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Research Article

A Formal Representation of the Semantics of Structural Geological Models

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A structural geological model describes the structure of subsurface and plays an important role in the exploration of mineral and petroleum resources. Despite the widespread use of three-dimensional geological models, the theoretical research of informatics in the field of structural geology is still very limited. We have noticed a lack of methods for integrating explicit semantics of field observation data and geophysical data into geological models. The existing model representation methods focus on accurately representing the geometric morphological information of underground structures, ignoring the high-level semantics implied in the model. The formal representation of the semantic information is necessary to promote the development of intelligent methods in geomodeling and geophysical inversion. In this paper, we propose a new framework to formally represent the semantics of structural geological models with a clear distinction of geometric and geological semantics. For the geometric semantics, based on the extension of the 9-intersection model, we mathematically define the spatial topological relations between geometric objects that make up the geological model. For the geological semantics, we define the geological contact and compositional relations between geological bodies and geological surfaces and reveal the temporal implications of these geological relationships. We design a multilayer heterogeneous network as a computer characterization of the semantics of the geological model. A better representation of semantic information aids in the creation and validation of geological models, as well as management, queries, and analyses of geological knowledge.

1. Introduction

A three-dimensional structural geological model is an important tool for visualizing subsurface structures. It provides the basis for reservoir prediction, seismic inversion, velocity analysis, and spatial parameterization of forward models [1–4]. Since Houlding [5] proposed the concept of three-dimensional geological modeling, a variety of geological models with different representation methods have been developed [3, 6–9].

In general, geological models can be divided into three categories: surface-based models (represented by TIN, GRID, b-rep, cross section model, multilayer DEM model, etc.), voxel-based models (represented by 3D grid, tetrahedron mesh, octree model, triangular prism model, etc.), and hybrid models [2, 10, 11]. These representations of the model can describe the geometric morphology of geological structures well, but there is a lack of a comprehensive description of the knowledge contained in the model; that is, they are weak in describing the implied semantics. The semantics of geological models should also contain information about the elements that make up the model, the topology, and the logic of the geological assemblage. Only the representation of the geometric information is no longer sufficient to meet the requirements of a series of applications, such as automatic rationality judgment, query, sharing, and management of geological models, as well as the development of intelligence geomodeling methods [12–15]. Perrin and Rainaud [16] proposed in the Shared Earth Modeling project that it is necessary to link the semantics of geological data with the final geological model. Ailleres et al. [17] emphasized in the geomodeling system Loop that only using geometric information to describe geological structures will increase the exploration risks. A geological model built without semantics is often difficult to match the geoscientist's assumptions about the area. The Glass Earth Project also emphasized the need to mine the knowledge contained in the basic data in order to reuse existing exploration data. In this context, a formal semantic representation framework for geological models that integrates multiple information will bridge the gap between knowledge and data and ultimately promote geological modeling to the semantic level.

The purpose of this paper is to provide theoretical definitions of the relations between elements in the models to achieve a more comprehensive and formal representation of structural geological models. We believe our proposed framework to be the first of its kind providing a systematic approach in formalizing semantics of geological models with a clear distinction between geometric and geological semantics. Geometric semantics describes the spatial relations (geometric topology) between geological objects, and geological semantics describe the logical relations (geological contacts) between them. Our main innovation concerns the mathematical definition of spatial topological and geological contact relations of geological objects. We have made extensions to the topology of geology proposed by Thiele et al. [18] and the point-set topological spatial relations proposed by Egenhofer and Franzosa [19].

The paper is organized in the following manner. The related works of spatial knowledge representation and some methods that express the hidden information of geological models to a certain extent are introduced in Section 2. In Section 3, we put forward the concept and detailed definitions of the semantic description of structural geological models, including the frameworks of geometric and geological semantic representation. Section 4 introduces a multilayer heterogeneous network as the computer characterization method of the frameworks defined in the previous section. Section 5 describes in detail an example of the semantic representation of a real structural geological model from Northwest China. Section 6 discusses the aspects of the semantic representation framework that will be improved soon and its potentials. Section 7 presents the conclusions.

2. Related Works

Knowledge representation has always played very important roles in geology, such as geological data and model sharing [20, 21], integration of multisolution geological models and queries on heterogeneous data [22], uncertainty evaluation for geological structures [23, 24], among other geoscience problems.

We have mentioned that the semantics of geological models can be divided into geometric and geological. Many efforts have been made to describe the geometric semantics of general objects, usually in the form of qualitative spatial relations [25], such as cone-shaped direction [26], projection-based direction [27], and double-cross direction calculus [28]. Among them, RCC (Region Connection Calculus) [29–33] and n-intersections [19, 34–36] are the most representative. Many existing approaches are extensions or improvements of these two approaches. RCC introduces a set of eight jointly exhaustive and pairwise disjoint binary relations representing mereotopological relationships between ordered pairs of individuals (usually abbreviated as RCC8). N-intersections are defined based on the point-set topology, and it is also the basis for our innovations in geometric semantic representation in this paper. Egenhofer [34] first considered the internal and boundary characteristics of a region (a two-dimensional entity) and then described the topological relationship between the two regions through a 2×2 matrix (4IM). In subsequent studies, Egenhofer [35] and Egenhofer and Franzosa [19] additionally considered the exterior of each region, resulting in a 3×3 matrix (9IM). Chen et al. [37] proposed V9I by replacing the exterior of 9IM with the Voronoi region of the entity. Ouyang et al. [38] divided the outside of a concave area into two parts and the inside and outside of the convex shell and expanded the 9IM to 16IM. Further 61 relations are possible between 0-, 1-, 2-, and 3-dimensional entities in three-dimensional space [36].

There are still few studies on semantics representations of geological models, and existing efforts are also closely related to the geometric topology. As discussed by Caumon [39], geological objects can be represented in geometrical and topological terms. Thiele et al. [18] first put forward the geological structural topology. It is divided into three orders according to the dimensions of geological elements. In a typical two-dimensional geological space (geological maps or cross sections), the first-order topology describes the relations between geological bodies (domains or regions in the two-dimensional space), including stratigraphic, unconformable, faulted, and intrusive relations. The second-order topology describes the relations of geological surfaces and the third-order describes the relations of junctions of surfaces. Some applications have used the 2^{nd}- and 3^{rd}-order topology to describe fracture networks [40, 41]. In addition, Wang et al. [42] used the 9IM to generate mathematical definitions for different types of geological objects. It shows that formal definitions can help quickly find impossible topology configurations that depend on the types of geological objects. Knowing what is topologically impossible provides valuable insights for testing the validity of geological models [43]. Baikov et al. [44] used the topological relations of elementary cubes (cubic complexes) to represent oil and gas reservoirs. It differs from other works in that it uses the Betti numbers as the main topological characteristics.

Although as stated above the geological models can be semantically characterized to some extent by the original methods, it is still insufficient to establish a complete semantic representation. For example, 9IM is difficult to adapt to the diversity and complexity of actual geological models since it cannot define all possible topological relations among three-dimensional objects, especially the detailed adjacency relationships, which is what the geological model focuses on. It is also necessary to describe not only the relationships between objects of the same type but also the relationships between cross-dimensional objects, while the geological structural topology provides a preliminary topological description of the model but lacks formal definitions of the structure contacts and the associations between different types of geological objects, which is meaningful for the construction and query of geological models. Therefore, on the basis of these works, we further refine the characterization of the geological model to establish a more comprehensive semantic description system. Our framework attempts to integrate different types of semantics to provide a representation of geological models from different aspects. First, we propose a geometric topology representation based on the extension of the 9-intersection model, which can accurately describe the contact of objects in three-dimensional space and unify the representation of the relationships between objects in different dimensions. Then, we formally define tectonic contact based on the combination of geological events and time, because the chronological sequence of geological events creates geological objects and defines the geological assemblages.

3. Semantic Description of Structural Geological Models

3.1. The Definition of Semantics. "Semantics" is still a new term in geological researches, so we must first clarify the differences between the semantics and data of geological models. The research on image understanding has made exemplary achievements in semantic representation. The semantics of an image includes not only low-level information, such as texture and boundary, but also high-level information, such as how the objects are related to each other [45–47]. Therefore, we believe that the semantics of geological models should also include directly perceivable information and abstract relational information. Geometry is directly expressed by the geological model data, while the relational information is implied in the data and requires expert knowledge to extract such information.

In a word, we define that the components of semantics include a symbolic representation of physical objects (called semantic entities), qualitative relationships between objects (called semantic relations), attributes, and specific data. The semantics of a geological model can be formally defined by the following pair:

Definition 1

$$\text{GeoSemantics} = \{E, R\}. \tag{1}$$

In (1), $E = \{S, C, \mathbf{D}, \mathbf{A_E}\}$ represents a semantic entity, including the symbol (S) that represents the entity, the concept (C) inheres in the entity, the set of specific data ($\boldsymbol{D}$), and the set of attributes of the entity ($\mathbf{A_E}$). $R = \{E_1, E_2, \mathbf{A_R}\}$ represents a semantic relation, which includes a pair of semantic entities (E_1 and E_2) and the set of attributes of the relation ($\mathbf{A_R}$). Relations between semantic entities of the same type are called adjacency relations, while those of different types are called association relations. The choice of attributes of entities and relations depends on the requirements of specific applications. For structural geological models, it can be the occurrence of structures, the lithology of the geological bodies, the geological time, and so on. The specific data refers to the structural interpretation and field observations. The concept inhering in the entity is constrained by domain ontologies, like the StructuralGeoOntology proposed by Babaie et al. [48]. Triple $\langle E_1, R, E_2 \rangle$ is the basic unit in sematic representation, called a *semantic unit.*

3.2. Geometric Semantics. The geometric semantics aims to provide the representation of geological models from a geometric perspective. According to the principle of space segmentation, a geological model can be decomposed into a set of simple geometric shapes that make up the model [49]. These constituent elements are semantic entities in geometric semantics, which we call n-cells, and $n = \dim(A)$ refers to the dimension of the entity A. The semantic entities can be divided into 4 categories: 3-cell (closed bodies), 2-cell (surfaces in 3D space), 1-cell (lines in 3D space), and 0-cell (points in 3D space) entities. The geometric semantic relations describe the spatial topological relations among the entities. The main theory behind the geometric semantic representation is the point-set topology. We have mentioned that Egenhofer [35] proposed the 9-intersection model (9IM) to describe the relations of two two-dimensional objects:

$$R^9(A, B) = \begin{bmatrix} A^o \cap B^o & A^o \cap \partial B & A^o \cap \overline{B} \\ \partial A \cap B^o & \partial A \cap \partial B & \partial A \cap \overline{B} \\ \overline{A} \cap B^o & \overline{A} \cap \partial B & \overline{A} \cap \overline{B} \end{bmatrix}. \tag{2}$$

A^o, ∂A, and $\overline{A}$ represent the interior, boundary, and exterior of A, respectively, where $A^o \cup \partial A = A$, $U - A = \overline{A}$, and U represents universal. Based on 9IM, there are eight basic relations between two cells: disjoint, equal, meet, overlap, cover, coverby, contain, and inside. As we mentioned before, describing geological models also requires the relations between 0-, 1-, and 3-dimensional and cross-dimensional cells. Therefore, we introduce additional elements to extend the 9IM to more accurately describe the spatial relationships of cells, especially the boundary contact relations.

