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Three-dimensional Reconstruction of Geological Solids Based on Section Topology Reasoning

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Abstract In order to solve the dynamic reconstruction and local updating problem of three-dimensional geological solids, topology reasoning is used for three-dimensional geological modeling. This can advance the level of the corresponding section automation in implementing the 3D geological solid dynamical reconstruction by the construction of and reasoning on topology on the 3D curved surface. This method has been successfully used in the Nanjing city geological modeling and the Zijin gold mine modeling. The results prove that this method adapts to coplanar section and noncoplanar section data, and improves the efficiency of 3D geological modeling.

Keywords geological section; topology reasoning; 3D geological solid reconstruction
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Introduction

Because most of the geological solids are covered up, they are invisible such that their survey data are often indirect and not self-contained. Qualitative data, from which much geological knowledge is based, could not be used for geological modeling in the past. The problem with three-dimensional geological solid reconstruction is always a difficult one [1,2,3]. Since the 1990s, many experts have thought that dynamical reconstruction based on the pure grid division method can suit simple spatial solids or regular spatial solids but not complex spatial solids. Much more geological knowledge and artificial intelligence reasoning are needed in the process of complex geological modeling as it can not implement dynamical reconstruction automatically. So this research places emphasis on the fact that the dynamical reconstruction method of geological solids has changed from pure spatial modeling data structure and algorithms to geological knowledge expression and reasoning in the process of the dynamical reconstruction of geological solids.

In 1998, Chiaruttini C et al. studied the problem of applying spatial reasoning in the geological modeling procedure. They used a subsurface model and discussed the spatial restriction rule problem and the problem of diagnosing the geological model. Perrin M presented the geological syntax for the first time, and discussed geological consistency. In 1999, Roberto et al. discussed artificial intelligence reasoning algorithm in the process of explaining geology. In 2002, Schoniger et al. brought forward geological reasoning analysis under uncertain conditions, and

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used it in their research on underground water solid reconstruction. In 2005, Minor et al. studied the geological structure modeling algorithm based on case reasoning. On the basis of SEM (Shared Earth Model), Perrin presented the knowledge-driven modeling method which could be used in petroleum basin reconstruction. Its data structure was also a subsurface model[11]. In China, Wu Chonglong et al. presented a new geological modeling method based on B-Rep and coding attributes in 1998[1]. In 2000, Wu Lixin et al. presented the General Tri-Prism Model[3]. In 2006, Zheng Liang and Li Deren presented an event-driven space-time data model. They did not study the model reconstruction method. Although the research achievements mentioned above did not study section topology reasoning in geological solid reconstruction, they advanced spatial reasoning application research in geological solid modeling, and laid a foundation for the study of dynamical reconstruction of geological solids.

In order to resolve the geological section correspondence problem and enable the three-dimensional geological solid model to be reconstructed and updated dynamically, this paper presents a dynamic modeling method based on noncoplanar geological section topology reasoning. By geological section topology relationship construction and reasoning on the three-dimensional curved surface, this method increases the dimensions of the geological section correspondence, and implements three-dimensional geological modeling dynamically. This method has been used in the Nanjing city geological modeling by implementation of GeoView software. The results indicate that this method is suitable for many kinds of section data, which include coplanar sections and noncoplanar sections, and improves the efficiency of 3D geological modeling.

1 Generation of topology on noncoplanar sections

The section data is the main source of 3D geological modeling. In existing modeling methods based on section data, the sections are mostly coplanar surfaces, and the surfaces of the 3D geologic solids often are generated by contour lines on the section in the process of modeling[5,7,8]. This kind of modeling method mainly includes four problems, i.e. the correspondence problem, tiling problem, branching problem, and fitting problem[12]. Studies have presented 3D geological modeling from topological cross-sections, but the topology on the sections is constructed manually[9,11]. Auto-generation of the topology on the noncoplanar section is still a key and difficult problem.

