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Research paper

Geo3DML: A standard-based exchange format for 3D geological models

Zhangang Wang[a,*], Honggang Qu[b], Zixing Wu[b], Xianghong Wang[b]

[a] College of Geosciences and Surveying Engineering, China University of Mining and Technology, Beijing, 100083 China
[b] Development & Research Centre, China Geological Survey, Beijing, 100037, China

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ABSTRACT

A geological model (geomodel) in three-dimensional (3D) space is a digital representation of the Earth's subsurface, recognized by geologists and stored in resultant geological data (geodata). The increasing demand for data management and interoperable applications of geomodelscan be addressed by developing standard-based exchange formats for the representation of not only a single geological object, but also holistic geomodels. However, current standards such as GeoSciML cannot incorporate all the geomodel-related information. This paper presents Geo3DML for the exchange of 3D geomodels based on the existing Open Geospatial Consortium (OGC) standards. Geo3DML is based on a unified and formal representation of structural models, attribute models and hierarchical structures of interpreted resultant geodata in different dimensional views, including drills, cross-sections/geomaps and 3D models, which is compatible with the conceptual model of GeoSciML. Geo3DML aims to encode all geomodel-related information integrally in one framework, including the semantic and geometric information of geoobjects and their relationships, as well as visual information. At present, Geo3DML and some supporting tools have been released as a data-exchange standard by the China Geological Survey (CGS).

1. Introduction

3D geological modeling methods have matured in recent years and have been widely applied (Mallet, 1997; De Kemp, 1999; Lemon and Jones, 2003; Sprague and De Kemp, 2005; Apel, 2006; Caumon et al., 2009; Caumon, 2010; Collon et al., 2015). Geological survey organizations (GSOs) from different countries have put forward 3D geological modeling and mapping programs, which aim toward building a 3D geological framework that provides a basic platform for full 3D cognition of the subsurface (DGSM, 2005; USGS, 2007; Kessler et al., 2009; Berg et al., 2011; CSIRO, 2012; Gupta et al., 2015). In general, from the view of geological recognition or data observation and collection, so-called geological data (geodata) mainly include boreholes, cross-sections, geologic maps and 3D models and these data are actually specific forms of geological models (geomodels), which provide an interpretative cognition and digital representation of Earth's subsurface (Mallet, 2002). The continuing progress in the generation and analytical methods of geomodels or geodata creates strong expectations on agencies, especially geological survey organizations (GSOs), for exchanging and sharing re-usable geodata, just as OneGeology (2008) shares 2D geoscience data via the internet.

It is necessary to provide standardized information encoding rules, making data providers and users process the contents of geodata in a consistent way (Howard et al., 2009). The contents of a single geological object (geoobject) generally include two important and distinct aspects: (1) human words or vocabulary-based conceptual attributes; and (2) location or shape related geometric information. Currently, there are several standards developed to describe the geoobject-related contents. GeoSciML (Sen and Duffy, 2005) defined very basic geological data structures and document formats based on GML (2007), and GeoSciML 4.1 has now been adopted as an OGC standard (GeoSciML, 2016). The geometry data type from GML can be used to represent the shape of a geoobject. RESQML (2012) is mainly used for data exchange of 3D reservoir objects in the oil and gas exploration industry. However, these still lack holistic geomodel representations. The purpose of designing an exchange standard is more than providing a readable file format. The holistic representation of geomodels encompasses the rules of space partitioning, the semantic structures of geoobjects and the identification of relations between geoobjects (Wang et al., 2016), as well as other information for exchange, including metadata, quality evaluation, visual information, etc. All such information can be considered as geomodel-related data for reuse, and should be organized and encoded in a unified framework. Thus, Geo3DML is proposed to provide a standardized representation and exchange format for 3D geomodels based on

* Corresponding author.
E-mail address: millwzg@163.com (Z. Wang).

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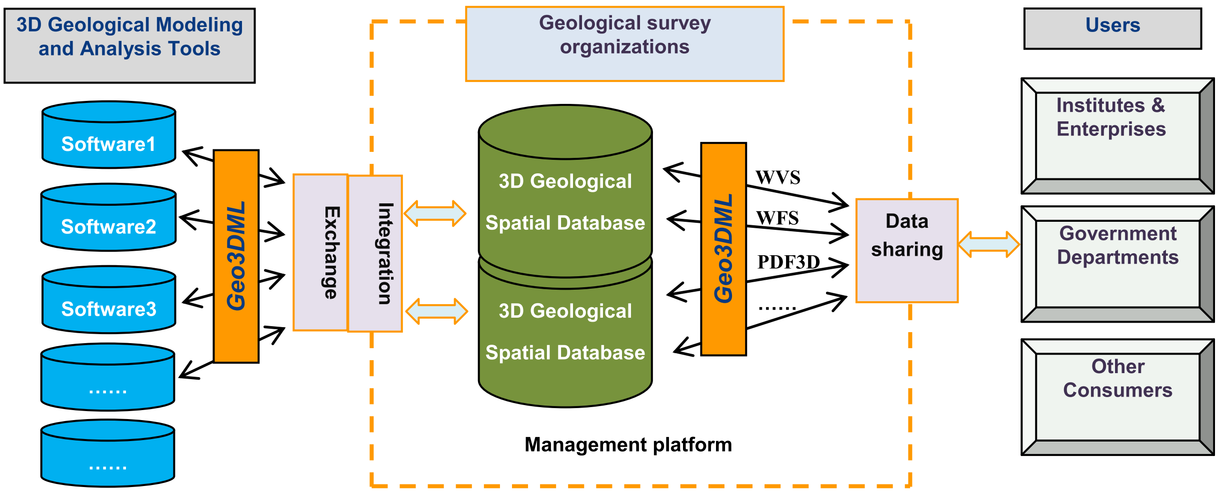


Fig. 1. Requirements for exchanging and sharing geomodels using Geo3DML for GSOs.

Table 1
Relevant standards used in Geo3DML.

- Modularity and extendibility. Geo3DML uses the XML Schema language and UML to define the framework (see Section 4.1), which mainly includes the seven modules shown in Fig. 2. The function of each module is given in Table 2.

Abbreviation	Standard name	Version	Contribution in Geo3DML
FE	Filter Encoding	1.1.0	Extension for encoding 3D visual parameters
GeoSciML	Geoscience Markup Language	4.1	Definition of geoobjects and their relations
GMD	Geographic Information-Metadata		Extension for encoding project and geomodel metadata
GML	Geography Markup Language	3.2.1	Extension for encoding geometry-related shape objects and field data
SE	Symbology Encoding	1.1.0	Extension for encoding 3D visual parameters
SWE	Sensor Web Enablement Common Data Model	2.0	Definition of the attribute structure of geoobjects

the existing standards.

The remainder of this paper is structured as follows. The design principles of Geo3DML are given in Section 2. Section 3 introduces a unified and formal method of representing interpreted resultant geomodels in different dimensional views. Section 4 introduces the framework and main components of Geo3DML. Section 5 gives information relating to supporting tools. Section 6 discusses the features and limits of Geo3DML. Section 7 presents our conclusions and plans for future work.

