Localized Enhancement of Infrared Radiation Temperature of Rock Compressively Sheared to Fracturing Sliding: Features and Significance

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Previous experiments indicated that infrared radiation temperature (IRT) was applied in monitoring rock stress or rock mass fracturing, and abnormal IRT phenomena preceding rock failure or tectonic earthquakes were frequently reported. However, the characteristics of IRT changing with rock fracturing and frictional sliding are not clear, which leaves much uncertainties of location and pattern identification of stress-produced IRT. In this study, we investigated carefully the localized IRT enhancement of rock compressively sheared to fracturing and sliding (named as CSFS) with marble and granite specimens. Infrared thermogram and visible photos were synchronously observed in the process of rock CSFS experiment. We revealed that localized IRT enhancement was determined by local stress locking, sheared fracturing, and frictional sliding, and the relations between the $K_{cv}$ of IRT and the shear force are almost linear in wave length $3.7-4.8 \mu m$. In the process of rock CSFS, the detected $\Delta IRT$ which resulted from thermoelastic effect is 0.418 K, while the detected $\Delta IRT$ resulted from friction effect reaches up to 10.372 K, which is about 25 times to the former. This study is of potential values for infrared detection of rock mass failure in engineering scale and satellite remote sensing of the seismogenic process in the regional scale.

Keywords: remote sensing rock mechanics (RSRM), infrared radiation temperature, localized IRT enhancement, compressively shearing to fracturing and sliding (CSFS), seismogenic process

HIGHLIGHTS:

1) Localized IRT enhancement of the rock specimen in the process of CSFS is determined by local stress locking, sheared fracturing, and frictional sliding.

2) The $K_{cv}$ of IRT and shear force displays a linear relationship before and after the rock being compressively sheared to fracturing and frictional sliding.

3) In the process of rock CSFS, the detected IRT enhancement resulted from friction effect exceeded 10 K, being 25 times about that resulted from thermoelastic effect.
INTRODUCTION

Earthquake is one of the most unexpected and most serious natural disasters, which is mainly resulted from the local locking of crustal stress and the sudden fracturing of rock mass or tectonic faults (Liu et al., 2016; Huang et al., 2018). Since Gornv (1988) observed thermal infrared radiation anomalies before some medium-to-strong earthquakes in Central Asia, satellite remote sensing has been applied, or tried to be used in earthquake monitoring and precursor analysis (Saraf et al., 2009; Piroddi et al., 2014; Bhardwaj et al., 2017). Although the geoscience community has devoted decades to study the mechanism of seismicity and to seek for methods to monitoring rock fracturing and seismogenic process (Freund, 2003; Scoville and Freund, 2021), reliable abnormality recognition from remote sensing signals and accurate precursor identification are still challenging problems in the world.

Referring to the pioneering work of Geng et al. (1992) and Wu et al. (2000) in remote sensing rock mechanics (RSRM), the IRT change of stressed rock was investigated by many scholars (Wu et al., 2006a, 2006b; Liu et al., 2006; Liu et al., 2018; 2021; Wang et al., 2016; Salami et al., 2017; Huang et al., 2018; Huang et al., 2021; Zhao et al., 2019; Zhou et al., 2019; Cao et al., 2020; Huang et al., 2021; Yang et al., 2021) and applied to explore the rock fracturing behavior and related abnormal phenomenon. Wu et al. (2006a, 2006b) discovered that strong IRT emerged at the moment of rock bursting, and the anomalies of IRT image could be used as a precursor of rock fracturing. Liu et al. (2006) indicated that the fracturing mode of loaded rock affects IRT variation greatly, and IRT features were related to loading conditions and failure modes. Liu et al. (2018) also studied IRT localized enhancement in the condition of water infiltration in mine tunnels, and revealed thermogram was greatly affected by rock moisture. Wang et al. (2016) discussed specific relationship between IRT and stress, Salami et al. (2017) and Zhao et al. (2019) revealed that IRT localization on crack tips, and Yang et al. (2021) used IRT to investigate quantitatively crack initiation, propagation, and coalescence during rock fracturing. Zhou et al. (2019) indicated that the loading rate had some impacts on IR images, and Cao et al. (2020) proposed a quantitative index of energy dissipation with the IRT ratio to analyze and monitor rock failure and instability. Besides, Watson et al. (1975) used IRT images to identify the near-surface physical state of geologic materials, by using a quantitative theoretical model for geothermal mapping and thermal inertia mapping, and Sch¨opf et al. (2011) utilized IRT images to determine the vent locations by stress field modeling in a Vulcano island, Italy.