1.1 Three-dimensional topology model

In vector spaces, the number of topology relationships between two linear spatial objects is 56; the number of topology relationships between two area spatial objects is 57; the number of topology relationships between one linear spatial object and one area spatial object is 97[4]. If we import the point spatial object and solid spatial object into the three-dimensional vector space, the topology relationships formed by them will be very complex. We thus need to predigest the topology model around the noncoplanar section. Fig.1 is the predigestion model of the three-dimensional topology. The object whose prefix is “geom” is the geometry object. The object whose prefix is “topo” is the topology object. We use *TopoPoint, TopoPolyline, TopoPolygon, TopoSurface* and *TopoSolid* to represent the 3D topology relationships. The *TopoPolygon* represents a simple polygon object, and the *TopoSurface* represents a curved surface with topology relationship. To some degree, a *TopoSurface* object is a noncoplanar section with topology relationship. We can also use many *TopoSurface* objects to represent a noncoplanar section with topology relationship if we wish.

For the auto-generation topology relationship on the noncoplanar section, we use the extended 3D node (*TopoPoint*), 3D Arc (*TopoPolyline*), and 3D face (*TopoPolygon* and *TopoSurface*) to represent the topology on the noncoplanar section. *TopoPoint* is a kind of special 3D point; it can be the start node or the end node of the *TopoPolyline*. *TopoPolyline* is a 3D directional curve; it can only intersect with other *TopoPolylines* on the 3D node. The *TopoPolygon* is a coplanar polygon in 3D space, whose boundary is composed of some 3D arcs. The *TopoSurface* is a set of *TopoPolygons*. It can be noncoplanar. The *TopoSolid* is composed of one or many *TopoSurfaces* and a mesh in the solid space. The construction of the topology relationship on the curved surface or on the noncoplanar section is based on the frontal four topology objects. This model resolves the compatibility problem between the 2D topology model and the 3D topology model.

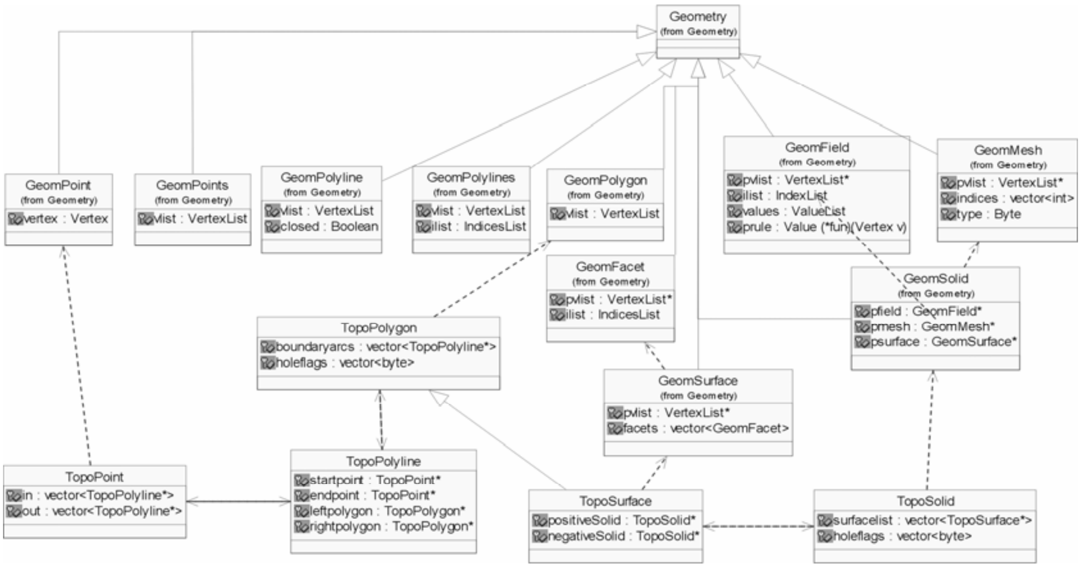


Fig.1 Three-dimensional topology data structure model

1.2 Auto-generation algorithm of topology relationship on a curved surface

At present, the auto-generation algorithms of 2D topology are ripe[13-17], but there is no algorithm implemented for the auto-generation of 3D topology. This paper thus presents an algorithm, called the auto-generation of topology on the 3D curved surface based on projection (AGTP), to solve this problem. The basic principle is to set up the projection relationship between the 3D section and the 2D section and ensure the topology is not changed by projection. The main steps are as follows.

