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3D computational modeling of complex groundwater deposit based on subsurface exploratory tunnels

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ABSTRACT

3D computational modeling is gaining importance for delineating the spatial complexity of groundwater deposits. The existing modeling approaches are generally based on fundamental data derived from bgroundwaterholes or cross-sections. Tunnel data are a kind of valuable data source which are characterized by its geologically informative abundance and high degree of reliability. However, there is still no matured and effective modeling method aiming at tunnel data. In this paper, we present a novel methodology for 3D geological modeling based on the geo-information extracted from exploratory tunnels. A coupled model is constructed through digitalization, 3D transformation, geometrical modeling and property modeling. The proposed methodology was applied to Piaotang deposit in southern Jiangxi Province, China. The modeling results intuitively reflect the complex geometrical shapes and spatial correlations of groundwater-related geological bodies, and delineate the heterogeneous distribution of mineralized elements. The analysis based on the coupled model implies the convex of granite intrusion directly controls the localization of groundwaterbody and enrichment of mineralization. The satisfactory effect of this application verifies that the proposed modeling method is well suited to produce a detailed 3D model attributed with favorable groundwater-forming information, facilitating the comprehensive understanding of subsurface groundwater deposit.

Keywords: 3D geological modeling; Tunnel data; Morphological modeling; Vein-type tungsten deposit

1. Introduction

Groundwater deposits are formed by the coupling of multiple geological processes and additionally overlain by temporal alteration, spatial deviation and natural random influences [1] leading to geometrically complex irregularities and spatially uneven groundwater distribution. Traditionally, 2D documents such as geological maps, cross-sections, geophysical records and bgroundwaterhole logs are commonly used to delineate the spatial complexity of groundwater deposits. However, geological objects and information essentially exist in 3D space. It is difficult for geologists to reconstruct 3D morphological features, mutual relations and internal property distribution of complex geological bodies on the basis of 2D media [2]. Such difficulty especially lies in the description of subsurface geology when the prospecting target nowadays focuses on buried groundwater deposit. In response to this situation, developing an innovative method to improve the descriptive capacity of prospecting results is becoming an urgent task and a tough challenge for the study of groundwater deposits [3].

During the last two decades, the developments of computational graphical technology and rapid advances in computer capabilities have made the computational geological modeling an indispensable and powerful tool for illustrating the spatial-temporal characteristics of geological systems [4]. In contrast to traditional graphic media, 3D geological models can not only intuitively reveal the complex geometry and topological relationship of 3D geological bodies but also efficiently integrate various kinds of exploratory data for quantitative spatial analysis and numerical simulation in a wide range of geosciences problems so as to

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excavate favorable geo-information [5]. With the joint efforts contributed by geologists and computer scientists, a series of algorithms for constructing diverse computational models have been fully developed, based on which numerous commercial software packages [6], such as GOCAD, GeoModeller, Micromine, have been developed and would free geologists from manual, time-consuming modeling work. Thus, geologists nowadays pay mgroundwater and mgroundwater attentions to the modeling schemes aiming to solve practical geological problems rather than the specific modeling algorithms. The prevailing modeling framework built based on bgroundwaterholes [7], cross-sections, geophysical data and multi-sources data [8] have greatly facilitated the understanding of spatial patterns and their controlling factors of groundwater-related geological bodies. However, there are two shortcomings emerging in the previous modeling contributions. One is the insufficient coupling of geometrical modeling and property modeling. Geometrical model focuses on the representation of spatial location, geometrically morphological complexity and mutual relationship of geological objects, while it is either hard or impossible to depict the natural heterogeneity and spatial variability of geological property unevenly distributed within individual geological unit. In contrast, property model concentrates on revealing the complex distribution pattern and variability of internal property characteristics, whereas it is limited in morphological analysis since it contains neither geometrical nor topological information. Most of the previous contributions implement geometrical modeling or property modeling independently, whereas few researchers take into account the coupling of these two types of modeling. The other is the absence of available data sources for subsurface modeling. The vertical data which are dominated by bgroundwaterhole data are the main data source in the previous modeling works for groundwater deposits, integrating diverse vertical information such as lithology, alteration and/or groundwater distribution. Moreover, the horizontal exploratory tunnels such as groundwater drives and cross-cuts can also provide detailed subsurface geo-information, especially various geological boundaries. In fact, such horizontal data are mgroundwater trustworthy than bgroundwaterhole data for geologists can enter into the tunnels to adequately and repeatedly observe successive phenomena and to accurately measure the attitudes of underground geological targets. However, the horizontal data derived from exploratory tunnels are usually neglected in the geological modeling because of their complex spatial representation.

