

Article

Physio-Mechanical Properties and Meso-Scale Damage Mechanism of Granite Under Thermal Shock

Kai Gao ^{2,3}, Jiamin Wang ^{1,3,*} , Chi Liu ¹ , Pengyu Mu ¹  and Yun Wu ^{4,*}

¹ Academy of Deep Earth Sciences, Chinese Institute of Coal Science, Beijing 100013, China; twfcrztt@163.com (C.L.); mu_3687@163.com (P.M.)

² China Fiber Quality Monitoring Center, Beijing 100007, China; gaokailarry@163.com

³ State Key Laboratory for Geo-Mechanics and Deep Underground Engineering, Beijing 100083, China

⁴ State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China

* Correspondence: jiasmin1029@163.com (J.W.); wy1562254170@163.com (Y.W.)

Abstract

Clarifying the differential effects of temperature gradient and temperature change rate on the evolution of rock fractures and damage mechanism under thermal shock is of great significance for the development and utilization of deep geothermal resources. In this study, granite samples at different temperatures (20 °C, 150 °C, 300 °C, 450 °C, 600 °C, and 750 °C) were subjected to rapid cooling treatment with liquid nitrogen. After the thermal treatment, a series of tests were conducted on the granite, including wave velocity test, uniaxial compression experiment, computed tomography scanning, and scanning electron microscopy test, to explore the influence of thermal shock on the physical and mechanical parameters as well as the meso-structural damage of granite. The results show that with the increase in heat treatment temperature, the P-wave velocity, compressive strength, and elastic modulus of granite gradually decrease, while the peak strain gradually increases. Additionally, the failure mode of granite gradually transitions from brittle failure to ductile failure. Through CT scanning experiments, the spatial distribution characteristics of the pore–fracture structure of granite under the influence of different temperature gradients and temperature change rates were obtained, which can directly reflect the damage degree of the rock structure. When the heat treatment temperature is 450 °C or lower, the number of thermally induced cracks in the scanned sections of granite is relatively small, and the connectivity of the cracks is poor. When the temperature exceeds 450 °C, the micro-cracks inside the granite develop and expand rapidly, and there is a gradual tendency to form a fracture network, resulting in a more significant effect of fracture initiation and permeability enhancement of the rock. The research results are of great significance for the development and utilization of hot dry rock and the evaluation of thermal reservoir connectivity and can provide useful references for rock engineering involving high-temperature thermal fracturing.

Keywords: thermal shock; mechanical properties; CT scanning; meso-structure; granite



Academic Editor: Nikolaos Koukoulas

Received: 20 September 2025

Revised: 9 October 2025

Accepted: 10 October 2025

Published: 11 October 2025

Citation: Gao, K.; Wang, J.; Liu, C.; Mu, P.; Wu, Y. Physio-Mechanical Properties and Meso-Scale Damage Mechanism of Granite Under Thermal Shock. *Energies* **2025**, *18*, 5366. <https://doi.org/10.3390/en18205366>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Geothermal energy refers to the thermal energy stored within the Earth, featuring low carbon emissions, cleanliness, wide distribution, abundant reserves, safety, and renewability. Among various forms of geothermal energy, hot dry rock (HDR) geothermal energy holds significant development potential due to its extensive distribution and high

geothermal reservoir temperature [1,2]. Deep HDR is typically low-permeability granite, with temperatures ranging from 150 °C to 650 °C. Although natural fractures exist in such granite, their connectivity is poor, making it difficult to extract geothermal energy with economic value using conventional methods. Consequently, reservoir reconstruction is essential, and the Enhanced Geothermal Systems (EGS) project represents a key technology for the efficient development of geothermal energy. Fracturing technology can be used to create artificial fractures or improve existing fractures in underground high-temperature thermal reservoirs to make them have sufficient permeability [3,4]. Liquid nitrogen (LN₂) is a potential and effective cooling medium for reservoir fracturing and reconstruction. Currently, it has been widely applied in fields such as shale gas and oil extraction and also exhibits promising application prospects in EGS project [5–7]. During the reservoir fracturing process, when high-temperature granite near the wellbore comes into contact with liquid nitrogen, an abrupt temperature gradient is generated. This causes shrinkage of mineral particles inside the rock, weakening of cementation, and initiation and development of fractures, ultimately increasing the permeability of the reservoir. Therefore, it is necessary to conduct in-depth research on the damage and permeability-enhancing mechanisms of high-temperature granite under the impact of liquid nitrogen cooling and analyze the effects of temperature gradients on the physical and mechanical properties, fracture evolution, and permeability characteristics of granite. This study is of great significance to the exploitation of geothermal resources and can provide a theoretical basis and guiding suggestions for deep rock mass engineering.

The thermal shock effect induced by temperature gradient is one of the key factors affecting the mechanical properties of deep rock. A large number of scholars have studied the mechanical properties, crack evolution characteristics, and thermal damage and fracture mechanisms of high-temperature rocks through physical and mechanical experiments (such as acoustic wave test, Brazilian splitting, and uniaxial/triaxial compression experiments) [8–10] and micro-mesoscopic observation methods (such as scanning electron microscopy (SEM), computed tomography (CT) scanning, and nuclear magnetic resonance) [11–15]. Wu et al. [16] obtained the pore size distribution characteristics and porosity of granite after exposure to different high temperatures using nuclear magnetic resonance technology and concluded that the fundamental reason for the attenuation of rock mechanical properties lies in the change in its micro-structure. Wang et al. [17] investigated the mechanical behavior and micro-structural changes in high-temperature granite (150 °C~750 °C) under water cooling and found that with the increase in heating temperature, the peak stress and elastic modulus of the rock gradually decreased, while the porosity and permeability showed a non-linear increasing trend. Gomah et al. [18] studied the failure modes and micro-structural change laws of high-temperature granodiorite under different cooling rates and found that different thermal shock effects led to differences in the degree of micro-structural damage inside the rock. Kumari et al. [19] explored the influence of two cooling methods (rapid cooling and slow cooling) on the mechanical properties and crack formation modes of granite at temperatures ranging from 0 °C to 800 °C, and the results showed that a higher cooling rate would cause faster initiation and propagation of cracks in granite. Bu et al. [20] studied the relationship between the equivalent thermal conductivity of granite and heating temperature as well as cooling rate and found that the thermal conductivity decreased non-linearly with the increase in heating temperature, and the faster the cooling rate, the greater the decrease amplitude of thermal conductivity. Qin et al. [21] explored the physical and mechanical properties of granite before and after high-temperature treatment from room temperature to 1000 °C and found that when the temperature exceeded 400 °C, the granite gradually exhibited softening characteristics. Fan et al. [22] studied the spatial distribution characteristics of damage in high-temperature

granite after rapid cooling in water using CT scanning technology and found that the damage degree near the sample surface was greater than that inside the sample. In general, the thermal fracture of rock induced by thermal shock is essentially an interactive feedback process between meso-structural damage and macro-mechanical behavior. Current experimental research methods and approaches are mainly reflected in the following three aspects. First, exploring the degradation laws of mechanical properties (e.g., compressive/tensile strength) of rocks after heat treatment through mechanical tests, with an emphasis on the quantitative characterization of macro-mechanical indicators. Second, analyzing the wave velocity attenuation characteristics of rocks and their internal damage-fracture states using testing methods such as ultrasonic waves and acoustic emission, enabling indirect monitoring of damage evolution. Third, observing the surface morphology of rocks and the evolution characteristics of micro-pore and fracture structures before and after thermal damage via techniques like scanning electron microscopy (SEM), optical microscopy, and nuclear magnetic resonance (NMR), focusing on the static description of meso-structures. However, existing studies still have significant limitations. On the one hand, research on the differences in thermal degradation effects and damage-fracture mechanisms of rocks caused by different temperature gradients and temperature change rates is relatively scarce, making it difficult to reveal the regulatory mechanism of thermal shock parameters on the rock damage process. On the other hand, the cross-scale correlation analysis between macro-mechanical responses and meso-structural damage is severely lacking, which restricts in-depth understanding of the essence of rock thermal fracture.

In view of this, in this study, taking the high-strength dense granite in the hot dry rock rich area of Zhangzhou Basin, Fujian Province, as the research object, the physio-mechanical properties, meso-structural evolution, and damage characteristics of high-temperature granite under the rapid cooling effect of liquid nitrogen are studied through mechanical experiments, micro-mesoscopic observation, and theoretical analysis. Using CT scanning and digital image processing technology, a three-dimensional reconstruction model of thermally damaged fractures in granite is established. The crack volume, fractal dimension, and other parameters are analyzed to clarify the mesoscopic causes of rock fracture behavior from both geometric and mechanical perspectives. This study forms a multi-dimensional damage evaluation system for rocks, establishes a cross-scale connection between the meso-structural damage and macro-fracture process of granite under thermal shock, realizes semi-quantitative analysis of composition, structure and mechanics of granite under thermal shock, and reveals the permeability-enhancing and fracturing mechanism of granite induced by thermal shock. The research results can provide theoretical parameters and technical guidance for the design of geotechnical engineering such as deep geothermal resource exploitation.