1) S is the origin section. By polyline intersection and cut calculation, we obtain the node table and the arc table. By this step, for example, the section shown in the Fig.2 will generate Tables 1 and 2.

2) Handle micro-arcs and hanging arcs.

3) Select the projection plan. The selection of the projection plan must ensure that the topology relationships have not been changed after the projection is executed. If the coplanar plan S_p is the projection plan of section S, any vertical line of S_p has only one intersection point with section S. This is very important. The essential part of this step is to set up a projection matrix M_p. The M_p must have a converse matrix, noted as M_r, for a successful conversion opera-

Table 1 Node list

Node name	In-arc	Out-arc
P_1	L_1, L_2	L_7
P_2	L_3, L_4	L_1
P_3	L_5, L_7	L_4, L_6
P_4	L_6	L_5, L_8
P_5	L_8	L_2, L_3

Table 2 Arc list

Arc name	Start node	End node	Left polygon	Right polygon
L_1	P_2	P_1	NULL	NULL
L_2	P_5	P_1	NULL	NULL
L_3	P_5	P_2	NULL	NULL
L_4	P_3	P_2	NULL	NULL
L_5	P_4	P_3	NULL	NULL
L_6	P_3	P_4	NULL	NULL
L_7	P_1	P_3	NULL	NULL
L_8	P_4	P_5	NULL	NULL

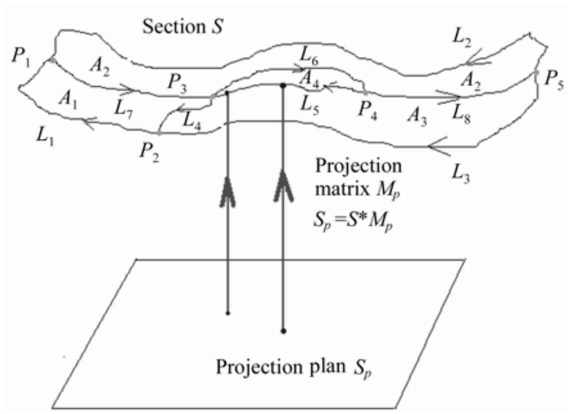


Fig.2 Noncoplanar section and projection plan

tion.

4) Projection transformation. Transform the arcs and nodes by the projection matrix, with the projection plan being S_p. If we want to use an existing 2D topology reconstruction algorithm, we can add a rotation and translation matrix, called M_t (the matrix must have A converse matrix), which can make S_p*M_t parallel to the XOY, or XOZ, or YOZ plan. The nodes transformed by M_p*M_t are called PP_i, corresponding to P_i. The arcs transformed by M_p*M_t are called LP_i, corresponding to L_i. This operation can transform the noncoplanar section into a coplanar section (Fig.3).

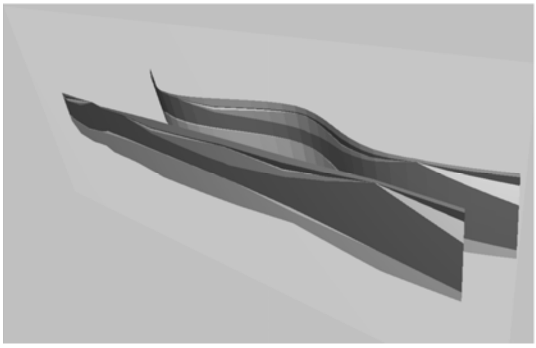


Fig.3 Noncoplanar section and projection section

5) Select LP_i, obtain its start node and end node, and call the start node P_s.

