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GIS Application to Regional Geological Structure Relationship Modelling Considering Semantics

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Abstract: GIS modelling, which is often employed to establish the abstract structural forms of geological phenomena and their structural relationships, is of great importance for the expression and analysis of geological structures to describe and express such phenomena accurately and intuitively. However, current GIS modelling schemes value structural forms over structural relationships, and existing geological semantic expressions in the modelling of geological relationships are incomplete. Therefore, this paper categorizes geological relationships into three levels: geological phenomena, geological objects and geological spatial objects: (1) based on their definitions, this work categorizes geological relationships into internal composition relationships and external combined relationships for a total of two categories, eight classes and 27 small groups; (2) this work also improves the system with a total of 33 classified geological objects by transforming the relationships between geological phenomena into relationships between geological objects; and (3) based on the 27 small groups of geological relationships, through the corresponding geometric and semantic expressions between topological rules and geological rules and between relationship rules and geological rules, this work then expresses internal composition relationships as topological relationships between geological spatial objects and expresses external combined relationships as association relationships between geological spatial objects. A GIS model of geological relationships that integrates their geometries and semantics is then built. Finally, taking the Dagang-Danyang section of the Ningzhen mountains as an example, the results show that the proposed GIS modelling method can better store and express geological phenomena, geological objects and geological spatial objects in a way that integrates geometry and semantics.

Keywords: regional geological structure; geological relationship; semantics; object-orient; GIS modelling

1. Introduction

The geographic information system (GIS) modelling [1] of geological phenomena is a method used to directly represent the abstract concepts of structural shapes and structural relationships of geological features [2] using GIS technology [3], which is vital for the expression and analysis of geological relationships. Structural shapes of geological features refer to the geometry features and spatial position features of geological phenomena. Structural relationships of geological features refer to the spatial constituents and the combined forms of geological phenomena, that is, the interior constitution and exterior constitution. This method employs the GIS modelling of the geometrical features of geological structures and their relationships to reveal and visualize the spatial locations and geometries of geological phenomena using dots, lines, planes and other geometric objects [4–8]. To further understand this process, many geologists have performed detailed research on models of geological geometric features [9,10]; these models can be divided into several types: wire-frame models, surface models, voxel models, constructive solid geometry (CSG) models, boundary representation (B-rep) models, and hybrid models. Triangular irregular networks (TIN) [11], Tetrahedral network (TEN) [12], B-rep [13], and Generalized tri-prism (GTP) [14] models are commonly used for the fast and accurate geometrical construction [15] of specialized geological phenomena, although difficulties still exist in building spatial relationships between geometric objects. These models mainly focus on the geometry modelling of geological phenomena [16], and a few of them consider the relationships of geological phenomena in strata, but it cannot fully describe the geological relationships [17] between folds, faults, and strata, and it lacks corresponding description of geological semantics [18,19] for geometric elements in the modelling process.

Geological relationship model places a particular emphasis on the relationships of constituents of geological phenomena such as folds, faults and strata, and the relationships of combined forms of different geological phenomena [20]. In GIS, the geological phenomena are abstracted as geological objects, and then are expressed through spatial relationships and semantic relationships of geological objects. The GIS modelling of geological relationships includes a geological semantic ontology model [21,22], a geological topological model [23], and a geometric model of geological boundaries.

The geological semantic ontology model is employed to construct a concept system and hierarchical relationships [24–26] using geological concepts. This model is effective in describing semantics of geological phenomena, for it expresses the relationships of geological phenomena based on the relationships between semantic features and geometry features such as 'part of', 'is-a' and 'instance-of' but is weak at representing their spatial topological relations. This ontology model uses geological ontology to define the hierarchical relations between concepts of geological objects and relationships, clarifying semantic relationships between strata concepts, although it still needs further study on distinguishing geological spatial relations and building mapping of semantic and geometric features in geological relations.

The geological topological model is used to represent the spatial relationships of geological objects via reflecting the topological relations among the geometric elements (including dots, lines and planes) of geological phenomena. This model is good in expressing spatial relationships of geological phenomena but lacks an explication of geological concepts [27] for spatial relationship and geological phenomena, or, in other words, it lacks a description of semantic relationships of geological phenomena. The geological topology model adopts GIS topological relations to express the interior constitution between geological phenomena while it lacks incidence relations to express exterior constitution of geological phenomena.

The geological topological model is used to represent the spatial relationships among geological objects via reflecting the topological relationships among the geometric elements (including dots, lines and plane) of geological phenomena. This model is effective in expressing spatial relationships of geological phenomena but lacks an explication of geological concepts for spatial relationship and geological phenomena, or, in other words, it lacks a description of semantic relationships of geological phenomena. A geological topological model adopts GIS topological relationships to express the interior constitution between geological phenomena while it lacks incidence relations to express exterior constitution of geological phenomena.

The geological boundary geometric model is mainly based on dots, lines and planes to establish the geometric boundary that satisfies geological body constraints and geological rules. When there are geological interfaces between geological bodies, such as unconformable contact and fault contact, the generally used methods to deal with the 'polygon–polygon' topological relations are surface cutting and surface adjusting in order to eliminate the inconsistency of geological surfaces. However, it is weak at describing topological relations such as 'line–line' and 'line–polygon' relations. The geological boundary geometric model is used to show well-defined surfaces, the effectiveness of their contact relation, and surfaces' geometric consistency from the perspective of geological boundary layers [28] and surface layers [29]. With the attribute data of strata [30], this model can better express the geometric features, topological relationships and geological meanings for strata. However, the model ability to express the geological relationships for folds and faults is relatively weak.

To sum up, this modelling focuses more on spatial relation expressions that describe topological relations of geometry objects such as dots, lines and planes and cannot fully explain the associated semantic relationships of geological phenomena. For instance, geological relations, such as conformable contact and intrusive contact, are expressed more comprehensively and more clearly when geological objects are abstracted and spatial relations as well as semantic relations between geological objects are fully expressed based on geological geometry modelling.

Therefore, problems still exist in geological relations models: how to combine geological relations, topological relations and incidence relations when modelling; how to better describe interior constitution and exterior constitution of geological phenomena; and how to establish geological relationships as a whole. This paper aims to build a GIS model of geological relationships, regarding the problems in existing GIS models.

Evidently, a comprehensive GIS model of geological relationships capable of expressing both geometric spatial relationships and geological meanings is lacking. Moreover, different issues are encountered within each of the existing models; for example, there are no corresponding expressions of spatial relationships and geological meanings, and the expressions used for geological relationships are incomplete. Therefore, to unify the geometric and semantic expressions for geological relationships via GIS methods [31], a geological relationship model that can combine geometric features with semantic expressions is proposed in this paper. Geological objects are used to express geological relationships whose geological meanings [32,33] can be divided into two parts: an interior constitution and an exterior constitution. Based on geometric objects, the interior constitution of geological phenomena is shown by their topological relationships, while the exterior constitution is shown via the syntagmatic relationship between geometric objects. The purpose of this model is to build a bridge between GIS and semantics of geological relationship described by geologists, which is significant for both GIS modelling and analysis in geological phenomena.