Being a universal physical parameter in the process of solid material loaded to fracturing, IRT is usually used for identifying unstable rock slope (Mineo et al., 2015) and geothermal basin (Heasler and Jaworowski, 2018). There are basically two mechanisms of IRT rise: 1) force-induced thermomechanical coupling effect (Harwood et al., 1991) and 2) friction thermal effect (Wu et al., 2004). Freund et al. (2006a, 2006b) discovered that rock positive charge (P-holes) could be activated by stress and stimulate also infrared emission on the rock surface. However, the characteristics and mechanisms of localized IRT enhancement related to rock stress and local fracturing are not carefully studied or clearly interpreted.

In this study, compressively sheared to fracturing and sliding (CSFS) experiments on marble and granite specimens are conducted. IRT-localized enhancements captured by an infrared image are carefully studied both in time and space aspects. The relation between IRT enhancement and shear force is revealed, and the mechanisms of localized IRT enhancement are discussed.

EXPERIMENT METHODOLOGY

Preparation of Rock Specimens

Homogeneous marble and granite are selected to make rock specimens to avoid the anisotropic influence of mineral particles of different compositions and varied sizes. The uniform size of the specimens is 150 mm × 150 mm × 150 mm. The marble and granite specimens are labeled from “MHS-1” to “MHS-7” and “GSD-1” to “GSD-7,” respectively. The marble specimen’s mineral compositions include dolomite (60–65%), tremolite (25–30%), and calcite (5–8%). The granite specimen is an intrusive and egg-white rock with fine grains and a micrographic texture, and contains plagioclase (35–50%), potash feldspar (25–30%), quartz (20–25%), hornblende (3–5%), and biotite (2–5%).

The specimen is of glassy luster from mineral grains such as hornblende, quartz, and biotite, which are capable of inhomogeneous specular reflection. To prevent the uncertain impact of inhomogeneous specular reflection on IRT images, the specimen surface to be IRT imaged was painted evenly with black ink and then dotted randomly with white chalk beforehand, which assisted in achieving a homogenous infrared reflection background, enhance the optical visibility, and improved the local identification of shear fracturing (Figure 1A). Validation test shows that the black ink and chalk dots have no negative impact on IRT detection (Figure 1B).

Boundary Conditions

The boundary conditions of tested rock specimens are shown in Figure 2. The shearing plane is the place where sheared fracturing and frictional sliding will happen. The active loading boundaries are composed of a normal force boundary at the up side and a shear loading boundary at the upper left side; oppositely, both the down side and lower right side act as passive loading boundaries. With both the upper right side and lower left side remaining free, the shear loading boundary provides horizontal load as shearing force, while the normal force boundary provides vertical load as normal stress.

Laboratory Equipment

The experimental system (Figure 3) comprises a loading system (RLW-3000, China), an infrared imaging system (InfraTec 8,325, Germany), and a CCD camera (Pike F-421, Germany). The setup of the laboratory equipment should be consistent to guarantee the
conformity of experiment data of different rock specimens (Ishida et al., 2017). The various components of the whole systems are set as follows:

1) Loading system: The vertical moving of loader along the axial direction is set as force control, and the loading rate is set as 1 kN/s. The horizontal moving of loader along shear direction is controlled by displacements, and the moving rate is set as 0.15 mm/min.

2) Infrared imaging system: The spectral range is 3.7–4.8 μm. The spatial resolution and sampling rate of the infrared monitoring system are set as 640 pixels × 512 pixels and 80 P/s, respectively. The accuracy of IRT measurement is set as ±0.1 K.

3) CCD camera: The spatial resolution and the sampling rate of CCD camera are set as 640 pixels × 512 pixels and 80 P/s, respectively.