2. Design principles

One of the main responsibilities of GSOs is to manage processed digital geodata and to promote geodata services in different applications, as shown in Fig. 1(dash line). The geodata can not only realize the conceptual description of subsurface information, but can also record visual information. Geo3DML,through standard encoding of geomodels in 3D geospace, is designed to transfer geodata in different stages, encompassing: (i) exchanging geomodels between different software; (ii) ensuring geomodels integrated within spatial databases; and (iii) sharing geomodels in a standardized service-oriented architecture, such as WFS (2005) and WVS (2010), or other applications, e.g., PDF3D (2007). Then, users can download, visualize or query the geodata. Thus, the principles in creating Geo3DML include:

- Platform independent and integrated data model. As a public exchange format, Geo3DML is independent of specific geomodeling software. Moreover, Geo3DML provides a unified way to express structural models and attribute models and organize the hierarchical

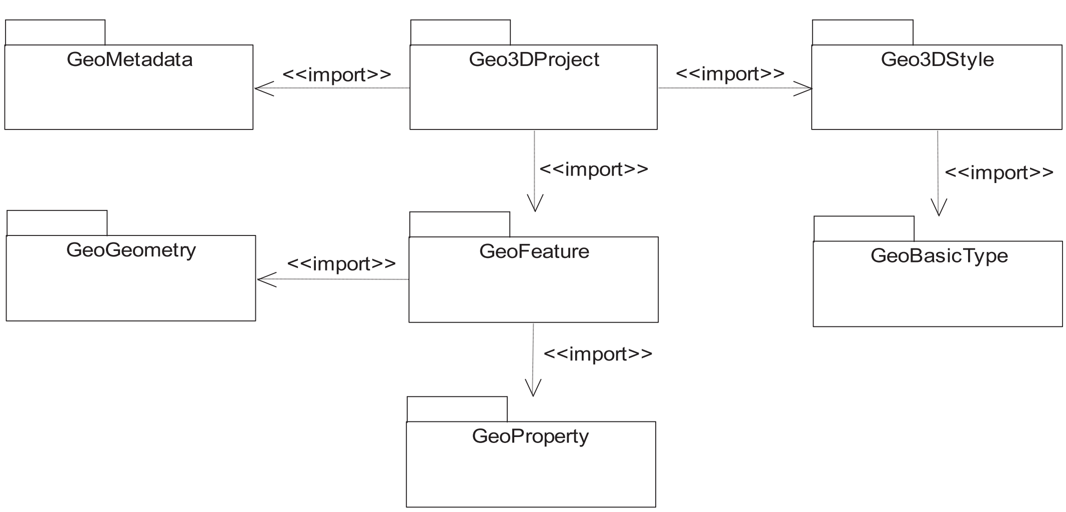
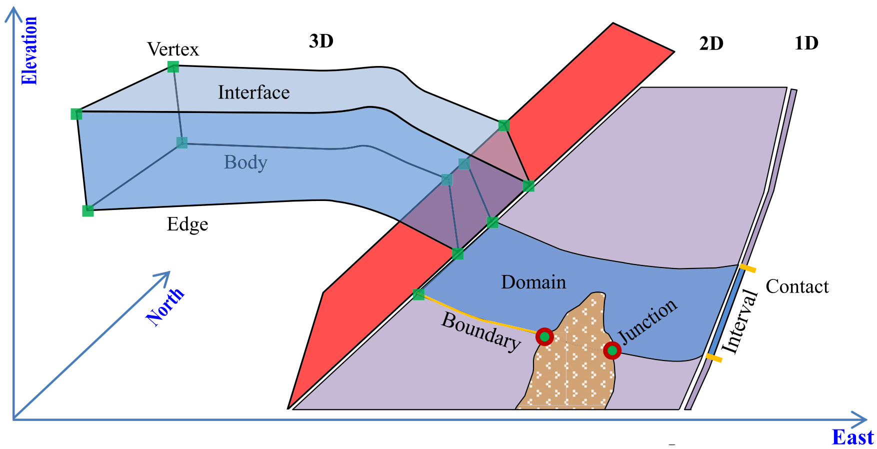


Fig. 2. Modular components of Geo3DML.



Dimension of GeoModel	Dimension of Geometric elements 3	2	1	0
3 (3D model)	Body	Interface	Edge	Vertex
2 (map, section)		Domain	Boundary	Junction
1 (drill, traverse)			Interval	Contact

The '⟶' arrow means the 'equivalent' representation of elements

Fig. 3. Geometric elements of geomodels in one, two and three dimensional views (Burns, 1988; Thiele et al., 2016).

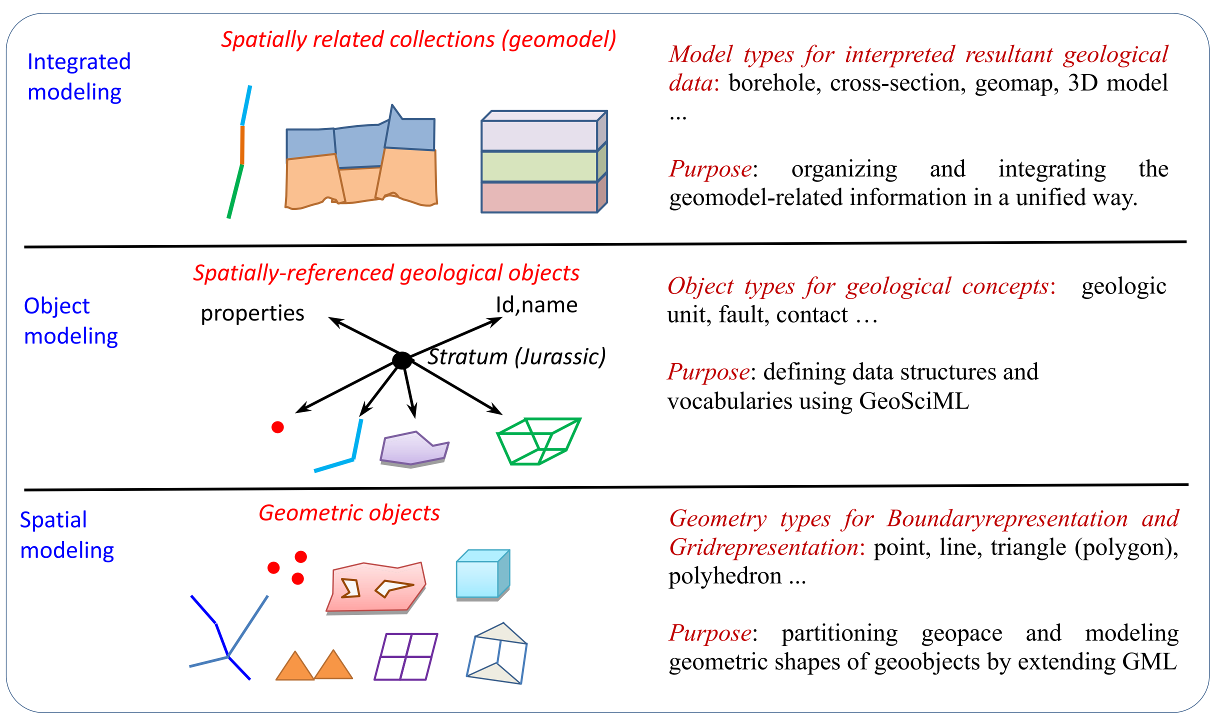


Fig. 4. Three levels of geomodels in Geo3DML.

structure of geodata, including drills, cross-sections/geomaps and 3D models (see Section 3).

