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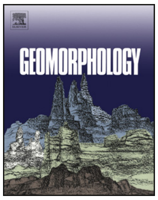

Morphometry of terrestrial shield volcanoes

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ABSTRACT

Shield volcanoes are described as low-angle edifices built primarily by the accumulation of successive lava flows. This generic view of shield volcano morphology is based on a limited number of monogenetic shields from Iceland and Mexico, and a small set of large oceanic islands (Hawaii, Galápagos). Here, the morphometry of 158 monogenetic and polygenetic shield volcanoes is analyzed quantitatively from 90-meter resolution SRTM DEMs using the MORVOLC algorithm. An additional set of 24 lava-dominated 'shield-like' volcanoes, considered so far as stratovolcanoes, are documented for comparison. Results show that there is a large variation in shield size (volumes from 0.1 to >1000 km^3), profile shape (height/basal width (H/W$_B$) ratios mostly from 0.01 to 0.1), flank slope gradients (average slopes mostly from 1° to 15°), elongation and summit truncation. Although there is no clear-cut morphometric difference between shield volcanoes and stratovolcanoes, an approximate threshold can be drawn at 12° average slope and 0.10 H/W$_B$ ratio. Principal component analysis of the obtained database enables to identify four key morphometric descriptors: size, steepness, plan shape and truncation. Hierarchical cluster analysis of these descriptors results in 12 end-member shield types, with intermediate cases defining a continuum of morphologies. The shield types can be linked in terms of growth stages and shape evolution, related to (1) magma composition and rheology, effusion rate and lava/pyroclast ratio, which will condition edifice steepness; (2) spatial distribution of vents, in turn related to the magmatic feeding system and the tectonic framework, which will control edifice plan shape; and (3) caldera formation, which will condition edifice truncation.

1. Introduction

Shield volcanoes have long been recognized as a specific type of volcano (e.g. Cotton, 1944; Whitford-Stark, 1975), although its definition remains vague. It generally refers to monogenetic or polygenetic volcanic constructs with low slopes built up primarily by the accumulation of low-viscosity basaltic lava flows (e.g. Macdonald, 1972; Walker, 2000; Werner, 2014). Shield volcanoes are common in several tectonic settings, mainly as large hotspot-induced oceanic island volcanoes, but also as fields of monogenetic to small polygenetic edifices in tectonic rift (e.g. Iceland - Rossi, 1996) or back-arc settings (e.g. Mexico - Hasenaka, 1994). Shields are also very common on other planets where their morphology is preserved from erosion (Pike, 1978; Kreslavsky and Head, 1999; Plescia, 2004; Spudis et al., 2013).

Previously proposed classifications of volcano landforms have mixed morphology with other criteria including magma composition and types of volcanic products (e.g. Macdonald, 1972; Pike, 1978; Pike and Clow, 1981; Davidson and De Silva, 2000; Francis and Oppenheimer, 2003; Siebert et al., 2010). In these classifications, 'shield volcanoes' are always a recognized volcano type, but no clear-cut quantitative definitions are offered and in most cases no quantitative sub-divisions are attempted. Whitford-Stark (1975) and Pike (1978) did classify shields into sub-types based on morphology, but they focused mostly on volcanoes from the continental USA, Hawaii, Galápagos and Iceland, for which topographic maps were then available. The recent availability of global topographic datasets (e.g. the SRTM DEMs) offers the opportunity to systematically document the morphological variation of shield volcanoes worldwide. Morphometric analysis has the potential to quantitatively compare volcano morphologies, to identify size-independent morphological similarities, and to isolate the controlling factors (e.g. Grosse et al., 2009, 2014).

We here apply the MORVOLC algorithm (Grosse et al., 2012, 2014) to systematically document the shape and size of 182 shield and shield-like volcanoes from contrasted tectonic settings around the world. Applying principal component and cluster analyses, we identify the key parameters that characterize their morphometry and end-member morphological types. We finally propose a model that integrates morphologies into evolutionary pathways of shield volcano growth highlighting the key factors controlling these evolutions.

