Physical and Mechanical Properties of Thermally Cracked Andesite Under Pressure

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Abstract

The effects of thermal crack damage on the physical properties and rupture processes of andesite were investigated under triaxial deformation at room temperature. Thermal cracking was induced by slowly heating and cooling samples. The effects of heat treatment temperatures ranging between 500 °C and 1100 °C on the P-wave velocities and on the microstructure were investigated. Then, the mechanical properties of andesite samples treated at 930 °C were investigated under triaxial stress at room temperature using constant strain rate tests and confining pressures ranging between 0 and 30 MPa. Similar triaxial experiments were conducted on non-heat-treated samples. Our results show that: (1) for heat treatments at temperatures below 500 °C, no significant changes in the physical properties are observed; (2) for heat treatments in the temperature range of 500–1100 °C, crack density increases; and (3) thermal cracking has no influence on the onset of dilatancy but increases the strength of the heat-treated samples. This last result is counterintuitive, but seems to be linked with the presence of a small fraction of clay (3%) in the non-heat-treated andesite. Indeed, for heat treatment above 500 °C, some clay melting is observed and contributes to sealing the longest cracks.

Keywords Andesite · Thermal crack · Ultrasonic velocity · Crack density · Onset of dilatancy · Brittle Strength · Partial melting · Crack sealing

List of Symbols

ϵ_a	Axial strain
ϵ_r	Radial strain
ϵ_v	Volumetric strain
Q	Differential stress
S	Total surface of crack
ϕ	Crack porosity
P_c	Confining pressure
σ_1	Maximum principle stress
σ_3	Minimum principle stress
ρ	Crack density
l_i	Length of the i -th crack
N	Total number of cracks embedded in the representative elementary volume V
V	Representative elementary volume
E	Young's modulus of the (intact) andesite
ν	Poisson's ratio of intact andesite
G_{IC}	The energy release rate of andesite under mode I

$\Delta\alpha$	Thermal expansion contrast between plagioclase and quartz/tridymite or glass	39
ΔT	Temperature difference of heat treatment	41
l	Grain size	42
w	Crack half aperture	43
c	Crack radius	44
ξ	Aspect ratio	45
C'	Onset of dilatancy	46
μ	Friction coefficient on pre-existing flaws	47
K_{IC}	Fracture toughness	48
a	Length of pre-existing flaws	49
D_0	Initial damage	50
N_V	Number of sliding cracks initially	51

1 Introduction

The physical properties and mechanical behavior of andesite are of interest for the understanding of several natural processes and for engineering design. Natural processes include ground deformation due to magma rising below volcanoes (Jaupart 1998; Costa et al. 2009; Heap et al. 2014), eruption activity and cessation of dikes (Gudmundsson 2006, 2011;

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Browning et al. 2015), or fault activity in volcano systems (Rowland and Sibson 2001). Industrial contexts are geothermal reservoir engineering (Siratovich et al. 2014) and CO₂ sequestration (Trias et al. 2017).

In volcanic areas, where hot fluids circulate, temperature is a parameter that should be taken into account when investigating mechanical behavior. Temperature variations can induce intragranular cracks and intergranular cracks or even melting of the rock (Friedman et al. 1979; Wong 1989), leading to large changes in the microstructure. A common way to investigate the effect of temperature on the mechanical behavior is to use heat-treated samples.

Many studies have been performed on the role of thermal effects in the mechanical behavior of igneous rocks, including intrusive and extrusive rocks (Heap et al. 2016, 2014, 2015; Vinciguerra et al. 2005; Fortin et al. 2011; Stanchits et al. 2006; Meredith et al. 2005; Wang et al. 2013). Increasing temperature can modify fluid transport properties (Vinciguerra et al. 2005; Nasser 2009; Faoro 2013; Darot 2000; Geraud 1994), elastic wave velocities (Walsh 1965; Nasser 2007), and mechanical properties (Faulkner et al. 2003; Wang et al. 2013). Thermal cracking has been shown to weaken different rocks, including granite (Homand-Etienne and Houpert 1989; Chaki et al. 2008), gabbro (Keshavarz et al. 2010), calcarenite (Brotóns et al. 2013), and carbonate (Sengun et al. 2014). P-wave velocity changes due to thermal cracking are expected. Such changes are important for seismic tomography inversion of volcano systems and may be useful for investigating magma chamber activity and dike eruption. According to Griffith et al. (2017) and Browning et al. (2016), more cracks are created during the cooling stage than during the heating stage.

In contrast with intrusive rocks, extrusive rocks have a different structure resulting from fast cooling: a fine groundmass and phenocrysts. Note that the ultrasonic velocities and transportation properties of andesite have been investigated in previous studies (Fortin et al. 2011; Fatquharson et al. 2015; Heap et al. 2014, 2015; Siratovich et al. 2015; Heap and Kennedy 2016).