6) If the left polygon of LP_i is empty, left polygon searching will be done. Get the end node firstly, get all the arcs connected with this node secondly, then eliminate the arcs positioned at the right of LP_i; select the arc called LP_t, which ensures that the inclination between LP_i and LP_t is minimal.

7) Let LP_i=LP_t, repeat step 6 until the end node of LP_t (if the directions of the two adjacency arcs are face to face, it will be the start node of LP_t) is equal to P_s, save all the passed arcs, and construct the polygon AP_l using the arcs. Then set the left polygon or left polygon of the arcs to be equal to AP_l.

8) If the right polygon of LP_i is empty, right polygon searching will be done. Get the end node firstly, then get all the arcs connected with this node, then eliminate the arcs positioned at the left of LP_i; select the arc called LP_t, which ensures that the inclination between LP_i and LP_t is minimal.

9) Let LP_i=LP_t; repeat step 8 until the end node of LP_t (if the directions of the two adjacency arcs are face to face, it will be the start node of LP_t) is equal to P_s, store all the passed arcs and construct the polygon AP_l using the arcs, then set the left polygon or left polygon of the arcs to be equal to AP_l.

10) Repeat steps 5 to 9 for all the arcs, and the topology will be constructed. The polygon set we obtained is called ASP, APS= $\{AP_i|0<i<m$, m is the number of the polygons$\}$.

11) Replace $\{LP_j\}$ with $\{L_j\}$, and reconstruct the polygon A_i; the $\{ LP_j \}$ is the arc list of AP_i. Do this operation for all the polygons on the projection plan and set up the 3D topology relationship model. If the reverse matrix of M_p*M_t is valid, the geometric information of the topology polygons can be received by the reverse transformation.

By all of the steps above, we can construct the topology relationship on the 3D curved surface. In this paper, the 3D curved surface is in the noncoplanar section. The following topology reasoning for modeling is based on it.

2 Topo-reasoning for modeling

In this paper, the geology section topology reasoning adopts a production system. A production system (or production rule system) is a computer program typically used to provide some form of artificial intelligence, which consists primarily of a set of rules about behavior. These rules, termed productions, are a basic representation found useful in AI planning, expert systems and action selection. A production system provides the mechanism necessary to execute productions in order to achieve some goal for the system. Productions consist of two parts: a sensory precondition (or “IF” statement) and an action (or "THEN"). If a production's precondition matches the current state of the world, then the production is said to be triggered. If a production's action is executed, it is said to have fired. A production system also contains a database, sometimes called working memory, which maintains data about the current state or knowledge, and a rule interpreter. The rule interpreter must provide a mechanism for prioritizing productions when more than one is triggered.

2.1 The rules of reasoning for 3D modeling

For the sake of a compact and clear statement, we bring out the following definitions.

Definition 1 The unique property, which is used to judge whether topology polygon *A* and *B* are of the same type or not, is called the key type property. For instance, if topology polygon *A*'s stratum lithology is *Q*, it is represented as *KeyTypeProperty*(*A*,*Q*).

Definition 2 The adjacent key type property set is a set composed of all the key type properties of topology polygon *A*'s adjacent topology polygons. This operation is called *AdjacentKTPSet*.

Definition 3 If polygon *A* on section *SA* and polygon *B* on section *SB* are both part of the same geological solid , and the two polygons corresponded with each other, then we say that *A* matches *B*, represented as *Corresponding* (*A*, *B*).

Definition 4 If sections *SA* and *SB* are adjacent to each other, polygon *A* is on section *SA*, noted as *Existing* (*SA*, *A*); but if the polygon matching *A* on section *B* does not exist, it is noted as *Inexisting* (*SB*, *A*); then *A* is annihilating on section *SB*, represented as *Annihilating*(*SA*, *A*, *SB*).

