Journal of Volcanology and Geothermal Research 250 (2013) 42–60

Contents lists available at SciVerse ScienceDirect

Journal of Volcanology and Geothermal Research

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

Thermal weakening of the carbonate basement under Mt. Etna volcano (Italy): Implications for volcano instability

M.J. Heap [a,*], S. Mollo [b], S. Vinciguerra [c], Y. Lavallée [d], K.-U. Hess [e], D.B. Dingwell [e], P. Baud [a], G. Iezzi [f]

[a] Laboratoire de Déformation des Roches, Institut de Physique de Globe de Strasbourg (UMR 7516 CNRS, Université de Strasbourg/EOST), 5 rue René Descartes, 67084 Strasbourg cedex, France
[b] Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605 00143 Rome Italy
[c] Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso 35, 10125, Turin, Italy
[d] Department of Earth, Ocean and Ecological Sciences, School of Environmental Sciences, University of Liverpool, United Kingdom
[e] Earth and Environment, LMU, University of Munich, Theresienstr, 41/III, 80333 München, Germany
[f] Dipartimento DIGAT, Università G. d'Annunzio, Via Dei Vestini 30, I-66013 Chieti, Italy

ARTICLE INFO

Article history:
Received 19 April 2011
Accepted 9 October 2012
Available online 17 October 2012

Keywords:
Mt. Etna
Temperature
Carbonate basement
Decarbonation
Strength
Ultrasonic wave velocities, Elastic moduli
Vp/Vs ratio
CO_2 budget
X-ray powder diffraction
Thermo-gravimetric analysis
Microstructure

ABSTRACT

The physical integrity of a sub-volcanic basement is crucial in controlling the stability of a volcanic edifice. For many volcanoes, this basement can comprise thick sequences of carbonates that are prone to significant thermally-induced alteration. These debilitating thermal reactions, facilitated by heat from proximal magma storage volumes, promote the weakening of the rock mass and likely therefore encourage edifice instability. Such instability can result in slow, gravitational spreading and episodic to continuous slippage of unstable flanks, and may also facilitate catastrophic flank collapse. Understanding the propensity of a particular sub-volcanic basement to such instability requires a detailed understanding of the influence of high temperatures on the chemical, physical, and mechanical properties of the rocks involved. The juxtaposition of a thick carbonate substratum and magmatic heat sources makes Mt. Etna volcano an ideal candidate for our study. We investigated experimentally the effect of temperature on two carbonate rocks that have been chosen to represent the deep, heterogeneous sedimentary substratum under Mt. Etna volcano. This study has demonstrated that thermal-stressing resulted in a progressive and significant change in the physical properties of the two rocks. Porosity, wet (i.e., water-saturated) dynamic Poisson's ratio and wet Vp/Vs ratio all increased, whilst P- and S-wave velocities, bulk sample density, dynamic and static Young's modulus, dry Vp/Vs ratio, and dry dynamic Poisson's ratio all decreased. At temperatures of 800 °C, the carbonate in these rocks completely dissociated, resulting in a total mass loss of about 45% and the release of about 44 wt.% of CO_2. Uniaxial deformation experiments showed that high *in-situ* temperatures (>500 °C) significantly reduced the strength of the carbonates and altered their deformation behaviour. Above 500 °C the rocks deformed in a ductile manner and the output of acoustic emissions was greatly reduced. We speculate that thermally-induced weakening and the ductile behaviour of the carbonate substratum could be a key factor in explaining the large-scale deformation observed at Mt. Etna volcano. Our findings are consistent with several field observations at Mt. Etna volcano and can quantitatively support the interpretation of (1) the irregularly low seismic velocity zones present within the sub-volcanic sedimentary basement, (2) the anomalously high CO_2 degassing observed, (3) the anomalously high Vp/Vs ratios and the rapid migration of fluids, and (4) the increasing instability of volcanic edifices in the lifespan of a magmatic system. We speculate that carbonate sub-volcanic basement may emerge as one of the decisive fundamentals in controlling volcanic stability.