The selected rock for this study is an andesite from Guadeloupe, France. Guadeloupe is located in the Lesser Antilles arc. This arc results from the subduction of the North American Plate under the Caribbean Plate (Bouysse et al. 1990). The Bouillante (Guadeloupe, France) geothermal power plant has been operating for 30 years (Jaud and Lamethe 1985). GEOTREF (A project aimed at improving understanding fractured geothermal reservoirs) is planning a new geothermal project in the area from which the samples were taken. Faults and active fluids are present in the volcano system and cause significant seismicity activity (Feuillet et al. 2001, 2002). Because induced seismicity is possible during geothermal exploration, it is important to systematically determine the geomechanical behavior and

to characterize its evolution resulting from thermal stresses. This paper aims to investigate the effect of heat treatment on the mineralogical composition, microstructural parameters (porosity, crack density), and petrophysical parameters (permeability, elastic wave velocities) of andesite. For this purpose, we selected an andesitic block from a quarry located in Guadeloupe, France, and samples were heat-treated at different temperatures. Then, petrophysical and mechanical properties were measured.

2 Materials and Methods

2.1 Materials

2.1.1 Rock Samples

The samples of andesite were cored from a single block, which was obtained from a quarry located in Déhaies (Guadeloupe, France). Cylindrical samples were cored with diameters of 40 mm and lengths of 80 mm. No bedding related to volcanic features was identified in the block. After coring, boundary surfaces were polished to ensure smooth horizontal surfaces.

The samples have a mean density of 2670 kg/m³, and the porosity varies between 1.5% and 2.3% with a mean porosity of 1.9%. The porosity is estimated by comparing the weight of a water-saturated sample with the weight of the same sample dried under a vacuum at 40 °C for 4 days. The permeability of the non-heat-treated andesite is approximately 10⁻²¹ m². The P-wave velocity of the non-heat-treated andesite samples is 5400 m/s with a measurement error of 200 m/s.

The andesite is composed of a fine groundmass with large phenocrysts (Fig. 1). The matrix is composed of quartz and plagioclase (50–60%). The mean grain size of the matrix is 2 µm. Phenocrysts are plagioclase (25–35%), pyroxene (15–20%), and oxides (4–5%). The mean grain size of phenocrysts is 100 µm (Fig. 1).

Figure 1 shows that this andesite is naturally microcracked. Cracks can be observed inside the phenocrysts (Fig. 1c). Figure 2 also shows that the andesite sample has a few long cracks in the matrix, with lengths on the order of 300 µm–500 µm.

2.1.2 Procedure of The Heat Treatment

Samples were heat treated to four different temperatures: 500 °C, 800 °C, 930 °C, and 1100 °C. Samples were placed in a programmable Meker MHT-3 furnace (Nicolas et al. 2016), and the temperature was increased at a rate of 140 °C/h to the target temperature. The furnace atmosphere was not controlled by air–oxygen fugacity. The target

Fig. 1 **a** SEM images of a non-heat-treated andesite sample at low magnitude. **b** High magnification view of the matrix. **c** High magnification view of the phenocrysts

Intact Andesite

Fig. 2 Cracks in the matrix. The longest cracks have a length of 300–500 μm

temperature was held constant for 2 h. Samples were slowly cooled to room air temperature. The cooling rate was controlled by the thermal inertia of the oven and remained slow (~ 10 h to decrease from 930 °C to room temperature). The effects of the heat treatment amplitude on the petrophysical properties of the andesite are presented in Sect. 3.1. The particular temperature of 930 °C was selected for a detailed triaxial deformation test. This temperature corresponds to that of the second magma chamber temperature in La Soufrière, Guadeloupe (Villemant et al. 2014), which is where the dikes begin (Villemant 2014). The mechanical properties of the heat-treated andesite samples are investigated and compared to the mechanical properties of the non-heat-treated samples.

2.2 Experimental Methods

2.2.1 Experimental Apparatus

Triaxial deformation experiments are performed on the triaxial cell installed at the Laboratoire de Géologie at École Normale Supérieure in Paris (Fig. 14 in Appendix 1). The axial load is applied by an axial piston with a maximum load of 680 MPa and is measured with a sensor with an accuracy of approximately 10^{-3} MPa. The confining pressure is applied by a volumetric servo pump that can provide pressure up to a maximum of 100 MPa and is measured by a pressure transducer with an accuracy of 10^{-3} MPa (Ougier-Simonin et al. 2011; Nicolas et al. 2016). The pressure-conducting medium is silicone oil.