2. Research Methods

2.1. Experimental SAMPLES

The Zhangzhou Basin in Fujian Province is located in the collide, compress, and subduct convergence zone where the Eurasian Plate and the Philippine Sea Plate. Tectonic activities here are highly active [23,24], and it is one of the most important distribution areas of high-radioactivity granite in China (Figure 1a). The granite used in this study was collected from a depth of approximately 600 m in the Zhangzhou Basin. In accordance with the rock mechanics test sample preparation standards of the International Society for Rock Mechanics (ISRM), the granite was processed into cylindrical specimens with a diameter of 25 mm and a height of 50 mm, which were used for permeability testing of the granite before and after thermal shock. In addition, to maximize the CT scanning accuracy, cylindrical specimens with a diameter of 10 mm and a height of 20 mm were also

prepared. These specimens were used for wave velocity testing, uniaxial compression tests, CT scanning experiments, and optical microscopic scanning of thermally damaged granite (Figure 1b). A non-metallic ultrasonic rebound comprehensive tester (Figure 2a) was used to measure the acoustic velocity of the granite samples, and the samples with similar test results were selected as experimental samples to minimize errors in physical properties. The experimental samples were divided into groups of three, and liquid nitrogen cooling experiments were conducted after subjecting them to different high-temperature treatments. The XRD tests showed that the main mineral components of the granite samples are feldspar (65.2%), quartz (32.5%), and mica (2.3%).

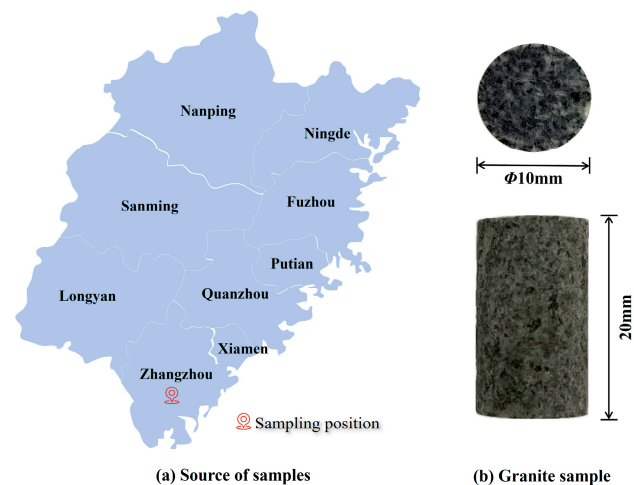


Figure 1. Experimental sample.

2.2. Thermal Shock Experiments

The temperature range of hot dry rock (HDR) is quite wide, generally between 150 °C and 650 °C. In this study, granite samples were placed in a box-type resistance furnace and heated to 150 °C, 300 °C, 450 °C, 600 °C, and 750 °C, respectively, with a heating rate set to 5 °C/min to avoid thermally induced cracks caused by drastic changes in temperature gradient during the heating process. After reaching the preset temperature, the samples were held at a constant temperature for 2 h to ensure uniform heating inside the rock samples. The results of physical and mechanical experiments as well as meso-structural tests on granite samples at room temperature (approximately 20 °C) were used as the control group. After being treated at different high temperatures, the granite samples were taken out and quickly placed into a liquid nitrogen tank at −196 °C for cooling until reaching a constant temperature. Then wiping off the liquid nitrogen on the surface, and the samples were placed in a vacuum drying oven until the mass became constant.

2.3. Physical and Mechanical Property Tests

2.3.1. Permeability Tests

The permeability test of granite after thermal shock was conducted using a CAT112 gas permeability measuring instrument (Coretest Systems Inc., Morgan Hill, CA, USA), as shown in Figure 2b. Before the test, the airtightness of the instrument was inspected, and the instrument was calibrated with standard specimens. Subsequently, each granite sample was sealed in a holder under a confining pressure of 200 psi. The upstream and downstream gas chambers were connected to both ends of the granite, allowing dry air to flow through the sample steadily. Finally, the inlet and outlet pressures of the air as well as the air flow rate were measured.

The permeability of the granite specimens can be calculated using the following equation [25,26].

$$K = 2000 \frac{P_{atm} \mu Q_a L}{A(P_1^2 - P_2^2)} \quad (1)$$

where K represents permeability, P_{atm} represents atmospheric pressure, μ represents the gas viscosity coefficient, P_1 and P_2 represent the inlet pressure and outlet pressure, respectively, Q_a represents the gas flow rate, and L and A represent the length and cross-sectional area of the specimen, respectively.

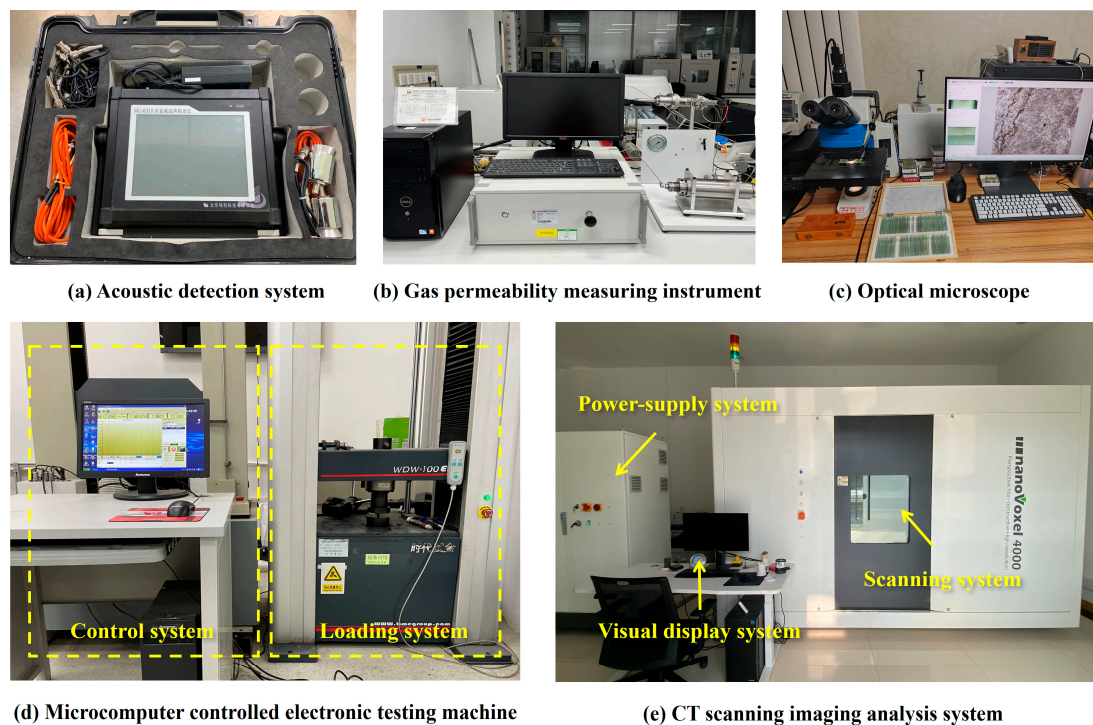


Figure 2. Main experimental equipment.

2.3.2. Uniaxial Compression Tests

The uniaxial compression test of granite after thermal shock was conducted using a WDW-100E microcomputer-controlled electronic testing machine (Shidai Shijin Test Instrument Co., Ltd., Jinan, China) (Figure 2d). The system adopts microcomputer closed-loop control, featuring accurate loading speed and force measurement range, as well as high precision and sensitivity in the measurement and control of load and displacement. Through a fully digital measurement and control system, the load, peak value, displacement, speed, and test curve during the test process are displayed synchronously. In this study, the displacement loading method was used for the mechanical experiment, with the loading rate set to 0.05 mm/min. By conducting the compressive strength test of granite, the mechanical behavior of granite after treatment with different temperatures and liquid nitrogen cooling can be observed, and mechanical parameters such as the peak strength, Young's modulus, and peak strain of the rock can be calculated.

2.4. Microstructural Observation Experiments

CT Scanning Experiments

The nanoVoxel-4000 ultra-high-resolution in situ loading imaging CT scanning comprehensive analysis system (Sanying Precision Instruments Co., Ltd., Tianjin, China) was used to obtain the meso-structure of granite. This system consists of an X-ray source, a

sample stage, and a flat-panel detector, as shown in Figure 2e. The basic principle of the CT scanning system is to generate projection data by utilizing the difference in the penetrating power of X-rays through objects, and then process and analyze the projection data in combination with modern computer technology and digital image correlation technology [27,28], as illustrated in Figure 3. The resolution of the CT scanning system is directly related to the size of the sample. Reducing the sample size as much as possible within a reasonable range can maximize the scanning accuracy. In this study, the scanning resolution of the cylindrical granite samples (10 mm in diameter and 20 mm in height) can reach 5.65 μm .

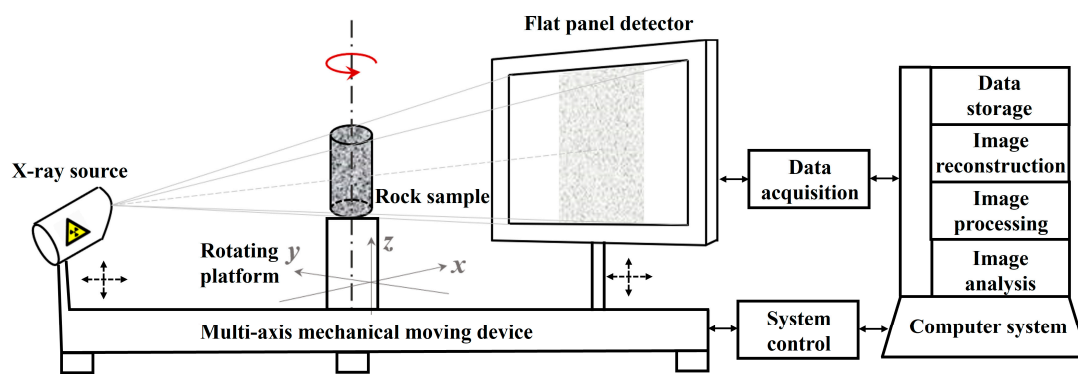


Figure 3. The process of digital image acquisition and analysis.