2. Geological Definitions and the Classification of Geological Relationships

The geological relationships in this paper refer to the spatial constituents and the combined forms of three small-scale geological phenomena, namely, folds, faults, and strata, which compose the abovementioned interior constitution and exterior constitution of geological structures. The geological relationships that are represented by folds, faults and strata constitute basic geological structural units. To differentiate these relationships, different grown forms are used to establish their geology. Based on the descriptions [34] of geological phenomena [35] with natural language [36,37], this paper classifies [38,39] the relationships among these three phenomena into 33 types, as shown in Table 1, by referring to following documents:

- GB/T9649 The terminology classification codes of geology and mineral resources (containing GB/T 9649.1-35),
- GB958-99 Geological legends used for regional geological maps,
- DZ/T0001-91 Principles for regional geological surveys (1:50,000),
- The Spatial Database of the Digital Geological Map by the China Geological Survey.

Table 1. Classification of geological phenomenon in regional geological structures.

Geological Structure	Geological Meaning References [40–44]	Geological Phenomena
Folds	A geological fold occurs when one surface or a stack of originally flat and planar surfaces, such as sedimentary strata, are bent or curved as a result of permanent deformation. A set of folds distributed on a regional scale constitutes a fold belt, a common feature of orogenic zones.	Hinge of fold, limb of fold, folding axis line, folding axis surface, fold (syncline and anticline), anticlinorium, synclinorium, comb-like fold, wide-spaced synclines, linear fold, brachyaxis fold, structural dome and structural basin
Faults	A fault is a planar fracture or discontinuity in a volume of rock, across which there has been significant displacement along the fracture as a result of movements at the Earth's surface. Large faults within the Earth's crust result from plate tectonic forces; the largest faults form the boundaries between plates such as subduction zones or transform faults.	Fault plane (<45° and >45°), fault wall (hanging wall and foot wall), normal fault, reverse/thrust fault, wrench fault, longitudinal fault, transverse fault, diagonal fault, strike-slip fault, dip-slip fault, oblique fault and bedding fault
Strata	In geology and related fields, a stratum (plural: strata) is a layer of sedimentary rock or soil with internally consistent characteristics that distinguish it from other layers. The stratum is the fundamental unit in a stratigraphic column and forms the basis of the study of stratigraphy.	Geological boundary, rock formation boundary, fault line, stratum contact plane (conformable contact and unconformable contact), rock contact plane (intrusive rock, sedimentary rock and igneous rock), fault contact plane, chronostratigraphic element, and lithostratigraphic element

This paper chooses two typical types of geological structures, including eight secondary types and 27 types of geological relationships, which are widely recognized in the field of geology to perform a further classification. In this paper, a geological relationship consists of geological constituents and their combined forms. Specifically, the constituents are geological phenomena that possess geometric meanings. In terms of the classification consisting of folds, faults and strata, these constituents can be divided into 10 types of main classes: hinge of fold and fold, limb of fold and fold, folding axis line, fault wall (hanging wall) and fault plane, fault wall (foot wall) and fault plane, conformable contact, unconformable contact, intrusive contact, sedimentary contact, and faulted contact. The combined forms refer to various combinations of geological phenomena under certain grouping conditions and orders. By pairing fold with fold, fold with stratum, fault with fold, fault with fault, and fault with stratum, 17 types of combined forms are generated, as shown in Table 2: anticlinorium, synclinorium, linear fold, brachyaxis fold, structural dome, structural basin, longitudinal fault, transverse fault, diagonal fault, horst and graben structure, imbricate reverse fault, reverse/back-thrust fault, conjugate fault, strike-slip fault, dip-slip fault, oblique fault and bedding fault.

Table 2. Classification of geological relationships.

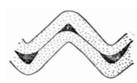
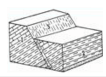
L1	L2	L3	Geological Meaning References [40–44]	Graphs References [40–44]
Geological phenomena constituents	Fold elements	Hinge of fold	The hinge is where the flanks join together. The hinge point is the point of minimum radius (maximum curvature) along a fold.	
		Limb of fold	The limb of a fold is a portion of strata that is folded or bent into an anticline or syncline or that connects two horizontal or parallel portions of strata of different levels (as a monocline). The limbs are the flanks of the fold.	
		Folding axis line	The axial trace is the line of intersection of the axial surface with any other surface (i.e., the ground, side of a mountain, or geological cross-section).	
	Fault elements	Hanging wall	The hanging wall occurs above the fault plane.	
		Foot wall	The footwall occurs below the fault plane.	

Table 2. *Cont.*

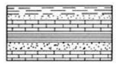
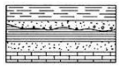
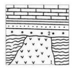
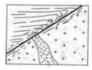
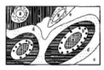
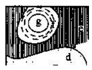
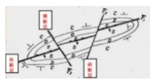
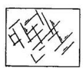
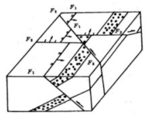
L1	L2	L3	Geological Meaning References [40–44]	Graphs References [40–44]
	Stratum elements	Conformable contact	The geological boundary lies along the conformable contact surface.	
		Unconformable contact	The geological boundary lies along the unconformable contact surface.	
		Intrusive contact	The rock formation boundary slices the stratum.	
		Sedimentary contact	The stratum boundary slices the rock formation.	
		Faulted contact	The rock formation boundary is the fault zone.	
Geological phenomena Combined forms	Fold and fold	Anticlinorium	A compound anticline consisting of a series of subordinate anticlines and synclines, where the whole structure has the general contour of an arch.	
		Synclinorium	A synclinorium (plural synclinoriums or synclinoria) is a large syncline with superimposed smaller folds.	
	Fold and stratum	Linear fold	The trend and plunge of linear features, such as the axis of a fold, describing the azimuth of the line and its deviation from the horizontal plane.	
		Brachyaxis fold	In arched, fractured and block-type basins, open brachyanticlines often form.	
		Structural dome	An anticline structure whose aspect ratio is smaller than 3:1	
		Structural basin	A syncline structure whose aspect ratio is smaller than 3:1	
	Fault and fold	Longitudinal fault	Controlled by a structural trap, an orebody located in the core of a brachyanticline or a pitching part of a plunging anticline intersected by a high-angle longitudinal fault.	
		Transverse fault	A transform fault or transform boundary is a plate boundary where the motion is predominantly horizontal. It ends abruptly and is connected to another transform fault, a spreading ridge, or a subduction zone.	
		Diagonal fault	A diagonal fault strikes obliquely or diagonally to the strike of the adjacent rocks.	
	Fault and fault	Horst and graben structure	Controlled by normal faults (growth faults), they assume the general characteristics of horst–graben or semihorst–semigraben structures.	
		Imbricate reverse fault	Reverse faults with the same occurrence and hanging walls thrusting upwards successively.	
		Reverse/back-thrust fault	A tear fault intersected by a low-angle normal fault or thrust fault can form some traps, e.g., a trap-door structural trap. Two reverse faults with the same/different tendencies are accompanied by an anticline.	
		Conjugate fault	Made up of two groups of conjugate faults.	