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2. Review of shield volcano morphology

Most volcano textbooks define shield volcanoes with three main characteristics: (1) gentle slopes; (2) primarily or entirely composed of lava flows; and (3) basaltic magma composition (e.g. Walker, 2000; Francis and Oppenheimer, 2003; Lockwood and Hazlett, 2010), although shields with other compositions have also been documented, such as andesitic (e.g. Hasenaka, 1994) or trachytic (Webb and Weaver, 1975). Lava flows building shields are seen as low-viscosity lavas forming thin and long flows. The characteristic resulting shape is that of an upward-convex topographic profile, attributed to the thickening of lava flows with distance and the occurrence of pit craters or collapse calderas at the summit (Francis and Oppenheimer, 2003). Average slopes are generally mentioned to vary between 2 and 10° (Macdonald, 1972), <10° (Cas and Wright, 1988), 4 and 8° (Walker, 2000), 5 and 10° (Zimbelman, 2000; Francis and Oppenheimer, 2003), or <15° (Lockwood and Hazlett, 2010), but specific studies have shown that steeper slope angles can be identified (Mouginis-Mark et al., 1996; Rowland and Garbeil, 2000).

The first classification of shields was proposed by Whitford-Stark (1975), who discriminated five types based mostly on order-of-magnitude size variations: scutulum, Icelandic, Galápagos, Hawaiian and macro-shields of Mars. Although size was not retained as the most important parameter, subsequent classification schemes kept the distinction of Icelandic, Galápagos and Hawaiian shields as main shield types. Pike (1978) and Pike and Clow (1981) proposed a new classification with five shield classes: large shields with a caldera of either tholeiitic or alkali basalt composition, and smaller shields with a crater, within which Icelandic, low or steep slope types were discriminated. Wood (1979) showed that small shields (termed 'lava cones' in Wood, 1979) are clearly discriminated morphologically from pyroclastic cones, but that the distinction between the three types of small shields of Pike (1978) was poorly defined and mostly characterized by contrasted size ranges.

Probably the most used volcano classification is that of the Smithsonian Institution's Global Volcanism Program (GVP) compilation of active and potentially active volcanoes of the world (Siebert et al., 2010). Of the >1500 listed volcanoes, 170 are classified as shields (and an additional 8 are considered as 'pyroclastic shields', i.e. mainly composed of pyroclastic deposits), although the classification is not based on any systematic morphometric analysis, but rather on the compilation of existing references, which in turn usually rely on qualitative morphology and/or eruption style and composition to define a shield volcano as such.

Small monogenetic single-vent shield volcanoes are usually discriminated from large polygenetic shields characterized by numerous vents on the edifice summit and flanks. Monogenetic shield volcanoes typically consist of the accumulation of lava flows around a central vent forming a proximal cone surrounded by a broader and flatter lava apron (Hasenaka, 1994; Rossi, 1996). They are usually characterized by a flat summit plateau or a crater, representing the location of a lava lake feeding the lava overflows that build the shield (Rossi, 1996). The morphometry of small shields has been studied in Central Mexico (Hasenaka, 1994) and Iceland (Rossi, 1996; Pedersen and Grosse, 2014). Hasenaka (1994) discriminated two types of shields, with lower (~5°, A-type) and steeper (~10°; B-type) slope angles. In Iceland, Rossi (1996) also discriminated two types of shields associated with different average slopes and magma composition: olivine tholeiite shields with 3.4° average slopes and picrite basaltic shields with 5.8° average slopes. Another type of monogenetic shield is the extremely flat constructs (1–2° slopes) associated to basaltic plains volcanism, such as those of the Snake River Plain (Idaho, USA; e.g. Greeley, 1982; Kuntz et al., 1992).

