



OPEN Micro-mechanisms of temperature-dependent triaxial strength in Beishan granite and implications for high-level radioactive waste disposal

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Beishan granite, China's candidate host rock for high-level radioactive waste (HLW) disposal, experiences alterations in strength and failure characteristics under prolonged thermo-mechanical coupling conditions, impacting the long-term stability evaluation. In this study, the strength and failure behavior of Beishan granite specimens, which were heated to 25, 200, 300, 400, 500, and 600 °C, and subsequently cooled to room temperature, were investigated by triaxial tests under confining pressures of 5, 15, and 25 MPa. The results indicated that the triaxial compression strength (TCS) exhibited non-monotonic strength variation with temperature. Below 300 °C, TCS increases by 10.2–14.7% through crack closure from differential thermal expansion (quartz $\alpha = 11 \times 10^{-6}/^{\circ}\text{C}$ and feldspar $\alpha = 5 \times 10^{-6}/^{\circ}\text{C}$) and evaporation-induced effective stress enhancement. Beyond 400 °C, TCS shows an average decline of 14.27%, primarily governed by intergranular cracking as expansion stresses exceed intergranular bonding forces. Acoustic emission monitoring revealed that crack propagation transitions from distributed micro-fracturing to localized macro-cracking as the temperature exceeds 400 °C. Moreover, the strength degradation rate with increasing temperature of Beishan granite declines from 19.4% to 9% with increasing confining pressure (5 to 25 MPa), demonstrating that elevated in-situ stresses (representing greater disposal depths) effectively suppress thermal damage. These findings establish a critical temperature threshold and depth-compensation principle, providing thermo-mechanical design criteria for HLW repository engineering.

Keywords Beishan granite, High-temperature, Non-monotonous strength variation, Triaxial compression, Critical temperature threshold

Deep geological disposal has been internationally accepted as an effective way to deal with high-level radioactive waste (HLW), and the low native permeability and high strength of Beishan granite are selected as the ideal host rock^{1–3}. However, large amounts of heat are released during the disposal of HLW, which can lead to elevated temperatures in the surrounding rock mass⁴. While temperatures in a geological repository are designed to remain below thresholds that would compromise safety (typically < 100–200 °C), understanding the fundamental response of the host rock to a wide range of temperatures remains crucial for safety assessment and fundamental rock mechanics research. Extreme temperatures, such as those reported in early concepts like nuclear self-storage (where temperatures could reach up to 1200 °C⁵, which could induce thermal cracking and increase radionuclide release risk.

The mechanical properties and failure behaviors of granite after thermal treatment have been extensively investigated in laboratory tests^{6–9}. The effect of high-temperature treatment can lead to inhomogeneous expansion,

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dehydration, and thermal reactions of mineral grains in granite specimens, which affect the mechanical properties and failure behaviors. In general, the parameters such as the uniaxial and triaxial compression strength, elastic modulus, and cohesion gradually decrease with increasing temperature. On the contrary, failure strain, Poisson's ratio, and friction angle showed an increasing trend with increasing temperature^{10–12}. However, the mechanical properties of granite specimens do not decrease monotonously with increasing temperature; rather, the granite is strengthened by heating in the mild temperature range^{13,14}. The dominant mechanisms for the positive contribution (strengthening) of high-temperature treatment to rock strength were summarized: the positive role of microcrack closure and the dual effect of water-related changes¹⁵. In the mild temperature range, the thermal expansion of mineral grains is the dominant cause of rock compaction and strengthening. In addition, the evaporation of absorbed water in the rock temporarily increases the effective stress and the friction between mineral particles is increased by water loss¹⁶. As the heating temperature continues to increase, the strength of the granite specimens decreases with increasing temperature. This “thermal damage” effect is essentially related to two mechanisms^{15,16}: (1) the propagation of existing cracks or the formation of new microcracks attributed to the thermal expansion of minerals¹⁷. The mismatch in thermal expansion among different mineral grains can induce microcracks at mineral contacts, while the anisotropy in thermal expansion of individual minerals can lead to the generation of internal microcracks within the grains¹⁸. (2) the collapse of mineral structure due to the enhanced thermal reactions. Specifically, many changes in the properties of the rock are associated with the α - β quartz transition occurring around 573 °C^{19,20}.

Meanwhile, the real-time source locating technique provides an effective method for monitoring the nucleation and growth of fractures. Wang et al.^{21,22}, utilizing a 3D acoustic emission monitoring system, obtained the temporal and spatial development process of microcracks in Beishan granite specimens under the effect of temperature and stress conditions. The results indicate that increasing the temperature may accelerate the initiation of thermally induced cracks and increase the volumetric strain rate. However, confining pressure can inhibit the propagation and aggregation of microcracks²³. The main method for deep geological disposal is to permanently store HLW in underground geological repositories at depths ranging from 500 to 1000 m, where the in-situ stresses in the surrounding rock gradually increase with depth²⁴.

While extensive studies have characterized the strength and deformation behavior of granite under thermal loading, the micromechanical processes governing its non-monotonic mechanical response, particularly the critical transition from thermal strengthening to weakening under true triaxial conditions (i.e., with confining pressure), remain inadequately quantified for Beishan granite. Specifically, a precise critical temperature threshold defining this transition and a comprehensive micro-mechanical explanation linking mineralogical behavior to macroscopic strength variation are yet to be established. To address this gap, we conduct a systematic investigation of Beishan granite through integrated triaxial compression tests conducted on specimens previously heated to the target temperatures and 3D acoustic emission monitoring. In this study, we elucidate the micromechanical processes underlying temperature-dependent strength variations, identify the critical temperature threshold for the transition in triaxial compressive behavior of Beishan granite, and ultimately provide practical insights for repository design based on depth-dependent thermal compensation effects. The findings of this study are expected to provide references for enhancing the safety of high-level radioactive waste (HLW) geological disposal.

Materials and methods

Specimen preparation

The samples were taken from the Beishan pre-selection area for geological disposal of HLW, as shown in Fig. 1. The rock is an off-white, homogeneous, and dense granite. Quantitative X-ray diffraction of powdered material gives the following modal abundances: Qtz 35%, Pl 30%, Kfs 25%, Bt 8%, others 2%. According to the recommendations of the ISRM, the granite samples were polished and processed into a standard cylindrical specimen with a diameter of 50 mm and a height of 100 mm. At the same time, to minimize the variability brought by the specimens and ensure the reliability and correctness of the test results, granite specimens with no defects in appearance and flat at both ends (± 0.05 mm of non-parallelism) were selected and tested for their basic physical properties, and the results are shown in Table 1. The P-wave velocity of the specimen was 3310 ± 125 m/s, and the natural density was 2.73 ± 0.02 g/cm³ (The measured density is consistent with that expected for a fresh, compact granite composed primarily of quartz and feldspars).

Test procedure

The TNX-1400 muffle furnace was used for high-temperature heat treatment of granite. The processed specimens were numbered and grouped according to the temperature level of high-temperature heat treatment. In this paper, six test groups were divided into room temperature (25 °C), 200, 300, 400, 500, and 600 °C. The specific operation steps of high-temperature heat treatment of the Beishan granite specimens are as follows: firstly, the specimens were heated to a predetermined temperature according to a heating rate of 8 °C/min^{25,26}. The specimens were then kept at the target temperature for 2 h to ensure a uniform thermal field. Subsequently, the furnace power was switched off, and the specimens were allowed to cool down naturally to room temperature inside the closed furnace. This specific cooling protocol, which resulted in a slow and natural cooling rate of approximately 1–2 °C/min, was applied consistently to all thermally treated specimens, including those subjected to the 25 °C baseline condition. This ensured that all specimens underwent an identical thermal history, thereby allowing for a valid comparison of the effects induced solely by the different peak temperatures.

Although the maximum anticipated temperature in the Beishan host rock is below 200 °C under normal repository conditions, specimens were heated to 400 °C, 500 °C, and 600 °C to establish an extreme-condition strength envelope and to provide data for the calibration of numerical models that may be used for accidental-

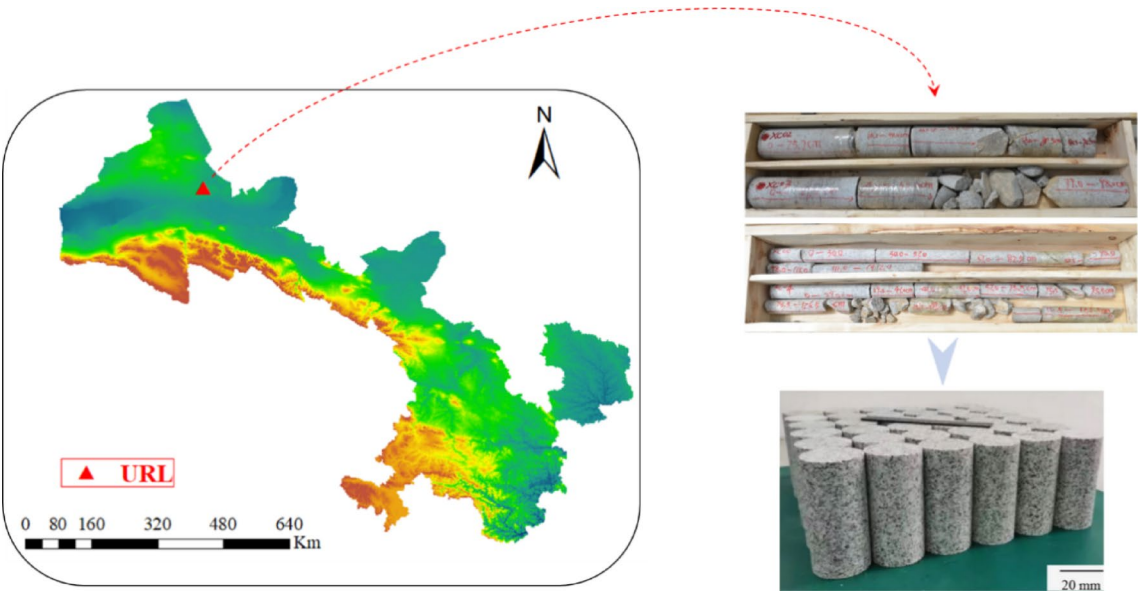


Fig. 1. Location map of the drill core collection site (Xinchang site) in the Beishan area, Gansu province, China⁷. (The base map was generated using Digital Elevation Model (DEM) data from the National Geomatics Center of China (<http://www.ngcc.cn>) and processed with Esri ArcGIS software.).