- Segregation of geomodel data and visual information. The core framework of Geo3DML in Section 4.1 is based on a loosely coupled segregation policy, such that Geo3DML can support modular data exchange. In other words, geodata can be separated or shared as needed. For example, data users can obtain a complete geomodel without visual information.
- Reusing and extending existing standards. Geo3DML mainly uses the existing OGC standards (Table 1), based on GML extensions, and the conceptual model of geoobjects is derived from OGC GeoSciML. Thus, Geo3DML is allowed compatibility with the existing OGC web-service architectures.

3. Methods of representing geomodels

3.1. Three levels for representing geomodels

The formal representation of geomodels is the foundation of Geo3DML, providing a unified framework to integrate geological

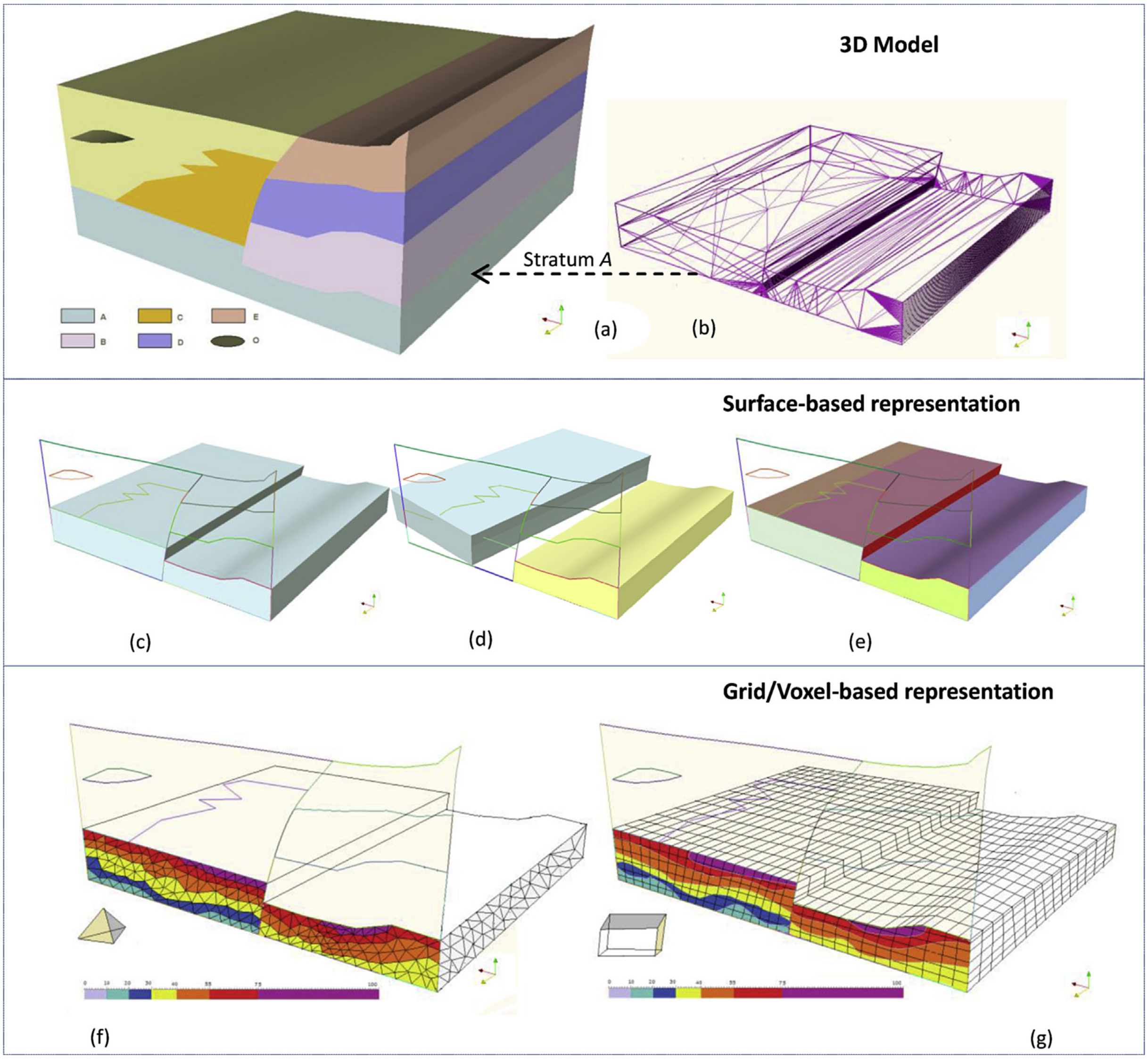


Fig. 5. Methods of representation of a 3D geomodel: (a) A 3D structural geomodel; (b) Wireframe representation of stratum *A* using triangulated irregular networks (TINs); (c) *A* is formed using one fully-closed surface; (d) *A* is composed of two components split by a fault; (e) *A* is topologically formed by combining boundary surfaces; (f) A discrete attribute model embedded in stratum *A* using tetrahedral meshes; and (g) An attribute model using cornerpoint grids.

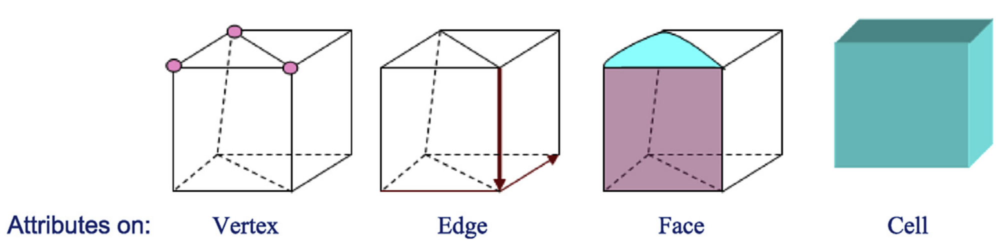


Fig. 6. Four binding types for storing the value of attribute fields in a geometric cell.

information. Several studies attempted to represent geomodels, but their focus was on constructing and editing a geological model, such as the G-maps (Lienhardt, 1994; Mallet, 2002), the Sealed Geological Model (Caumon et al., 2004) and the Wire frame (Xu and Tian, 2009). The geomodels represented by G-maps have complete mathematical theories to describe spatial data in any spatial dimensions, which have been extended into the spatio-temporal domain (Le et al., 2013). More relevant discussions about these models were given in Wu and Caumon's studies (Wu, 2004; Caumon, 2010). Mallet (2002) noted that a geomodel provides an abstract digital representation of the Earth's subsurface, composed of both a geological structural model, which stores the shapes and relations of geoobjects utilizing surface-based boundary representations, and an associated attribute model, used to describe the material properties of these geoobjects. Such representation involves spatial partitioning under specific conditions by constructing a mapping relationship between the segmented spaces and geoobjects (Wang et al., 2016). Geomodels consist of a set of exclusive and interconnected geoobjects, which define their geological semantics and geometric properties, and

Table 2
Description of the Geo3DML modules.