Definition 5 If sections *SA* and *SB* are adjacent to each other, the polygon *A* is on the section *SA*, and the key type property is *Q*; there are two polygons B_1 and B_2 on section *SB*, and both the two polygons' key type property are *Q*; then *A* has two branches on section *SB*, noted as *Bifurcating*(*A*, B_1, B_2).

Notice Definition 5 just states cases 1 to 2. The other bifurcating cases are complex, but they all can be brought out case by case.

Definition 6 The basic rule in the process of topology reasoning for modeling based on geological sections is as follows.

If topology polygon *A* is on the section S_1, and the topology polygon *B* is on section S_2, they can fit the four conditions:

(1) *A* and *B* have the same stratum lithology *Q*;

(2) *A* and *B* have the same topology node numbers;

(3) *A* and *B* have the same topology arc numbers;

(4) *A* and *B* have the same adjacent key type property sets.

Then we say that *B* is the extension of *A* on section S_2. If so, polygon *A* and *B* will be connected to tiling. We can list all the facts of the relationships among the sections, topology polygons, arcs, and notes, and then do reasoning based on the facts and the rules. In this way, the section corresponding problem is transformed to the topology reasoning problem. In the next content, we will discuss the topology reasoning in the following four cases.

2.2 Topology reasoning and modeling for the case which has no topology change

Shown in Fig.4 is the common simple geological section series wherein the adjacent two sections have the same topology relationship set. We can thus build the fact database and rule database for reasoning and the polygon corresponding query.

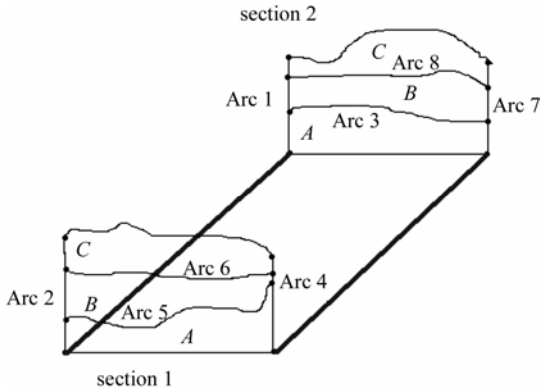


Fig.4 Simple section series

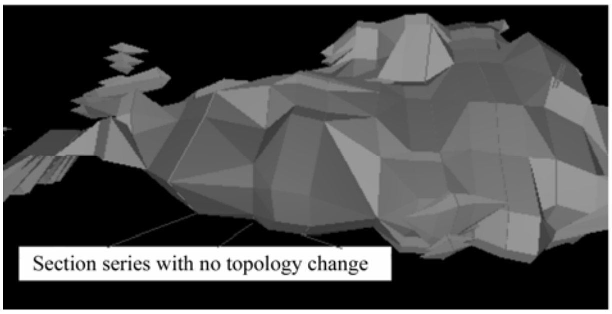


Fig.5 Mine solid constructed by a simple section series

The corresponding polygon is the key to implement the dynamic reconstruction of the geology solid based on the sections. The code above implements the corresponding reasoning of the two polygons on different sections. The problems left for the dynamical reconstruction is the tiling and fitting. The references have presented the solutions for these two problems[8], and we will not discuss them again in this paper. In the next context we will often refer to this method about topology reasoning and modeling for the case in which no topology change occurs. We briefly call it the "Basic Method". Fig.5 shows a part of an actual mine solid constructed by this method.

2.3 Topology reasoning and modeling for the case which has stratum annihilation

Geologic actions such as faults, magma inrush, etc., may result in stratum annihilation. Stratum *B* appeared in section 1, but not in section 2, as shown in Fig.3. In this condition, the annihilation stratum *B* can not find the corresponding stratum on the adjacent section. So we need to insert a dummy section named section1-2 between section 1 and section 2 by the half-distance rule. In the process of mutual modeling, the operator can judge which cases have stratum annihilation, but the computer can not because only the operator can reason on the information he obtains using his/her brain. In order to make the computer have the capability to reason on this case, a reasoning model based on the annihilation stratum case must be constructed firstly.