The scanning and image processing steps for rock samples are as follows:

Step 1: The granite sample is placed in the center of the rotatable sample table, and the position of the sample table is adjusted by the three-dimensional positioning system to ensure that the sample is always in the center of the scanning field of view during X-ray penetration and avoid edge distortion. The sample table is controlled to rotate at preset angular intervals, and all-angle ray intensity data are collected in real time by flat panel detector and automatically converted into a two-dimensional tomographic image sequence.

Step 2: Using Avizo three-dimensional visual image processing software, the scanned image is processed by image enhancement, filtering and noise reduction to improve the contrast of different mineral components and fracture structures in scanning image.

Step 3: Based on the difference in mineral density and gray scale characteristics, the multi-level threshold segmentation method is used to identify different minerals and fracture structures in scanning images.

Step 4: Three-dimensional reconstruction algorithm is used to superimpose two-dimensional scanning slices according to spatial coordinates to generate a three-dimensional volume model of granite, and the thermal damage cracks of granite are visually displayed and quantitatively analyzed.

3. Analysis of Physical and Mechanical Properties of Granite Under Thermal Shock

3.1. Mass Change in Granite

The mass of granite samples may decrease after thermal shock treatment, which is a direct manifestation of mesoscopic damage in the rock under drastic temperature changes. Essentially, when high-temperature rock is rapidly impacted by low-temperature fluid, thermal stress concentration inside the rock causes the initiation and propagation of fractures, which destroys the structural integrity of the rock and ultimately leads to mass loss. The mass change in granite before and after thermal shock is shown in Figure 4.

Meanwhile, the mass loss rate can be used to characterize the mass change in the rock, and the definition of the mass loss rate is given in Equation (2).

$$K_m = \frac{m_0 - m}{m_0} \times 100\% \quad (2)$$

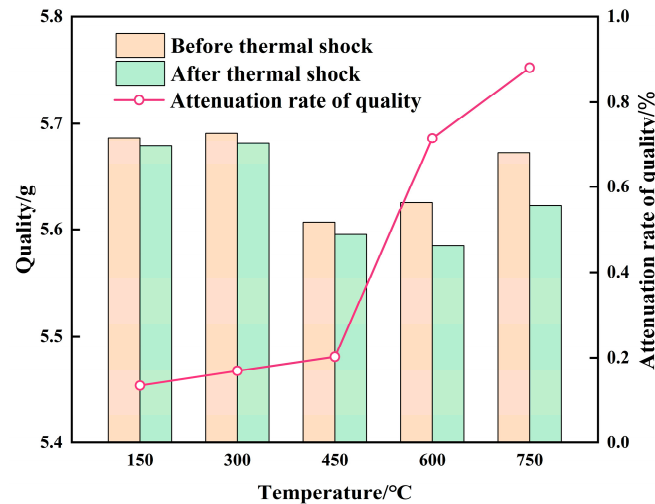


Figure 4. Mass change in granite after thermal shock.

Among them, K_m represents the mass loss rate, and m_0 and m represent the mass of the granite sample before and after thermal shock treatment, respectively.

It can be seen from the figure that as the heat treatment temperature increases, the mass of the granite gradually decreases and the mass loss rate increases progressively. This is because when the granite is subjected to temperature shock, the difference in thermal expansion between minerals generates enormous thermal stress. When this stress exceeds the bonding strength of the minerals, micro-cracks form at the mineral boundaries and within the minerals themselves. As the temperature gradient increases or the temperature change rate accelerates, the cracks continue to propagate and connect, and some minerals peel off, resulting in a decrease in the overall mass of the rock.

3.2. P-Wave Velocity Change in Granite

P-wave velocity is highly sensitive to the development of the internal pore structure of rocks and serves as an excellent indicator for evaluating rock structural damage [29]. Therefore, the degree of rock damage caused by thermally induced micro-cracks can be assessed by comparing the P-wave velocities of granite samples before and after thermal shock. The P-wave velocities of granite were measured along the axial direction of the rock samples, each sample was tested three times, and the average value of the P-wave velocities was taken as the final result (Figure 5). The average P-wave velocity of the granite in its initial state was 4100 ± 150 m/s. When the heat treatment temperature ranged from 20 °C to 450 °C, the P-wave velocity decreased approximately linearly with increasing temperature, but the magnitude of the decrease was not significant. This indicates that heating and cooling treatment had a relatively small impact on the internal pore structure of the granite during this stage. When the heat treatment temperature reached 600 °C, the wave velocity attenuation rate of the granite reached 65.80%, indicating a significant increase in the degree of internal structural damage. When the temperature rose to 750 °C, the P-wave velocity of the granite was only about 25% of that at room temperature. At this point, the rock structure was severely damaged, and the propagation of internal micro-cracks hindered the transmission of P-waves within the rock. In addition,

the physical and chemical effects of the liquid nitrogen cooling process also exacerbated the meso-structural damage of the rock to a certain extent.

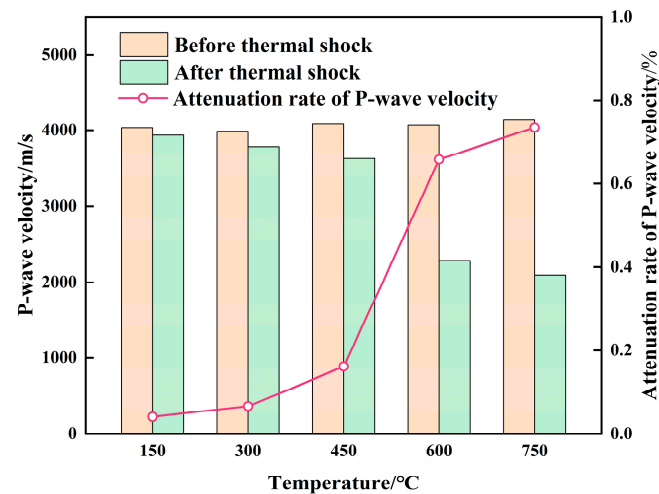


Figure 5. P-wave velocity change in granite after thermal shock.

3.3. Mechanical Properties of Granite Under Thermal Shock

The stress–strain curves of high-temperature granite after liquid nitrogen cooling are shown in Figure 6. These stress–strain curves can be divided into four stages, namely the compaction stage, elastic stage, plastic stage, and failure stage. The morphological characteristics of the curves exhibit a regular evolution as the heat treatment temperature increases, specifically manifested by a gradual decrease in the initial slope of the curves and a gradual extension of the plastic stage. When the heat treatment temperature does not exceed 450 °C, the morphological differences in the stress–strain curves at different temperatures are relatively small. The axial strain shows a gentle increasing trend with the increase in stress. After entering the failure stage, the stress drops sharply as the rock breaks suddenly, with no obvious yield buffering process. When the heat treatment temperature exceeds 450 °C, the ductility of the rock increases significantly, showing obvious non-linear behavior. After reaching the peak stress, the curve does not drop rapidly; instead, while the stress decreases slowly, the axial strain can still increase continuously, and the plastic stage is greatly extended. This indicates that high temperatures have significantly changed the internal structure and mechanical response mechanism of the granite, transforming its failure mode from brittle failure to ductile failure with plastic deformation.

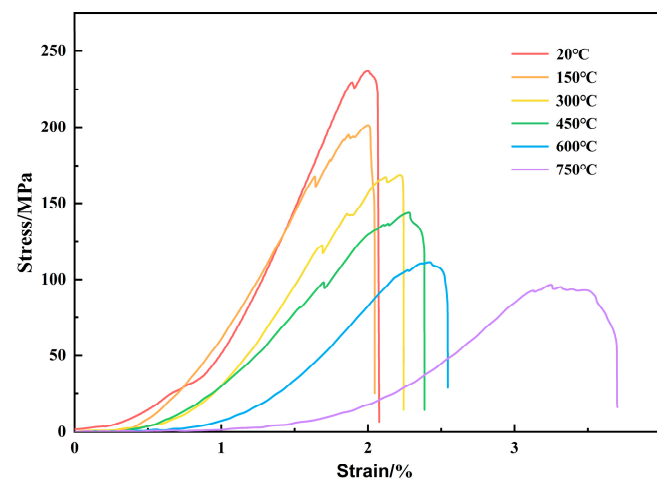


Figure 6. Stress–strain curve of granite after thermal shock.