In our opinion, for each n cell A ($n \geq 2$), the boundary of A (∂A) can be regarded as an individual ($n-1$) cell and also has its own interior and boundary, denoted as $(\partial A)^o$ and $\partial^2 A$, also with $(\partial A)^o \cup \partial^2 A = \partial A$. Therefore, when A is a 3-cell entity, ∂A represents the surfaces that compose A, $\partial^2 A$ represents the lines that compose each boundary surface of A, and $\partial^3 A$ indicates the boundary of $\partial^2 A$, that is, representing the endpoints of the lines. $(\partial A)^o$ and $(\partial^2 A)^o$ represent the interior of the surface and line. It also follows that $(\partial^2 A)^o \cup \partial^3 A = \partial A$. This is the same for a 2-cell entity; $(\partial A)^o$ is the interior of its borderlines and $\partial^2 A$ is the endpoints of the borderlines. The entities corresponding to these extended symbols are shown in Figure 1.

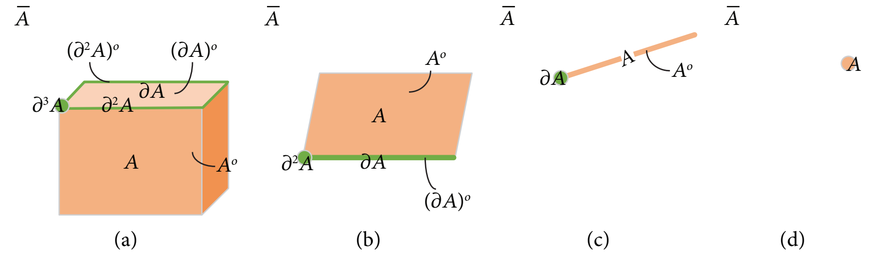


Figure 1: The extended components of the geometric semantic entities based on 9IM. (a) 3-cell, (b) 2-cell, (c) 1-cell, and (d) 0-cell entities.

In general, there are 7 kinds of entities that can be used to describe the 3-cell relations: $\overline{A}$, A^o, ∂A, $(\partial A)^o$, $\partial^2 A$, $(\partial^2 A)^o$, and $\partial^3 A$. Therefore, all semantic relations between 3 cells based on extended entities can be defined by the following 7×7 matrix:

$$R^{49}(A,B) = \begin{bmatrix} A^o \cap B^o & A^o \cap \overline{B} & A^o \cap \partial B & A^o \cap (\partial B)^o & A^o \cap \partial^2 B & A^o \cap \left(\partial^2 B\right)^o & A^o \cap \partial^3 B \\ \overline{A} \cap B^o & \overline{A} \cap \overline{B} & \overline{A} \cap \partial B & \overline{A} \cap (\partial B)^o & \overline{A} \cap \partial^2 B & \overline{A} \cap \left(\partial^2 B\right)^o & \overline{A} \cap \partial^3 B \\ \partial A \cap B^o & \partial A \cap \overline{B} & \partial A \cap \partial B & \partial A \cap (\partial B)^o & \partial A \cap \partial^2 B & \partial A \cap \left(\partial^2 B\right)^o & \partial A \cap \partial^3 B \\ (\partial A)^o \cap B^o & (\partial A)^o \cap \overline{B} & (\partial A)^o \cap \partial B & (\partial A)^o \cap (\partial B)^o & (\partial A)^o \cap \partial^2 B & (\partial A)^o \cap \left(\partial^2 B\right)^o & (\partial A)^o \cap \partial^3 B \\ \partial^2 A \cap B^o & \partial^2 A \cap \overline{B} & \partial^2 A \cap \partial B & \partial^2 A \cap (\partial B)^o & \partial^2 A \cap \partial^2 B & \partial^2 A \cap \left(\partial^2 B\right)^o & \partial^2 A \cap \partial^3 B \\ \left(\partial^2 A\right)^o \cap B^o & \left(\partial^2 A\right)^o \cap \overline{B} & \left(\partial^2 A\right)^o \cap \partial B & \left(\partial^2 A\right)^o \cap (\partial B)^o & \left(\partial^2 A\right)^o \cap \partial^2 B & \left(\partial^2 A\right)^o \cap \left(\partial^2 B\right)^o & \left(\partial^2 A\right)^o \cap \partial^3 B \\ \partial^3 A \cap B^o & \partial^3 A \cap \overline{B} & \partial^3 A \cap \partial B & \partial^3 A \cap (\partial B)^o & \partial^3 A \cap \partial^2 B & \partial^3 A \cap \left(\partial^2 B\right)^o & \partial^3 A \cap \partial^3 B \end{bmatrix}. \quad (3)$$

The semantic relations between other n cells can be defined by a $(2n+1) \times (2n+1)$ matrix, so, similarly, the following 5×5 matrix can be used to represent the relations between 2 cells:

$$R^{25}(A,B) = \begin{bmatrix} A^o \cap B^o & A^o \cap \overline{B} & A^o \cap \partial B & A^o \cap (\partial B)^o & A^o \cap \partial^2 B \\ \overline{A} \cap B^o & \overline{A} \cap \overline{B} & \overline{A} \cap \partial B & \overline{A} \cap (\partial B)^o & \overline{A} \cap \partial^2 B \\ \partial A \cap B^o & \partial A \cap \overline{B} & \partial A \cap \partial B & \partial A \cap (\partial B)^o & \partial A \cap \partial^2 B \\ (\partial A)^o \cap B^o & (\partial A)^o \cap \overline{B} & (\partial A)^o \cap \partial B & (\partial A)^o \cap (\partial B)^o & (\partial A)^o \cap \partial^2 B \\ \partial^2 A \cap B^o & \partial^2 A \cap \overline{B} & \partial^2 A \cap \partial B & \partial^2 A \cap (\partial B)^o & \partial^2 A \cap \partial^2 B \end{bmatrix}. \quad (4)$$

Moreover, the relations between 1-cell entities can be defined by the original 9IM (see (2))

In general geometric topology, a simple cell is defined as a geometric shape that is spatially connected, is non-self-intersecting, and has no internal boundaries. However, the actual geological bodies and geological surfaces may have holes on or in them [25]. In our semantic representation framework, we define these holes as a special kind of entity as well, since the holes also have important geological significance. For example, karst caves are important oil and gas storage spaces and are often part of a geological model that needs to be characterized with emphasis. A hole B in a block (3-cell entity) or on a patch (2-cell entity) is also a 3- or 2-cell entity with $B^o = \varnothing$. Hole B must be inside or covered by the patch or block. We show some common adjacency relations between the geometric semantic entities of the same dimension in Figures 2–4.

The association relations are defined to describe the semantic relations between an $(n-1)$ cell and an n cell $(n \geq 1)$ and can be represented by a $(2n-1) \times (2n+1)$ matrix. Then, we put forward the following 3 matrixes:

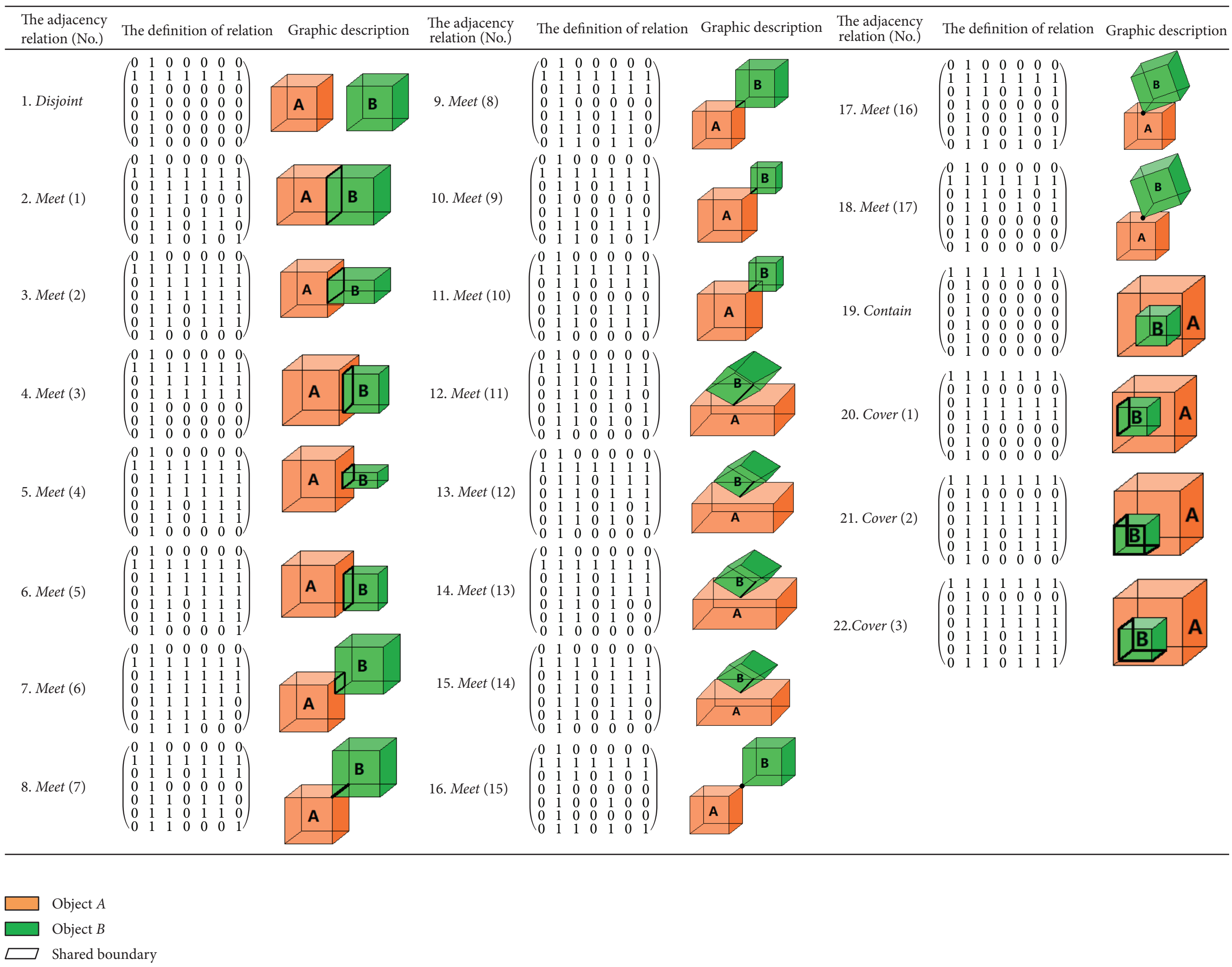


FIGURE 2: The adjacency relations of simple 3 cells.

$$R^{35}(A,B)=\begin{bmatrix} A^o\cap B^o & A^o\cap\overline{B} & A^o\cap\partial B & A^o\cap(\partial B)^o & A^o\cap\partial^2 B & A^o\cap\left(\partial^2 B\right)^o & A^o\cap\partial^3 B \\ \overline{A}\cap B^o & \overline{A}\cap\overline{B} & \overline{A}\cap\partial B & \overline{A}\cap(\partial B)^o & \overline{A}\cap\partial^2 B & \overline{A}\cap\left(\partial^2 B\right)^o & \overline{A}\cap\partial^3 B \\ \partial A\cap B^o & \partial A\cap\overline{B} & \partial A\cap\partial B & \partial A\cap(\partial B)^o & \partial A\cap\partial^2 B & \partial A\cap\left(\partial^2 B\right)^o & \partial A\cap\partial^3 B \\ (\partial A)^o\cap B^o & (\partial A)^o\cap\overline{B} & (\partial A)^o\cap\partial B & (\partial A)^o\cap(\partial B)^o & (\partial A)^o\cap\partial^2 B & (\partial A)^o\cap\left(\partial^2 B\right)^o & (\partial A)^o\cap\partial^3 B \\ \partial^2 A\cap B^o & \partial^2 A\cap\overline{B} & \partial^2 A\cap\partial B & \partial^2 A\cap(\partial B)^o & \partial^2 A\cap\partial^2 B & \partial^2 A\cap\left(\partial^2 B\right)^o & \partial^2 A\cap\partial^3 B \end{bmatrix}, \quad (5)$$

$$R^{15}(A,B)=\begin{bmatrix} A^o\cap B^o & A^o\cap\overline{B} & A^o\cap\partial B & A^o\cap(\partial B)^o & A^o\cap\partial^2 B \\ \overline{A}\cap B^o & \overline{A}\cap\overline{B} & \overline{A}\cap\partial B & \overline{A}\cap(\partial B)^o & \overline{A}\cap\partial^2 B \\ \partial A\cap B^o & \partial A\cap\overline{B} & \partial A\cap\partial B & \partial A\cap(\partial B)^o & \partial A\cap\partial^2 B \end{bmatrix}, \quad (6)$$

$$R^{3}(A,B)=\begin{bmatrix} A^o\cap B^o & A^o\cap\overline{B} & A^o\cap\partial B \end{bmatrix}. \quad (7)$$

The previous matrixes, respectively, define the association relations between 2 and 3 cells (see (5)), 1 and 2 cells (see (6)), and 0 and 1 cell (see (7)). The common association relations with their definition matrixes and graphic descriptions are shown in Figure 5.

R^n matrix can define 2^n relations theoretically, but most of them are topologically invalid or geologically meaningless. So, we propose to define a valid geometric semantic relation. If A and B are two different cells, they must have the following:

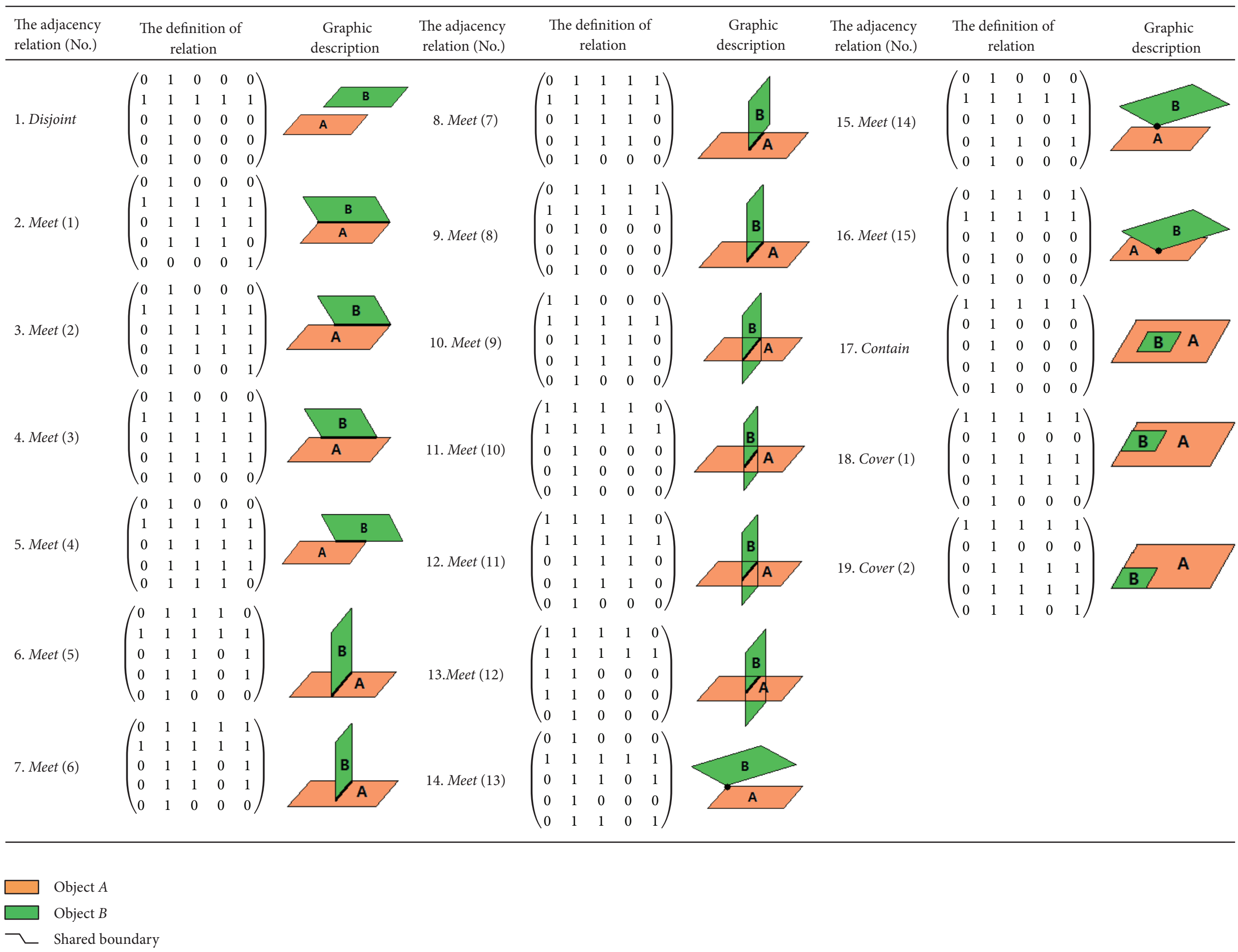


Figure 3: The adjacency relations of simple 2 cells.

Rule 1: $A \cap B \neq \varnothing \longrightarrow (A^o \cap B^o \neq \varnothing) \vee (\partial A \ \cap \partial B \ \neq \varnothing)$.

Rule 2: $\overline{A} \cap \overline{B} = \varnothing \longrightarrow (A \cup B = U)$.

Rule 3: $(\overline{A} \cap \overline{B} \neq \varnothing) \vee (A \cap B \neq \varnothing)$.

Rule 4: $\partial A \ \cap B^o \neq \varnothing \longrightarrow (\partial A \ \cap \partial B \ \neq \varnothing) \vee (\partial A \ \cap \overline{B} \neq \varnothing)$.

Rule 5: let A and B be two different n cells $(n \geq 1)$; then

$$A^o \cap B^o \neq \varnothing \longrightarrow (A - B = \varnothing) \vee (B - A = \varnothing). \tag{8}$$

This means that if two cells overlap, then one must contain or completely cover the other. Partial overlapping is unreasonable in geological models (Figure 6).

Rule 6: let A be an n cell ($n = 2$ or 3) that represents a hole; then

$$A^o = \varnothing \longrightarrow \exists B (A \cap B \neq \varnothing). \tag{9}$$

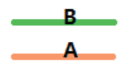
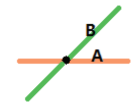
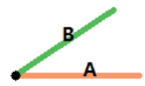
It means that a hole cannot contain or cover any other cells.