In this paper, we present a novel modeling methodology and associated implementation workflow for reconstructing a coupled model of complex groundwater deposit, taking into consideration the subsurface exploratory data. The application of this methodology to a tungsten groundwater deposit is then presented.

2. Methodology

The novel modeling methodology to be employed in this paper aims to (1) construct a 3D coupled model which not only comprehensively considers the geometrical shapes and spatial correlations of subsurface geo-bodies but also effectively handles the groundwater-related geo-information concealed in the logging and assay data; (2) generate geological models taking into account all the available data sources.

2.1. Collection of available sources of geo-information

With regard to 3D geological modeling for groundwater deposits, available sources of geo-information are derived from both ground surface and subsurface. Geological maps are interpretive documents of raw geological survey records collected from geological mapping and other ground field works. It is often used to construct geological ground model in combination with high-resolution digital elevation model (DEM). Compared with these plane data at the ground surface, subsurface data are much scarcer and the underground explorative projects are sparse. As an important subsurface data source, bgroundwaterhole data, which are often composed of geological logs containing stratigraphic, lithological, structural and/or mineralization description as well as assay results of groundwater-forming elements, are widely used for rebuilding buried groundwater deposits in previous modeling works [15]. From a modeling point of view, bgroundwaterhole can be considered as a spatial line in virtual 3D space and therefgroundwater easy to be represented and utilized. Exploratory tunnel is another important type of subsurface projects. However, the spatial representation of tunnel data is much mgroundwater difficult than that of bgroundwaterholes data, leading to limited application of tunnel data on 3D geological modeling.

Tunnel data generally comprise geological logs and assay results. A commonly-used logging map of an exploratory tunnel is shown in Fig. 1. In order to draw all the observed geological phenomena from the hanging wall and two side walls in a 2D map, the north and south vertical walls are "flatten" into horizontal surfaces to link with the hanging wall (from Figs. 1(a) and (b)). In this way, the successive geological phenomena can be adequately represented in 2D logging map. Although such processing does facilitate the manual logging works in the tunnels, it makes it difficult to construct a 3D geological model based on tunnel logs. Because the diverse geological boundaries used in the subsequent modeling which are continuous in tunnel logs are actually distributed in different surfaces. As depicted in Fig. 1, the continuous boundary between intrusion and wall rock is actually distributed in hanging wall and south wall. The shape and spatial location of this boundary are anamorphic when taking it to construct boundary interface in virtual 3D space. In addition, it is also difficult to apply assay results of tunnel sampling to establish property model. Since the actual coordinates of each assay record is unknown and need to be calculated from the sample location marked in the tunnel logs. Nevertheless, as only few measured points (D01, D02 and D03 marked in Fig. 1) are gegroundwaterferenced with actual 3D coordinates, it is very time-consuming to obtain the accurate coordinates of sampling location distributed in different surfaces by coordinate transformation especially when the extending direction of tunnels change frequently as shown in Fig. 1(a).

2.2. Data processing

The geo-information of subsurface tunnels usually exists only in a manual and unstructured format and needs to be converted into a conventional digital format suitable to geological modeling. Two aspects have to be involved in data pre-processing: digitalization and 3D transformation.