2.2.2 Strain and Ultrasonic Instrumentation

Four groups of strain gauges are glued at different positions directly on the sample. (Fig. 15 in Appendix 1). Each group is composed of one axial gauge and one radial gauge. Strain gauges Tokyo Sokki TML FCB 2–11 are employed. The axial strain ϵ_a , and radial strain ϵ_r are both averaged across the four strain gauges in each orientation. The volumetric strain is deduced as $\epsilon_v = \epsilon_a + 2\epsilon_r$. Neoprene tubing is used to separate the sample from the oil of the confining medium. Then, 12 P-wave sensors (PI 255 PI Ceramics, 1 MHz resonance frequency) and four polarized S-wave sensors (Shear PZT plate) are glued directly on the surface of the rock and sealed with a two-component epoxy (Fig. 15 in Appendix 1). The network of ultrasonic sensors used allows us to record (i) acoustic emissions (passive mode) and (ii) the evolution of the ultrasonic velocities in different directions (active mode). For the ultrasonic wave velocity survey, a 250 V high-frequency signal is pulsed every 2 min on each sensor while the others are recording. In passive mode, these sensors can record the acoustic emissions (AE) that take place in the sample. The AEs are amplified at 40 dB and

can be discretely recorded with a maximum rate of 12 AE/s. (Schubnel et al. 2006, 2007; Brantut et al. 2011; Ougier-Simonin et al. 2011; Nicolas et al. 2016).

2.2.3 Experimental Procedure

For all the samples, the P-ultrasonic wave velocity is measured at room temperature and atmospheric pressure. Permeability is measured with water using transient pulse or steady flow methods at 2.5 MPa effective confining pressure. For non-heat-treated samples and samples heat-treated to 500 °C, permeability is measured using the transient pulse (Brace et al. 1966) (two symmetrical measures are performed by switching the flow direction in the sample); for samples heat-treated to 800 °C and 930 °C, permeability is measured with steady state flow.

For non-heat-treated andesite samples and heat-treated (at 930 °C) andesite samples, experiments are performed under dry conditions at room temperature, with confining pressures of 5, 15 and 30 MPa (non-heat treated samples) and 0, 15 and 30 MPa (heat-treated samples). Differential loading is applied up to peak stress using a controlled constant strain loading rate of 10^{-6} /s. During triaxial deformation, ultrasonic measurements are made on all samples every 2 min.

In the following, we adopt the convention that compressive stresses and compactive strains are positive. The differential stress is noted by $Q = \sigma_1 - \sigma_3$, and the mean stress by $P = (\sigma_1 + 2\sigma_3)/3$, where σ_1 and $\sigma_3 = P_c$ are the vertically applied (maximum) stress and the confining pressure (minimum), respectively.

3 Results

3.1 Properties of Samples Heat-Treated at Different Temperatures

3.1.1 P-Wave Velocity, Crack Density and Permeability

The samples were heat-treated at different temperatures: 500 °C, 850 °C, 930 °C and 1100 °C. The evolution of the P-wave velocity and permeability as functions of the temperature of the heat treatment are shown in Fig. 3. In addition, we invert the P-wave velocity to obtain the crack density, as defined by $\rho = \sum_N \frac{l_i}{V}$, where l_i is the length of the i -th crack and N is the total number of cracks embedded in the representative elementary volume V . When the crack length is smaller than the wavelength, effective medium theory is an appropriate method (Ougier-Simonin et al. 2010). The effective elastic properties are mainly controlled by cracks (Gueguen and Kachanov 2011). A noninteractive assumption is employed (Kachanov 1994). Noninteractive effective medium theory has been shown to be valid when cracks

Fig. 3 P-wave velocity (green curve), crack density (blue curve). Permeability (red curve). Note that the percolation threshold (crack density of 0.1) is indicated as a blue dashed line

are distributed randomly and crack density does not exceed 0.2–0.3 (Kachanov 1994; Sayers and Kachanov 1995; Gueguen and Sarout 2009). The details of the inversion in crack density are given in the appendix “Crack density inversion method—Isotropic case” (Ougier-Simonin et al. 2010; Mallet et al. 2014; Fortin et al. 2011; Nicolas et al. 2016)

A small decrease in the P-wave velocity of 70 m/s (1.3%) is recorded (Fig. 3) for a heat treatment of 500 °C. However, the decrease reaches 1000 m/s (18%) for a temperature of 800 °C and 2250 m/s (41%) for a temperature of 1100 °C, indicating a major change at approximately 500 °C, which should be associated with a significant change in microstructure. The crack density inverted from the P-wave velocity increases from 0.01 for a heat treatment of 500 °C to 1.4 for a heat treatment of 1100 °C. This last value is outside the range in which effective medium theory is valid. However, the value points to very intense cracking. The induced crack density reaches the percolation threshold of 0.1 (Guéguen and Dienes 1989) for a heat treatment between 500 °C and 800 °C. This result is in good agreement with the permeability evolution, which shows no change below 500 °C, but shows an increase by four orders of magnitude for a heat treatment of 930 °C (Fig. 3).

