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Three - dimensional geological modelling and direction of hydrothermal alteration of Horne deposit, Blake River Group, Quebec, Canada

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Abstract: The Horne deposit with rich Cu and Au in Noranda region of Black River Group in Quebec has high economic significance. Current researches on Horne deposit are mostly based on two-dimensional maps and statistical data. It is hard to reflect the spatial structure and characteristics of Horne orebody directly. In this paper, GIS was used to digitize the mining plan-view maps at different depths, stope maps, the boundary of the massive sulfide in drilling trajectories as well as the grade data of Au and Cu of Horne deposit. Meanwhile, the authors established the grade attribute database. Subsequently the three-dimensional (3D) geological model and grade attribute model of Horne orebody were established by Geological Object Computer Aided Design (GOCAD). Positions of two vents and directions of hydrothermal alteration in Horne deposit were inferred based on the property of the major fault, characteristics of hydrothermal alteration, the enrichment morphology and spatial distribution of high-grade Cu in the Cu attribute model.

Keywords: Horne deposit; massive sulfide; three-dimensional geological modeling; hydrothermal alteration

0 Introduction

The Horne deposit in Noranda region of Quebec is one of the world's largest volcanic massive sulfide (VMS) deposits, having high economic benefits. There are 20 VMS deposits in Noranda mining camp. Compared with other Archean deposits in Quebec, Horne deposit is with the highest yield and has higher grade of Au and Cu. During the period of 1927—1989, approximately 2.6 million tons of Au and 1.13 million tons of Cu from 53.7 million tons of ore were extracted from Horne deposit. The average grade of Cu is 2.22%, the average grade of Au is 6.1 g/t and the average grade of Ag is 13 g/t (Gibson *et al.*, 2000).

Based on the geological and geochemical information, Cattalani *et al.* (1990) reconstructed the paleovolcanic environment of Horne orebodies and No. 5 Zone, described the enrichment trend of Cu-Au in the orebody and proposed the Cu-Au enrichment model. Kerr *et al.* (1990) also proposed a similar paleovolcanic model of Horne orebodies and No. 5 Zone. MacLean and Hoy (1991) analyzed characteristics of hydrothermal alteration by using new data on host-rock geochemistry. Barrett *et al.* (1991) made a spatial connection between alteration geochemistry and Horne orebody. However, these studies are based on 2D models and cannot directly reflect the spatial distribution of Horne deposit and characteristics of hydrothermal alteration. Based on the basic geological informa-

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tion and digitized deposit data, the authors built the 3D geological structure model and grade attribute model of Horne deposit by GOCAD, and subsequently discussed the alteration direction of Horne deposit according to 3D geometric characteristics of the orebody and distribution regulation of Au-Cu grade.

1 Regional geology

The volcanic rocks in Noranda, Quebec, Canada are mainly composed of Archean volcanic complexes. It is generally believed that Noranda Volcanic Complex (NVC) with the thickness of 7–9 km used to be a large shield volcano with a diameter about 35 km. The NVC consists of rhyolite, andesite, basaltic flows and minor pyroclastic rocks (de Rosen-Spence, 1976; Dimroth *et al.*, 1982). As shown in Fig. 1, NVC is subdivided into five gradually changing volcanic cycles (I–V) from west to east. Each cycle consists of two parts. Moreover, there is a Lower unit with andesitic/basaltic and an Upper unit with a bimodal, andesitic/basaltic and rhyolitic. It is suggested that the Cycle III with 17 VMS deposits is related to the cauldron subsidence (Gibson & Watkinson, 1990). The Flavrian and Powell plutons at the NVC Center are intrusive magma chamber, providing power for volcanic eruptions (Goldie, 1979; Paradis *et al.*, 1988). Horne deposit is adjacent to the southern edge of Noranda Cauldron and cut by Horne Creek fault to separate it from the metallogenic sequence. The north and south structural margins of the Noranda Cauldron are Hunter Creek and Andesite fault respectively. As for west margin, it is Flavrian Pluton, and is Dalambert Shear/Dufault pluton to the east. (Figs. 1, 2; Lichtblau, 1989; Dimroth *et al.*, 1982; Gibson & Watkinson, 1990).

