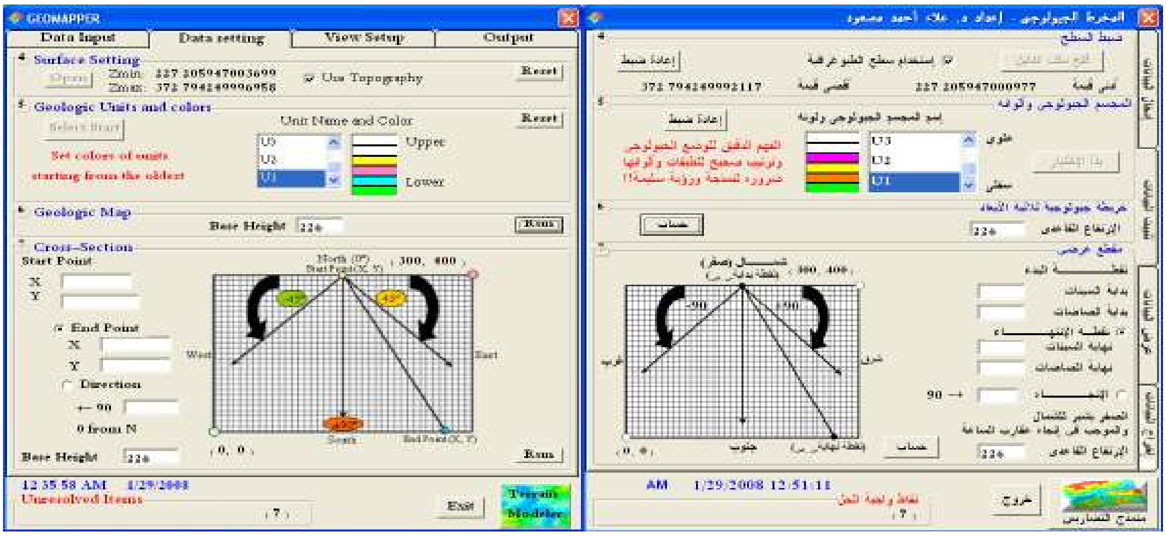
(4) (5) (6) (7)

Fig. 4: Data input panel with English (left) and Arabic (right) GUI.

Data setting panel allows the user to set the 3D model topography, colors for different geologic entities, the base height, and the cross-section geometry (Fig. 5). Cross-sections can be created as a source start point coordinates and the end point is defined either as coordinates or bearing (0 to ±90) from the source. The coordinates of the start and end points are set from the input data displayed on the panel.

Multi-dimensional visualization of the geologic models is essential for the models' efficient interpretation. Visualization process provides a feedback to the model reliability and allows real time monitoring of modifications caused by the different modeling tools which give the user a much more accurate insight of the model than a regular computer screen. The view setup panel in GEOMAPPER provides interactive capabilities to rotate and scale the 2D/3D model, display contours with user-specified start, end, and interval values, set the background colors and the model frames as well as the legend.



Zmin: 227.205947003699
Zmax: 372.794249996958
☑ Use Topography
Base Height 226

Fig. 5: Data setting panel with English (left) and Arabic (right) GUI.

The output from the modeling tools are 2D/3D views of the geologic models and cross-sections that can be saved either to bitmapped images or to the windows clipboard to be edited and retouched in different graphics software packages. Parameters of the drawn geologic map and the cross-section are displayed on the panel to be used as a reference for later use.

4. EXAMPLES FOR 3D SOLID GEOLOGIC MODELS

In order to clarify the applicability of the developed tools, examples for faulted and landslide structures are shown. For the sake of clarity, simple boundary surfaces are represented and combined to build the solid models. However, projecting various complex non-layered geologic entities with irregular boundaries is also possible once their grid boundaries and logical models are available.

4.1. FAULTED GEOLOGIC MODEL

In this example model, a one fault could be satisfactory to construct a geologic model where a one or more data points define the location of the fault, and one or more orientation data define its attitude; then the fault surface can be constructed from these data. The fault surface divides the geologic space into two subspaces; hanging wall (*hw*) and foot wall (*fw*). Geologic entities and boundaries can be defined in reference to these walls (Fig. 6). In addition to the DEM data, boundary surfaces with information show on Table 1 are used to build the model shown on Figure 6. The geologic model is shown on Table 2.

Table 1: Location and orientation information for boundary surfaces of the faulted geologic model shown on figure 6.

Boundary Surfaces	Dip Azimuth	Dip Angle	X	Y	Z
$\mathbf{S1}_{fw}$	90	15	6700	3200	1260
$\mathbf{S2}_{fw}$	90	15	8080	3800	1600
$\mathbf{S1}_{hw}$	90	15	2100	7900	1500
$\mathbf{S2}_{hw}$	90	15	5400	2900	1400
Fault	270	65	6060	3000	1050

Table 2: Logical model of the faulted geologic structure with entities and boundaries defined on figure 6.