3.1.2 Microstructural Observations of The Heat-Treated Samples

The microstructures are shown in Fig. 4. In the sample heat-treated at 500 °C (Fig. 4a, b), few cracks can be observed. In the samples heated at 800 °C (Fig. 4c, d) and 930 °C (Fig. 4e, f), cracks surrounding the large inclusions with lengths of 50–200 µm can be observed, including intergranular and

intragranular cracks. Small cracks begin to appear in the matrix. Partial melting occurs above 500 °C; the details and effects of partial melting are presented in Sect. 3.2. The sample treated at 1100 °C shows the highest crack density (Fig. 4g, h). In particular, in the matrix (Fig. 4h), the number of cracks with lengths ranging between 1 µm and 20 µm is greatly increased, and most cracks are located at the boundaries of the crystal grains of quartz, tridymite, and plagioclase. Overall, the evolution of the microstructure is in good agreement with the evolution of the P-wave velocity and the permeability (Fig. 3).

3.2 Mineralogical Effects of Heat Treatment on Andesite

3.2.1 Mineralogical Composition

The mineralogical compositions of non-heat-treated andesite samples and heat-treated andesite samples were analyzed with EBSD (electron backscatter diffraction) and XRD (X-ray diffraction).

For non-heat-treated andesite samples, the ratio of different phases is shown in Table 1. A more detailed composition is given in Appendix A. The non-heat-treated andesite sample is composed of 70.8% plagioclase (including bytownite, sanidine and albite), 14.1% pyroxene (including diopside, hypersthene and augite), 9.2% other silicates (including tridymite and quartz) and 2.5% iron oxides. The clay content is 3.4%, mainly smectite due to plagioclase alteration (Table 2).

The mineralogical composition is slightly changed for samples heat-treated at 500 °C and 930 °C. In particular, the smectite (clay) disappears, and another form of clay appears: illite. The samples heat treated at 930 °C and 1100 °C are similar (disappearance of smectite); in addition, the proportion of plagioclase decreases by 2%, whereas the proportion of silicate increases by 2%, but this last result could be due to the heterogeneity existing in the samples. Irreversible dehydration and loss of swelling properties of smectite have been shown (e.g., Greene-Kelly 1953; Russel and Farmer 1964) to occur at temperatures between 350 °C and 550 °C, while dihydroxylation of smectite occurs at temperatures between 550 °C and 800 °C (Malek et al. 1997).

3.2.2 Partial Melting

The non-heat-treated andesite contains smectite (clay) related to the alteration of plagioclase, the smectite is mainly located in the vicinity of plagioclase (Fig. 5a).

As the heat treatment reaches 930 °C, partial melting is observed in the samples from SEM images (Fig. 5a). Glass is visible in the porosity (Fig. 5b). Smectite melting results in voids with sizes ranging from 5–10 µm, mainly located

Fig. 4 SEM pictures of andesite samples heat-treated to 500 °C, 800 °C, 930 °C and 1100 °C

Table 1 Chemical composition of andesite samples heat treated to different temperatures

Sample	Plagioclase(%)	Pyroxene (%)	Silicon (%)	Ironoxides (%)	Smectite (%)	Illite (%)
Andesite	70.8	14.1	9.2	2.5	3.4	0.0
HT500	70.9	15.5	7.8	2.2	0.0	3.5
Andesite HT930	73.2	14.4	8.0	1.9	0.0	2.5
Andesite HT 1100	68.7	13.6	11.0	2.9	0.0	3.9

Table 2 Chemical composition of andesite samples heat treated to different temperatures

Classification	Mineral (%)	Andesite (%)	Andesite 500 (%)	Andesite 930 (%)	Andesite 1100 (%)
Plagioclase	Bytownite	7.4	24.7	23	14.8
	Sadine	10.6	11.4	12.7	14.3
	Albite	52.8	34.8	37.5	39.6
Pyroxene	Diopside	1.7	2.3	3.3	0.8
	Hypersthene	6.4	8.4	9.1	6.4
	Augite	6.1	4.8	2.1	6.5
Silicon	Tridymite	8.0	7.2	5.0	9.2
	SiO ₂	1.2	0.6	3.1	0.8
Iron-oxides	Ilmenite	0.2	0.0	0.0	1.9
	Magnetite	2.4	2.2	1.9	0.9
Clay	Smectite	3.4	0.0	0.0	0.0
	Illite	0.0	3.5	2.5	3.9

near plagioclase (where the smectite was located). In the matrix, small pores of 0.5–1 μm are also observed, mostly at the boundaries of oxides. These pores may also be due to the melting of smectite.

3.3 Triaxial Deformation of Non-Heat-Treated Andesite and Heat-Treated Andesite

3.3.1 Stress–Strain Behavior of Non-Heat-Treated Andesite

Triaxial deformation tests were performed at confining pressures of 5 MPa, 15 MPa and 30 MPa under dry conditions at room temperature. The differential stress and mean stress are plotted versus axial strain and volumetric strain, respectively, in Fig. 6.