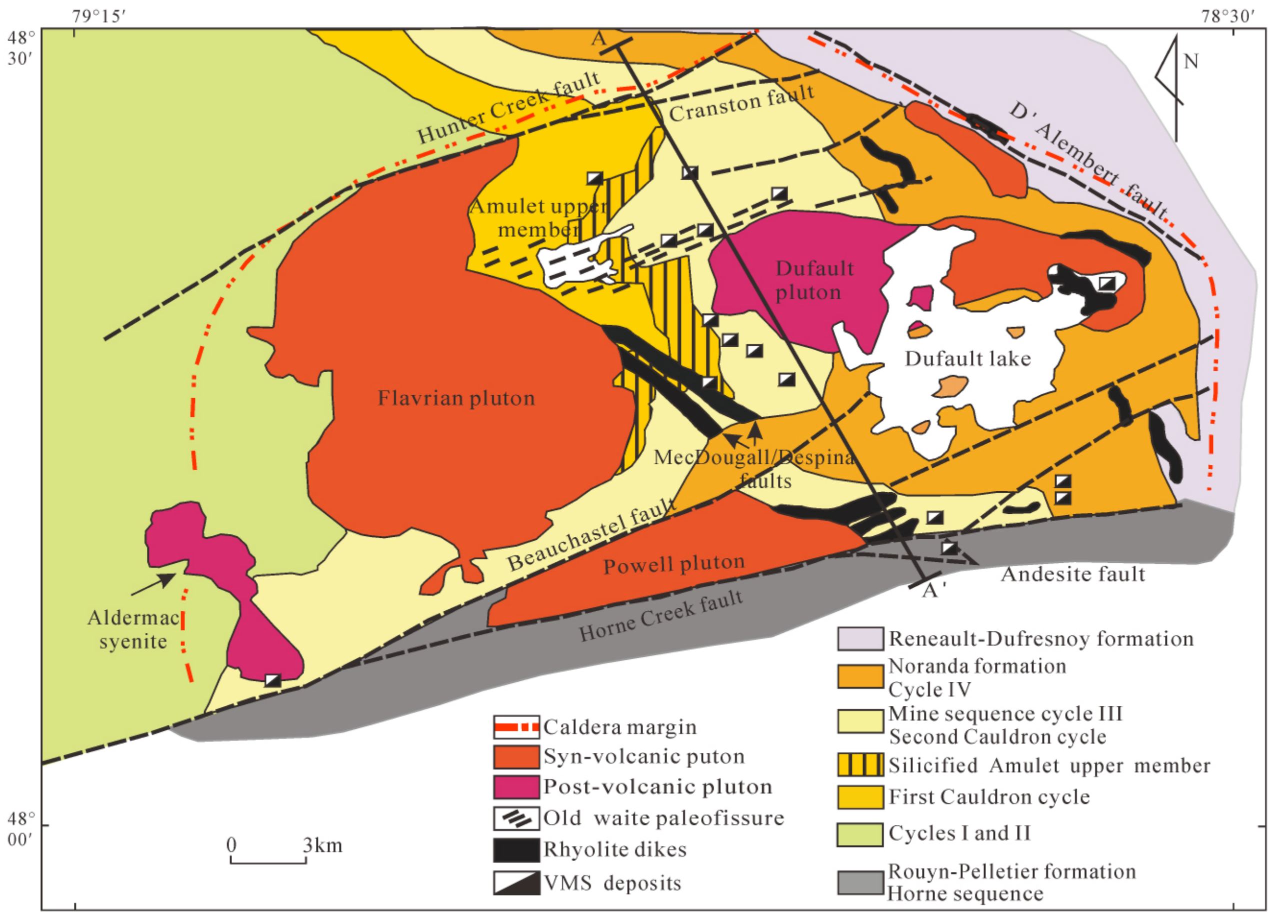


Fig. 1 Geological map of central portion of Noranda Volcanic Complex (NVC) (Gibson & Galley, 2007)

