

3-D MODELING AND VISUALIZATION OF GEOLOGIC STRUCTURES USING OPEN SOURCE GRASS GIS

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ABSTRACT

The present work aims at introducing a basic theory, algorithms and implementing methodology for three dimensional modeling and visualization of geologic model using GRASS GIS. 3-D geologic model is constructed from the boundary surfaces of geologic units and the logical model of geologic structure. The algorithms for construction and visualization of the proposed model are based on the geologic function g . The geologic function g assigns a unique geologic unit to every point in the objective 3-D space. The boundary surface that divides the objective space into two subspaces, were estimated using data from field survey. The logical model showing the hierarchical relationship between these boundaries surfaces and geologic units can be automatically generated based on the stratigraphic sequence and knowledge of geologic structures. Based on these algorithms, 3-D geologic model can be constructed virtually on GRASS GIS. Applying this model, various geologic surface and section models can be visualized in GRASS GIS environment. Further, "Nviz" was used for dynamic visualization of geologic cross-sections and generation of animated image sequences.

1. INTRODUCTION

Recently, the need of the geologic information has been rising in many fields such as environmental geology, disaster mitigation, and urban geological applications. For these fields, it is effective to provide geologic information as a 3-D model that can be generated and visualized in general purpose GIS software. The present work aims at introducing a basic theory, implementing methodology and algorithms for 3-D modeling and visualization of geologic model using the Open Source GRASS GIS environment.

2. BASIC THEORY AND ALGORITHMS

2.1 Geologic function and logical model of geologic structure

Let a 3-D subspace Ω be a survey area and suppose that the area Ω is composed of n geologic units that are relatively prime:

$$b_1 \cup b_2 \cup \dots \cup b_n = \Omega, \quad (1)$$

$$b_i \cap b_j = \phi \quad (i \neq j). \quad (2)$$

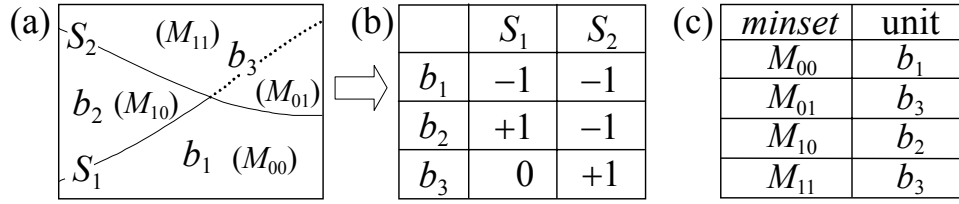


Figure 1. Basic elements of a geologic model. a) relation between geologic units and surfaces in geologic section, b) logical model (+1; S_i^+ , -1; S_i^- , and 0; no specific relation with the surface.), c) relational code table.

In order to realize a 3-D geologic visualization in the GIS environment, we have introduced a concept of a geologic function \mathbf{g} which assigns a unique geologic unit to every point in the 3-D space Ω (Sakamoto *et al.*, 1993; Shiono *et al.*, 1994).

$$\mathbf{g} : \Omega \rightarrow \mathbf{B}, \text{ where } \mathbf{B} = \{b_1, b_2, \dots, b_n\}. \quad (3)$$

Fundamentals of the geologic function \mathbf{g} is explained using a simple geologic structure composed of three geologic units as shown in Fig. 1(a). Three geologic units b_1 , b_2 and b_3 are defined by two boundary surfaces S_1 , and S_2 which divide Ω into two subspaces as follows;

$$b_1 = S_1^- \cap S_2^-, \quad b_2 = S_1^+ \cap S_2^-, \quad b_3 = S_2^+, \quad (4)$$

where S_i^+ and S_i^- give subspaces that lie above and below the surface S_i , respectively. These equations can be expressed in a tabular form as shown in Fig. 1(b). The above equations and table define the relation between geologic units and their boundaries, i.e. the logical model of geologic structure (Sakamoto *et al.*, 1993).

