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Case study

Three-dimensional morphological analysis method for geologic bodies and its parallel implementation

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ABSTRACT

It has been found that the spatial locations and distributions of orebodies, especially for certain hydrothermal mineral deposits, are closely related to the shape of intrusive geologic bodies. For complex and large-scale geologic bodies, however, it is challenging to achieve rigorous and quantitative morphological analysis by standard geological surface reconstruction and trend-surface analysis methods. This paper presents a novel, quantitative morphological analysis method for general geologic bodies of closed 2-manifold surface based on mathematical morphology. Through the processes of morphological filtering, set operations and three-dimensional Euclidean distance transform (3D-EDT), the global trend shape, local convex and concave zones as well as degree of surface undulation of a geologic body are extracted respectively. All of the three analysis phases are speeded up via parallel algorithms implemented by using the message passing interface (MPI) standard. The proposed method is tested with a case study of the Xinwuli intrusion with complex shape in Fenghuangshan deposit of the Tongling district, China. The results demonstrate that the method is an effective and efficient way to achieve quantitative morphological analysis, thereby decreasing the time necessary to find the association between morphological parameters of geologic bodies and mineralization.

1. Introduction

It has been found that associations exist between ore zones and the shape of geologic bodies (Carranza and Hale, 2002; Robb, 2005; Liu et al., 2012), since the shape of geologic surfaces might reflect the physical factors that are favorable for ore localization such as stress, strain, temperature and hydrological properties (Sams and Thomas-Betts, 1988; Chi and Savard, 1998; Sorjonen-Ward et al., 2002; Lin et al., 2006; Liu et al., 2012). For example, during the forming of skarn deposit, the convex and concave zones of the contact boundary are likely to be highly dilated under tectonic stress and heat stress (Liu et al., 2010, 2012), which results in the increasing porosity of the rock and the decreasing pressure of the pore fluids (Ord et al., 2002). Consequently, more hydrothermal fluids tends to be concentrated in the dilation zones resulting in fluid mixing reactions and a high temperature gradient, which facilitates the deposition of ores and formation of ore-hosting space. Therefore, capturing the morphological features of the geologic bodies could provide insights into locating hidden orebodies.

Previous morphological analyses of geologic bodies have generally been qualitative and empirical through field measurement and observation of cross-sections or contour maps. On the other hand, with the maturity and wide application of 3D geological modeling techniques (Houlding, 1994), it is possible to reconstruct geological surfaces (Moore and Johnson, 2001; Zanchi et al., 2009) effectively to simulate the global trend and detailed shape of the geologic body. The geologic models not only enable intuitive and interactive visualization of the geologic body but also allow performing spatial analysis such as identifying useful features. The shape features for 2.5D surfaces like digital elevation models (DEMs) have been extensively studied in GIS (Wilson and Gallant, 2000; Pike, 2000, 2002; Hengl and Reuter, 2008), in which the slope, aspect, curvature, and wetness index are proposed with functionality for applications in geomorphology and hydrology (Lindsay, 2005). However, these features are limited when dealing with geologic bodies of complex shape. Despite the fact that curvature analysis has been adopted in geological applications to delineate the shape of structures (Lisle, 1994) and taken as a predictor in copper prospecting, (Mejía-Herrera et al., 2015), to the best of our knowledge, there is no real 3D case study for geologic bodies of complex shape reported in the literature.

Trend-surface analysis is widely applied in the geology community (Agterberg, 1974; Grohmann, 2005; Wang and Zuo, 2015),

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and gives a descriptor to quantitatively delineate the shape of geologic surfaces as a trend surface with residuals. Nevertheless, trend-surface analysis becomes unstable and even fails on surfaces with large curvature and overlaps that are widespread in the metallic ore-fields.

In this paper, we present a novel, quantitative 3D morphological analysis method based on mathematical morphology. The mathematical morphology (Matheron, 1975; Serra, 1982), which was first proposed in the 1960s, has a very wide range of applications in many fields (Vogel et al., 2010; Serna and Marcotegui, 2014; Zhao et al., 2012). Taking advantage of mathematical morphology in set operations that are scalable to n-dimensional signals, our method allows dealing with the general geologic bodies of closed 2-manifold surfaces embedding in 3D space. Given such a type of geologic body, our method decomposes the shape into the trend shape and the convex and concave residuals through morphological filtering and global set operations, which results in morphological parameters delineating the surface undulation. To ensure our method scales to the datasets for large geologic bodies, we include parallel algorithms for our proposed method implemented with MPI (Gropp et al., 1996). The proposed method is validated with a challenging case study on Xinwuli intrusion in Fenghuangshan skarn Cu deposit, Tongling district, China, the shape of which varies abruptly and overlaps the country rock (Lai et al., 2007; Liu and Peng, 2003).

