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The strength and permeability of tuffisite-bearing andesite in volcanic conduits

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Abstract

Tuffisites result from volcanically-induced subsurface fragmentation, transport and deposition, and are common in explosive volcanic environments. Their study provides direct insight to explosive volcanic processes operating within volcanic conduits. Here we report the influence of tuffisite veins on the fundamental physical properties of andesitic rocks. We find that: (1) strength is unaffected by the presence and/or orientation of tuffisites, (2) permeability doubles when tuffisites are oriented favorable (45 degrees to fluid flow), and (3) seismic wave velocities show a continuous increase with depth, independent of vein orientation. Although the influence of tuffisites on andesitic rock properties is modest, we emphasize that the material tested represents the post-eruptive state of tuffisite. Thus, these results delineate the upper boundary of strength and lower boundary of permeability and porosity. All evidence suggests that tuffisites become compacted and lithified on relatively short time scales, restoring the strength of the rock to their initial host rock values.

1 Introduction

Tuffisites are veins comprising lithified mixtures of particles of juvenile volcanic material interspersed and intimately mixed with host rock fragments of similar size (Cloos, 1941). These veins represent cracks and crevices formed within the subsurface host rocks and/or within the magma itself that are simultaneously in-filled by transportation and deposition of material (juvenile and lithic) deriving from subsurface fragmentation. They are common to many exhumed volcanic environments and provide direct evidence of the subsurface processes operating in the conduit during explosive eruptions (Lavallée et al., 2012a).

Tuffisites have been described over a wide range of chemical composition and diverse volcanic environments, from basaltic diatremes (Cloos, 1941) to andesitic fossil conduits (Noguchi et al., 2008) and rhyolitic conduits (Tuffen et al., 2003). The fragmental nature of tuffisites suggests that their formation will increase the porosity and permeability and reduce the strength of otherwise competent country rock. Ultimately, the strength of the conduit filling material and the properties (e.g. permeability) of the enclosing conduit wall rocks are key properties governing both eruption style effusive or explosive; (Collinson and Neuberg, 2012; Kennedy et al., 2010) and eruption dynamics catastrophic or continuous; (Taisne and Jaupart, 2008). Here we present the first experimental study on the permeability, porosity, uniaxial compressive strength (UCS), and P-and S-wave velocities (V_p and V_s) of andesite containing tuffisite veins.

2 Experimental materials and methodology

2.1 Experimental materials

The 2005 eruption of Volcán de Colima in Mexico disrupted parts of the lava domes sitting in the upper eruptive conduit (Lavallée et al., 2012b) and provided a unique opportunity to collect tuffisite-bearing andesite from an active volcano. The host rock is a coherent porphyritic andesite. The phenocryst assemblage (Fig. 1) comprises 30 vol. % plagioclase (0.2 to 2.5 mm length), 10 vol. % pyroxene (0.1–to 2 mm diameter), and less (~5 vol. %) (average 0.1 mm) opaque oxides. The groundmass comprises needle shaped, microcrystalline plagioclase (average 25 vol. %), pyroxene (average 15 vol. %), opaque oxides (average 10 vol. %) and minor (average 5 vol. %) interstitial glass. The bulk porosities for all samples of andesite with and without veins range from 7.8 % to 11 % (Table 1).

The thicknesses of the tuffisite veins vary from approximately 3 to ca. 50 mm. The veins consist of fully crystalline fragmental material. Petrographic analysis shows the tuffisite is devoid of glass, dominated by ~80 vol. % fragments of crystals (plagioclase, pyroxene and opaque oxides) between 0.25 mm and 1 mm, and contain lesser (~ 20 vol. %) amounts of larger (3 to 20 mm), comminuted and rounded lithic clasts of varying composition. Neither devitrification textures nor shapes suggestive of glass shards are present, therefore this tuffisitic material is a true product of the fragmentation of a crystalline solid. The absence of volcanic glass was confirmed by dilatometric measurements of tuffisite vein material; samples were heated to 1000 °C at a rate of 10 °C min^{-1} and show a linear expansion in length suggestive of crystalline material and no softening characteristic of glass. The diversity of lithic clasts suggests that the vein material is a mixture of autochtonous and allochtonous material (see Fig. 1).