- Ease of use. A series of support tools have been developed in order to help users to check the veracity of Geo3DML files, visualize geomodels and program Read-Write interfaces.

No	Module name	Description
1	Geo3DProject	Defines the project information, and the structure of geomodels. This is the main component of the data transfer format defined by Geo3DML
2	GeoMetadata	Defines the structure of the GeoModel metadata
3	Geo3DStyle	Defines the 3D visualization parameters and the structure of the parameter library
4	GeoFeature	Defines the geological features and the structure of the classes of geological objects
5	GeoGeometry	Defines the extended structure of geometric objects stated in the GML specifications
6	GeoProperty	Defines the extended structure stated in gmlcov: Abstract-Coverage and is used to describe the 3D property fields
7	GeoBasicType	Defines the structure of the basic data used by Geo3DML

Table 3
Spatial representations of an *n*-GeoModel in various dimensions.

n	*n*-GeoModel	Shape of *Geologic Boundary* (*n*-1-Geometry)	Shape of *Geologic Unit* (*n*-Geometry)	Attribute model (Primitives embedded in *n*- Geometry)
0	Observed Point	/	Point	Node
1	Borehole	Point	Line	Segment
2	Cross-section/ Geomap	Line	Polygon	Grid (Triangle)
3	3D Model	Surface	Body	Polyhedron (Grid3D)

specify topological relationships and self-consistencies. Moreover, a geomodel is recognized and processed by geologists, and appears in interpreted resultant geodata, such as boreholes, sections/geomaps, and 3D models (Fig. 3), which are conventionally portrayed on maps or rendered in a 3D scene. These data can be used to understand geological phenomenon along a line path, a surface, or in 3D space. Thus, geomodels provide geological cognition of the subsurface in various dimensional views and have three levels (Fig. 4): (i) spatial modeling is for modeling the geometric shapes of geoobjects, and uses vector or raster data types to portray locations and graphic characteristics; (ii) object modeling is for modeling single, spatially referenced geoobjects, where an object models the information about itself, particularly a representation of the geological setting and concepts, essential attributes and linked geometries as spatial properties; and (iii) integrated modeling is for modeling spatially related collections and repositories of geoobjects and for forming geomodels with explicit spatial relations between objects and model-related information.

A sample of a 3D model, composed of both a structural model and associated attribute model, is shown in Fig. 5. The modeling process involves the partitioning and discretization of the 3D subsurface. The boundary surfaces of the structural model are generated based on a number of geological boundary conditions (e.g., faults or horizons), and then each complete geoobject is closely formed by the corresponding surfaces. In current practice, the representation of geoobjects can differ in their semantic and spatial relationships. For example (Fig. 5c, d and e), three possible common types of topological representations of geo-unit *A* can be categorized, where the third method represents explicit topologic al relationships between *A* and geological boundaries. The attribute model of this sample is constructed using a grid/voxel-based model, supporting discretization of the space of a sealed geo-unit *A* (Fig. 5f and g) to generate the distribution of geological attribute fields (Caers et al., 1999; Mallet, 2002; Caumon, 2010).

3.2. Integrated model

A geomodel is first and foremost a spatial data model. A full description of a spatial model involves three aspects: spatial partitioning, constructive rules, and supported objects and primitives (Zlatanova et al., 2004). As introduced in our work for 3D models (Wang et al., 2016), geomodels in *n*-dimensional views under the same time and observation scales can be formally given:

$$\mathrm{n-GeoModel} = \{\mathrm{Gp}, \mathrm{O}, \mathrm{R}, \mathrm{A}\} \quad (\mathrm{n} = 0, 1, 2 \text{ and } 3) \tag{1}$$

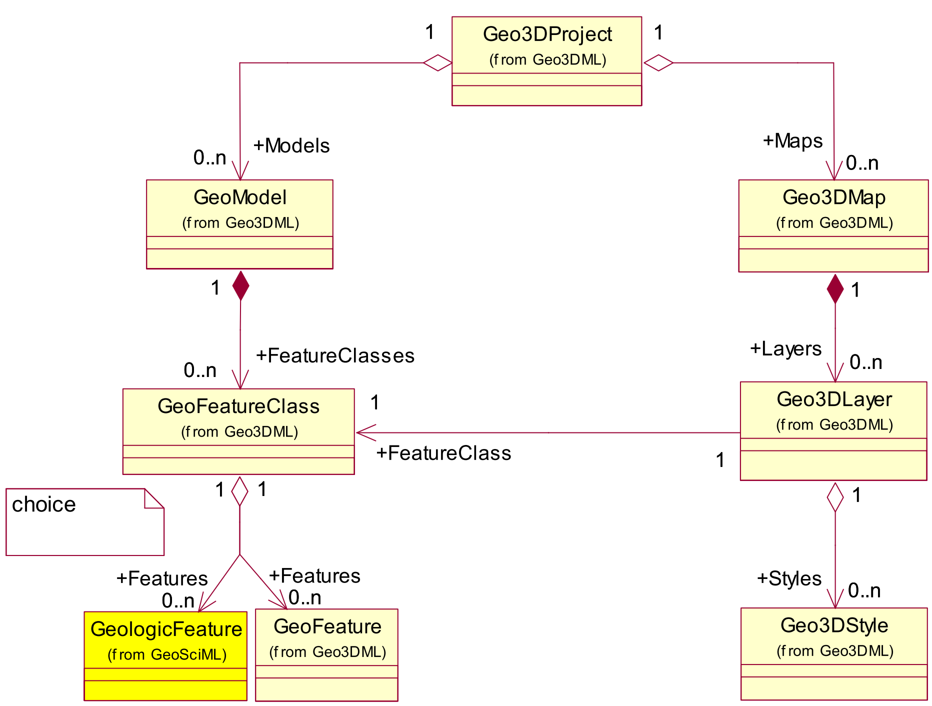


Fig. 7. UML class diagram: framework of top-level components.

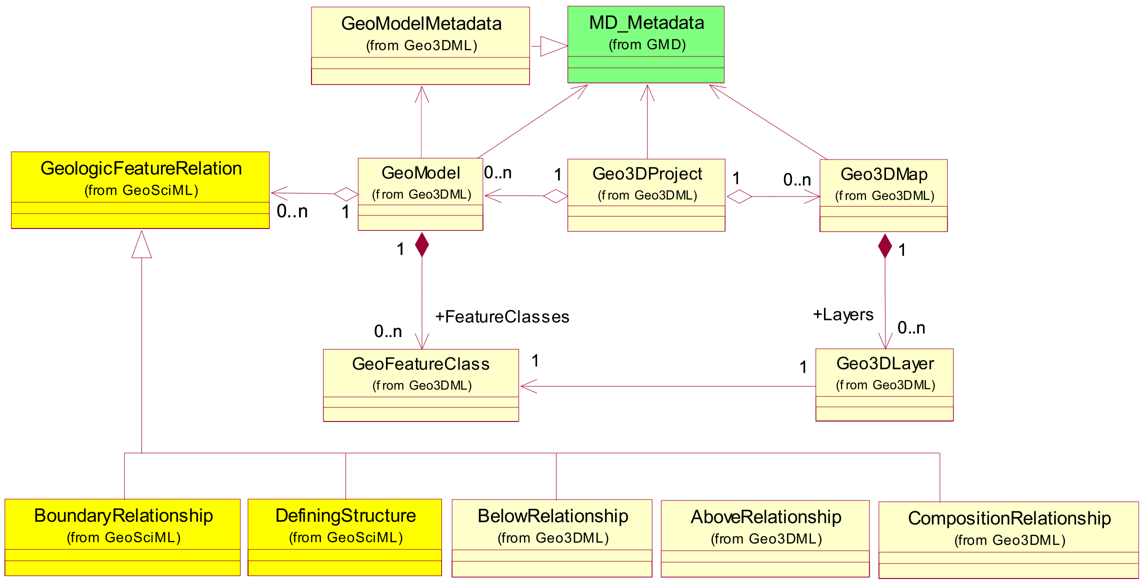


Fig. 8. UML class diagram: metadata and relationships.

