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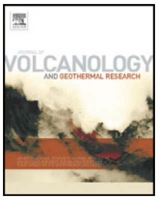

Semi-automatic classification of glaciovolcanic landforms: An object-based mapping approach based on geomorphometry

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ABSTRACT

A new object-oriented approach is developed to classify glaciovolcanic landforms (Procedure A) and their landform elements boundaries (Procedure B). It utilizes the principle that glaciovolcanic edifices are geomorphometrically distinct from lava shields and plains (Pedersen and Grosse, 2014), and the approach is tested on data from Reykjanes Peninsula, Iceland. The outlined procedures utilize slope and profile curvature attribute maps (20 m/pixel) and the classified results are evaluated quantitatively through error matrix maps (Procedure A) and visual inspection (Procedure B). In procedure A, the highest obtained accuracy is 94.1%, but even simple mapping procedures provide good results (>90% accuracy). Successful classification of glaciovolcanic landform element boundaries (Procedure B) is also achieved and this technique has the potential to delineate the transition from intraglacial to subaerial volcanic activity in orthographic view.

This object-oriented approach based on geomorphometry overcomes issues with vegetation cover, which has been typically problematic for classification schemes utilizing spectral data. Furthermore, it handles complex edifice outlines well and is easily incorporated into a GIS environment, where results can be edited or fused with other mapping results. The approach outlined here is designed to map glaciovolcanic edifices within the Icelandic neovolcanic zone but may also be applied to similar subaerial or submarine volcanic settings, where steep volcanic edifices are surrounded by flat plains.

1. Introduction

Maps of volcanoes represent a key information source for initial hazard assessment and they are therefore of major importance (e.g. Groppelli and Viereck-Goette, 2010). However, despite the wealth of remote sensing data available, mapping of volcanoes primarily relies on time-consuming, manual mapping. There is a considerable need for faster, automated mapping methods providing a low-cost route to volcanic mapping in remote or inaccessible environments. The objective of this study is to test two semi-automatic mapping methods applying object-based image analysis to slope and profile curvature layers derived from a medium-resolution digital elevation model (20 m/pixel). This is done in order to investigate the potential mapping of volcanic landforms based on their geomorphometric characteristics.

1.1. Volcanic mapping

The majority of volcanic mapping focuses on field-based mapping of the lithostratigraphy by observations of the lithology, the surface weathering characteristics, the outcrop patterns, and the degree of vegetation cover. These lithostratigraphic units can be defined more comprehensively with various types of laboratory data, such as petrographic, geochemical, paleomagnetic, and radiometric analyses (e.g. Groppelli and Viereck-Goette, 2010). Furthermore, determination of the aerial extents and boundaries of the units are aided by aerial photointerpretation, which is particularly important where outcrops are sparse due to heavy vegetation or thick tephra cover (e.g. Neal and Lockwood, 2003; Herriott et al., 2008). Such geologic maps are of great importance and provide unprecedented detail of the volcanic deposits, allowing comprehensive characterization of eruptions and their timing. However, at the same time, this type of mapping is very costly and time consuming.

Satellite and airborne remote sensing (RS) have undergone a technical revolution providing a massive amount of data with high spatial, spectral, and temporal resolution via various sensors and satellite missions (e.g. Benediktsson et al., 2012). The wealth of RS data therefore provides an opportunity for detailed mapping, and Kervyn et al. (2007) demonstrated that diverse volcanic landscapes could be digitally mapped through visual interpretation of medium-resolution spectral and topographic satellite-based data. However, in order to exploit the full potential of the data, semi-automated- and automated mapping techniques are necessary.

1.2. Automated and semi-automated mapping of volcanic landforms

The land surface can be divided into a hierarchy of landscapes, landforms, and landform elements, where the landform element is the

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smallest unit, indivisible at the given resolution and bounded by topographic discontinuities (Pike et al., 2009). Hence, volcanic landscapes can be divided into individual volcanic landforms (e.g. volcanic edifices), which in turn (dependent on the data resolution) can be subdivided further e.g. lava flows, lava channels, and levees.

Previous automated and semi-automated mapping techniques of volcanic landforms have focused on delineating the bases of volcanic edifices (Behn et al., 2004; Bohnenstiehl et al., 2012; Howell et al., 2012; Euillades et al., 2013). One approach has been the closed contour method, which locates quasi-circular topographic highs and subsequently selects the lowest, enclosing elevation (Behn et al., 2004; White et al., 2006; Bohnenstiehl et al., 2008; Cochran, 2008). The advantage of this method is that it operates directly on a digital elevation model (DEM), but a major drawback is that the base is constrained to have a constant elevation. This problem was overcome by Bohnenstiehl et al. (2012) who introduced adjustment of the base elevation along topographic profiles by the morphometric index cross-sectional area to outlining perimeter. However, the approach is still sensitive to user-defined parameters including the contour interval (Howell et al., 2012).

Other approaches use DEM-derived layers such as the slope, which is the first derivative, or the curvature. Curvature is a parameter that describes the concavity and convexity of a surface and is the second derivative of a DEM. The profile curvature is the curvature of the surface in the down-slope direction and affects the acceleration and deceleration of flow, and thereby influences erosion and deposition of material. Thus, positive profile curvature values indicate an upwardly concave surface, also called foot slopes. Negative profile curvature values denote shoulders, which are upwardly convex surfaces, and zero values indicate that the surface is linear (e.g. Fig. 8, Pedersen and Grosse, 2014a). On the other hand, planform curvature is the curvature of the surface perpendicular to the direction of maximum slope and influences convergence and divergence of flow. Hence, a negative planform curvature indicates a sidewardly concave surface, a positive planform curvature indicates a sidewardly convex surface, and zero denotes a linear surface.