From these samples, cylindrical (25 mm diameter and 50 mm length) cores were drilled perpendicular and at an angle ∼45° to the tuffisite veins. Orienting the tuffisite vein at 45 degrees allows for preferred stress concentration along the tuffisite veins during compression. The orientations of the tuffisite veins are somewhat irregular and the actual angles may vary from the reported values by ±5°. The sample core ends were ground flat in order to reduce edge effects during deformation.

2.2 Hydrostatic experiments

Sample porosity, permeability, and ultrasonic wave velocity measurements were made under increasing confining pressures in a 300 MPa hydrostatic pressure vessel equipped with two 70 MPa servo-controlled pore fluid intensifiers or volumometers located in the Rock & Ice Physics Laboratory (RIPL) at University College London (UCL). We have selected one tuffisite-free core sample (from the same tuffisite-bearing block) to serve as a baseline for comparison (COL-TUF-CR). Four andesite samples having similar connected porosities (see Table 1) were carefully selected for experimentation: two cores contain tuffisites oriented perpendicular to the flow direction (COL-TUF-P2 and –P3) and two have veins oriented at 45 degrees to the flow direction (COL-TUF-A1 and –A2). On that basis, we suggest that any differences in their measured physical properties should therefore be related solely to the orientation of the tuffisites. The effects of sample heterogeneity are therefore of second order.

The two volumometers were used in an “upstream” and “downstream” configuration, with a 1 MPa pressure difference across the jacketed sample to provide the flow required to calculate permeability using Darcy’s law, once steady-state flow had been established. For the experiments in this study, the pore pressure was kept at 9.5 and 10.5 MPa in the two pore pressure intensifiers, respectively. Confining pressure was applied by pumping silicon oil into the pressure vessel at 15 MPa, 20 MPa and then every 10 MPa increment up to 60 MPa, yielding effective confining pressures (P_{eff}) between 5 and 50 MPa. For the purpose of this study we apply the simple effective pressure law of $P_{\mathrm{eff}} = \mathrm{Pc} - \alpha \mathrm{Pp}$, assuming that $\alpha = 1$ (Guéguen and Palciauskas, 1994). The permeability was re-measured for each pressure increment, together with ultrasonic wave velocities, and sample porosity. Ultrasonic wave velocity measurements were made via piezoelectric P- and S-wave transducer crystals housed within each of the sample end caps using a Agilent Technologies 1.5GHz “Infiniium” digital storage oscilloscope and a JSR DPR300 35MHz ultrasonic pulser/receiver.

The sample porosity was calculated by: (1) isolating one of the pore pressure intensifiers from the sample, (2) setting the open pore pressure intensifier to 10 MPa and allowing the sample time to equilibrate, and (3) increasing the confining pressure whilst monitoring the displacement of the open pore pressure intensifier. The porosity was then recalculated using the volume of water expelled from the rock (e.g. Benson et al., 2005). Finally, we converted our values of P_{eff} into depths (h) using the simple relationship $P_{\mathrm{eff}} = \rho g h$, where ρ is the density (reported in Table 1) and g is the acceleration due to gravity.

2.3 Strength experiments

The uniaxial compressive strength (UCS) experiments were carried out in the high temperature uniaxial press, described in detail by (Hess et al., 2007), at Ludwig-Maximilians University in Munich (LMU). Reubi and Blundy (2008) and Savov et al. (2008) estimated pre-eruptive temperatures between 960 and 1020 °C for the Colima andesite. Our experimental investigation of bulk rock strength, and the mechanisms of deformation, of tuffisite-bearing and tuffisite-free samples was, therefore, carried out at 940 °C so that we approximate the minimum pre-eruptive temperatures in the volcanic conduit. A heating rate of 1 $^{\circ}\mathrm{C\,min}^{-1}$ per minute was applied until we reached the target temperature. The sample temperature was monitored via a thermocouple that was inserted into the sample. Once the temperature was reached the upper piston was brought into contact with the sample and the sample was allowed to thermally re-equilibrate for one hour. The experiments started at a low compressive stress of 3 MPa after which the samples were loaded at a constant stressing rate of 2 MPa min^{-1} until failure. Simultaneously, the output of AE energy was monitored throughout via two piezoelectric transducers with a high response band over the range 100 kHz–1 MHz. AE signals were recorded by a PC1-2 based MISTRAS fast data-acquisition system at a sampling rate of 10 MHz.

