

Permeability evolution in fine-grained Aji granite during triaxial compression experiments

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Abstract

Triaxial compression experiments were carried out on samples of fine-grained Aji granite to measure the evolution of permeability during deformation prior to failure under confining pressures of 20 and 40 MPa. During the initial stages of deformation, a small decrease in permeability was observed, due to the closure of pre-existing microcracks; permeability then increased with increasing differential stress. During deformation, permeability varied by up to two orders of magnitude, and we observed a small pressure dependence, with a larger variation observed at 20 MPa than at 40 MPa. This suggests that more cracks developed during brittle deformation under the lower confining pressure. The observed increase in permeability during our experiments was approximately proportional to inelastic volumetric strain, which corresponded to the volume of dilatant cracks. On the other hand, prior to brittle failure, we observed a further increase in permeability that was greater than the inelastic volumetric strain, suggesting crack aperture opening accelerated at this stress level ($> \sim 80\%$). The permeability enhancement resulting from the crack dilation affects the gas-sealing capacity of the fluid-saturated caprock. Our experimental findings would be beneficial for the safety assessment in applications such as the long-term storage of various gaseous wastes.

KEYWORDS

reservoir geophysics, rock physics

INTRODUCTION

Fluid flow in rocks plays a key role in various geological processes, including crustal deformation (Byerlee, 1975; Sibson, 1996), fluid-induced seismicity (Talwani & Acree, 1985) and geothermal development (Shapiro et al., 1997). Laboratory experiments on rock samples have yielded a wide range of permeabilities (10^{-12} – 10^{-23} m²) that are controlled by lithology, porosity and pore geometry (Gueguen & Palciauskas, 1994). Under hydrostatic conditions, an increase in pressure reduces permeability through the progressive closure of pores within a rock (Brace et al., 1968; Fortin et al., 2011). During the deformation of porous rocks such as sandstone, perme-

ability consistently decreases due to the inelastic compaction by grain crushing and pore collapse (Baud et al., 2012; Zhu & Wong, 1997). In contrast, brittle deformation of crystalline rocks such as granite can rapidly enhance permeability and affect fluid-flow processes. Although a small decrease in permeability occurs upon the application of small stresses, a further increase in stress results in a marked increase in permeability as the rock approaches failure (Mitchell & Faulkner, 2008; Zoback & Byerlee, 1975). These stress-induced permeability variations are accompanied by dilatancy associated with microcrack nucleation and growth. However, due to the rapid crack growth during the pre-failure stage, gas permeability is expected to show a different trend than water

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permeability due to its lower viscosity. This is because it takes time for water pressure gradient to reach equilibrium, especially in impermeable rocks. This is particularly important for assessing the design and safety of long-term storage of carbon dioxide and high-level radioactive waste, as several gasses may be generated from bacterial activity and water radiolysis in the post-deposition phase.

Some studies have been conducted to elucidate the gas permeability of granitic rocks. For example, Konečný and Kožušnicková (2016) measured the gas permeability at elevated hydrostatic pressure with Czech granitic rocks and showed that the gas permeability decreased by less than an order of magnitude with increasing pressure. Zhang et al. (2018) conducted hydrostatic tests with granite samples heated to 25–900°C. They reported that the gas permeability proportionally increased with the increase in porosity, indicating crack formation induced by the heating–cooling process. However, these experiments were conducted under hydrostatic pressure and did not reveal the relationship between gas permeability and microfracture network. Fluid flow in crustal rocks, including granite, is known to be controlled by fractures such as fault zones in addition to the bulk transport property (e.g. Kranz et al., 1979). The fault zone consists mainly of the fault core and the surrounding damage zone, each of which contributes to fluid flow. Although the fault core can act as a flow path during shear displacement, grain-size reduction and mineral precipitation following deformation may cause the fault core to act as a barrier to fluid flow (Caine et al., 1996). On the other hand, the damage zone is the network of small faults and/or cracks, which can enhance the permeability of the fault zone relative to the fault core (Faulkner et al., 2010). Despite its importance, gas flow in the damage zone, represented by the microfracture network that develops during triaxial compression, remains unknown.

The change in the internal structure of the rock sample has been investigated by measuring the strain associated with triaxial deformation tests. Brace et al. (1966) showed that dilatancy, which represents an increase in pore volumes associated with open axial cracks (i.e. parallel to the loading direction), begins at the stress at which the stress–volumetric strain curve deviates from the linear (i.e. elastic) regime. In addition, it has been theoretically shown that the cracks encounter stable and unstable propagation stages at the higher differential stress (Bieniawski, 1967a). Stable propagation of a crack is slow and can be stopped by removing the applied stress, whereas unstable propagation is fast and can continue even under a constant stress condition. It has been experimentally reported that the crack propagation pattern transits with the stress level where the stress–volumetric strain curve changes from increasing to decreasing (Bieniawski, 1967b). Overall, the in situ measurement of volumetric strain can provide detailed information about microcracking due to its high sensitivity; however, the effect of such crack propagation pattern on gas permeability has not yet been clarified.

