Journal of Volcanology and Geothermal Research 357 (2018) 152–162

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

Investigating collapse structures in oceanic islands using magnetotelluric surveys: The case of Fogo Island in Cape Verde

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A R T I C L E I N F O

Article history:
Received 13 September 2017
Received in revised form 17 April 2018
Accepted 25 April 2018
Available online 30 April 2018

Keywords:
Volcanic ocean islands
Magnetotelluric
Flank collapse
Island structure
Resistivity

A B S T R A C T

One of the most remarkable natural events on Earth are the large lateral flank collapses of oceanic volcanoes, involving volumes of rock exceeding tens of km^3. These collapses are relatively frequent in recent geological times as supported by evidence found in the geomorphology of volcanic island edifices and associated debris flows deposited on the proximal ocean floor. The Island of Fogo in the Cape Verde archipelago is one of the most active and prominent oceanic volcanoes on Earth. The island has an average diameter of 25 km and reaches a maximum elevation of 2829 m above sea level (m a.s.l.) at Pico do Fogo, a young stratovolcano located within a summit depression open eastward due to a large lateral flank collapse. The sudden collapse of the eastern flank of Fogo Island produced a megatsunami ~73 ky ago. The limits of the flank collapse were deduced as well from geomorphologic markers within the island. The headwall of the collapse scar is interpreted as either being located beneath the post-collapse volcanic infill of the summit depression or located further west, corresponding to the Bordeira wall that partially surrounds it. The magnetotelluric (MT) method provides a depth distribution of the ground resistivity obtained by the simultaneous measurement of the natural variations of the electric and magnetic field of the Earth. Two N-S magnetotelluric profiles were acquired across the collapsed area to determine its geometry and boundaries. The acquired MT data allowed the determination of the limits of the collapsed area more accurately as well as its morphology at depth and thickness of the post-collapse infill. According to the newly obtained MT data and the bathymetry of the eastern submarine flank of Fogo, the volume involved in the flank collapse is estimated in ~110 km^3. This volume –the first calculated onshore– stands between the previously published more conservative and excessive calculations –offshore– that were exclusively based in geomorphic evidence. The model for the summit depression proposing two caldera collapses preceding the collapse of the eastern flank of Fogo is supported by the MT data.

1. Introduction

Volcanic edifices become progressively unstable as they grow and, therefore, large volcanoes may suffer swift large-scale geomorphological changes produced by collapse processes. These major volcano-tectonic events include gravitational caldera vertical collapses and lateral flank collapses that occur periodically during the evolution of large volcanoes (Merle and Lénat, 2003). Vertical collapses of caldera type, truncating the volcano summit, are common in the evolution of large volcanoes due to a deficit of mass in depth (magma reservoirs) as a consequence of magma transfer. Lateral flank collapses may occur when the volcanic structure becomes gravitationally unstable, a process enhanced by the island geological structure, which is usually characterized by seawards dipping layers of alternating coherent and incoherent volcanic and sedimentary deposits.

Large lateral flank collapses in oceanic volcanoes, involving volumes exceeding tens of km^3, are one of the most remarkable natural events on Earth (Ward and Day, 2001). Although no such event has been observed in historical times, their evidence in the geomorphology of volcanic island edifices and from the associated debris flows and turbidites deposited on the surrounding ocean floor indicate their relatively frequent occurrence in recent geological times. Numerous examples of lateral collapses have been described in most volcanic archipelagos. As examples we mention Cape Verde (Day et al., 1999; Amelung and Day, 2001; Masson et al., 2008; Madeira et al., 2008; Ramalho et al., 2015); Canaries (Watts and Masson, 1995; Masson, 1996; Day, 2001; Masson et al., 2002; Carracedo, 2014), Hawaii (Morgan et al., 2003; Coombs et al., 2004; Okubo, 2004); Stromboli in the Aeolian Islands (Tibaldi, 2001; Acocella and Tibaldi, 2005; Vezzoli and Corazzato, 2016); Ritter Island in Papua-New Guinea (Ward and Day, 2003; Day et al., 2015);

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https://doi.org/10.1016/j.jvolgeores.2018.04.028
0377-0273/

Reunion Island (Oehler et al., 2008). This type of events is also reported in continental volcanoes such as the 7200 years BP Socompa flank collapse in the Andes (De Silva and Francis, 1991) or Colima in México (Cortés et al., 2010), among others.

