

How pore size distribution affects fracture-enhanced permeability in lava domes

Mathieu Colombier

`m.colombier@lmu.de`

Ludwig-Maximilians-Universität München

Jackie E. Kendrick

Ludwig-Maximilians-Universität München

Janine Birnbaum

Ludwig-Maximilians-Universität München

Jérémie Vasseur

Ludwig-Maximilians-Universität München

Anthony Lamur

Ludwig-Maximilians-Universität München

Yan Lavallée

Ludwig-Maximilians-Universität München

Katherine. J. Dobson

University of Strathclyde

Takahiro Miwa

National Research Institute for Earth Science and Disaster Resilience (NIED)

Bettina Scheu

Ludwig-Maximilians-Universität München

Ulrich Kueppers

Ludwig-Maximilians-Universität München

Research Article

Keywords: Lava dome, Mt Unzen, Pore size distribution, Fracturing, Permeability, Lattice Boltzmann

Posted Date: October 22nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11258970/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Lava domes are unstable components of volcanic edifices that can experience multiple eruptive phases and collapses. During these cycles, dome rocks undergo various degrees of fracturing due to stresses during emplacement and subsequent cooling-induced contraction. Fractures directly influence gas escape, pressure accumulation, fragmentation, brecciation and abrasion. Here, we use X-ray microtomographic data obtained on a dacite from a block-and-ash flow deposit from the 1990–1995 eruption of Mt Unzen (Japan), and simulate pore-controlled fracturing in the 3D volume through a watershed-type image analysis. We explore the combined role of fractures and pore size distribution on pore connectivity and permeability, using two different starting pore networks: (1) macro-porosity surrounded by micro-pores and (2) macro-pores only. We quantify the influence of fracture number density and width on the evolution of pore connectivity with porosity for the two pore networks, and use Lattice Boltzmann simulations to quantify the porosity-permeability relationships of the virtually cracked rocks. Our results show that connectivity and permeability increase rapidly as a result of cracking in crystal-rich dome rocks, and that the initial pore geometry and size distribution have an important control on the impact of fracturing on connectivity and permeability. Whilst connectivity depends mostly on fracture number density, permeability is more sensitive to fracture width. Combining measurements of connectivity and permeability may be key when assessing the extent and mode of fracturing in volcanic edifices such as lava domes. We discuss the implications of our results for the stability and eruptive style of silicic lava domes.

Introduction

Dome-building eruptions are a complex expression of hybrid, effusive to explosive volcanism at the Earth's surface. They are characterized by frequent and rapid shifts in eruptive style that make them highly unpredictable and hazardous (e.g., Druitt et al. 2002; Calder et al. 2015). The evolution of a lava dome is commonly accompanied by multiple episodes of endogenous and exogenous growth, explosive events and gravitational collapses (Kaneko et al. 2002). This multifaceted behavior is strongly influenced by the thermal and rheological evolution of ascending magma (Melnik and Sparks 1999), the rheological and mechanical response of lavas and rocks in the dome (Lavallée et al. 2008; Harnett et al. 2019), and the efficiency of gas release through the dome and edifice (Mueller et al. 2008; Farquharson et al. 2016).

Gas escape or entrapment in lava domes depends mostly on the permeability of the porous networks at different scales (Klug and Cashman 1996; Saar and Manga 1999; Mueller et al. 2005; Rust and Cashman 2011). Pores consist of a complex assembly of (i) gas bubbles formed in hot magma during decompression and stalling at shallow depths, (ii) their vesicle remnants in quenched lavas, (iii) micro- to macro-fractures in either lavas or rocks, and (iv) intergranular void space between fragments in brecciated or pyroclastic domains (Gardner et al. 1999; Blower 2001; Colombier et al. 2017). The porous network is transient and constantly evolves via volatile exsolution and resulting bubble nucleation, growth, coalescence and collapse (e.g., Sparks 1997; Burgisser et al. 2020), shear (Okumura et al. 2008, 2013; **Lavallée et al. 2015**; Gonnermann et al. 2017), brittle-fracturing and fracture-healing (e.g., Tuffen et

al., 2003; Kushnir et al., 2017; Lamur et al. 2019), viscous or solid-state sintering in fragmented and brecciated domains such as tuffisite veins or localized shear zones (e.g., Kendrick et al. 2016; Ryan et al. 2018; Unwin et al. 2021) and hydrothermal alteration (e.g., Ball et al., 2015). The timing and extent of these processes relies strongly on the extant pressure, temperature and deformation rate (e.g., Coats et al. 2018; Colombier et al. 2020; Ryan et al. 2020) which drive the generation and destruction of permeable pathways (e.g. Lavallée et al 2021).

The process by which porosity is created or destroyed dictates its connectivity, evolution and the related percolation threshold (the critical porosity at which the transition from closed-to open-system degassing occurs; Colombier et al. 2017). In lava domes, porosity-enhancing processes such as vesiculation (with or without shear) and fracturing are compensated by porosity-reducing processes such as bubble collapse, sintering, fracture sealing/ healing and crystallization from a vapor-phase (Vasseur et al. 2013; Horwell et al. 2013; Kendrick et al. 2016; Colombier et al. 2017; Lamur et al. 2019). In crystal-rich dome rocks, complex bubble-crystal interactions during vesiculation, deformation and outgassing create preferential interconnected pore pathways promoting gas migration and porosity redistribution (e.g., Laumonier et al. 2011; Oppenheimer et al. 2015; Colombier et al. 2020; Saito et al. 2025). These processes modulate the porosity of dome rocks such that porosity rarely exceeds 0.5, and commonly exhibit a bimodal distribution (Mueller et al. 2011 and references therein). Several studies have pointed to a shift in the porous architecture across this porosity range with dense dome rocks having microstructures that are more fracture-dominated than more vesicular dome rocks (e.g., Coats et al. 2018).

Fracturing is a crucial contributor to the development of connected, permeable pore networks (Okumura et al. 2010; Kushnir et al. 2017; Lamur et al. 2017). Fracture initiation and propagation in volcanic rocks are strongly influenced by the presence of pre-existing pores and crystals (Heap et al. 2014; Ündül et al. 2015). In a poorly-connected or even isolated pore network formed by vesiculation or bubble collapse, fractures can cause the system to cross the percolation threshold, even at very low porosities (Colombier et al. 2017). Once pore connectivity is achieved, variations in fracture width can then strongly modify permeability (Lamur et al. 2017). Whilst it is viable to experimentally determine the influence of the width of a single fracture on permeability, it has historically been challenging to explore the width of more complex fracture networks in equal detail. To overcome this, here we use X-ray micro-tomography and simulate pore-controlled fracturing through a watershed-type image analysis, in which we explore the combined role of fractures and pore size distribution on porosity, pore connectivity and tortuosity of crystal-bearing dacite from Mt. Unzen volcano (Japan). We then use Lattice Boltzmann simulations to quantify the impact of the virtual fracture networks on permeability. Finally, we discuss the implications for a broad range of processes associated with dome-forming eruptions.

Methods

a) X-ray micro-tomography and image processing

For this study we used a dacitic dome rock from a block-and-ash flow (hereafter BAF) deposit formed during the 1990–1995 eruption of Mt Unzen (Japan). This eruption was characterized by repeated episodes of exogenous and endogenous dome growth, frequently leading to gravitational collapse causing the formation of block and ash flows (e.g., Sato et al. 1992; Yamamoto et al. 1993; Ui et al. 1999). A dense, porphyritic dacite with a porosity of 0.12 was selected. Compared to density and porosity distributions of the dome and block and ash flow deposits at Unzen (Kueppers et al. 2005; **Scheu et al. 2006**), this rock is representative of the denser end-member of the eruption. A cylinder of 26 mm diameter and 13 mm height was cored from the rock. X-ray computed tomography was performed using GE Phoenix X-ray CT v|tome|x s 240 (TUM, Garching), at 110 kV and 110 μ A. A 0.1 mm Copper filter was used to remove any beam hardening. 1440 projections were captured with an exposure time of 1000 ms, and reconstruction was done using the Ge proprietary software giving a reconstructed voxel resolution of 16.4 μ m.

The reconstructed 3D volume was subsequently analysed in Avizo (v2022.2, Thermo Fisher Scientific). A rectangular region of interest of 15.01 mm x 16.19 mm x 12.38 mm = 3010 mm³ volume (Fig. 1a) was cropped from the data. This volume of interest was close to 1000 times the volume of the largest pore and crystal ($\sim$ 50 and 73 mm³, respectively). This volume is smaller than, but still comparable to, the sizes of samples previously used for laboratory measurements of petrophysical and rock mechanical properties of Unzen dacites (e.g., Mueller et al. 2005; Kueppers et al. 2006; Scheu et al. 2008; Coats et al. 2018; **Kendrick et al. 2021**). The dacite has similar macroscopic characteristics as previously described for Unzen BAF samples; that is, abundant phenocrysts (mostly plagioclase with amphibole) frequently in contact with macro-pores (Saito et al. 2025), surrounded by a groundmass consisting of glass, microlites and microporosity (e.g., Nakada and Motomura 1999; Coats et al. 2018; **Kendrick et al. 2021**). The pixel size of 16 μ m achieved in the XCT measurements does not resolve very fine microporosity nor thin vesicle walls, yet enabled us to resolve populations of macro-and micro-pores with a bimodal distribution.

In what follows we use the terms pore, pore size distribution and micro- or macro-porosity to refer to either vesicles or diktytaxitic voids that are difficult to distinguish in such highly crystalline dome rocks (e.g., **Kushnir et al. 2016**). When referring to porosity and pore connectivity after introducing the fracture network, these terms and values also encompass fractures.

We segmented our sample using manual binarization in the segmentation editor of the Avizo software (Fig. SM1b in the Online Resource). A first segmentation approach (hereafter S1) consisted of including all pores (i.e., both macro- and micro-porosity) using a simple thresholding binarization (using grayscale values of 0 to 16 in the masking module of the segmentation editor in Avizo, as these values yielded the best visual result). Total porosity (ϕ) was then measured by dividing the volume of pores by the domain volume. Following this step, we separated pores into (i) those connected to the exterior of the sample (hereafter referred to as connected pores or porosity) and (ii) individual pores or pore clusters not connected to the exterior (hereafter isolated pores or isolated porosity) (Fig. SM1c in the Online Resource). In this study, our definition of pore connectivity (C) is analogous to that obtained using

Helium pycnometry in the laboratory (e.g., Colombier et al. 2017) and is therefore comparable to measurements of connected porosity commonly obtained on Unzen dacites from previous studies (Mueller et al., 2005; Kueppers et al., 2006; Coats et al. 2018; **Kendrick et al. 2021**). For S1, this approach yielded a starting pore network that was highly interconnected and permeable. We note the presence of a branching network of fractures connecting both micro- and macro-pores in this initial volume for S1.

In a second segmentation method (S2), we performed an erosion step of 2 pixels to remove micro-porosity, followed by a dilation of 2 pixels to restore the full size of macro-pores and a remove islands module with a threshold of 30 voxels (Figs. 1b&c). This yielded a macro-porous network with slightly lower connectivity, and produced an initially impervious volume (i.e. no permeable pathways across the sample length in any direction). The micro-porosity is thus defined by the difference between segmentations S1 and S2.