In previous experiments, water permeability has been measured using the pulse transient technique, which requires the interruption of deformation to make measurements (Zoback & Byerlee, 1975). This may induce a relaxation of the axial loading stress, and the permeability may be affected, particularly during the dilatant stage. Mitchell and Faulkner (2008) measured the water permeability evolution of Western granite during continuous triaxial compression using the pressure oscillation technique. However, the high fluid viscosity required a relatively long response time to achieve equilibrium of permeability during deformation. The absence of actual measurements of volumetric strain also hinders a detailed discussion of the relationship between permeability evolution and microcracking. In the present study, we measure permeability continuously during triaxial compression using a gas flow method, where it is sensitive to the presence of deformation microstructures. We used nitrogen gas because it is chemically inert, thereby preventing geochemical interactions and ensuring that the observed variation in permeability results exclusively from mechanical processes. To elucidate the impact of microcrack nucleation and growth on gas permeability, the volumetric strain of granites was monitored simultaneously with the gas flux. Based on the comprehensive interpretation of these experimental data, we newly demonstrate the possible process of permeability evolution and microcracking behaviour.

EXPERIMENTAL METHODS

For our experiments, we used sample of fine-grained granite from Aji, Japan. The average grain size of Aji granite is 0.3 mm, and it comprises 30% quartz, 37% plagioclase, 24% K-feldspar and 8% biotite (Kudo et al., 1992). The samples have a bulk density of 2.66 g/cm³ and an apparent initial porosity of 0.62% (Yukutake, 1989). Based on the elastic wave velocity measurements, the textures within the Aji granite are considered to be nearly isotropic (Watanabe & Higuchi, 2015), which allows us to obtain reproducible data for our experiments. Each sample was prepared as a cylindrical shape with a diameter of 20 mm and a length of 40 mm (uncertainty <0.05 mm). The samples were then enclosed in polyolefin tubes to prevent interaction with the confining oil.

Triaxial deformation tests were performed using an intravessel deformation fluid-flow apparatus at Hiroshima University. The axial piston was advanced at a constant rate, and the confining pressure was kept constant using a servo-controlled system (Figure 1). We performed multiple experiments under confining pressures of 20 and 40 MPa, which correspond to depths of 1–2 km and are typical for various applied engineering fields such as geological storage of CO₂ and enhanced geothermal systems, and displacement rates of 0.04 and 0.02 mm/min. Our machine lacks a high-resolution feedback system to control post-failure processes, and we therefore

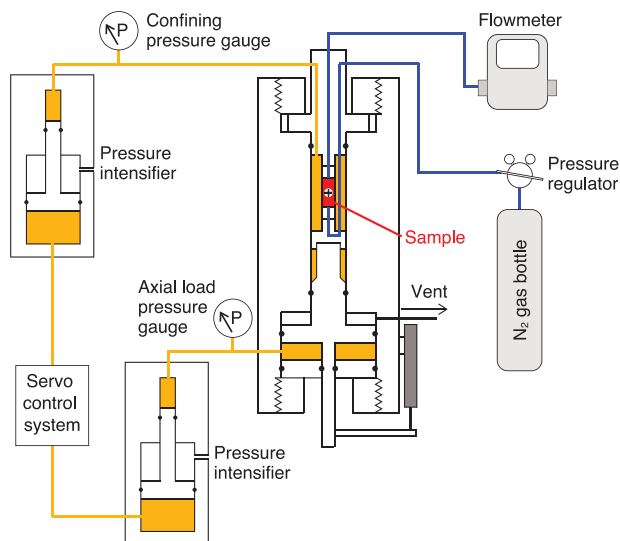


FIGURE 1 Overview of the intra-vessel deformation fluid-flow apparatus.

focus on the evolution of permeability until the attainment of maximum differential stress.

Permeability was measured during deformation by a gas flow method using nitrogen gas as a pore fluid, in which a constant upstream pore pressure was maintained ($P_p = 1.5$ MPa). To achieve steady-state fluid flow during the initial stages of deformation, the desired pore pressure was applied an hour prior to deformation. Permeability (k) was determined from the flow rate as follows:

$$k = \frac{\mu L}{A(P_1 - P_2)} \bar{Q}, \quad (1)$$

where μ is the viscosity of the pore fluid, P_1 is the upstream pore pressure, P_2 is the downstream pore pressure (atmospheric pressure), A and L are the cross-sectional area and length of the sample, respectively, and $\bar{Q}$ is the mean flow rate as measured by a digital flow metre (Tanikawa et al., 2008). In these calculations, we applied a correction to the pore fluid volume to account for the compressibility of nitrogen gas. Although changes in gas flow rate occur adjacent to pore walls, which results in pore pressure dependent permeability (i.e. Klinkenberg effect), we focus on the relative change in gas permeability under a constant pore pressure gradient.