3 Results

3.1 Hydrostatic experiments

Our experimental results are summarized in Fig. 2 by plotting the measured values of permeability, P- and S-wave velocity, and porosity against the model depth (consistent with the experimental confining pressure). The data include measurements on samples with tuffisites at 45 degrees or perpendicular to the flow direction and on andesite without tuffisite veins. The plot shows that, as depth (i.e. P_{eff}) increases, both P- and S-wave velocities increase (Fig. 2b) whilst the permeability (Fig. 2a) and porosity (Fig. 2c) both decrease. Over the pressure range of 50 MPa (i.e. 200–1800 m depth) the samples show a ∼20 % increase in ultrasonic wave velocities and a ∼5 % decrease in porosity. Permeability values show a different pattern. The samples having tuffisite veins perpendicular to flow have permeability values within the same range as the host-rock, tuffisite-free andesite. However, the permeability of samples having tuffisite veins oriented at 45 degrees to fluid flow (the two dashed lines on the right of the plot) show a strong (more than double) decrease in permeability at depths >220 m. Specifically, as depth increases, the permeability of these samples decreases markedly and converges with permeability values of all other samples at depths of ∼2 km.

3.2 Strength tests

The results of our high-temperature UCS tests are summarized by plotting, both, stress and cumulative AE energy (ΣAE) against cumulative strain (Fig. 3). The data show that as the samples deform under increasing stress there is little deviation from linear elastic behaviour and very little AE until immediately prior to the peak stress. While approaching peak stress, all samples reach a yield point within the last 0.2 % strain. Ultimately the samples fail catastrophically which is accompanied by a large, and sudden stress drop and a dramatic increase in AE rate, characteristic of brittle behaviour. The UCS for each sample is reported in Table 1. This experimental dataset for andesite hosting tuffisite veins (Fig. 3) establish that at high temperatures: (1) the deformation behaviour remains brittle, and (2) the UCS of the andesites is unaffected by the presence and orientation of the tuffisite veins. The UCS was found to be constant within 24 MPa (17 % of the peak stress).

4 Discussion

We have provided benchmark experimental data on the influence of tuffisite veins on the physical properties of andesite. Our experiments have demonstrated that porosity and permeability decrease, and ultrasonic wave velocities increase, as depth is increased. In detail, at a depth of about 2 km, the permeability is reduced by about one order of magnitude, whereas ultrasonic wave velocities and porosity increase by 20 % and decrease by 5 %, respectively. The physical properties are largely unaffected by the presence and orientation of the tuffisite veins, although those with veins oriented at 45 degrees to the flow direction are about twice as permeable at shallow depths. The reduction in porosity and permeability, and the increase in ultrasonic wave velocities, with increasing depth can be explained by the closure of pre-existing microcracks (Vinciguerra et al., 2005). Indeed, andesites from Volcán de Colima have been previously shown to contain a pervasive network of microcracks (Petrakova et al., 2012). Despite the textural diversity of the andesite-tuffisite sample cores, our experiments document a profound homogeneity in UCS (about 125 MPa).

We take these data as evidence that these rocks have healed and approached porosities, permeabilities, and strengths close to the initial properties of the erupting magma. The holocrystalline nature of these rocks precludes recovery and lithification by the processes that govern welding of other volcanic rocks i.e. healing via relaxation of melts: e.g. (Quane and Russell, 2005). Other potential processes include, for example hot pressing (Olgaard and Fitz Gerald, 1993), solid-state diffusion (Venkatachari and Raj, 1986) and precipitation of minerals from fluids (Taran et al., 2001) as these fragmented materials are subject to significant pressures, elevated temperatures and circulating fluids while residing in the volcanic edifice. Indeed, hot pressing at magmatic temperatures has been shown to almost annihilate any porosity in ceramics on the timescale of hours (Venkatachari and Raj, 1986; Wang et al., 2002). Independent of which process is dominant, we find that tuffisites can recover their original rock properties. The proposed recovery mechanisms can act on relatively short timescales (Ben-David et al., 2010; Olgaard and Fitz Gerald, 1993; Russell and Quane, 2005; Venkatachari and Raj, 1986) and we therefore speculate that tuffisites spend most of the time in the edifice in this recovered state.