Table 2. *Cont.*

L1	L2	L3	Geological Meaning References [40–44]	Graphs References [40–44]
	Fault and stratum	Strike-slip fault	In a strike-slip fault (also known as a wrench fault, tear fault or transcurrent fault), the fault surface (plane) is usually nearly vertical, and the footwall moves laterally (i.e., sinistrally or dextrally) with very little vertical motion.	
		Dip-slip fault	Dip-slip faults can be either normal (extensional) or reverse. In a normal fault, the hanging wall moves downward relative to the footwall. A reverse fault is the opposite of a normal fault, i.e., the hanging wall moves up relative to the footwall.	
		Oblique fault	A fault that has a component of dip-slip and a component of strike-slip.	
		Bedding fault	A bedding fault is a fault plane parallel to the bedding.	

3. Modelling Methods for Geological Relationships

3.1. Modelling Approaches

A GIS model for a geological relationship is based on semantics [45,46], and it integrates geological geometrical features and relationships to unify the geometry, semantics, and geological structures [47]. This paper generalizes geological phenomena into three levels of geological objects and then into geological spatial objects based on both the structured text expressions of geological spatial relationships presented in Ref. [42] and the geological modelling methods for geological information (e.g., geological geometries, semantics and relationships) from Ref. [44]. At the first level, the geological relationships of regional geological structures are divided into the interior constitutions and exterior constitutions of three geological phenomena: folds, faults and strata. At the second level, geological objects are used to express those geological relationships, which can then be generalized to represent the relationships between geological objects. At the third level, geological spatial objects are used to reveal geological structures. Therefore, the relationships between geological objects can be generalized to determine the spatial relationships and incidence relations between geological spatial objects, as shown in Figure 1.

Based on the semantic classification rules for regional geological structures [38], this paper designs a classification system for multi-layer [48] geological objects with discernable relationships to improve the original rules. Object-oriented modelling is used, and 33 types of object elements and geometric expressions are designed based on four geometry types: points, polylines, polygons, and polycurves. The 33 types of geological objects created from combinations of folds, faults and strata are stored in the datasets of fold objects, fault objects and stratum objects. In a data model, a geometric element can be divided into different subtypes via a description of its concept. For example, folds include synclines and anticlines; fault walls include hanging walls and foot walls; fault surfaces include those with dips of <45° and >45°; geological boundaries include conformable lines and unconformable lines; rock formation contacts are classified by the presence of metamorphic rock, sedimentary rock and igneous rock. In this paper, textual and numeral coding methods are used to assign values to the subtypes, thereby ensuring the data integrity.

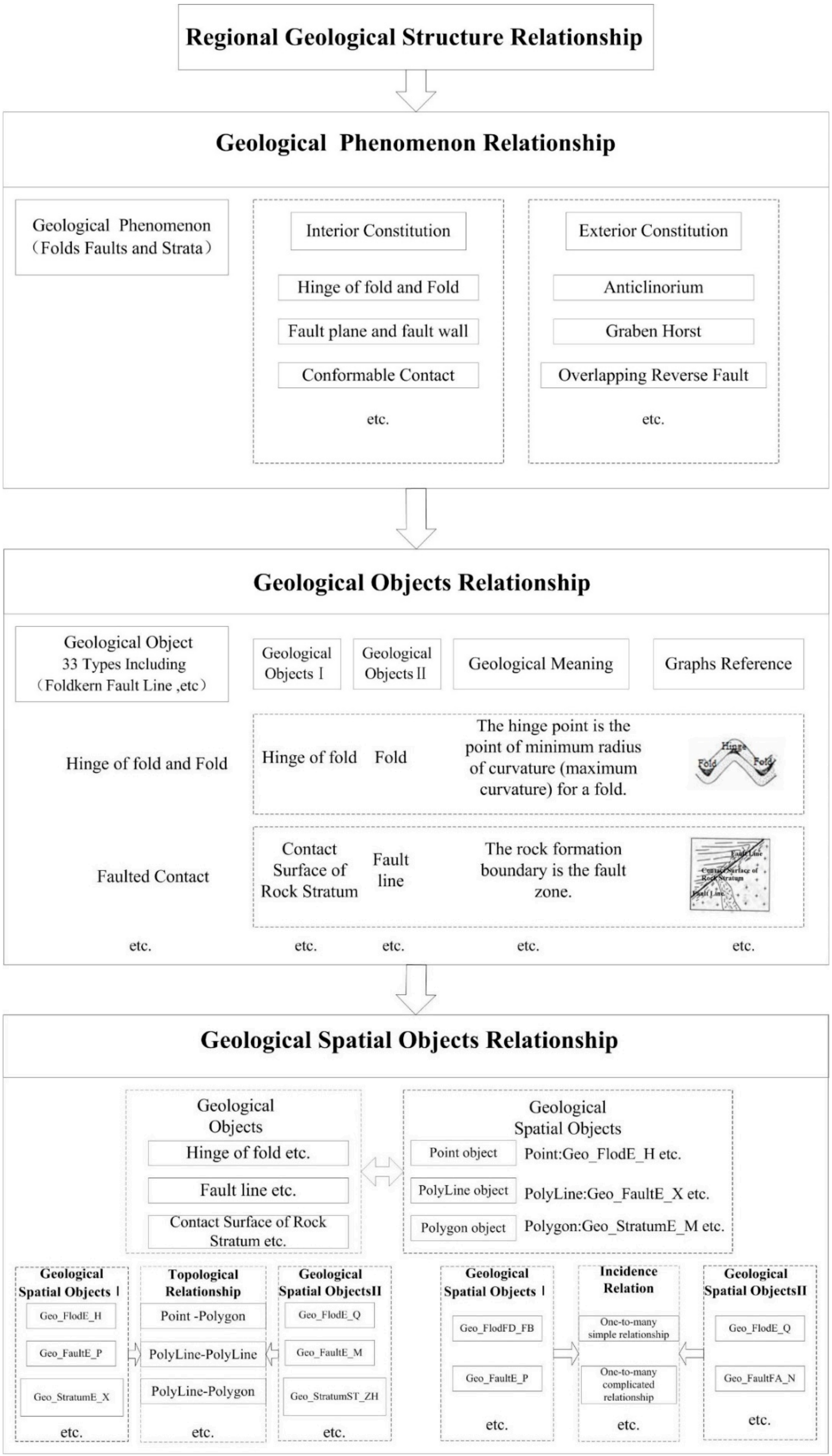
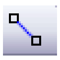
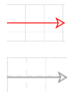


Figure 1. Modelling solutions of geological relationships at three levels.

Environmental Systems Research Institute (ESRI) contains two object-oriented database modelling software programs: ArcGIS Case Tools and ArcGIS Diagrammer. ArcGIS Case Tools is used with ArcGIS Desktop and Office Visio. First, a database model is built using Office Visio. This model is then used to export an X Exrensible Markup Language (XML) file to ArcGIS, and the data structure is automatically generated. ArcGIS Diagrammer is the production tool used by GIS professionals to create, edit and analyse geographic database structures. Database structures are rendered in the form of editable graphics, as shown in Table 3. Using the catalogue window in ArcCatalogue or ArcMap, these documents can be exported or imported into the geographic database. Because ArcGIS Case Tools needs to work with Office Visio, ArcGIS Diagrammer is more convenient for modelling purposes. ArcGIS Diagrammer models various interfaces, such as objects, false alarms, modelling areas, unified modelling language (UML) previews, object attributes, and previews. There are various defined objects (e.g., collected data, dot elements, image datasets, relations, and geometric networks) that allow users to perform basic operations, such as modifying names, adding fields and elements, and exporting XML files that can be subsequently edited with ArcGIS Desktop.