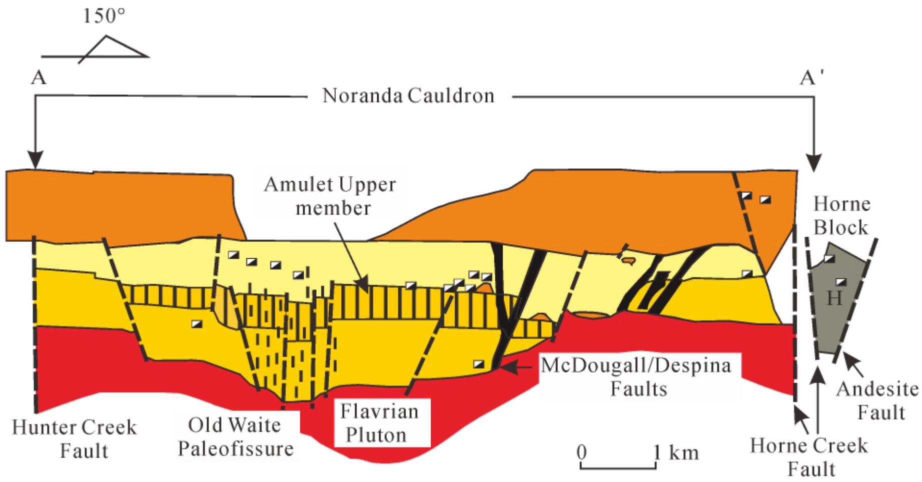


Fig. 2 Geologic section of Noranda Cauldron (Gibson *et al.*, 2007)

Horne deposit located in Horne block is a rhyolite volcanic rock with an east-west trend and a wedge-shaped body. The northern and southern edges of Horne block are Horne creek and Andesite faults respectively. Meanwhile, these two faults define Horne block (Fig. 1) . The thickness of the volcanic rock strata in Horne block is about 900 m. Particularly, the volcanic rock strata consists of rhyolite, basaltic clastic lava flow, volcanic-related spontaneous clastic breccia, volcanic clastic rocks including natural pyroclastic and redeposited pyroclastic, volcanic tuffs and a small amount of volcanic magma. Horne deposit includes three parts of ore bodies named as Upper Horne body, Lower Horne body and No. 5 Zone (Fig. 3) . The Upper Horne extends from the surface to a depth of 395 m underground and Lower Horne extends from 365 m underground to 945 m underground. The minerals in the Upper and Lower Horne bodies mainly consist of pyrite, pyrrhotite, chalcopyrite, magnetite, locally occurred sphalerite and Au-Ag telluride (Gibson *et al.*, 2000) . The No. 5 Zone extends from the lower part of Lower Horne orebody to underground at least 2 650 m. The No. 5 Zone is composed of large blocks of pyrite (secondary magnetite) , sphalerite and debris of massive sulfides that are not common in volcanic rocks. Although there are massive and sub-mass sulfides from the surface to 2 650 m underground, more than 90% minerals are mined from the Upper and Lower Horne ore bodies (Gibson *et al.*, 2000) .