We measured strain in sample during deformation using double-cross strain gauges. Volumetric strain (ϵ_v) was obtained from the axial (ϵ_a) and lateral strain (ϵ_r) as follows:

$$\epsilon_v = \epsilon_a + 2\epsilon_r. \quad (2)$$

During the initial stages of deformation, volumetric strain varied linearly with applied differential stress. However, at stresses approaching the strength of the sample, non-linear

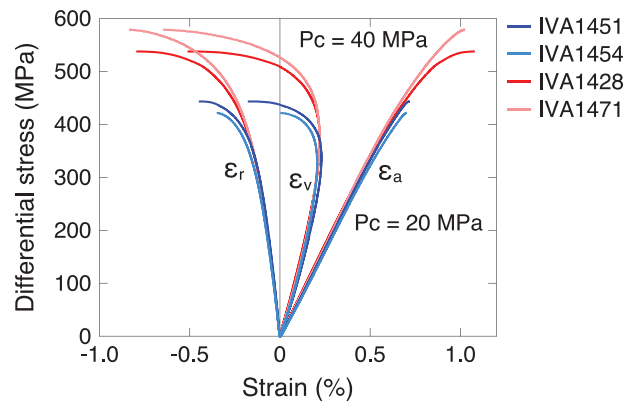


FIGURE 2 Relationships among differential stress and axial strain (ϵ_a), radial strain (ϵ_r) and volumetric strain (ϵ_v) of Aji granite under confining pressures of 20 and 40 MPa. Compressive strain was taken as positive, and extensional strain as negative. The bluish lines represent experimental results conducted at 20 MPa confining pressure (blue: IVA1451, light blue: IVA1454), whereas the reddish lines are at 40 MPa confining pressure (red: IVA1428, light red: IVA1471).

behaviour was observed during dilation of the samples due to the development of microcracks. As transport properties are influenced by the formation and connection of pores, we discuss the relationship between permeability and inelastic volumetric strain during deformation.

RESULTS

Experimental conditions and results are listed in Table 1. Permeabilities prior to deformation ranged from 1.1×10^{-19} to 2.6×10^{-19} m², showing a small pressure dependence, with higher permeabilities observed at the lower confining pressure (20 MPa). The maximum differential stress of Aji granite at a confining pressure of 20 MPa ranged from 416 to 444 MPa, whereas that at a confining pressure of 40 MPa ranged from 538 to 585 MPa (Table 1).

Figure 2 shows stress-strain curves for experiments conducted under confining pressures of 20 and 40 MPa. We use positive strain to represent compression and negative for extension. The maximum differential stress varied with confining pressure, with experiments at high confining pressure (40 MPa) producing higher differential stresses than those at 20 MPa. Under both confining pressures, stress-strain behaviour was linear-elastic during the initial stages of deformation and became non-linear under higher differential stress. This non-linear relationship prior to failure is typical behaviour during brittle deformation and reflects the development of microcracks in the samples. This process is referred to as dilatancy, and the volume is observed to increase during inelastic deformation. We determined the onset of dilatancy by following the method of Brace et al. (1966). The results indicate that dilatancy begins at ~40% of the maximum

TABLE 1 Summary of experimental conditions and results.

No.	P_c (MPa)	Displacement rate (mm/min)	Onset of dilatancy		Crack damage stress		Onset of stage IV		Maximum differential stress (MPa)	$k_{initial}$ (m ²)	k_{max} (m ²)
			MPa	%	MPa	%	MPa	%			
IVA1387	20	0.04							441	1.63×10^{-19}	5.54×10^{-18}
IVA1389	20	0.02							428	2.06×10^{-19}	4.66×10^{-18}
IVA1424	20	0.04	162	37.9	265	62.1			427	1.25×10^{-19}	4.06×10^{-18}
IVA1438	20	0.04	187	42.2	302	68.2	318	71.7	444	1.19×10^{-19}	1.39×10^{-17}
IVA1444	20	0.04	176	42.3	282	67.8	323	77.7	416	1.71×10^{-19}	3.83×10^{-18}
IVA1451	20	0.04	186	42.2	330	74.7	338	76.6	441	2.59×10^{-19}	2.28×10^{-17}
IVA1454	20	0.04	176	41.6	326	77.3			422	2.19×10^{-19}	1.17×10^{-17}
IVA1397	40	0.04							580	1.37×10^{-19}	3.47×10^{-18}
IVA1403	40	0.02							585	1.48×10^{-19}	3.60×10^{-18}
IVA1410	40	0.04							568	1.06×10^{-19}	3.26×10^{-18}
IVA1421	40	0.04							544	1.12×10^{-19}	1.63×10^{-18}
IVA1428	40	0.04	234	43.5	370	68.7	453	84.2	538	1.40×10^{-19}	2.97×10^{-18}
IVA1443	40	0.04	213	38.0	362	64.6	528	94.1	561	1.21×10^{-19}	1.89×10^{-18}
IVA1471	40	0.04	234	40.3	374	64.6	443	76.4	579	1.22×10^{-19}	3.90×10^{-18}