Table 3. Editable graphics in Diagrammer.

Palette	Symbol	Graphics in Diagrammer	Diagrammer Meaning
Link mode			Red arrows describe "relationships". Black arrows denote "contains".
Feature classes		fault wall Feature Class	A collection of geographic features with the same polygon geometry, attributes, and spatial reference.
Dataset		Faults Feature Dataset	A collection of geographic feature classes stored together that share the same spatial reference; that is, they share a coordinate system, and their features fall within a common geographic area.
Topology		Faults_Topology Topology	The arrangement that constrains how point, line, and polygon features share a geometry.
Relationship		strike fault Relationship	An item in Geodatabase that stores information about a relationship.
Subtype		foot wall Subtype	A subset of feature class or objects in a table that share the same attributes.

Based on the classifications of geological phenomena and their relationship with natural languages found in the previous section, the object-oriented [49] method is used with ArcGIS Diagrammer [50] to construct complicated geological objects and their topological relationships. Additionally, relationship association rules are built, and a geological relationship data model integrating geometric attributes and semantics is designed. The modelling process is as follows:

- Based on the geological meaning, design the geometric types, feature class names, and subtypes for a geological object.
- If there exists a topological relationship between geological objects (geological object subtypes), confirm the topological name and the rules of the topological relationship. Then, store the feature classes related to the topological relationship and set the parameters in Geodatabase.

- If an association exists between geological objects, confirm the relation name and rule, and store the origin class and destination class in Geodatabase.

3.2. Modelling for Composition Relationships of Geological Phenomena

The modelling of the composition relationship of geological phenomena is performed via the construction of a model based on ten geological relationships: hinge of fold and fold, limb of fold and fold, folding axis line, fault wall (hanging wall) and fault plane, fault wall (foot wall) and fault plane, conformable contact, unconformable contact, intrusive contact, sedimentary contact, and faulted contact. This modelling approach includes three aspects: the design of the corresponding topological description in the composition relationship, the building of the topological relationship logical model, and the development of topological rules.

During the modelling of the geological relationships, certain rules are necessary for the data model to comply with the real geological situation. The constitution of geological phenomena describes geometric topological relationships between geological objects. Therefore, mechanisms are required to describe the geological rules and topologies to ensure that the topological relationships in the model comply with the semantic descriptions of real geological relationships, as shown in Table 4. Based on Geodatabase topological rules, this paper designs a series of rules. These include, for example, description rules for topological relationships (such as lines and planes) and geological relationships (such as conformable contacts). Furthermore, corresponding descriptions should exist for the geological rule stating "The boundary of a polygon (or conformable contact surface) should coincide with the line element (geological boundary)" and the topological rule stating "Boundary must be covered by". Consequently, a mechanism is constructed for the corresponding topological description found in the composition relationships.

Table 4. Corresponding topological descriptions in the composition relationships.

Composition Relationships	Geological Rules	Meanings of Topological Rules Reference [38]	Graphs
Hinge of fold and Fold	Every fold hinge (**Point**) must be properly inside the fold (**Polygon**).	Point features from one layer must be properly contained inside the area features from another layer.	
Folding axis line	No axis (**Polyline**) can intersect with or overlap another axis	A line feature from one layer must not intersect with itself.	
Limb of fold and Fold	Every fold limb (**Polyline**) must be covered by the fold (**Polygon**) element boundary.	Line features from one layer must coincide with the boundaries of the area features of another layer.	
Hanging wall and Fault plane	The boundary of a hanging wall (**Polyline**) must be covered by a fault plane (**Polygon**).	The boundaries of an area feature from one layer must be covered by the line features of another layer.	

Table 4. *Cont.*

Composition Relationships	Geological Rules	Meanings of Topological Rules Reference [38]	Graphs
Foot wall and Fault plane	The boundary of a foot wall (**Polyline**) must be covered by a fault plane (**Polygon**).	The boundaries of an area feature from one layer must be covered by the line features of another layer.	
Conformable contact	The boundary of a conformable contact (**Polyline**) must be covered by a geological boundary (**Polygon**).	The boundaries of an area feature from one layer must be covered by the line features of another layer.	
Unconformable contact	The boundary of an unconformable contact (**Polyline**) must be covered by a geological boundary (**Polygon**).	The boundaries of an area feature from one layer must be covered by the line features of another layer.	
Intrusive contact	The boundary of a stratum contact (**Polyline**) must be covered by a rock boundary (**Polygon**).	The boundaries of an area feature from one layer must be covered by the line features of another layer.	
Sedimentary contact	The boundary of a rock contact (**Polyline**) plane must be covered a geological boundary (**Polygon**).	The boundaries of an area feature from one layer must be covered by the line features of another layer.	
Faulted contact	The boundary of a planar rock contact (**Polyline**) must be covered by a faulted line (**Polygon**).	The boundaries of an area feature from one layer must be covered by the line features of another layer.	

Based on the ArcGIS Diagrammer Geodatabase model and according to the 10 topological relationships with which the geological objects comply, this paper builds logical models for topological relationships between different or identical elements consisting of folds, faults and strata. Figure 2 shows the Geodatabase data model of the topology of folds, Figure 3 shows the Geodatabase data model of the topology of fault elements, and Figure 4 shows the Geodatabase data model of stratum elements.

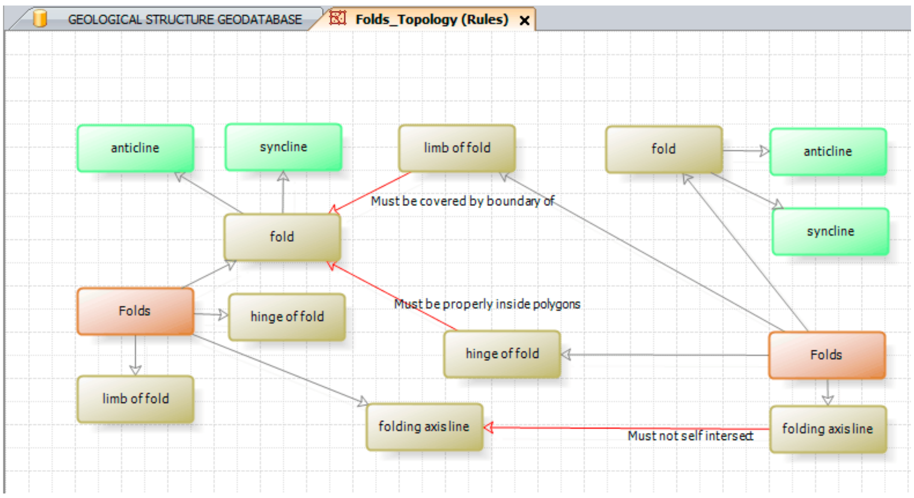


Figure 2. Geodatabase data model of the topology of fold elements.