As connectivity assessment is likely affected by thresholding artefacts related to partial volume effect (e.g., Ketcham and Carlson 2001) and our manual segmentation method, we also used a separate object module with a marker extent of 1 to produce a third segmented pore network S3. This step caused a separation of pores within clusters, allowing us to remove the effect of a large interconnected pore cluster. This maintained a similar porosity to S1, with a much lower connectivity.

These different segmentation steps produced 3 synthetic volumes representing different porous networks (Fig. SM2 in the Online Resource); S1 with macro-pores surrounded by clusters of micro-pores, S2 with only macro-pores and S3 in which pore clusters (including macro- and micro-pores) were separated. We then analysed the pore size distributions for both macro- and micro-pores for S1, S2 and S3. These segmentation and basic quantification analyses were followed by our virtual fracture modelling.

b) Virtual fracturing

Fracture propagation in natural samples is dominated by the stress concentrations caused by macro-porosity (Heap et al. 2014). We propagated virtual fractures in our starting volumes (S1 and S2) following segmentation using the binarized pore networks and the Separate Objects module of Avizo (Fig. SM1 in the Online Resource). This module is a simple separation tool based on the watershed principle in which fractures propagate based on irregularities (Van Helden et al. 2024). To control the fracture number density we reduce the pores available for fracturing using an erosion step of 9, 6, 3, 2, 1, or 0 pixels applied on the starting binarized porous networks (without distinction of isolated and connected pores) with (i) all porosity (S1) and (ii) macro-porosity only (S2). This step caused different degrees of shrinking of the pores initially present in the volume (Fig. SM1 in the Online Resource). Fractures were generated within the solid phase without distinction between phenocrysts and the glassy, microlite-rich groundmass. It is noteworthy that individual fractures also propagate through both phenocrysts and groundmass in natural Unzen samples (e.g., Coats et al. 2018; **Kendrick et al. 2021**),

although phenocrysts add complexity in the fracture propagation geometry which is simplified in our model.

The number density of fractures formed depended upon the extent of the erosion step; for extensive erosion (e.g., shrinking of each pore by 9 pixels) only a few macro-pores remained in the volume and a low fracture number density was thus achieved during propagation between the pores, whilst on the contrary high fracture number density was created between pores subjected to low erosion. After each cracking event, any pore volume that was removed in the previous erosion step was replaced in the volume using a OR IMAGE module (Fig. SM1h in the Online Resource). From this point, the connected and isolated fractions of all pores (macro-pores, micro-pores if present initially, and newly formed fractures) were segmented and porosity and connectivity were calculated again (Fig. SM1i in the Online Resource).

For each simulated fracture network, with an initial fracture width of 1 pixel, we then increased the fracture width by dilation to 3, 5 or 7 pixels (corresponding to widths of 16, 48, 80 and 112 μm , respectively). Fracture number density was calculated on one 2D slice selected in the same position for all volumes with a fracture width of 16 μm (1 pixel) and an Auto Skeleton module was used to determine the total number of segments in the skeleton (i.e., the medial axis of the porous network). Dividing this number of segments by the pore-free area yielded the fracture number density in mm^{-2} . All these steps were performed on S1 and S2, whereas a single erosion step (i.e., a single fracture number density) and a single crack width (16 μm) were explored for S3 (Table 1) to quantify the impact of a lower starting pore connectivity.

c) Lattice Boltzmann simulations

Palabos is an open-source parallel C++ library based on the Lattice Boltzmann Method (LBM) and is widely used as a fluid flow simulator across the fluid dynamics and geoscience communities (see Latt et al. 2021 for more information). It has been extensively calibrated and validated for pore-scale simulations. The method discretizes the pore space into a regular lattice of fluid nodes, where packets of fluid mass are propagated and undergo collisions according to a D_3Q_{19} lattice arrangement where D_3 stands for the number of dimensions of space and Q_{19} represents the number of discrete velocity vectors for the directions in which fluid particles can move. A pressure gradient of $10^{-2} \text{ Pa}\cdot\text{m}^{-1}$ was applied, and the fluid density and dynamic viscosity were set to $1.2047 \text{ kg}\cdot\text{m}^{-3}$ and $1.8205\times 10^{-5} \text{ Pa}\cdot\text{s}$, respectively (values corresponding to air at ambient pressure and temperature conditions). These parameters yield a dimensionless pressure gradient of $\sim 4\times 10^{-9}$ in lattice units, ensuring that the flow remains within the laminar regime. We simulated fluid flow in each direction through the sample pore space and, during each simulation, the volume-averaged fluid velocity was computed every 50 iteration steps. Convergence (i.e., when the flow reaches steady state) is assumed when the norm of the volume-averaged fluid velocity changes by less than 10^{-5} for two consecutive evaluations spaced 50 iterations apart. This criterion ensures that the simulation achieves a steady state before termination. Permeability

(k) is then computed from the resulting steady-state fluid velocity and the applied pressure gradient using Darcy's law.

As permeability is rather isotropic in our sample and because the simulations were computationally challenging due to the domain size, we only measured permeability in the x and z directions. Permeability was measured for two fracture widths (16 and 112 μm) and two fracture number densities (erosion steps of 1 and 9 pixels) for both S1 and S2, as well as on the starting porous network before cracking for S1 (9 samples in total) (Table 2). We measured surface area and tortuosity (τ) of the connected pore network for the same volumes on which permeability was measured. Surface area was measured using the label analysis module of Avizo which yields the voxel surface area that is then converted to a surface area in m^2 . Quantification of tortuosity first involved skeletonization of the connected pore network. A Dijkstra's algorithm was then used to compute the shortest path for each node of the skeleton located at the two extremities of the connected pore network in a given direction (e.g., Fu et al. 2021). The geometric tortuosity was then calculated in all directions as the ratio of the average shortest path to the Euclidian distance (i.e., length of the sample in the given direction in the region of interest).

Results

a) Existing porous network of the starting material

Porosity of the initial volume is ~ 0.12 , of which ~ 0.07 is macro-porosity and ~ 0.05 is micro-porosity (Fig. 1; Table 1). The pore-free phenocryst content is 0.18, which is slightly lower than previous estimates for Unzen dacites (e.g., 0.23–0.28 in Nakada and Motomura 1999), likely due to an underestimation caused by limited contrast between plagioclase and glass in our XCT imaging.

The pore size distributions are overall bimodal with a population of macro-pores and a population of micro-pores (Fig. 2). We observe a peak at a few millimeters for macro-porosity and a main mode at a few tens to hundreds of microns for micro-porosity, as constrained by our segmentation methodology following visual observations. The peak at very large sizes for micro-porosity corresponds to the presence of an inter-connected network of individual pores (Fig. SM3). Such a highly connected pore cluster is common in the analysis of volcanic rocks using XCT (e.g., Valdivia et al. 2022) and may be an artefact as connectivity is highly sensitive to thresholding, and the blurred interface between micro-pores and groundmass (partial volume effect; Ketcham and Carlson 2001) and the rather coarse resolution used in our study prevents an accurate quantification of initial connectivity. Applying an automated pore separation algorithm during segmentation in S3 caused isolation of micro-pores (and thereby the disappearance of the large connected cluster) and a reduction in the number of macro-pores larger than ~ 2.5 mm (Fig. 2). Segmentation S1 has a high starting connectivity of $C_i=0.84$. Removing micro-porosity completely only reduced connectivity of the macropores to an initial value of $C_i=0.81$ for S2, but caused the transition from a permeable to impermeable pore network. Separating all pores using segmentation S3 yielded a significantly lower initial pore connectivity $C_i=0.32$ (Table 1).

b) Virtual fracturing

We produce a variety of virtual fracture networks that increase the sample connectivity, with increasing fracture density when separating domains using ever smaller pores (Fig. 3). We note the similarity between branching fracture networks obtained by virtual cracking and those formed during rock mechanics testing (supplementary material in Coats et al. 2018). When increasing fracture number density and width, we see a concomitant increase in porosity and connectivity of the porous network (Figs. 3, 4 and 5). The increase in porosity largely results from the increase in fracture width and is impacted to a lesser degree by fracture number density. The increase in connectivity is instead mostly influenced by the fracture number density, although increasing fracture width also increases connectivity by (i) adding volume to the connected fraction and (ii) increasing the likelihood of intersecting micro-pores.

For the highest fracture number density, fractures connect all pores present in the initial volume (i.e., the case when no erosion was performed) resulting in a connectivity of 1 (Fig. 5). We note that adding more fractures to such a volume would result in increasing porosity while following a horizontal trend with $C = 1$. At a constant fracture number density while increasing fracture width, we observe a more pronounced change in porosity with also a slight increase in connectivity (Fig. 5b). In the S3 porous network in which all the pores were initially separated, with the same porosity as S1, but lower initial connectivity, cracking causes an abrupt increase in connectivity from $C_i=0.32$ to $C = 0.89$ (Fig. 5a).

The change in connectivity ΔC and change in porosity $\Delta\phi$ with fracture number density are different for the porous networks S1 (all porosity) and S2 (macro-porosity only) (Fig. 6). ΔC increases more efficiently and at a lower fracture number density in the presence of macro-pores only (S2) compared to a system with both macro- and micro-pores (S1) (Figs. 6). This is because micro-pores will contribute longer to the isolated fraction during our virtual cracking as (i) they require a higher number density (i.e., less erosion) to contribute to the initial fracture propagation and (ii) they have a lower probability of intersection with a fracture after virtual cracking.

Surface area of the connected pore network increases overall from 0.01152 m^2 before cracking up to a maximum of 0.03254 m^2 after cracking (Fig. 7a), whereas tortuosity drops in all directions from ~ 1.68 (in the absence of fractures) down to a minimum value of 1.04 after cracking (Fig. 7b, Table 2).

Permeability increases with porosity during increase in fracture number density and fracture width in both x and z directions (Fig. 7c). Although the simulations did not reach stable flow conditions for the starting material S1, its permeability is estimated at around 10^{-13} - 10^{-14} m^2 based on the minimum volume-averaged fluid flow velocity reached. Permeability after virtual cracking is in the range of 10^{-12} - 10^{-10} m^2 (Fig. 7c). At a given fracture number density, increasing fracture width from 16 to $112 \mu\text{m}$ causes an increase in permeability by more than one order of magnitude. For S2 (macro-porosity only), cracking causes the transition from impermeable conditions to high permeabilities up to 10^{-10} m^2 .