Note: P_c is confining pressure; $k_{initial}$ is initial permeability; k_{max} is permeability at maximum differential stress, where the differential stress is defined as the difference between axial stress and confining pressure. The stage IV was defined as the regime of the concurrence of new crack formation and crack aperture dilation.

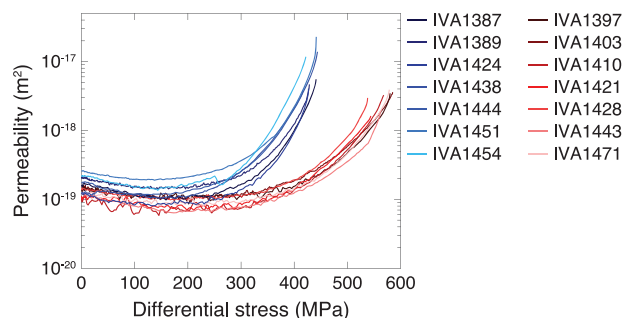


FIGURE 3 Evolution of permeability as a function of differential stress under confining pressures of 20 (blue dots) and 40 MPa (red dots). The data points of IVA1389 and IVA1403 represent experiments conducted at a slower deformation rate of 0.02 mm/min. All other data represent experiments conducted at a deformation rate of 0.04 mm/min.

differential stress, above which inelastic volumetric strain increased further as the stress increased. When approaching macroscopic failure, a reversal of stress–volumetric strain curve was observed at the stress level 62%–77% of the maximum value. This stress threshold (termed “crack damage stress”) corresponds to the point of the maximum volumetric strain where unstable crack growth initiates (Bieniawski, 1967b).

Figure 3 shows permeability results for our experiments under confining pressures of 20 and 40 MPa. In all experiments, permeability initially decreased due to the closure of pre-existing cracks and then increased under higher differential stress. Approaching the maximum differential stress, a more pronounced increase in permeability was observed. At the maximum differential stress, permeabilities were $0.4\text{--}2.3 \times 10^{-17} \text{ m}^2$ and $1.6\text{--}3.9 \times 10^{-18} \text{ m}^2$ at 20 and 40 MPa, respectively, and the maximum increase in permeability during deformation was approximately two orders of magnitude. The variation in permeability was larger at 20 MPa than at 40 MPa. Although most experiments were conducted at a constant displacement rate of 0.04 mm/min (strain-rate of $\sim 1.7 \times 10^{-5} \text{ s}^{-1}$), some runs were conducted at a slower rate of 0.02 mm/min; these experiments showed a similar evolution of permeability (Figure 2). After reached the maximum differential stress, permeability continued to increase until macroscopic failure. However, quantitative measurement of this stage was prevented because the axial load was not controlled by a servo-system, and brittle fracture occurred rapidly.

DISCUSSION

Comparison with previous experiments

Our experiments yielded systematic changes in permeability during brittle deformation, and we first compare our