The average grain-size of the particles in the tuffisites is 250 microns with the largest particles being as large as 20mm and the smallest in the micron range. Studies of granular material having comparable particle size distributions report porosity values between 17 and 27 % (Zou et al., 2011). Shepherd (1989) describes the permeability of materials with similar grain sizes and varying degrees of consolidation to be between 10^{-10} and 10^{-13} m^2. We suggest that the values for porosity and permeability of the tuffisite veins themselves immediately after formation should be within these ranges. The implication is that the samples tested in this study have undergone a porosity reduction of at least 9 percentage points and a decrease in permeability of four orders of magnitude. The timescales for this recovery process may be in the range of hours or days (Venkatachari and Raj, 1986). Any major influence tuffisite veins can have on the eruptive behaviour is therefore restricted to the time period between fragmentation and healing.

5 Conclusions

1. At eruptive temperatures (940 °C) the tested tuffisite-bearing andesites deform in a strictly brittle manner and their UCS is independent of presence and/or orientation of tuffisite veins.
2. The permeability of tuffisite-bearing andesite is dependent on the orientation of tuffisites and depth. Whereas the samples with tuffisites perpendicular to flow lie within the same range as the country rock, the permeability of the samples with tuffisites at 45 degrees to fluid flow doubled. In all samples the permeability decreases with increasing depth.
3. Our results report the physical properties of tuffisites in a recovered state and therefore the upper limit of UCS and the lower limit of permeability. At the point of formation and during the recovery process these rocks might be weaker and more permeable and therefore have a different effect on the eruptive behaviour.

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Table 1. Physical properties of the sample collection.

sample name	mean density (g cm^{-3})	porosity (%)	UCS at 940 °C (MPa)
COL-TUF-CR	2.7867	7.76	114.5
COL-TUF-P2	2.7828	9.07	119.1
COL-TUF-P3	2.812	9.83	123.9
COL-TUF-A1	2.7986	8.81	127.0
COL-TUF-A2	2.8648	10.97	138.4

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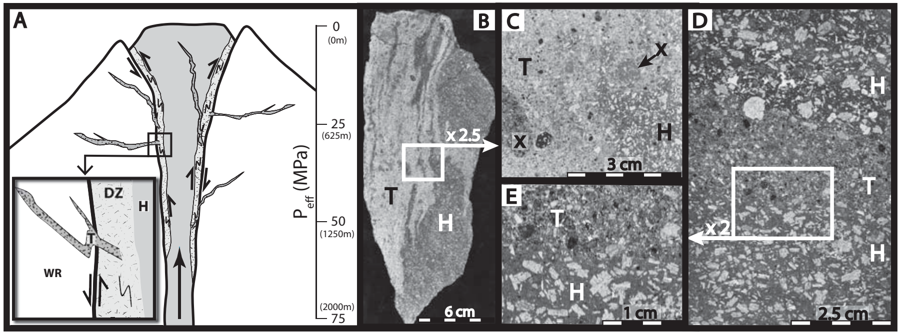

Fig. 1. **(A)** Cartoon of a dome building eruption showing the occurrence of tuffisite veins in volcanic edifices. (tuffisite veins have been reported near the surface (Tuffen et al., 2003) and up to more than 500 m depth (Heiken et al., 1988)) **(B)** Photograph of a slab cut from a tuffisite (T) bearing sample of andesite (H) from Colima, Mexico. **(C)** Scanned thin section prepared from the slab in **(B)** showing rounded lithic clasts (X). **(D)** Scanned thin section of an approx. 1 cm wide tuffisite vein. **(E)** Zoom on the interface between host rock (H) and tuffisite (T).