Discussion

a) Implications for petrophysical properties and outgassing

Our virtual fracture propagation model in a 3D porous network of a dacite from a block and ash flow at Unzen volcano quantifies the impact of pore size distribution (macro- vs. micro-porosity) on the link between petro-physical rock properties (porosity, connectivity, tortuosity and permeability) and fracturing. Our results show that fracturing in crystal-rich dome rocks increases connectivity and permeability, as seen in previous observational and experimental studies (e.g., Mueller et al. 2005; Colombier et al. 2017; Kushnir et al. 2017; Lamur et al. 2017). Fracturing hence acts in combination with other processes such as extensive shearing (Lavallée et al. 2021) and vesicle clustering around crystal frameworks (Saito et al. 2025) to favor permeable gas escape at Unzen and other crystal-rich lava domes. Colombier et al. 2017 discussed that pore connectivity of volcanic rocks strongly depends on fracture number density and size, and that cracking may promote a low percolation threshold by connecting isolated bubbles in an impermeable network. This was verified in the virtual cracking of the initially impermeable S2 and S3 networks (Figs. 5, 6 & 8). Our modelled porosity-connectivity relationships compare well with trends observed in natural samples at Unzen, consistent with the importance of cracking in natural intermediate crystal-rich effusive lavas (Fig. 8). Permeability-porosity evolution of the virtual samples falls within the upper range of natural Unzen dacites (Fig. 9; Mueller et al. 2005; **Kendrick et al. 2021**). The model may modestly overestimate permeability compared to the natural samples due to (i) the relatively high fracture width used in the virtual samples compared to their natural counterparts – a limitation of the image resolution and/or (ii) a lower localized tortuosity of our simplified virtual fractures, with the absence of natural asperities that would otherwise increase surface roughness and friction, decreasing permeability in the simulations (Fig. 7). There is also the possibility that the high fracture number density and high permeability samples are not an artifact of the virtual cracking model, but rather evade a survivorship bias present within the natural samples, in which very highly fractured rocks would disaggregate either in the field or during sample preparation precluding measurements of their permeability. Although these samples may not survive into the lab setting, highly fractured samples may contribute to outgassing pathways in the natural setting, and would be very sensitive to changes in confining or effective pressure (**Lamur et al. 2021**) under processes such as ascent, collapse-driven unloading, increased vapor pressure, or pore water pressure from precipitation or hydrothermal circulation.

The initial pore size distribution has a strong impact on fracture propagation and connectivity and permeability. Networks with only macropores (S2) show a higher increase in connectivity at a given fracture number density compared to networks with both macro- and micro-pores (S1) (Figs. 5, 6). This is because micro-pores contribute more easily to the isolated pore fraction and require more fractures to become interconnected. The impact of initial connectivity on cracking for a given pore network is illustrated by the comparison between S1 ($C_i=0.84$) and S3 ($C_i=0.32$) (Fig. 5). After initial cracking, both pore networks reach a similar connectivity of $C = 0.90$ and $C = 0.89$, respectively (Fig. 5). This shows that fractures have a larger effect on final connectivity than initial vesicle/ void connectivity in fracture-rich samples. In addition, networks with only macro-pores (S2) also display a slightly higher permeability at a

given porosity and fracture width (Fig. 7c). We attribute this to (i) the higher connectivity for S2 compared to S1 and (ii) the likely higher average pore throat resulting from removal of micro-porosity.

In nature, the size and number of pores modify fracture propagation, with macro-fractures preferentially connecting larger macro-pores and micro-fractures rather connecting micro-porosity. The different trends observed in ϕ -C and ϕ -k trends for Unzen rocks reflect a complex interplay of different initial porosity and connectivity, variable pore size distribution and variable number of micro- vs. macro-fractures.

Fractures have a different influence on pore connectivity (here defined as in pycnometry where pores connected to the exterior contribute to connectivity without necessarily being percolating pathways) than permeability. Our dataset suggests that connectivity for a given pore network depends mostly on fracture number density, whereas permeability is in turn more sensitive to fracture width (Figs. 5, 6 and 7). Combining both measurements of connectivity and permeability may be a key to assess the degree and mode of fracturing in volcanic edifices such as lava domes. In addition, connectivity trends observed here confirm that the percolation threshold in magma/lavas/volcanic rocks can be very small when cracking occurs through an initially isolated pore network (Colombier et al. 2017).

b) Permeability models applied to fractured lava dome rocks

We can compare our virtual crack model to previous permeability models applied to lava dome rocks. The Kozeny-Carman model has frequently been used in volcanology to yield simple relationships between porosity and permeability (e.g., Klug et al., 2002; Rust and Cashman, 2004; Farquharson et al. 2015), as well as other factors such as tortuosity. Following Costa (2006), permeability k can be written as follows:

$$k = \frac{c * \Phi^3}{8 * a_v^2 * \tau * (1 - \Phi)^2}$$

Where c is an empirical geometrical parameter, Φ is connected effective porosity (i.e., the fraction of pores connected from one side of a sample to the other), a_v is the specific surface area (the surface area of the connected pores divided by the solid volume) and τ is the geometric tortuosity. The only unknown in our virtual crack model is the geometrical constant c, which depends on pore geometry. For geometric context, the analytical values of c for an ideal straight tube and a flat plane are 4 and ~ 2.67 , respectively (Torquato 2002). We therefore can quantify c in directions x and z (i.e., those for which permeability was measured) during cracking and related increase in fracture number density, as a function of fracture properties (width and number density) and for both S1 and S2 (Fig. 7d). For small fracture widths (16 μm), we observe a continuous increase of c during cracking from nearly zero up to values of ~ 1.5 – 2.5 . For thicker fractures (112 μm), c first reaches a maximum value of ~ 4.5 – 5.5 for S2 and S1, respectively, and then decreases down to ~ 3 – 4.5 with further increase in fracture number density. The initial increase of c corresponds to a simplification of the average pore geometry during cracking, whereas the

subsequent decrease for large fracture width may be due to a higher complexity of fracture geometry at higher number density due to tighter branching and important fracture overlap (e.g., Fig. 3).

Farquharson et al. (2015) previously discussed that the Kozeny–Carman relation may not adequately capture the microstructural complexity of volcanic rocks as it fails to predict connectivity. We note that the role of connectivity and microstructural complexity are directly integrated in our model as they influence the evolution of permeability, specific surface area, porosity and the geometric constant c during fracturing.

c) Implications for mechanical failure and eruptive processes

Our present model may shed light on the role of pore size distribution and cracking on mechanical properties of dome rocks. Several studies discussed the effect of porosity, pore size and pore heterogeneities on fracture propagation and consequences for mechanical properties (e.g., Heap et al., 2014; Vasseur et al., 2015; Wadsworth et al., 2025). Pore connectivity may contribute to the strength and Young's Modulus of volcanic rocks (Harnett et al., 2019; Lavallée and Kendrick, 2021). Our study extends these previous findings and allows us to link petro-physical properties of dome rocks to a controlled network of virtual fractures and the effect of textural properties of volcanic rocks on these relationships. Pore size distribution has been shown to have a strong influence on fracture propagation and subsequently on connectivity and permeability, even at a narrow range of low porosities used in our model, and we propose that this may contribute to explain the broad range of failure response to stress observed in low porosity dome rocks at Mt. Unzen and other volcanoes worldwide.

In natural dome lavas/rocks, the increase in connectivity and permeability during fracture propagation and coalescence may lead to macroscopic failure and transition to a granular medium. This failure can be localized and non-explosive (e.g., brecciation in the conduit; Stasiuk et al. 1996; Tuffen et al. 2003) or may in turn result in explosive magma fragmentation (**Gonnermann and Manga 2003**; Kueppers et al. 2006). Fracture width, connectivity, permeability, stress conditions and gas pressure within pores will determine whether (i) the rock will stay cohesive or not during cracking, and (ii) the granular fragments will be ejected explosively from the vent (i.e., pyroclasts), and thereby modulate the transition between effusive and explosive processes. This transition to granular media caused by fracturing is also critical to understand the effects of long-term deformation (Hirakawa et al. 2018) and cooling on potential collapse at Unzen volcano (Shi et al. 2018). In addition, our model may have implications for processes occurring not only in the dome but also during transport following explosive or gravity-driven collapse. The characteristics of the fracture network within blocks generated during partial dome collapse and subsequent abrasion in pyroclastic flows control ash generation (Miyabuchi, 1999; Scheu et al. 2008; Kueppers et al. 2012) with important implications for secondary hazards related to co-PDC ash plumes generated at Unzen volcano and elsewhere (Watanabe et al. 1999; **Engwell and Eychenne 2016**).

d) Further considerations

Our model captures the effect of pore geometry and size distribution on the fracture propagation direction (and ultimately their geometry). However, the effect of pores on fracture propagation is more complex and can affect the fracture width population (Wadsworth et al. 2025) which is not represented in our model. Phenocrysts will also exert a strong control on fracture nucleation and propagation. In natural dome rocks, this is shown by polymodal fracture width and number density populations (Calder et al. 2015; Coats et al. 2018).

Finally, further work is necessary to generalize beyond the single sample explored in this work. Although we varied the pore size distribution by removal of the micro-porosity (i.e., S1 vs. S2), we expect a higher variability in pore populations for natural Unzen dacites and dome rocks in general. In such a case, cracking would create a unique pathway for each sample on a connectivity-porosity or permeability-porosity plot (Figs. 8 and 9).

Conclusion

Fractures play a key role in regulating the permeability and strength of lavas/rocks emplaced during dome-building eruptions. Our virtual cracking model highlights the influence of textural features of lava dome rocks on fracture formation and related petro-physical properties. We were able to link pore size distribution-controlled fracture propagation and consequences for porosity, connectivity, tortuosity and permeability evolution. Our study showed that the tendency of fractures to exploit micro-porosity, approximated by removing micro-porosity from the fracture generation, has a strong control on fracture number density and connectivity evolution. Fracture number density and width and their consequences for connectivity and tortuosity all contribute to modify the permeability increase during cracking. In lava domes, the interplay between fracturing and other pore-changing processes such as fragmentation, sintering, vesiculation, collapse and others must be considered to understand (i) permeable transfer through dome edifices and (ii) the transition between ductile and brittle behavior, both being primary in controlling the hazards associated with lava domes. Fractures are formed at different length- and timescales in a dome and influence eruptive processes spanning from effusive emplacement, collapse and explosive events and long-term cooling and hydrothermal activity in the edifice. Our approach is a first step in modelling the role of fractures at the scale of effusive and explosive dome rocks usually studied in the laboratory. Future work may be needed to upscale these results to the architecture and lifespan of silicic lava domes during long-term mechanical and thermal stress.

Declarations

Funding

We acknowledge funding by the German Research Foundation (DFG) – Project-ID 555278243 as well as support from an ERC Consolidator Grant on ‘Magma Outgassing During Eruptions and Geothermal Exploration’ (MODERATE; no. 101001065).

Author Contribution

MC conceptualized the study, performed the data analysis, interpreted the results and wrote the text. KJD and MC conducted the X-ray micro-tomography. JEK, AL, and JB contributed to the interpretation of the results and revised the text. JV ran the Lattice Boltzmann fluid simulations. UK, BS, and TM reviewed the manuscript. All authors approved the final manuscript.

Acknowledgement

We thank several Japanese colleagues for logistic support during many field campaigns of LMU staff on Unzen volcano.