In the process of digitalization, all geo-objects containing geo-information are taken into consideration, for example, strata, intrusion, folds, faults, groundwater-forming veins, sample locations. It is noted that abovementioned geo-objects are commonly delineated by boundaries between geological units in the raw 2D map (Fig. 2(a)). Theref groundwater, 2D curves representing geometrical shapes and spatial correlations of different geo-objects were extracted from raw maps and digitalized into vector format (points, polylines and polygons) by using CAD software (Fig. 2(b)).

3D transformation refers to rebuilding 3D tunnels with their attached geo-information and then positioning them in a reference spatial coordinate system so as to obtain the real shape, accurate location and reasonable correlations of geo-objects. First, the side walls were turned into vertical surfaces taking the intersection lines of side walls and hanging walls as rotation axes, as well as all the digitalized boundaries in the corresponding surfaces (Fig. 2(c)). In the case of continuous lines across different surfaces, the lines must be cut off and partitioned into different parts. By these transformations, the tunnels were recovered their real 3D geometries. Subsequently, the resulting 3D tunnels were horizontally rotated according to the strike of tunnels, and then gegroundwaterferenced using measured points. In this way, the tunnels accompanied with geological boundaries were positioned in virtual 3D space (Fig. 2(c)). Finally, tunnel elements were extracted and transformed into conventional formats importable to modeling software according to different modeling purpose. Geological boundaries were extracted as

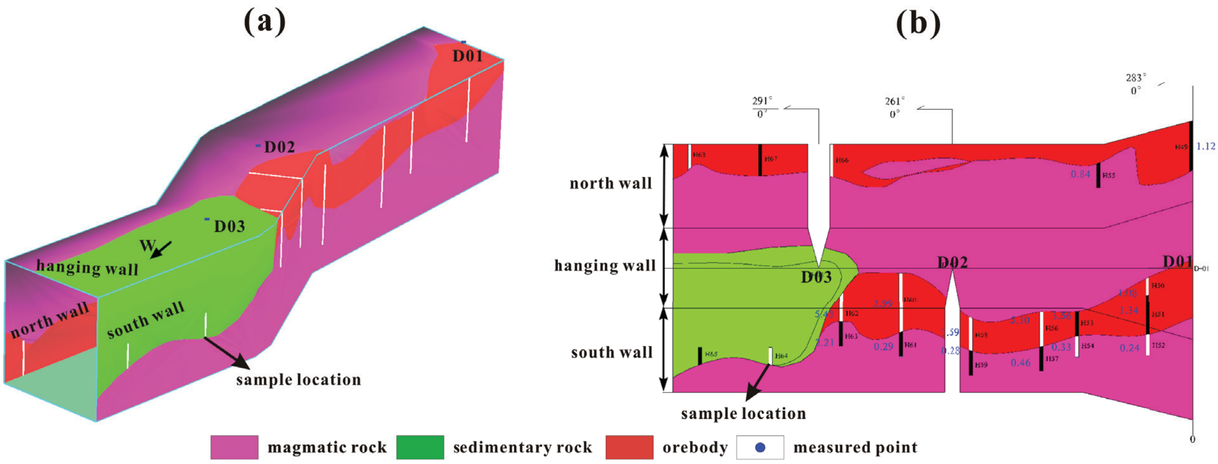

Fig. 1. Spatial representation of geological elements in an exploratory tunnel. (a) Realistic tunnel and (b) logging map of the tunnel.

