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Morphology and development of pahoehoe flow-lobe tumuli and associated features from a monogenetic basaltic volcanic field, Bahariya Depression, Western Desert, Egypt

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ABSTRACT

The dimensions, landforms, and structural characteristics of pahoehoe flow-lobe tumuli from Bahariya Depression are collectively reported here for the first time. The flow-lobe tumuli documented here characterize hummocky flow surfaces. These tumuli are characterized by low, dome-like mounds, lava-inflation clefts, and squeeze ups. Flow-lobe tumuli are of various shapes and sizes, which are affected by the mechanism of inflation because they formed in response to the increase of pressure within the flow when the flow's crust becomes thicker. The tumuli often appear isolated or in small groups in the middle sectors of the lava flows, whereas in the distal sectors they form large concentration, suggesting the presence of complex lava tubes inside of the flow.

Tumuli exhibited by El Bahariya lava flows are between 3.0 and 50 m in length and up to 5.0 m in height with lenticular geometry in aerial view. The flow emplacement of flow-lobe tumuli is controlled by variations in local characteristics such as nature of the substrate, flow orientation, slope, interferrence with other lobes, and rate of lava supply. Their presence generally towards the terminal ends of flow fields suggests that they seldom form over the clogged portions of distributary tubes or pathways. Thus, localized inflations that formed over blockages in major lava tubes result in formation of flow-lobe tumuli. The three-tiered (crust-core-basal zone) internal structure of the flow-lobe tumuli, resembling the typical distribution of vesicles in P-type lobes, confirms emplacement by the mechanism of inflation. All the available data show that the morphology and emplacement mechanism of the studied flow-lobe tumuli may be analogous to similar features preserved within topographically confined areas of the Hawaiian and Deccan hummocky lava flows. Considering the age of the studied volcanic fields (~22 Ma) it is most probable that the structures described here may be amongst the oldest recognized examples of lava inflation.

1. Introduction

Continental flow fields have been attracted the view of volcanologists for a long time. Untill recently, the development of great lengths of these flows was interpreted as being due to low viscosity, high effusion rates, and a rapid emplacement (e.g., Walker, 1967; Shaw and Swanson, 1970; Walker, 1973). Recent researches carried out on active and historic lava flows from Hawaii have changed this traditional view of the process (e.g., Walker, 1989, 1991; Wilmoth and Walker, 1993; Cashman et al., 1998; Hon et al., 1994; Keszthelyi, 1994, 1995; Trusdell, 1995; Keszthelyi and Denlinger, 1996; Self et al., 1998; Calvari, 2004; Riker et al., 2009). Particularly, Hon et al. (1994) proposed an emplacement mechanism for moderate volume effusions (0.1–10 km^3) known as "inflation". This process initiates with a thin lava sheet, not exceeding 0.5 m in thickness, termed "sheet flow" (Ballard et al., 1979) that becomes thicker through the entire flow in response to the continuous addition of lava under an external chilled crust that wraps the flow. As inflation progresses, the upper surface of the flow lifts, and the separation between individual flow lobes vanishes, forming a molten core of interconnected pathways within the flow (Hon et al., 1994; Kauahikaua et al., 1998; Self et al., 1998; Anderson et al., 1999; Schaefer and Kattenhorn, 2004; Anderson et al., 2012; Hoblitt et al., 2012). Inflation broadly affects the

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entire flow because of this hydraulic connection. The result is a flat to hummocky flow surface bounded by steep, rifted margins (Anderson et al., 2005, 2012; Hoblitt et al., 2012).

Hummocky flow surfaces are characterized by the presence of tumuli-low, dome-like mounds, commonly 1–5 m high, but occasionally exceeding 10 m in height (e.g., Wentworth and Macdonald, 1953; Walker, 1991; Chitwood, 1994). Most tumuli are crudely circular to elliptical in map view with deep axial cracks (e.g., Walker, 1991) and form in response to magmatic overpressure within the flow as the flow's crust thickens (Walker, 1991; Hon et al., 1994; Peterson et al., 1994; Anderson et al., 1999, 2012). Those areas that inflate the most form tumuli, while the lows between tumuli experience significantly less, or even no, inflation. In practice, all low mounds that define the surface of hummocky flows, and which formed by inflation, are called tumuli. These aspects are linked to the control of intrinsic and extrinsic factors of volcanic activity such as duration and effusion rates of the eruption, viscosity of the lava, and topography of the emplacement area. It has been demonstrated that surface textures and crustal thickness of tumuli may help quantify eruption duration (Mattisson and Hoskuldsson, 2005; Nemeth, 2010).

In some instances, inflation is focused over preferred pathways, such as incipient tubes, within a flow to form a discontinuous series of elongate tumuli (Kauahikaua et al., 1998; Glaze et al., 2005). Such chains of tumuli can also form when pāhoehoe lava on a low-slope surface fails to spread out, for instance by lateral topographic confinement (Glaze et al., 2005). In this case, the geometry of the flow alone focuses inflation within the flow's narrow width, so that tumuli appear to be aligned. While the formation of a series of tumuli over a well-established lava tube occurs relatively rarely (Walker, 1991; Anderson et al., 2012), such occurrences have been documented (Kauahikaua et al., 1998; Duncan et al., 2004). Lava tubes offer an efficient thermal delivery to the lava because of their lower cooling gradient (≈0.5 °C/km) (Greeley, 1987; Pinkerton and Wilson, 1994; Keszthely, 1995; Sakimoto et al., 1997; Cashman et al., 1998; Keszthelyi and Self, 1998; Sakimoto and Zuber, 1998). Where tumuli form over such lava tubes, they tend to be more elongate, sometimes with a sinuosity that matches that of the underlying lava tube (Keszthelyi and Pieri, 1993; Hon et al., 1994; Cashman and Kauahikaua, 1997; Self et al., 1998).