Data Availability

All data are available in the paper and in the supplementary material

References

1. Ball JL, Stauffer PH, Calder ES, Valentine GA (2015) The hydrothermal alteration of cooling lava domes. *Bull Volcanol* 77(12):102. <https://doi.org/10.1007/s00445-015-0986-z>
2. Blower J (2001) Factors controlling permeability–porosity relationships in magma. *Bull Volcanol* 63(7):497–504. <https://doi.org/10.1007/s004450100172>
3. Burgisser A, Arbaret L, Martel C, Forien M, Colombier M (2020) The role of oxides in the shallow vesiculation of ascending magmas. *J Volcanol Geoth Res* 406:107072. <https://doi.org/10.1016/j.jvolgeores.2020.107072>
4. Calder ES, Lavallée Y, Kendrick JE, Bernstein M (2015) Lava dome eruptions. In *The encyclopedia of volcanoes* (pp. 343–362). Academic Press. <https://doi.org/10.1016/B978-0-12-385938-9.00018-3>
5. Coats R, Kendrick JE, Wallace PA, Miwa T, Hornby AJ, Ashworth JD, Lavallée Y (2018) Failure criteria for porous dome rocks and lavas: a study of Mt. Unzen, Japan. <https://doi.org/10.5194/se-9-1299-2018>
6. Colombier M, Wadsworth FB, Gurioli L, Scheu B, Kueppers U, Di Muro A, Dingwell DB (2017) The evolution of pore connectivity in volcanic rocks. *Earth Planet Sci Lett* 462:99–109. <https://doi.org/10.1016/j.epsl.2017.01.011>
7. Colombier M, Wadsworth FB, Scheu B, Vasseur J, Dobson KJ, Cáceres F, Dingwell DB (2020) In situ observation of the percolation threshold in multiphase magma analogues. *Bull Volcanol* 82(4):32. <https://doi.org/10.1007/s00445-020-1370-1>
8. Costa A (2006) Permeability-porosity relationship: A reexamination of the Kozeny-Carman equation based on a fractal pore-space geometry assumption. *Geophys Res Lett* 33(2).

<https://doi.org/10.1029/2005GL025134>

9. Druitt TH, Young SR, Baptie B, Bonadonna C, Calder ES, Clarke AB, Voight B (2002) Episodes of cyclic Vulcanian explosive activity with fountain collapse at Soufrière Hills Volcano, Montserrat. <https://doi.org/10.1144/GSL.MEM.2002.021.01.13>
10. Gardner JE, Hilton M, Carroll MR (1999) Experimental constraints on degassing of magma: isothermal bubble growth during continuous decompression from high pressure. *Earth Planet Sci Lett* 168(1–2):201–218. [https://doi.org/10.1016/S0012-821X\(99\)00051-5](https://doi.org/10.1016/S0012-821X(99)00051-5)
11. Farquharson J, Heap MJ, Varley NR, Baud P, Reuschlé T (2015) Permeability and porosity relationships of edifice-forming andesites: a combined field and laboratory study. *J Volcanol Geoth Res* 297:52–68. <https://doi.org/10.1016/j.jvolgeores.2015.03.016>
12. Farquharson JI, Heap MJ, Baud P (2016) Strain-induced permeability increase in volcanic rock. *Geophys Res Lett* 43(22):11–603. <https://doi.org/10.1002/2016GL071540>
13. Fu J, Thomas HR, Li C (2021) Tortuosity of porous media: Image analysis and physical simulation. *Earth Sci Rev* 212:103439. <https://doi.org/10.1016/j.earscirev.2020.103439>
14. Gaunt HE, Sammonds PR, Meredith PG, Smith R, Pallister JS (2014) Pathways for degassing during the lava dome eruption of Mount St. Helens 2004–2008. *Geology* 42(11):947–950. <https://doi.org/10.1130/G35940.1>
15. Gonnermann HM (2003) Explosive volcanism may not be an inevitable consequence of magma fragmentation. *Nature* 426.6965. 432–435. <https://doi.org/10.1038/nature02138>
16. Gonnermann HM, Giachetti T, Fliedner C, Nguyen CT, Houghton BF, Crozier JA, Carey RJ (2017) Permeability during magma expansion and compaction. *J Geophys Research: Solid Earth* 122(12):9825–9848. <https://doi.org/10.1002/2017JB014783>
17. Harnett CE, Kendrick JE, Lamur A, Thomas ME, Stinton A, Wallace PA, Lavallée Y (2019) Evolution of mechanical properties of lava dome rocks across the 1995–2010 eruption of soufrière hills volcano, Montserrat. *Front Earth Sci* 7:7. <https://doi.org/10.3389/feart.2019.00007>
18. Heap MJ, Xu T, Chen CF (2014) The influence of porosity and vesicle size on the brittle strength of volcanic rocks and magma. *Bull Volcanol* 76(9):856. <https://doi.org/10.1007/s00445-014-0856-0>
19. Hirakawa Y, Usuki N, Fujita K, Tanaka T, Kaneko M, Ueno T, Shimokubo K (2018) Monitoring system of a large rockslide in Heisei-Shinzan Lava Dome, Mt. Unzen, Japan. In *Symp. Proc. of the INTERPRAENENT 2018 in the Pacific Rim* (Vol. 2018, pp. 1–10)
20. Hornby AJ, Lavallée Y, Kendrick JE, De Angelis S, Lamur A, Lamb OD, Chigna G (2019) Brittle-ductile deformation and tensile rupture of dome lava during inflation at Santiaguito, Guatemala. *J Geophys Research: Solid Earth* 124(10):10107–10131. <https://doi.org/10.1029/2018JB017253>
21. Horwell CJ, Williamson BJ, Llewellyn EW, Damby DE, Le Blond JS (2013) The nature and formation of cristobalite at the Soufrière Hills volcano, Montserrat: implications for the petrology and stability of silicic lava domes. *Bull Volcanol* 75(3):696. <https://doi.org/10.1007/s00445-013-0696-3>
22. Kaneko T, Wooster MJ, Nakada S (2002) Exogenous and endogenous growth of the Unzen lava dome examined by satellite infrared image analysis. *J Volcanol Geoth Res* 116(1–2):151–160.

[https://doi.org/10.1016/S0377-0273\(02\)00216-0](https://doi.org/10.1016/S0377-0273(02)00216-0)

23. Kendrick JE, Lavallée Y, Varley NR, Wadsworth FB, Lamb OD, Vasseur J (2016) Blowing off steam: tuffsite formation as a regulator for lava dome eruptions. *Front Earth Sci* 4:41. <https://doi.org/10.3389/feart.2016.00041>
24. Ketcham RA, Carlson WD (2001) Acquisition, optimization and interpretation of X-ray computed tomographic imagery: applications to the geosciences. *Comput Geosci* 27(4):381–400. [https://doi.org/10.1016/S0098-3004\(00\)00116-3](https://doi.org/10.1016/S0098-3004(00)00116-3)
25. Klug C, Cashman KV (1996) Permeability development in vesiculating magmas: implications for fragmentation. *Bull Volcanol* 58(2):87–100. <https://doi.org/10.1007/s004450050128>
26. Klug C, Cashman KV, Bacon C (2002) Structure and physical characteristics of pumice from the climactic eruption of Mount Mazama (Crater Lake), Oregon. *Bull Volcanol* 64(7):486–501. <https://doi.org/10.1007/s00445-002-0230-5>
27. Kueppers U, Scheu B, Spieler O, Dingwell DB (2005) Field-based density measurements as tool to identify preeruption dome structure: set-up and first results from Unzen volcano, Japan. *J Volcanol Geoth Res* 141(1–2):65–75. <https://doi.org/10.1016/j.jvolgeores.2004.09.005>
28. Kueppers U, Scheu B, Spieler O, Dingwell DB (2006) Fragmentation efficiency of explosive volcanic eruptions: a study of experimentally generated pyroclasts. *J Volcanol Geoth Res* 153(1–2):125–135. <https://doi.org/10.1016/j.jvolgeores.2005.08.006>
29. Kueppers U, Putz C, Spieler O, Dingwell DB (2012) Abrasion in pyroclastic density currents: insights from tumbling experiments. *Phys Chem Earth Parts a/b/c* 45:33–39. <https://doi.org/10.1016/j.pce.2011.09.002>
30. Kushnir AR, Martel C, Champallier R, Arbaret L (2017) In situ confirmation of permeability development in shearing bubble-bearing melts and implications for volcanic outgassing. *Earth Planet Sci Lett* 458:315–326. <https://doi.org/10.1016/j.epsl.2016.10.053>
31. Lamur A, Kendrick JE, Eggertsson GH, Wall RJ, Ashworth JD, Lavallée Y (2017) The permeability of fractured rocks in pressurised volcanic and geothermal systems. *Sci Rep* 7(1):6173. <https://doi.org/10.1038/s41598-017-05460-4>
32. Lamur A, Kendrick JE, Wadsworth FB, Lavallée Y (2019) Fracture healing and strength recovery in magmatic liquids. *Geology* 47(3):195–198. <https://doi.org/10.1130/G45512.1>
33. Latt J, Malaspinas O, Kontaxakis D, Parmigiani A, Lagrava D, Brogi F, Chopard B (2021) Palabos: parallel lattice Boltzmann solver. *Comput Math Appl* 81:334–350. <https://doi.org/10.1016/j.camwa.2020.03.022>
34. Laumonier M, Arbaret L, Burgisser A, Champallier R (2011) Porosity redistribution enhanced by strain localization in crystal-rich magmas. *Geology* 39(8):715–718. <https://doi.org/10.1130/G31803.1>
35. Lavallée Y, Meredith PG, Dingwell DB, Hess KU, Wassermann J, Cordonnier B, Kruhl JH (2008) Seismogenic lavas and explosive eruption forecasting. *Nature* 453(7194):507–510. <https://doi.org/10.1038/nature06980>