The samples under confining pressures varying between 5 MPa and 30 MPa are deformed in the brittle regime. The differential stress reaches a peak stress followed by macroscopic failure. The peak stress is observed to increase with confining pressure: the maximum differential stress increases by 20% as the confining pressure increases from 5 MPa to 15 MPa and increases by 27% as the confining pressure increases from 5 MPa to 30 MPa. Note that at the beginning of the loading, the stress–strain curves (Fig. 6) are almost linear, which indicates that the number of pre-existing crack is very small.

Another result of interest is the identification of the D' point, which is the point where volumetric strain reverses

(Fig. 6). Beyond D', dilatancy dominates over compaction (Heap et al. 2014). The differential stress for D' increases as the confining pressure is increased from 5 MPa to 30 MPa. The stress state of D' increases by 22% as the confining pressure increases from 5 MPa to 15 MPa and increases by 50% as the confining pressure increases from 5 MPa to 30 MPa.

3.3.2 Ultrasonic Velocity Evolution of Non-Heat-Treated Andesite

The P-wave velocity evolution during the triaxial deformation of andesite samples under confining pressures of 5 MPa, 15 MPa and 30 MPa is shown in Fig. 7b. In Fig. 7a, the rays of the different P-wave velocities are plotted. The P-wave velocities were measured at four fixed angles (0°, 22°, 48°, 53°). During the first phase of loading, in the quasi-elastic regime, the P-wave velocity is almost constant. This observation agrees with the almost linear stress–strain curve and indicates that the amount of crack porosity is very low (Walsh 1965). The P-wave velocity decreases at the onset of dilatancy, marked as point C' (Brace et al. 1966), as cracks nucleate and propagate. The stress state C' corresponds to the beginning of the P-wave velocity decrease (acoustic data) and to the stage where the volumetric strain curve deviates from linearity (mechanical data) (Brace et al. 1966), as shown in Fig. 7b.

Fig. 5 **a** Partial melting, in samples heat-treated at 930 °C. Melting occurs at the boundaries of the phenocrysts, i.e., where the clay (smectite) is located. **b** Glass is spotted in the porosity, indicating partial melting

Fig. 6 Conventional triaxial experiments on non-heat-treated andesite samples under dry condition. **a** Differential stress versus axial strain under confining pressure of 5 MPa, 15 MPa and 30 MPa. **b** Mean stress versus volumetric strain

For the three experiments, P-wave anisotropy is observed as the sample is deformed, with the P-wave velocity for rays at 90° with respect to the axial stress decreasing most.

3.3.3 Stress–Strain Relation of Heat-Treated Andesite

Triaxial experiments were performed on andesite samples heat-treated (at 930°C) under confining pressures of 0 MPa

(ultrasonic sensor and strain gauges are glued directly on the sample, measured inside the triaxial cell), 15 MPa and 30 MPa under dry conditions. The differential stress and mean stress are plotted versus axial strain and volumetric strain, respectively, in Fig. 8.

As in the case of the non-heat-treated andesite samples, the mechanical behavior of the heat-treated samples is brittle. The peak stress increases by 56% as the confining pressure increases from 0 MPa to 15 MPa and by 200% as the confining pressure increases from 0 MPa to 30 MPa.

A clear effect of pre-existing crack closure is shown on the stress–strain curve in Fig. 8, which is denoted by the concave curve at the beginning of loading.

3.3.4 Ultrasonic Velocity Evolution of Heat-Treated Andesite

The P-wave velocity evolution during the triaxial deformation of heat-treated andesite samples under confining pressures of 0 MPa, 15 MPa and 30 MPa is shown in Fig. 9. In Fig. 9, the evolution of P-wave velocities along different traces from 0° to 53° (Fig. 7.a) is plotted. A clear difference can be observed in comparison with Fig. 7b for heat-treated samples, the P-wave velocity increases at the beginning of loading, indicating the closure of pre-existing cracks (Stage I). This observation agrees with the stress–strain curve of heat-treated andesite samples, which is concave at the beginning of loading.

During stage II (from C' to D'), the P-wave velocity reaches a plateau. There is competition between pre-existing crack closure and new crack nucleation and propagation. The onset of dilatancy (point C') corresponds to new crack nucleation. Point C' is determined from both acoustic data and mechanical data, as shown in Fig. 9. Regarding the acoustic data, point C' corresponds approximately to the stage where the radial P-wave velocity stops increasing. At stage III, from point D' to the failure point, a clear decrease in P-wave velocities is observed as well as clear P-wave anisotropy indicating the propagation and nucleation of mainly axial cracks.