Mass (g)	Volume (cm ³)	Density (g/cm ³)	P-wave velocity (m/s)
522.30 ± 7.10	192.05 ± 3.50	2.73 ± 0.02	3310 ± 125

Table 1. Physical properties of Beishan granite specimens.

heating scenarios (e.g., waste-canister breach or gallery fire). These elevated-temperature tests are therefore conservative bounds rather than representations of the expected operating environment.

As shown in Fig. 2, Conventional triaxial compression and AE monitoring were used to monitor the damage process of specimens. Conventional triaxial compression loading tests were performed on the MTS 815 Flex Test GT rock mechanics test system, as shown in Fig. 2a. During the test, a 3D acoustic emission monitoring system was performed using a Micro-II acoustic emission meter manufactured by Physical Acoustics Corporation (PAC), and eight Nano-30 miniature AE sensors were used to detect the AE signals during rock fracturing, as shown in Fig. 2b. To ensure the coupling effect between the specimen and the sensors, an appropriate amount of Vaseline was applied to the surface of the sensors. Two linear variable differential transducers (LVDTs) and one axial extensometer are employed to measure axial deformation, while circumferential deformation is measured by one extensometer, as shown in Fig. 2c.

According to the in-situ stress results measured in the Beishan pre-selection area, the vertical stress $\sigma_v = 13.5$ MPa, the maximum horizontal principal stress $\sigma_H = 15 \pm 3$ MPa, and the minimum horizontal principal stress $\sigma_h = 10 \pm 1.5$ MPa of the rock mass at a depth of 500 m^{24,25}. Therefore, in this paper, three levels of 5, 15, and 25 MPa were selected for the conventional triaxial tests to compare and analyze the triaxial compressive strength and deformation characteristics of the heat-treated granite.

Experimental results and analysis

Triaxial stress-strain response of granite under different temperatures

The axial deviatoric stress-strain curves of Beishan granite specimens with different temperatures under triaxial compression conditions are shown in Fig. 3. The deviatoric stress was calculated as $\sigma_1 - \sigma_3$, where σ_1 is the maximum principal stress and σ_3 is the confining pressure; ϵ_1 is the axial strain and ϵ_3 is the circumferential strain. It can be observed from Fig. 3 that the axial deviatoric stress-strain curves for Beishan granite specimens at different temperatures all exhibited a similar trend: initial concavity, followed by a linear elastic phase, and finally convexity leading to the peak stress.

The axial deviatoric stress-strain curve exhibits nonlinear deformation at the initial stage, characterized by an upward concave curve, particularly at lower confining pressures, which is attributed to the closure of initial pores and fissures in the rock^{26,27}. Generally, the more noticeable initial pore and fissure compaction stage with increasing heating temperature indicates that the high-temperature effect enlarges the pores and microfractures in the rock. Compared to the effect of temperature, the shape and variation law of the curves are more sensitive to the confining pressure. The initial deformation of the specimen gradually decreased with the increase of the



Fig. 2. Conventional triaxial compression by the MTS 815 Flex Test GT rock mechanics test system and AE monitoring system by the PCI-II.

confining pressure, which is mainly because the pre-applied confining pressure affected the closure of the initial pores and cracks before the deformation was recorded.

Subsequently, with a further increase in the load, the stress-strain response gradually enters into a linear stage (i.e., the elastic deformation stage). The deviatoric stress shows a linear increase with increasing axial and circumferential strains. The slope between the deviatoric stress and axial strain increases with increasing confining pressure, mainly because the confining pressure restrains the displacement and enhances the friction between the grains. After high-temperature treatment, the slope of the linear stage does not decrease consistently but increases slightly under mild temperature conditions (within 300 °C), with the evaporation of absorbed water in the rock^{28,29} and the thermal expansion of different mineral grains^{16,30,31}.

Next, the stress-strain response gradually deviates from its linear phase, and the slope between the deviatoric stress and axial strain decreases with an increase in the load, and the circumferential strain increases nonlinearly (i.e., the plastic deformation stage). The stress concentration leads to localized damage in the granite, so the deformation resistance is weakened. With the increase in temperature, the thermal-induced microcracks increased, and the bearing structure of the granite specimens was damaged. Therefore, the ability of the granite specimens to store strain energy decreased. At the same heating temperature, confining pressure enhances the deformation resistance in granite specimens.

Finally, the stress-strain response enters a post-peak failure stage, where the axial and circumferential strain increase rapidly with an increase in the load. Therefore, macrocracks form, and stress decreases rapidly. The granite specimens generally fail along the shear rupture plane due to the creation of short, coarse-grained cracks in front of the rupture tips. At $T \leq 300$ °C, the elastic energy stored in the granite specimen can maintain crack propagation, leading to a self-sustained failure (Class II of post-peak behavior), and this phenomenon is more noticeable with the increase of the confining pressure^{32,33}. As the temperature increases, the ability of granite to store elastic energy decreases due to the generation of thermally induced intergranular cracks, leading to Class I behavior failure.

The deviator stress-volume strain of the Beishan granite specimens with different temperatures under triaxial compression conditions was derived from the test data, which are shown in Fig. 4. The parameter ε_v refers to the volume strain (i.e., $\varepsilon_v = \varepsilon_1 + 2\varepsilon_3$) following the convention that compressive strain is positive, while expansion strain is negative. The shapes of the deviatoric stress-volume strain curves of the Beishan granite specimens were similar after high-temperature treatment and for different confining pressures. The volumetric strain is characterized by beginning with a compaction-dominated phase, followed by a dilatancy-dominated phase. As shown in Fig. 4c, point A refers to the crack closure. The axial deviatoric stress corresponding to point B was the crack damage threshold (σ_{cd}) of the specimen (The rate of compaction and dilatancy are equal, and the volumetric strain curve shows an inflection point)^{14,34,35}. After point B, the volumetric deformation of the specimen switched from compaction-dominated to dilatancy-dominated. Eventually, as the stress increases, the specimen reaches the peak deviatoric stress (point C) and then continues to increase until the specimen fails.

The confining pressure acts as a restriction on the volumetric shrinkage of the specimen during loading, and the amount of shrinkage of the Beishan granite specimen decreases with the increase in the confining pressure before the σ_{cd} is reached, especially in the case of the Beishan granite under the room temperature (25 °C). This is

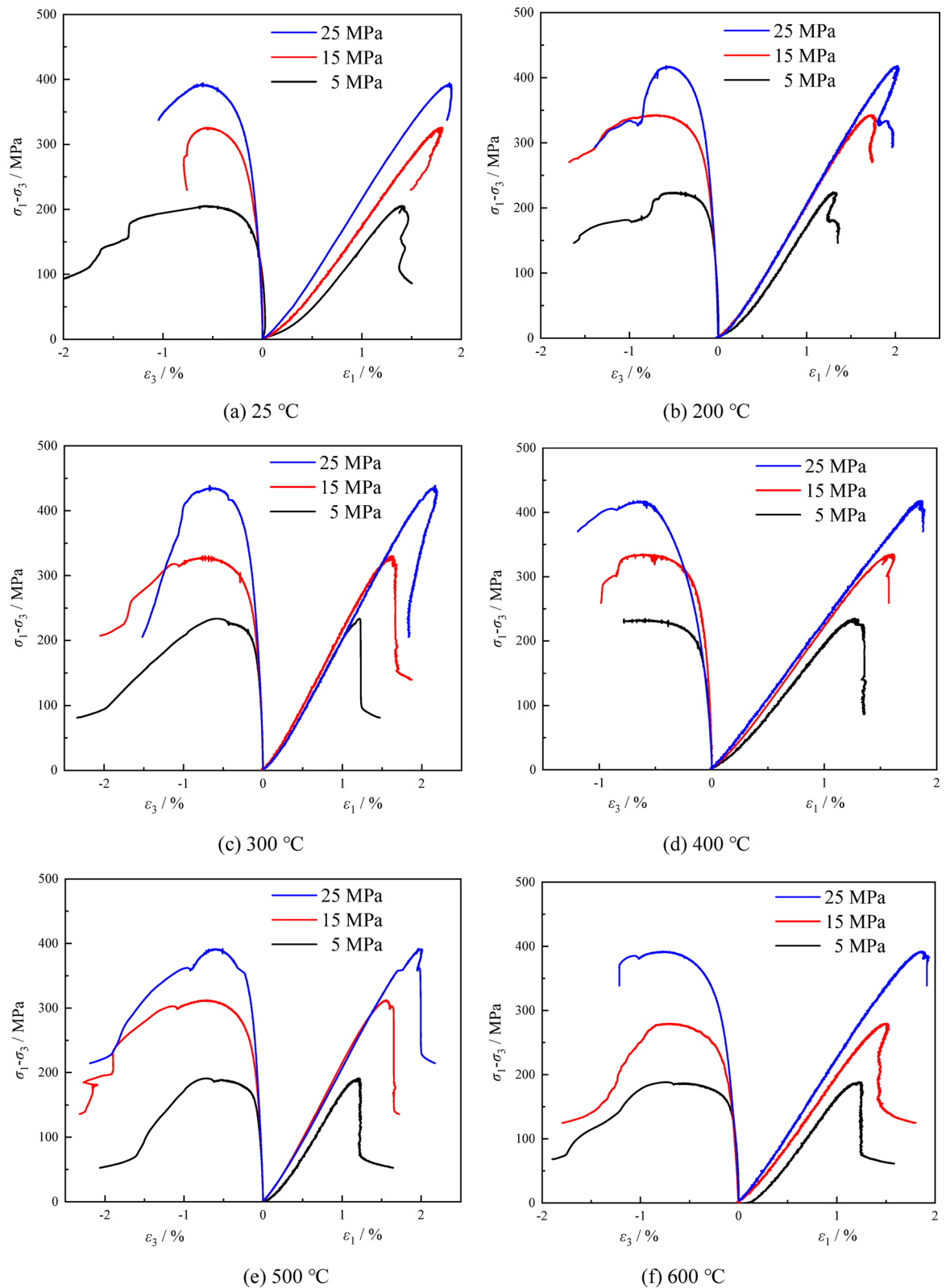


Fig. 3. Deviatoric stress-axial strain and circumferential strain curves of the Beishan granite specimens with different temperatures under triaxial compression conditions. (a) 25 °C, (b) 200 °C, (c) 300 °C, (d) 400 °C, (e) 500 °C, (f) 600 °C.