36. Lavallée Y, Miwa T, Ashworth JD, Wallace PA, Kendrick JE, Coats R, Tuffen H (2021) Transient conduit permeability controlled by a shift between compactant shear and dilatant rupture at Unzen volcano (Japan). *Solid Earth Discussions*, 2021, 1–39. <https://doi.org/10.5194/se-13-875-2022>
37. Lavallée Y, Kendrick JE (2021) A review of the physical and mechanical properties of volcanic rocks and magmas in the brittle and ductile regimes. *Forecasting and planning for volcanic hazards, risks, and disasters*, 153–238. <https://doi.org/10.1016/B978-0-12-818082-2.00005-6>
38. Melnik O, Sparks RSJ (1999) Nonlinear dynamics of lava dome extrusion. *Nature* 402(6757):37–41. <https://doi.org/10.1029/2004JB003183>
39. Miyabuchi Y (1999) Deposits associated with the 1990–1995 eruption of Unzen volcano, Japan. *J Volcanol Geoth Res* 89(1–4):139–158. [https://doi.org/10.1016/S0377-0273\(98\)00129-2](https://doi.org/10.1016/S0377-0273(98)00129-2)
40. Mueller S, Melnik O, Spieler O, Scheu B, Dingwell DB (2005) Permeability and degassing of dome lavas undergoing rapid decompression: an experimental determination. *Bull Volcanol* 67(6):526–538. <https://doi.org/10.1007/s00445-004-0392-4>
41. Mueller S, Scheu B, Spieler O, Dingwell DB (2008) Permeability control on magma fragmentation. *Geology* 36(5):399–402. <https://doi.org/10.1130/G24605A.1>
42. Mueller S, Scheu B, Kueppers U, Spieler O, Richard D, Dingwell DB (2011) The porosity of pyroclasts as an indicator of volcanic explosivity. *J Volcanol Geoth Res* 203(3–4):168–174. <https://doi.org/10.1016/j.jvolgeores.2011.04.006>
43. Nakada S, Motomura Y (1999) Petrology of the 1991–1995 eruption at Unzen: effusion pulsation and groundmass crystallization. *J Volcanol Geoth Res* 89(1–4):173–196. [https://doi.org/10.1016/S0377-0273\(98\)00131-0](https://doi.org/10.1016/S0377-0273(98)00131-0)
44. Okumura S, Nakamura M, Tsuchiyama A, Nakano T, Uesugi K (2008) Evolution of bubble microstructure in sheared rhyolite: Formation of a channel-like bubble network. *J Geophys Research: Solid Earth* 113(B7). <https://doi.org/10.1029/2007JB005362>
45. Okumura S, Nakamura M, Nakano T, Uesugi K, Tsuchiyama A (2010) Shear deformation experiments on vesicular rhyolite: Implications for brittle fracturing, degassing, and compaction of magmas in volcanic conduits. *J Geophys Research: Solid Earth* 115(B6). <https://doi.org/10.1029/2009JB006904>
46. Okumura S, Nakamura M, Uesugi K, Nakano T, Fujioka T (2013) Coupled effect of magma degassing and rheology on silicic volcanism. *Earth Planet Sci Lett* 362:163–170. <https://doi.org/10.1016/j.epsl.2012.11.056>
47. Oppenheimer J, Rust AC, Cashman KV, Sandnes B (2015) Gas migration regimes and outgassing in particle-rich suspensions. *Front Phys* 3:60. <https://doi.org/10.3389/fphy.2015.00060>
48. Rust AC, Cashman KV (2004) Permeability of vesicular silicic magma: inertial and hysteresis effects. *Earth Planet Sci Lett* 228(1–2):93–107. <https://doi.org/10.1016/j.epsl.2004.09.025>
49. Rust AC, Cashman KV (2011) Permeability controls on expansion and size distributions of pyroclasts. *J Geophys Research: Solid Earth* 116(B11). <https://doi.org/10.1029/2011JB008494>

50. Ryan AG, Russell JK, Heap MJ (2018) Rapid solid-state sintering in volcanic systems. *Am Mineral* 103(12):2028–2031. <https://doi.org/10.2138/am-2018-6714>
51. Ryan AG, Heap MJ, Russell JK, Kennedy LA, Clynne MA (2020) Cyclic shear zone cataclasis and sintering during lava dome extrusion: Insights from Chaos Crags, Lassen Volcanic Center (USA). *J Volcanol Geoth Res* 401:106935. <https://doi.org/10.1016/j.jvolgeores.2020.106935>
52. Saar MO, Manga M (1999) Permeability-porosity relationship in vesicular basalts. *Geophys Res Lett* 26(1):111–114. <https://doi.org/10.1029/1998GL900256>
53. Saito K, Hoshino M, Goto A, Namiki A, Saito et al (2025) *Sci Rep*. <https://doi.org/10.1038/s41598-025-28770-4>
54. Sato H, Fujii T, Nakada S (1992) Crumbling of dacite dome lava and generation of pyroclastic flows at Unzen volcano. *Nature* 360(6405):664–666. <https://doi.org/10.1038/360664a0>
55. Scheu B, Kueppers U, Mueller S, Spieler O, Dingwell DB (2008) Experimental volcanology on eruptive products of Unzen volcano. *J Volcanol Geoth Res* 175(1–2):110–119. <https://doi.org/10.1016/j.jvolgeores.2008.03.023>
56. Shi X, Jiang Y, Hirakawa Y (2018) Growth and potential collapse of the lava dome in Unzen volcano and the estimation on block-and-ash flows. *Geosci J* 22(2):273–286. <https://doi.org/10.1007/s12303-017-0051-3>
57. Sparks RSJ (1997) Causes and consequences of pressurisation in lava dome eruptions. *Earth Planet Sci Lett* 150(3–4):177–189. [https://doi.org/10.1016/S0012-821X\(97\)00109-X](https://doi.org/10.1016/S0012-821X(97)00109-X)
58. Stasiuk MV, Barclay J, Carroll MR, Jaupart C, Ratté JC, Sparks RSJ, Tait SR (1996) Degassing during magma ascent in the Mule Creek vent (USA). *Bull Volcanol* 58(2):117–130. <https://doi.org/10.1007/s004450050130>
59. Torquato S (2002) Random heterogeneous materials: microstructure and macroscopic properties, vol 16. Springer, New York
60. Tuffen H, Dingwell DB, Pinkerton H (2003) Repeated fracture and healing of silicic magma generate flow banding and earthquakes? *Geology* 31(12):1089–1092. <https://doi.org/10.1130/G19777.1>
61. Ui T, Matsuwo N, Sumita M, Fujinawa A (1999) Generation of block and ash flows during the 1990–1995 eruption of Unzen Volcano, Japan. *J Volcanol Geoth Res* 89(1–4):123–137. [https://doi.org/10.1016/S0377-0273\(98\)00128-0](https://doi.org/10.1016/S0377-0273(98)00128-0)
62. Ündül Ö, Amann F, Aysal N, Plötze ML (2015) Micro-textural effects on crack initiation and crack propagation of andesitic rocks. *Eng Geol* 193:267–275. <https://doi.org/10.1016/j.enggeo.2015.04.024>
63. Unwin HE, Tuffen H, Phillips E, Wadsworth FB, James MR (2021) Pressure-driven opening and filling of a volcanic hydrofracture recorded by tuffsite at Húsafell, Iceland: A potential seismic source. *Front Earth Sci* 9:668058. <https://doi.org/10.3389/feart.2021.668058>
64. Valdivia P, Marshall AA, Brand BD, Manga M, Huber C (2022) Mafic explosive volcanism at Llaima Volcano: 3D x-ray microtomography reconstruction of pyroclasts to constrain shallow conduit processes. *Bull Volcanol* 84(1):2. <https://doi.org/10.1007/s00445-021-01514-8>

65. van Helden KM, Schmith J, Downs DT (2024) The influence of vesicularity on grain morphology in basaltic pyroclasts from Mauna Loa and Kīlauea volcanoes. *J Appl Volcanology* 13(1):6. <https://doi.org/10.1186/s13617-024-00145-w>
66. Vasseur J, Wadsworth FB, Lavallée Y, Hess KU, Dingwell DB (2013) Volcanic sintering: timescales of viscous densification and strength recovery. *Geophys Res Lett* 40(21):5658–5664. <https://doi.org/10.1002/2013GL058105>
67. Vasseur J, Wadsworth FB, Lavallée Y, Bell AF, Main IG, Dingwell DB (2015) Heterogeneity: The key to failure forecasting. *Sci Rep* 5(1):13259. <https://doi.org/10.1038/srep13259>
68. Wadsworth FB, Vasseur J, Heap MJ (2025) An analytical form of the pore-emanating crack model in 3-D with implications for the uniaxial compressive strength of sandstone. *Geophys J Int* 241(1):495–510. <https://doi.org/10.1093/gji/ggaf047>
69. Watanabe K, Ono K, Sakaguchi K, Takada A, Hoshizumi H (1999) Co-ignimbrite ash-fall deposits of the 1991 eruptions of Fugen-dake, Unzen Volcano, Japan. *J Volcanol Geoth Res* 89(1–4):95–112. [https://doi.org/10.1016/S0377-0273\(98\)00126-7](https://doi.org/10.1016/S0377-0273(98)00126-7)
70. Yamamoto T, Takarada S, Suto S (1993) Pyroclastic flows from the 1991 eruption of Unzen volcano, Japan. *Bull Volcanol* 55(3):166–175. <https://doi.org/10.1007/BF00301514>

Tables

Tables 1 and 2 are available in the Supplementary Files section.

Figures

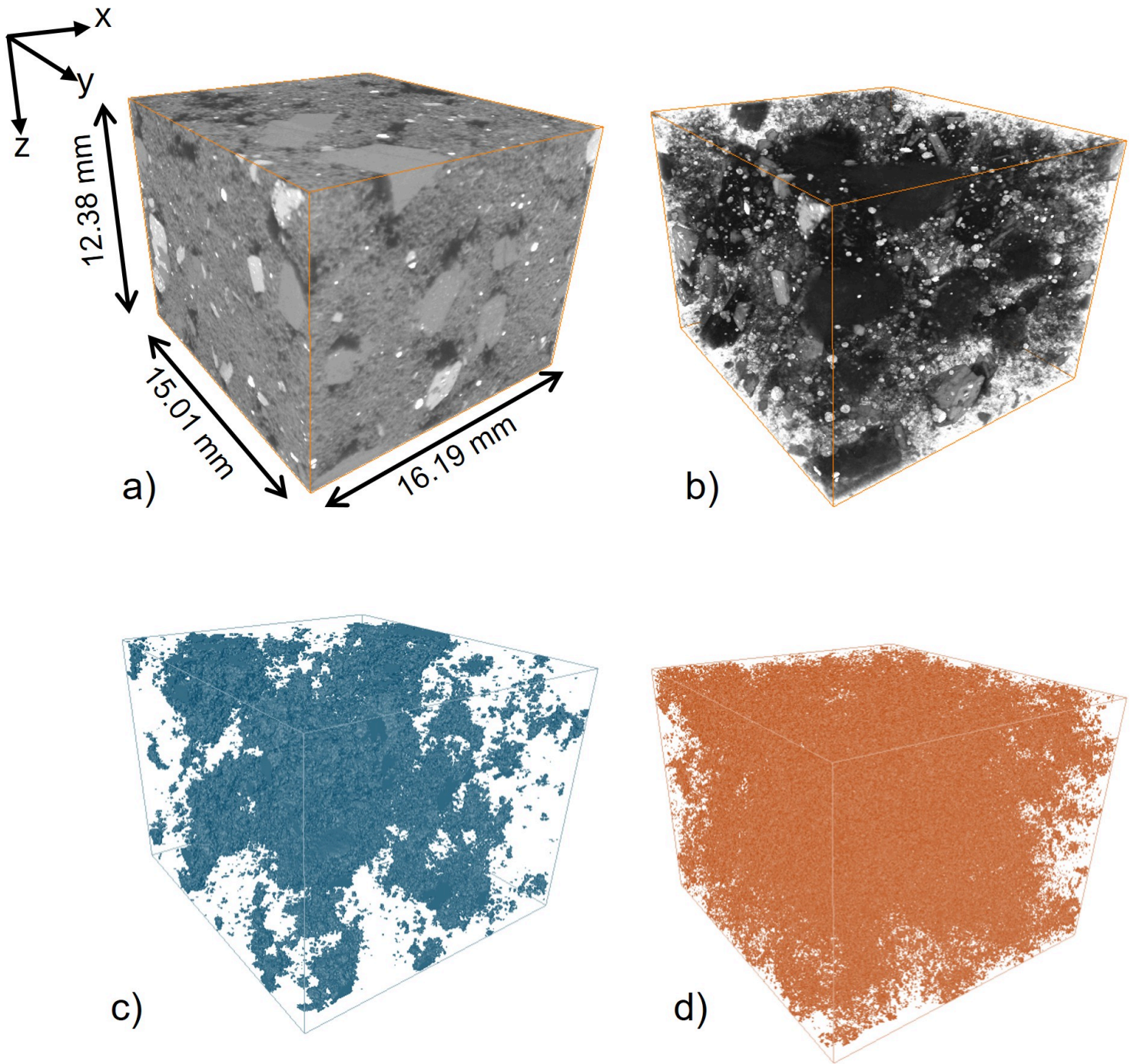


Figure 1

Sample volume renderings showing all phases (a), phenocrysts and micro-phenocrysts (b), macro-porosity (c) and micro-porosity (d).