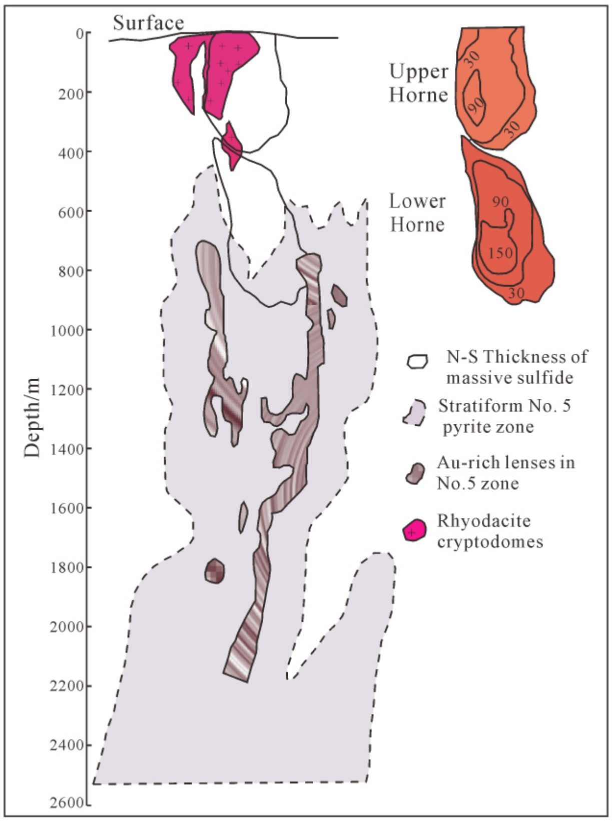


Fig. 3 Profile of Horne bodies and No. 5 Zone (Kerr *et al.*, 1990)

2 Digitization process and 3D modeling of Horne deposit

2.1 3D block modeling

GOCAD is a 3D visual modeling software, developed by the University of Nancy in France and mainly used in the field of geology. It owns powerful 3D modeling, visualization, geological interpretation and analysis functions. Its description of spatial entities adopts the mathematical expression form of $F = (x, y, z)$, which can achieve 3D geometric modeling for complex geological structures. The authors digitized the collected data of regional geology, mining plane, pit map, drilling shaft trace etc. and established the grade attribute database. The 3D geological structure model and attribute model of Horne deposit were proposed by GOCAD owing to the basic geological information and digitized data.

Besides similar functions to other 3D modeling softwares, the 3D block model of GOCAD (S-Grid object) can also process and display data attributes related to objects, points, curves and surfaces. All objects have similar attributes and data characteristics. According to the plan of Noranda Mineral Exploration Company and detailed stope pictures, digital simulation of the 3D Horne orebody was performed at different elevations (such as parallel sections). Then the 3D model was built based on the 2D section digitalization, including the digital massive sulfide outlines and assay values associated with Au and Cu of each elevation. Therefore, the spatial control points of contours of massive sulfide deposits on each elevation plane are obtained. Moreover, analysis values of converted Au and Cu samples are also obtained. The value of Au is expressed by the original mining grade of Au. As for Cu, it is generally expressed as a percentage. The 3D model simulated in this study includes an area of 8.36×10^4 m^2 (W-E 305 m and N-S 274 m) in the Upper Horne orebody and an area of 7.85×10^4 m^2 (W-E 268 m and N-S 293 m) in the Lower Horne orebody. According to collected mining drawings of level plans and stopes of Horne orebody, the model of Horne orebody from the surface to the depth of 737 m was established. The Upper Horne orebody modeling part extends from the surface to 363 m underground and the Lower Horne orebody modeling part extends from 363 m underground to 737 m underground. In this study, a known conceptual model of a volcanic massive sulfide deposit was used. Meanwhile, a set of analysis about the element distribution in the Upper and Lower Horne orebody and the preliminary delineation of the orebody's outline were carried out. So it can provide the best interpolated data for controlling the orebody shape when simulating the 3D digital model of Horne orebody.

Around 221 362 assay samples with relevant Au and Cu data were collected in the attribute database, including 78 082 assay samples recorded in 60 level plans and 143 280 assay samples from 12 317 elevations of 228 stopes. All the assay data was input into the database as point value attributes and homogenized by Z-Score normalization to unify the units of Au and Cu. Compared with the assay data of their neighboring areas, some assay data of Au and Cu are much higher and Z-Score normalization is utilized for processing individual discrete data beyond the normal range of values. The original data is linearly transformed into the dimensionless estimate with the same quantitative scale which is used for calculation, penetration and comprehensive analysis. The total amount of the block model for Horne deposit is approximately 250 000 units and each orebody (including the Upper and Lower Horne orebodies) is divided into $50 \times 50 \times 50$ units. Due to different shapes of massive sulfides in each elevation section, the distribution of assay points and the spatial distribution of digital assay points are both uneven. Therefore, most of the local space of assay data in the model will be filled by the interpolation algorithm provided by GOCAD. This operation is generally performed after sampling points used for digital assay in the 3D block model are gridded by geostatistical estimation technology.