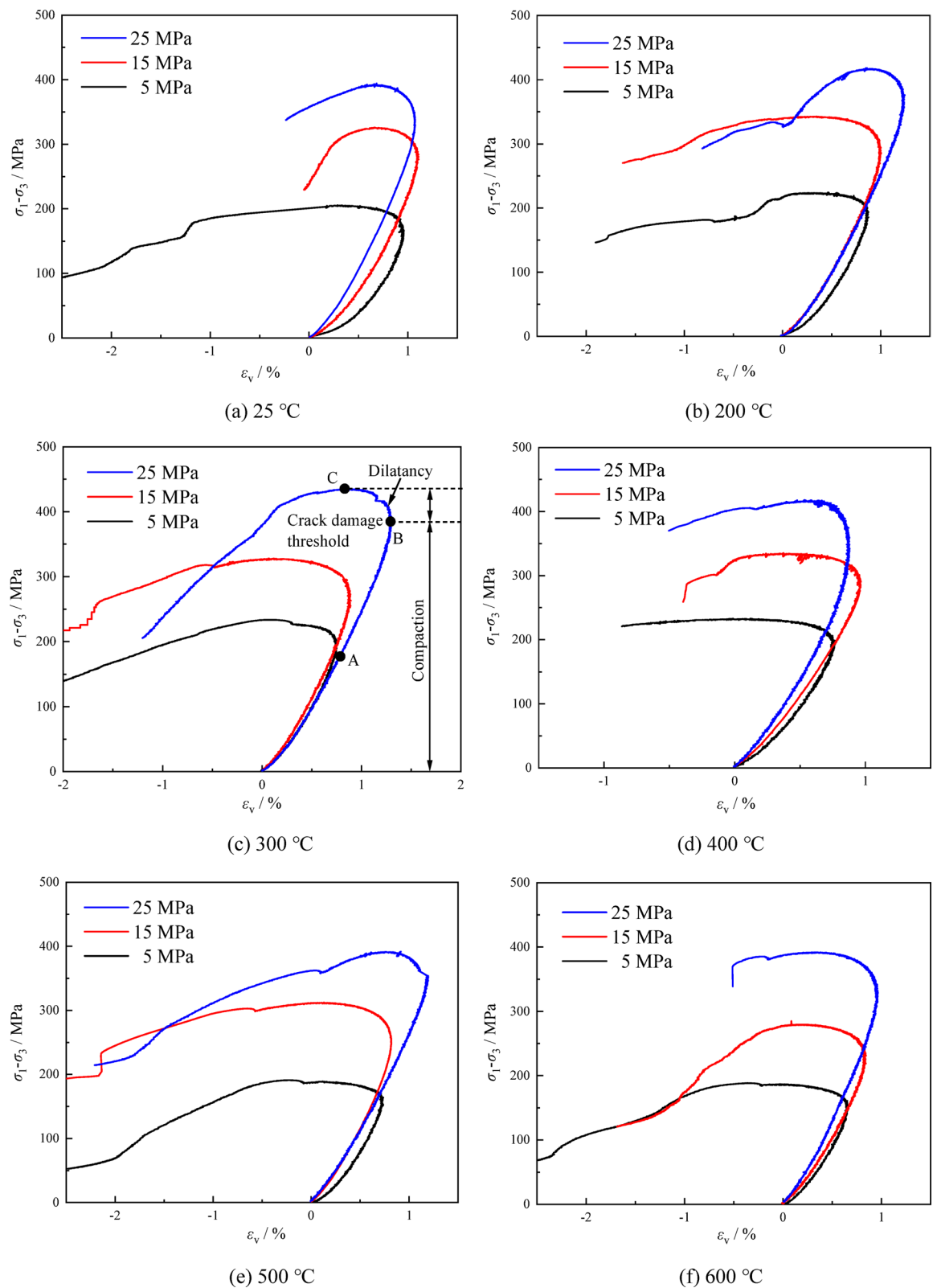


Fig. 4. Deviatoric stress-volume strain curves of the Beishan granite specimens with different temperatures under triaxial compression conditions. (a) 25 °C, (b) 200 °C, (c) 300 °C, (d) 400 °C, (e) 500 °C, (f) 600 °C.

due to the closure of the partial cracks under the effect of the confining pressure, and the potential of volumetric shrinkage during the subsequent loading process is small¹⁴. With the evaporation of absorbed water in the rock and the positive effect of thermal expansion of mineral particles ($T \leq 400\text{ }^{\circ}\text{C}$), the effective stress in the rock and the friction between minerals are made to increase, providing more space for the compaction shrinkage of the specimen during the loading process¹⁶. The intergranular slip in the rock is more likely to occur due to the generation of thermally induced microcracks and the breaking of the bearing structure with the increase in heating temperature, leading to the expansion of the specimen. Similarly, the confining pressure acts as a restriction on the volume expansion of the specimen during the loading process, and the volume expansion rate decreases with the increase of the confining pressure after the σ_{cd} is reached.

Effect of temperature on the triaxial compressive strength of granite

The properties of Beishan granite specimens with different temperatures under triaxial compression tests are listed in Table 2. The relationships between these properties and the temperature or confining pressures are exhaustively discussed and presented in the next sections.

In this section, we simultaneously examined the effects of temperature and confining pressure on the Beishan granite specimens. Figure 5 illustrates the relationship between temperature and the TCS of the specimens under the three levels of confining pressures. The relationship between the TCS and temperature is described as follows:

$$\sigma_{1p}(T) = a \times T^2 + b \times T + c \tag{1}$$

where T is the heating temperature; a , b , and c are constants determined from triaxial compression tests. More details are presented in Table 3.

It can be observed that the TCS of Beishan granite exhibits a consistent pattern of initial increase followed by a decrease with increasing temperature under identical confining pressures. The critical temperature threshold at which the triaxial compressive mechanical behavior of Beishan granite changes was found to be between 300 and 400 °C. Specifically at 25 MPa confining pressure, TCS reaches 463.8 MPa at 300 °C, representing a 10.7% increase from room temperature conditions (419.1 MPa at 25 °C). This strengthening phase correlates with microstructural observations of crack closure due to differential thermal expansion between quartz ($\alpha = 11 \times 10^{-6}/^{\circ}\text{C}$) and feldspar ($\alpha = 5 \times 10^{-6}/^{\circ}\text{C}$), which enhances TCS by 10.2–14.7% at temperatures below 300 °C. Conversely, when exceeding 400 °C, TCS shows progressive reduction, decreasing by 9% at 600 °C relative to 400 °C. Under varying confining pressures, the TCS exhibits an average reduction of 14.27%, with intergranular cracking being the dominant mechanism as thermal expansion stresses surpass intergranular bonding forces.

In addition, the stabilizing influence of confining pressure manifests in two aspects. First, TCS exhibits the expected stress-dependent enhancement; at room temperature, the strength at 15 MPa (340.8 MPa) and 25 MPa (419.1 MPa) represents an increase of 58.7% and 92.1%, respectively, over the baseline value at 5 MPa (210.5 MPa). Second, and more notably, elevated confining pressures significantly mitigate high-temperature strength degradation - the 600 °C strength loss reduces from 19.4% at 5 MPa to just 9.0% at 25 MPa, demonstrating the critical role of lithostatic pressure in counteracting thermal damage.

Based on the data presented in Table 2; Fig. 6 illustrates the effect of the different temperatures on the triaxial strength envelopes of Beishan granite. Generally, the TCS of Beishan granite specimens under different

Temperature (°C)	Confining pressures σ_3 (MPa)	TCS σ_{1p} (MPa)	Elastic modulus E_s (GPa)	Failure strain ϵ_f (%)	Poisson's ratio
25	5	210.51	73.51	1.44	0.41
	15	340.83	97.32	1.80	0.35
	25	419.1	112.93	1.92	0.36
200	5	229.33	89.54	1.30	0.34
	15	374.52	108.31	1.76	0.38
	25	443.13	113.22	2.03	0.34
300	5	238.54	96.02	1.24	0.47
	15	345.22	107.04	1.62	0.46
	25	463.76	110.32	2.17	0.35
400	5	239.7	94.22	1.28	0.47
	15	350.19	107.55	1.66	0.40
	25	458.12	117.97	1.99	0.38
500	5	196.06	80.58	1.21	0.58
	15	327.3	104.98	1.57	0.46
	25	416.77	112.05	1.94	0.32
600	5	193.33	72.41	1.34	0.46
	15	299.73	99.31	1.52	0.48
	25	416.96	113.15	1.87	0.43

Table 2. Triaxial test results of Beishan granite specimens with different temperature treatments.