Based on the stress–strain curves of granite, mechanical indicators such as uniaxial compressive strength, elastic modulus, and peak strain can be further calculated [30]. The variations in these indicators under different thermal shock conditions are shown in Figure 7. In the initial state, the average uniaxial compressive strength, elastic modulus, and peak strain of the granite samples are 236.92 MPa, 21.54 GPa, and 1.99%, respectively. With the heat treatment temperature increases, the mechanical parameters exhibit regular changes. The uniaxial compressive strength and elastic modulus generally show a downward trend, while the peak strain gradually increases. Moreover, such changes display significant differences in different temperature ranges. Within the temperature range of 150 °C~450 °C, the variation degree of the mechanical parameters of all samples is relatively small, and the rock can still maintain relatively stable mechanical properties. When the heat treatment temperature exceeds 450 °C, affected by the intensified temperature gradient and cooling rate, the strength and elastic modulus of the granite decrease significantly. At 600 °C and 750 °C, the uniaxial compressive strength decreases by 53.02% and 59.80%, respectively, and the elastic modulus decreases by 53.71% and 66.25%, respectively. Meanwhile, the peak strain of the rock increases sharply, showing obvious ductile failure characteristics. At this stage, the granite suffers severe structural damage, and its integrity after failure deteriorates. A large number of micro-cracks initiate around the through cracks, accompanied by the spalling of a large amount of debris, which intensifies the damage degree of the rock.

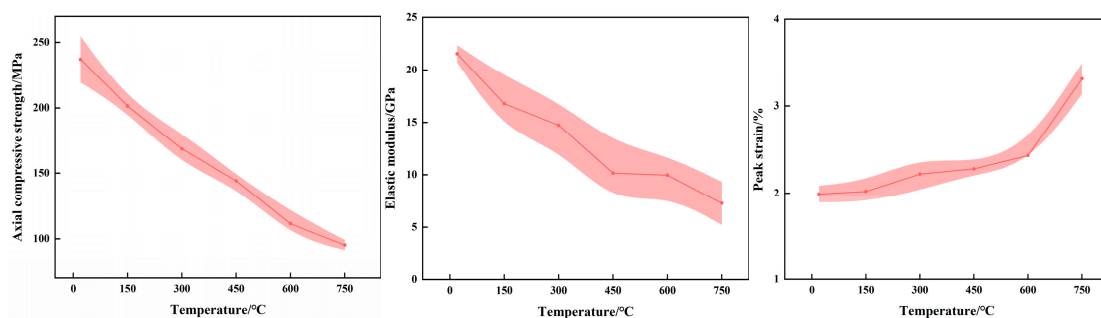


Figure 7. Variation in mechanical properties of granite after thermal shock.

4. Variation in Meso-Structure of Granite Under Thermal Shock

4.1. Analysis of 2D CT Scanning Images

Existing research results (www.engineeringtoolbox.com) show that among the main mineral components of granite samples, mica has the highest density, approximately 2.7~3.4 g/cm³, followed by quartz with a density of about 2.65 g/cm³, and feldspar with a density of roughly 2.54~2.61 g/cm³. Other mineral components account for a relatively small proportion in granite and can be ignored during mineral segmentation. According to the principle of CT scanning, the higher the density of a mineral in the rock, the stronger its ability to absorb X-rays. Therefore, mica minerals appear the brightest in the grayscale images obtained by CT scanning, followed by quartz, and feldspar is the darkest mineral. The lateral scanning slice of granite in natural state is shown in the leftmost picture of Figure 8, where the white part represents mica, the light gray part represents quartz, and the dark gray part represents feldspar. It can be seen that mica minerals generally exhibit a banded or massive distribution and are mostly associated with quartz minerals. By adopting the multi-level threshold segmentation method, mica, quartz, and feldspar minerals can be segmented and assigned different colors to generate a reconstructed image of the rock.

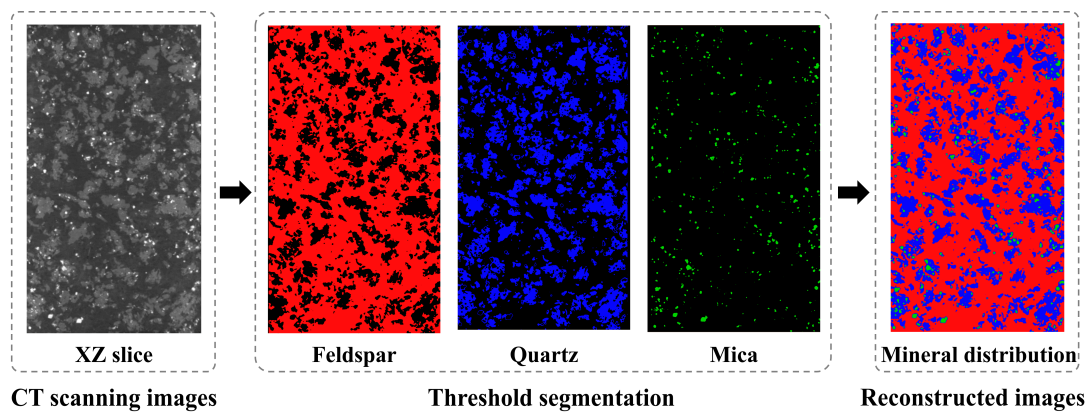


Figure 8. The threshold segmentation results of granite minerals.

Figure 9 shows the 2D CT scanning images of granite after exposure to high temperatures and liquid nitrogen cooling, and the damage cracks are marked with red dotted circles to highlight. With the heat treatment temperature increases, the development characteristics of meso-cracks in the granite CT scanning images exhibit significant differences. When the heat treatment temperature is 150 °C and 300 °C, the mineral particles inside the rock are tightly bonded, and almost no obvious damage cracks can be observed in the images. This indicates that the thermal effect in this temperature range has not yet caused significant meso-structural damage. When the temperature rises to 450 °C, the micro-cracks in the scanning images are mainly concentrated at the mineral boundaries between quartz and feldspar. This is because the thermal expansion coefficient of quartz is significantly higher than that of other minerals. After being heated, it undergoes incompatible deformation with surrounding minerals, forming local high stress at the grain boundaries and leading to grain boundary cracking. Meanwhile, thermally induced micro-cracks are mostly distributed at the edges or ends of the rock. When the temperature gradient changes sharply, the spatial temperature variation at the rock edges is more drastic, resulting in a more significant stress concentration effect. When the temperature reaches 600 °C and 750 °C, the number of micro-cracks in the images increases significantly, showing a trend of propagation and connection. In addition to the continuously developing intergranular cracks, obvious intragranular cracks begin to appear inside feldspar and quartz. Due to its relatively low strength, feldspar is prone to internal cracking under thermal stress. The quartz will undergo α - β phase transformation at a high temperature of 573 °C, and α -quartz has a spiral silicon-oxygen tetrahedron chain. When the phase transition occurs, its silicon atoms and oxygen atoms will slightly shift and further transform into β -quartz. The thermal vibration space between β -quartz atoms is larger than that of α -quartz, so its thermal expansion coefficient is larger. This change in crystal structure of quartz accelerates the thermal cracking process inside its grains [31]. Furthermore, the low-temperature impact of liquid nitrogen not only exacerbates the difference in thermal stress between minerals but also causes the cementing substances between some mineral grains to dissolve or the grains to fall off. This further intensifies the meso-damage of the rock and significantly reduces the integrity of its overall structure.

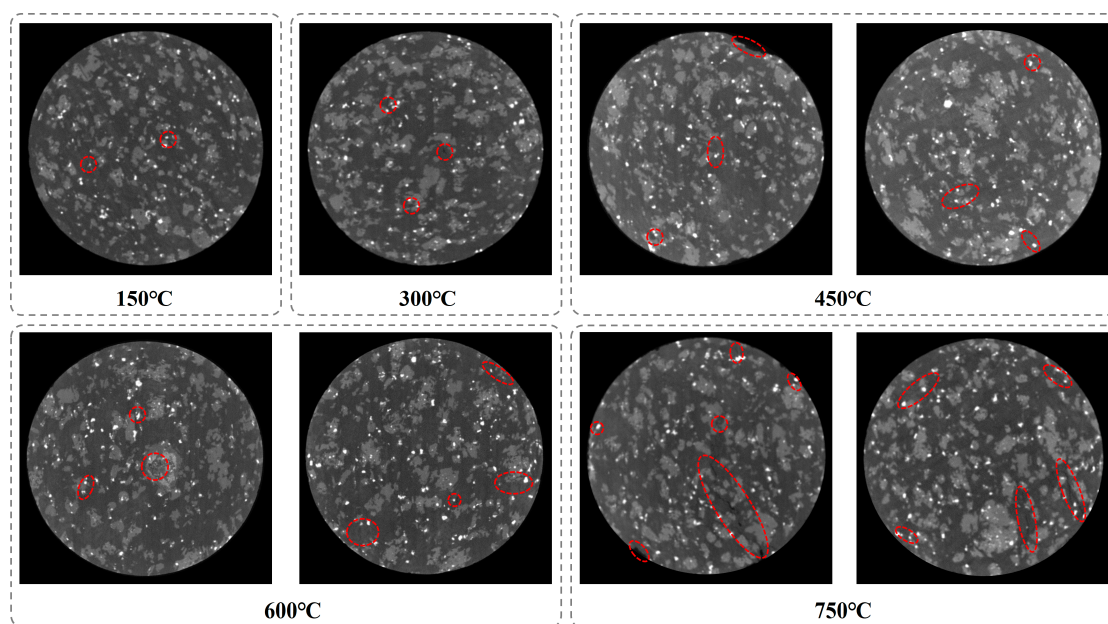


Figure 9. CT scanning images of granite after thermal shock.