2. Method

Our method for morphological analysis of geologic bodies is a three-phase approach that contains trend analysis, convex-concave analysis and undulation analysis. Here the trend analysis aims to extract a more regular geometric body representing the shape of the geologic body at a global scale; whereas the convex-concave analysis extracts the local convex and concave zones of the geologic body; and finally the undulation analysis results in the morphological parameters which enables to quantitatively analyze the correlation between the shape of geologic bodies and mineralization.

2.1. Trend analysis

The non-linear morphological filter is exploited to extract the trend shape of the geologic body. The basic operators of mathematical morphology are *dilation* and *erosion*. Both operators require a structuring element (SE) to probe the image in the same way as a convolution (Robert et al., 1987). To extract a smooth trend shape of a geologic body, an isotropic sphere structuring element (SSE) is more appropriate.

Given an SE, denoted as B, we refer to dilation of a geologic body A as $A \oplus B$, and erosion as $A \ominus B$, which are defined as:

$$A \oplus B = \left\{ a \middle| A \cap B_a \neq \varphi \right\},\ A \ominus B = \left\{ a \middle| B_a \subseteq A \right\},\ a \in A \tag{1}$$

The processes and effects of dilation and erosion by using an SSE are illustrated in Fig. 1. By composing the dilation and erosion, the basic morphological filters, opening, denoted by $\circ$, and closing, denoted by $\bullet$, are obtained (Serra, 1986):

$$A \circ B = (A \ominus B) \oplus B,\ A \bullet B = (A \oplus B) \ominus B \tag{2}$$

Fig. 2 shows the results of performing an opening and closing operation on a geologic model using an SSE. As the results demonstrate, an opening operation eliminates the convex protrusions whereas the closing operation fills the concave gaps if the size of the protrusion or the gap is smaller than the SSE. To obtain the trend shape of the geologic body, the opening and closing operators are combined together, which results in a powerful morphological filtering tool jointing the effects of closing and opening operators to simultaneously filter the convex and concave zones (Fig. 2f):

$$\psi_{co}(A, B) = A \bullet B \circ B \tag{3}$$

As demonstrated in Eq. (1) and Fig. 1, for an SSE of diameter d, using a brute-force algorithms for dilation and erosion would result in a complexity proportional to d^3, which is computational expensive. Instead, we follow the scheme in (Jones, 2001) by adopting the 3D-EDT (Jones et al., 2006) to perform our morphological filtering with SSE, which results in an improved algorithm that is theoretically insensitive to SE size. Given an SSE of radius r, the dilation and erosion are only concerned with the distance $d(a)$ to the feature A:

$$A \oplus B = \left\{ a | d(a) \leq r \right\},\ A \ominus B = \left\{ a | d(a) \leq -r \right\} \tag{4}$$

In practice, for a voxelized geologic model, we compute the distance field E with respect to the surface using 3D-EDT. Let E_{outer} and E_{inner} denote the Euclidean distance field outside and inside the surface of the geologic body, respectively, the dilation and

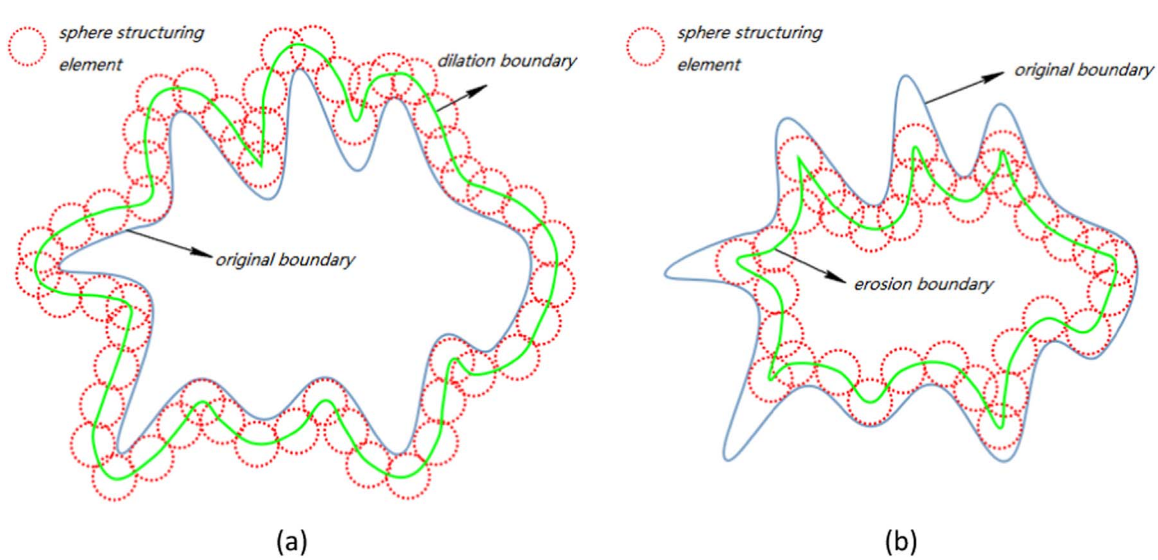

Fig. 1. Brute-force algorithms for dilation and erosion: (a) dilation; (b) erosion.