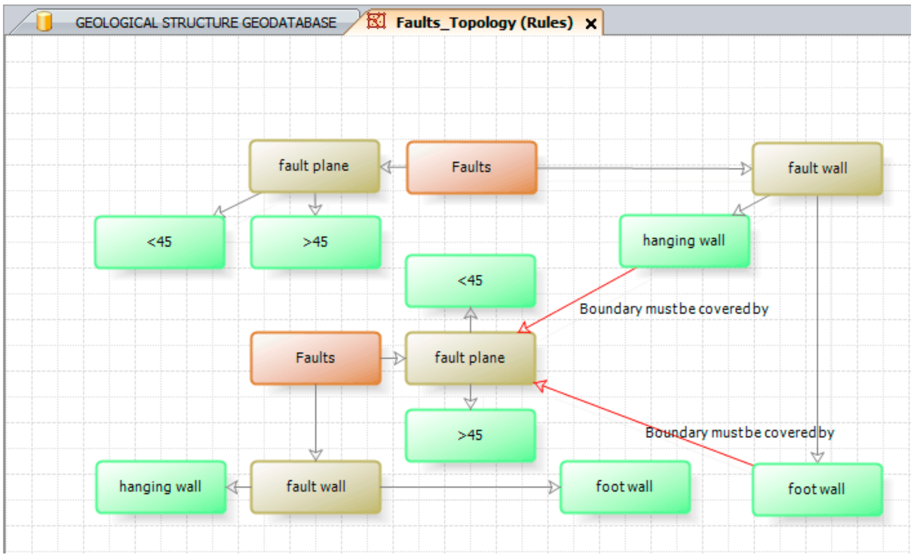


Figure 3. Geodatabase data model of the topology of fault elements.

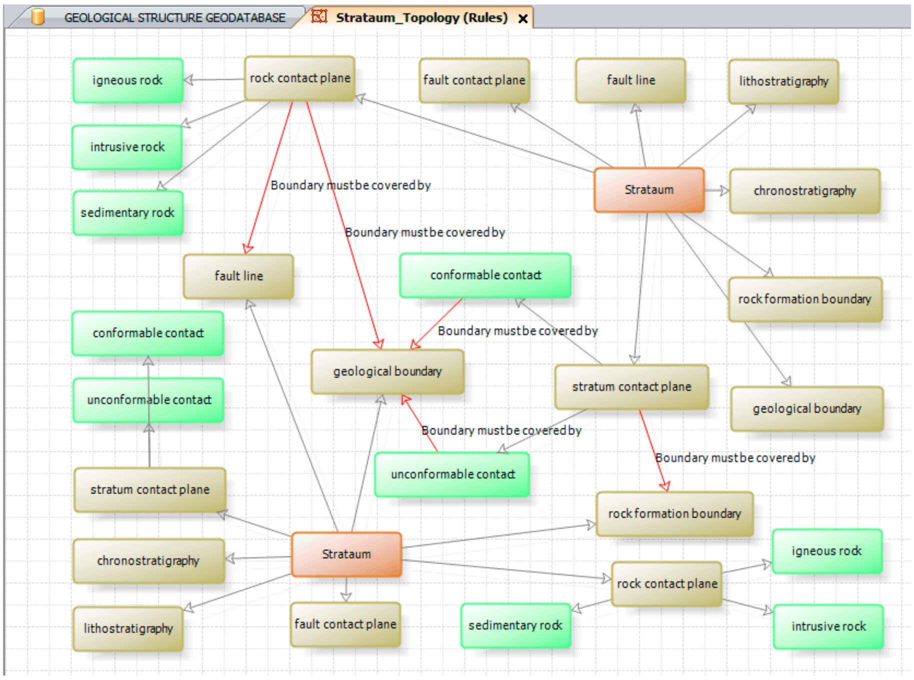


Figure 4. Geodatabase data model of the topology of stratum elements.

Based on the ArcGIS Diagrammer Geodatabase model and according to the 10 topological relationships with which geological objects comply, this paper builds Geodatabase data models for the topological relationships between different or identical elements consisting of folds, faults and strata. Figure 2 shows the Geodatabase data model of fold elements, Figure 3 shows the Geodatabase data model of fault elements, and Figure 4 shows the Geodatabase data model of stratum elements. In Figure 2, the feature dataset is composed of folds, namely, folds, fold hinges, fold limbs, and folding axes; anticlines and synclines are subtypes of a fold. In Figure 3, the feature dataset consists of faults, namely, fault planes and fault walls; faults with dips of <45° and >45° are subtypes of a fault plane, while hanging walls and foot walls are subtypes of a fault wall. In Figure 4, the feature dataset consists of stratum elements, namely, geological boundaries, rock formation boundaries, fault lines, stratum contact planes, rock contact planes, fault contact planes, and chronostratigraphic and lithostratigraphic elements; conformable contacts and unconformable contacts are subtypes of stratum contact planes, and intrusive rocks, sedimentary rocks and igneous rocks are subtypes of rock contact planes. The semantics of red arrows constitute a "link mode" topological relation, and the semantics of black arrows constitute a "contains" relationship.

Based on the description of geological relationships with natural languages, this paper follows classified geological rules to build logical models for each topological relationship through a Topology Rule. A Topology Rule includes the following key elements: OriginClassId, OriginSubtype, DestinationClassId, Destination, and TopologyRuleType. Take the conformable contact as an example: its OriginClassId is a stratum contact plane, its OriginSubtype is a conformable contact plane, its DestinationClassId is a geological boundary, and its TopologyRuleType is esriTRTAreaBoundaryCoveredByline, as shown in Figure 5.

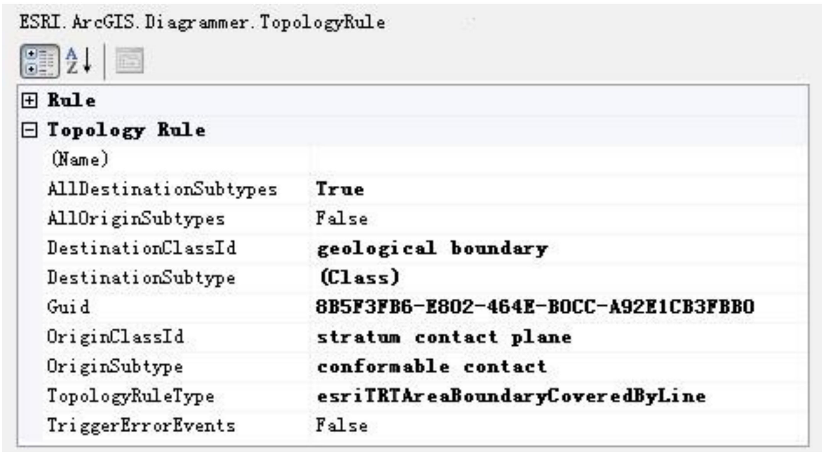


Figure 5. Procedure for building topological rules (an example of a conformable contact relationship).