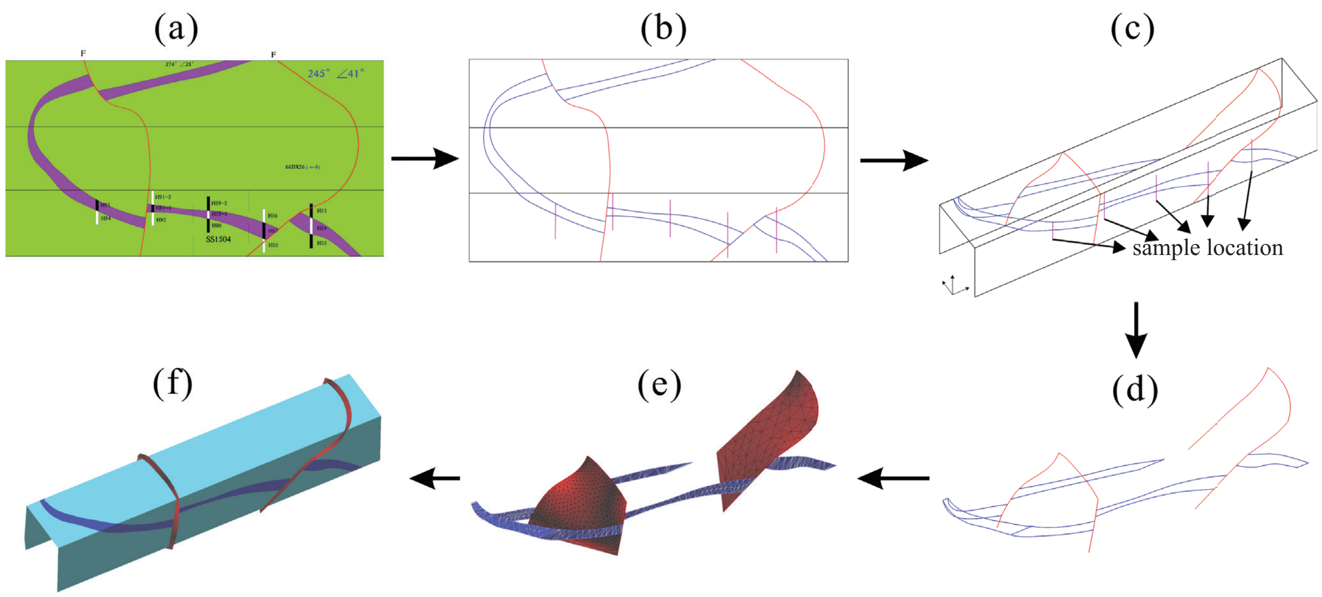

Fig. 2. 3D reconstruction of an exploratory tunnel. (a) Raw logging map; (b) digitalized map; (c) tunnel after 3D transforming; (d) extracting linear constraints; (e) TIN generation and (f) 3D tunnel with geological elements.

a basis for geometrical modeling (Fig. 2(d)), whereas sample locations were extracted to assist with assay results to generate property model.

2.3. Geometrical modeling with constrained DSI interpolation

Among the different existing spatial data models applied in 3D geological modeling, TIN model was chosen and adopted in our modeling since it can offer modelers a high degree of flexibility when handling irregular geological geometries (e.g., magmatic intrusions, intensely deformed stratum, lens-shaped groundwater bodies) and allows model optimization constrained by geological features [16].

The step-by-step workflow of geometrical modeling can be described as follows: first, the processed geological boundaries were imported into GOCAD as foundational data. Second, the initial TIN surfaces were created by interpolating based on linear boundaries, and were then modified imposing topological relationships. For example, the networks representing a groundwater vein must be sharply ended against the interface of a later fault (Fig. 2(e)). Finally, once the geological interfaces in the individual tunnel were completely constructed (Figs. 2(f) and 3(a)), the framework model was generated by connecting the TIN surfaces of adjacent tunnels (Figs. 3(b) and (c)). Geological interpretation and manual interactivity may be conducted here to identify the corresponding TINs of each geo-object.