1. Introduction

The stability of a volcanic edifice is a significant element of risk assessment (McGuire, 1996). Volcanoes, built from successive eruptions, effusive or explosive, can be depicted as pseudo-stable piles of rocks. In contrast to non-volcanic mountains, which form by very slow uplift, volcanoes are built rapidly and heterogeneously, both in time and space. One clear consequence is their high propensity for mass wasting. Volcanic edifice instability need not "merely" result in the slow, gravitational spreading and episodic to continuous slippage of unstable flanks, but can also encourage instantaneous and devastating flank collapse (Siebert, 1992). Field surveys worldwide have shown that the collapse of volcanic flanks is common, if not ubiquitous in the prolonged lifetime of a volcano (Davidson and De Silva, 2000). The consequences of such events can be enormous, both in humanitarian and in economic terms. The integrity of the sub-volcanic basement (the foundation on which the pseudo-stable

* Corresponding author. Tel.: +33 368850039.
E-mail address: heap@unistra.fr (M.J. Heap).

http://dx.doi.org/10.1016/j.jvolgeores.2012.10.004

volcanic pile rests) must be of paramount importance in volcano stability. Previous studies have indeed highlighted the importance of the sub-volcanic basement in edifice stability (McGuire, 1996; Van Wyk De Vries and Borgia, 1996, 1997; Szakács and Krézsek, 2006). Unfortunately (in terms of stability), as is the case for many high-risk, active volcanoes, when the sub-volcanic basement is comprised of thick carbonate sequences it is prone to thermally-induced reactions. Heat, provided by magmatic activity (e.g., see Bonaccorso et al., 2010), can result in detrimental mineralogical, chemical, and textural modifications to carbonate rock, leaving it intensely altered, fractured, and thus weakened (e.g., Homand-Etienne and Troalen, 1984; Samtani et al., 2002; Chen et al., 2009; Mao et al., 2009). The presence of large, sub-volcanic carbonate sedimentary successions within volcanic systems is common. Sub-volcanic carbonate basements seen at high-risk volcanoes worldwide: Mt. Etna volcano (e.g. Lentini, 1982; Grasso and Lentini, 1982; Pedley and Grasso, 1992), Mt. Vesuvius (Bruno et al., 1998; Iacono-Marziano et al., 2009), the Colli Albani volcanic district (Chiodini and Frondini, 2001; Iacono-Marziano et al., 2007; Freda et al., 2008; Gaeta et al., 2009; Mollo et al., 2010a) and the Campi Flegrei volcanic district (D'Antonio, 2011) in Italy, Popocatépetl volcano (Goff et al., 2001) and the Colima volcanic complex (Norini et al., 2010), both Mexico, Yellowstone volcanic system, USA (Werner and Brantley, 2003) and Merapi, Indonesia (Chadwick et al., 2007; Deegan et al., 2010; Troll et al., 2012). It becomes clear therefore, that an important element of volcano stability must focus on the understanding of the potential thermally-induced weakening of rock representative of the carbonate successions present under active volcanoes.

In this study, we used Mt. Etna (Italy), the largest volcanic edifice in Europe (40 km wide and standing 3.3 km above sea level), as a case study. Mt. Etna volcano represents an ideal candidate for our study. Firstly, Mt. Etna is one of the most intensively monitored volcanoes on Earth. Over the last 20 years, new technological developments and denser monitoring networks at Mt. Etna have provided one of the highest quality volcanological, geophysical, and geochemical datasets available for any volcano in the world (Bonaccorso, 2004; Acocella and Puglisi, 2012). Studies have shown that there is a continuous large-scale ESE seaward sliding of the eastern flank of Mt. Etna (e.g., Borgia et al., 1992, 2000a,b; Bonforte and Puglisi, 2003; Rust et al., 2005; Bonforte and Puglisi, 2006; Palano et al., 2008, 2009), with an average rate, calculated from geodetic data collected at the Pernicana fault since 1997, of about 2.8 cm/year (Azzaro et al., 2001; Palano et al., 2009). A large décollement surface, potentially dictating this large-scale deformation by driving gravity-driven edifice spreading, has been inferred to exist either at a depth of about 5 km (e.g., Froger et al., 2001; Lundgren et al., 2004; Neri et al., 2004) or at a depth between 1.5 and 3 km (e.g., Bonforte and Puglisi, 2003; Palano et al., 2008).