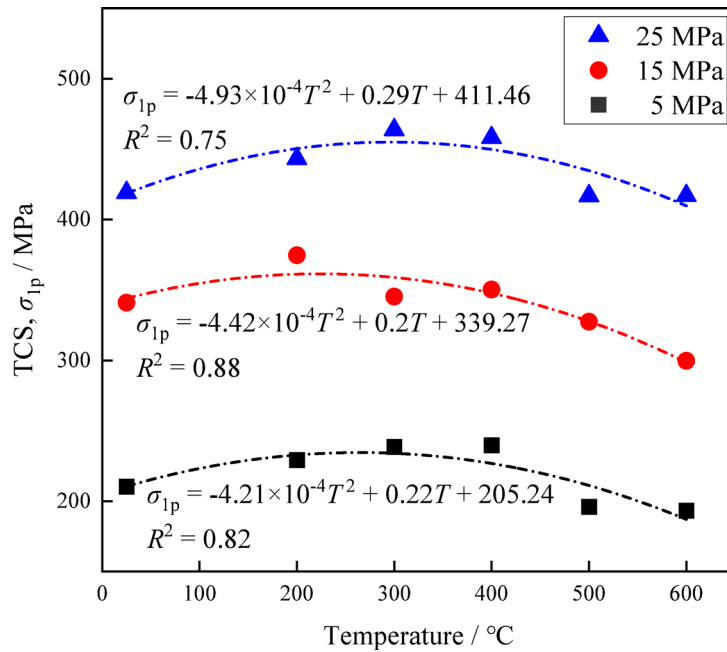


Fig. 5. Variation of the TCS with different temperatures under different confining pressures.

Confining pressure (MPa)	Fitting parameters for σ_{1p} - T curves $\sigma_{1p}(T) = a \times T^2 + b \times T + c$			
	a	b	c	R^2
5	-4.21×10^{-4}	0.22	205.24	0.82
15	-4.42×10^{-4}	0.20	339.27	0.88
25	-4.93×10^{-4}	0.29	411.46	0.75

Table 3. Triaxial test results of Beishan granite specimens with different temperature treatments.

temperature treatments increased with increasing confining pressure, which is consistent with the results of previous studies^{1,36}. The classical Mohr-Coulomb failure criterion was used to describe the strength characteristics of Beishan granite under different temperature treatments. A linear function described the relationship between the TCS and confining pressure under different temperature treatments:

$$\sigma_{1p} = \alpha \times \sigma_3 + \beta \quad (2)$$

where α and β are constants determined from the tests, and the correlation coefficient (R^2) for the linear fit is presented in Table 4. According to the Mohr-Coulomb strength criterion, α and β are related to the friction angle and cohesion of the rock, respectively, as we can derive³⁷:

$$C = \frac{\beta}{2\sqrt{\alpha}} \quad (3)$$

$$\varphi = \arcsin \frac{\alpha - 1}{\alpha + 1} \quad (4)$$

where C is the cohesion and φ is the friction angle, respectively. Figure 7 illustrates the effect of temperature and confining pressure on the Mohr circles. Under the same confining pressure condition, the Mohr circles do not decrease invariably but show a trend of increasing first and then reducing with the increase of heating temperature. Generally, at $T \leq 400$ °C, the Mohr circles show an increasing trend; at $T > 400$ °C, the Mohr circles show a reducing trend (compared with the Mohr circle at room temperature). Equations (2) and (3) calculate the cohesion and friction angle of Beishan granite, respectively, and are shown in Table 4. As can be seen, the cohesion increases with the temperature increase when the temperature is lower than 400 °C. There are 11.55%, 3.85%, and 4.88% relative increases in the cohesion after the samples were treated with 200 °C, 300 °C and 400 °C. Once the temperature exceeds 400 °C, the cohesion decreases with the temperature increase until the temperature reaches 600 °C. There are 13.95% and 21.59% relative reductions in the cohesion after the samples were treated with 500 °C and 600 °C. The change range of the internal friction angle is within 1.22°.

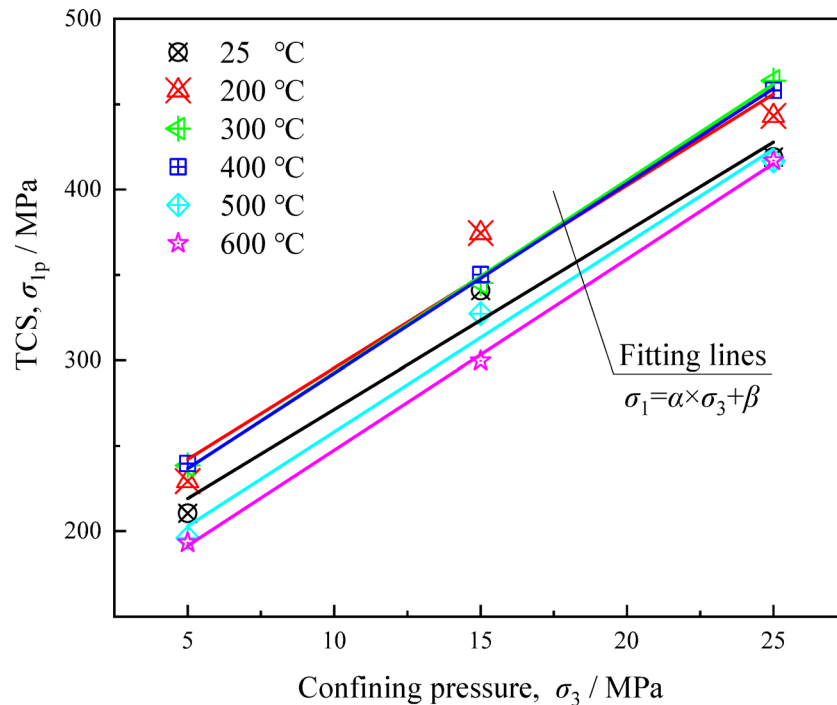


Fig. 6. The effect of the different temperatures on the triaxial strength envelopes of Beishan granite.

Heating temperature (°C)	Fitting parameters of $\sigma_{1p}-\sigma_3$ $\sigma_{1p} = \alpha \times \sigma_3 + \beta$			Calculated cohesion and friction angle	
	α	β	R^2	C (MPa)	φ (°)
25	10.43	167.04	0.96	25.86	55.59
200	10.69	188.64	0.92	28.85	55.99
300	11.26	180.26	0.99	26.86	56.81
400	11.02	180.09	0.99	27.12	56.47
500	11.04	147.84	0.98	22.25	56.49
600	11.18	135.62	0.99	20.28	56.70

Table 4. Parameters of the regression lines of the strength envelopes and the calculated cohesion and friction angle of Beishan granite specimens under different temperature treatments.

Effect of temperature on the deformation parameters of granite

The deformation characteristics of Beishan granite specimens under triaxial compression at different temperatures, including the elastic modulus and Poisson's ratio, are presented in Table 2. In order to take into account the effect of the confining pressure, we used the following method to determine the elastic modulus (E_s) and Poisson's ratio (ν). For Beishan granite specimens under conventional triaxial compression conditions ($\sigma_2 = \sigma_3$, $\varepsilon_2 = \varepsilon_3$), the bulk modulus (K) and shear modulus (G) can be calculated according to the generalized Hooke's law as follows:

$$E = \frac{9KG}{3K + G} = \frac{\sigma_1^2 + \sigma_1\sigma_3 - 2\sigma_3^2}{(\sigma_1 + \sigma_3)\varepsilon_1 - 2\sigma_3\varepsilon_3} \quad (5)$$

$$\nu = \frac{3K - 2G}{6K + 2G} = \frac{\sigma_3\varepsilon_1 - \sigma_1\varepsilon_3}{(\sigma_1 + \sigma_3)\varepsilon_1 - 2\sigma_3\varepsilon_3} \quad (6)$$

Equations (4) and (5) show that the elastic modulus and Poisson's ratio of Beishan granite were closely related to the stress level, axial strain, and radial strain, which are not fixed values. Therefore, in this study, the stress state corresponding to the stress value of one-half of Beishan granite strength was used to determine E_s and ν :

$$E_s = \frac{(\sigma_3 + 0.5\sigma_p)^2 + (\sigma_3 + 0.5\sigma_p)\sigma_3 - 2\sigma_3^2}{(2\sigma_3 + 0.5\sigma_p)\varepsilon_f - 2\sigma_3\varepsilon_{rf}} \quad (7)$$

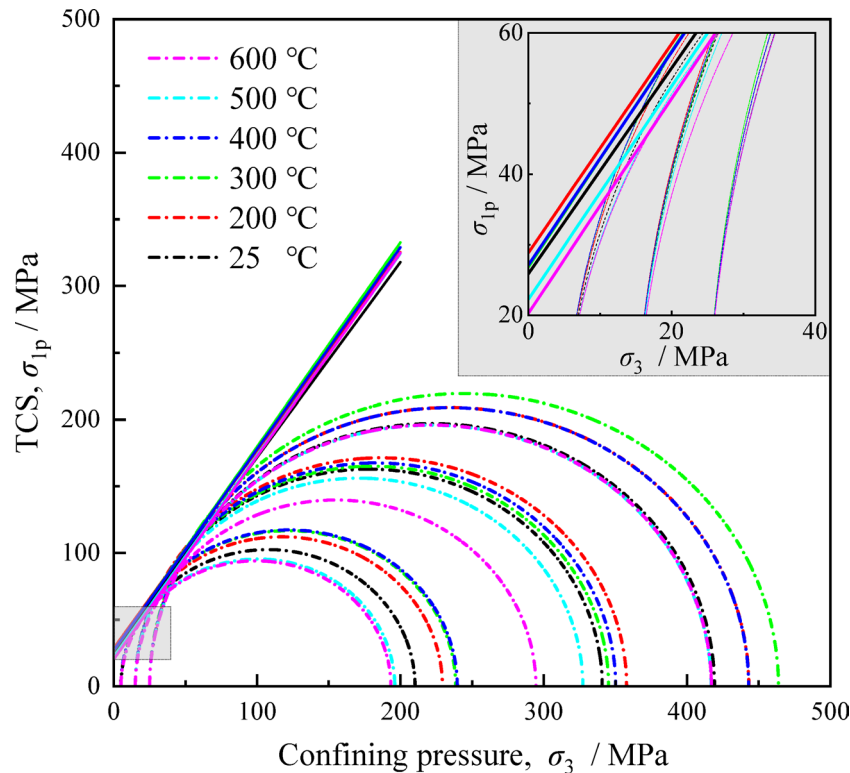


Fig. 7. The effect of temperature and confining pressure on the Mohr circles.

$$v = \frac{\sigma_3 \varepsilon_f - (\sigma_3 + 0.5\sigma_p) \varepsilon_{rf}}{(2\sigma_3 + 0.5\sigma_p) \varepsilon_f - 2\sigma_3 \varepsilon_{rf}} \quad (8)$$

where ε_f and ε_{rf} represent the axial and radial strain at failure, respectively.