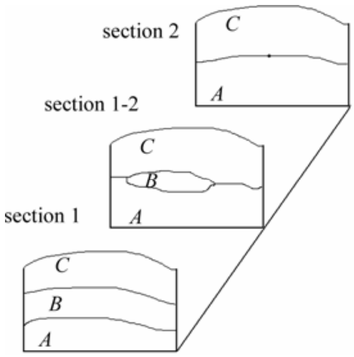


Fig.6 Section series with stratum annihilation

The rule for judging stratum annihilation among the adjacent sections is that if stratum *A* appears on section *SA* but not on section *SB*, then stratum *A* annihilates on section *SB*. In this way, we can let the computer judge the stratum annihilation. In the case that has stratum annihilation, the procedure of modeling is no different from the case stated in the "Basic Method" except for the judging and reasoning on stratum annihilation additionally. Otherwise, definition 6 must erase condition (2), condition (3) and condition (4) for the geological solid reconstruction in this case. Fig.7 shows an actual mine solid model for this case.

2.4 Topology reasoning and modeling for the case that has stratum bifurcation

In the actual geological environment, there is another instance called the stratum bifurcation which

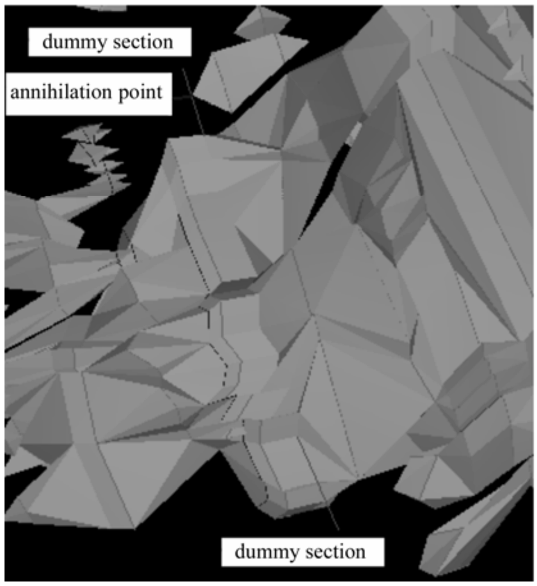


Fig.7 Mine solid with annihilation case

does not include stratum annihilation. Section 1 shows a mine solid contour and a wall rock contour, but the mine solid contour is divided into two contours in section 2 in Fig.8. In this case, the mine solid contour polygon can not find its corresponding polygon on section 2 directly. So we must insert a dummy section named section1-2 between section1 and section 2 by the half-distance rule if stratum bifurcation appears.

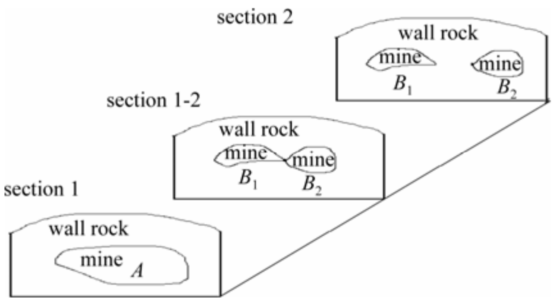


Fig.8 Section series with stratum bifurcation

In the procedure of mutual modeling, the operator can directly judge which case has stratum bifurcation, but the computer can not. So the most important thing is to make the computer have the capability to reason on the case that has stratum bifurcation.

We note the mine solid contour polygon on section 1 as *A*, and the mine solid contour polygons on section 2 as B_1 and B_2. The key type property of the mine solid is *Q*. In the case that has stratum bifurcation, the procedure of modeling has no difference with the case stated in 2.3 except for the judging and reasoning for the stratum bifurcation additionally. It must be denoted that this paper aims just to study the case with 1 to 2 branches; the other bifurcating cases are complex, but they all can be concluded by this simple case. Fig.9 shows an actual mine solid model for this case.