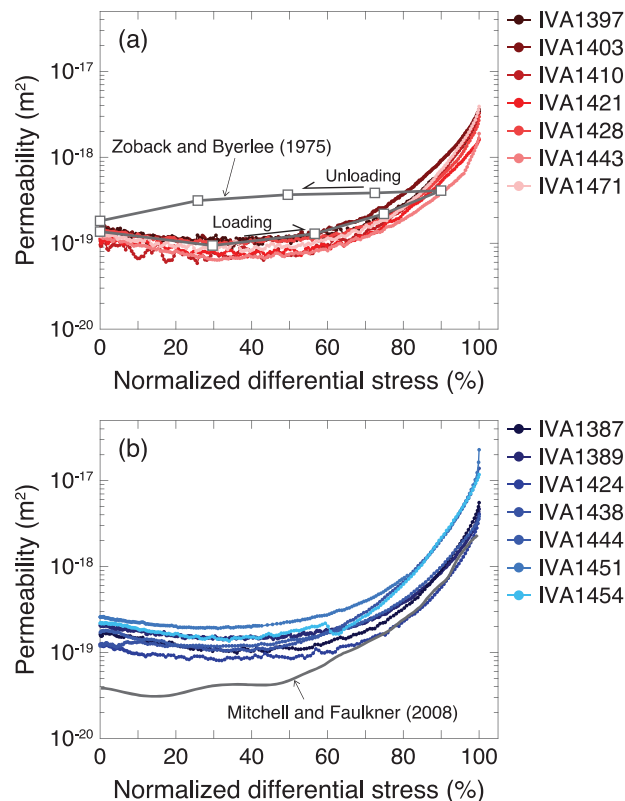


FIGURE 4 Comparison of our experiment data with those of previous experimental studies. The horizontal axes represent the differential stress normalized by the maximum differential stress. (a) Experimental results at $P_c = 40 \text{ MPa}$ compared with the data of experiments on Westerly granite at an effective pressure of 39 MPa (Zoback & Byerlee, 1975), with permeability measured by a pulse transient method using argon gas. (b) Experimental results at $P_c = 20 \text{ MPa}$ compared with the data obtained from Westerly granite at an effective pressure of 20 MPa (Mitchell & Faulkner, 2008), with permeability measured by a pore pressure oscillation method using water as a pore fluid.

results with previous experiments. Pioneering experiments by Zoback and Byerlee (1975) investigated the permeability evolution during triaxial deformation of Westerly granite samples. During loading, their results are similar to those presented here (Figure 4a). However, their experiments were cycled and did not reach macroscopic failure, and hence, variations in permeability were limited to a factor of four, much less than those found in our experiments until failure occurred. Mitchell and Faulkner (2008) measured the permeability of Westerly granite samples using a pore pressure oscillation technique at effective confining pressures of 10, 15 and 20 MPa. They observed a continuous increase in permeability after reaching approximately half of the maximum differential stress; however, in contrast to our experiments, an initial transient decrease in permeability associated with the closure of pre-existing cracks was not clearly observed (Figure 4b). This difference likely resulted from their use

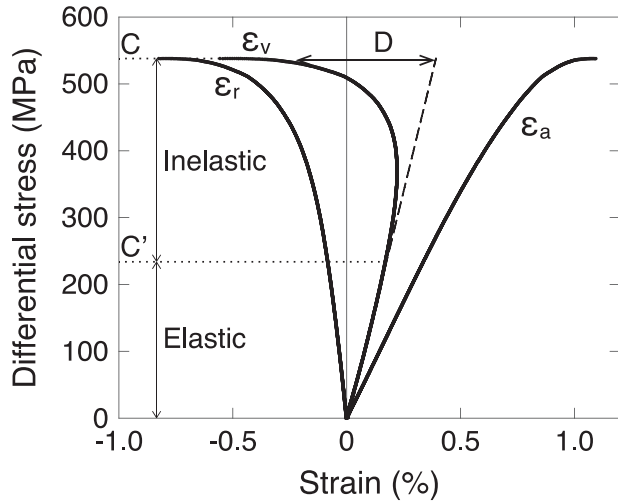


FIGURE 5 Typical relationship among differential stress and strains during triaxial compression experiments of Aji granite samples at $P_c = 40$ MPa. The parameters C , C' and D represent the maximum differential stress, onset of dilatancy and inelastic volumetric strain, respectively. The dashed line represents the ideal elastic volumetric strain extrapolated from 20% to 30% of the maximum differential stress.

of water as a pore fluid, which has a higher viscosity than nitrogen gas, thereby limiting flow through the narrow cracks during initial stage of loading. Fortin et al. (2011) reported similar behaviour during triaxial deformation of basaltic rocks (an initial decrease in permeability followed by an increase approaching failure), but the variation was less than a factor of three, likely due to competition between the closure of pre-existing cracks and the nucleation and growth of newly formed vertical cracks.

Relationship between permeability and inelastic volumetric strain

The inelastic behaviour of the stress–volumetric strain relationship (i.e. dilatancy) initiates $\sim 40\%$ of the maximum stress (C' in Figure 5). As this dilatancy is related to the development of microcracks, the increasing crack volume could enhance transport properties including permeability. To explore the possible relationship between dilatancy and permeability during deformation, we evaluated inelastic volumetric strain (D in Figure 5) by subtracting an elastic extrapolation from the measured volumetric strain.

Figure 6 shows the relative change in permeability and dilatancy as a function of the stress level normalized by the maximum value. Permeability decreased slightly during the early stages of deformation and then began to increase at approximately half of the maximum differential stress. This increase in permeability was accompanied by an increase in inelastic volumetric strain. The change in permeability