The evolutions of the elastic modulus of Beishan granite specimens with different temperatures under different confining pressures, as shown in Fig. 8. For the temperature-treated samples, Young's modulus slightly increases when the temperature increases from 25 to 400 °C and decreases when the temperature increases from 400 to 600 °C, and the same trends can be observed for the different confining pressures. For example, at the 15 MPa confining pressure, Young's modulus increased by 10.51% at 400 °C concerning room temperature (25 °C) and decreased by 7.66% at 300 °C relative to 400 °C. However, Young's modulus shows an increasing trend with the increase in the confining pressure. When the confining pressure is increased from 5 MPa to 15 MPa, Young's modulus shows a varying increase in the range of 11.48% (300 °C) to 30.28% (500 °C). As the confining pressure is further increased to 25 MPa, Young's modulus shows a varying increase in the range of 14.9% (300 °C) to 39.06% (600 °C). Note that the increase in the confining pressure leads to the closure of some of the thermally induced cracks¹⁴. The relationship between the elastic modulus and temperature or confining pressure is described as follows:

$$E_S(T) = d \times T^2 + e \times T + f \quad (9)$$

$$E_S = m \times \sigma_3 + n \quad (10)$$

where d , e , f , m , and n are constants determined from triaxial compression tests. The parameters of the elastic modulus of Beishan granite specimens with different temperatures under triaxial compression tests are shown in Tables 5 and 6, respectively.

The evolutions of the Poisson's ratio of Beishan granite specimens with different temperatures under different confining pressures, as shown in Fig. 9. Generally, Poisson's ratio increases gradually with the increase of heating temperature. Poisson's ratio increased from 0.41 (25 °C) to 0.58 (500 °C) at 5 MPa confining pressure, from 0.35 (25 °C) to 0.48 (600 °C) at 15 MPa confining pressure, and from 0.36 (25 °C) to 0.43 (600 °C) at 25 MPa confining pressure, respectively. After high-temperature treatment, the granite specimens contained more thermally-induced microcracks and the mineral particles were more easily rotated. Therefore, the granite specimens are more likely to expand in the circumferential direction. However, the mineral particles were more easily reoriented or slid past one another due to the weakened grain boundaries and microcracks. The variation range of Poisson's ratio of the granite specimens under the effect of different temperatures becomes gradually smaller, which are 0.34–0.58 ($\sigma_3 = 5$ MPa), 0.35–0.48 ($\sigma_3 = 15$ MPa), and 0.32–0.43 ($\sigma_3 = 25$ MPa), respectively. With the increase of confining pressure, the Poisson's ratio of granite specimens under different temperatures showed a

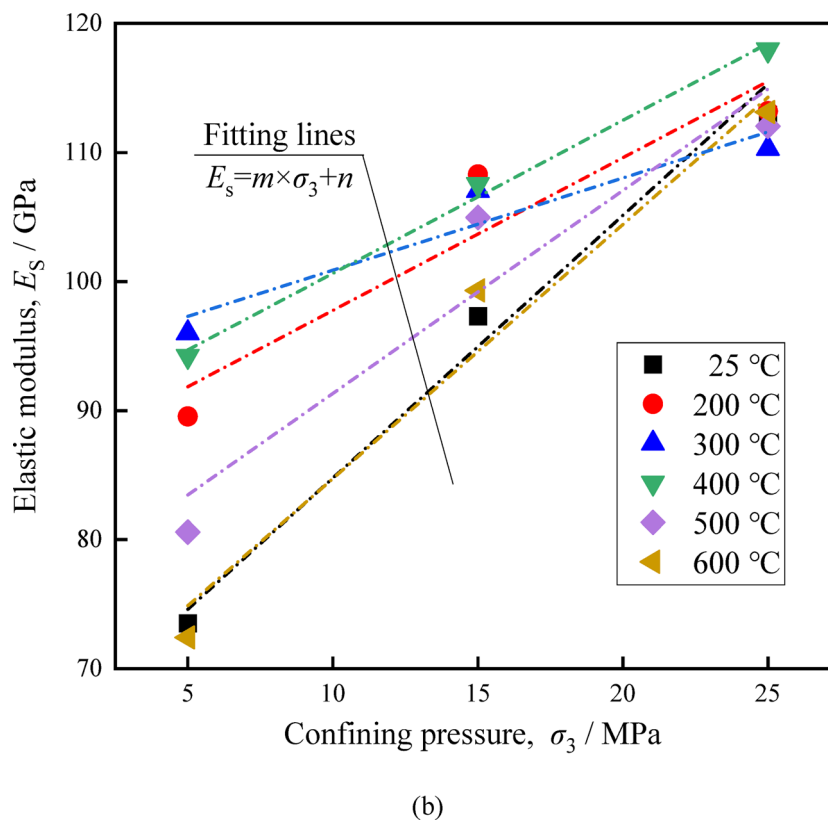
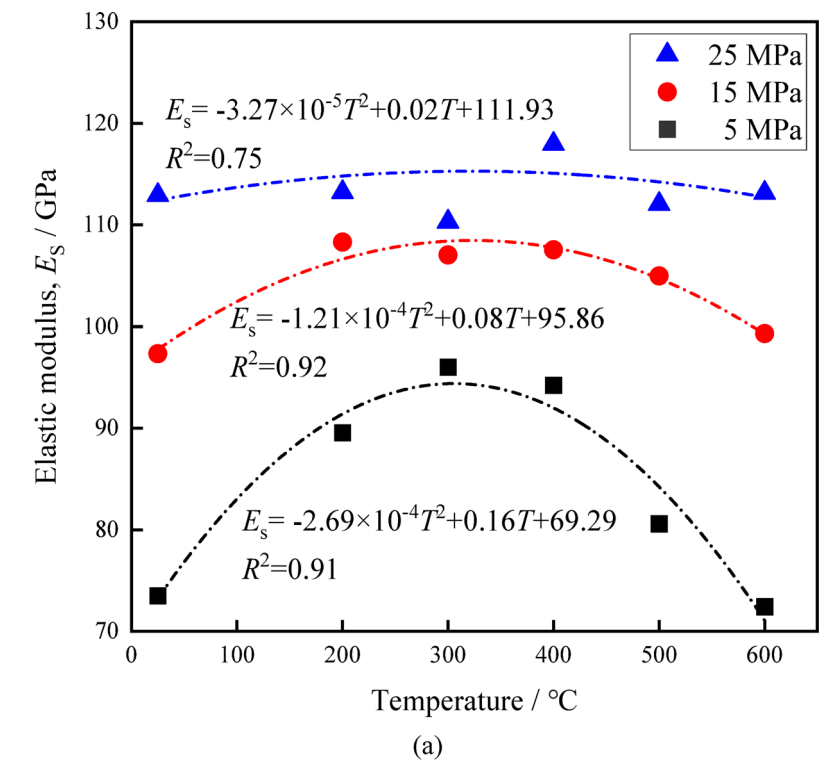


Fig. 8. Variation of elastic modulus of Beishan granite specimens (a) with different temperatures (b) under different confining pressures.

Confining pressure (MPa)	Fitting parameters for E_s -T $E_s(T) = d \times T^2 + e \times T + f$			
	d	e	f	R ²
5	-2.69×10^{-4}	0.16	69.29	0.91
15	-1.21×10^{-4}	0.08	95.86	0.92
25	-3.27×10^{-5}	0.02	111.93	0.75

Table 5. Parameters of the regression curves of the elastic modulus of the specimens with different confining pressures.

Temperature (°C)	Fitting parameters for E_s - σ_3 $E_s = m \times \sigma_3 + n$		
	m	n	R ²
25	1.97	65.03	0.97
200	1.18	85.93	0.80
300	0.72	93.73	0.82
400	1.19	88.77	0.99
500	1.57	75.60	0.82
600	2.04	64.41	0.93

Table 6. Parameters of the regression curves of the elastic modulus of the specimens with different temperatures.

decreasing trend, which was most significant in the Beishan granite specimens after 500 °C high-temperature treatment.