3.3. Modelling of Association Relationships of Geological Phenomena

The model of the association relationships of geological phenomena is constructed with the following 17 types of geological relationships: anticlinorium, synclinorium, linear fold, brachyaxis fold, structural dome, structural basin, longitudinal fault, transverse fault, diagonal fault, horst and graben structure, imbricate reverse fault, reverse/back-thrust fault, conjugate fault, strike-slip fault, dip-slip fault, oblique fault and bedding fault. This modelling scheme includes three aspects: the design of the corresponding description mechanism of the association relationships in combined relationships, the building of association models, and the development of association rules.

In addition to a topological relationship, geological objects also contain an association relationship that is not affiliated with the geometric features; rather, this relationship reflects the association between geological phenomena. For example, an anticlinorium is made up of folds (synclines and anticlines); an anticlinorium or synclinorium refers to the anticlines or synclines in the limbs of the folds that are complicated by a series of secondary folds. Therefore, a corresponding mechanism is required to describe the association relationship in the combined relationship, ensuring that the association in the model complies with the semantic description of the real geological association, as shown in Table 5. Based on the Geodatabase association relationship rules, this paper designs the origin class and destination class for elements, such as an anticlinorium and a fold, and association rules, such as one-to-many simple relationships, to build the corresponding description mechanism.

Table 5. Corresponding description of the association relationship in each combined relationship.

L1	L2	L3	Origin Class	Destination Class	Association Rule
Association relationship of geological phenomena	Fold and fold	Anticlinorium	Anticlinorium	Fold	One-to-many simple relationship
		synclinorium	synclinorium	Fold	One-to-many simple relationship
	Fold and stratum	Linear fold	Linear fold	Stratum contact plane	One-to-many simple relationship
		Brachyaxis fold	Brachyaxis fold	Stratum contact plane	One-to-many simple relationship
		Structural dome	Structural dome	Stratum contact plane	One-to-many simple relationship
		Structural basin	Structural basin	Stratum contact plane	One-to-many simple relationship
	Fault and fold	Longitudinal fault	Longitudinal fault	Folding axis	One-to-one simple relationship
		Transverse fault	Transverse fault	Folding axis	One-to-one simple relationship
		Diagonal fault	Diagonal fault	Folding axis	One-to-one simple relationship
	Fault and fault	Horst and graben structure	Fault wall	Normal fault	One-to-many complicated relationship
		Imbricate reverse fault	Hanging wall	Reverse fault	One-to-many complicated relationship
		Reverse/back-thrust fault	Anticline	Reverse fault	One-to-many simple relationship
		Conjugate fault	Wrench fault	Stratum line	One-to-many simple relationship
	Fault and stratum	Strike-slip fault	Strike-slip fault	Rock formation contact plane	One-to-many simple relationship
		Dip-slip fault	Dip-slip fault	Rock formation contact plane	One-to-many simple relationship
		Oblique fault	Oblique fault	Rock formation contact plane	One-to-many simple relationship
		Bedding fault	Bedding fault	Rock formation contact plane	One-to-many simple relationship

Based on the ArcGIS Diagrammer Geodatabase model, this paper builds an element dataset to store the association relationships. In the dataset, there are 17 relationship classes following the geological association rules used to complete the model design for the association relationships of geological phenomena (such as an anticlinorium and a synclinorium), as shown in Figure 6.

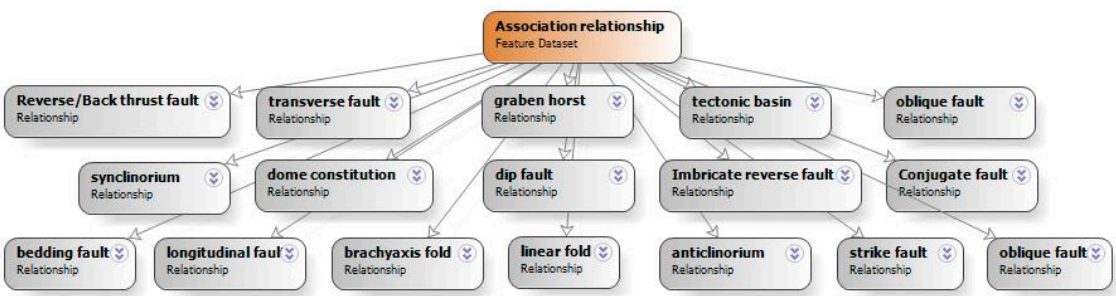


Figure 6. Logical model map of the feature dataset for the combined relationships.

The association rules shown in Table 4 are better explained with a UML diagram that clearly shows the number of constraints. Figure 7 shows the association rules of an anticlinorium. Its OriginClassId is an anticlinorium, and its DestinationClassId is a fold; its DestinationSubtype is an anticlinorium and synclinorium, and its association rule is one-to-many. Figure 8 shows the association rules of a synclinorium. Its OriginClassId is a synclinorium, and its DestinationClassId is a fold. Its DestinationSubtype is an anticlinorium and a synclinorium, and its association rule is one-to-many. The red arrows describe "origin" and "dest" associations, while black arrows denote a subtype feature "contained" within an anticlinorium and synclinorium.

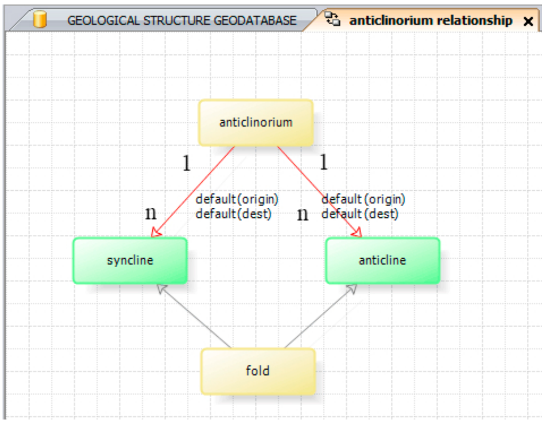


Figure 7. Association rule of an anticlinorium.

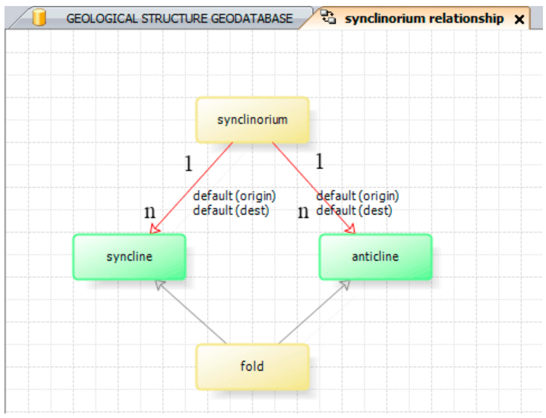


Figure 8. Association rule of a synclinorium.

4. Study and Discussion

In this paper, the section from Dagang to Danyang in the Nanjing-Zhenjiang Mountains is used as the research area. Based on the ArcGIS Diagrammer Geodatabase model, the object-oriented method is used to build a geological relationship model. With an XML workspace document as the working document, the elements, topology, and associations of a geological relationship are stored prior to importing them into Geodatabase 10.2 to build the geological relationship models that unify the geometrical features and semantics.