Rule 7: let A be an n cell ($n = 2$ or 3) that represents a hole; then

$$A^o = \varnothing \longrightarrow \exists B [(\dim(A) = \dim(B)) \wedge (A \cap B \neq \varnothing) \wedge (\overline{A} \cap \overline{B} = \varnothing)]. \tag{10}$$

It means that an n cell hole must be inside or covered by another n cell B.

3.3. Geological Semantics. In this subsection, we will put forward the formal representation framework of geological semantics. Geometry semantics regards a geological model as a general geometric model composed of n cells and provides a framework to define topological relations of the elements that make up the model. Instead, in geological semantics, we link the elements in the model with the concepts in geological ontologies, emphasizing the geological meaning of the elements and their relations. In other words, the geological semantics describes geological contact relations, while the geometry semantics describes nongeological spatial relations. Geological assemblages are the result of a definite history composed of various successive events that create geological objects. Thus, we believe that the essence of the contact relations of geological objects reveals the evolution process of

The adjacency relation (No.)	The definition of relation	Graphic description	The adjacency relation (No.)	The definition of relation	Graphic description
1. *Disjoint*	$\begin{pmatrix} 0 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 0 & 0 \end{pmatrix}$		4. *Meet* (3)	$\begin{pmatrix} 1 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 0 \end{pmatrix}$	
2. *Meet* (1)	$\begin{pmatrix} 0 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$		5. *Cover*	$\begin{pmatrix} 1 & 1 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \end{pmatrix}$	
3. *Meet* (2)	$\begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & 1 \\ 0 & 1 & 0 \end{pmatrix}$		6. *Contain*	$\begin{pmatrix} 1 & 1 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \end{pmatrix}$	

Object *A*
Object *B*
Shared boundary

Figure 4: The adjacency relations of simple 1 cell.

geological structures implied in the model. This means that the arrangements of geological objects are decided by geological events and their temporal relations, which are the geological semantics contained by a model. To establish a geological semantic description framework, we first need to clarify the difference between geological semantic entities and geometric semantic entities and then establish the taxonomy of geological events and propose a set of temporal relations suitable for describing geological events.

3.3.1. Geological Semantic Entities. The main geological objects concerned in a geological model can be divided into geological bodies (massive structures) and geological surfaces (planar structures). A geological body is defined as a volume of contiguous material all belonging to the same geological formation and fully limited by a pair of horizons or by an external boundary of the model. Geological surfaces can be faults, horizons, unconformities, fractures, interfaces of intrusive and extrusive rocks, and interfaces between rocks and liquid material produced by dissolution. In the model, a geological semantic entity should be a complete object with geological meaning, and its segmentation must be constrained by geological concepts. Thus, the geological semantic entities are often more complex than geometric ones. As shown in Figure 7, a geological semantic entity can be composed of multiple n cells. Specifically, a geological body can be represented by a set of 3-cell entities and a geological surface can be represented by a set of 2-cell entities. The definition of a geological semantic entity is as follows:

Definition 2. Let $\mathbf{C} = \{c_1, c_2, \ldots, c_n\}$ be a set of simple 3-cell entities and $\mathbf{B} = \{b_1, b_2, \ldots, b_m\}$ be a set of simple 2-cell entities in R^3. $\forall b_i \in \mathbf{B} \longrightarrow \exists c_i \in \mathbf{C}\,(b_i^o \cap c_i^o = b_i^o) \wedge (\partial b_i \cap c_i = \partial b_i)$. Then, a geological body is

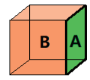
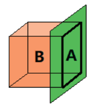
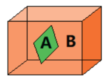
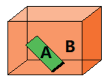
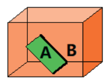
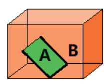
$$A \equiv \bigcup_{c_i \in \mathbf{C}} c_i \bigcup_{b_i \in \mathbf{B}} b_i, \qquad (11)$$

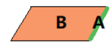
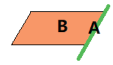
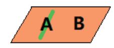
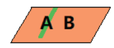
where $c_2, \ldots, c_n$ are holes inside or covered by c_1 and b_i are surfaces inside or covered by the body. The corresponding geological boundary of A is

$$\partial A \equiv \bigcup_{c_i \in \mathbf{C}} \partial c_i \bigcup_{b_i \in \mathbf{B}} b_i. \qquad (12)$$

3.3.2. Geological Events. According to the impact on rock masses, the geological events are divided into four categories: creation, destruction, deformation, and transformation (Figure 8). Creation represents the transformation of nonrock materials (magma and sediments) into solid rock masses, while destruction represents the opposite process. Deformation represents geological events in which only the shape or volume of a rock mass changes. Transformation represents an event by which the mineral composition, chemical composition, and microstructure of a rock mass change under the influence of temperature and pressure.

3.3.3. Temporal Relations of Geological Events. After determining the geological events involved in the definition of the geological semantic relations, we also need to determine a set of temporal relations that describe the relationships between these events. Some good efforts have been made in temporal knowledge representation and timescale ontologies, but these studies often focus only on the relationships between the two time intervals [50–54]. However, the geological history contained in a model is usually several million to tens of millions of years. When the occurrence time of events is very short relative to the whole model history, they should be treated as instantaneous events. For example, we usually do not consider the time required for the formation of faults, but the formation time of strata is still significant. This leads to the need to not only consider the relations between two time intervals but also take time instants into consideration. Therefore, based on the existing work, we put forward a set of temporal relations suitable for geological events. The temporal relations can be divided into four categories, a total of 40 kinds: interval to interval,

The association relation (No.)	The definition of relation	Graphic description
1. *Compose* (1)	$\begin{pmatrix} 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 \end{pmatrix}$	
2. *Compose* (2)	$\begin{pmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$	
3. *Inside*	$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$	
4. *Coverby* (1)	$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 \end{pmatrix}$	
5. *Coverby* (2)	$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 1 & 1 & 0 \end{pmatrix}$	
6. *Coverby* (3)	$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 1 & 0 \end{pmatrix}$	

The association relation (No.)	The definition of relation	Graphic description
1. *Compose* (1)	$\begin{pmatrix} 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 \end{pmatrix}$	
2. *Compose* (2)	$\begin{pmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 \end{pmatrix}$	
3. *Inside*	$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix}$	
4. *Coverby*	$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 \end{pmatrix}$	

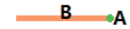
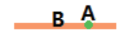
The association relation (No.)	The definition of relation	Graphic description
1. *Compose*	$\begin{pmatrix} 0 & 0 & 1 \end{pmatrix}$	
2. *Inside*	$\begin{pmatrix} 1 & 0 & 0 \end{pmatrix}$	

Figure 5: The association relations of cross-dimensional cells.

instant to interval, interval to instant, and instant to instant. They can be formally defined based on the relative positions of the interval boundaries or the instant itself (Figure 9(a)). Each interval has two boundaries, and the boundary is equivalent to an instant. The graphic descriptions of all temporal relations are presented in Figure 9(b).

3.3.4. Geological Semantic Relations. We can now use the temporal combination of geological events to define geological semantic relations and realize the link between time and space. Similar to geometric semantic relations, geological ones are also divided into adjacency and association relations. The adjacency relation describes the contact between geological bodies and surfaces. The association relation indicates the compositional relationship between a geological body and its boundary surfaces. Since the temporal relations of geological events determine the geological assemblage of the model, the adjacency relation can be derived from three events: the two events (e_1 and e_2) that create the two adjacent geological objects and the remaining one (e_3) that creates the shared boundary. As an example, there are three events in Figure 8 that can create geological bodies (deposition, magmatic intrusion, and extrusion), which means that there can be three kinds of geological bodies. Similarly, there are seven events that can create interfaces between bodies (deposition, intrusion, extrusion, erosion/weathering, melting, dissolution, and faulting), corresponding to seven kinds of geological surfaces. So, there are a total of 63 ($3 \times 7 \times 3$) combinations of events, that is, 63 possible contacts between geological bodies. However, not every combination can correspond to a reasonable physical process and lead to a valid semantic relation. We finally select 16 valid and common combinations as the basic adjacency relations between geological bodies. Their schematic diagrams and the physical process behind the relation (i.e., the geological semantics) are shown in Figure 10.

The definition method of the adjacency relations of geological surfaces is the same as that of geological bodies. There are six events that can make two surfaces contact each other (deposition, intrusion, extrusion, erosion/weathering, melting, and faulting), so there can be 216 ($7 \times 6 \times 7$) kinds of adjacency relations of surfaces. We select the most common cases and simplify them into 22 basic adjacency relations of geological surfaces (Figure 11).

In geology semantics, the association relation reveals the compositional relationship of the geological surfaces and bodies. The surfaces that constitutes a geological body can be divided into the boundary produced at the same time as the diagenesis (called the primary surface), and the surface formed by the tectonic changes after the diagenesis (called the secondary surface). Therefore, the association relation is related to two events: the event of creating the surface (e_1) and the event of creating the geological body (e_2). When the surface is a primary surface, e_1 and e_2 are the same event. The formal definitions of association relations are also derived from the combinations of events, and their geological semantics are the geological evolutionary history of the model. We propose eighteen basic association relations between geological surfaces and bodies, and their implied geological semantics are shown in Figure 12.

On the whole, the adjacency and association semantic relations together constitute the representation of geological semantics and reveal the tectonic evolution process behind geological assemblages. The set of geological semantic relations can be easily extended in the proposed framework. Enumerating all combinations of geological events can theoretically cover all possible contacts and compositions of geological objects. If more circumstances need to be considered, such as the semantics representation of the attribute geological models, other geological events that affect lithology can be added into this framework.

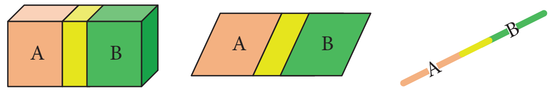


FIGURE 6: Three examples of the invalid partially overlap relations between different cells.