Although published works has been done on the stratigraphy of the Bahariya Depression (El Sharkawi et al., 1987; El Aref et al., 1999; Helba et al., 2001; El Aref et al., 2006; Salama et al., 2014), the physical volcanology of the basaltic lavas remains largely unknown. We focus here on the development of the tumuli and its associated features that occurred in response to fluctuations in discharge. So, the goal of this paper is first to report on and describe the morphological characteristics and the emplacement mechanism of tumuli lava flow accompanying lava tube within the Bahariya flows. The young age of the flow fields and the semi-arid to arid climate of the Bahariya Depression have preserved excellent exposures for the study of lava surface features and flow features, unique for this area.

2. Terminology and methodology

Three major groups of tumuli involving lava-coated tumuli, shallow-to moderate-slope tumuli, and flow-lobe tumuli have been distinguished based on the morphology (Walker, 1991; Nemeth et al., 2008; Nemeth, 2010). Duraiswami et al. (2001) concluded that any distinction of tumuli based on slope is unsuitable usage because of the ancient and eroded nature of the volcanics like El Bahariya volcanics. In the latter, flow-lobe tumuli could be distinctly recognized accordingly.

A geological mapping of the studied area was performed through multispectral satellite images. Analyses of these images defined the eruptive vents, the length and areal extension of the tumuli, and verified the influence of different external controls to the flow advance such as slopes and ground obstacles. The length (tl), width (tw), and height (th) of the tumuli were measured using a metal carpenter'stape. Crustal width (cw), which is the sum of the widths of various crustal slabs minus that of the clefts, has also been measured. Besides these, tumuli orientation and their position within flows are also recorded. The morphological aspects of the flow-lobe tumuli are described in Table 1.

3. Geological setting

The Bahariya Depression (1800 km^2) is located between 27°48′ and 28°30′N latitude and 28°35′ and 29°10′E longitude (Fig. 1). It has a large oval shape with its major axis running northeast that was naturally excavated in the Western Desert at about 320 km, SW of Cairo. Its greatest length, northeast to southwest, is about 94 km; and its greatest width measured at right angles to its length is about 42 km. Its capital town El Bauiti is situated 350 km south west of Cairo (Fig. 1). The average depth, from the general desert plateau level to the floor of the excavation, is less than 100 m. It is enclosed from all sides by plateau of Eocene carbonates with, and locally without Upper Cretaceous rocks. Its floor and surrounding scarps are mostly made up of Cenomanian clastic deposits (Fig. 2) (Soliman et al., 1970; Dominick, 1985; El Bassyouny, 1994; Sadek, 2010). The study areas involving the volcanic rocks are the southern reach of the northeastern plateau of this depression. These areas are typical karst terrains dominated by conehills with cockpits and discrete depressions of which, El Hefhuf, El Gedida, Ghorabi and El Harra are the most pronounced. These depressions which host high grade ironstones are excavated Cenomanian clastics. Whereas, El Gedida is a closed depression within the plateau, the other three depressions are opened to the main Bahariya depression. However, each of these depressions is characterized by a central elevated hills or inselberg (e.g. Ghorabi inselberg and Lion hills in El Gedida mine area), being partially or completely surrounded by annular or semicircular valleys.

The Bahariya Oasis, situated on the Stable–Unstable Shelf contact, is highly deformed (Said, 1962). Structurally, the distinct wrench deformation affects this Oasis (Sehim, 1993, 2000; Moustafa et al., 2003). A series of double-plunging anticlines and synclines being arranged in an echelon pattern along NE-dextral wrench faults (Fig. 2A, Ghorabi & El Harra faults) are reported (Sehim, 1993; Iron Exploration Project IEP, 1993–1997). The wrench deformation prevailed in Late Cretaceous and occasionally reactivated during Late Eocene (Sehim, 1993; Moustafa et al., 2003). Ghorabi, Dumbell, El Ghaziya, El Gedida, and El Harra domes and anticlines are the most pronounced examples of the wrench-related folding.

Several volcanic episodes took place during the Phanerozoic in north Egypt (Said, 1962). Most of them occurred in Mesozoic and Cenozoic times, particulary in the Neogene. The age of Cenozoic volcanism extended from Late Eocene to Middle Miocene (40-15 Ma: Steen, 1982; Meneisy, 1990). These volcanics are part of the Afro-Arabia Large Igneous Province (Bryan and Ernst, 2008). In Bahariya Depression, these volcanics flowed over Cretaceous and Tertiary sedimentary rocks (Fig. 2). Their eruptive rocks occur in the form of fluvio-lacustrine compound pahoehoe lava flows and volcanic cones in NNE–SSW and NE–SW alignments through fissures in areas presently surrounded by the populated zones (Figs. 2 and 3A). Frequently, flat topography of the flow surface is interrupted by lava landforms, which are associated to the lava emplacement mechanism. These morphological features mainly comprise tumuli, lava rises, tumuli channel, and tumuli ridges. The lava flows and its