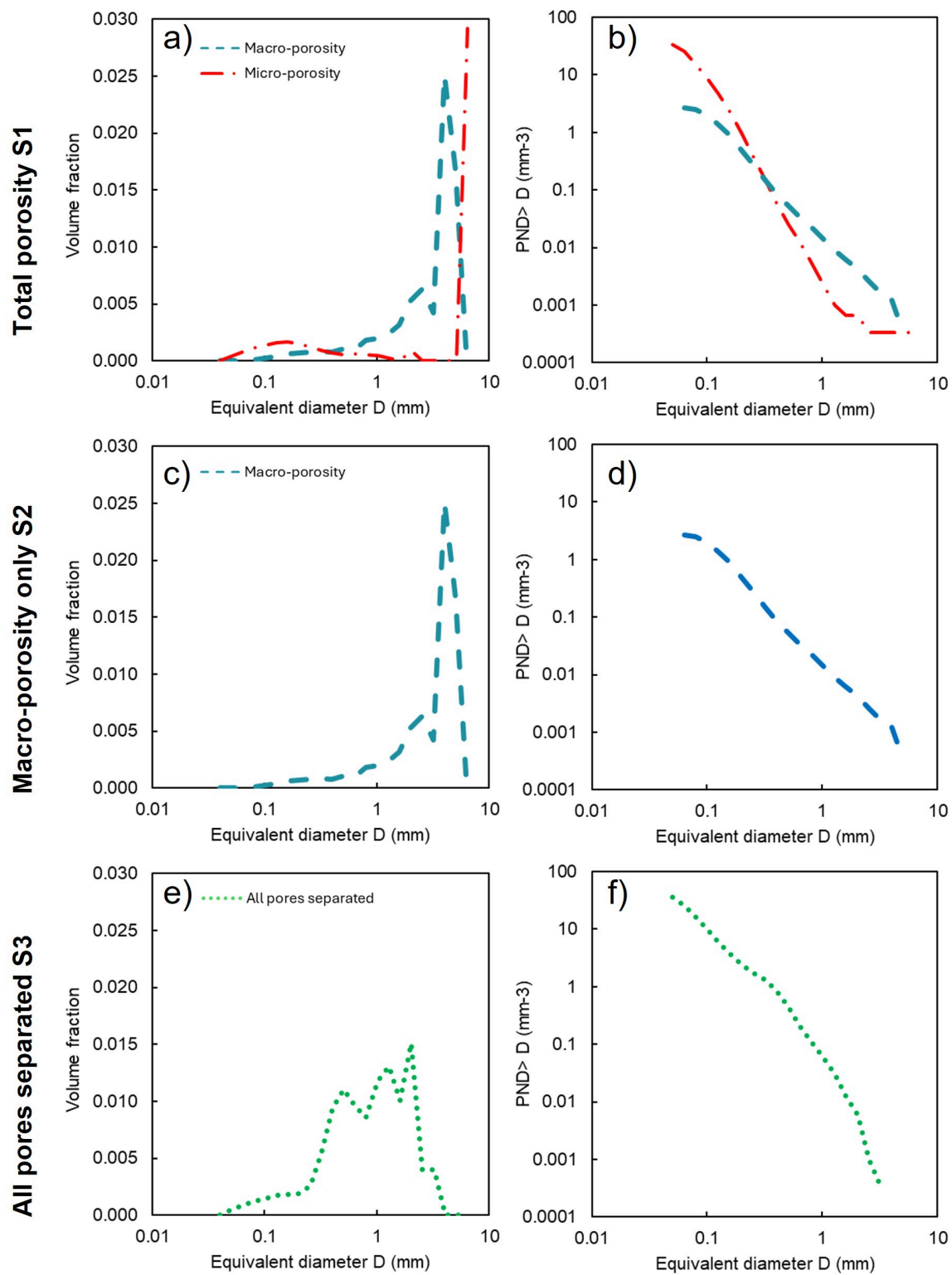


Figure 2

Pore size distributions in the segmented XCT of the Unzen dome rock. Volume fraction distribution (left panel) and Cumulative pore number densities (PND; right panel) are shown for the segmentations S1 (a,b), S2 (c,d) and S3 (e,f). Pore size distribution for S1 consists of a combination of macro-pores and micro-pores (a,b). These are shown separately because a large portion of micro-pores are, in reality, connected to macro-pores. The spike at high equivalent diameter for micro-pores corresponds to the

existence of a large interconnected pore cluster (see Fig. SM3 in the Online Resource). Pore size distribution for S2 was obtained after removal of micro-porosity, so that S2 consists of only macro-pores (c,d). Separation of all pores in S3 (e,f) causes a disappearance of pore clusters in both macro- and micro-pore populations.

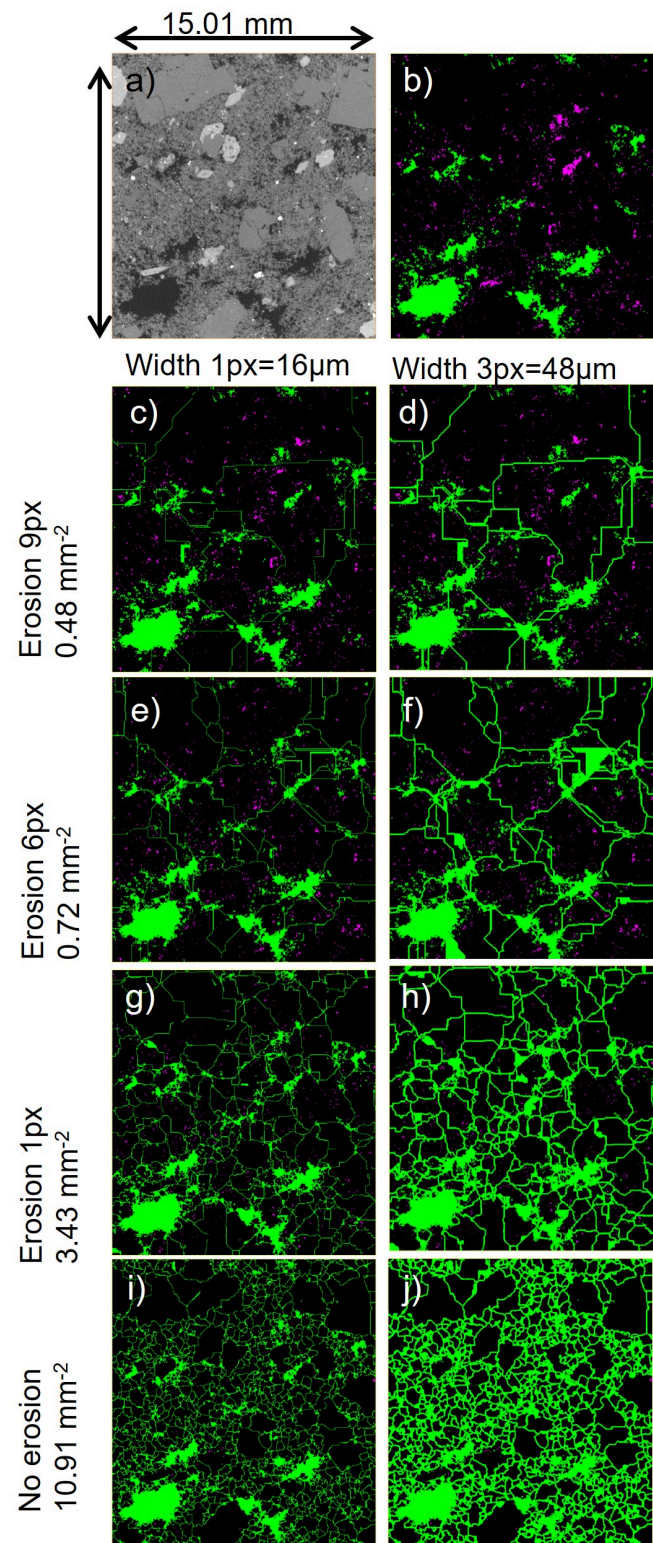


Figure 3

2D slices of the 3D volumes generated before and after virtual fracturing. a) Initial grayscale image. b) Initial connectivity (green: connected pores and purple: isolated pores) prior to virtual fracturing. c to j) Evolution of the pore network during increase in fracture number density (top to bottom) at a given width, and increase in fracture width (left to right) at a given number density.