Fig.9 Mine solid bifurcating case

2.5 Topology reasoning and modeling for the case that has faults

Because of the influence of faults, the touch relationships among the strata may change. Stratum break and slippage will happen with fault action. It will result in the arc set of the fault, and the polygons connected to these arcs change. All of these will make the polygon corresponding by the algorithm in 2.1 abort. In order to state the situation clearly, we insert a dummy assistant section named section 1-2 between section1 and section 2, shown in Fig.10.

In section 1, there are three geological solids originally, but in the presence of faults, the three geological solids are divided into nine geological monocases. They are B_1, B_2, and B_3, which have the same lithologies B, A_1, A_2, A_3, and C_1, C_2, C_3, which have the same lithology C. There are still two faults named F_1 and F_2 in section 1. The fault F_1 is composed of 5 arcs, the wide line arc named $Arc\_F_1\_A$ is special because the left and right polygons' lithology are both A. In the same way, there are still two special arcs named $Arc\_F_1\_B$ and $Arc\_F_1\_C$. This type of arc, wherein the key type properties of the left polygon and right polygon are the same, is called the "connatural arc". The properties of the connatural arcs are named "connatural arc properties".

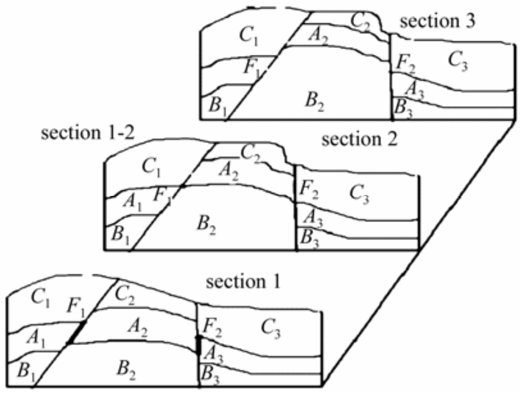


Fig.10 Section series with faults

When the two adjacent sections with the faults can fit the following two conditions: ① the numbers of the connatural arcs included by the corresponding fault pair are equal to each other; ② the connatural arc property set of the connatural arcs included by the corresponding faults are equal to each other. We consider that there are no topology changes between the two adjacent sections. In this case, we can use the method in the "Basic Method" for modeling.

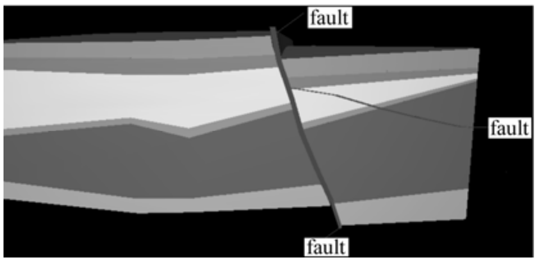
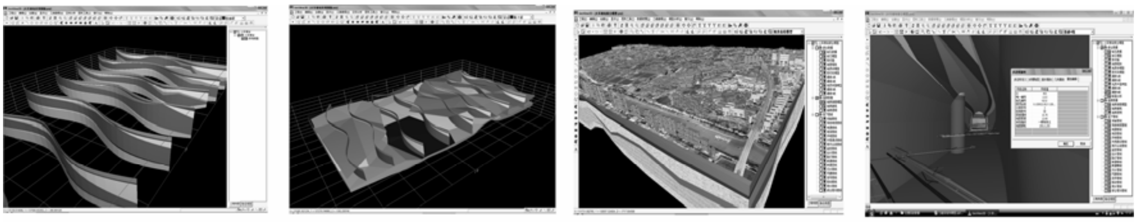


Fig.11 Geological solid with faults

If any one of the two conditions is false, there are topology changes happening between the two adjacent sections. This is the rule used by the computer to judge whether there is a need to insert a dummy section or not. Except for the judging and reasoning on the fault and topology, the procedure of modeling is the same as in 2.1, but the conditions of definition 6 must be changed. The change is that all the arcs in the faults in the section should not be counted in arc operations. Fig.11 shows an actual geological solid model for this case.

