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The evolution of elastic moduli with increasing crack damage during cyclic stressing of a basalt from Mt. Etna volcano

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ABSTRACT

Volcanic edifices, such as Mt. Etna (Italy), are commonly subject to repeated cycles of stress over time due to the combination of magma emplacement from deep reservoirs to shallow depths and superimposed tectonic stresses. Such repeated stress cycles lead to anisotropic deformation and an increase in the level of crack damage within the rocks of the edifice and hence changes to their elastic moduli, which are a key parameter for reliable modelling of deformation sources. We therefore report results of changes in elastic moduli measured during increasing amplitude cyclic stressing experiments on dry and water-saturated samples of Etna basalt. In all experiments, the Young's modulus decreased by approximately 30% over the total sequence of loading cycles, and the Poisson's ratio increased by a factor of approximately 3 ± 0.5. Microseismicity, in terms of acoustic emission (AE) output, was also recorded throughout each experiment. Our results demonstrate that AE output only re-commences during any loading cycle when the level of stress where AE ceased during the unloading portion of the previous cycle is exceeded; a manifestation of the Kaiser stress-memory effect. In cycles where no AE output was generated, we also observed no change in elastic moduli. This result holds for both mechanical and thermal stressing. Our results are interpreted in relation to measurements of volcano-tectonic seismicity and deformation at Mt. Etna volcano.

1. Introduction

Elastic moduli are the key parameters for defining relationships between stress and strain. They determine the distribution and magnitude of sub-yield stresses, the propagation velocity of elastic (seismic) waves and can be used to relate strain measurements to in-situ stresses within the Earth's crust. In volcanic regions, reliable estimates of mechanical properties and their degradation under multiple episodes of stressing are crucial to the accurate modelling of routinely monitored data such as ground deformation, and the calibration of damage-mechanics criteria for the weakening of rocks forming volcanic edifices.

Mt. Etna is Europe's largest volcano, and one of the most active on Earth. It lies near the eastern (Ionian) coast of Sicily (Italy) (Fig. 1). Mt. Etna is a stratovolcano formed by the superposition of several volcanic edifices, has a volume of at least 350 km^3 and a height of about 3300 m. It is one of the most densely monitored volcanoes on the planet and has a documented record of eruptions extending to several centuries BC. The geological and structural complexity of Mt. Etna means that the mechanisms by which magma rises to the surface and drives volcanic eruptions are still not fully understood. However, volcanic activity on Mt. Etna may be divided into two main types: (1) persistent activity with episodic paroxysmal events, which generally occurs at or near the summit and is not preceded by seismic precursors (e.g. Lombardo and Cardaci, 1994), and (2) cycles of hazardous flank eruptions (Guest, 1982), which are preceded by intense seismic activity (Castellano et al., 1997; Vinciguerra et al., 2001), often including shallow destructive earthquakes (Azzaro et al., 2000), which indicates the acceleration of brittle failure mechanisms (Patanè et al., 2004). Over the last 20 years, new technological developments and denser monitoring networks at Mt. Etna volcano have provided one of the highest quality volcanological, geophysical and geochemical data sets for any volcano in the world (Bonaccorso et al., 2004a). Following the 1991–1993 eruption, the largest effusive eruption of the 20th century (Patanè et al., 1996), the volcano has experienced a cycle of intense activity (Allard et al., 2006 and references therein) evolving from (1) initial recharging of the plumbing system and inflation, to (2) powerful summit eruptions and, finally, to (3) a sequence of flank eruptions accompanied by major slip of the eastern flank and intense fracturing. In this framework, pre-eruptive patterns defined from seismic fault plane solutions and deformation events (Bonaccorso et al., 1996; Patanè et al., 2003, 2006) suggest that magma intrusion has induced strike-slip faulting within a strongly anisotropic stress field. Importantly, a number of field and monitoring based studies have revealed that open fissures were formed first, and magma was then extruded thorough

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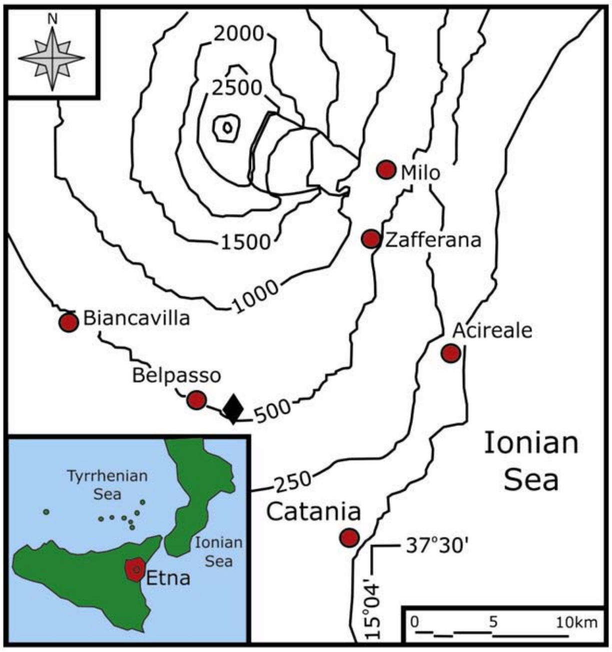

Fig. 1. Location map of Mt. Etna showing main towns and morphological features. The solid diamond indicates the position of the quarry from which the EB test material was collected.

these fissures at a later stage (Tibaldi and Groppelli, 2002; Branca et al., 2003; Alparone et al., 2004; Carbone and Greco, 2007).

