Journal of Volcanology and Geothermal Research 180 (2009) 277–291

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Growth and evolution of an emergent tuff cone: Considerations from structural geology, geomorphology and facies analysis of São Roque volcano, São Miguel (Azores)

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ARTICLE INFO

Available online 10 October 2008

Keywords:
tuff cones
morphological changes
tectonic
facies analysis
Azores

ABSTRACT

The syn-eruptive and post-eruptive history of São Roque tuff cone, its geological setting and volcanological features were studied in detail to understand the role played by the different factors that contributed to the morphological evolution of this relatively simple and small volcanic edifice.

In addition, attention was also focused on the series of natural changes that affected the tuff cone during the course of the years and that finally led to its structural disassembly. A novel model is proposed to explain this process.

The São Roque volcanic centre, located on the island of São Miguel (Azores), consists of two well-consolidated bodies and numerous small islets that formed more than 4700 years ago during the hydromagmatic activity that took place along an intruding dyke, whose NNW–SSE trend is in agreement with the regional tectonic pattern. The eruptive vents probably migrated progressively from SSE to NNW, forming small edifices through the rapid accumulation of sediments during alternating phases of "dry" and "wet" magmatic emissions. Syn-eruptive partial collapses greatly modified the original morphological structure of these edifices, probably allowing sea water to continuously flow into the vents. The complex interaction of these factors controlled the depth of magma fragmentation, producing different types of deposits, in which the ash-lapilli ratio varies considerably. The high-water saturation degree of these deposits caused syn-eruptive and post-eruptive remobilization which resulted in collapses and some small-scale landslides.

Post-eruptive, WNW–ESE trending transtensional and extensional tectonic activities operated during the initial dissection of the cone, generating instability. Furthermore, the rapid accumulation of "wet" tephra, and its following consolidation, caused selective collapses that favoured the fragmentation of the deposit and caused the formation of numerous islets separated by radially-arranged channels. Collapses also involved the lava units emplaced in more recent times around the tuff cone, which show that brittle deformation has been significant in the area for a prolonged period.

1. Introduction

Landforms created by the accumulation of volcanic material around a vent include a wide range of morphological structures, mainly related to the eruption style and to the physico-chemical parameters of ascending magma (Thouret, 1999), but also depending on the geometry of the feeding dyke and on the pre-existing relief. During a single eruptive event, there may be considerable changes in the eruption style due to changes in the volume and velocity of ascending magma in the feeder dyke (Houghton and Hackett, 1984; Houghton and Schmincke, 1986; Houghton et al., 1999). Additionally, the influence of numerous other factors, such as type, level, and lithology of aquifers, resistance of country rocks, ground-water characteristics may affect the eruptions style (Sohn, 1996; White, 1996). The active stress-field of the area is a crucial factor controlling the rise of magma through the crust (Zanon, 2005), and therefore is a major influence on eruptions magnitude and intensity, controlling the rise of magma batches through the crust, leading to their eruption.

The complex dynamics of water-magma interaction determines the nature of explosive activity, characterized by variable energy outputs and different degrees of magmatic or hydromagmatic fragmentation (Wohletz and Sheridan, 1983; Houghton and Hackett, 1984; Kokelaar, 1986; White and Houghton, 2000; Mastin et al., 2004). Depending on the extent of water-magma interaction, deposits can be formed by fallout layers made of couplets of ash and lapilli, by the alternation of fallout layers and surge deposits, or by the simultaneous concurrent deposition from both processes, leading to the formation of highly complex deposits made of numerous (from few tens to over thousands) of thin tephra beds (e.g. Cas and Wright, 1987; Sohn and Chough, 1989; Dellino and La Volpe, 1995; Chough and Sohn, 1990; Dellino and La Volpe, 2000; Dellino et al., 2001; Dellino et al., 2004). As a consequence, hydromagmatic deposits show remarkable variability in grain-size from layer-to-layer and within layers.