The key element of this study is to construct and store the topologies and associations of complicated geological relationships described by regional natural languages using GIS geometry and semantic data and to further create comprehensive expressions for geological objects. For the storage of the model, 33 types of geometric and semantic properties must be designed. For example, "OBJECTID", "SHAPE", "SHAPE_Length", "Lithology", "Axis length", "Axis strike" and "Two-limb stratum" are all found for a folding axis in the fold dataset. Additionally, "OBJECTID", "SHAPE", "SHAPE_Area", "Stratum unit name", "Stratum unit symbol", "Stratum unit time" and "Stratum thickness" are found for a chronostratigraphic element in the stratum dataset. The field names, types and features of a folding axis and chronostratigraphic element are shown in Figures 9 and 10, respectively.

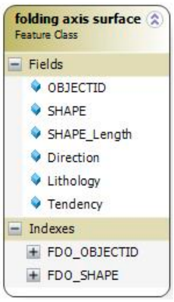


Figure 9. Feature field design of a fold axis.

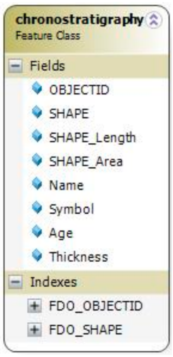


Figure 10. Feature field design of a chronostratigraphic element.

A unified physical model is required to store the compensation and association relationships of geological phenomena. Based on the ArcGIS Diagrammer Geodatabase model, the following five classes are used to achieve unified physical storage: Feature Class, Subtype, Feature Dataset, Topology, and Relationship. These classes are used as shown in Figure 11.

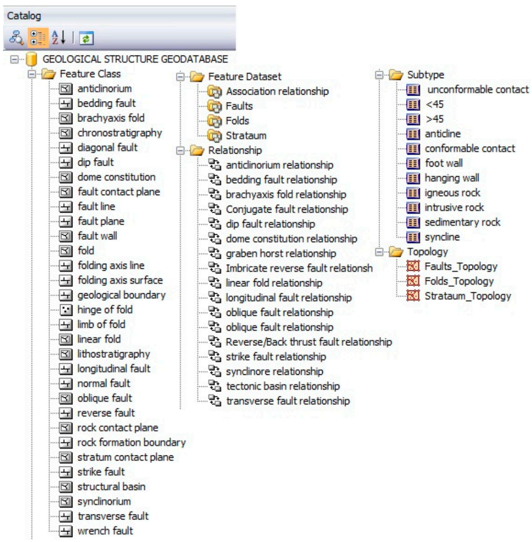


Figure 11. Physical storage of the geological relationship model.

According to the geological relationship model shown in Figure 11, the Feature Class stores 33 types of geological features, the Feature Dataset stores the datasets for folds, faults, strata and association relationships, the Relationship class stores 17 types of relationships, including anticlinorium and synclinorium, the Subtype class stores all subtypes of geological elements, and the Topology class stores the topological relationships of folds, faults and strata.

The geometrical objects in geological objects of the pansection from Dagang to Danyang in the Nanjing-Zhenjiang Mountain are expressed in the model. Figures 12 and 13 are used in the study of regional geological structure data to establish the model of "fold", "fault" and "strata", in order to express the geometric features of the three kinds of objects graphically. Figure 12 shows the results of the integrated expression of geometry and semantics for fold objects with the classify standard of the natural language of fold (syncline and anticline) and the results for fault objects, with the classify standard of the natural language of fault (wrench fault, normal fault and reverse fault). Figure 13 presents the results for the stratigraphic objects. In Figure 13, according to the natural language of geological age of the regional geological structure of Ning-Zhen mountain area, with the classify standard from new to old (sinian system, cambrian system, silurian system, etc.), it sets the stratigraphic object element class to realize the integrated expression of geometry and semantics for the geological age of stratigraphic objects.

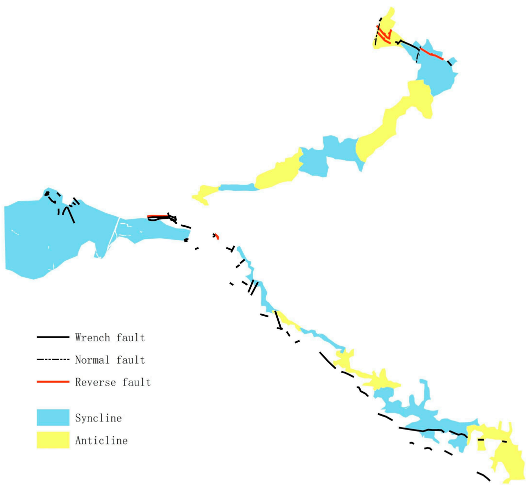


Figure 12. Modelling of fold and fault objects.

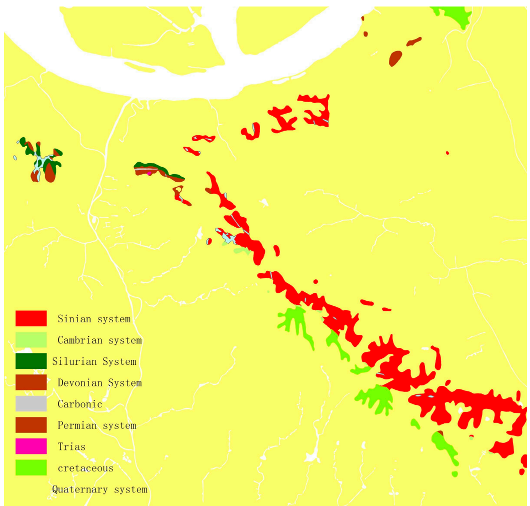


Figure 13. Modelling of strata objects.

The model shows geolocation relationships through topologies and various relationships. The topology system is built as follows:

- Three types of topological rules are established in the fold dataset: hinge of fold and fold, limb of fold and fold, and folding axis;
- Two types of topological rules are established in the fault dataset: fault wall (hanging wall) and fault plane and fault wall (foot wall) and fault plane;
- Five types of topological rules are established in the stratum dataset: conformable contact, unconformable contact, intrusive contact, sedimentary contact and faulted contact.

The association relationship system consists of 17 relationship rules: anticlinorium, synclinorium, linear fold, brachyaxis fold, structural dome, structural basin, longitudinal fault, transverse fault, diagonal fault, horst and graben structure, imbricate reverse fault, reverse/back-thrust fault, conjugate fault, strike-slip fault, dip-slip fault, oblique fault and bedding fault.

Figure 14 shows the geological relationships of regional structures based on the geological relationships described within the *Memoir on Geology of Nanjing-Zhenjiang Mountains.* Figure 14a–d show the relationships among the anticlinorium, folding axis, conformable contact, and faulted contact, which are all stored in the same data model.