4 Discussion

4.1 Effect of The Heat Treatment on The Crack Density

4.1.1 Heat Treatment and Crack Density

Cracks formed in heat-treated andesite are mainly due to thermal stresses because minerals or aggregates have different thermal expansion coefficients (Friedrich and Wong 1986). According to theoretical considerations based on

Fig. 7 **a** Sketch illustrating how P-wave velocities are measured with different angles with respect to σ_1 . **b** P-wave velocity and differential stress measured during triaxial deformation experiments on intact andesite samples under confining pressure of 5 MPa, 15 MPa

and 30 MPa. P-wave velocity and differential stress are plotted versus axial strain. P-wave velocity and volumetric strain are plotted versus axial strain. The point C' indicates the onset of dilatancy, D' indicates dilatation over dominates compaction, failure is marked

Fig. 8 Conventional triaxial experiments on heat treated (at 930 °C) andesite samples under dry condition. **a** Differential stress versus axial strain under confining pressure of 0 MPa, 15 MPa and 30 MPa. **b** Mean stress versus volumetric strain

thermoelasticity and fracture mechanics, the total surface of crack S (per unit volume) created during heat treatment and due to different thermal expansion of minerals is given by (Davidge and Green 1968; Fredrich and Wong 1986):

$$S = \frac{1}{8G_{IC}} \left[\frac{E}{1-2\nu} \right] (\Delta\alpha \Delta T)^2 \quad (1)$$

where E is Young's modulus of the (intact) andesite ($E=64.7$ GPa), ν is Poisson's ratio of intact andesite ($\nu=0.28$) and

$\Delta\alpha$ is the thermal expansion contrast between plagioclase and quartz/tridymite or glass, which can be estimated as $14 \times 10^{-6}/^\circ\text{C}$. ΔT is the temperature of the heat treatment. G_{IC} is the energy release rate of andesite under mode I and is estimated to be $5\text{--}6.5 \text{ J/m}^2$ (Fredrich and Wong 1986; Tutluoglu and Keles 2011; Talukdar 2018). In addition, the relationship between the total surface of the crack S and the crack density, $\rho = Nl^3/V$, is $S = 2\pi\rho/c$, where c is the mean radius of the crack in the volume V ($l=2c$).

Following Wang et al. (2013), and assuming that the average thermal crack size is that of the grain size, l , (i.e., $c=l/2$), we can estimate the crack density created (i) in the matrix or (ii) at the interface between the large inclusions and the matrix. In the matrix, grains of plagioclase and quartz/tridymite have an average length of $1 \mu\text{m}$, which leads to a crack density of $0.04\text{--}0.053$. However, the large inclusions have average lengths of $100\text{--}200 \mu\text{m}$, which lead to crack densities of $0.4\text{--}0.53$, values much higher than the crack density generated in the matrix. The estimated initial crack density is $\rho=0.6$ (Fig. 3) for andesite samples heat-treated at 930°C . Note that this figure is out of the range of validity for effective medium theory. However, this value quantitatively indicates a high degree of cracking.

In addition, we can define the aspect ratio $\xi = w/c$, where w is the crack half aperture. The total crack porosity is equal to $\phi = 2\pi\rho\xi$, which is 3.7% after the heat treatment. This value leads to a crack aspect ratio of approximately 10^{-2} , an order of magnitude that agrees with those in previous studies (Wang et al. 2013; Adelinet et al. 2011).

4.1.2 Crack Density and Anisotropy

The evolution of the crack density during loading can be deduced from the evolution of the elastic P-wave velocities (Fortin et al. 2011). More precisely, assuming a transversely isotropic symmetry, noninteraction and dry conditions, the two components of the crack density tensor can be deduced from the ultrasonic measurements (Gueguen and Kachanov 2011). An alternative and equivalent method is to estimate, from the ultrasonic measurements, the vertical crack density and the randomly oriented crack density (Gueguen and Kachanov 2011; Fortin et al. 2011; Nicolas et al. 2016). See also the appendix "Crack density inversion method—Transversely isotropic symmetry".

The evolution of the crack density for the experiments performed at $P_c=30 \text{ MPa}$ on the non-heat-treated samples and heat-treated samples is shown in Fig. 10. In the non-heat-treated samples, the crack density evolution is directly correlated with the initiation and propagation of cracks at the onset of dilatancy. These induced cracks are mainly axial, and the density of the randomly oriented cracks is almost equal to zero during the loading (Fig. 10a).

Fig. 9 P-wave velocity and differential stress measured during triaxial deformation experiments on heat treated (at 930 °C) andesite samples under confining pressure of 0 MPa, 15 MPa and 30 MPa. P-wave velocity and differential stress are plotted versus axial strain. P-wave

velocity and volumetric strain are plotted versus axial strain. The point C' indicates the onset of dilatancy, D' indicates dilatation overdominates compaction, failure is marked

In heat-treated samples that contain pre-existing thermal cracks, the randomly oriented crack density starts to decrease at the beginning of differential loading, while the axial crack density increases significantly beyond the onset of dilatancy. The axial crack density in Fig. 10b increases even before the onset of dilatancy. As the axial stress increases, the pre-existing randomly oriented cracks close while the axial cracks open. Crack opening causes a decrease in the P-wave velocity and an increase in the crack density.