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doi:10.1016/j.jvolgeores.2008.09.018

Tuff cones rank among the most common volcanic landforms in the world (Cas and Wright, 1987; Vespermann and Schmincke, 2000; Schmincke, 2004). They are generated during single-stage eruptions, marked by variable degrees of interaction between surface water and ascending magma. Their morphology depends on the variation in the parameters that control the extent of this interaction (e.g. magma supply rate, vent radius, degassing rate, magma chemistry and amount of participating water).

During hydromagmatic eruptions, freshly deposited ash layers are usually rapidly eroded by wave action (e.g. Castro Bank, Azores, 1720 - Machado and Lemos, 1998; Sabrina Island, Azores, 1811 - Chaves, 1915; Ferdinandea/Graham Island, Sicily, 1831 - Washington, 1909; Myōjin-Shō, Japan, 1952–53 - Fiske et al., 1998; Metis Shoal, Tonga, 1995 - Taylor and Ewart, 1997; Home Reef, Tonga, 2006 - Vaughan et al., 2007). A rapid erosion process however, offers the advantage of making large portions of the innermost sectors of these structures accessible to study in order to understand their syn-eruptive depositional processes and the complex contemporaneous and post-eruptive destructive dynamics (Cole et al., 2001; Sohn and Park, 2005; Németh and Cronin, 2007).

The tuff cone of São Roque, in São Miguel Island (Azores) was studied in detail, both at macro- and meso- scales in order to better understand the generation of a volcanic cone and its subsequent destruction.

2. Geological setting

The Azores Archipelago consists of nine volcanic islands that formed in the period from Miocene/Oligocene to Holocene (Johnson et al., 1998; Cannat et al., 1999), above the Azores oceanic plateau in the North Atlantic Ocean. Three major structures define the tectonics of the eastern Azores plateau: the Mid-Atlantic Ridge (MAR) to the west; the East Azores Fracture Zone (EAFZ) to the south, a westward extension of the transcurrent/transpressive Gloria Fault; and the dextral transtensional Terceira Rift (TR) in the northern part of the platform (Machado, 1959; Searle, 1980; Jiménez-Munt et al., 2001) (Fig. 1). The latter is considered to be an ultra-slow spreading rift with an extension rate of 2–4 mm/year (Madeira and Ribeiro, 1990; Gente et al., 2003; Vogt and Jung, 2004).

São Miguel Island, on the eastern side of Terceira Rift, has three caldera lake-dominated volcanoes intersected by fissure systems (or “Waist Zones” - e.g. Booth et al., 1978), characterized by the presence of numerous monogenic basaltic scoria- and tuff- cones as well as tuff rings, along the coasts of the island (Fig. 1).

São Roque tuff cone is located on the southern coast of São Miguel, <1 km west of Ponta Delgada, the islands main town. It is partially embedded within lava flows and is related to the fissure volcanism of “Região dos Picos”.

The stratigraphy of Região dos Picos Waist Zone consists of two units identified on the basis of their relative position in respect to the *Fogo-A* member (e.g. Walker and Croasdale, 1971; Booth et al., 1978), erupted from Água de Pau volcano about 4700 years ago (Snyder et al., 2007): *Ponta Delgada* unit that includes all the basaltic lavas and pyroclastic rocks produced before *Fogo-A*, and *Pinhal da Paz* whose formation is more recent than *Fogo-A* and includes basaltic members produced in the last 4700 years, mainly along the central ridge (Ferreira, 2000) (Fig. 2).

The stratigraphy around São Roque tuff cone shows that the lava fountain fallouts of Pico das Faias (to the west), Pico das Canas and associated lavas to the east, as well as the southernmost lava on the shoreline, and São Roque tuff cone itself are older than *Fogo-A* (Ponta Delgada Unit), whereas the other lava flows that cover this area are younger and belong to the *Pinhal da Paz* unit (Fig. 2).

3. Methodology

A preliminary field study was carried out to understand field relationships among the different volcanic structures present in an area of about 9 km^2 surrounding São Roque tuff cone. Relative ages were determined on the basis of the stratigraphic history of the studied area, using the *Fogo-A* deposit as a stratigraphic marker.