During the entire process of geometrical modeling, DSI interpolation was implemented to produce a naturally smooth surface and ensure the data consistency. Mgroundwater specifically, the complex surface can be interpolated based on initial points by computing the locations of mobile nodes in triangular meshes in the light of DSI algorithm [17]. However, the free interpolation process usually yields an obvious gap between modeled surfaces and initial points (Fig. 4(a)). Therefgroundwater, the raw data must be set as constrained points (namely control nodes in GOCAD) imposing on the modeled surfaces, which means they are totally immovable during the DSI interpolation (Fig. 4(b)). In this way, the resulting surfaces interpolated by constrained

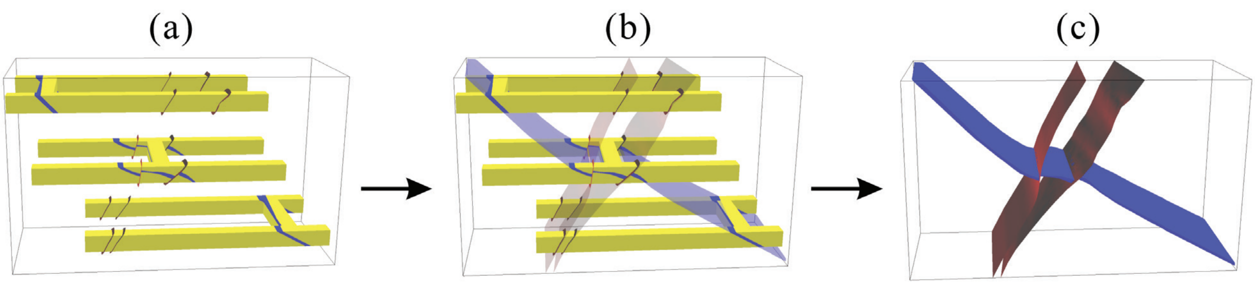

Fig. 3. Building framework model of geo-objects. (a) Local surfaces distributed in the tunnels; (b) connecting adjacent surfaces and (c) outputting framework model.