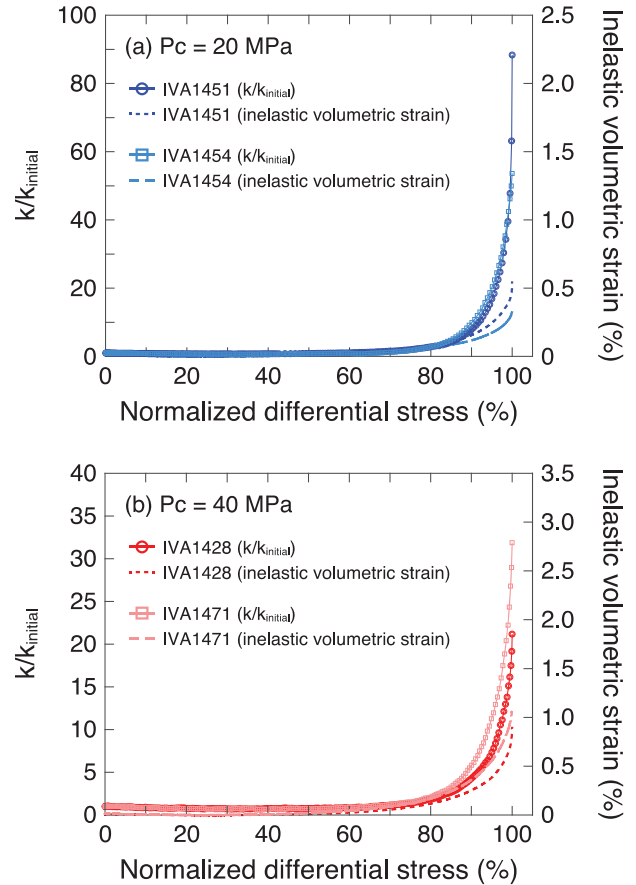


FIGURE 6 Inelastic volumetric strain and permeability normalized to the initial values (k/k_{initial}) as functions of differential stress normalized to the maximum differential stress at $P_c = 20$ (a) and 40 MPa (b).

during this stage is attributed primarily to an increase in dilatant crack porosity, considering that the inelastic volumetric strain corresponds to the crack porosity. However, as samples approached brittle failure, permeability increased more rapidly than inelastic volumetric strain. The differential stress at which the change in permeability deviates from that of inelastic volumetric strain is $\sim 70\%$ – 80% of the maximum stress. As a factor affecting the change in permeability apart from crack porosity, Gueguen and Dienes (1989), Sueyoshi et al. (2020) theoretically suggested the contribution of the geometric characteristics (e.g. aperture) to permeability. Therefore, we infer that although permeability depends primarily on crack porosity, it is also influenced by geometric factors.

One possible approach to estimate the contribution of crack geometric characteristics to permeability is to clarify the power law between permeability (k) and porosity (ϕ) (Bernabé et al., 2003):