4.2. Analysis of 3D Fracture Reconstruction Models

The spatial superposition and reconstruction processing are performed on the 2D scanning images to obtain a 3D fracture reconstruction model of the granite after thermal shock, as shown in Figure 10. The gray cylindrical area represents the granite matrix, and the blue area represents the thermally induced damage fractures inside the rock extracted through threshold segmentation. When the heat treatment temperature is 450 °C and below, only a small number of fine cracks are generated in the granite samples, which are distributed discretely inside the rock. The connectivity of the fractures is poor, and their impact on the integrity of the rock structure is limited. At a temperature of 600 °C, the originally isolated fine cracks gradually expand, extend, connect with each other, and merge under the action of thermal stress, forming larger-sized cracks. When the heat treatment temperature further increases to 750 °C, the thermal damage characteristics in the entire analysis area become more obvious. The internal structure of the rock is severely damaged, and the cracks connected to form a fracture network. This severe meso-structural deterioration will directly lead to a significant decline in the mechanical properties of the rock, with a substantial reduction in compressive strength and elastic modulus. Notably, the crack density at the edge of the rock sample is significantly higher than that in the internal area, which is consistent with the characteristic that the edge stress concentration effect is more significant when the temperature gradient changes sharply.

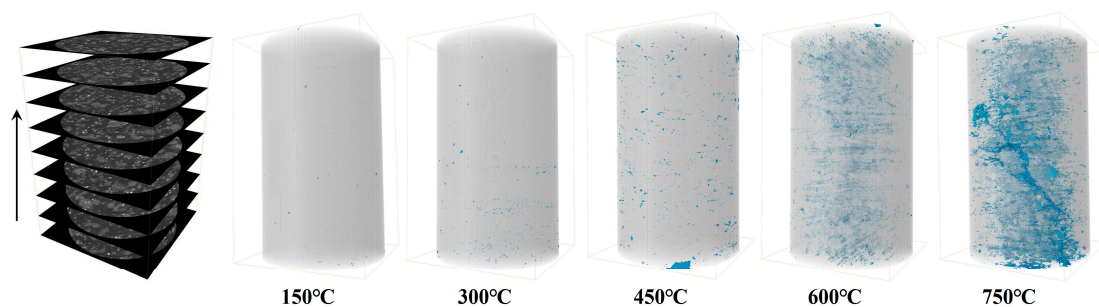


Figure 10. Three-dimensional fracture reconstruction model of granite after thermal shock.

4.3. Quantitative Characterization and Analysis of Thermally Induced Damage Fractures

The 2D scanning images and 3D fracture reconstruction models of granite can be regarded as collections of numerous pixels and voxels, respectively, with each pixel and voxel having a uniquely corresponding grayscale value. Using Avizo 2021.1 software, the number of pixels and voxels occupied by rock fracture structure can be automatically counted and analyzed. Figure 11 shows the variation in porosity layer by layer along the vertical diameter direction of granite after exposure to high temperatures and liquid nitrogen cooling. Affected by the heterogeneous distribution of rock minerals and the differences in thermal expansion properties of different mineral particles, the distribution of thermally induced cracks in 2D CT scanning images exhibits randomness, and the density gradually increases with the rise in heat treatment temperature. Correspondingly, the change in porosity shows a significant temperature-dependent characteristic. When the heat treatment temperature is 450 °C and below, the porosity of granite remains below 0.2%, and the overall structure maintains a dense state. This indicates that the thermal effect and liquid nitrogen cooling in this temperature range do not cause a significant increase in porosity. When the heat treatment temperature rises to 600 °C and 750 °C, the thermal damage effect of granite becomes significantly apparent, and the porosity increases sharply. This phenomenon is mainly related to the phase transformation characteristics of quartz minerals. The α -phase (cubic crystal system) of quartz will transform into the β -phase (hexagonal crystal system), which causes volume expansion. This expansion intensifies the stress concentration at mineral interfaces and inside minerals, promoting the massive initiation and propagation of micro-cracks, and ultimately leading to a substantial increase in porosity.

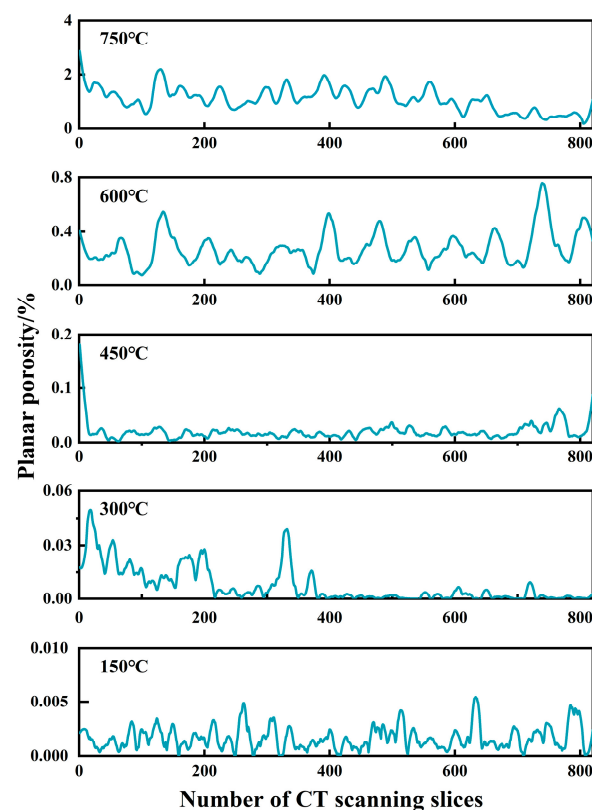


Figure 11. Porosity distribution of CT scanning slices of granite after thermal shock.

To quantitatively analyze the effects of heat treatment temperature and liquid nitrogen cooling on the mesoscopic structure of granite, the proportion of fracture structures in different volume distribution intervals is statistically analyzed, as shown in Figure 12.

When the heat treatment temperature is 600 °C or below, the pore volume distribution of granite exhibits obvious interval characteristics, mainly concentrating in three intervals: $\leq 10^5 \mu\text{m}^3$, $10^5 \sim 10^6 \mu\text{m}^3$, and $10^6 \sim 10^7 \mu\text{m}^3$, with a small number of fractures distributed in the $10^7 \sim 10^8 \mu\text{m}^3$ interval. As the heat treatment temperature increases, the proportion of fractures in the $\leq 10^6 \mu\text{m}^3$ interval decreases continuously, which reflects the characteristic that small and medium-sized fractures gradually expand under thermal action. After the heat treatment temperature rises to 750 °C, the fracture volume distribution of granite changes significantly. Fractures with volumes $\geq 10^8 \mu\text{m}^3$ and $\geq 10^9 \mu\text{m}^3$ appear inside the sample, which accounts for a large proportion, indicating that the high temperature of 750 °C combined with liquid nitrogen cooling has promoted the formation of a fracture network inside the granite. The strong thermal shock effect accelerates the expansion and connection of thermally induced damage fractures, ultimately leading to the massive occurrence of large-volume fractures.

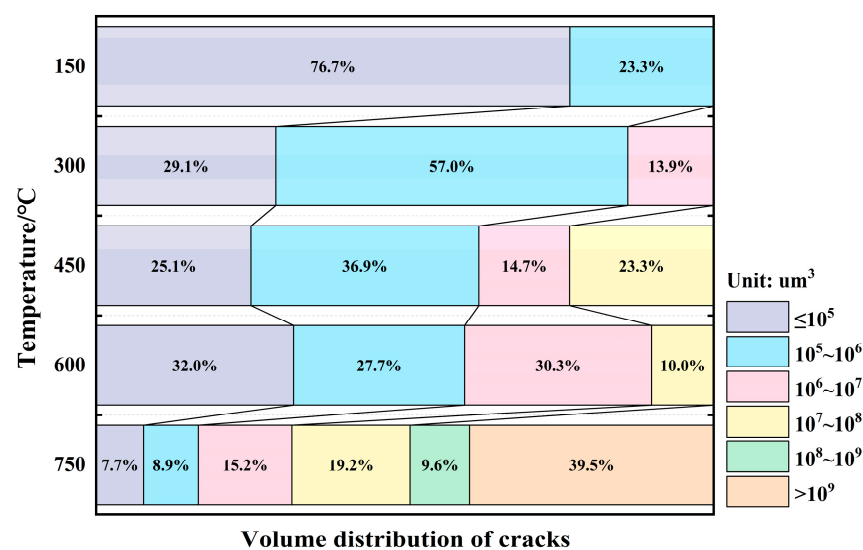


Figure 12. Pore volume distribution ratio of granite after LN₂ cooling.

4.4. Relationship Between Overall Porosity and Permeability Characteristics of Granite

The connectivity of fractures in reservoir rocks determines the exploitation efficiency of hot dry rock, and permeability is a parameter used to evaluate the ability of rocks to allow fluids to flow through the internal pore spaces. Therefore, studying the variation in permeability is of great significance for intuitively assessing the fracture-induced permeability enhancement effect of thermal shock on granite. Meanwhile, permeability and porosity of rock have a certain correlation. Based on the Carman–Kozeny equation [32,33], the relationship between permeability and porosity can be expressed as shown in Equation (3).

$$k \propto \frac{\phi^3}{(1 - \phi)^2} \quad (3)$$

where k represents the rock permeability, and ϕ represents the rock porosity.