Growing instability as volcanoes become taller and steeper may originate failures of variable scale, ranging from minor rock falls to giant megaslides involving volumes of rock of the order of tens to hundreds of km^3 (McGuire, 1996). Generally, major structural failure is limited to the larger volcanic edifices. Persistent dyke emplacement producing rifting and generating local seismicity, deformation and changes in edifice pore-pressure, together with environmental factors, constitute potential failure triggers. In addition, ground deformation induced by magma injection and ground shaking caused by tectonic earthquakes and/or surface fault rupture may contribute in the instability of the volcanic edifices. Other processes that can activate a lateral collapse are: asymmetric distribution of buttressed flanks (Romagnoli et al., 1993; Romagnoli and Tibaldi, 1994), glacio-eustatic sea-level variations (Della Seta et al., 2013; Lee, 2009), slope erosion by marine abrasion on littoral areas (Tibaldi et al., 1994; Ramalho et al., 2013) and hydrothermal alteration in the core of volcanoes (López and Williams, 1993; Day, 1996; Voight and Elsworth, 1997; Martí et al., 1997; Van Wyk de Vries et al., 2000; Reid et al., 2001; Ferrer et al., 2010; Merle et al., 2010).

The Island of Fogo in the Cape Verde archipelago (Fig. 1a) is a very active and prominent oceanic volcano (Ribeiro, 1960). The island has an average diameter of 25 km and reaches a maximum elevation of 2829 m above sea level (m a.s.l.) at Pico do Fogo, a young stratovolcano located within a summit depression open eastwards due to a large lateral flank collapse (Brum da Silveira et al., 1997; Day et al., 1999; Paris et al., 2011; Le Bas et al., 2007; Madeira et al., 2008; Masson et al., 2008). The lateral limits of the flank collapse in Fogo can be deduced from geomorphological markers, namely the 400 m tall Espigão escarpment marking its southern lateral limit and a more subdued escarpment, partially covered by recent volcanic deposits, at its northern edge. The headwall of the flank collapse scar is interpreted as either being located beneath the post-collapse volcanic infill of the summit depression (Brum da Silveira et al., 1997; Torres et al., 1998) or located further west, corresponding to the Bordeira wall (Fig. 1) that partially surrounds the summit depression (Day et al., 1999). There are two genetic interpretations for the summit depression. According to Brum da Silveira et al. (1997), Torres et al. (1998) and Madeira et al. (2008), it is the result of two caldera collapses: an older southern caldera, 6 km in diameter, and a younger and smaller northern one, 3.5 km in diameter, whose floor lies approximately 50 m lower than the southern caldera. The intersection of the two calderas forms the Monte Amarelo spur (Fig. 1b). According to these authors the summit caldera depression was opened to the east by a large flank collapse. Another interpretation is presented by Day et al. (1999) that consider the whole depression as being produced by a large collapse of the eastern flank of the volcano, with the Bordeira corresponding to its headwall (Fig. 1c). Most subsequent works follow the later interpretation (i.e. Masson et al., 2008; Paris et al., 2011; Maccaferri et al., 2017). These two alternative interpretations have important consequences in terms of area and volume of the flank collapse and in understanding the evolution of the island. Besides the uncertainty on the surface trace of the collapse scar, the calculation of the volume involved depends also on the volcano morphology prior to the flank collapse and the depth of the rupture surface which was unknown until now. The geology and geomorphology show that it lies below sea-level at the island eastern seaboard, but its depth inland was still unknown. This problem can only be addressed by drilling or by geophysical methods.