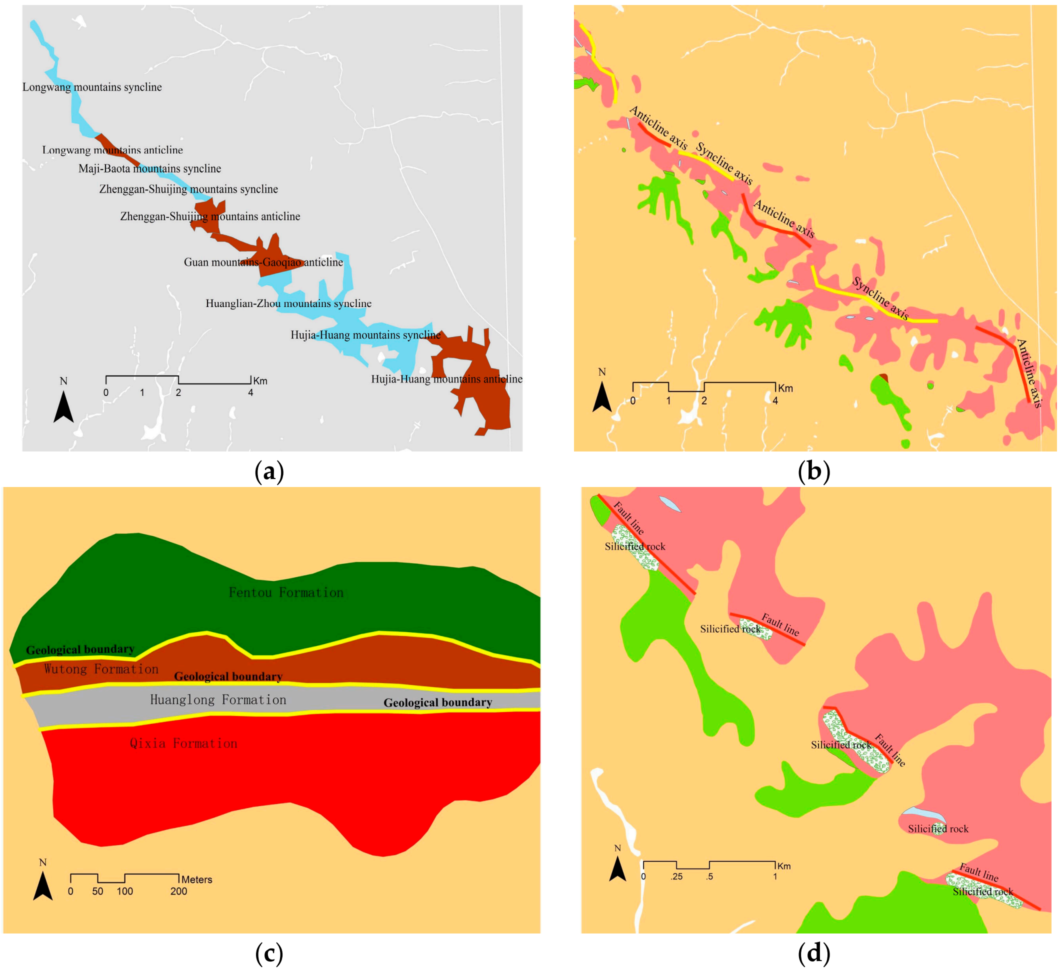


Figure 14. Geological relationships among regional geological structures. (**a**) Jizhuang-Houzhuxiang anticlinorium; (**b**) Jizhuang-Houzhuxiang folding axis line; (**c**) conformable contact relationship; (**d**) faulted contact relationship.

1. Figure 14a shows the geometric expression of the anticlinorium. This model complies with the semantic description of the topological relationship that states "The anticlinorium is made up of some folds (syncline and anticline)" and the association rule of "one-to-many simple relationship".
2. Figure 14b shows the geometric expression of the folding axis. This model complies with the semantic description of the topological relationship that states "The axis cannot intersect with or be covered by the geological boundary", that is, the topological rule of "must not self intersect".
3. Figure 14c shows the geometric expression of the conformable contact. This model complies with the semantic description of the topological relationship that states "The boundary of the conformable contact plane must be covered by the geological boundary", that is, the topological rule of "Boundary must be covered by".
4. Figure 14d shows the geometric expression of faulted contact. This model complies with the semantic description of the topological relationship that states "The boundary of the rock contact plane must be covered by a faulted line", that is, the topological rule of "Boundary must be covered by".

From a geometric perspective, the geographic expressions of geological objects can effectively reflect the geometric features of folds, faults and strata. From a topological perspective, such expressions can reveal the spatial relationships among real geological phenomena and store the topological relationships found between geological objects. From a relationship perspective, such expressions can effectively represent the composition relationships of real geological phenomena at a macroscopic level and store their association relationships. From a semantic perspective, such expressions can correspondingly show the topological and relation rules to store and express geological relationships via GIS data. The results show that this GIS modelling method can better store and express geological phenomena, geological objects and geological spatial objects in a way that integrates their geometry and semantics.

5. Conclusions

Our GIS modelling method integrating geometry and semantics uses object-oriented technology via a Geodatabase spatial data model supported by a standard relation database. Our method uses the ArcGIS Diagrammer Geodatabase model and designs relationships via modelling in consideration of geological semantics. This paper aims to build a GIS model of geological relationships, regarding the problems in existing GIS models. The purpose of this model is to build a bridge between GIS and semantics of geological relationship described by geologists, which is significant for both GIS modelling and analysis in geological phenomena. The construction of the data model mainly includes the following key aspects:

1. Based on the geological definitions, the model categorizes geological relationships as internal composition relationships and external combined relationships, resulting in a total of two categories, eight classes and 27 small groups.
2. The corresponding descriptions of topological rules are designed for each composition relationship, and the corresponding descriptions of association rules are designed for each association relationship.
3. The model then expresses the internal composition relationships as topological relationships between geological spatial objects, thereby defining the Origin, Dest and TopologyRuleType for each Topology Rule, and expresses the external position relationships (i.e., combined relationships) as association relationships between geological spatial objects, thereby defining the Origin, Dest and RelationRuleType for each Relationship Class.

The results show that this GIS modelling method can better store and express geological phenomenon, geological objects and geological spatial objects in a way that integrates their geometry and semantics.

This paper discusses the geological relationships of three geological phenomena, namely, folds, faults and strata, based on their geological definitions and develops an expression that unifies the geometries and semantics of those relationships. A GIS model that can unify the geometries and semantics of geological relationships has the following features:

1. Define and classify the geological relationships. Explain the geological phenomena and their relationships based on their geological meanings.
2. Generalize the three levels of geological relationships from geological phenomena to geological objects and geological spatial objects to construct their interior constitution expressions by topological relationships and their exterior constitution expressions by association relationships between spatial objects.
3. According to this study, the developed model can express geological meanings and store geometric elements, and it can show the corresponding geological relationships well.

Some issues still persist that must be investigated through further research:

1. Based on the relationship classification system of multiple tectonic scales (such as tectonics, regional structures, and microstructures), GIS modelling could be used to study the geological relationships at multiple dimensions and scales and unify the levels of spatial expression.
2. Using the geological rules of geological relationships as the platform for recognition and judgement, the GIS model could be used to recognize and judge the relationships of complicated structures.

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