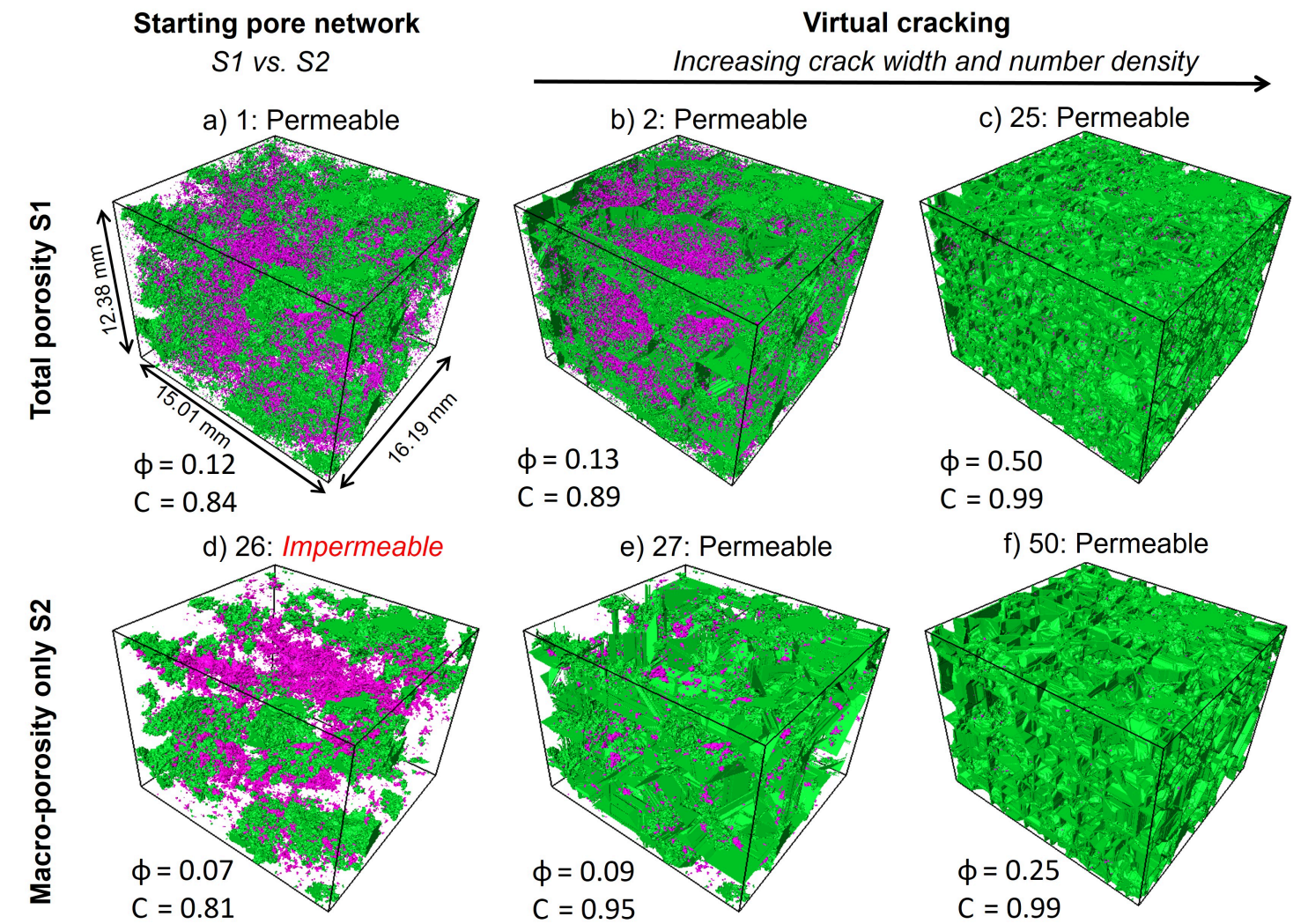


Figure 4

3D volume renderings of pore connectivity for segmentations S1 and S2 before and after virtual fracturing. Green colors represent interconnected pores and purple represents isolated pores. a to c) Increasing porosity and connectivity during (a to b) initial virtual fracturing and (b to c) increasing fracture number density and width in segmentation S1. d to f) Increasing porosity and connectivity during (d to e) initial virtual fracturing and (e to f) increasing fracture number density and width in segmentation S2. The numbers (1, 2, 25, 26, 27 and 50) indicate the volumes generated by segmentation and virtual fracturing as shown in Table 1.

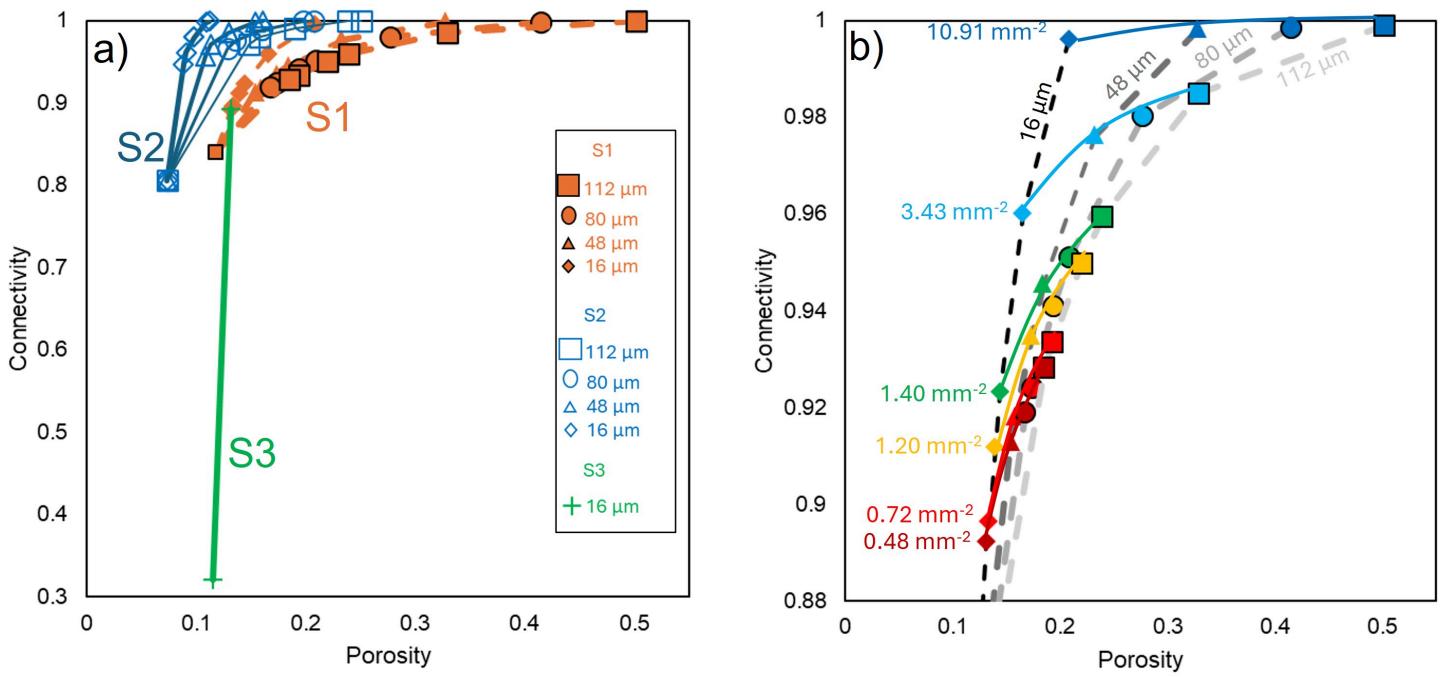


Figure 5

Porosity-connectivity evolution during virtual cracking for (a) segmentations S1, S2 and S3, and (b) a zoom in S1 showing the effect of fracture number density (colored lines) and width (grey dashed lines) on porosity-connectivity relationships. Note the strong influence of fracture number density on connectivity at a given width, while fracture width increases both porosity and connectivity at a given number density.

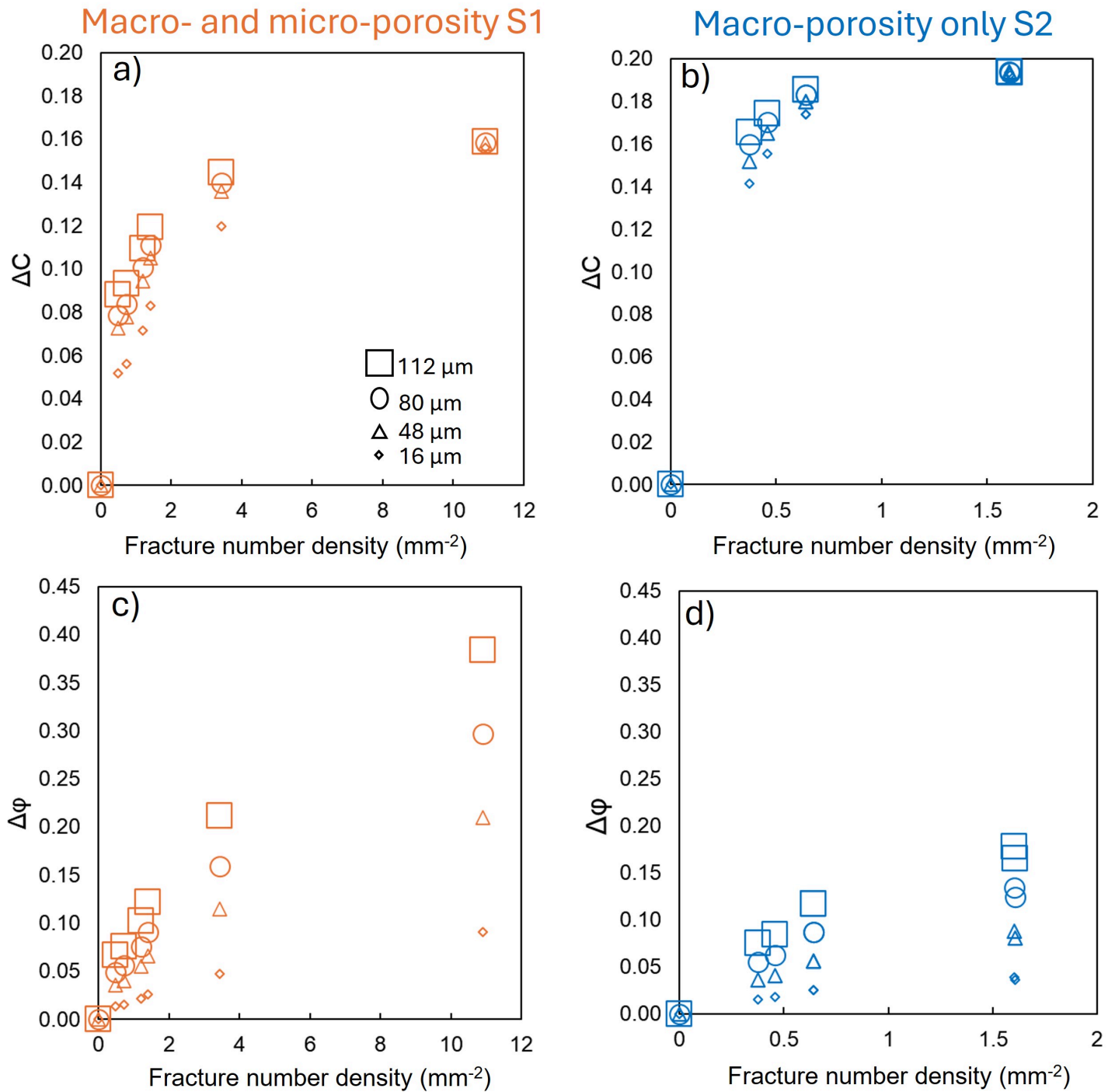


Figure 6

The relationship between (a-b) change in connectivity ΔC and (c-d) change in porosity $\Delta \Phi$ during cracking as a function of fracture number density and fracture width (symbols) for segmentation S1 (left) and S2 (right). Note the differing scales in x axis, with significantly higher fracture number density required to increase connectivity for S1 compared to S2.