3 Results and conclusions

In order to solve the dynamic reconstruction and part updating problem of three-dimensional geological solids, topology reasoning is imported to three-dimensional geological modeling, and the complex cases with stratum annihilation, stratum bifurcation and fault action are discussed in this paper. This method increases the dimensions of the geological section correspondence, and advances the level of the section automation corresponding to implement the 3D geological solid dynamical reconstruction by the construction and reasoning of topology on the 3D curved surface. This method has been used in the Nanjing city geologic modeling and the Zijin gold mine modeling successfully. Fig.12 shows some results. Fig.12(a) shows the imported noncoplanar sections; Fig.12(b) shows the geological solid constructed by these noncoplanar sections; Fig.12(c) shows the integration geological solid model created by this method; Fig.12(d) is the cutting model of mode *C* in Fig.12(c). This proves that this method is fit for coplanar section and noncoplanar section data, and improves the efficiency of 3D geological modeling.



(a) (b) (c) (d)

Fig.12 Some results implemented by this method in GeoView

References

[1] Wu Chonglong (1998) Development and applications of geological and mineral resources information system (GMPIS)[J]. *Earth Science-Journal of China University of Geosciences*, 23(2): 194-198

[2] Wu Chonglong, Liu Gang, Tian Yiping, et al. (2005) Discussion on geological information science[J]. *Geological Science and Technology Information*, 24(3): 1-8

[3] Wu Lixin, Shi Wenzhong (2005) On three dimensional geosciences spatial modeling[J]. *Geography* ,1:1-4

[4] Du Xiaochu (2005) Research on equivalency of spatial topological relations in multiple representation[D]. Wuhan: Wuhan University, 2005

[5] Wu Chonglong, Mao Xiaoping, et al.(2006) Digital basins and their 3D visualization modeling[J]. *Geological Science and Technology Information*, 25(4): 1-9

[6] Tipper J C (1976) The study of geological objects in three dimensions by the computerized reconstruction of serial sections[J]. *Geology*, 84 (4): 476-484

[7] Muller H, Klingert A (1993) Surface interpolation from cross sections[J]. *Focus on Scientific Visualization*, 1: 139-189

[8] Herbert M J, Jones C B (2001) Contour correspondence for serial section reconstruction: complex scenarios in paleontology[J]. *Computers & Geosciences*, 4: 427-440

[9] Wang Yong, Xue Sheng, Pan Mao, et al.(2003) An automatic 3D vector data creation algorithm based on topology of section[J]. *Computer*, 39(5): 1-2

[10] Mallet J L(1989) DSI: discrete smooth interpolation[J]. *ACM Transactions on Graphics*, 8 (2): 121-144

[11] Qu Honggang, Pan Mao, Wang Yong, et al. (2006) Three-dimensional geological modeling from topological cross-sections[J]. *Acta Scicentiarum Naturalum Universitis Pekinesis*, 11, 42(6): 717-723

[12] Meyres D, Skinner S, Sloan K (1992) Surfaces from contours[J]. *ACM Transactions on Graphics*, 11(3): 228-258

[13] Qi Hua, Liu Wenxi (1996) Qi algorithm for node-arc topology relation construction[J].*Aata Geodaeticaet Cartographica Sinca*, 25(3): 233-235

[14] Yang Haihong, Li Tianhong, Xu An (1998) Optimization on automatic topological relation generating algorithm with double neighboring point judgment method[J]. *Journal of Image and Graphics*, 3(7): 583-587

[15] Yan Haowen, Yang Weifang (2000) A fast algorithm of topological polygon auto-construction based on azimuth calculation[J]. *Journal of Image and Graphics*, 5A(7): 563-567

[16] He Zhenwen (2007) Progressive simplification of general meshes in geological modeling[C]. 2007IAMG, Beijing