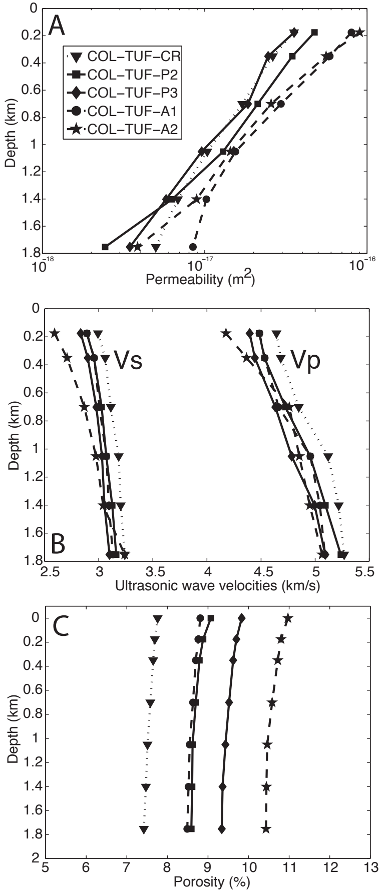

Fig. 2. **(A)** Depth vs. log of permeability showing a similar evolution for all samples over depth. At depths shallower than 1 km the permeability for samples with tuffisite veins oriented at 45 degrees to flow doubles relative to the samples with tuffisite veins oriented perpendicular to flow. **(B)** Depth vs. ultrasonic wave velocities showing similar evolution of both Vp and Vs with depth for all samples. **(C)** Depth vs. porosity showing similar evolution of porosity with increasing depth for all samples.

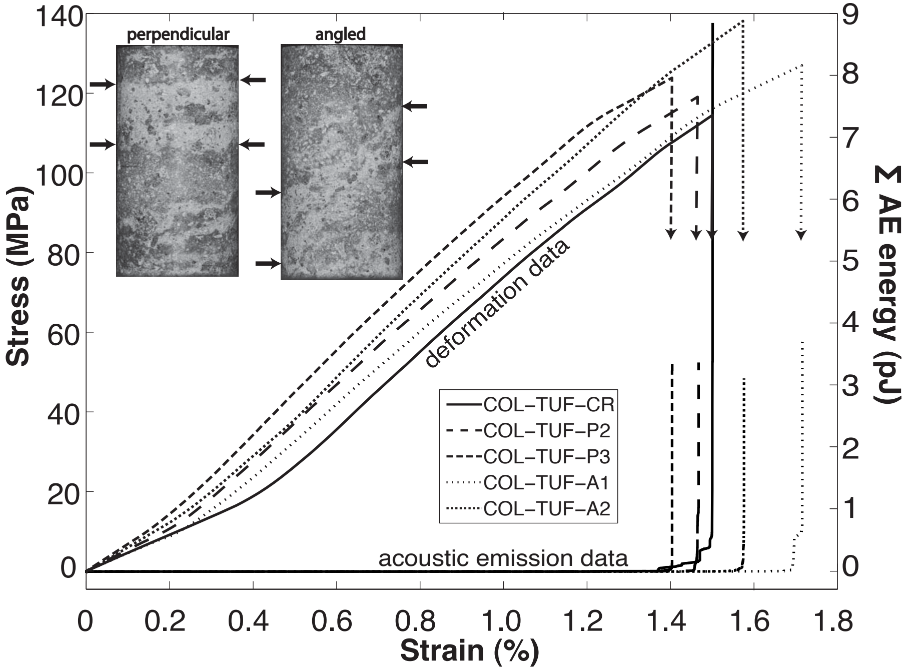

Fig. 3. Plots of stress vs. strain and cumulative AE energy (ΣAE) against strain for constant loading experiments on andesite free of tuffisite (COL-TUF-CR), with tuffisite at 45° (COL-TUF-A1 and -A2) and perpendicular (COL-TUF-P2 and -P3) to sigma 1. The UCS for all samples are constant within 17 % of the maximum UCS. Inserts show examples of core samples with tuffisites at 45 degrees and perpendicular to compression. Arrows indicate the top and bottom boundaries of tuffisite veins.