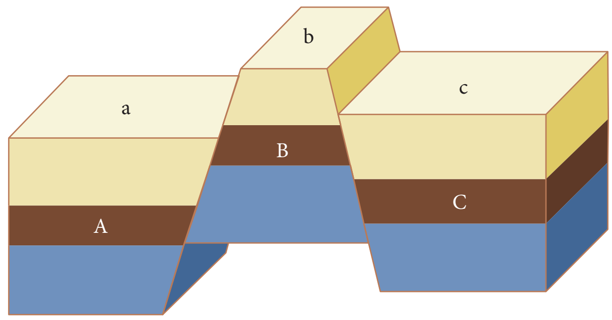


FIGURE 7: The schematic diagram of a horst. Geological semantic entities may consist of multiple simple geometric objects (n cells). For example, the blocks A, B, and C are three geometric semantic entities, but they together constitute strata, corresponding to one geological semantic entity. Similarly, the patches a, b, and c are three 2 cells and one horizon.

4. Computer Characterization of the Semantics of Geological Models

In order for the semantics to participate in the applications of geological models, we need to represent it in a form that computers can recognize and understand. The computer characterization of the semantics provides a way for computers to cognize the connotation of geological models. As we have defined, semantics consists of different types of semantic entities and the two kinds of semantic relations connecting them. These features are exactly the elements of a complex network, so we can characterize the semantics as a hierarchical heterogeneous network (Figure 13). The vertices in the network represent the semantic entities, and the vertices in the same layer represent semantic entities of the same kind. The edges between different layers refer to the association relations, and those in the same layer are the adjacency relations. The triple $(\text{node}_1, \text{edge}, \text{node}_2)$ forms a basic network unit to indicate that there is a relationship between node_1 and node_2, just like the semantic unit $(\text{entity}_1, \text{relation}, \text{entity}_2)$ we defined before.

The semantics characterized in the form of the network can not only reveal the pairwise relationships between the semantic entities but also discover the implied connections between objects that are not in direct contact, such as the relations among intersection lines of a fault with different horizons. This characterization provides an overall description of the geometric and geological topology of the model.

5. Application in a Real Geological Model

In this section, we apply the proposed semantic representation framework to a real geological model from a petroleum producing area located in Junggar basin in Xinjiang province, Northwest China (called HASAN model). The structural interpretation of this survey and corresponding 3D model are shown in Figure 14. There are 10 strata, which are divided into 15 blocks (3 cells) by faults. The fault types in this survey are mainly thrust faults and reverse faults, so a stratum will be divided into multiple geological bodies. Six horizons (interfaces between different strata) and ten faults are divided into 29 patches (2 cells) by the intersections between geological surfaces, of which horizon H3 is an unconformity created by erosion.

(a) There is a cross section of the HASAN seismic data with structural interpretation. The structural interpretation comes from the understanding of the model by structural geologists and geophysicists.

(b) We have the surface-based and block-based model of the HASAN survey, which are the two visualization forms of the geological model.

There are two ways to obtain the semantics: automatic extraction from the model data (structural interpretation or polygon meshes) and manual input. The automatic extraction of semantics is actually a process of computers cognizing geological data, just as humans perform structural interpretation. It involves a series of complex issues that go beyond geology, such as the representation of expert knowledge, multisource data fusion, computer perception, and knowledge reasoning. In geosciences, researches on the automatic extraction of semantics have begun to receive attention in recent years, providing foundations for our research. Thiele et al. [18] proposed an automatic method to extract cellular topology networks, which provides a basis for the extraction of semantics. Jessell et al. [55] achieved the calculation of the adjacency matrices for 3D models with a 6-neighbor framework. A more accurate and complete method of automatically extracting semantics is our near-future research, and it can be obtained by manual input at this stage. The entities

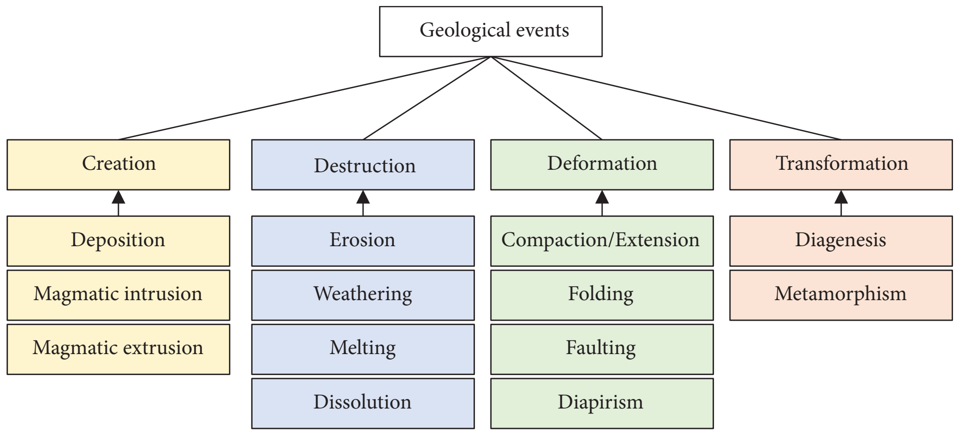


FIGURE 8: The taxonomy of geological events based on the impact on rock masses. The geological events mentioned here refer to the main geological processes that are at work in structural geology and structural geological models.

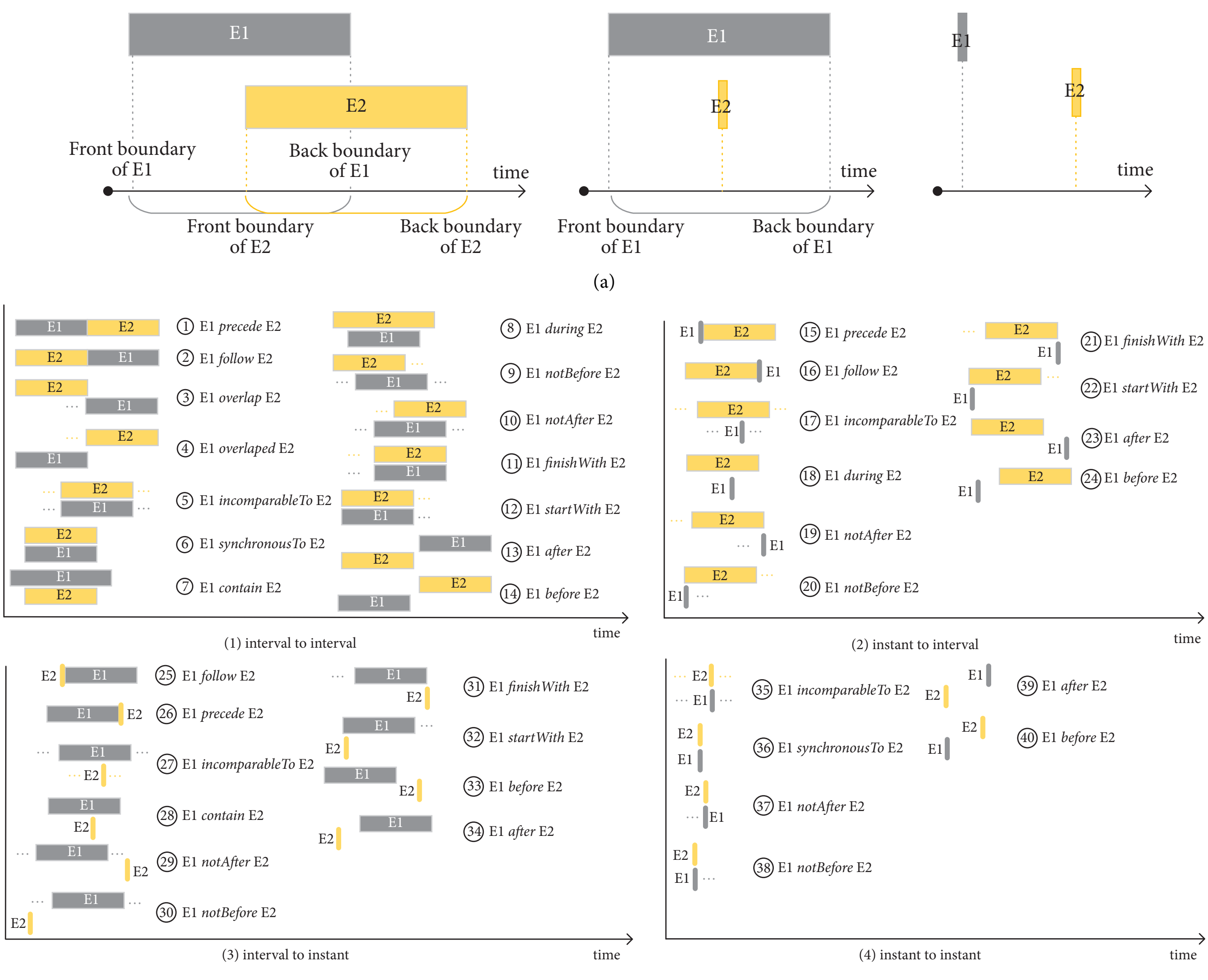


FIGURE 9: (a) The complete definition of the temporal relations is determined according to the boundaries of the time units. (b) Our binary temporal relations that are suitable for describing the order of geological events.