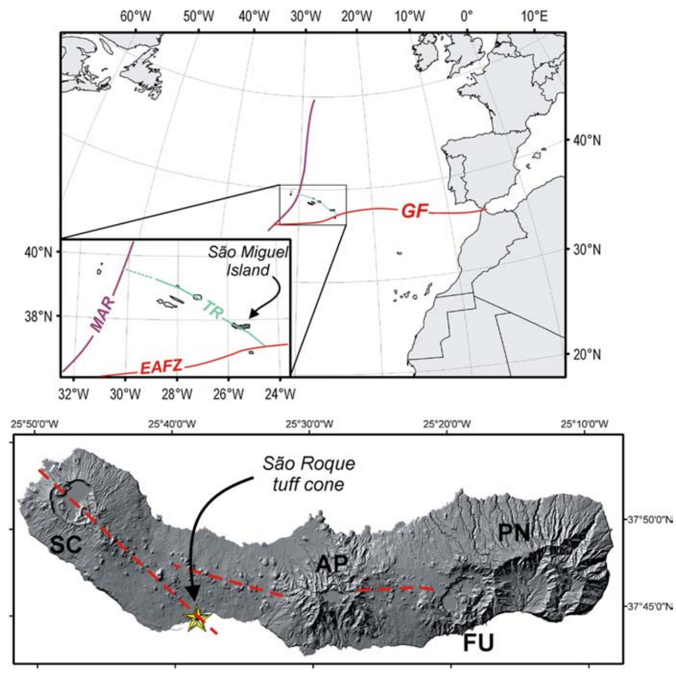

Fig. 1. Map of the Azores archipelago. The uppermost map shows the position of São Miguel Island and its main tectonic features, according to Searle (1980) and Vogt and Jung (2004). The acronyms: MAR stands for Mid-Atlantic Ridge, TR for Terceira Rift, EAFZ for East Azores Fracture Zone, GF for Gloria Fault. The location of São Roque tuff cone is indicated by a star in the digital elevation model of São Miguel Island. Four main volcanic complexes, some of which have caldera lakes, are indicated by acronyms (SC — Sete Citades, AP — Água de Pau, FU — Furnas, PN — Povoação-Nordeste). Dashed lines indicate the areas of structural weakness, characterised by the presence of numerous basaltic monogenic cones.

Detailed field studies were then carried out on the outcrops of the tuff cone and on the surrounding lava platform, including lithofacies analysis, sampling, determination of bed attitudes, and characterization of fractures (down to about ~2.5 mm wide). An exhaustive analysis of the study area was also performed by aerial photo interpretation.

Field observations were located using a portable GPS receiver with an average precision of ±5.6 m and 1:10.000 scale aerial photos. Geographical data was handled using a 1:25.000 scale topographic map and corrected on high-resolution geo-referenced orthophotomaps.

Studies of the petrographic characteristics of representative hydromagmatic samples were accomplished by binocular microscope analysis.

4. Tuff cone morphology

The tuff outcrop of São Roque has a crescent shape in plan view, opening towards the northeast. It covers an area of about 11,000 m^2 and consists of two main eroded bodies and numerous small islets (each measuring a few square meters), which barely emerge above sea level (Fig. 2a). The eastern and southern sectors of the cone were extensively eroded and no longer crop out.

The largest outcrop (ca 5300 m^2; maximum height 27 m a.s.l.) is located near the village of São Roque and forms a prominent, SW-oriented, morphological structure extending along the coastline. Its depositional units show quaquaversal bedding dips that progressively rotates from SW towards NE, from N35°E to N75°E, with a maximum dip angle of 40° on the inner slopes of the cone. While the outer slopes are smooth, the inner slopes are rough due to numerous fractures and vertical incisions that extend for several meters into the sea. Some small collapse scars and overturned beds are visible here. The south-western edge of this outcrop ends abruptly, exposing a depositional sequence for several meters (Fig. 2b).