Effect of temperature on the AE and failure behavior of granite

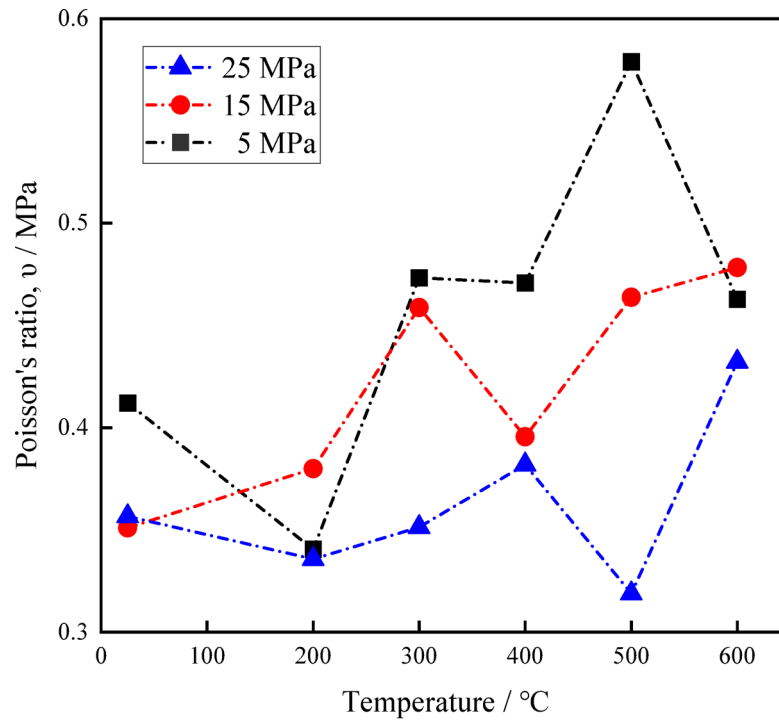
The acoustic emission (AE) monitoring technique provides critical insights into the real-time microcracking activity within the rock, directly complementing the stress-strain behaviors observed in Figs. 3 and 4. The temporal evolution of cumulative AE hits typically correlates with the key stages of deformation: the compaction of pre-existing microcracks (corresponding to the initial concave-upward nonlinear zone, up to the crack closure stress σ_{cc}), stable crack propagation during the linear elastic phase, accelerated damage accumulation beyond the crack damage threshold σ_{cd} (Point B in Fig. 4c), and ultimate macro-fracture formation post-peak.

To further reveal failure characteristics of the Beishan granite with different temperatures under triaxial compression conditions, a real-time source locating technique was adopted to locate the AE event, the accumulated number of AE events as shown in Fig. 10. The temporal and spatial distribution of AE events revealed the evolution of microcracks during the deformation process. Microcracks are generated during the loading as the rock is gradually deformed; therefore, the AE events released during the process of microcrack generation are dispersed more uniformly in the specimen. However, as the load gradually reaches and exceeds the bearing capacity of the granite specimen, the AE events are mainly localized on the shear rupture surface, and the source intensity of the AE events increases. The specimen slips along the rupture surface until the shear stress exceeds the cohesion of the granite specimen, which leads to the formation of macroscopic cracks and the failure of the specimen.

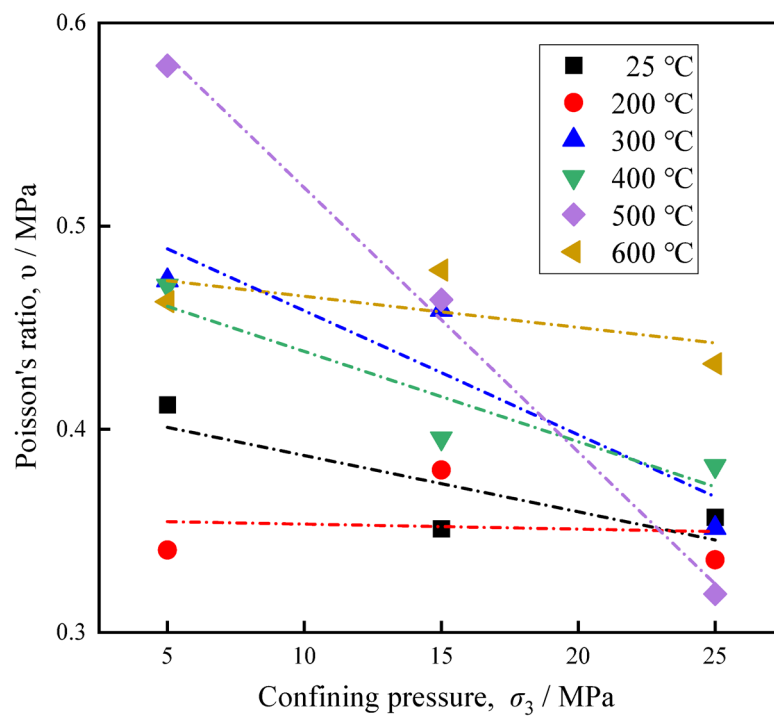
The ultimate failure modes of Beishan granite after thermal treatment under triaxial compression conditions, as shown in Fig. 10. It can be seen that the Beishan granite specimens fail in a shear mode under triaxial compression. A similar phenomenon has been verified by previous studies^{14,38}. The failure pattern of granite greatly depends on the confining pressures but is also influenced by the heating temperature. Taking the granite specimen after 200 °C high-temperature treatment as an example, the angle between the shear rupture surface and the horizontal plane shows a decreasing trend with the increase of confining pressure. Similar test results for the triaxial compression of granite have been reported by Zhou et al.³⁸. Under the same confining pressure condition ($\sigma_3 = 15$ MPa), the angle between the shear rupture surface and the horizontal plane increased gradually with the increase of heating temperature, from 64° at room temperature to 69° under the effect of high-temperature treatment at 200 °C, and finally to 73° under the effect of high-temperature treatment at 600 °C.

Discussion

The test results showed that thermal heating and confining pressure affect the mechanical properties and failure characteristics of the Beishan granite specimens to different degrees. As can be seen from Figs. 5 and 8a, the TCS and E_s varied parabolically with the increase of the heating temperature. At mild temperatures (below 300 °C), the TCS and E_s gradually increased with the increase in heating temperature, while they gradually decreased with the continued increase in heating temperature. For the Beishan granite specimens under the three confining pressures, as shown in Figs. 6 and 8b, the TCS and E_s increased linearly with the increase in confining pressure.



(a)



(b)

Fig. 9. Variation of Poisson's ratio of Beishan granite specimens (a) with different temperatures (b) under different confining pressures.

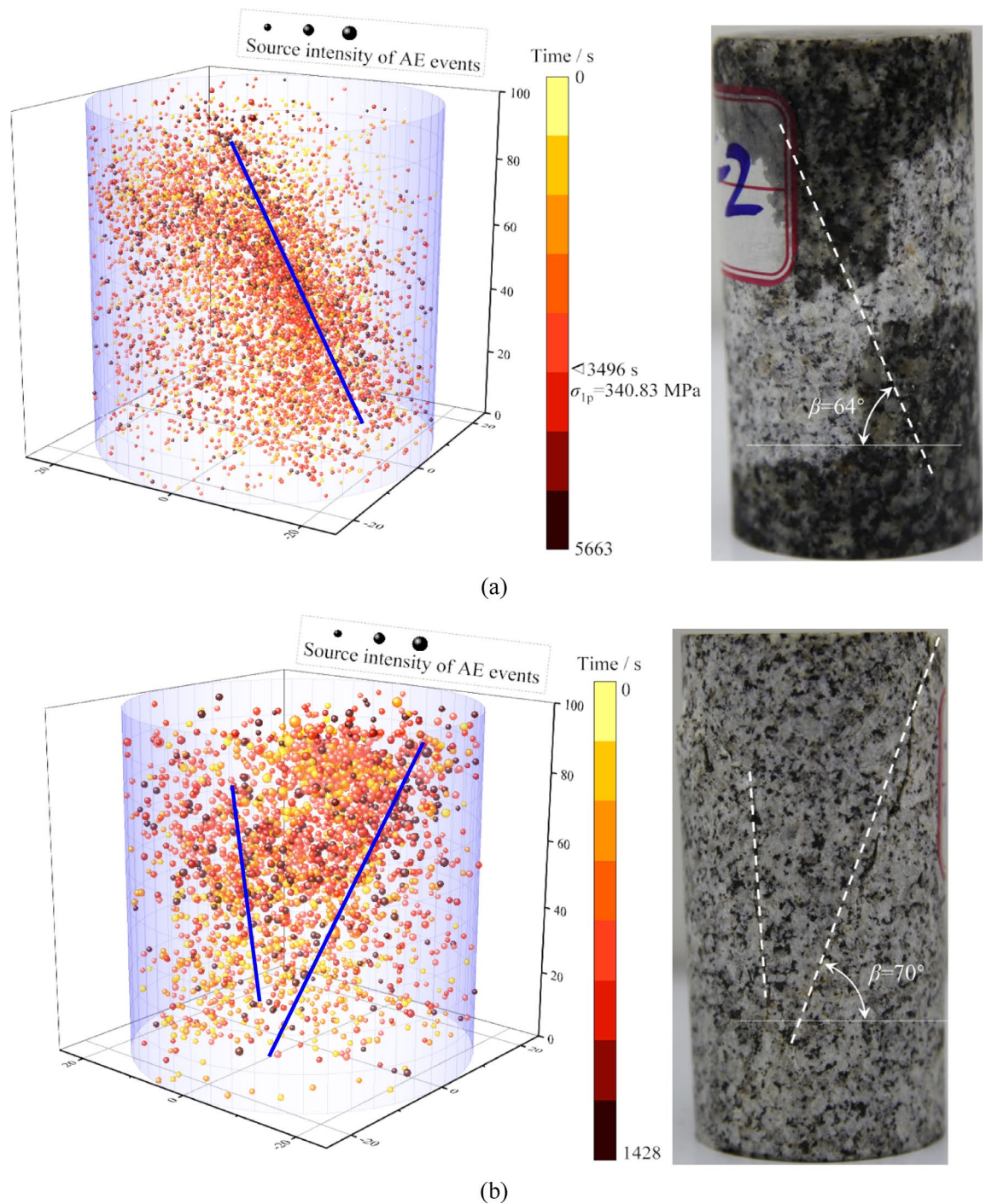


Fig. 10. Accumulation of AE events of Beishan granite specimens with different temperatures under triaxial compression conditions (a) 25 °C and 15 MPa, (b) 200 °C and 5 MPa, (c) 200 °C and 15 MPa, (d) 600 °C and 15 MPa.

The correlation coefficients (with values above 0.75) presented in Tables 3, 4, 5 and 6 indicate that the results in this study are statistically significant and that fitted equations can be used to quantify the effect of different heating temperatures on the mechanical parameters and failure behaviors of Beishan granite.