The overall porosity, permeability, and their growth rates of high-temperature granite under liquid nitrogen cooling are shown in Figure 13. It can be observed that the permeability of granite exhibits a phased variation pattern of slow growth followed by rapid growth as the heat treatment temperature increases. When the heat treatment temperature does not exceed 450 °C, the variation range of the average permeability of granite is relatively small. However, when the heat treatment temperatures are 600 °C and 750 °C, the permeability growth rates of the granite samples reach 885.88% and 1661.88%, respectively.

This dramatic growth stems from the strong temperature gradient and rapid temperature change rate formed by high temperature and liquid nitrogen cooling, which significantly increase the internal thermal stress of the rock. This not only accelerates the expansion of existing cracks but also drives the massive initiation of new cracks, and the connectivity of the pore–fracture structure is greatly improved, ultimately leading to a sharp increase in permeability.

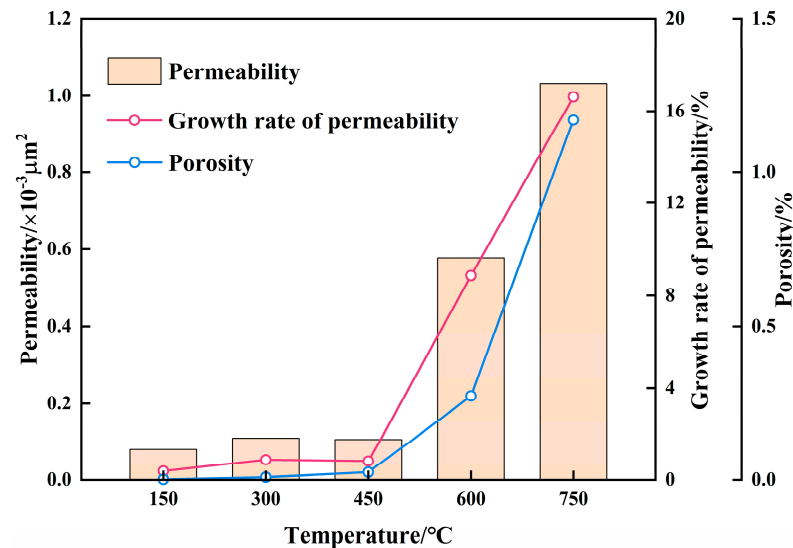


Figure 13. Relationship between permeability and porosity.

From the relationship between the changes in the overall porosity and permeability of the rock, it can be seen that the effects of temperature gradient and temperature change rate on the rock's porosity and permeability are synchronous. When the change in porosity is minimal, the mineral particles inside the rock can still maintain a tight arrangement. Although heat treatment can cause the generation and expansion of microcracks, the relatively low temperature makes it difficult to form effective connected channels inside the rock, so the increase in permeability is small. When the temperature reaches 600 °C, the thermal shock effect promotes a simultaneous and significant increase in the rock's porosity and permeability. At this point, the connectivity of the internal pores of the granite is significantly enhanced, forming large-scale seepage channels that facilitate the free movement of fluids inside the rock.

4.5. Optical Microscopic Characteristics of Thermally Induced Damage Fractures

To further analyze the types of thermally induced cracks in granite, optical microscope observations were conducted on the granite, as shown in Figure 14. By identifying mineral morphology, crystallization characteristics, alteration phenomena, and microcrack distribution, the degree of damage to the rock's mesoscopic structure caused by temperature gradients and cooling rates is evaluated. The main minerals of granite have different characteristics in thin slices. Feldspar minerals belong to the monoclinic or triclinic crystal system, exhibit a platy or prismatic distribution, and have a low refractive index. Quartz is mostly colorless or white and transparent, and it may also appear light green or grayish-black due to impurities, with a smooth surface and few cleavages. Biotite is mainly black or dark brown and distributed scattered [20]. Based on the above characteristics, different minerals in the granite optical thin slices can be distinguished and labeled. The biotite, quartz, plagioclase, and orthoclase are labeled as Bt, Qtz, Pl, and Kfs, respectively. When the heat treatment temperature is ≤ 450 °C, the mineral boundaries are clear, no significant changes occur in the rock structure or mineral morphology, and there is no recrystallization

phenomenon. The cracks first initiate at the boundaries of quartz grains, and with the temperature increases, a small number of intragranular microcracks also begin to appear inside the quartz. When the heat treatment temperature reaches 600 °C, intergranular microcracks develop extensively at the boundaries between quartz and other minerals, as well as at the quartz-quartz interfaces. The length, width, and quantity of cracks increase significantly. Intragranular microcracks are dense in large quartz grains, with a more pronounced sense of grain fragmentation and blurred boundaries. The opacity on the feldspar surface intensifies, and internal cracks becomes more obvious, some even connects with cracks in quartz grains to form trans granular cracks. The biotite shows lightened in color and turns brown due to oxidation reactions. When the heat treatment temperature further increases to 750 °C, the number of cracks on the feldspar surface increases drastically, and the length extends until penetration. A large number of crack clusters forms on the quartz surface, the quartz is eroded by other minerals at the cracks and distributes intermingled with other minerals, showing strong alteration characteristics. At this time, the thermal shock effect has caused severe damage to the mesoscopic structure of the granite. In the follow-up research, it is necessary to optimize the design scheme of optical scanning experiment in existing research. For the same sample, the optical microscopic images at room temperature are compared with the images after thermal shock treatment, so as to reduce the problem of inaccurate observation of experimental results caused by the error of the granite samples.

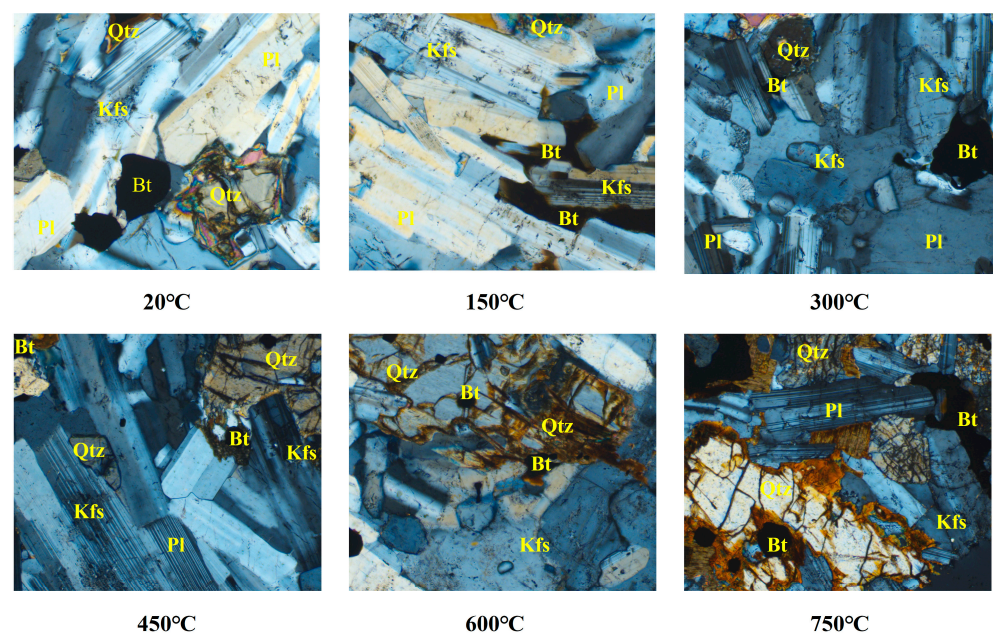


Figure 14. Optical micrograph of thermal damage cracks in granite.

5. Discussions

5.1. Analysis of Thermal Damage Mechanism of Granite

The above test results on the physio-mechanical properties and mesoscopic structure of granite after thermal shock indicate that high heat treatment temperatures and fast cooling rates exacerbate the thermal damage of granite. Specifically, this is manifested in the obvious deterioration of physio-mechanical properties such as P-wave velocity, strength, and elastic modulus, the rapid development of microcracks inside the rock, and a significant enhancement in permeability. The damage process is closely related to temperature ranges, and its core mechanism stems from thermally induced physicochemical changes and pore structure evolution. Within the temperature range of 20 °C~450 °C, the damage to granite is mainly driven by moisture loss and uneven mineral expansion. The free

water and adsorbed water inside the rock gradually evaporate, leading to initial changes in the pore structure. The thermal expansion coefficients of different mineral particles are significantly different, and anisotropic expansion will occur when the temperature is raised, which will cause thermal stress between mineral particles. When the thermal stress exceeds the tensile strength of the rock, tensile cracks will be induced. Because the overall thermal stress is small at these temperature stages, the damage of rock structure is limited, and the thermal cracks are mainly micro-pores and small pores, and the physical and mechanical parameters are slightly deteriorated. In the temperature range of 450 °C~600 °C, the damage mechanism of granite becomes more complex and its impact intensifies. The bound water and crystallization water inside the rock decompose, the mineral lattice structure is damaged, and quartz undergoes a phase transformation from α to β at approximately 573 °C, accompanied by volume expansion and significant changes in crystal structure, these processes further promote the expansion of microcracks inside the granite [34,35]. The thermal stress caused by the uneven expansion of mineral particles further increases, the number of intergranular and intragranular cracks surges, and internal pores continue to develop and connect. Ultimately, this leads to the rapid attenuation of physical parameters (such as strength and elastic modulus) [36]. When the heat treatment temperature rises to the range of 600 °C~750 °C, some metallic bonds in feldspar minerals break, resulting in a sudden drop in mineral strength. The existing fracture network further develops and expands, to form a complex fracture network. The permeability of granite is greatly improved, its mechanical properties continue to deteriorate, and its failure mode transitions from brittle failure to ductile failure.