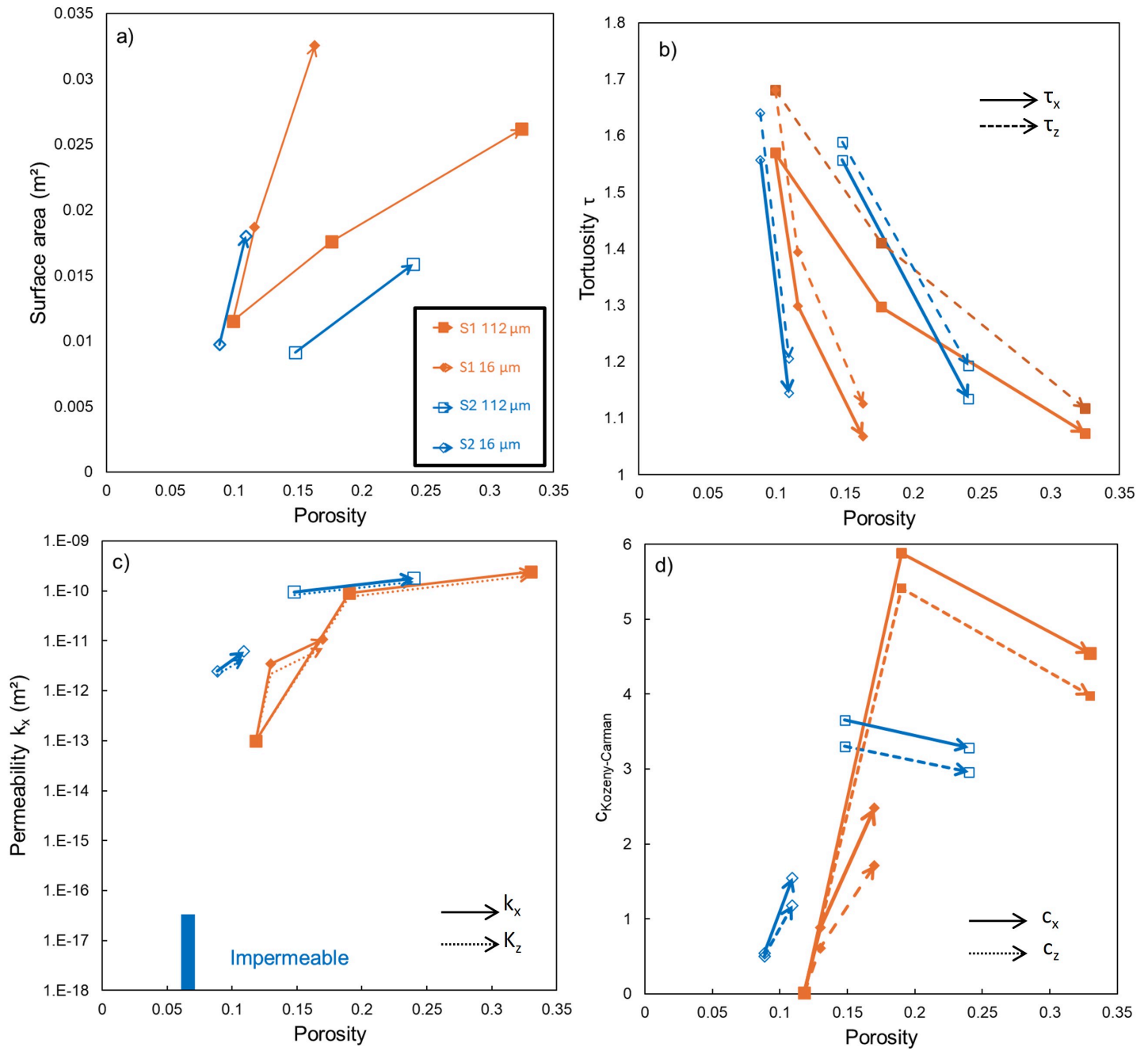


Figure 7

The evolution of surface area (a), tortuosity (b) and permeability (c) as a function of porosity during virtual fracturing. The empirical geometrical parameter c obtained using a modified version of the Kozeny-Carman equation combining surface area, tortuosity and permeability (**Costa, 2006**) was quantified for the different simulations (d). The arrows are for guidance only and indicate porosity increase during cracking and increase in fracture number density for a given segmentation (S1 vs. S2) and fracture width.

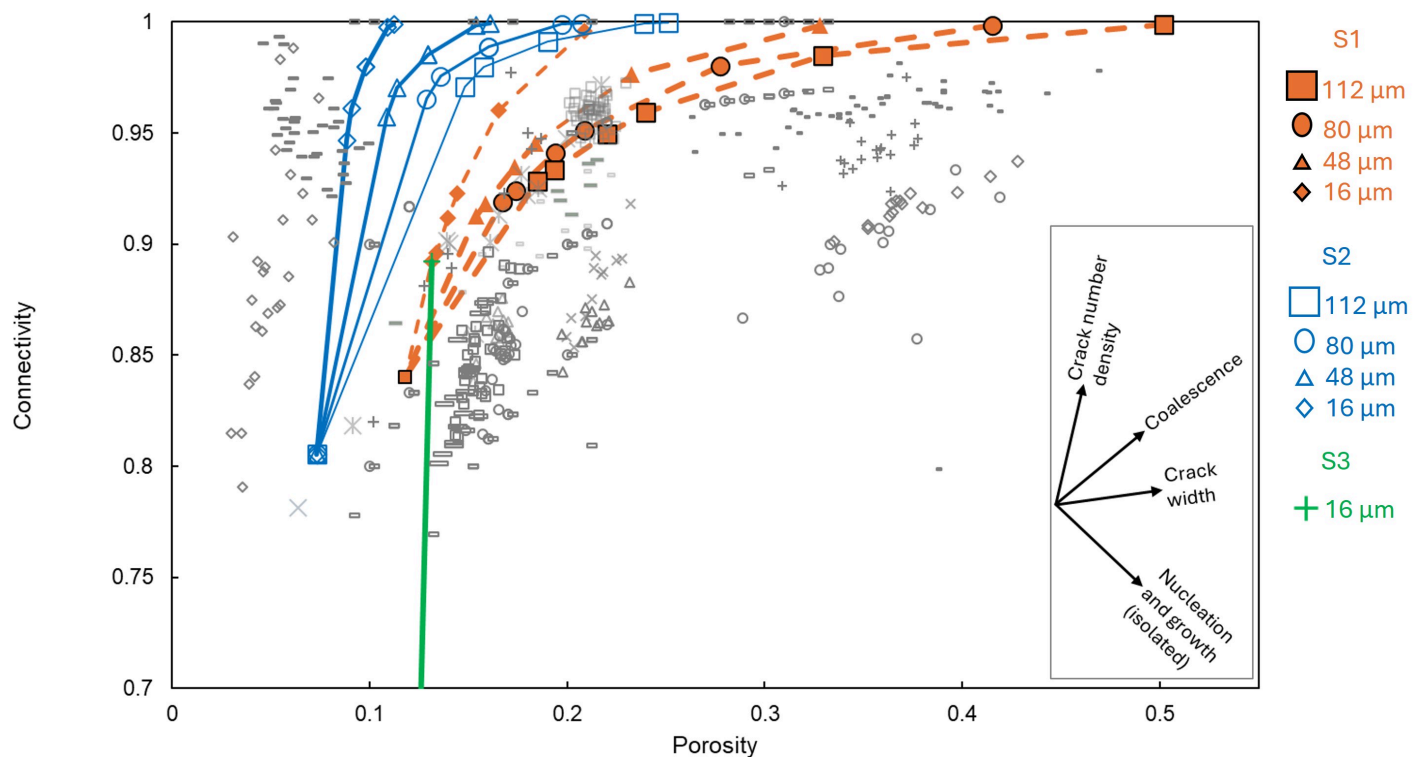


Figure 8

Comparison between modelled porosity-connectivity trends and a compilation of data on natural and experimental Unzen dacites (data from **Mueller, 2005; Coats et al., 2018** and **Kendrick et al., 2021**). Each type of grey marker for the natural Unzen dacites includes data from several samples cored from the same block. Inset illustrates how cracking and vesiculation processes can influence porosity-connectivity trends.

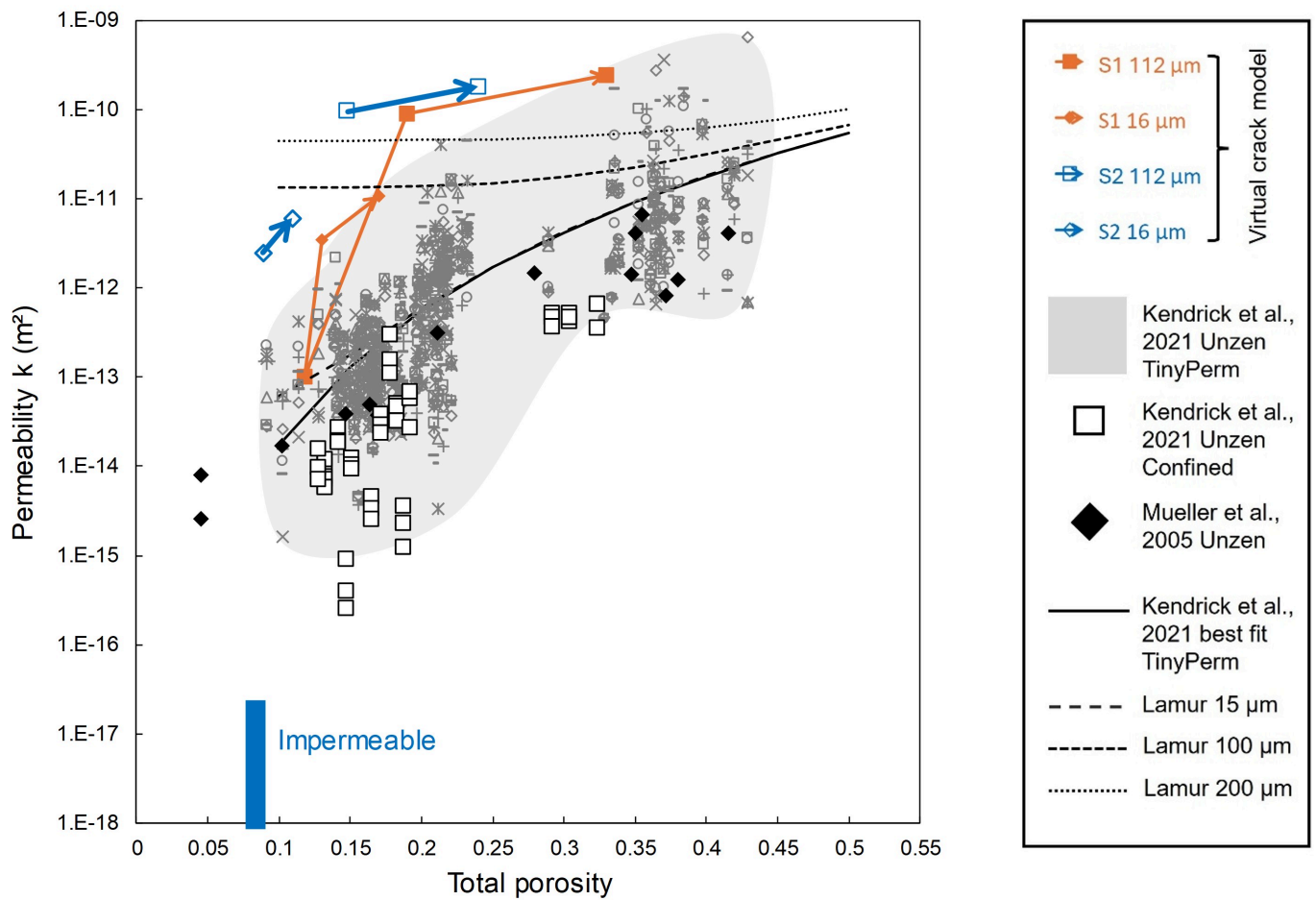


Figure 9

Permeability-positivity relationships for the virtual and natural Unzen samples (shown in grey). Data on natural Unzen dacites correspond to unconfined and localized permeability measurements on Unzen dacitic blocks by **Kendrick et al., (2021)**. For higher readability, permeability is only shown in the x direction for the virtual samples in this figure. The blue shaded area illustrates the onset of permeability (i.e., the approximate percolation threshold) during cracking for the S2 segmentation (macro-porosity only). Note that the modelled permeability-positivity relationships obtained for different fracture widths using the model of **Lamur et al. (2017)** were calculated assuming connected porosity instead of total porosity.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Table1.jpg](#)
- [Table2.jpg](#)

- [ESM1.docx](#)