Journal of Volcanology and Geothermal Research 239–240 (2012) 92–110

Contents lists available at SciVerse ScienceDirect

Journal of Volcanology and Geothermal Research

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

Geological and geomechanical models of the pre-landslide volcanic edifice of Güímar and La Orotava mega-landslides (Tenerife)

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ARTICLE INFO

Article history:
Received 1 August 2011
Accepted 8 June 2012
Available online 17 June 2012

Keywords:
Volcanic landslides
Geomechanical models
Güímar and La Orotava mega-landslides
Tenerife
Canary Islands

ABSTRACT

The geological and geomechanical characterizations of the volcanic rock mass succession affected by the Güímar and La Orotava mega-landslides (Tenerife, Canary Island) are presented here for the first time. The estimated subaerial volume of rocks mobilized by each of these landslides is in the range of 30–50 km^3, one of the largest known in the world. Field data, gallery surveys and borehole drilling have allowed the main types of materials and their structural arrangement to be identified. Based on these information a geological model of the pre-landslide volcanic edifice is proposed. A palaeo-morphological reconstruction has been produced and possible slope angles and heights of the pre-landslide volcanic edifice are presented. Five main lithological units have been identified in the emerged part of the edifice, three of them forming the flanks and two forming the structural axis of the island. On the flanks, lava flows predominate with different degrees of alteration and proportion of dikes increasing near the structural axis. The predominant materials on the structural axis are pyroclastic deposits, lava flows and dikes. In the submarine edifice four main lithological units have been distinguished, formed by hyaloclastites, pillow-lavas, dikes and gravitational deposits (slope and basin facies). The geomechanical characterization of these materials has been obtained from field data, boreholes, laboratory tests and literature review. The geological and geomechanical models obtained provide the fundamental basis for the explanation of the instability processes that generated the Güímar and La Orotava mega-landslides.

1. Introduction

Many of the world's volcanoes have suffered large gravitational landslides on their flanks during their geological history. These instability processes are related to the rapid growth of the volcanic edifices and are part of their natural evolution. The occurrence of these processes on volcanic island flanks has been investigated in the Hawaiian Ridge (Moore, 1964; Duffield et al., 1982; Lipman et al., 1988; Moore et al., 1989, 1994; Morgan et al., 2003), La Réunion (Chevallier and Bachelery, 1981; Duffield et al., 1982; Lénat et al. 1989; Labazuy, 1996; Ollier et al., 1998; Bret et al., 2003; Merle and Lénat, 2003; Oehler et al., 2004, 2005), Lesser Antilles (Roobol et al., 1983; Boudon et al., 1984; Semet and Boudon, 1994; Mattioli et al., 1995; Deplus et al., 2001), Ritter Island and Bismarck Ridge (Johnson, 1987), Tristan da Cunha (Holcomb and Searle, 1991), the Canary Islands (Holcomb and Searle, 1991; Watts and Masson, 1995; Teide Group, 1997; Urgeles et al., 1997, 1998; Krastel et al., 2001; Masson et al., 2002; Acosta et al., 2003), Stromboli (Pasquaré et al., 1993; Kokelaar and Romagnoli, 1995; Tibaldi, 1996, 2001; Apuani et al., 2005a, 2005b), French Polynesia (Wolfe et al., 1994; Clément et al., 2002; Clouard and Bonneville, 2004), Cape Verde (Elsworth and Day, 1999; Masson et al., 2008), Ischia (Chiocci and Alteriis, 2006) or Vulcano island (Tommasi et al., 2007). The flanks of volcanic edifices may fail and slide in the last phases of their growth when they reach critical dimensions or when specific triggering factors occur, e.g. large explosive eruptions with associated seismicity (Voight and Elsworth, 1997; Tibaldi, 2001). When the materials from the mega-landslides fall into the sea, extensive debris avalanches are deposited on the seabed.

In the Canaries at least ten large palaeo-landslides have occurred over the last 1.5 million years (Krastel et al., 2001; Masson et al., 2002; Acosta et al., 2003; Fig. 1). The landslides which caused the Güímar and La Orotava valleys, on the NE side of the island of Tenerife, are two exceptional cases. The valleys are both "U"-shaped depressions, 10 km wide, bounded by impressive vertical scarps (500–600 m high) (Fig. 2). The landslides that generated these valleys, during the Pleistocene, mobilized a subaerial volume of rocks in the range of 30–50 km^3. However, although these landslides are among the largest in the world

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doi:10.1016/j.jvolgeores.2012.06.013