Damage during the cooling process mainly stems from the combined effect of differential mineral deformation and temperature gradient stress. Under the cooling effect of liquid nitrogen, the thermal conductivity of different minerals and the contact distance between the sample and the cooling medium are different, which will form an obvious temperature gradient and induce thermal stress of temperature gradient. Meanwhile, the mineral on both sides of the thermally induced crack in the rock shrinks when it is cold, resulting in tensile stress. When it exceeds the tensile strength at the crack tip, it will lead to the further expansion of microcracks [37,38]. Under the combined influence of intergranular thermal stress and temperature gradient stress, the damage degree of granite increases significantly, further exacerbating the deterioration of physical properties of granite. This is also the main reason why liquid nitrogen cooling exhibits outstanding performance in inducing thermal fracturing of rocks [39].

5.2. Implications for Enhanced Geothermal System Development

From the above research results, it can be seen that thermal shock will significantly improve the porosity and permeability of rocks. In the Enhanced Geothermal System (EGS) project, a cooling medium, such as liquid nitrogen or other low-temperature fluids, can be injected into the thermal reservoir in a planned way to fracture the reservoir and improve the heat exchange efficiency [40]. However, it should be noted that excessive thermal shock may lead to the mechanical properties of rocks being too low, exceeding the stability threshold of surrounding rocks, inducing man-made disasters such as microseisms and threatening the safe production of engineering projects. However, in practical application, this method still has many limitations in fracturing technology and investment risk. First, it is difficult to control the fracturing pressure. If the pressure is too low, it can't effectively fracture, while if it is too high, it will easily lead to excessive rock breakage and scattered fractures, which is not conducive to subsequent heat exchange and fluid circulation, and may also induce geological disasters. Second, the controllability of fracture evolution is poor. It is difficult to accurately control the fracture propagation path and shape, which

easily leads to the mismatch between the actual fracture and the designed production plan and affects the fracturing effect. Third, there is still a gap between the laboratory and the field application. The sample size of the experimental study is centimeter level, the distribution of minerals in granite is relatively uniform, and the effects of heating and liquid nitrogen cooling can be transmitted to the whole sample in a short time. However, the on-site reservoir is in the range of meters to kilometers, and the scale difference causes the heterogeneity of thermal shock to be enlarged, and the heat is slowly transferred along the rock matrix, which leads to the rapid cooling around the injection point, while the temperature in the remote area has almost no obvious change. Fourth, a lot of money needs to be invested in exploration, fracturing equipment procurement, drilling construction and water resources recovery after fracturing in the early stage of hot dry rock engineering. If the final effect fails to meet expectations, the investment may not be effectively recovered, and a lot of technical optimizations are still needed to reduce the cost risk. Therefore, in view of the above shortcomings, on the one hand, we should deepen the research on the interaction mechanism between liquid nitrogen and granite, especially the influence of mineral differences, primary fractures and scale effect on thermal shock cracking performance in heterogeneous reservoirs, so as to narrow the gap between laboratory research and field practice. On the other hand, break through the bottleneck of key fracturing technologies, develop adaptive pressure control system and new-type guided fracturing technology, realize on-demand fracturing and precise fracture control, improve the controllability of the project, and promote the large-scale and commercial application of EGS project.

6. Conclusions

- (1) High temperature and cooling shock cause the deterioration of the physical and mechanical properties of granite. When the heat treatment temperature ranges from 20 °C to 450 °C, the attenuation rate of the P-wave velocity of granite after liquid nitrogen cooling shock increases linearly. In this stage, relatively few thermally induced damage cracks are generated, the change in mechanical properties is not obvious, and granite exhibits brittle failure characteristics. When the heat treatment temperature exceeds 450 °C, the attenuation rate of the P-wave velocity of granite increases sharply, its mechanical properties deteriorate significantly, the rock gradually transitions to ductile failure, and the degree of fragmentation increases.
- (2) The porosity of granite meso-structure is positively correlated with the heat treatment temperature. The heterogeneous distribution of rock minerals and the difference in thermal expansion between different mineral particles lead to the random distribution of thermal damage cracks, and the number and density of thermal damage cracks gradually increase with the increase in heat treatment temperature. Under the high temperature of 600 °C or above, the internal cracks in granite gradually expand and penetrate, and a fracture network is formed, and quartz undergoes α - β phase transformation and expands in volume, which promotes the further expansion of thermal damage cracks.
- (3) Under the influence of different cooling rates, the mechanical response and meso-damage of rocks are different, especially for high-temperature rocks over 450 °C, the connectivity and permeability of cracks in granite are significantly improved under the condition of liquid nitrogen cooling, which also reflects that liquid nitrogen cooling has a good application prospect in the reservoir fracturing and permeability enhancement reconstruction of EGS system. Liquid nitrogen can be injected into deep high-temperature rock mass in a planned way to form a temperature gradient, which will generate thermal stress inside the rock, induce mineral particles to shrink, weaken

the degree of cementation, initiate and develop fractures, and finally improve the fracture connectivity and reservoir permeability of deep rock mass.

Author Contributions: Conceptualization, K.G.; Methodology, J.W., C.L. and Y.W.; Validation, K.G. and P.M.; Investigation, K.G., J.W., C.L. and Y.W.; Data curation, P.M.; Writing—original draft, K.G. and J.W.; Visualization, Y.W.; Supervision, J.W. and Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by National Natural Science Foundation of China (Grant No. 52374206), Innovation and Entrepreneurship Funding Program of China Coal Technology & Engineering Group Corporation (Grant No. 2024-TD-MS018), and Open Project of National Key Laboratory of Geological Disaster Prevention and Geological Environment Protection (Grant No. SKLGP2024K022).

Data Availability Statement: All data used during this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

References

1. Fan, D.J.; Zhang, C.Y.; Ji, Y.L.; Zhao, X.G.; Zhao, Z.H.; He, M.C. Permeability evolution of rough fractures in Gonghe granite subjected to cyclic normal stress at elevated temperatures: Experimental measurements and analytical modeling. *Rock Mech. Rock Eng.* **2024**, *57*, 11301–11318. [\[CrossRef\]](#)
2. Wang, J.M.; Zhang, P.; Bu, M.H.; Luan, Z.L.; Wang, S.G. Mechanical behavior of granite subjected to thermal treatment: Insight from experiment and numerical simulation. *Bull. Eng. Geol. Environ.* **2023**, *82*, 400. [\[CrossRef\]](#)
3. Wang, G.L.; Zhang, W.; Ma, F.; Lin, W.J.; Liang, J.Y.; Zhu, X. Overview on hydrothermal and hot dry rock researches in China. *China Geol.* **2018**, *1*, 273–285. [\[CrossRef\]](#)
4. Zhang, C.Y.; Fan, D.J.; Elsworth, D.; He, M.C.; Zhao, X.G.; Zhu, C.; Zhang, H. Mechanisms of stress- and fluid-pressure-driven fault reactivation in Gonghe granite: Implications for injection-induced earthquakes. *Int. J. Rock Mech. Min. Sci.* **2024**, *174*, 105642. [\[CrossRef\]](#)
5. Xue, Y.; Wang, L.C.; Liu, J.; Ranjith, P.G.; Gao, F.; Cai, C.Z.; Xie, H.P. Experimental study on the effect of heating and liquid nitrogen-cooling cyclic treatment on mechanical properties and fracturing characteristics of granite. *Int. J. Rock Mech. Min. Sci.* **2024**, *176*, 105691. [\[CrossRef\]](#)
6. Yuan, Y.; Zheng, K.; Wang, C.; Zhao, Y.; Bi, J. Thermal damage and acoustic emission characteristics of high-temperature granite under liquid nitrogen cooling. *Nat. Resour. Res.* **2025**, *34*, 581–597. [\[CrossRef\]](#)
7. Rong, G.; Sha, S.; Li, B.; Chen, Z.H.; Zhang, Z.Y. Experimental investigation on physical and mechanical properties of granite subjected to cyclic heating and liquid nitrogen cooling. *Rock Mech. Rock Eng.* **2021**, *54*, 2383–2403. [\[CrossRef\]](#)
8. Jin, P.H.; Hu, Y.Q.; Shao, J.X.; Zhao, G.K.; Zhu, X.Z.; Li, C. Influence of different thermal cycling treatments on the physical, mechanical and transport properties of granite. *Geothermics* **2019**, *78*, 118–128. [\[CrossRef\]](#)
9. Zhou, L.; Zhu, Z.; Oterkus, E.; Oterkus, S.; Xu, H. Research on the effects of heating and cooling processes on the mechanical properties of yellow rust granite. *Geohazard Mech.* **2023**, *1*, 231–243. [\[CrossRef\]](#)
10. Sun, Q.; Zhang, W.Q.; Zhu, Y.M.; Huang, Z. Effect of high temperatures on the thermal properties of granite. *Rock Mech. Rock Eng.* **2019**, *52*, 2691–2699. [\[CrossRef\]](#)
11. Guo, P.Y.; Zhang, P.; Bu, M.H.; Wang, J.M.; Zheng, X.; He, M.C. Microcracking behavior and damage mechanism of granite subjected to high temperature based on CT-GBM numerical simulation. *Comput. Geotech.* **2023**, *159*, 105385. [\[CrossRef\]](#)
12. Li, Z.H.; Wong, L.N.Y.; Teh, C.I. Influence of thermal and mechanical loading on development of microcracks in granite. *Rock Mech. Rock Eng.* **2020**, *53*, 2035–2051. [\[CrossRef\]](#)
13. Liu, Z.X.; Wu, Y.; Li, X.Z.; Huang, Z.; Lin, J.; Pan, X.H. Effects of thermal treatment on the macroscopic physical properties and microstructure of Beishan fine grained granite. *Bull. Eng. Geol. Environ.* **2022**, *81*, 190. [\[CrossRef\]](#)
14. Tian, W.L.; Yang, S.Q.; Elsworth, D.; Wang, J.G.; Li, X.Z. Permeability evolution and crack characteristics in granite under treatment at high temperature. *Int. J. Rock Mech. Min. Sci.* **2020**, *134*, 104461. [\[CrossRef\]](#)
15. Xiao, P.; Li, X.N.; Li, Y.; Tang, Y.D.; Ge, X.F.; Qin, Y.; Tian, H.; Zheng, J. Experimental technique for modeling multi-field coupled transport in multi-fracture geothermal reservoirs. *Energies* **2025**, *18*, 18549. [\[CrossRef\]](#)
16. Wu, Y.; Hu, L.H.; Yu, J.; Li, X.Z.; Yang, L.N.; Xue, S.; Zhang, K. The sensitivity of mechanical properties and pore structures of Beishan granite to large variation of temperature in nuclear waste storage sites. *Environ. Sci. Pollut. Res.* **2023**, *30*, 75195–75212. [\[CrossRef\]](#) [\[PubMed\]](#)