While the absolute strength values measured in these laboratory tests on intact samples are significantly higher than the differential stresses expected in the repository near-field, they serve to identify critical thermal thresholds and quantify the relative degradation of mechanical properties due to thermal damage. The evolution of in-situ stresses around a repository, including thermal-induced stresses and potential uplift, involves complex interactions within a fractured rock mass at a larger scale, which is beyond the scope of this intact sample study but represents an essential area for future coupled modeling efforts.

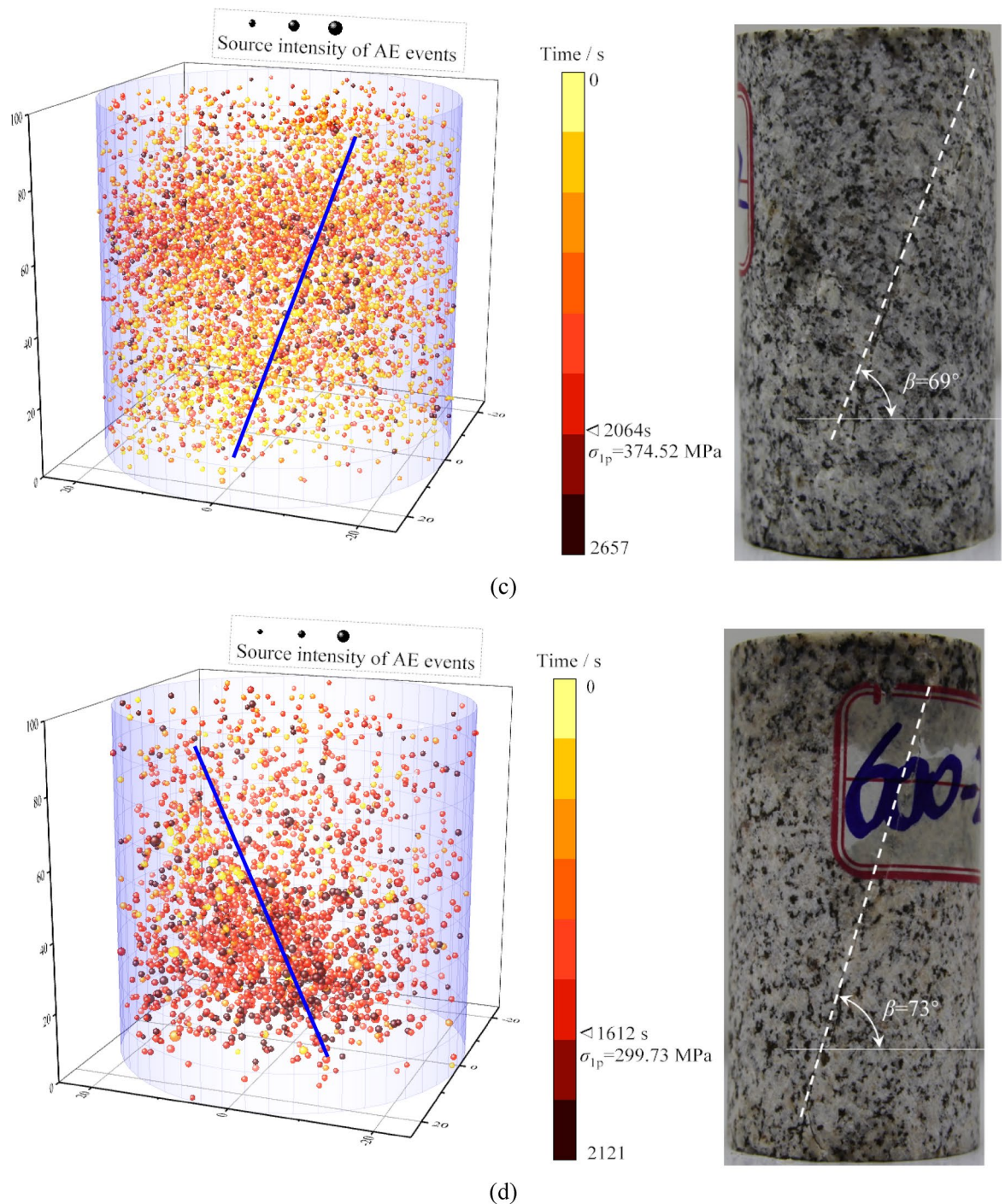


Fig. 10. (continued)

Numerous studies have investigated the triaxial mechanical properties of granite at elevated temperatures, though reported trends in strength variation with temperature vary significantly. Through literature analysis, the variation of the normalized strength of granite from different sources in the literature with the treated temperature is summarized. It can be observed from Fig. 11 that the variation of normalized strength with treated temperature shows a great variation in different works. Yang et al.^{39–41} obtained a monotonically decreasing strength trend with temperature from room temperature to 150 °C in triaxial compressive tests. However, Kumari et al.^{13,14}, and this work obtained granite strength results in triaxial compressive tests under high-temperature conditions, showing an increasing and then decreasing trend (Non-monotonic variation characteristics). It was analyzed that the key factor causing the differential mechanical behavior of granites to temperature may be caused by the differences in the mineral composition, especially the content of biotite or quartz³⁶. These ideas have been

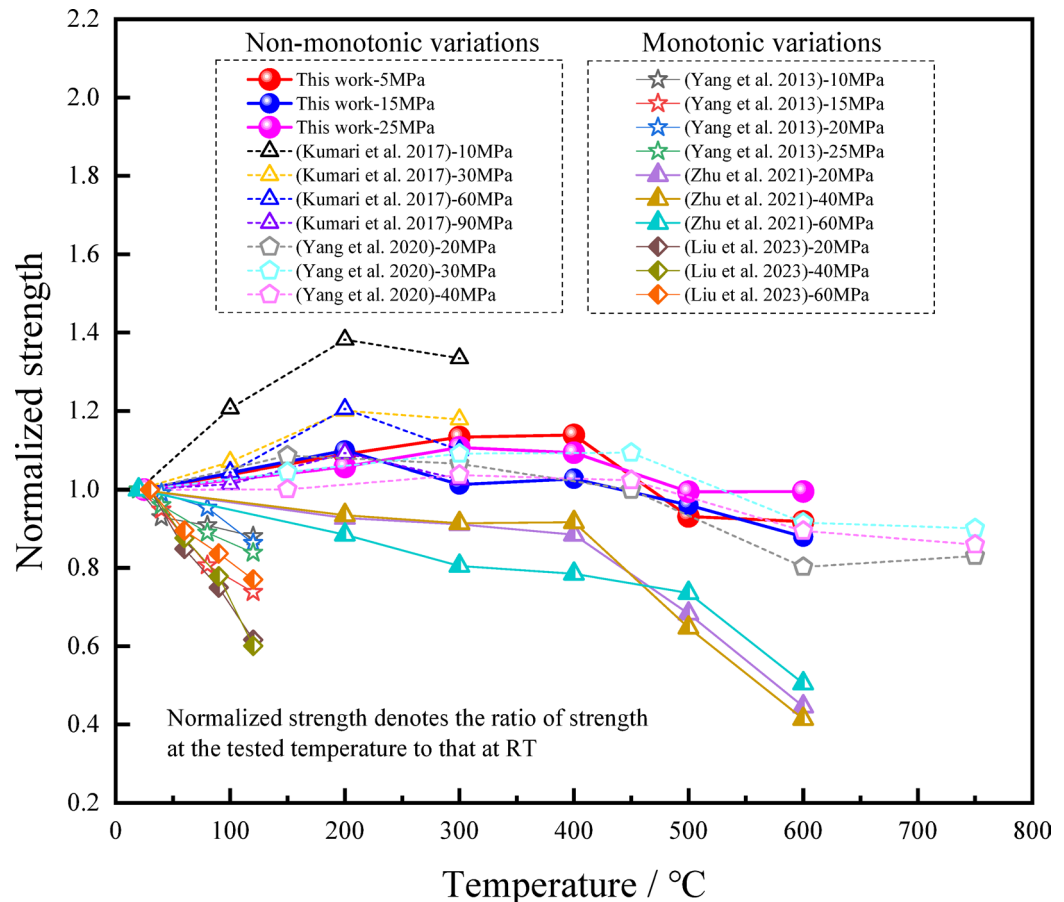


Fig. 11. Variation of triaxial compressive strength of granite with treated temperature.(modified from Liu et al. 2023).

demonstrated in the work of Liu et al.⁴¹. In this paper, we focus on analyzing the thermal effect mechanisms that induce the non-monotonically varying behavior of granite strength.

Several possible mechanisms have been proposed to characterize the effect of heating temperature on rock strength, e.g., variations in water state, thermal stress, and phase transformations of minerals. However, these variations are not always disadvantageous and monotonic. In the mild temperature range (within 300 °C), the mechanical properties of granite were strengthened; whereas, as the heating temperature continues to increase, its mechanical properties gradually deteriorate^{15,16}. Therefore, a mechanism of thermal effects needs to be proposed to explain the non-monotonic strength variations in the Beishan granite.

The micro-mechanisms of non-monotonic strength variations in the Beishan granite induced by temperature changes are analyzed in Fig. 12. In the mild temperature range (below 300 °C), the positive contribution (strengthening) mechanisms for the high-temperature to rock strength were summarized: the positive effect of water-related changes and microcrack closure¹⁵. The water within granite changes its existing state during the heating process, including absorbed water, bound water, and mineral water. The adsorbed water in the form of free water was gradually evaporated when the temperature rose to around 100 °C. The weakly bound water evaporates as the temperature approaches 150 °C, and strongly bound water evaporates in the range of 200–300 °C^{42,43}. The evaporation of water is interpreted to enhance the strength of granite in two aspects. Firstly, the removal of water reduces any pre-existing pore pressure and eliminates the lubricating effect of water films, thereby increasing the effective normal stress and frictional resistance at mineral contacts^{15,44}.