Taken together, these observations suggest that repeated episodes of deformation can lead, through brittle mechanisms, to an increase in the level of crack damage within the rocks of the edifice, and hence to changes in their elastic moduli. Furthermore, quantifying the mechanical properties, such as the elastic moduli and strength, of the rocks constituting Mt. Etna volcano's edifice is of key importance in establishing the reliability of modelled deformation sources. This is because values for the elastic moduli (in particular Young's modulus and Poisson's ratio) are essential input parameters for such models. Previous studies of Mt. Etna volcano have assumed fixed values of Young's modulus ranging from 50 to 100 GPa and a Poisson's ratio of 0.25 (Cayol and Cornet, 1998; Bonaccorso and Davis, 1999).

Basaltic rocks from Mt. Etna volcano have been the subject of a number of mechanical studies in recent years. In an attempt to characterize fracture propagation, Ciccotti et al. (2000) measured mode I subcritical crack growth parameters. Also, quantitative investigations of lava flow fracturing dynamics have been pursued through mechanical tests in both tension (Balme et al., 2004) and compression (Rocchi et al., 2004) at high temperatures and low pressures. Under compression, their extrusive basalt exhibited a low strength of around 100 MPa that varied little with confining pressure, and a low Young's modulus around 40 GPa at temperatures up to 600 °C. Above this temperature both strength and elastic modulus were observed to decrease even further (Rocchi et al., 2004). Investigations of the physical properties of the basalt used in this study have yielded unexpectedly low ultrasonic wave velocities and unexpectedly high fluid permeability. Both observations have been attributed to the presence of a high level of connected pre-existing microcrack damage (Vinciguerra et al., 2005). Such microcracks are interpreted as being of thermal origin, since values of physical properties are not affected by further thermal stressing (Vinciguerra et al., 2005).

Numerous experimental studies have also shown that, generally for crystalline rocks, the level of microcrack damage greatly influences both static (Alm et al., 1985; Martin and Chandler, 1994; Eberhardt et al., 1999; Lau and Chandler, 2004; Heap and Faulkner, 2008) and dynamic (Birch, 1960, 1961; Walsh, 1965; Anderson et al., 1974; O'Connell and Budiansky, 1974; Soga et al., 1978; Ayling et al., 1995; Sayers and Kachanov, 1995; Guéguen and Schubnel, 2003; Reuschlé et al., 2003; Fortin et al., 2005; Takemura and Oda, 2005) elastic moduli. Therefore, each stress cycle within a volcanic edifice can result in an increase in the level of crack damage, as evidenced by the output of seismic energy.

Here, we report results from an experimental study in which we measured the degradation of elastic moduli during cyclic stressing of samples of an extrusive basalt from Mt. Etna volcano to increasing levels of maximum stress. Acoustic emission (AE) output was recorded continuously during each cycle of each experiment as a proxy for the onset of increasing crack damage.

2. Material investigated and experimental methodology

The most representative basalt from Mt. Etna volcano is a porphyritic, intermediate, alkali basalt (Tanguy et al., 1997). The Etna basalt used in this study (collected from the location indicated in Fig. 1, and hereinafter called EB) has a bulk density of 2700 kg m^{-3}, a connected porosity (measured with a helium pycnometer) of 4.4% and a total porosity of 4.8%. It is composed of a fine-grained groundmass (~60%), with crystals of feldspar (25%), pyroxene (8.5%) and olivine (4%). In its as-received state, EB has an anomalously low ultrasonic *P*-wave velocity for basalt of approximately 3.2 km s^{-1}, which exhibits essentially zero anisotropy under ambient laboratory conditions. These characteristics have been attributed to an extensive pre-existing network of interconnected microcracks of thermal origin, caused by the relatively fast cooling rates of Mt. Etna lava flows (Vinciguerra et al., 2005).

In this study, increasing-amplitude, stress-cycling experiments were performed on both oven-dry (at 80 °C, see Glover et al., 1995) (hereinafter referred to as 'dry') and water-saturated (hereinafter referred to as 'wet') samples of EB to investigate the evolution of crack damage and elastic moduli during cyclic loading. All samples were cored from the same block of material to a diameter of 25 mm and were precision-ground to 75 mm in length, resulting in a length:diameter ratio of 3:1 (Mogi, 1966; Hawkes and Mellor, 1970). All experiments were performed in a servo-controlled, uniaxial loading frame and were conducted at room temperature. Axial and radial strains were continuously monitored throughout each experiment using displacement transducers. Output of AE energy, used as a proxy measure for the onset of new crack damage, was recorded by a MISTRAS-2001 AE recording system via a broadband PZT piezoelectric AE transducer located inside the bottom loading anvil (Fig. 2). The AE transducer has a high response band over the range from 100 kHz–1 MHz and data was recorded at a sampling rate of 10 MHz. Cumulative AE energy was calculated by summing the envelope of each AE waveform (see Cox and Meredith, 1993 for a detailed description of the AE recording methodology). The experimental arrangement is shown in Fig. 2. A series of constant strain rate (7.0×10^{-6} s^{-1}) experiments were performed on dry samples of EB prior to the stress-cycling experiments in order to determine the unconfined compressive strength (UCS). This is required to guide the choice of the amplitude and frequency of cycles during stress-cycling experiments.

During the increasing-amplitude stress-cycling experiments, samples were first loaded to a maximum stress of 20 MPa at a controlled strain rate of 7.0×10^{-6} s^{-1}, and then unloaded at the same rate to 8 MPa. In each subsequent cycle the maximum stress was increased by 10 MPa, and samples again unloaded to 8 MPa. Stress-cycling was continued in this way until samples eventually failed. Fig. 3 shows an example of a loading path for a dry sample that failed on the 14th loading cycle.

3. Results

Fig. 4 shows the stress-strain curves from one of a series of constant strain rate experiments on EB that yielded a mean UCS of 140 ± 5 MPa.