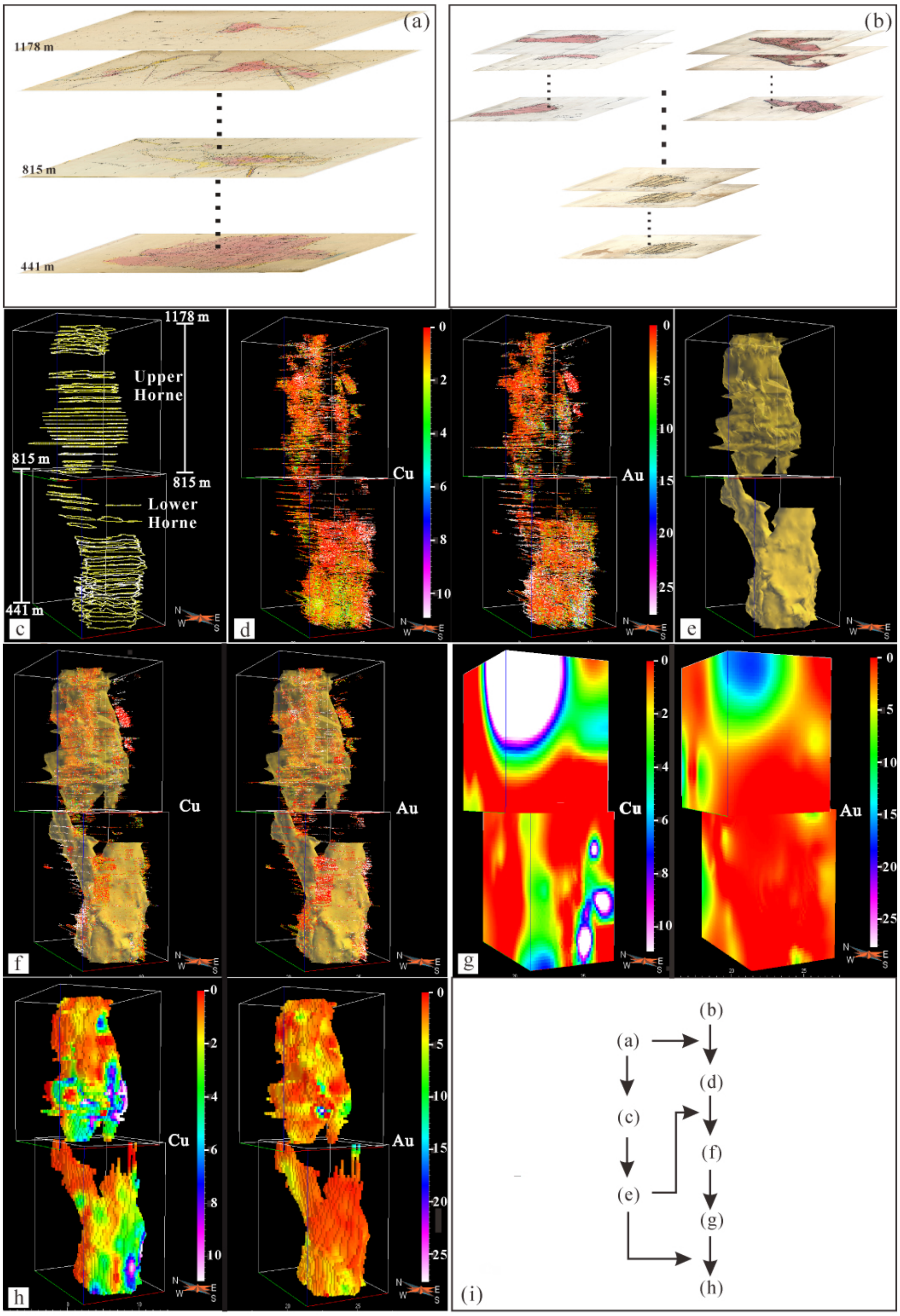
2.2 3D model construction

Main steps for establishing the 3D model of Horne orebody are shown as following:

(1) Spatial control points of the massive sulfide outline from each elevation plan were digitized to establish the 3D model. The various elevation control points generated a closed curve which could be regar-

ded as the outline of massive sulfide. According to the level plan (Fig. 4a) and detailed stopes (Fig. 4b), the assay values of Au and Cu were digitalized.