In addition, the thermal expansion between minerals under the mild temperature range also contributes positively to the increase in granite strength. Assuming for convenience that the mineral particles generate thermal stresses only in the direction perpendicular to the interface (i.e., in a one-dimensional state of stress), the thermal stresses $\sigma_{\Delta T}$ at the crystal interface can be expressed as⁴⁵:

$$\sigma_{\Delta T} = \frac{(\alpha_1 - \alpha_2)\Delta T E_1 E_2}{(E_1 + E_2)} \quad (12)$$

where E_1 , α_1 , E_2 and α_2 are the elastic moduli and thermal expansion coefficients of two adjacent mineral particles I and II, respectively, and the ΔT is the temperature difference. The main minerals of the Beishan granite include plagioclase, quartz, K-feldspar, and biotite⁴⁶. Using the thermal expansion contrast between

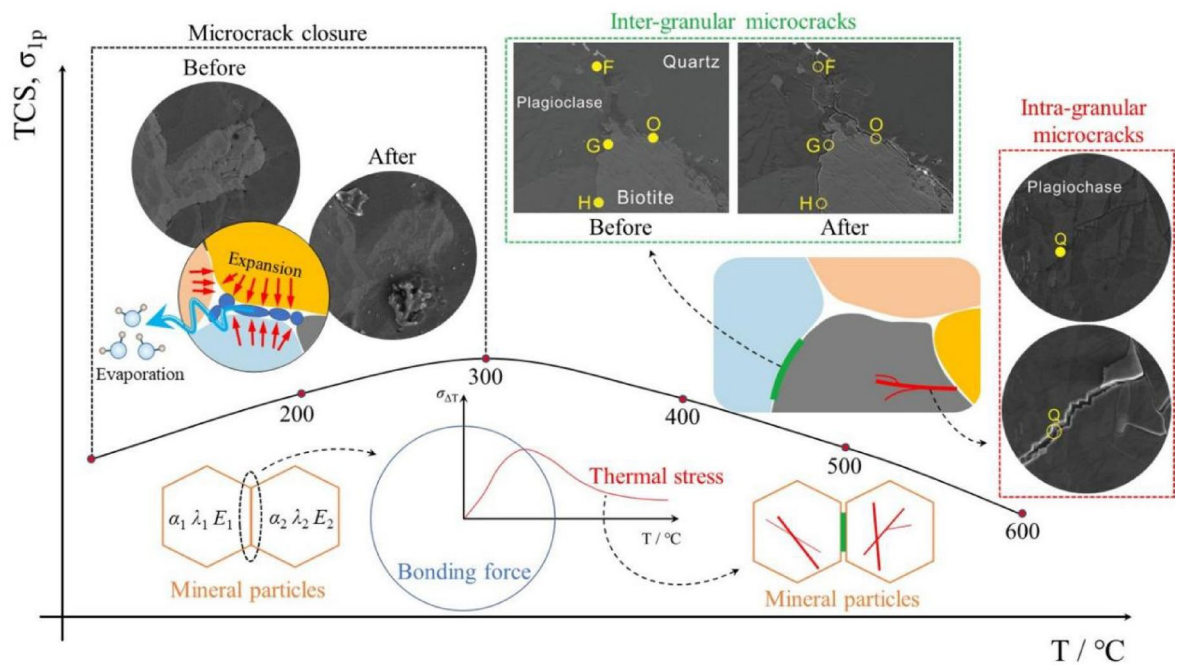


Fig. 12. Diagram of the thermal effect mechanism of the Beishan granite (The SEM image referenced from Zhao et al. (2018) of the Beishan granite).(modified from Yin et al. 2021; Zhao et al. 2018).

quartz ($\alpha = 11 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$) and feldspar ($\alpha = 5 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$) together with their representative elastic moduli ($E_{\text{qtz}} = 80 \text{ GPa}$, $E_{\text{fsp}} = 60 \text{ GPa}$), Eq. 12 yields an interface tensile stress $\sigma_{\Delta T} \approx 12 \text{ MPa}$ for $\Delta T = 275 \text{ K}$ (25 to 300 $^{\circ}\text{C}$). This stress is sufficient to close pre-existing micro-cracks of 1–3 μm aperture yet remains just below the typical grain-boundary tensile strength ($\sim 15 \text{ MPa}$), thereby explaining the 10–14% strength increase observed in this temperature range^{45–47}. During the heating process, the difference in thermal conductivity between the minerals would lead to a temperature difference. Therefore, Thermal stresses ($\sigma_{\Delta T}$) are generated at mineral interfaces due to differences in both the thermal expansion coefficients (α) of adjacent minerals and the temperature gradients (ΔT) between them. The left pores by the evaporation of water and the apparent net closure of some pre-existing microcracks after the heating-cooling cycle (as inferred from the initial compaction phase of the stress-strain curves and supported by some studies on Beishan granite⁴⁶ are interpreted to have contributed to the strength increase. However, the permanence of thermal crack closure can be complex and may depend on the specific thermal path and initial microstructure.

However, water evaporation and thermal stress-induced mineral expansion have a dual effect, and their contribution to rock strength assumes a negative role when the heating temperature exceeds a threshold value¹⁵. From the experimental results of this study, and concerning the results of previous studies on Beishan granite¹⁶, a threshold temperature (approximately 300–400 $^{\circ}\text{C}$ for Beishan granite), marking the transition from strengthening to weakening, can be determined. At temperatures exceeding approximately 300 $^{\circ}\text{C}$, structurally bound water (e.g., from mineral phases like biotite or amphiboles) is released. This dehydration process can destabilize and damage the crystal structure of the host minerals⁴³. On the other hand, thermally induced microcracks occur when the thermal stress from mineral expansion exceeds the bonding force of the mineral-crystal interface, and the type is dominated by intergranular microcracks. As shown in Fig. 12, intergranular microcracks gradually generate between different minerals, for example, quartz and feldspar (point F)⁴⁶. In addition, with further increase in heating temperature, the minerals would gradually occur phase transition reactions (transformation or decomposition), e.g., quartz α - β transformation at 573 $^{\circ}\text{C}$ or the decomposition of certain sheet silicate minerals at 400–700 $^{\circ}\text{C}$, and these reactions would lead to the generation of intra-granular microcracks, as shown in Fig. 12⁴⁶. Hence, the negative effects (i.e., strength reduction) caused by water evaporation and thermal stress-induced mineral expansion, as well as the thermal reaction of the minerals, have combined to cause a reduction in the strength of the Beishan granite.

This study provides critical scientific support for HLW geological disposal by: (1) Defining a critical temperature threshold (~ 300 –400 $^{\circ}\text{C}$) for significant thermal damage in Beishan granite, suggesting that repository temperatures should ideally be maintained below this range, e.g., below 300 $^{\circ}\text{C}$, to provide a safety margin and prevent strength degradation; (2) Demonstrating the substantial suppression effect of in-situ stress ($\sigma_3 \geq 15 \text{ MPa}$ reduces strength loss by 37.5%), validating the inherent advantage of deep geological environments ($> 500 \text{ m}$ depth), where higher confining pressures significantly suppress the development of thermal microcracks and thus mitigate associated strength loss, as demonstrated by our experimental results (e.g., reduced strength degradation rate at higher σ_3). These findings suggest that the higher in-situ stresses present at greater depths provide a confining pressure regime that can potentially suppress the development of thermal microcracks in the rock mass away from immediate excavation disturbances, thereby enhancing long-term stability.

Conclusion

This study performed triaxial compression tests to assess the triaxial strength and failure characteristics of heat-treated Beishan granite specimens. The experimental results showed that high-temperature treatment affects not only the mechanical properties but also the failure behaviors of Beishan granite. The following are the main conclusions:

1. The triaxial compressive strength (TCS) of Beishan granite exhibits a thermally driven threshold behavior, transitioning from strength enhancement (10.2–14.7% increase at ≤ 300 °C) to degradation (9–21.6.6% decrease at > 400 °C) with increasing temperature. This non-monotonic response, accurately captured by quadratic polynomial fitting ($R^2 > 0.85$), demonstrates a critical transition zone at 300–400 °C across all tested confining pressures (5–25 MPa).
2. Thermally treated specimens consistently failed in shear mode, with acoustic emission (AE) monitoring revealing three-stage damage accumulation: (i) microcrack nucleation at 50–60% peak stress, (ii) localized crack coalescence near peak strength, and (iii) macroscopic shear plane formation post-failure. The AE monitoring results corresponded well with the macroscopic failure patterns.
3. The non-monotonic strength variations in the Beishan granite induced by the thermal effect are illustrated through a fine-scale analytical perspective. In the mild temperature range (below 300 °C), positive contribution (strengthening) mechanisms involve increased effective stress (primarily through reduced lubrication and any pre-existing pore pressure) between minerals due to water evaporation and microcracks compaction from differential thermal expansion among minerals. Beyond 300 °C, negative effects include the mineral crystal structure, phase transitions, and the generation of intergranular and intragranular microcracks due to expansion stresses surpassing intergranular bonding forces.

The experimental data presented here provide a foundational dataset that can be utilized in future numerical modeling studies to explore further the thermo-mechanical behavior of Beishan granite under more complex repository conditions. Nevertheless, due to the great variety of rocks on Earth, the results of the study may be only applicable to the Beishan granite. Whether the microscopic mechanism of the other case of monotonous strength variation is the same as that of the non-monotonous case needs to be further investigated. In addition, in this paper, we consider the possibility that HLW may lead to a temperature increase up to 600 °C under long-term exothermic conditions with poor heat dissipation.

Data availability

Data available on request from the corresponding author (Yun Wu, wy1562254170@163.com).

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Author contributions

All authors contributed to the study conception and design. Wei Zeng: writing-original draft, visualization, investigation, data curation; Yun Wu and Lihua Hu: writing-original draft, investigation, funding acquisition; Xiaozhao Li and Zhen Huang: investigation, software, validation; Junqiao Yu, Jian Lin and Peng Zhao: formal analysis, methodology.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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