Note that the crack density inverted in Fig. 3 is based on the measurement of the P-wave velocity at ambient pressure, whereas the crack density inverted in Fig. 10 is based on the measurement of the P-wave velocity under a confining pressure of 30 MPa. Due to the effect of pressure, the P-wave velocities increase as the pressure increases; thus, the crack density decreases as the confining pressure increases. This phenomenon explains why the initial crack density in Fig. 10 is lower than that reported in Fig. 3.

4.2 Effect of Heat Treatment on The Microstructure: Partial Melting

The question is: where does the melt go? Fig. 11 shows that the melt seals some cracks, especially the cracks with the largest apertures. We also observe that bubbles are distributed in the melt in agreement with the observations of Simmons and Richter (1976), Swanenberg (1980), and Roedder (1981), indicating that the bonding strength is recovered. The melt flows into the cracks, and as it cools, the glass bonds the two surfaces of cracks. Bubbles are clearly observed in the SEM (Fig. 6). Since the spherical bubbles represent relatively stable pore shapes, we refer to the bubble planes as being strength recovered.

SEM and EBSD reveal that the melt content is an amorphous phase that contains Fe, K, and Mg. Partial melting probably results from the presence of smectite, which has lowered melting point of other minerals. Indeed, the melting point of pyroxene and plagioclase is 1400 °C, whereas smectite melts at temperatures of 400–500 °C.

4.3 Effect of Heat Treatment on Mechanical Strength

4.3.1 Effect on The Onset and Development of Dilatancy

The stress states at the onset of dilatancy (C') during constant strain rate triaxial deformation experiments of intact and heat-treated andesite samples are plotted in Fig. 12. Heat treatment does not induce any change in the stress state at the onset of dilatancy despite the dramatic increase in damage (crack density). This result can be explained by the fact that C' is sensitive to crack nucleation or propagation regardless of the initial crack density.

Wing crack damage models are currently used to quantitatively analyze the dilatancy evolution under axisymmetric loading. Brittle faulting can be modeled by a sliding wing crack model (Cotterell and Rice 1980). Following Ashby and Sammis (1990), wings are expected to start to grow from pre-existing flaws at an axial stress equal to:

$$\sigma_1 = \frac{(1 + \mu^2)^{1/2} + \mu}{(1 + \mu^2)^{1/2} - \mu} \sigma_3 + \frac{\sqrt{3}}{(1 + \mu^2)^{1/2} - \mu} \frac{K_{IC}}{\sqrt{\pi a}} \quad (2)$$

where σ_1 and σ_3 are the maximum and minimum principal stresses, μ is the friction coefficient on pre-existing flaws, K_{IC} is the fracture toughness and a is the length of pre-existing flaws. Note that this criterion (Eq. 2) is not directly sensitive to the crack density. The length of pre-existing flaws, a , is estimated to be in the range of 100–300 μm , which corresponds to the average length of large inclusions. Fitting the onset of dilatancy for triaxial deformation experiments performed at different confining pressures on intact samples, the friction coefficient μ is estimated to be equal to 0.57, and the fracture toughness K_{IC} is in the range from 1.1 $\text{MPa m}^{1/2}$ to 1.9 $\text{MPa m}^{1/2}$. The friction coefficient is in good agreement with the mean values found in rocks (Byerlee 1978), and the fracture toughness is in the range of values obtained for andesite (1–2 $\text{MPa m}^{1/2}$), as measured by Ouchterlony (1990), Tutluoglu and Keles (2011), and Nara et al. (2012).

The friction coefficient μ_{HT} is estimated to be 0.57, the same value as for non-heat-treated samples. The fracture toughness for heat-treated andesite samples K_{IC-HT} is estimated in the range 1–1.7 $\text{MPa m}^{1/2}$, values slightly lower than those for non-heat-treated samples.

4.3.2 Effect on The Peak Strength

Heat-treated samples of andesite have higher peak stresses than intact samples (Fig. 13).

The 2D damage model previously presented to analyze the onset of dilatancy can also be used to quantitatively model the failure of the samples (Ashby and Sammis 1990;

Kemeny and Cook 1991; Baud et al. 2014; Mallet et al. 2014). This model leads to a brittle failure envelope that can be described as:

$$\sigma_1 = A(\mu, D_0)\sigma_3 + B(\mu, D_0)\frac{K_{IC}}{\sqrt{\pi a}}, \quad (3)$$

where A and B are constants that depend on the friction coefficient on pre-existing flaws and on the initial damage (D_0) defined as $D_0 = \frac{4}{3}\pi(\alpha a)^3 N_V$, where N_V is the number of sliding cracks initially present. According to the model prediction, peak strength decreases with initial damage, assuming a is a constant, which may seem to contradict our results showing an increase in peak stress after heat treatment despite an increase in initial damage.