As the geologic units b_1, b_2, \dots, b_n are defined by surfaces, they can be expressed in a “*minset standard form*” (Gill, 1976). The *minset* is a minimum subspace that is divided by the boundaries $S_1, S_2, \dots, S_i, \dots, S_{n-1}$ in the 3-D space Ω . Let $Md_1d_2\dots d_i\dots d_{n-1}$ be a *minset* defined by ;

$$Md_1d_2\dots d_i\dots d_{n-1} = h_1(d_1) \cap h_2(d_2) \cap \dots \cap h_i(d_i) \cap \dots \cap h_{n-1}(d_{n-1}), \quad (5)$$

$$\text{Where } h_i(d_i) = \begin{cases} S_i^+; d_i = 1 \\ S_i^-; d_i = 0 \end{cases}.$$

In the case of Fig. 1(a), four *minsets* can be defined as follows;

$$M_{00} = S_1^- \cap S_2^-, \quad M_{01} = S_1^- \cap S_2^+, \quad M_{10} = S_1^+ \cap S_2^-, \quad M_{11} = S_1^+ \cap S_2^+, \quad (6)$$

The *minset standard forms* can be derived for the geologic units as follows;

$$b_1 = M_{00}, \quad b_2 = M_{10}, \quad b_3 = M_{01} \cup M_{11}. \quad (7)$$

It is evident that each *minset* is included in only one of geologic units as shown below;

$$M_{00} \subset b_1, \quad M_{01} \subset b_3, \quad M_{10} \subset b_2, \quad M_{11} \subset b_3. \quad (8)$$

The relation between *minsets* and geologic units can be expressed by a function \mathbf{g}_1 from a class of *minsets* \mathbf{I} into \mathbf{B} :

$$\mathbf{g}_1: I \rightarrow B. \quad (9)$$

This function \mathbf{g}_1 can be represented by the relational code table shown in Fig. 1(c).

Further, for a point $P(x, y, z)$ in a space Ω , a *minset* $Md_1d_2\dots d_i\dots d_{n-1}$ can be assigned a value of $d_i=1$ or $d_i=0$ depending on whether $P(x, y, z)$ falls in S_i^+ or S_i^- , respectively. This correspondence between every points in Ω and *minsets* is expressed by a function \mathbf{g}_2 :

$$\mathbf{g}_2: \Omega \rightarrow I. \quad (10)$$

Consequently, a convolution of functions $\mathbf{g}_1: I \rightarrow B$ and $\mathbf{g}_2: \Omega \rightarrow I$ provides a rule to define the geologic unit that includes a given point $P(x, y, z)$:

$$\mathbf{g}(x, y, z) = \mathbf{g}_1(\mathbf{g}_2(x, y, z)). \quad (11)$$

The function $\mathbf{g}: \Omega \rightarrow B$ defines a rule to assign a unique geologic unit to every point in a 3-D space Ω .

2.2 Geologic profiles and Geologic boundary surfaces

According to the definition of geologic function \mathbf{g} , a point on the boundary surface is included in the lower side of the boundary. When the point on the boundary was input to the geology function \mathbf{g} , It was defined that the point belongs to the *minset* under the boundary by the function \mathbf{g}_2 . Therefore, the point lying on the boundary and the region under the boundary have the same geologic unit name. In the vertical section, the boundary surface is shown as a boundary line, and the *minset* is shown as a polygon of the *minset* section surrounded by the multiple boundary line. This polygon and the upper boundary line bounding this polygon have the same geologic unit name. Consequently, the geologic profile can be drawn by assigning the polygon of the *minset* with the color corresponding to the geologic unit name of the upside boundary line.

In the function \mathbf{g} , the boundary surface that divides a space Ω into two subspaces is not a geologic boundary surface. Removing the area where upper and lower sides of the boundary surface are the same geology can show the geologic boundary surfaces that actually exist as a boundary of the geologic unit. This judgment can be drawn by comparing the geologic unit name on either side of the boundary surface using the geologic function \mathbf{g} .