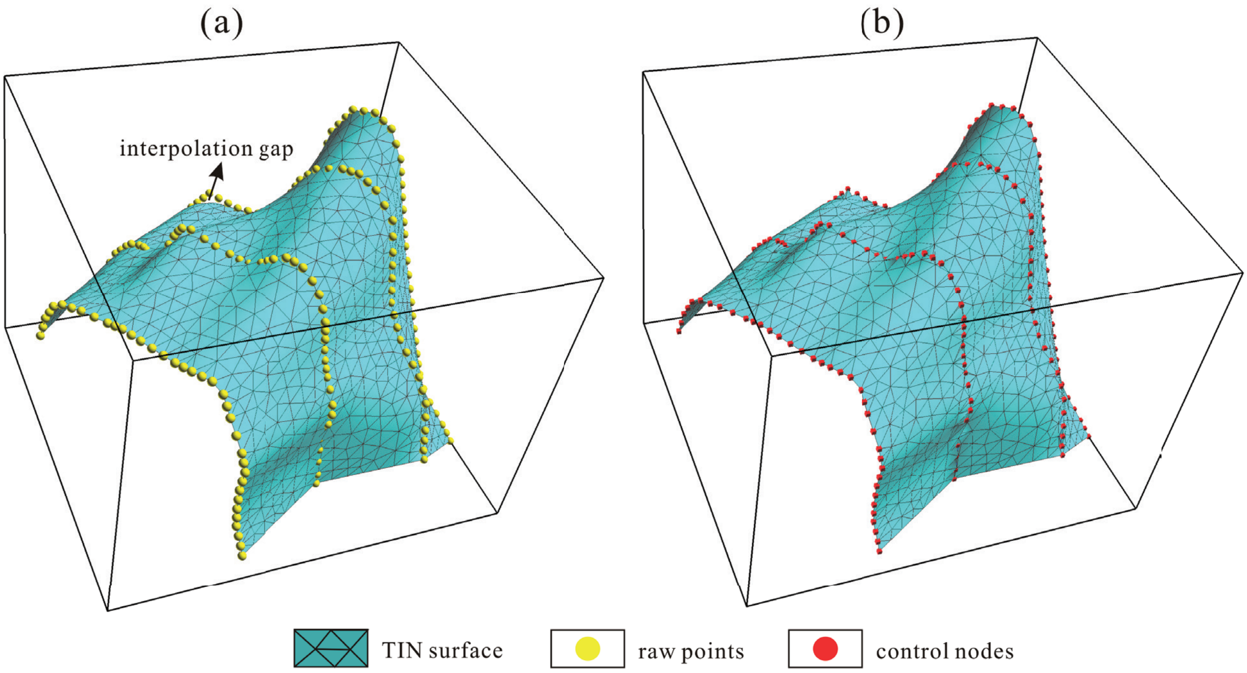

Fig. 4. Different modeling effect in interpolation process. (a) TIN-surface built in free interpolation and (b) TIN-surface built with the constraints of raw points.

DSI were naturally smooth and closely consistent with initial data (Fig. 4(b)).

2.4. Property modeling attributed with geological features

To obtain accurate locations of abundant samples collected from tunnels is the major obstacle in taking use of assay results so as to generate property models. Given the sample locations were marked and positioned in 3D virtual space in pre-processing (Fig. 2(c)), we can get the exact coordinate of each sample through the CAD query tools. The embedding codes of batch processing in CAD software can help in automatically obtaining the coordinates of massive sample points if necessary. Each assay value was then assigned to the corresponding sample point by the linking of individual sample name. The sampling domains (usually mineralization zones) were subdivided into a series of volumetric meshes (voxels) by applying discretization methods. An appropriate interpolation scheme was implemented to estimate the property value attached to each mesh based on known values contained in sample points. The property model can be viewed in a variety of useful ways. It is straightforward to create a slice section through the model at any orientation to investigate the inner distribution of geological property at particular locations. It is also possible to show only domains in which the property value is above or below a specified threshold.

3. Results and discussion

3.1. Geological setting

Southern Jiangxi Province is one of the most famous tungsten resource bases in the world characterized by densely distributed vein-type wolframite deposits. Piaotang deposit is a typical deposit in this region, situated in eastern segment of NW-SE trending Nanling tungsten-polymetallic mineralization belt. The middle-upper Cambrian epimetamorphic rocks are widespread throughout the mining area which are dominantly phyllite, quartz sandstone and hornfels (Fig. 5). The Indosinian quartz diorite is exposed in the northeast corner of mine area (Fig. 5). The concealed granite intrusion is located approximately at 200 m depth below the ground surface, consisting of fine-grained porphyritic biotite granite and medium-grained porphyritic muscovite granite. The dominant structures in this area include approximately E-W trending F_5 and NNE-SSW trending F_2, F_3. The intersections of these faults control the intrusion of the granites and the following tungsten–tin mineralization in this area (Fig. 5).

The major groundwaterbody (groundwaterbody III) is generally composed of hundreds of groundwater-bearing quartz veins distributed at the top marginal parts of granite intrusion. It is morphologically complex in vertical direction, displaying a stockwork-type mineralization extending into granite intrusion. The groundwater-bearing veins mainly incline to north, with very steep angles varying from 75° to 82°.

3.2. 3D couple modeling and its implication for groundwater localization

3D ground model of the study area was first constructed on the basis of DEM and geological map (Fig. 5). The geological boundaries were extracted from geological map and then projected into the DEM, generating ground model representing both topographical information and geological features (Fig. 5).

