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Ductile flow in sub-volcanic carbonate basement as the main control for edifice stability: New experimental insights

Richard R. Bakker [a,*], Marie E.S. Violay [a,b], Philip M. Benson [a,c], Sergio C. Vinciguerra [d,e,f]

[a] *Geological Institute, ETH Zürich, Swiss Federal Institute of Technology, Zürich, Switzerland*
[b] *Laboratory of Experimental Rock Mechanics, Station 18, CH-1015 Lausanne, Switzerland*
[c] *Rock Mechanics Laboratory, School of Earth and Environmental Sciences, University of Portsmouth, United Kingdom*
[d] *Department of Geology, University of Leicester, United Kingdom*
[e] *British Geological Survey, Keyworth, Nottingham, United Kingdom*
[f] *Department of Earth Sciences, University of Turin, Italy*

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ABSTRACT

Limestone in volcanic basements has been identified as a hazard in terms of edifice stability due to the propensity of calcite to decompose into lime and CO_2 at high temperatures (>600 °C), causing a decrease in mechanical strength. To date, such hypotheses have been tested by experiments performed at ambient pressure. The present work determines the mechanical strength of limestone under sub-volcanic conditions of pressure and temperature and evaluates the effect of calcite decomposition. To this end, we use Mt. Etna as a case study, deforming sub-Etnean carbonate samples under triaxial compression using a Paterson deformation apparatus. We evaluate the effect of thermal decomposition of calcite on sample strength by comparing closed and open systems and measuring the permeability evolution under static conditions. Mechanical and micro-structural observations at a constant strain rate of 10^{-5} s^{-1} and at a confining pressure of 50 MPa indicate that the rocks are brittle up to and including 300 °C. At higher temperatures the deformation becomes macroscopically ductile, i.e., deformation is distributed throughout the sample. The brittle to ductile transition is accompanied by an irreversible permeability decrease from $\sim 10^{-17}$ to $\sim 10^{-19}$ m^2 between 200 and 600 °C. We present new evidence that permanent change in permeability is due to ductile processes closing the initial pore space. Samples deformed at temperatures up to 900 °C do not contain any decarbonation products. At these temperatures, permeability is sufficiently low to permit CO_2 pore pressures to increase, thereby increasing local CO_2 fugacity, which in turn strongly limits the decarbonation reaction. We note that, for non-pure calcite rocks, permeability might be sufficient to allow decarbonation reactions to occur. As such, variability in lithologies may slightly influence the efficiency of decarbonation reactions. We conclude that, in a closed system, the instability of Mt. Etna is related to high temperature induced ductile flow of basement limestone rather than chemical/mineralogical changes. This may have important implication for the stability of volcanoes within carbonate-rich basement, as carbonates become significantly weak at high temperatures, which may increase the risk of sector collapse.

1. Introduction

Volcanic edifices are the result of accumulation of deposits from effusive and/or explosive eruptions (Odbert et al., 2015). However, their heterogeneity and rapid growth promote instability: in the worst-case scenario this might result in sector collapse (e.g. Mt. St. Helens, Christiansen and Peterson, 1981). Such instabilities are complex and likely result from the interplay between magmatic processes, active tectonics and gravitational collapse. The consequences of sector collapse are often catastrophic and may subsequently trigger new volcanic unrest. This can take the form of rapid influx of magma, as shown for Soufrière Hills Volcano, Monserrat (Cassidy et al., 2015), or increasing the eruptive potential of a magma due to decompression (e.g. Alidibirov and Dingwell, 1996). For this reason, deformation of volcanic edifices and their basements are actively monitored though varied methods such as GPS (Segall and Davis, 1997; Bonacorso et al., 2011), INSAR (e.g. Hooper et al., 2004) and location of local earthquakes (e.g. McNutt, 2005). These measurements are important in monitoring and forecasting edifice stability and to infer the physical mechanisms taking place in the subsurface.

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* Corresponding author.
E-mail address: richard.bakker@erdw.ethz.ch (R.R. Bakker).

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Previous work has suggested that the overall stability of volcanic edifices is controlled by the properties of their shallow structure along with that of the basement on which they are built (Van Wyk de Vries and Borgia, 1996). A thorough understanding of the subsurface geology in terms of its mechanical behavior of the involved lithologies is therefore critical when attempting to link surface deformation to sub-surface processes. Several volcanic edifices, such as El Chichon, Mexico (Duffield et al., 1984), Merapi, Indonesia (Troll et al., 2012), Vesuvius, Italy (Iacono-Marziano et al., 2009) and Etna, Italy (Mollo et al., 2011; Heap et al., 2013) are built on a carbonate basement. In the case of Mt. Etna, the edifice is made of $< \sim 2$ km thick lavas and pyroclasts unconformably covering a sedimentary basement, which is part of the fold and thrust belt developed at the margin of the Africa promontory during the Neogene Quaternary Europe–Africa convergence (Wiesmaier et al., 2015). This basement comprises a ca. 2 km thick stack of Miocene thrust sheets of clays, sandstones and carbonates, collectively known as the Apenninic–Maghrebian Chain (AMC) (Branca et al., 2011). These thrust sheets rest on the foreland domain, a thick Mesozoic to Mid-Pleistocene carbonate succession, collectively called the Hyblean Plateau (Catalano et al., 2004).

In general, volcanic basements are subjected to anomalously high geothermal gradients, i.e. a relatively shallow rock mass ($\sim$2 km) can be at higher temperatures than normal, ranging between 50–150 °C/km as reported for Icelandic geotherms (Flóvenz and Saemundsson, 1993). This is further enhanced by the existence of dykes and sills carrying magma to relatively cool country rocks, especially in areas where layered media exist of differing mechanical properties (e.g. Gudmundsson and Loetveit, 2005). The lithological contrast between volcanic deposits and basement carbonates, along with the large thermal gradients and complex geological structures at depth, generates a complex strength profile.