$$k \propto \phi^\alpha. \quad (3)$$

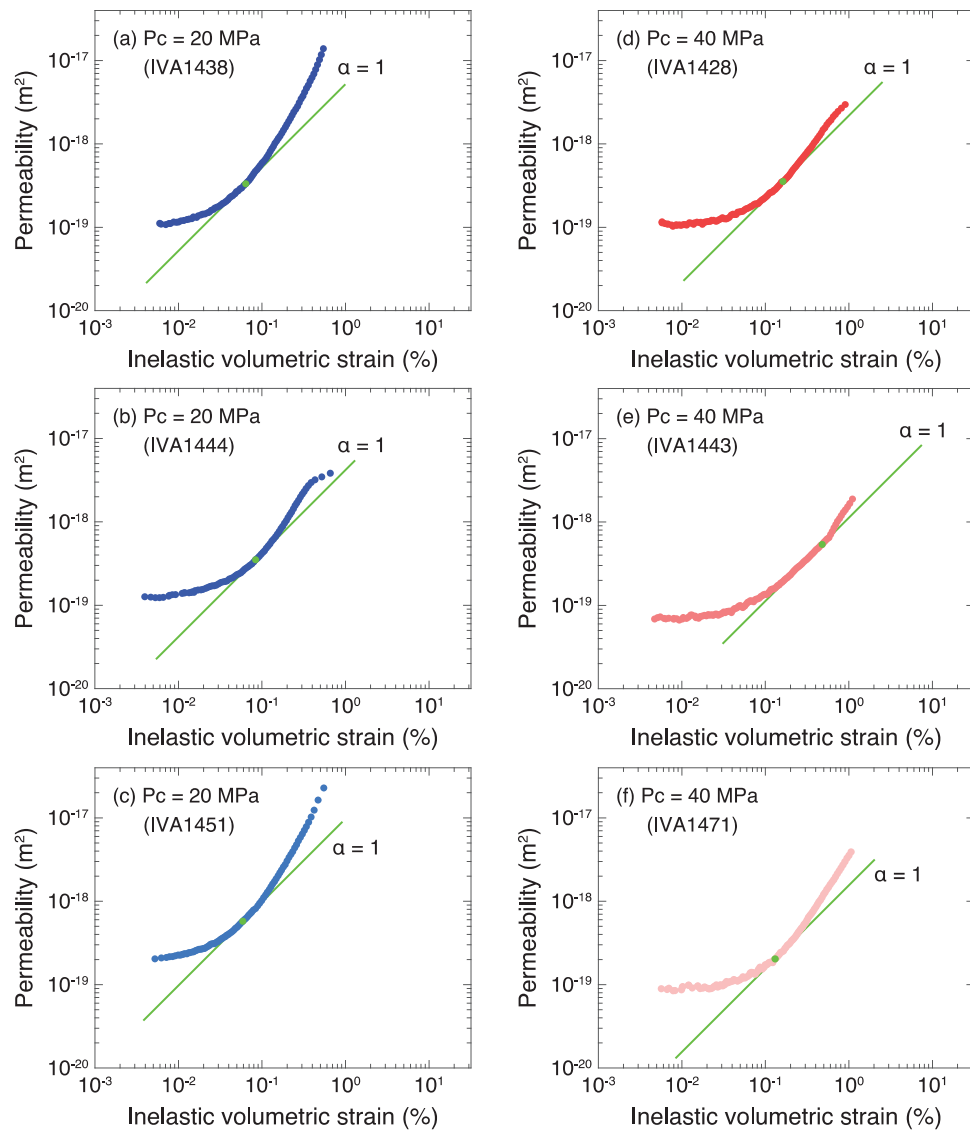


FIGURE 7 Permeability changes at confining pressure of 20 (a–c) and 40 MPa (d–f) plotted as a function of inelastic volumetric strain, defined after the onset of dilatancy. The straight lines represent the lines with slope 1 tangent to the permeability–inelastic volumetric strain curve. The green dots indicate the contact points of the tangent lines with slope 1.

The slope α depends on the processes leading to the evolution of the pore structure and lies between 1 and 2 during dilatant microcracking. According to Bernabé et al. (2003), this process corresponds to the co-occurrence of the decrease in distance between cracks and the increase in the crack aperture. Thus, microcrack evolution can be characterized by the stress level when α exceeds 1, where the formation of a new crack and crack aperture dilation simultaneously initiates. Based on the above, we estimated the changes in fluid-flow characteristics during the fracturing process from the relationship between the permeability and inelastic volumetric strain, comparable to the crack porosity in this study. Figure 7 shows representative results of the permeability–inelastic volumetric strain curve on a log–log scale. Note that the inelastic volumetric strain (D) is defined here after the stage of elas-

tic deformation (i.e. the onset of dilatancy), where the ratio of D to the ideal elastic volumetric strain (the dashed line in Figure 5) exceeds 3% (i.e. $D = \sim 0.005$). As the inelastic volumetric strain increases, there is a corresponding increase in permeability. Initially, this increase is small, but it transitions into rapid growth. This transition is indicated by the slope of the tangent line between permeability and inelastic volumetric strain (i.e. porosity). When this slope exceeds 1, it signifies the concurrent occurrence of new crack formation and the dilation of existing cracks (Bernabé et al., 2003). The differential stresses at which the slopes exceed 1 are 71.7%–77.7% at a confining pressure of 20 MPa, whereas 76.4%–94.1% at that of 40 MPa (Figure 7). Therefore, above these threshold stresses, a rapid increase in permeability can be characterized by the simultaneous occurrence of new crack formation

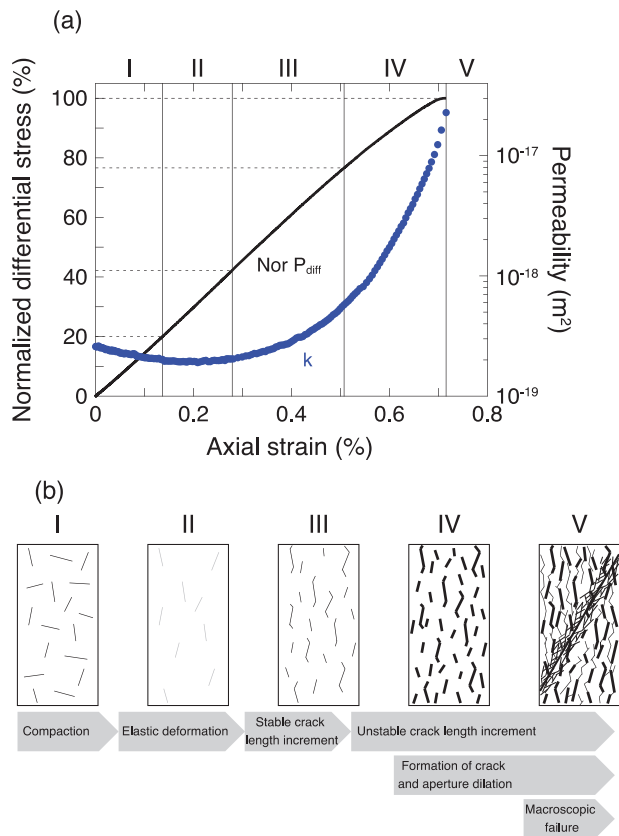


FIGURE 8 Deformation stages during a triaxial compression test in terms of the permeability evolution. (a) Typical changes in the differential stress normalized by the peak stress and permeability as functions of axial strain at confining pressure of 20 MPa. $Nor P_{diff}$ represents the differential stress normalized by the maximum differential stress. (b) Schematic illustrations of microcracking characteristics within a sample at each stage.