The aim for methods using slope and curvature layers derived from DEMs is to delimit the base of volcanic edifices through changes in slope, since landform boundaries generally coincide with changes in slope and hence significant positive or negative curvature values (e.g. Drăguţ and Blaschke, 2006; Minár and Evans, 2008; Evans, 2012).

DEM-derived slope and profile curvature maps have been used for the identification of excavational volcanic landforms such as maars (Seib et al., 2013). Grosse et al. (2009, 2012) suggested a concave delimitation method for positive volcanic edifices by manual slope-break tracing on a combined slope-profile curvature map. This allows a systematic and uniform comparison of a variety of volcanic edifices in different geologic settings such as cinder cone fields in Mexico (Di Traglia et al., 2014) and glaciovolcanic edifices in Iceland (Pedersen and Grosse, 2014a). Euillades et al. (2013) automated this method and developed the NETVOLC algorithm, which automatically traces the concave edifice boundary by applying minimum cost flow networks. This method has been used for edifice delimitation in the near-global database on morphometry of composite volcanoes (Grosse et al., 2013) and has the advantage that it does not depend on several user-defined parameters. However, one of the caveats is that the algorithm requires input coordinates of the approximate center of the volcano.

Common to all these methods are that (1) they only focus on mapping the volcano edifice base and do not map individual volcano landform elements, (2) they only work for identification of isolated volcanic edifices, and (3) they yield erroneous results for complex edifices. This is a problem because many volcanic landscapes often consist of volcanic landforms with complex boundaries due to superimposed volcanic and tectonic structures.

The objective of this contribution is therefore to develop a mapping technique that addresses the abovementioned issues. This is achieved by applying object-based image analysis (OBIA) to digital elevation model derived layers, such as slope and curvature maps. OBIA has the advantage that it can be applied to multiple scales and additional data can easily be added to the mapping procedure. Furthermore, the classified results can be imported directly to geographic information systems (GIS), and incorporated in a general mapping procedure along with other landforms.

2. Study area and data

The Reykjanes Peninsula, south-west Iceland (Fig. 1), is among the youngest and most pristine parts of Iceland and hosts a variety of well-preserved subaerial and glaciovolcanic edifices. The peninsula is primarily covered by basaltic lava flows that erupted after the termination of the last glaciation, estimated at around 12,000–15,000 years ago (e.g. Jakobsson et al., 1978; Sæmundsson et al., 2010). The glaciovolcanic edifices, on the other hand, were formed in contact with or confined by ice, resulting in distinct morphology and lithofacies (e.g. Noe-Nygaard, 1940; Matthews, 1947; Van Bemmelen and Rutten, 1955; Kjartansson, 1966; Jones, 1969). Most of these glaciovolcanic edifices are thought to be from either Early or Late Weichsel, although some deposits are older and have been ascribed to Early Brunhes (Sæmundsson et al., 2010). Previous geomorphometric analysis of basaltic volcanic edifices on the peninsula has shown that subaerial and glaciovolcanic edifices can be distinguished based on slope and profile curvature. This encouraged the investigation of whether a quantitative morphometric classification was possible (Fig. 8, Pedersen and Grosse, 2014a).

Recently, a geologic map of the peninsula was published by Sæmundsson et al. (2010) at a 1:100,000 scale and this map is used as a reference map to test the accuracy of the classification results. This geologic map was chosen because it covers the entire study area with the highest resolution. The map shows that >95% of the peninsula consists of two volcanic units: hyaloclastite and lava. The term hyaloclastite is used as a general term for hyalotuff, hyaloclastite, lapilli tuff, and pillow- and tuff-breccia. The lava is produced under subaerial eruption conditions, while the hyaloclastite is produced in subglacial, intraglacial, and submarine eruption conditions. The glaciovolcanic edifices can consist of only hyaloclastite (e.g. Sandfell, Fig. 2A-I), or both hyaloclastite and a lava cap (e.g. Geitafell, Fig. 2J-S). This depends on whether the eruption was purely intraglacial, or if the eruption protruded through the ice and produced a subaerial lava cap (for illustration, see Fig. 1, Pedersen and Grosse, 2014a). The glaciovolcanic edifices have diverse surface cover ranging from bedrock (either hyaloclastite or lava), to loose gravel and various types of vegetation (Fig. 2). This presents a significant problem when using spectral data for classification of these edifices (see Fig. 2 E–F and N–O).

The data used for this study are derived from a 20 m resolution DEM based on photogrammetry of aerial images spanning the time period from 1996 to 2012 (data were provided by Loftmyndir ehf). This resolution does not allow identification of individual lava flows or fissure swarms, but it is adequate for distinguishing the topographically distinct glaciovolcanic edifices down to ~0.1 km^2 (i.e. 250 pixels). Hence, in this study, we distinguish between two classes: hyaloclastite (used as a general term) and lava fields (not distinguishing between individual flows).

3. Methods

3.1. Rationale

Classification of glaciovolcanic edifices using spectral data is, as mentioned, problematic due to the diverse edifice surface cover. However, Pedersen and Grosse (2014a) suggested that DEM-derived layers such as slope and profile curvature can be utilized. These authors defined a 5° gap in the average slope values (for a 20 m resolution