Our work aims at defining the geometry of the lateral flank collapse in Fogo Island and, if possible, to choose between the two competing models for the collapse structure by means of the magnetotelluric (MT) method. MT data can provide depth distribution of the ground resistivity obtained by simultaneous measurement of the natural variations of the electric and magnetic field of the Earth (Vozoff, 1991). This method allows obtaining profile or map resistivity distributions down to depths of thousands of meters thus having the potential to image collapse scars in depth. Two profiles crossing the collapsed area, either caldera and/or flank collapses, were used to determine the geometry of Fogo collapse structures both at the surface and at depth, and thus estimating the area and volume involved.

2. Geological setting

Cape Verde Archipelago, located 570 km off the west coast of Africa, is formed by ten major islands (Fig. 2a) displaying a horseshoe shape open to the west. The islands are built on Late Jurassic to Cretaceous oceanic crust on top of a major topographic anomaly – the Cape Verde Rise. The magmatism is considered to be the result of a mantle plume (White, 1989) and the ages of the oldest subaerial lavas suggest that the islands emerged during the Miocene (Mitchell et al., 1983; Torres et al., 2002; Plesner et al., 2003; Duprat et al., 2007; Holm et al., 2008; Madeira et al., 2010; Dyhr and Holm, 2010; Ramalho et al., 2010; Ancochea et al., 2010, 2014 and 2015). The morphology of the islands is related to their age, so that the westernmost younger islands (Brava, Fogo, Santiago, São Nicolau, Santa Luzia, São Vicente, Santo Antão) present

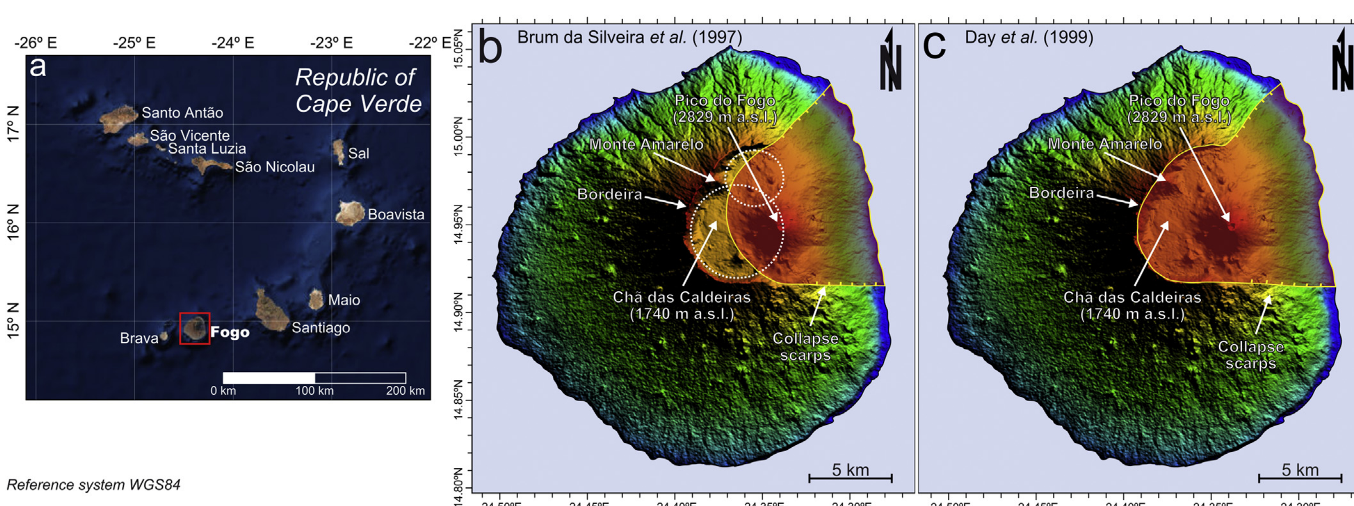

Fig. 1. Geographical location of the island of Fogo in Cape Verde archipelago (a). Models proposed for the origin of the Bordeira wall: (b) a combination of two caldera collapses followed by a flank collapse (Brum da Silveira et al., 1997) and (c) a single major collapse of the eastern flank of the volcanic edifice (Day et al., 1999). Modified from Ramalho et al., 2015.