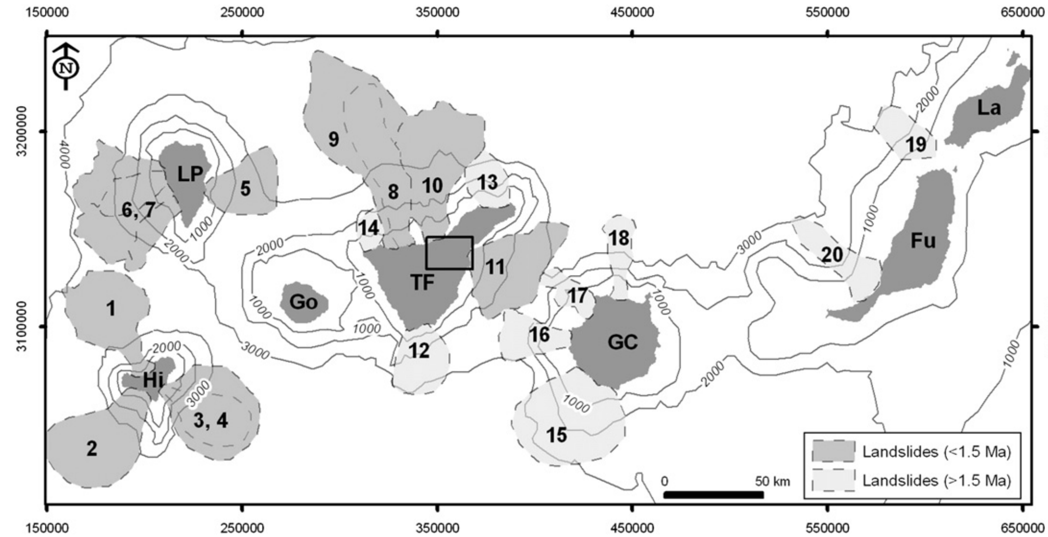

Fig. 1. Large landslide deposits on the submarine flanks of the Canary Islands. Debris avalanches in El Hierro (Hi): El Golfo (1), El Julán (2), Las Playas I, II (3, 4); La Palma (LP): Santa Cruz (5), Playa de la Veta complex (6), Cumbre Nueva (7); Tenerife (TF): Icod (8), Roques de García (9), La Orotava (10), Güímar (11), Bandas del Sur (12), Anaga (13), Teno (14); Gran Canaria (GC): Roque Nublo (15), Horgazares (16), North west coast (17), North coast (18); Fuerteventura (Fu): East Canary Ridge (19), Jandia (20). Data from Krastel et al. (2001), Masson et al. (2002) and Acosta et al. (2003). The rectangle indicates the study area where the Güímar and La Orotava valleys are. (UTM 28N/WGS84/Meters).

by volume, their causes and failure mechanisms are still not fully understood.

In the last years, engineering geological and rock mechanical methods have been applied to the study of instability processes on the flanks of volcanic edifices with considerable success (Paul et al., 1987; Elsworth and Voight, 1995; Iverson, 1995; Hürlimann, 1999; Reid et al., 2001; Concha-Dimas, 2004; Zimbelman et al., 2004; Apuani et al., 2005a, 2005b; Moon et al., 2005; Schiffman et al., 2006; Van Berlo, 2006, 2007; Thompson et al., 2008). The methods and software for stability analysis (limit equilibrium or stress–strain methods), traditionally used in slope stability analysis, provide relevant information on the influence of the factors involved in the instability processes (conditioning and triggering factors) and the characteristics of the failure mechanisms. For this type of analysis, geological and geomechanical models representative for the pre-landslide volcanic edifices are needed. These models have to consider the distribution, characteristics and geomechanical properties of the lithological units of the volcano affected by the landslide, as well as its original geometry and hydrogeological conditions. Therefore the results of the subsequent stability analysis depend largely on the validity and reliability of these models.

The first models for the analysis of instability processes of volcano flanks were very simple (Paul et al., 1987; Elsworth and Voight, 1995; Iverson, 1995; Hürlimann, 1999). They only distinguished a single lithological unit and their geomechanical properties were taken from generic theoretical data. Later, attention was focused on the analysis of the condition of the materials forming the flanks (Reid et al., 2001) and on the study of the physical and mechanical properties of the volcanic materials using rock mechanic methods (Watters et al., 2000; Concha-Dimas, 2004; Zimbelman et al., 2004). More recent investigations have pointed out the importance of differentiating and characterizing specific lithological units, and establishing the structural distribution of the geological model (Okubo, 2004; Apuani et al., 2005a, 2005b; Moon et al., 2005; Schiffman et al., 2006; Van Berlo, 2006; Del Potro and Hürlimann, 2008; Thompson et al., 2008). Table 1 shows a summary of the different geological models proposed by different authors and their most relevant characteristics.

This paper presents the results of the geological and geomechanical investigations carried out on the volcanic rock mass succession involved in the paleo-landslides of Güímar and La Orotava and the representative models obtained. These models are fundamental for the stability analysis of the flanks of the volcanic edifices and to determine the causes and failure mechanisms of these mega-landslides.

2. Geological setting

Tenerife is the largest island of the Canaries (2034 km^2) and also where the maximum height is reached (3817 m, Teide volcano). Its volcanic activity began in the late Miocene, around 12 Ma ago. The

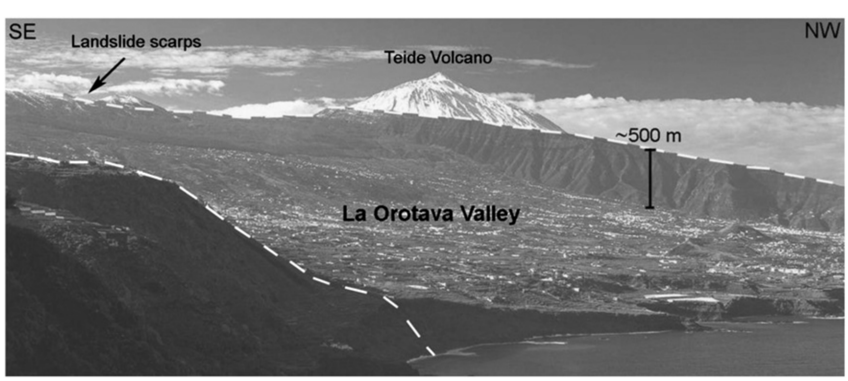

Fig. 2. View from the NE of the La Orotava valley in Tenerife. This "U"-shaped valley, 10 km wide, that was generated by a large paleo-landslide occurred in the Pleistocene. The dashed line indicates the boundary of the valley marked by impressive scarps (500–600 m high). In the background is the Teide volcano (3718 m high).