	$\mathbf{S1}_{fw}$	$\mathbf{S2}_{fw}$	$\mathbf{S1}_{hw}$	$\mathbf{S2}_{hw}$	**Fault**	**SE**
$\mathbf{E1}_{fw}$	-1	0	0	0	-1	-1
$\mathbf{E2}_{fw}$	+1	-1	0	0	-1	-1
$\mathbf{E3}_{fw}$	0	+1	0	0	0	-1
$\mathbf{E1}_{hw}$	0	0	-1	0	+1	-1
$\mathbf{E2}_{hw}$	0	0	+1	-1	+1	-1
$\mathbf{E3}_{hw}$	0	0	0	+1	+1	-1
$\boldsymbol{\alpha}$	0	0	0	0	0	+1

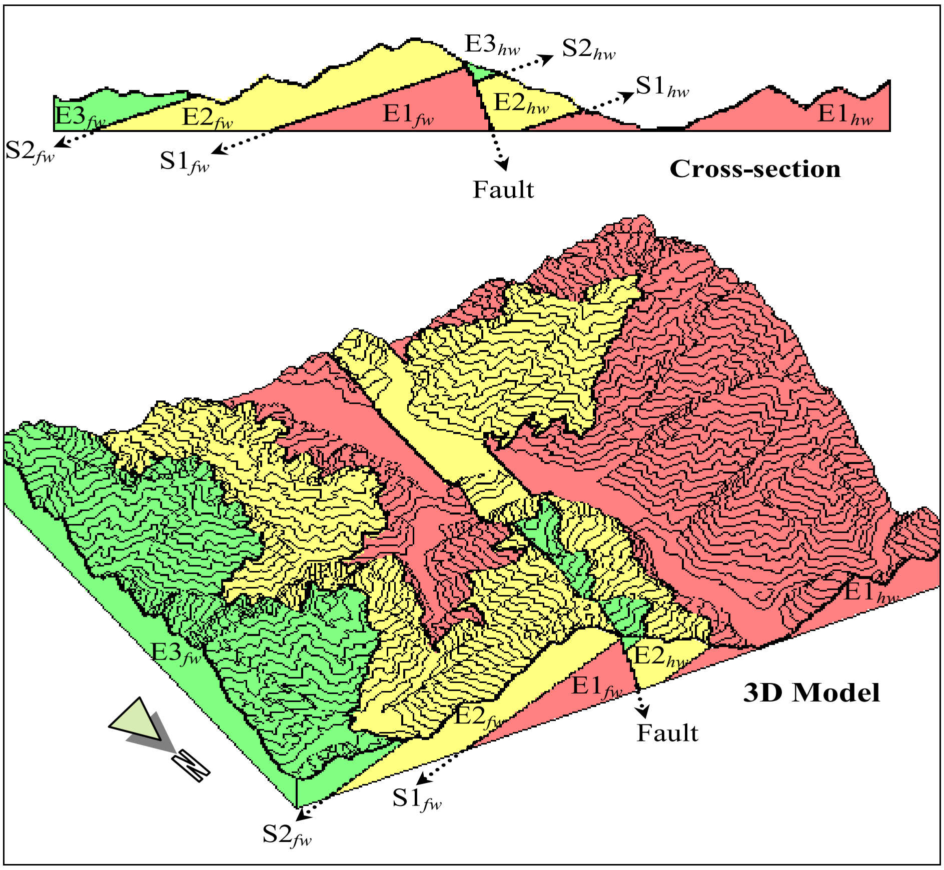
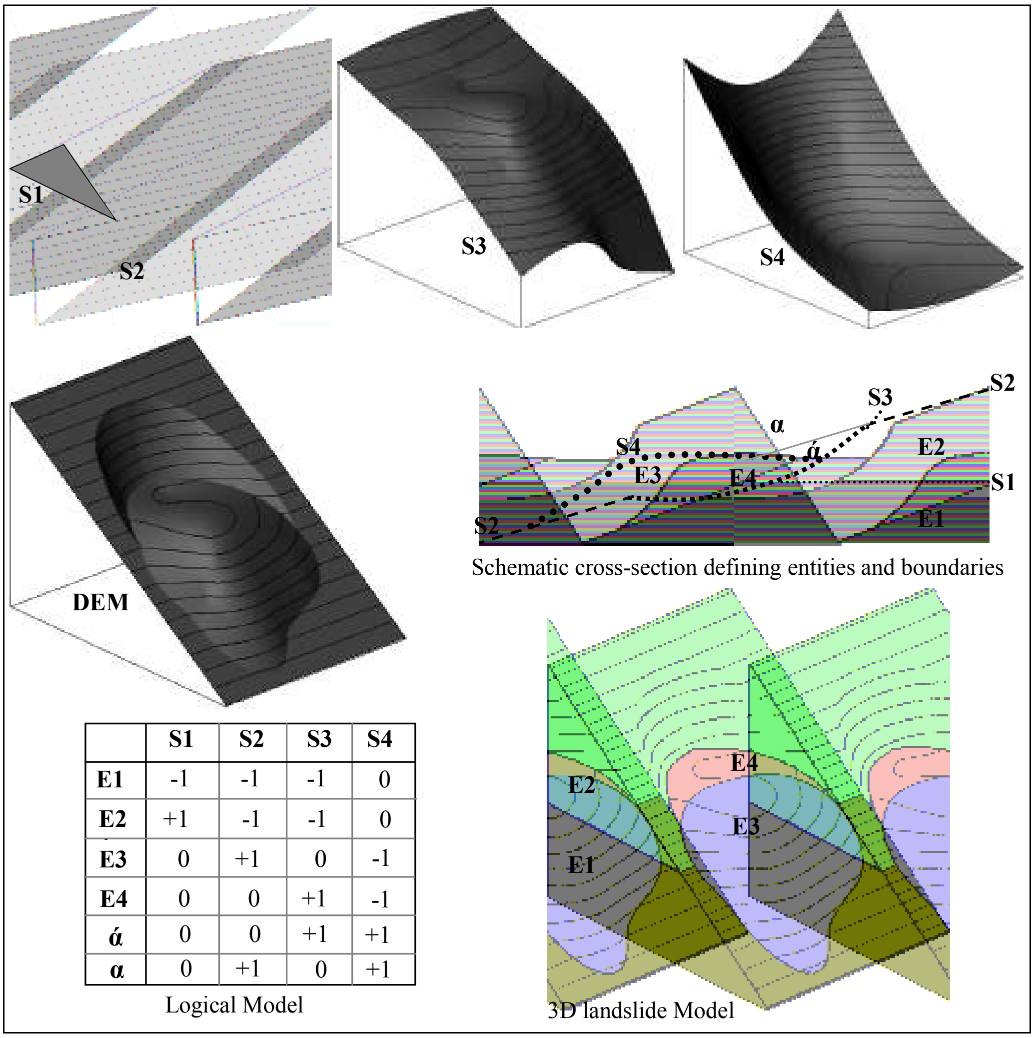