3. GEOLOGIC MODEING ON GRASS GIS

Based on the suggested algorithms, 3-D geologic model can be constructed virtually by implementing the geologic function \mathbf{g} on GRASS GIS. This geologic function \mathbf{g} has been modified to create the geologic category raster file of the input objective raster surface. The function \mathbf{g}_2 is constructed from the raster data defining the boundary surface elevation including topographic surface. Determination of the function \mathbf{g}_2 is implemented using a raster map calculation function “r.mapcalc”. In practice, a simple rule for the calculation can be constructed according to the number of boundary surfaces. The following 3 steps for each grid cell of the objective surface S_o can express this rule. Step 1; obtain the relation of the height between the surface S_o and every boundary surfaces (if lower and on surface then set

to “0”, or if higher then set to “1”), step 2; generate the binary code to arrange the boundary surfaces in their ascending order, step 3; convert the binary code into an integer number to create the respective cell value. For example, it is assumed that m is a number of the boundary surface, and $S_1, S_2, \dots, S_i, \dots, S_m$ is the raster file name of these boundary surface. The *minset* raster surface Mo of the objective surface So can be calculated by the following equation of the `r.mapcalc` command.

$$\begin{aligned} > \text{r.mapcalc } Mo = \text{if}(So-S_1,1,0,0)*2^{m-1} + \text{if}(So-S_2,1,0,0)*2^{m-2} + \dots + \text{if}(So-S_i,1,0,0)*2^{m-i} \\ & \quad + \dots + \text{if}(So-S_m,1,0,0)*2^0 \quad (\text{where } 2^k \text{ is the real value of } 2^k) \end{aligned}$$

The function g_1 is implemented to represent the geologic category map on the objective surface using the reclassification function “`r.reclass`” and the reclassification table converted from relational code table. The reclassification table file can be converted into integer from binary number of the relation code table. For example, it is assumed that Lm is a reclassification file name, and Mo is a *minset* surface calculated before. The geologic category map Go of objective surface So , can be accomplished by following “`r.reclass`” command and options.

$$> \text{r.reclass input} = Mo \text{ output} = Go < Lm \quad (\text{where, “} < \text{” is a redirection of unix}).$$

Finally, the geologic features along the objective surface can be visualized with the raster files Go and So using “`d.rast`”, “`d.3d`” and “`Nvis`”. Applying this method, various geologic surface and section models without vertical section can be visualized in GRASS GIS environment.

For the geologic profile filled by the color of geologic unit, the raster files that are defined as the geologic category number on the boundary surface can be calculated by the geologic function g . Here, it is assumed that the S_i is a elevation raster file of the boundary surface, and L_i is a *minset* raster file for S_i . The geologic category number raster files G_i can be calculated by the following;

$$\begin{aligned} > \text{r.mapcalc } L_i = \text{if}(S_i-S_1,1,0,0)*2^{m-1} + \text{if}(S_i-S_2,1,0,0)*2^{m-2} + \dots + \text{if}(S_i-S_i,1,0,0)*2^{m-i} \\ & \quad + \dots + \text{if}(S_i-S_m,1,0,0)*2^0 \quad (\text{where } 2^k \text{ is the real value of } 2^k). \end{aligned}$$

$$> \text{r.reclass input} = L_i \text{ output} = G_i < Lm .$$

For drawing the geologic boundary surfaces, the mask files must be defined to all boundary surfaces. These mask files can be generated by comparing the geology on either sides of the boundary. The lower side files were already calculated as the files G_i . Therefore, the calculation of the upper side files are only necessary. For example, it is assumed that H_i is a *minset* raster file for the upper side of the surface S_i . The geologic category number raster file U_i for the upper side of the surface can be calculated by the following;

$$\begin{aligned} > \text{r.mapcalc } H_i = \text{if}(S_i-S_1,1,1,0)*2^{m-1} + \text{if}(S_i-S_2,1,1,0)*2^{m-2} + \dots + \text{if}(S_i-S_i,1,1,0)*2^{m-i} \\ & \quad + \dots + \text{if}(S_i-S_m,1,1,0)*2^0 \quad (\text{where } 2^k \text{ is the real value of } 2^k). \end{aligned}$$

$$> \text{r.reclass input} = H_i \text{ output} = U_i < Lm .$$

The change of this equation means that the boundary surface is attributed to the upper side *minset* in the function g_2 . Finally, the mask file Ma_i can be calculated by the `r.mapcalc` command as follows;

> r.mapcalc $Ma_i = \text{if}(G_i - U_i, 1, 0, 1)$.