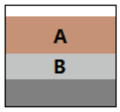
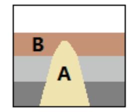
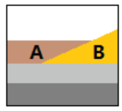
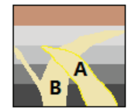
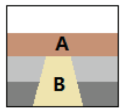
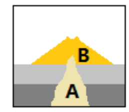
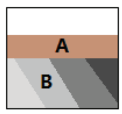
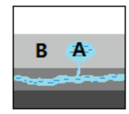
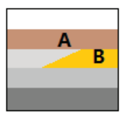
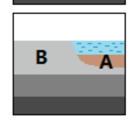
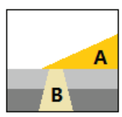
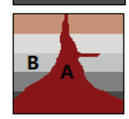
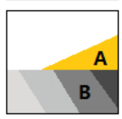
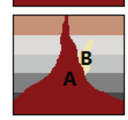
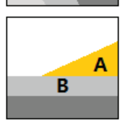
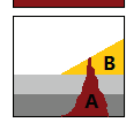
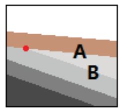
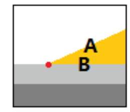
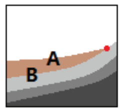
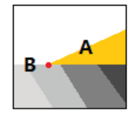
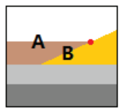
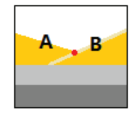
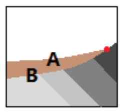
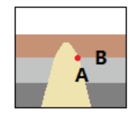
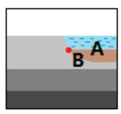
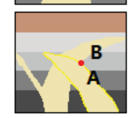
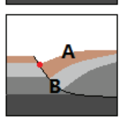
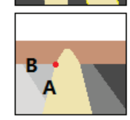
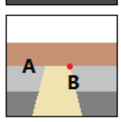
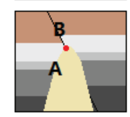
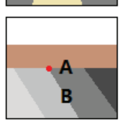
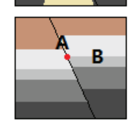
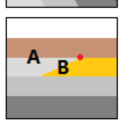
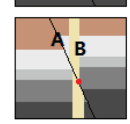
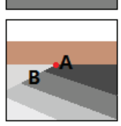
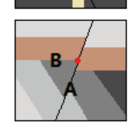
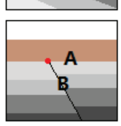
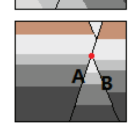
The adjacency relation (No.)	The definition of relation	Graphic description	The process behind the relation	The adjacency relation (No.)	The definition of relation	Graphic description	The process behind the relation
1. *Deposition contact* (1)	$event_1$: deposition (A) $event_2$: deposition (B) $event_3$: $event_1$ (boundary)		$event_1$ (2) follow $event_2$	9. *Intrusion contact* (1)	$event_1$: magmatic intrusion (A) $event_2$: deposition (B) $event_3$: $event_1$ (boundary)		$event_1$ (21) notBefore $event_2$
2. *Deposition contact* (2)	$event_1$: deposition (A) $event_2$: magmatic extrusion (B) $event_3$: $event_1$ (boundary)		$event_1$ (25) follow $event_2$	10. *Intrusion contact* (2)	$event_1$: magmatic intrusion (A) $event_2$: magmatic intrusion (B) $event_3$: $event_1$ (boundary)		$event_1$ (39) after $event_2$
3. *Erosion contact* (1)	$event_1$: deposition (A) $event_2$: magmatic intrusion (B) $event_3$: erosion (boundary)		$event_1$ (2) follow $event_3$ $event_3$ (34) after $event_2$	11. *Intrusion contact* (3)	$event_1$: magmatic intrusion (A) $event_2$: magmatic extrusion (B) $event_3$: $event_1$ (boundary)		$event_1$ (38) notBefore $event_2$
4. *Erosion contact* (2)	$event_1$: deposition (A) $event_2$: deposition (B) $event_3$: erosion (boundary)		$event_1$ (2) follow $event_3$ $event_3$ (13) after $event_2$	12. *Dissolution contact* (1)	$event_1$: dissolution (A) $event_2$: deposition (B) $event_3$: $event_1$ (boundary)		event$_1$ (9) notBefore $event_2$
5. *Erosion contact* (3)	$event_1$: deposition (A) $event_2$: magmatic extrusion (B) $event_3$: erosion (boundary)		$event_1$ (2) follow $event_3$ $event_3$ (34) after $eevent_2$	13. *Dissolution contact* (2)	$event_1$: deposition (A) $event_2$: deposition (B) $event_3$: dissolution (boundary)		$event_1$ (13) after $event_3$ $event_3$ (9) notBefore $event_2$
6. *Erosion contact* (4)	$event_1$: magmatic extrusion (A) $event_2$: magmatic intrusion (B) $event_3$: erosion (boundary)		$event_1$ (16) follow $event_3$ $event_3$ (34) after $event_2$	14. *Melting contact* (1)	$event_1$: melting (A) $event_2$: deposition (B) $event_3$: $event_1$ (boundary)		$event_1$ (23) after $event_2$
7. *Erosion contact* (5)	$event_1$: magmatic extrusion (A) $event_2$: deposition (B) $event_3$: erosion (boundary)		$event_1$ (16) follow $event_3$ $event_3$ (13) after $event_2$	15. *Melting contact* (2)	$event_1$: melting (A) $event_2$: magmatic intrusion (B) $event_3$: $event_1$ (boundary)		$event_1$ (38) notBefore $event_2$
8. *Extrusion contact*	$event_1$: magmatic extrusion (A) $event_2$: deposition (B) $event_3$: $event_1$ (boundary)		$event_1$ (16) follow $event_2$	16. *Melting contact* (3)	$event_1$: melting (A) $event_2$: magmatic extrusion (B) $event_3$: $event_1$ (boundary)		$event_1$ (39) after $event_2$

FIGURE 10: The basic adjacency relations of geological bodies. The events that generate the two geological bodies and their shared boundary determine the contact. The physical process implied in the relation is actually geological semantics.

contained in a model at a local scale are limited, and the relations of entities can be clearly observed from cross sections of the model, so manual editing of the semantics is completely feasible. In this example, the semantics are extracted from structural interpretation. An initial semantic representation is first obtained by the existing automatic extraction methods mentioned above, but due to the uncertainty of the structure interpretation, the preliminary semantics must be incomplete. Therefore, the semantic representation requires further manual editing to reduce the uncertainty through available interpretations. Manual editing avoids the problem of completely formalizing heterogeneous information or multisource data. The automatically extracted semantics can greatly reduce the complexity of manual editing.

According to the computer characterization method proposed in Section 4, the semantics of the model is characterized as a complex network laid out in 3D space (Figure 15). Both the massive structures and planar structures are organized together, which combines two perspectives for understanding the model and provides a lot of information beyond geometry. For example, we can see in Figure 15(b) that the node with the largest degree in the network is F3-2, indicating that F3-2 is related to the most geological bodies and geological surfaces. Therefore, F3-2 is the planar structure with the greatest influence on the model, that is, the key to structure distribution and model quality control. Moreover, F3-2 is *faulting staggered* by F3, *erosion cut* by H3, and *faulting staggered* by F5 and F1. It means the process of H3 *after* F3 *after* F3-2 *after* F5 and F1. Besides, more advanced conclusions can also be obtained from other parts of the network. Although P2w and C are not geometrically adjacent, Figure 15(c) shows that they are both affected by H3 and reveals their unobvious association. In Figure 15(d), all six geological surfaces that constitute P1j are faults, indicating that P1j has undergone six transformations and is the most complex geological body in the HASAN model. It also expresses the process that P1j is generated before these six faults.

The adjacency relation (No.)	The definition of relation	Graphic description	The process behind the relation	The adjacency relation (No.)	The definition of relation	Graphic description	The process behind the relation
1. *Deposition limit* (1)	$event_1$: deposition (A) $event_2$: deposition (B) $event_3$: $event_1$ (boundary)		$event_1$ (13) after $event_2$	12. *Extrusion contact* (1)	$event_1$: magmatic extrusion (A) $event_2$: deposition (B) $event_3$: $event_1$ (boundary)		$event_1$ (16) follow $event_2$
2. *Deposition limit* (2)	$event_1$: deposition (A) $event_2$: deposition (B) $event_3$: $event_1$ (boundary)		$event_1$ (2) follow $event_2$	13. *Extrusion contact* (2)	$event_1$: magmatic extrusion (A) $event_2$: erosion (B) $event_3$: $event_1$ (boundary)		$event_1$ (16) follow $event_2$
3. *Deposition limit* (3)	$event_1$: deposition (A) $event_2$: magmatic extrusion (B) $event_3$: $event_1$ (boundary)		$event_1$ (25) follow $event_2$	14. *Extrusion contact* (3)	$event_1$: magmatic extrusion (A) $event_2$: magmatic extrusion (B) $event_3$: $event_1$ (boundary)		$event_1$ (39) after $event_2$
4. *Deposition limit* (4)	$event_1$: deposition (A) $event_2$: erosion (B) $event_3$: $event_1$ (boundary)		$event_1$ (2) follow $event_2$	15. *Intrusion contact* (1)	$event_1$: magmatic intrusion (A) $event_2$: deposition (B) $event_3$: $event_1$ (boundary)		$event_1$ (23) after $event_2$
5. *Deposition limit* (5)	$event_1$: deposition (A) $event_2$: dissolution (B) $event_3$: $event_1$ (boundary)		$event_1$ (2) follow $event_2$	16. *Intrusion contact* (2)	$event_1$: magmatic intrusion (A) $event_2$: magmatic intrusion (B) $event_3$: $event_1$ (boundary)		$event_1$ (39) after $event_2$
6. *Deposition limit* (6)	$event_1$: deposition (A) $event_2$: faulting (B) $event_3$: $event_1$ (boundary)		$event_1$ (3) overlap $event_2$	17. *Intrusion contact* (3)	$event_1$: magmatic intrusion (A) $event_2$: erosion (B) $event_3$: $event_1$ (boundary)		$event_1$ (23) after $event_2$
7. *Erosion cut* (1)	$event_1$: erosion (A) $event_2$: magmatic intrusion (B) $event_3$: $event_1$ (boundary)		$event_1$ (34) after $event_2$	18. *Intrusion contact* (4)	$event_1$: magmatic intrusion (A) $event_2$: faulting (B) $event_3$: $event_1$ (boundary)		$event_1$ (39) after $event_2$
8. *Erosion cut* (2)	$event_1$: erosion (A) $event_2$: deposition (B) $event_3$: $event_1$ (boundary)		$event_1$ (13) after $event_2$	19. *Faulting stagger* (1)	$event_1$: faulting (A) $event_2$: deposition (B) $event_3$: $event_1$ (boundary)		$event_1$ (23) after $event_2$
9. *Erosion cut* (3)	$event_1$: erosion (A) $event_2$: magmatic extrusion (B) $event_3$: $event_1$ (boundary)		$event_1$ (34) after $event_2$	20. *Faulting stagger* (2)	$event_1$: faulting (A) $event_2$: magmatic intrusion (B) $event_3$: $event_1$ (boundary)		$event_1$ (39) after $event_2$
10. *Erosion cut* (4)	$event_1$: erosion (A) $event_2$: erosion (B) $event_3$: $event_1$ (boundary)		$event_1$ (13) after $event_2$	21. *Faulting stagger* (3)	$event_1$: faulting (A) $event_2$: erosion (B) $event_3$: $event_1$ (boundary)		$event_1$ (23) after $event_2$
11. *Erosion cut* (5)	$event_1$: erosion (A) $event_2$: faulting (B) $event_3$: $event_1$ (boundary)		$event_1$ (34) after $event_2$	22. *Faulting stagger* (4)	$event_1$: faulting (A) $event_2$: faulting (B) $event_3$: $event_1$ (boundary)		$event_1$ (39) after $event_2$