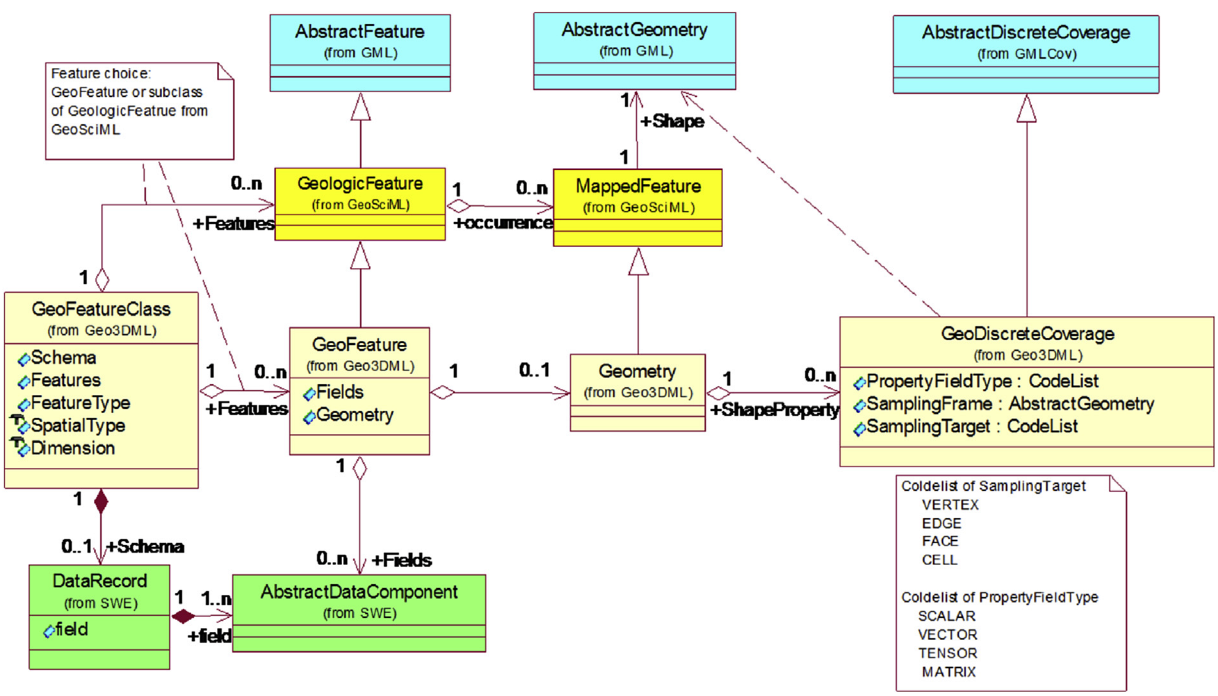


Fig. 9. UML class diagram: representation of geologic features.

- *Gp* represents geometric discretization and partitioning of subsurface space.
- *O* represents geoobjects (i.e., *GeologicFeatures* in GeoSciML and Geo3DML). Wang et al. (2016) gave the constructive rules and formal definitions of the basic types of geoobjects—*GeologicBoundary, GeologicUnit* and *GeologicStructure. GeologicBoundary* is a special type of *GeologicStructure*. It is an abstract representation of all geological boundary constraints for spatial partitioning, such as a part of a fault or a horizon (stratigraphic/lithological boundary) in an actual model. For a *GeologicUnit* object o, the geometrical dimension $\dim(o) = n$, and for a *GeologicStructure*, $\dim(o) = n\text{-}1$.
- *R* represents explicit spatial relationships between geoobjects. The formal representation of spatial relations is becoming increasingly important for alphanumeric query and analysis of spatial data (Bradley and Paul, 2014; Leopold et al., 2015; Thiele et al., 2016). GeoSciML has defined several abstract geological relations and spatial relations. Geo3DML emphasizes the topological relations and directional relations, where $R = \{above, below, at, boundary, composition\}$, as defined in Geoscience Spatial Framework (GSF) (DGSM, 2005) from BGS and GSIS (Ming et al., 2010). The '*above*' or '*below*' specifies a *GeologicBoundary* adjacent to a unique *GeologicUnit* above or below it. The '*at*' denotes a *GeologicBoundary* interpreted as a more specific *GeologicStructure*. The '*boundary*' specifies a relationship of the bounds of a *GeologicUnit* composed of *GeologicBoundaries*. The '*composition*' specifies a relationship of a *GeologiUnit* composed of other *GeologicUnits*, or the relationship of a *GeologicStructure* composed of other *GeologicStructures*.