Mt. Etna possesses an unstable eastern flank, which has been a topic of extensive study (e.g. Apuani et al., 2013). A combination of different monitoring techniques has revealed large-scale deformation at depth (e.g. Lundgren et al., 2004; Neri et al., 2004), supporting the hypothesis that a large detachment exists at depth (4–5 km) within the carbonates (e.g. Acocella and Puglisi, 2013) and more potential detachment surfaces between 1.5 and 3 km depth (e.g. Palano et al., 2008; Nicolosi et al., 2014). To further our understanding of the carbonate basement of Mt. Etna, recent studies have conducted rock deformation experiments (e.g. Mollo et al., 2011; Heap et al., 2013; Wiesmaier et al., 2015). Whilst such data are important to gain first order insights into the mechanical processes of the sedimentary units beneath Mt Etna, the experiments of the aforementioned studies were conducted under uniaxial conditions (i.e. room pressure). To obtain a more complete understanding, such studies need to be extended to higher pressure and temperature conditions. However, these are difficult to obtain due to the challenging pressure and temperature conditions that exist in volcanic areas (e.g. Flóvenz and Saemundsson, 1993).

From a thermo-chemical perspective, carbonate rocks are prone to thermal decomposition by the breakdown of calcite when exposed to temperatures over 600 °C (Rodriguez-Navarro et al., 2009); such temperatures are easily reached in volcanic settings. This process is known as decarbonation and implies the decomposition of calcite ($CaCO_3$ into lime (CaO) and carbon dioxide (CO_2) (Mollo et al., 2013 and references therein). The expelled carbon dioxide can potentially enrich nearby magmatic bodies (e.g. Marziano et al., 2007; Chiodini et al., 2011) contributing to the overall CO_2 decarbonation, which is considered a reliable marker of impending eruptions (e.g. Aiuppa et al., 2006). Furthermore, CO_2 can build up directly as local pore pressure, changing the effective confining pressure and subsequently affect the mechanical behavior of the sample. For example, as the brittle ductile transition is pressure dependent, a reduction in effective confining pressure could cause a switch from ductile to the brittle regime. Such mechanisms subsequently change the strength of the volcanic edifice in general. In any case, the key parameter controlling the pore pressure is the permeability, which indirectly determines how easily the gas can escape from the rock. Permeability is notably affected by deformation during which the internal structure of rocks is modified (e.g. Fischer and Paterson, 1992; Zhu and Wong, 1997). Furthermore, deformation is changed by elevated pore pressure as the effective stresses are reduced. Local pore pressures may significantly increase when the permeability is low, especially in the case of isolated pores (e.g. Zhang et al., 1994).

Previous studies have investigated the effect of temperature on the strength of carbonate rocks from the basement of Mt. Etna, but they have been limited to unconfined conditions (Mollo et al., 2011; Heap et al., 2013). In Mollo et al. (2011), brittle behavior was seen in all experiments up to 760 °C, with a noticeable trend of decreased total strain before failure as temperature increased. Conversely, Heap et al. (2013) reported brittle–ductile transition (BDT) at approximately 550 °C. In this work, the BDT is defined as the transition from a loss of strength during strain accumulation to strain accumulation without loss of strength (see Byerlee, 1968 and Rutter, 1986). Both Mollo et al. (2011) and Heap et al. (2013) indicate thermal decomposition by the presence of the mineral portlandite in post-test sample analysis, which itself formed due to lime reacting with ambient water. To confirm this observation, Mollo et al. (2012) studied thermal decomposition within a closed system (i.e. no free outflow of CO_2) by controlling the carbon-dioxide fugacity during experiments. They found that decarbonation is arrested in a closed system and argued that closed systems might not be realistic due to thermal microcracking, whereby any CO_2 produced would likely escape through the enhanced permeability due to the microcracks. However, these experiments were conducted at ambient pressure (an effective pressure of zero) in the CO_2 fugacity experiments (Mollo et al., 2012). Therefore, these results may not reflect the process at depth where confining pressure, temperature and differential stresses would influence the physio-mechanical behavior of the rock mass.

One of the most extensively studied rocks for which reliable mechanical data exists are carbonates (e.g. Rutter, 1995; Renner and Evans, 2002). Many experiments have focused on single crystals or single-phase aggregates of typical minerals such as calcite (e.g. Wang et al., 1996; De Bresser and Spiers, 1997). However, deformation of a natural assemblage from a volcanic area have received less attention in literature. The goal of this study is to extend the previous work to high confining pressure and temperatures. Moreover, we aim to better understand how elevated pressure/temperature conditions affect the rheological behavior of carbonates and investigate the thermo-chemical reaction in the carbonates beneath the Etnean volcanic system. The work focuses on a temperature range from 25 °C to 900 °C and confining pressures from 50 to 100 MPa (depth equivalent 2–4 km). We additionally assess how high temperatures may modify the permeability of sub-volcanic carbonates.

2. Material and methods

2.1. Sampling material

We used Comiso Limestone (hereafter CL), part of the large succession of thick Mesozoic to Mid-Pleistocene carbonates of the foreland area (Hyblean Plateau, Fig. 1). Cross sections suggest that the CL can be found at 4–6 km below Mt. Etna's peak (Branca et al., 2011), although rock types similar to CL may occur at shallower levels whereas large carbonate lenses are also known in the subsurface units (Wiesmaier et al., 2015).