17. Wang, J.; Wu, Y.; Mu, P.; Zhang, C.; Li, X. Meso-damage mechanism and physico-mechanical properties of Zhangzhou granite subjected to water-cooling treatment after elevated temperatures. *Geothermics* **2025**, *131*, 103397. [[CrossRef](#)]
18. Goman, M.E.; Li, G.C.; Bader, S.; Elkarmoty, M.; Ismael, M. Damage evolution of Granodiorite after heating and cooling treatments. *Minerals* **2021**, *11*, 779. [[CrossRef](#)]
19. Kumari, W.G.P.; Ranjith, P.G.; Perera, M.S.A.; Chen, B.K.; Abdulagatov, I.M. Temperature-dependent mechanical behaviour of Australian Strathbogie granite with different cooling treatments. *Eng. Geol.* **2017**, *229*, 31–44. [[CrossRef](#)]
20. Bu, M.H.; Zhang, P.; Guo, P.Y.; Wang, J.M.; Luan, Z.L.; Jin, X. Deterioration of equivalent thermal conductivity of granite subjected to heating-cooling treatment. *J. Rock Mech. Geotech. Eng.* **2024**, *16*, 4229–4246. [[CrossRef](#)]
21. Qin, Y.; Tian, H.; Xu, N.X.; Chen, Y. Physical and mechanical properties of granite after high-temperature treatment. *Rock Mech. Rock Eng.* **2020**, *53*, 305–322. [[CrossRef](#)]
22. Fan, L.F.; Gao, J.W.; Du, X.L.; Wu, Z.J. Spatial gradient distributions of thermal shock-induced damage to granite. *J. Rock Mech. Geotech.* **2020**, *12*, 917–926. [[CrossRef](#)]
23. Lin, W.J.; Chen, X.Y.; Gan, H.N.; Yue, G.F. Geothermal, geological characteristics and exploration direction of hot dry rocks in the Xiamen bay-Zhangzhou basin, southeastern China. *Acta Geol. Sin.* **2020**, *94*, 2066–2077. (In Chinese) [[CrossRef](#)]
24. Yuan, H.W.; Jing, T.Y.; Yin, Y.L.; Wei, S.C.; Gan, H.N.; Zhao, W.T.; Zhang, J. Geothermal model and development area of a fault-controlled geothermal zone along the Fujian coastal area of southeastern China. *Nat. Gas Ind. B* **2024**, *11*, 28–41. [[CrossRef](#)]
25. Yao, S.S.; Wang, Q.; Bai, Y.F.; Li, H.Z. A practical gas permeability equation for tight and ultra-tight rocks. *J. Nat. Gas. Sci. Eng.* **2021**, *95*, 104215. [[CrossRef](#)]
26. Sundaram, D.; Svidr , J.T.; Di szegi, A.; Svidr , J. Measurement of Darcian Permeability of foundry sand mixtures. *Int. J. Cast Met. Res.* **2021**, *34*, 97–103. [[CrossRef](#)]
27. Chen, L.; Chen, K.; Zhang, Z.; Zhang, Y.Y.; Liu, Z.Q.; Huang, Y.H. Macro and micro damage characteristics of Red-bed sandstone in Urumqi under freeze–thaw cycles. *Sci. Rep.* **2025**, *15*, 21785. [[CrossRef](#)] [[PubMed](#)]
28. Fan, L.F.; Gao, J.W.; Wu, Z.J.; Yang, S.Q.; Ma, G.W. An investigation of thermal effects on micro-properties of granite by X-ray CT technique. *Appl. Ther. Eng.* **2018**, *140*, 505–519. [[CrossRef](#)]
29. Wu, X.; Huang, C.; Li, P.; Zhang, S.L.; Xu, Z. Experimental study on evaluation of density, P-wave velocity, thermal conductivity, and thermal diffusion coefficient of granite after thermal treatments by using PCA. *Sci. Rep.* **2024**, *14*, 7748. [[CrossRef](#)]
30. Qian, R.P.; Liu, X.L.; Ma, Q.; Feng, G.R.; Bai, J.W.; Guo, J.; Zhang, S.; Wen, X.Z. Effect of water intrusion on mechanical behaviors and failure characteristics of backfill body and coal pillar composite specimens under uniaxial compression. *J. Clean. Prod.* **2025**, *502*, 145388. [[CrossRef](#)]
31. Johnson, S.E.; Song, W.J.; Cook, A.C.; Vel, S.S.; Gerbi, C.C. The quartz $\alpha \leftrightarrow \beta$ phase transition: Does it drive damage and reaction in continental crust? *Earth Planet. Sci. Lett.* **2021**, *553*, 116622. [[CrossRef](#)]
32. Costa, A. Permeability-porosity relationship: A reexamination of the Kozeny-Carman equation based on a fractal pore-space geometry assumption. *Geophys. Res. Lett.* **2006**, *33*, L02318. [[CrossRef](#)]
33. Safari, M.; Gholami, R.; Jami, M. Developing a porosity-permeability relationship for ellipsoidal grains: A correction shape factor for Kozeny-Carman’s equation. *J. Petrol. Sci. Eng.* **2021**, *205*, 108896. [[CrossRef](#)]
34. Wong, L.N.Y.; Zhang, Y.H.; Wu, Z.J. Rock strengthening or weakening upon heating in the mild temperature range? *Eng. Geol.* **2020**, *272*, 105619. [[CrossRef](#)]
35. Zhang, W.Q.; Sun, Q.; Hao, S.Q.; Geng, J.S.; Lv, C. Experimental study on the variation of physical and mechanical properties of rock after high temperature treatment. *Appl. Ther. Eng.* **2016**, *98*, 1297–1304. [[CrossRef](#)]
36. Yang, S.Q.; Ranjith, P.G.; Jing, H.W.; Tian, W.L.; Ju, Y. An experimental investigation on thermal damage and failure mechanical behavior of granite after exposure to different high temperature treatments. *Geothermics* **2017**, *65*, 180–197. [[CrossRef](#)]
37. Chen, C.C.; Chu, P.; Xie, H.P.; Li, M.H.; Li, C.B.; Shang, D.L. Fracture behavior of high-temperature granite subjected to liquid nitrogen cooling: Semi-circular bending test and crack evolution analysis. *Theor. Appl. Fract. Mech.* **2023**, *128*, 104100. [[CrossRef](#)]
38. Wu, X.; Huang, Z.; Song, H.; Zhang, S.; Cheng, Z.; Li, R.; Wen, H.; Huang, P.; Dai, X. Variations of physical and mechanical properties of heated granite after rapid cooling with liquid nitrogen. *Rock Mech. Rock Eng.* **2019**, *52*, 2123–2139. [[CrossRef](#)]
39. Shao, Z.; Tang, X.; Wang, X. The influence of liquid nitrogen cooling on fracture toughness of granite rocks at elevated temperatures: An experimental study. *Eng. Fract. Mech.* **2021**, *246*, 107628. [[CrossRef](#)]
40. Fan, Z.; Parashar, R. Analytical solutions for a wellbore subjected to a non-isothermal fluid flux: Implications for optimizing injection rates, fracture reactivation, and EGS hydraulic stimulation. *Rock Mech. Rock Eng.* **2019**, *52*, 4715–4729. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.