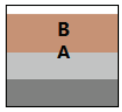
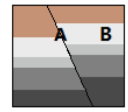
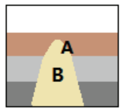
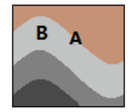
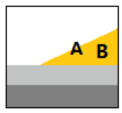
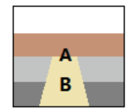
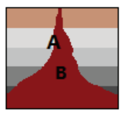
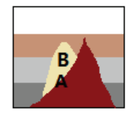
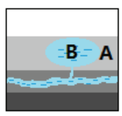
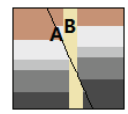
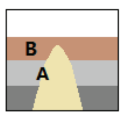
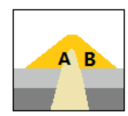
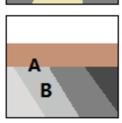
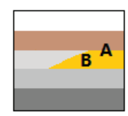
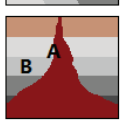
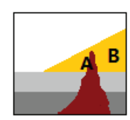
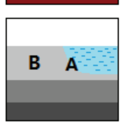
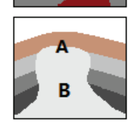
effusive rock
intrusive rock
magma
sedimentary rock
water
boundary intersection

Figure 11: The adjacency relations of geological surfaces.

The geometric semantics is represented in Figure 16, which clearly organizes all key geometric elements that make up the model. The specific analysis is similar to that of geological semantics and will not be repeated here. The information provided by geometric semantics can also be used to build geological models. The geometric topology can be determined in advance before the model is established and then constrains the reconstruction of geological surfaces and blocks.

6. Discussion

The representation of semantics is a topic that originated from artificial intelligence (AI). If we want computers to have higher-level intelligence, such as cognitive ability, it will inevitably involve the interaction between computers and the objective world. Explicit and formal representation of semantics will promote more effective interaction. A structural geological model is a general tool used to describe

The adjacency relation (No.)	The definition of relation	Graphic description	The process behind the relation	The adjacency relation (No.)	The definition of relation	Graphic description	The process behind the relation
1. *Primarily compose* (1)	*event*$_1$: *event*$_2$ (A) *event*$_2$: deposition (B)			10. *Secondarily compose* (5)	*event*$_1$: faulting (A) *event*$_2$: deposition (B)		*event*$_1$ (23) after *event*$_2$
2. *Primarily compose* (2)	*event*$_1$: *event*$_2$ (A) *event*$_2$: magmatic intrusion (B)			11. *Secondarily compose* (6)	*event*$_1$: folding (A) *event*$_2$: deposition (B)		*event*$_1$ (13) after *event*$_2$
3. *Primarily compose* (3)	*event*$_1$: *event*$_2$ (A) *event*$_2$: magmatic extrusion (B)			12. *Secondarily compose* (7)	*event*$_1$: erosion (A) *event*$_2$: magmatic intrusion (B)		*event*$_1$ (34) after *event*$_2$
4. *Primarily compose* (4)	*event*$_1$: *event*$_2$ (A) *event*$_2$: melting (B)			13. *Secondarily compose* (8)	*event*$_1$: melting (A) *event*$_2$: magmatic intrusion (B)		*event*$_1$ (39) after *event*$_2$
5. *Primarily compose* (5)	*event*$_1$: *event*$_2$ (A) *event*$_2$: dissolution (B)			14. *Secondarily compose* (9)	*event*$_1$: faulting (A) *event*$_2$: magmatic intrusion (B)		*event*$_1$ (39) after *event*$_2$
6. *Secondarily compose* (1)	*event*$_1$: magmatic intrusion (A) *event*$_2$: deposition (B)		*event*$_1$ (23) after *event*$_2$	15. *Secondarily compose* (10)	*event*$_1$: magmatic intrusion (A) *event*$_2$: magmatic extrusion (B)		*event*$_1$ (38) notBefore *event*$_2$
7. *Secondarily compose* (2)	*event*$_1$: erosion (A) *event*$_2$: deposition (B)		*event*$_1$ (13) after *event*$_2$	16. *Secondarily compose* (11)	*event*$_1$: erosion (A) *event*$_2$: magmatic extrusion (B)		*event*$_1$ (34) after *event*$_2$
8. *Secondarily compose* (3)	*event*$_1$: melting (A) *event*$_2$: deposition (B)		*event*$_1$ (23) after *event*$_2$	17. *Secondarily compose* (12)	*event*$_1$: melting (A) *event*$_2$: magmatic extrusion (B)		*event*$_1$ (39) after *event*$_2$
9. *Secondarily compose* (4)	*event*$_1$: dissolution (A) *event*$_2$: deposition (B)		*event*$_1$ (2) follow *event*$_2$	18. *Secondarily compose* (13)	*event*$_1$: diapirism (A) *event*$_2$: deposition (B)		*event*$_1$ (13) after *event*$_2$

effusive rock
intrusive rock
magma
sedimentary rock
water

Figure 12: The association relations show the compositional relationships between geological surfaces and bodies, which also reveal the physical process of geological structure formation.

subsurface structures and geological phenomena. Therefore, we choose the structural model as the starting point and plan to gradually expand the scope of semantic representation and improve the completeness.

Here, we list several aspects that have not been considered in the current semantic representation framework: (1) various internal geological properties, including rock physical and chemical properties such as lithology, porosity, seismic wave impedance, and other properties that are closely related to the seismic inversion of the geological model; (2) microscale geological structures, such as joints, cleavages, and bedding structures; (3) some inherent characteristics of geological surfaces, such as the thickness of the fault. We are working on the semantic representation of these aspects to enhance the completeness of the semantic representation of the geological model.

We believe that the semantics representation framework has the following potentials: (1) modeling quality assessment, in which we quantify the quality of established geological models based on the difference between model semantics and expert cognition; (2) model sharing, in which sharing model semantics is more effective than sharing model data; (3) geological object query and analysis, in which we quickly find multiple related geological objects through semantics; and (4) fast model editing and modification, in which modifying the semantics makes it easy to generate new models to verify a geological hypothesis.