(i.e. decrease in the distance between cracks) and crack aperture dilation. As shown in Figure 6, the change in permeability deviates from that of the inelastic volumetric strain at around 80% of the maximum stress, which can be caused by both new crack formation and crack aperture opening. Although the slope α ranges from 0 to 1 during the initial stage of inelastic deformation, this reflects the stable crack length increment, which contributes less to permeability enhancement than the subsequent crack growth.

Considering these results, we propose the deformation stage classifications in terms of the permeability evolution processes (Figure 8). In addition to the previous model (e.g. Paterson & Wong, 2005), a new stage, the permeability enhancement stage, is newly defined in this study. During *stage I*, a decrease in permeability is attributed to the closure of pre-existing cracks in the direction perpendicular to the maximum principal stress. In this study, the permeability reduction continued until the differential stress reached ~20% of the maximum value (Figure 3). *Stage II* is a stage of elastic behaviour and is characterized by constant permeability.

Stage III is characterized by a slight increase in permeability due to the initiation of the microcracking activity, with this stage beginning at ~40% of the maximum differential stress (Figure 2). When the differential stress reaches the crack damage stress (62%–77% of the maximum stress), the volumetric strain turns from compression to dilation, indicating the onset of unstable crack growth. The permeability enhancement behaviour shows no significant changes yet at this stress. As the differential stress increases further, the rate of change of permeability becomes much larger than that of inelastic volumetric strain before reaching *stage V* of macroscopic failure. We define *stage IV* as the regime of significant permeability enhancement where new crack formation and crack aperture dilation occur. The increase in the confining pressure may inhibit crack formation and dilation, although both the onset of dilatancy and crack damage stress are less dependent on the confining pressure. The key feature of *stage IV* is dominant in aperture increase, where we assume that the new crack formation corresponds to the opening of grain boundaries. On the other hand, *stage III* (the crack initiation stress and crack damage stress) can be characterized by the stable and unstable growth of the pre-existing crack length (Bieniawski, 1967b). The confining pressure is more likely to affect the crack aperture dilation than crack length growth, resulting in the pressure dependence on the onset of *stage IV*. This is also consistent with the experimental evidence that the crack aperture decreases with an increase in confining pressure (Sueyoshi et al., 2020). We note that these experimental results established the new relationship between permeability enhancement and microcracking behaviour. To obtain a more detailed permeability model, a quantitative analysis of the effects of geometric factors such as crack connectivity and aperture during deformation is required. Although further studies are needed to verify our hypothesis, micro X-ray CT observation during triaxial rock deformation has recently found a comparable trend of rapid aperture increase during the pre-failure stage (Cartwright-Taylor et al., 2020).

CONCLUSIONS

This study presents experimental data on the continuous evolution of permeability during triaxial compression. Using nitrogen gas as a pore fluid, we succeeded in measuring the permeability of granite during deformation until failure occurred. In all experiments, as differential stress increased, the permeability initially decreased due to the closure of pre-existing cracks and then began to increase at higher differential stress. Although permeability increased by approximately two orders of magnitude during deformation, the variation was larger at 20 MPa than at 40 MPa, suggesting that more cracks developed under the lower confining pressure. Based on the relationship between inelastic volumetric strain and

permeability, permeability was controlled mainly by increases in crack porosity during the initial stages of deformation, but a rapid increase in permeability prior to brittle failure was controlled by both new crack formation and crack aperture enhancement. As the crack aperture is greatly influenced by the confining pressure, the higher the confining pressure, the higher the stress level at which the permeability enhancement stage begins. We have shown that this new deformation stage is characterized by the concurrence of new crack formation and crack aperture dilation due to an increase in differential stress. The crack aperture dilation could be related to the gas pressure at which gas passes through the fluid-saturated rock (Sueyoshi et al., 2020), which is important for the gas-sealing capacity of the fluid-saturated caprock. In contrast, the crack growth may have minimal impact on the gas-sealing capacity because it weakly affects the gas pressure. Therefore, our experimental findings contribute to determining the effect of cracking (i.e. crack growth or aperture dilation) on the gas-sealing capacity based on the permeability change under a given stress state. These experimental results would be beneficial for the safety assessment in applications such as the long-term storage of various gaseous wastes.

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DATA AVAILABILITY STATEMENT

All datasets obtained or analysed during this study are presented in this paper.

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