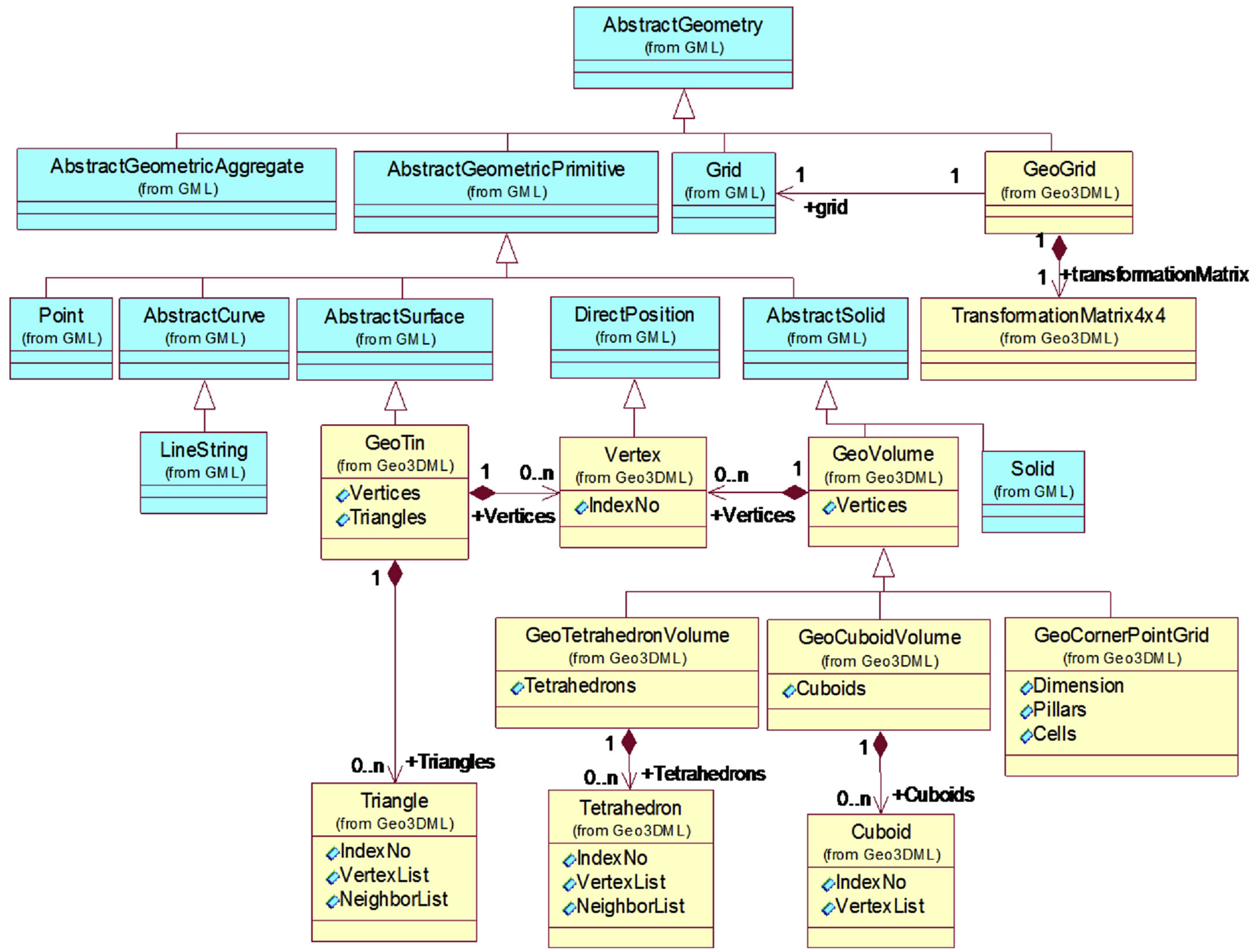


Fig. 10. UML class diagram: geometry.

- There are two choices for extending attributes of a *GeologicFeature* in Geo3DML. One is to use the specific GeoSciML subclass of *GeologicFeature*. The attribute *FeatureType* of *GeoFeatureClass* indicates the specific class name, e.g., *GeologicUnit* or *Contact*. Another makes use of the *GeoFeature* from Geo3DML to add user-defined attributes. The attribute *Schema* of *GeoFeatureClass* is an instance of *swe:DataRecord* from OGC SWE specifications (SWE, 2009), and is used for defining the structures of the attribute table. The attribute *Fields* of *GeoFeature* record the value of each corresponding field in *Schema*.
- The geometry-related shape objects and field data extend from the GML geometry and coverage definitions (GML, 2007). The shape of a *GeologicFeature* object, i.e., *MappedFeature*, is associated with an instance of *gml:AbstractGeometry*. GeoSciML only focuses on 2D geometry portrayed in geologic maps. However, *MappedFeature* cannot support coverages and hardly covers well-known geometric types used for surface-based and grid-based representations in 3D geomodeling software. Geo3DML defines the *Geometry* class to extend *MappedFeature* and provides more geometric types to represent *GeologicFeatures*, including structured and unstructured meshes, such as the tetrahedron-based model, cuboid-based model and cornerpoint grid, as shown in Fig. 10. Each geometry object can be stored in binary form in XML-based documents using OGC Well-Known Binary (WKB) encoding.
- Field data are dependent on a specific geometry object. Geo3DML defines *GeoDiscreteCoverage*, which inherits from *gmlcov:AbstractDiscreteCoverage*, to support the geological attribute model. It has three main extension attributes: (1) *SamplingFrame* points to an associated geometry object; (2) *SamplingTarget* refers to one of four binding types depicted in Fig. 6; and (3) *PropertyFieldType* refers to the field type, such as scalar, vector or tensor.

- *A* represents geological attribute fields ($v = \mathbf{F}(\mathbf{x})$) discretized and bound to a geometry object *G* using a grid/voxel-based representation. Any scalar, vector or tensor field can be discretely stored in a primitive (minimum cell) of *G* through four binding types as shown in Fig. 6.

Generally, *n*-GeoModels can be spatially represented in a unified form (Table 3) and the geological structures and units are presented by *n*-1- and *n*-Geometries, respectively. The *n*-Geometries can be further discretized into *n*-primitives, or other compatible Cartesian grids, to form the attribute models.

4. Components of Geo3DML

4.1. Framework

The top-level components of Geo3DML are shown in Fig. 7, and the core framework is composed of *GeoModel* and *Geo3DMap*. The class *GeoModel* is designed to represent the *n*-GeoModels (eq. (1)). The class *Geo3DMap* is used to define how to visualize the geomodels. Geomodels are usually created in a geological survey campaign or project, and the class *Geo3DProject* is used to organize all the relevant *GeoModels* and *Geo3DMaps*. *Geo3DProject* also records the project information such as