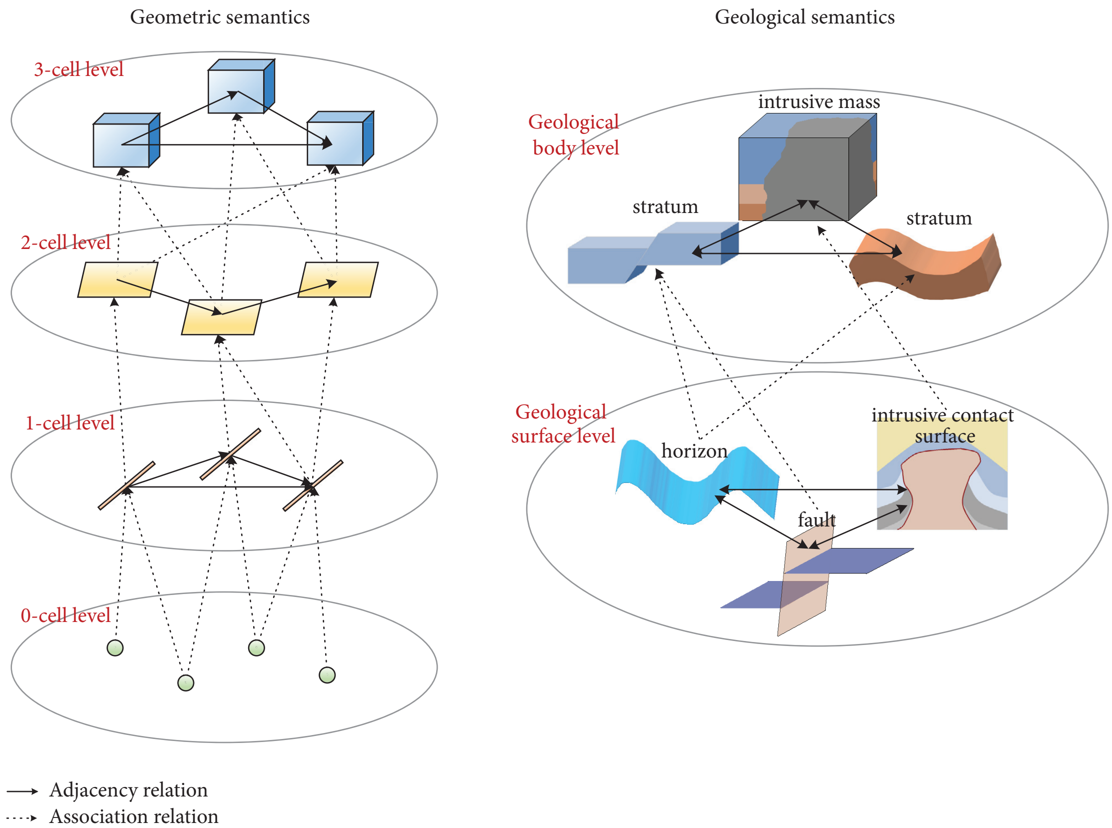
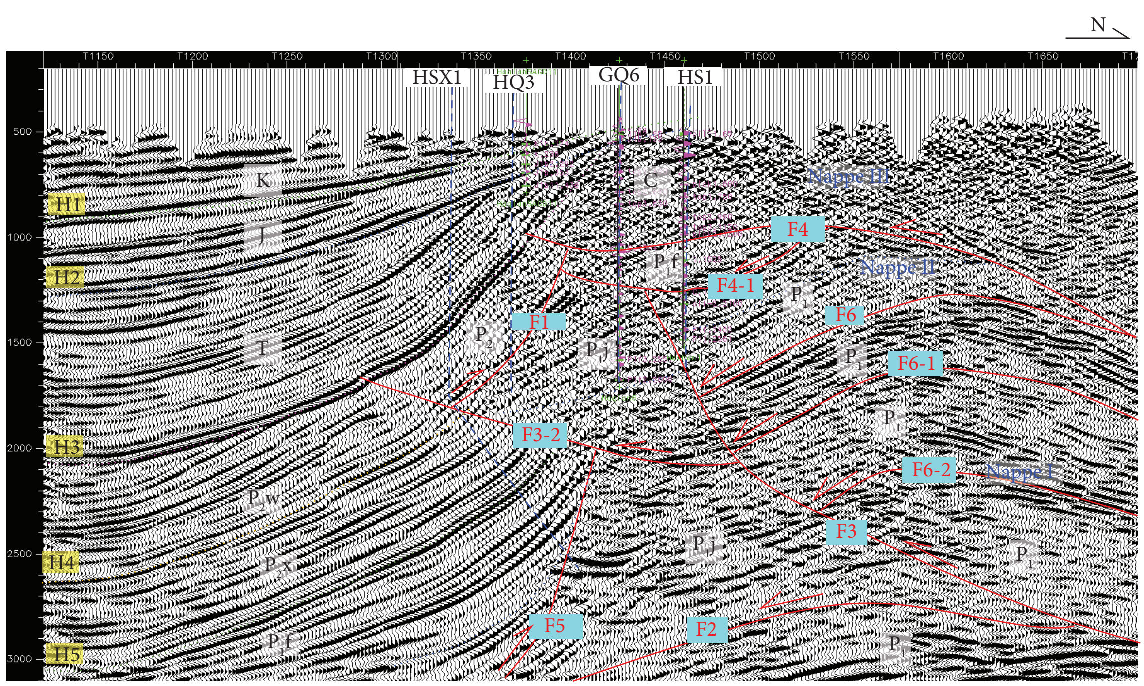
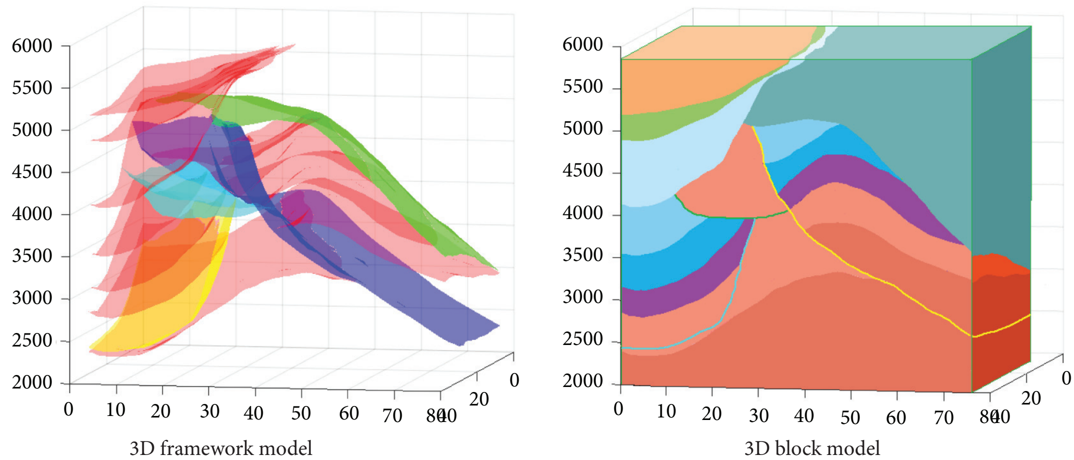


Figure 13: The schematic diagrams of a multilevel heterogeneous network structure, which is a computer characterization model of the semantics.



(a)

Figure 14: Continued.



(b)

Figure 14: A geological model example is used to show semantic representations in practical applications. (a) A cross section of the HASAN seismic data with structural interpretation. The structural interpretation comes from the understanding of the model by structural geologists and geophysicists. (b) The surface-based and block-based model of the HASAN survey, which are the two visualization forms of the geological model.

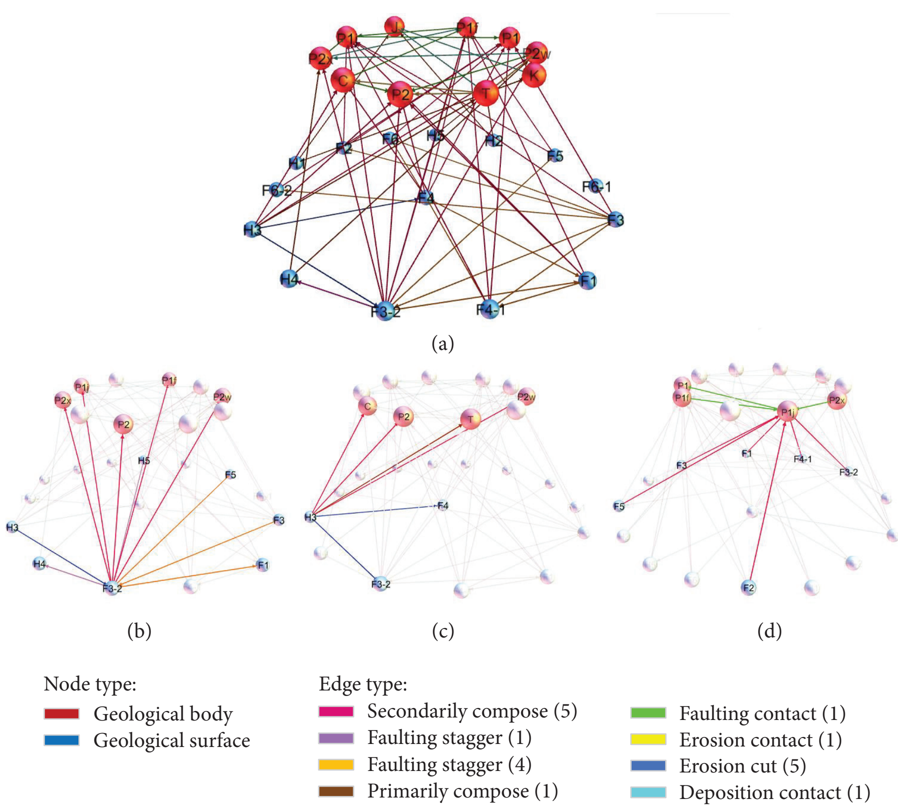


Figure 15: The representation of the geological semantics of the HASAN model. (a) The complete network representation. (b–d) Some details of the network. The geological semantics is explicitly expressed, and advanced knowledge can be derived from a large number of semantic relations.

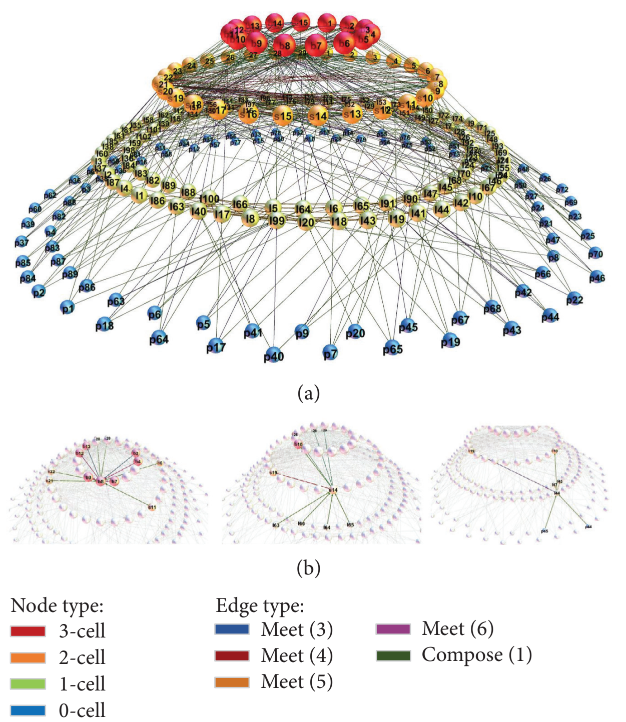


Figure 16: The representation of the geometric semantics of the HASAN model. (a) The complete four-layer network representation. (b) Some details of the network. The connected nodes can be highlighted for easy observation.

7. Conclusions

The lack of semantic representation in structural geological models hinders the information management and further intelligent application of geological models. In our research, we propose a structured and more comprehensive representation framework to formalize the semantics of geological models. The framework clearly divides semantics into geometric and geological parts to represent geological models from the geometric and geological perspectives, respectively. Geometric semantics focuses on describing the spatial topology of the elements that make up the model. On the other hand, the geological semantics focuses on describing the geological evolution implied by the contacts of geological objects. We then provide a multilayer heterogeneous network model as a computer characterization method of the semantics. Computer characterization allows us to store, process, and apply the semantics explicitly. It lays the foundation for the further applications of geological models, such as knowledge query, and quality control. We apply the semantic representation framework to an actual model dataset and visualize the geometric and geological semantics by two multilayer heterogeneous networks. The networks can provide knowledge beyond the geometric information about a certain geological surface, for example, by highlighting the key elements in the model and revealing the implicit connections between geological objects. We hope that our research can contribute to the development of geoinformation science by establishing a complete information theoretical framework for geological models.

Nomenclature

$\partial^2 A$: the boundary of ∂A, where A is an n cell $(n = 2, 3)$

Data Availability

The original data of the two geological models and the extracted networks of the semantics used in this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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