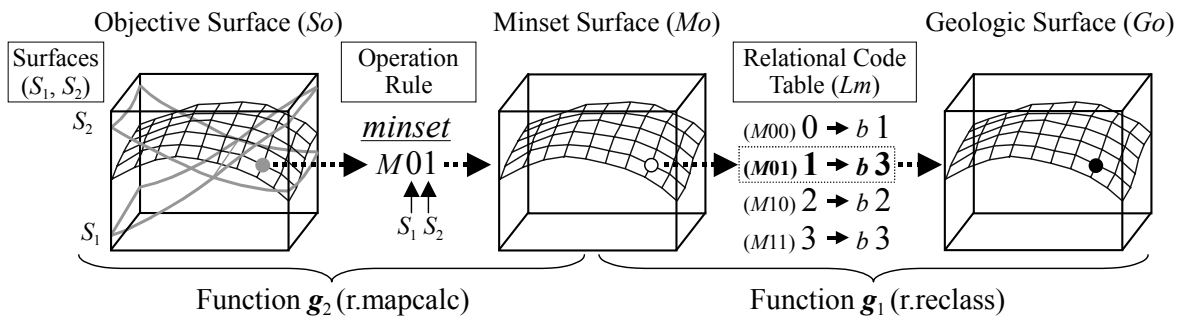


Figure 2. Flow of the 3-D geologic modeling using geologic function.

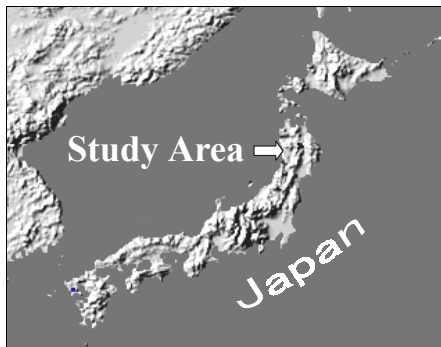


Figure 3. Location map of the study area.

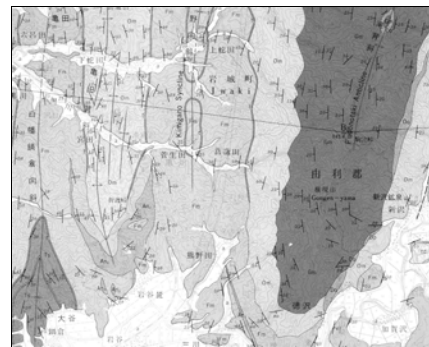


Figure 4. Geologic map of the study area.
(8.7x6.5km; Osawa *et al.*, 1977)

Table 1. Logical model of the geologic structure. (S1,...,S4; boundary surfaces, S5; DEM)

	S1	S2	S3	S4	S5
Gongenyama F.	-1	0	0	-1	0
Onnagawa F.	+1	-1	0	-1	0
Funakawa F.	+1	+1	-1	-1	0
Tentokuji F.	+1	+1	+1	-1	0
Alluvial Deposits	0	0	0	+1	-1
α (air)	0	0	0	+1	+1

The forementioned steps must be done to all of the boundary surfaces. To visualize the geologic boundary surfaces, the surfaces S_i and Ma_i are set to the topography and mask respectively in the surface panel of Nviz. For the geologic profile, the surfaces G_i is established to the surface color and the “T” is specified to paint section by color of the upper line in the cutting-plane of Nviz.

4. CASE STUDY

The study area is located in Honjyo region of Akita Prefecture, Northeast Japan (Fig. 3). The logical model of this area is shown in Table 2. The surfaces were estimated by Horizon2000 (Shiono *et al.*, 2001) using data extracted from geologic map (Fig. 4; Osawa *et al.*, 1977). The geologic boundary surfaces S1 and S5 are shown in Fig. 5. Examples of the horizontal and vertical sections are presented in Fig. 6 using 3-D geologic model.