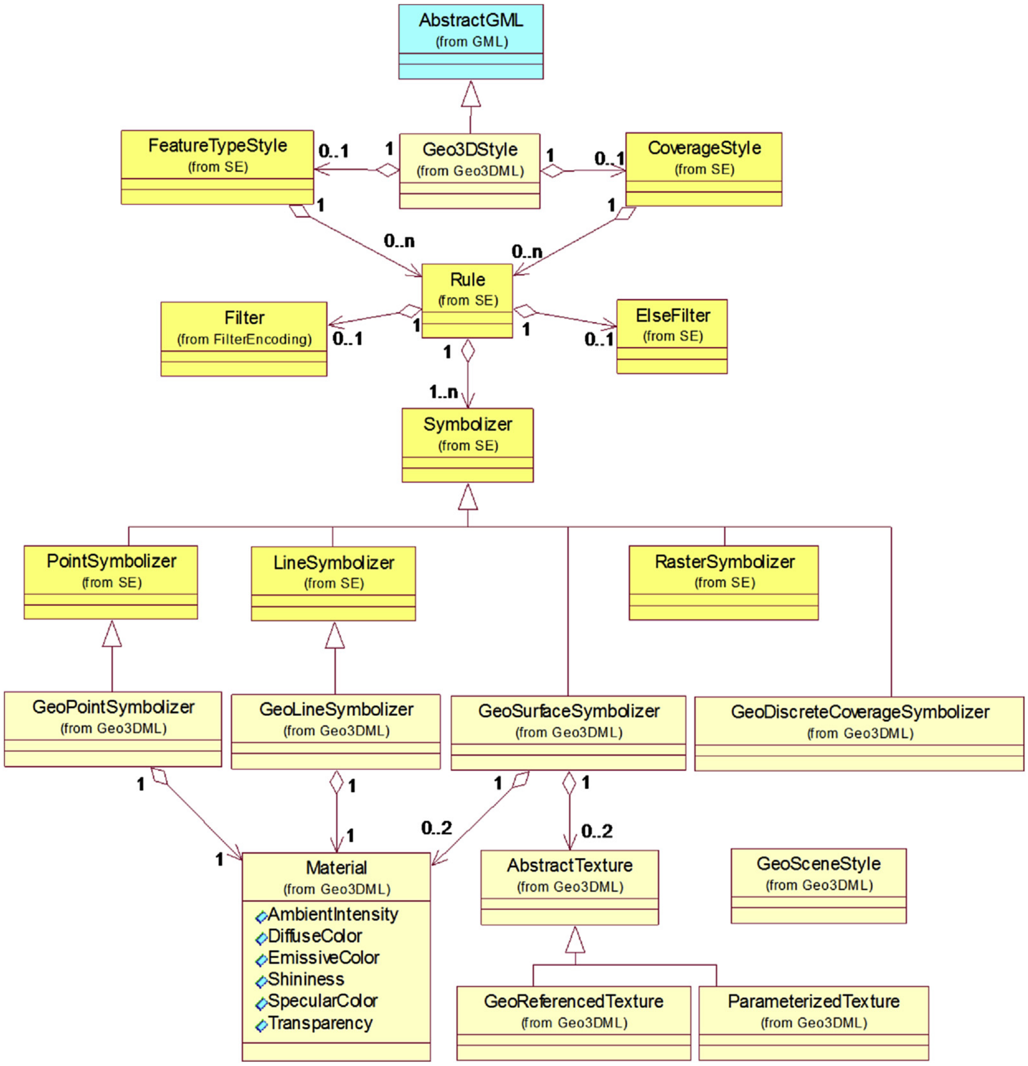


Fig. 11. UML class diagram: Geo3DStyle.

location, extent and responsible parties.

The configuration of *Geo3DMap* draws on the concept of the traditional map in 2D geographic information systems (GISs) and is composed of several layers. *Geo3DLayer* is a layer that is used for the combination of a set of geoobjects (*GeoFeatureClass*) and their visual information (*Geo3DStyle*). A *GeoFeatureClass* is capable of being visualized by a variety of *Geo3DStyles*, such as color or texture filling styles.

Geo3DML employs the fundamental class *GeologicFeature* from GeoSciML to model all geoobjects in a geomodel. However, the data structures (semantic attributes) of *GeologicFeature* defined by GeoSciML are fixed. Although GeoSciML-Lite (GeoSciML, 2016) provides an extendible way to allow additional attributes, it is still insufficient to exchange generic feature types. Geo3DML provides another choice for defining *GeoFeatures* (see Section 4.2). *GeoFeatureClass* is a set of *GeologicFeatures* with the same attribute configuration. The five spatial relationships mentioned in Section 3.2 are derived from the *GeologicFeatureRelation* from GeoSciML, as shown in Fig. 8. The model-related metadata, such as describing the project initiative and data sources or the process of constructing the geomodels, are given by *MD_Metadata* from GMD (2007).

4.2. Semantic and geometric attributes of geologic features

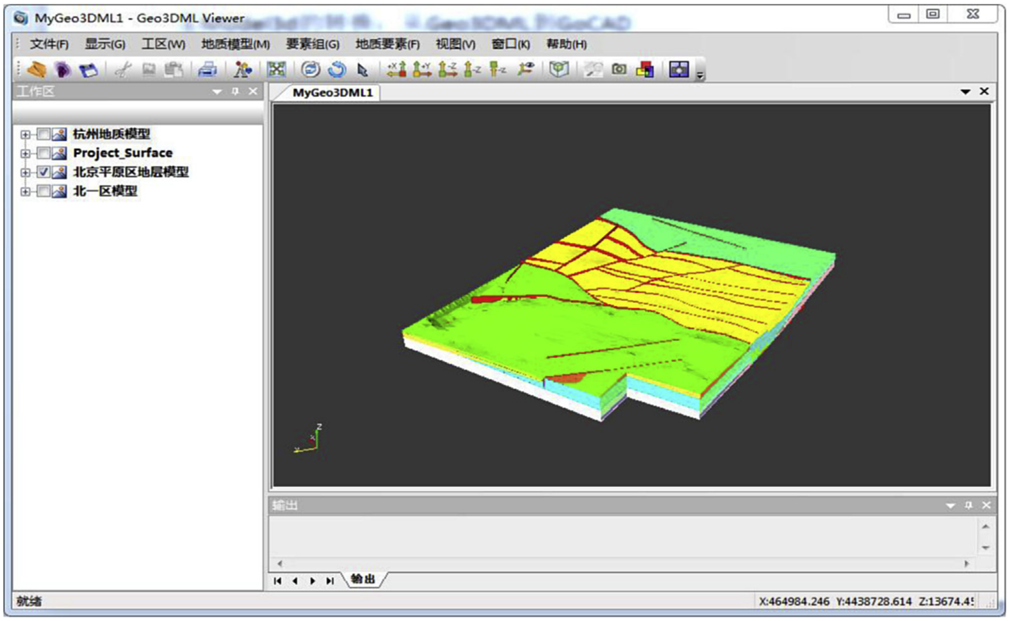
The procedure for modeling a single generic geoobject (Fig. 4) involves the definitions of semantic attributes, geometry data and attribute fields. Fig. 9 shows the data model of geologic features.

4.3. Geo3DStyle

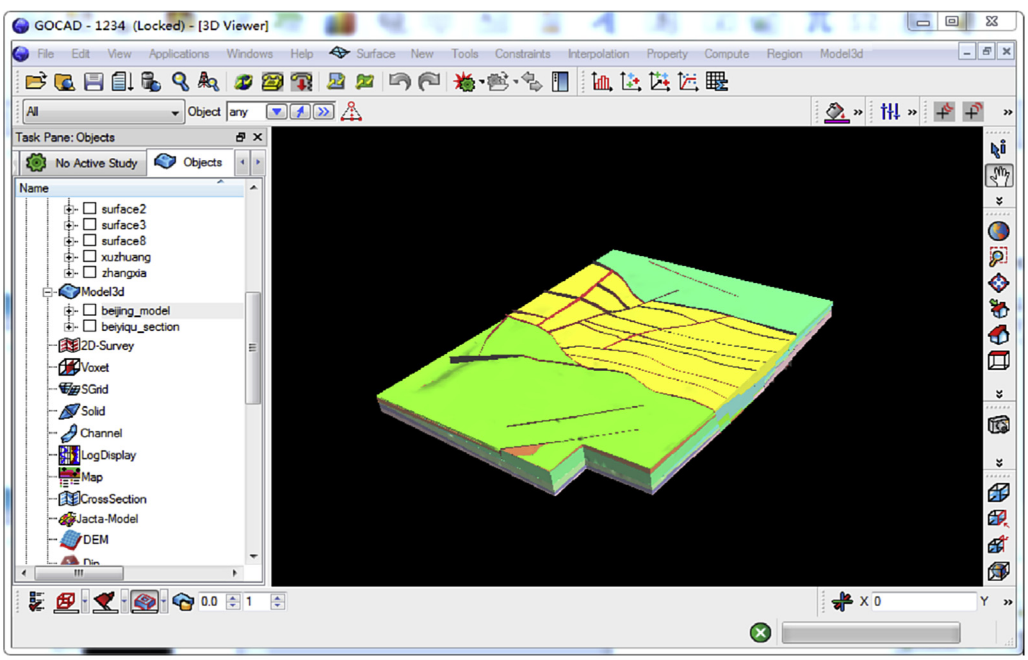
The visual information of a geomodel is recorded in *Geo3DStyles*. The core model is illustrated in Fig. 11. By referring to SLD (2005), CityGML (2012) and X3D (2004), the extension for encoding 3D visual parameters comes from the SE (2006) and FilterEncoding (FE, 2005) specifications. *FeatureTypeStyle* is used to define the visual parameters of geometric data, and *CoverageStyle* is used to define the visual parameters of the attribute fields. *Rule* classifies the specific visual parameters (*Symbolizer*) based on different geological attributes using *Filter* and *ElseFilter*. To support 3D visualization, Geo3DML gives common encoding of 3D visual information for point (*geo3dml:GeoPointSymbolizer*), line (*geo3dml:GeoLineSymbolizer*), surface (*geo3dml:GeoSurfaceSymbolizer*), and field data (*geo3dml:GeoDiscreteCoverage*).