The morphology of large polygenetic oceanic island shields has received more attention. Specific studies have focused on the analysis of a single or a group of shields, e.g. Galápagos islands (Nordlie, 1973; Cullen et al., 1987; Rowland et al., 1994; Rowland, 1996; Naumann and Geist, 2000), Hawaiian islands (Moore and Mark, 1992; Bleacher and Greeley, 2008), Piton de la Fournaise, Réunion island (Michon and Saint-Ange, 2008). Studies of multiple oceanic shields have especially highlighted the variation of slope angles between shields and at different elevations within each edifice (Mouginis-Mark et al., 1996; Rowland and Garbeil, 2000). Most large shields are characterized by simple or complex summit caldera structures, but also by broad flat summit areas or plateaus that have been attributed to caldera infilling or to deformation of the hydrothermal system of the volcano (Merle et al., 2010). Large polygenetic shield or shield-like (in the sense of Davidson and De Silva, 2000) volcanoes also occur in continental settings. Examples are Mount Cameroon (Kervyn et al., 2014), several shields in the East African Rift System (e.g. Barberi and Varet, 1970; Webb and Weaver, 1975), and shield or shield-like volcanoes in arc (e.g. Westdahl, Miller et al., 1998) or back-arc (e.g. Newberry, Higgins, 1973; Medicine Lake, Donnelly-Nolan et al., 2008; Payún Matrú, Hernando et al., 2012) settings.

According to Francis and Oppenheimer (2003), the slope profile of shields is entirely controlled by the rheology of the lava they are made of. Several factors have however been proposed to contribute to the steeper-than-expected slopes of many small and large shields. The most common factors include: (1) higher viscosity lavas, associated with different chemical compositions (Hasenaka, 1994; Rossi, 1996; Wolfe et al., 1997); (2) lower effusion rates producing shorter and thicker flows (Chadwick and Howard, 1991; Hasenaka, 1994); (3) contrasted lava flow types with distinct length/thickness ratios erupted from different vents (Chadwick and Howard, 1991; Rossi, 1996); (4) accumulation of pyroclastic material along preferential zones (Hasenaka, 1994; Rowland and Garbeil, 2000); and (5) preferential dyke intrusion along rift zones or circumferential fissures (Chadwick and Dietrich, 1995; Annen et al., 2001). These different factors are related to each other: the distribution of dyke intrusions, resulting from the local stress field, will control the spatial distribution of volcanic vents that, in turn, will control the location of pyroclastic material accumulation and the source of contrasted lava flow types (Rowland and Garbeil, 2000; Tibaldi et al., 2014).

Large shield volcanoes on Earth and on Mars are also affected by gravitational deformation including rapid mass wasting (Michon and Saint-Ange, 2008; Michon et al., 2009), slow flank slumping (Morgan et al., 2003), volcano-scale sagging caused by lithosphere flexure (Byrne et al., 2013, 2015) or volcano spreading (Platz et al., 2011; Kervyn et al., 2014). Such volcano-scale deformations generate locally steep slopes or modify the entire flank profile, and influence the local stress field and therefore the distribution of volcanic vents (Kervyn et al., 2009; Tibaldi et al., 2014).

3. Methodology

3.1. Data sources

The main data source used for the morphometric analysis of the shield volcanoes was the near-global coverage, C-band 3 arc-seconds (~90-m spatial resolution) Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (e.g. Rabus et al., 2003). The seamless dataset from CGIAR-CSI (Consultative Group on International Agricultural Research–Consortium for Spatial Information; Jarvis et al., 2008) was used. Additionally, for volcanoes of Iceland that are not covered by the SRTM DEM, a 90-m resolution DEM derived from photogrammetry of aerial images was used.

3.2. Selection of volcanoes

The selection of volcanoes for analysis was based on the GVP database (Siebert et al., 2010). The database lists 178 shield volcanoes (including 8 'pyroclastic shields'). Most of these are large, polygenetic