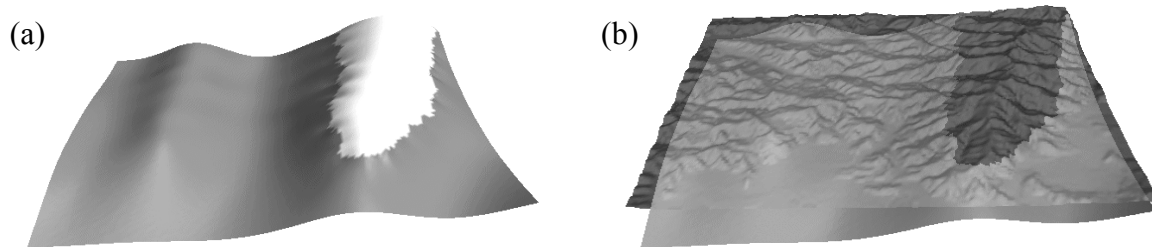


Figure 5. Geologic boundary surfaces. (a) Surface S1, (b) Surface S1 and S5 (DEM).

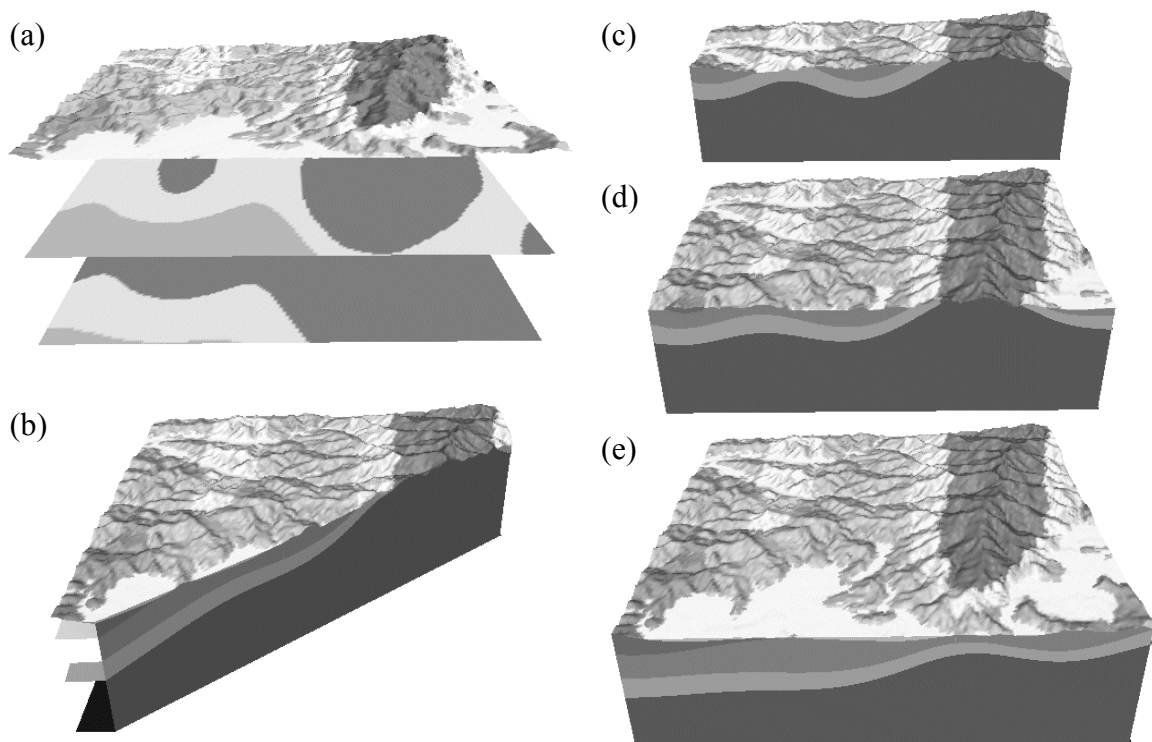


Figure 6. Examples of the horizontal and vertical sections using 3D geologic model. (a) Horizontal sections (top; DEM, middle; 0m, bottom; -500m), (b)~(e) Vertical sections.

5. REFERENCES

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