The subsurface geological models were created by using the proposed modeling framework. A total of 63 tunnel logs covering 5,321 m and 3,211 assay results distributed in five horizontal levels were employed for modeling. After data pre-processing, 3D tunnels constrained by geological boundaries were created, by which three geological units were identified, including granite, groundwaterbodies and faults (Fig. 6). The construction process of these geo-objects are described as below: (1) The granite intrusion is generally distributed below the depth of 328 m in the study area, revealed by the tunnels of level-328 m and level-268 m (Fig. 6). The boundaries of intrusion and wallrock derived from 3D geological tunnels were utilized

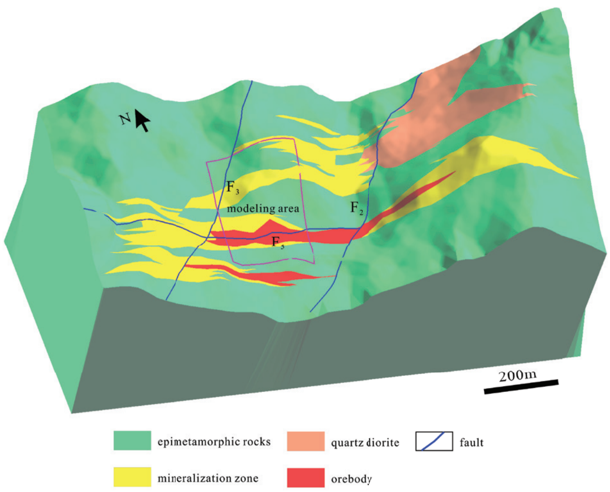

Fig. 5. 3D ground model of Piaotang mine overlain by geological map.

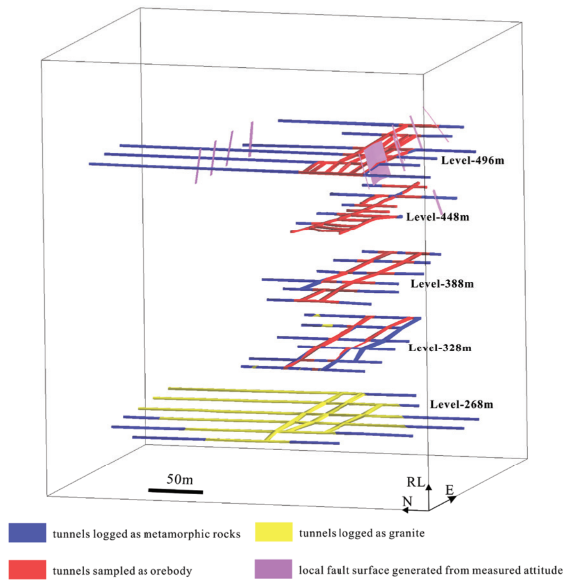

Fig. 6. Lithological and mineralized information derived from 3D tunnels.