Secondly, the thin (about 1.5 km thick) basaltic cover at Mt. Etna volcano rests upon a vast sub-volcanic sedimentary basement, comprising of a mélange of marly clays, marly limestones and quartz-arenitic rocks (about 2 km thick, see Catalano et al., 2004) from the Maghrebian–Appennine Chain, that overly a thick Mesozoic to Mid-Pleistocene carbonate succession of limestone and dolomite, referred to as the Hyblean Plateau, or Iblean Plateau (Lentini, 1982; Grasso and Lentini, 1982; Pedley and Grasso, 1992). The Hyblean Plateau is inferred to start at about a depth of 5 km underneath the volcanic edifice (Tibaldi and Groppelli, 2002; Behncke and Neri, 2003; Lundgren et al., 2004; Andronico et al., 2005) and has an average thickness of about 10 km (see Yellin-Dror et al., 1997 and references therein). Importantly, large, long-lived magma bodies are known to be present at depths corresponding to the Hyblean Plateau, as inferred by P-wave inversion tomography (Chiarabba et al., 2000), thermo-mechanical numerical modelling (Del Negro et al., 2009; Bonaccorso et al., 2010), and *b*-value mapping (Murru et al., 1999). However, the involvement of the Hyblean Plateau with the magmatic plumbing system at Mt. Etna volcano does not end there, as new heat sources, in the form of eccentric reservoirs or peripheral dykes that have fed recent flank eruptions are also inferred to populate these depth intervals (Acocella and Neri, 2003; Behncke and Neri, 2003; Andronico et al., 2005; Bonforte et al., 2009; Carbone et al., 2009), potentially exposing fresh, unaltered carbonate rock to high temperatures. Volcanic activity at the flanks of Mt. Etna during the 2001 eruptions (Acocella and Neri, 2003; Behncke and Neri, 2003) was considered to involve the emplacement of a shallow dyke (Bonaccorso et al., 2002; Patanè et al., 2002) at about 3.5 km depth; however, structural and seismic evidence exclude a shallow connection between the summit and the peripheral magmatic systems (Acocella and Neri, 2003). Since the connection between the summit and the peripheral magmatic systems is considered to be at deeper crustal levels (Acocella and Neri, 2003; Carbone et al., 2009), the peripheral dykes are likely to have traversed through rocks of the Hyblean Plateau previously unexposed to high temperatures. This was supported by the fact that, not only was the magma erupted at the flank chemically distinct from that from the summit, but it also contained abundant sedimentary (mostly calcarenites and sandstones) inclusions (Behncke and Neri, 2003). It was therefore postulated that a new eccentric reservoir, located within the Hyblean Plateau, fed these new flank eruptions (see Fig. 8 in Behncke and Neri, 2003). The 2002–2003 flank eruptions at Mt. Etna volcano were characterised by continuous explosive activity and intermittent lava extrusion, involving the opening of fissures on the north-eastern and southern flanks (Andronico et al., 2005). The magma erupted from the southern fissure during 2002–2003 was found to be similar in composition to that erupted in 2001, and also contained sedimentary xenoliths. It is believed that the 2002–2003 eruptions were fed by the same eccentric reservoir exploited in 2001 (Andronico et al., 2005), albeit the magma travelled to the surface using a new route. Although the lithology of the majority of the erupted xenoliths (in 2001 and 2002–2003) matched more closely with the sediments of the Maghrebian–Appennine Chain, we contend that such renewed activity at depth could have exposed fresh, unaltered carbonate rock of the Hyblean Plataeu to high temperatures. More recently, there was activity renewed at Mt. Etna between 2008 and 2009 (see Alparone et al., 2012 and references therein). However, evidence suggests that, although a new dyking mechanism may be responsible, it would be too shallow to create any new pathways through the Hyblean Plateau (Aloisi et al., 2009).

The geochemical signature of magma-carbonate interaction can sometimes be seen within volcanic products, and is known as "carbonate assimilation" (e.g., Wenzel et al., 2002; Barnes et al., 2005; Gaeta et al., 2006; Piochi et al., 2006; Chadwick et al., 2007; Freda et al., 2008; Deegan et al., 2010; Mollo et al., 2010a). Recent petrological studies have documented in detail that magma contamination is marked by the overgrowth of Ca-rich phases (mainly calcic clinopyroxene) on primary minerals (essentially olivine); as a result, the magma becomes progressively depleted in silica and enriched in alkalis. This results in the release of CO_2 and Ca-rich fluids (Ague, 2003) that are strongly controlled by the development of permeability within the rocks (Balashov and Yardley, 1998; Buick and Cartwright, 2000). Recently, Gaeta et al. (2009) and Mollo et al. (2010a) have provided new insights into the large-scale, magma-carbonate interaction processes occurring in magma chambers during magmatic contamination and differentiation. Mollo et al. (2010a) proposed that carbonate assimilation is a three-phase (solid, melt, and fluid) process whose main products are: diopside-CaTs clinopyroxene solid solution, silica-undersaturated CaO-Al_2O_3-rich melt, and C–O–H fluid phase. Whereas Gaeta et al. (2009) showed that magmatic skarns formed at the magma-carbonate interface act as a source of CaO-Al_2O_3-rich silicate melt and that the assimilation of this melt is the process responsible for magma contamination, rather than the ingestion of carbonate wall-rocks. However, whereas some evidence for the proximity of the carbonate basement to the magma sources at Mt. Etna have been provided in the form of: (1) variably-altered carbonate xenoliths,