Fig. 6: 3D model of an example faulted geologic structure

4.2. LANDSLIDE MODEL

Grid boundary surfaces represented by DEM, S1, S2, S3, and S4 are used to build the example landslide model shown in figure 7. *S*1 is the boundary surface of open space and filled space during the initial state, *S*2 is the erosion surface after sedimentation of E2, S3 is the slip surface, and S4 is the landform of the slump block E3 and E4. Geologic entities E1, E2, E3, and E4 are defined from the inter-relationship between different boundary surfaces as shown on the logical model. From the logical model when compared to the schematic cross-section on figure 7, the entity E1 is located below S1, S2, and S3 and has no relation to S4. E2 is located above S1, below S2 and S3, and has no direct contact to S4. E3 is not related to S1 and S3, and lies above S2 and below S4. E4 is not related to S1 and S2, and lies above S3 and below S4. The open space ά resulted from slipping has no relation to S1 and S2 and lies above S3 and S4. The original open space α has no relation to S1 and S3 and lies above S2 and S4. From these components, the solid geologic model of the landslide is drawn.



Schematic cross-section defining entities and boundaries

	S1	S2	S3	S4
E1	-1	-1	-1	0
E2	+1	-1	-1	0
E3	0	+1	0	-1
E4	0	0	+1	-1
ά	0	0	+1	+1
α	0	+1	0	+1

Logical Model

3D landslide Model

Fig. 7: 3D landslide model with its constituting boundary surfaces and logic model.

5- CONCLUSIONS

GEOMAPPER was developed and designed to provide a set of software tools throughout all aspects of the 3D solid geologic modeling and visualization process. Tools for 3D solid modeling included the optimal approximation for modeling boundary surfaces (topographic and geologic), building logical models, and the reconstruction of the 3D solid geologic models. 3-D solid geologic models are created by the logical integration of the boundary representations of the geologic entities. Each B-rep is created from elevation or depth information as well as strike and dip data depicted on geologic maps or gathered during field surveys and boreholes. Once the boundaries are built a logical model is proposed based on the stratigraphic setting and the history of geologic events to describe and maintain the hierarchical inter-relationships of entities. The software produces flexible 3D models that permits interactive refinement where complexity of boundary surfaces and entities can be easily implemented with updated interaction with the logical rules. Once the model is generated it may be viewed from any angle and level of magnification. Perspective views as well as cross-sections at any point with various heading and tilt angles can be easily portrayed. The major drawback of the developed package is that discretization of the grid boundary surfaces is a memory-intensive process and hence the computer specifications govern the speed for realizing and rendering large 3D models. The reconstruction methodology presented can be of particular interest for mineral and hydrocarbon exploration, where orientation data are commonly available. The software package, help files, and the example data are available upon request from the author’s website at http://faculty.ksu.edu.sa/Dr.Alaa.Masoud/Pages/DevelopedSoftware.aspx

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