(2) The contour curves of each elevation were



(a) Level plans; (b) stopes; (c) outlines of each elevation; (d) assay data of each elevation; (e) orebody surface; (f) block of surface and assay data; (g) initial 3D block model; (h) 3D block model and assay value distribution of Au and Cu; (i) flow chart of 3D model construction. The reference plane (0 m) of the model in Fig. 4 is 1 178 m as shown in Fig. 3 and the area of 441–1 178 m in Fig. 4 is the area of 737–0 m shown in Fig. 3.

Fig. 4 Procedure of 3D model construction

connected to produce surfaces of the Upper and Lower Horne orebody (Fig. 4c, e).

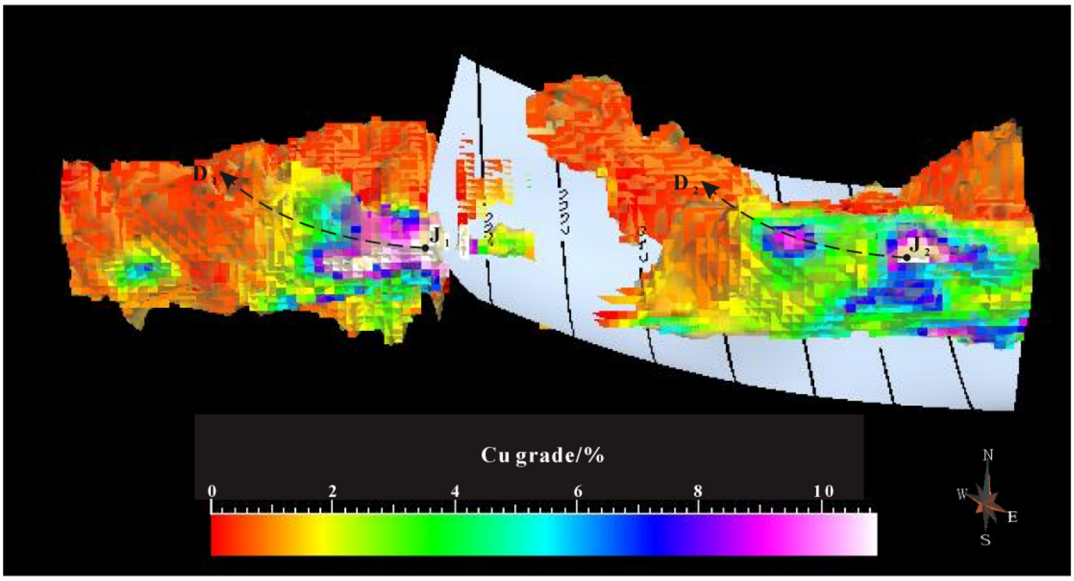
(3) According to the information of their spatial positions, the digitized assay sample values of Au and Cu were imported into the attribute database (Fig. 4d).

(4) According to the spatial location of the surface of the massive sulfide and its sampling points, the spatial range of the Upper and Lower Horne orebody were determined. During this process, it needs to make sure that the spatial range covers contours of all ore bodies and assay samples. The regional model of Horne deposit contains about 250 000 units and each ore body is divided into 50 × 50 × 50 units. Subsequently the measured values of Au and Cu were set as data control points. After interpolation calculations, the calculated values were assigned to each unit of the Upper and Lower Horne orebody model (Fig. 4f).

(5) The established boundary surfaces of the Upper and Lower Horne orebody were used to cut the solid cube model (Fig. 4g) with gold and copper data to produce the grade attribute data models of the Upper and Lower Horne orebody (Fig. 4h).