However, the previous model is probably too simple for at least two reasons. First, the enhancement of heat-treated sample strength relative to those of intact samples could be related to a crack sealing process. Microstructural observations show that the longest and largest fractures passing through the matrix are sealed. During the temperature increase, partial melting of some minerals occurs, and the melt flowed along the cracks that had already formed first due to thermal stress (This interpretation implies that parameter a is not a constant and is likely to decrease). The melt filled part of the cracks and finally led to amorphous medium filling and sealing of cracks during cooling.

A second reason is that the most dangerous cracks are the longest ones. Crack sealing of the longest cracks implies an effective crack length decrease. The longest cracks are segmented into smaller length cracks. In contrast with elastic moduli, which depend on crack density, the mechanical strength is controlled by the longest cracks.

5 Conclusions and Perspectives

This investigation aimed to quantify thermal treatment effects on the microstructure (cracking) and the physical and mechanical properties of andesite. In situ conditions (high temperature) and the presence of fluid might modify our observed results. At elevated temperatures during triaxial deformation, the high temperature range (500–1100 $^{\circ}\text{C}$) could lead to a brittle-ductile transition and thus more complicated mechanical behavior (Violay et al. 2017).

The main results of this work are as follows:

1. Due to thermal treatment, the P-wave velocity decreases by up to 50% as the temperature of heat treatment varies from room temperature to 1100 $^{\circ}\text{C}$. The crack density increases to 0.6.
2. A clay content as low as 1.5% in the intact rock leads to partial melting for a temperature of heat treat-

◀Fig. 10 Axial crack density and randomly oriented crack density evolution versus axial strain during triaxial deformation experiments on (a) non-heat-treated andesite samples under confining pressure of 30 MPa and (b) heat-treated (at 930 °C) andesite samples under confining pressure of 30 MPa

- 616 ment > 500 °C. Partial melting modifies the microstructure and the characteristics of the rocks.
- 617
- 618 3. A small amount of crack sealing changes the distribution of the crack size. The ultrasonic velocity is weakly
- 619 modified, but the mechanical strength is enhanced.
- 620

4. Thermal treatment could have a strengthening effect on a rock depending on the original microstructure of the rock and the mineral content. This result is counterintuitive but might be linked to the presence of clay in the andesite.

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Crack Sealing in Heat treated andesite at 930 °C

Fig. 11 Crack sealing observed in intergranular cracks. Bubbles observed in the melt which seals the cracks

Fig. 12 Stress states C' (onset of dilatancy) in non-heat-treated samples and heat-treated samples (at 930 °C)

Fig. 13 Stress states at failure in non-heat-treated samples and heat-treated samples (at 930 °C)

Appendix 2: List of Symbols

K	Effective bulk modulus	636
K_o	Effective shear modulus	637
ϵ_v	Volumetric strain	638
G	Bulk moduli of the crack-free matrix	639
G_o	Total surface of crack	640
ϕ	Shear moduli of the crack-free matrix	641
ρ_c	Scalar crack density	642
ν_o	Poisson's ratio of the crack-free matrix	643
n	Unit normal to a crack	644
nn	Dyadic product	645
ρ_i	The randomly oriented crack density	646
ρ_v	The axial crack density induced by the mechanical loading	647
C	Stiffness tensor	649
E_o	Young's modulus of the crack-free matrix	650
ν_0	Poisson's ratio of the crack-free matrix	651
ϕ	Propagation angles ϕ	652
$V_p(\phi)$	Wave phase velocities along the propagation angles ϕ	653
M	The least square value	655

K Effective bulk modulus

Crack Density Inversion Method: Isotropic Case

In the noninteraction approximation, the effective elastic properties in the dry case are given by Bristow 1960:

$$\frac{K_o}{K} = 1 + \rho_c \frac{h}{1 - 2\nu_o} \left(1 - \frac{\nu_o}{2}\right)$$

$$\frac{G_o}{G} = 1 + \rho_c \frac{h}{1 + \nu_o} \left(1 - \frac{\nu_o}{5}\right)$$

K is the effective bulk modulus that can be directly inverted from a combination of the P- and S-wave velocities, and G is the effective shear modulus that can be directly inverted from the S-wave velocities. K_o and G_o are the bulk and shear moduli of the crack-free matrix, and ν_o is the corresponding Poisson's ratio of this state. The value h is a factor given by

$$h = \frac{16(1 - \nu_o^2)}{9(1 - \frac{\nu_o}{2})}$$

Appendix 1

See Figs. 14 and 15 and Table 2

Fig. 14 Triaxial cell installed at École Normale Supérieure (Adapted from Ougier-Simonin et al. 2010, 2011)

with the minimum distance between predicted and measured velocities (Fortin et al. 2011; Nicolas et al. 2016).

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