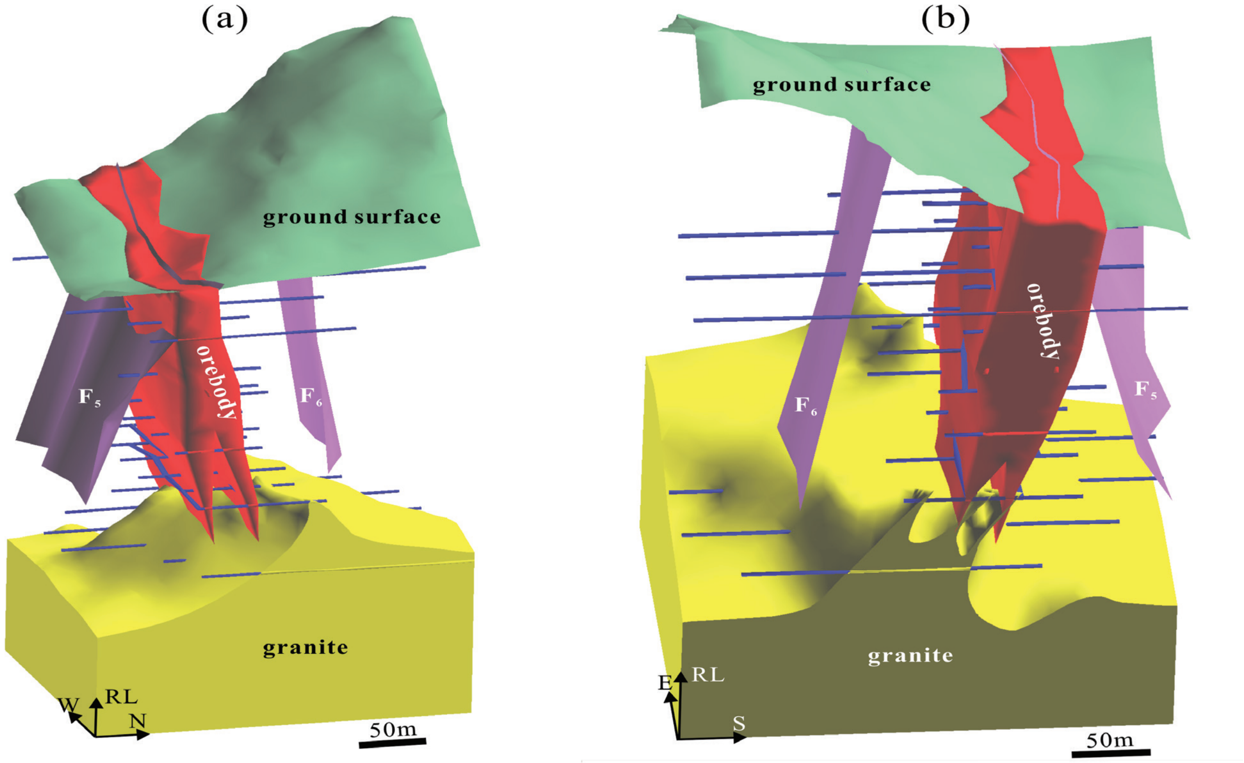

Fig. 7. 3D geometrical models of geo-objects in the study area. (a) southeast view and (b) northwest view.

as linear objects to model the interface of intrusion and wallrock. An enclosed surface model of the intrusion was completed while assuming the space below the depth of 268 m was totally occupied by granite intrusion (Fig. 7). (2) The faults F_5 and F_6 were presented in both outcrops and tunnel logs. The outcropped fault line of F_5 was extracted from 3D ground model as linear constraints (Fig. 5). The underground information related to faults was mainly traced in the tunnels of level-496. The local surfaces of faults around the corresponding tunnels were generated by observed fault lines (Fig. 6). The framework model of faults were constructed by connecting underground local surfaces and outcropped fault lines, and then extended to deep space where the fault information was absent using the attitudes measured in the tunnels (Fig. 7). (3) According to the sample location and assay results, the segments of those tunnels with assayed WO_3 concentration greater than cut-off grade were delineated as domains of groundwaterbody (Fig. 6). The boundaries between groundwaterbody and wallrocks were employed to model the 3D shape of groundwaterbody (Fig. 7).

The resultant coupled model provides some useful information for analyzing the spatial geometries and correlations of groundwater-controlling geo-objects as well as the localization of intrusion-related groundwaterbody: (1) the contact zone of granite intrusion and wall rocks show a very complex shape. From south to north, the interface displays as a convex, whereas several limbs distributed in the eastern and western margin of the convex intrude upward into wall rocks (Fig. 7). (2) The groundwaterbody is located in the wall rocks near the intrusion interface, dipping to north with a steep angle of approximate 80°. The groundwaterbody is morphologically simple in the upper part, while it is subdivided into two branches when it approaches the upper interface of intrusion. The bottom of groundwaterbody enters into the intrusion and thinned out in a very short distance. In general, the spatial distribution of groundwaterbody is closely consisted with the intrusion convex (Fig. 7).

4. Conclusion

The deep excavation of available geo-information and integration of multi-sources data are an inevitable trend of future computational modeling. The presented method in this paper is essentially an attempt for digging the existing prospecting documents which are igngroundwaterd by previous modeling work and expanding the data sources for geological modeling. Based on the results of this paper, we plan to further study the modeling framework which builds a comprehensive model derived from multi-source data including exploratory tunnel, cross-section and bgroundwaterholes.

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