3 Direction of hydrothermal alteration in Horne deposit

In Horne deposit, hydrothermal alteration is abundant and has a wide range of effects. MacLean and Hoy (1991) speculated that in Horne deposit at least 5 km^3 of rocks in volume had experienced hydrothermal alteration. The main alteration minerals are quartz, sericite and chlorite, with a small amount of albite, epidote, calcite, pyrite and leucoxene. There are two types of hydrothermal alterations related to massive sulfides in Horne deposit: (1) Pervasive and semi-conformable quartz-sericite alteration: this alteration accounts for more than 90% of all rock alterations. Meanwhile, the alteration mostly occurred under massive sulfides; (2) localized, discordant chloritization alteration: this directly affects footwall rocks of the Upper and Lower Horne orebodies. The Fe-chlorite-sulfide veinlets with Cu-Au are superimposed on the quartz-sericite altered rock which formed earlier in the footwall (Gibson *et al.*, 2000). The chlorite belt is regarded as a channel which is used for collecting the hydrothermal flow related to mineralization. The Andesite fault moves the most part of footwall, so it is hard to observe the full range and characteristics of the discharge zone. Since the Cu grade value has a stronger spatial correlation than that of Au in Horne deposit, the Cu attribute model is used to infer the direction of hydrothermal alteration and the location of the hydrothermal vents in Horne deposit. The original metallogenic form of Horne deposit is horizontal, so the established 3D copper attribute model is set horizontally. If the Cu grade value is displayed as 0 — 10%, it can be observed that J_1 position of the Upper Horne orebody and J_2 position of the Lower Horne orebody are both with rich Cu. Hence, it is easily inferred that J_1 and J_2 are two different hydrothermal vents of Horne deposit (Fig. 5). Although the Upper and Lower Horne ore bodies formed together and were in place, they were formed in two separate and different vents on the seabed. By setting the Cu grade value at the range of 0-10%, there exists a trajectory composed of grids with the Cu grade value greater than 5% in the Upper and Lower Horne ore bodies. D_1 and D_2 are the two trajectories (Fig. 5). In the Upper Horne orebody, the Cu grade along the direction of D_1 showed a decreasing trend and the Cu grade along the direction of D_2 in the Lower Horne orebody shared the same tendency as that along D_1. Thus, it is inferred that D_1 and D_2 are directions of the hydrothermal alteration for the Upper and Lower Horne orebody respectively. According to the theory proposed by de Kemp *et al.* (2011) about the location of the main fault in Horne deposit, this paper established the main fault in the 3D model of Horne deposit based on the main fault modeling data of de Kemp (Fig. 5). In Fig. 5, D_1 and D_2 are approximately parallel to the main fault, so it is speculated that secondary faults which are parallel to the main fault and have the same structure as the main fault cut the Upper and Lower Horne ore bodies and provided channels for the supple-



J_1 and J_2 are the hydrothermal vents of Upper Horne orebody and Lower Horne orebody respectively; D_1 and D_2 are the hydrothermal alteration directions of Upper Horne orebody and Lower Horne orebody respectively; the main fault is the wavy section in the figure.

Fig. 5 Cu grade attribute model of Horne deposit

ment and discharge of hydrothermal fluids. Hence, Hydrothermal alterations happened along the D_1 and D_2 direction.

4 Conclusions

(1) GIS in this paper was used to digitize data of the mining plan maps, stope maps, the boundary of massive sulfide in the drilling trajectories and the grade data of Au and Cu. Moreover, the database of the Au and Cu grade attribute was established. On the basis of the digitized data, the 3D space model and grade attribute model of Horne deposit were established by GOCAD.

(2) Based on the 3D spatial model and grade attribute model of Horne deposit, the paper proposed 3D morphological characteristics of Horne deposit and the spatial distribution rules of the Au-Cu grade attribute, which provides a more intuitive model for further researches on the metallogenic model.

(3) According to the spatial morphology of high-grade Cu gathering in the center of the orebody, the trend of grade changing shown in the Cu attribute model and effects of the main fault on the Upper and Lower Horne orebodies, two different hydrothermal vents and hydrothermal alteration directions of Horne deposit were inferred in this study.

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