5. Supporting tools

Geo3DML (Version 1.0) was accepted and released in December 2015 by CGS as a standardized data-exchange format for 3D geomodels. It is intended that Geo3DML will ultimately encompass a broad range of requirements for geomodel data interoperability. In the process of



(a)



(b)

Fig. 12. The 3D bedrock geomodel of Beijing generated by GSIS (Ming et al., 2010), and rendered in: (a) Geo3DML Viewer; and (b) GoCAD.

compiling the Geo3DML, five geomodeling software companies in China were invited to participate in the validation from multiple geological domains, including fundamental geology, hydrogeology, urban geology, mineral geology and so on. In order to facilitate the easy development of Geo3DML by different users, a series of supporting tools have also been provided, including: (1) Geo3DML Viewer is a tool to check the veracity of Geo3DML files and to visualize the data running on Windows; (2) Geo3DML SDK is an open-source C++/C# program for developing Read-Write interfaces for Geo3DML-based documents; and (3) other tools for data exchange between Geo3DML and other well-known file formats, such as the PDF3D convertor and GoCAD convertor. As shown in Fig. 12, for example, the 3D bedrock geomodel of Beijing generated by GSIS (Ming et al., 2010) was encoded using Geo3DML and rendered by Geo3DML Viewer and GoCAD (Version 2011; now named SKUA), respectively. The differences in visual effect between the two screenshots are due to the different settings of global scene rendering parameters, such as the number of light sources and ambient light. These parameters are not exchanged in Geo3DML.

In addition, a protosystem was developed to visualize Geo3DML-based geomodels in a web-service application implemented using WebGL (2014). All such information can be obtained from the Geo3DML website www.geo3dml.cn/en.

6. Discussion

At present, Geo3DML focuses on the exchange of geomodels—3D interpreted resultant geodata, serving GSOs. The purpose is to provide a standardized representation and encoding method based on the existing standards, especially representing geomodels associated with the conceptual model of GeoSciML. Geo3DML considers geomodels integrally to organize all the information in a unified way, as well as visual information. This feature is the main difference with other standards.

GeoSciML is most suited for geoobject modeling (Fig. 4), supporting descriptions of geological setting and concepts. However, the geometry of a *GeologicFeature* cannot be well modeled by the popular methods of boundary-based and grid-based representations. The current extensions of GeoSciML are always implemented to describe the conceptual attributes of geoobjects in specific geological domains, such as GWL (Boisvert and Brodaric, 2007) for hydrology, INSPIRE (2008) for multiple disciplines, GeoSciGraph (Gupta et al., 2015) and 3D-GEM (Tegtmeier et al., 2014) for geotechnics. The above researches hardly mention 3D geometry related extensions.

RESQML is used for the data exchange of 3D reservoir objects (RESQML, 2012). The main feature of RESQML is the relatively complete definitions of various types of 3D grids for numerical reservoir simulation. RESQML only defines some common geoobjects, like horizon and fault, which are derived from geophysical data interpretation. So the data structures of geoobjects are different from that of GeoSciML. Meanwhile, their definitions do not use or extend OGC GML or GeoSciML.

The characteristics of Geo3DML are summarized as follows:

- Geo3DML is based on a unified and formal representation of structural models, attribute models and hierarchical structures of geodata, including drill, cross-sections/geomaps and 3D models.
- The framework of Geo3DML is based on a policy of segregation of geomodel data and visual information, and draws on the common hierarchical management of spatial data in 2D GISs. In this way, users can be allowed to deal with the whole project, a geomap or some layers, and a geomodel or some features.
- The extensions of existing standards used in Geo3DML mainly entail geometry data and visual styles, supporting boundary-based and grid-based representation and visualization for geomodels.

The limits of the present version of Geo3DML include:

- Geo3DML provides two choices for the exchange of *GeologicFeatures.* Although it is flexible for data providers to choose the built-in classes or user-defined attributes, the flexibility may result in difficulties of understanding the contents of geoobjects.
- Not all 3D grid types are defined and supported, such as the PEBI mesh and GTP (Wu, 2004). Geo3DML now defines some widely used grid types and provides an extension mechanism for generalization of the class *GeoVolume* (Fig. 10).
- One geometry object or one array of field data is encoded in one data block (one element node in a xml document), which is not efficient for massive amounts of data. Dividing data into blocks and building a spatial index needs further consideration.
- Only the common 3D visual information including RGBA-based colors and textures is supported. Other visual parameters, such as the HSV color model, are not considered.
- Geo3DML now focuses on interpreted resultant geological models. Other data like geophysical data or data from other sources may not be well supported.
- Evaluation criteria of geomodels are not considered. The quantitative and qualitative descriptions of the quality measures of attribute models and structural models are still open. We will investigate these problems further.
- The definition of geomodel-related metadata is still simple and cannot standardize the structures and contents of provenience, modeling process and products.

7. Conclusions

This paper introduced Geo3DML, a solution to the exchange of 3D geomodels based on the existing OGC standards. The requirements for creating Geo3DML were derived from the need for interoperability of 3D geodata in GSOs. Geo3DML focuses on the exchange of interpreted resultant geomodels in different dimensional views, including drill, cross-sections/geomaps and 3D models. These geomodels are presented based on a unified and formal method. Geo3DML considers geomodels integrally to encode all the semantic and geometric information of geo-objects and their relationships, as well as visual information. Now, Geo3DML and some supporting tools have been released as a data-exchange standard for 3D geomodels in the CGS.

We also hope the design of Geo3DML will provide some inspiration to extend the GeoSciML available for 3D geomodels.

There have been some requirements and attentions regarding the evaluation and reuse of geomodels, such as quality and complexity measures (Wellmann and Regenauer-Lieb, 2012; Wellmann et al., 2014; Pellerin et al., 2015) and topologically-based geological analysis (Thiele et al., 2016). Thus, the future of Geo3DML will investigate a standardized encoding method for all quantitative and qualitative geomodel-related information for geomodel-based management, query and analysis.

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