The spectral range of 3–5 μm, named usually as intermediate infrared, is sensitive to be applied detecting the brightness temperature variation of objects with normal to high physical temperature. The detecting spectral range of the infrared imaging system, InfraTec 8,325, is 3.7–4.8 μm, which falls in the range of intermediate infrared, is good for detecting the IR enhancement in the process of rock loaded to fracturing.

Room temperature is controlled at 25°C approximately by an air conditioner, with temperature fluctuation being ±0.5 K. Light-blocking curtains are used to cover the laboratory windows to block sunshine and to prevent solar disturbance from outside in daytime. Furthermore, to reduce the disturbance of environmental radiation from walls and objects in the laboratory, several paper boards are set aside the rock specimen on the back, right, and left, leaving only the front side open to the infrared imaging system, as in Figure 3.

**Data Analysis**

Three indicators representing the variation of IRT, being AIRT, σsd, and KCV of IRT, are selected for data analysis. AIRT is the average IRT of all the pixels inside a selected area and reflects the global or local energy input of mechanical force and the energy dissipation in the manner of infrared radiation (Wu et al., 2006a; 2006b). σsd reflects the absolute discrete degree of IRT inside the
selected area of an IR image. $K_{CV}$ is a relative value used to represent the discrete level of IRT inside the selected area. The computations of these indicators are as following:

$$AIRT = \frac{\sum_{m=1}^{mn} \begin{bmatrix} IRT_{1x1} & \cdots & IRT_{1xn} \\ \vdots & \ddots & \vdots \\ IRT_{mx1} & \cdots & IRT_{mxn} \end{bmatrix}}{m \times n},$$

(1)

$$\sigma_{sd} = \frac{1}{m \times n} \sum_{i=1, j=m}^{mn} (IRT_{ixj} - AIRT)^2,$$

(2)

$$K_{CV} = \frac{\sigma_{sd}}{AIRT}.$$

(3)

RESULTS

The Process of Rock Fracturing

Normal force and shear force are applied gradually with a preset rate to reach the sheared fracture and frictional sliding. The process of CSFS of a rock specimen is depicted in Figure 4 with some typical moments in time sequence.

In the initial state (0s, Figure 4A), the rock specimen displayed homogeneous visible picture and infrared thermogram without structured differentiation; at 747.17s (Figure 4B), the visible picture displayed a small crack (V1), corresponding to T1 differentiation in thermogram; at 1,106.10s (Figure 4C), the visible picture appeared two cracks with V2 developing to be the shearing plane across the specimen and V3 occurred to the left end of the specimen, corresponding to T2 and T3 differentiations in thermogram. Besides, thermogram also exhibited two points (P1) of high IRT to the left end of the shearing plane along T2. At 1819.74s (Figure 4D), the visible picture displayed some fragment ejections (V6) corresponding to two low IRT zones (T6) occurred in thermogram, while several localized IRT enhancement points (P2) occurred notably along T2, which shows the undergoing compressive sliding behavior clearly.

Relationship Between Infrared Radiation Temperature and Shear Force

The relationship between IRT and shear force is beneficial to investigate IRT enhancement in the CSFS process. Accordingly, during the loading process, $K_{cv}$ of IRT also exhibits approximate variation as shear force. As in Figure 5 with marble specimen MHS-1 and granite specimen GSD-1 being examples, the mechanical process is divided into three stages, compressively loaded (stage I), compressively shearing loaded (stage II), and frictional sliding process (stage III).

1) Stage I, compressively loaded: the shear force of both marble and granite specimens kept an initial value, and the $K_{cv}$ curves of IRT manifest a small fluctuation.

2) Stage II, compressively shearing loaded: $K_{cv}$ and shear force increase at an accelerating rate with the constantly moving loader. The shear force curve of MHS-1 is slightly concaved, hinting a plastic deformation happens, while the shear force curve of GSD-1 is almost linear, hinting the elastic deformation happens and the granite is brittle.

3) Stage III, frictional sliding process: the curves of $K_{cv}$ and shear force change differently, both manifesting an uncertain variation. However, the curves of MHS-1 are more complex than those of GSD-1, for example, the alternate rising and falling in MHS-1 (Figure 5A), and the up and phase step-up in GSD-1 (Figure 5B).

Furthermore, the shear force curves also include a transition point of stress change, such as $T_m$ of specimen MHS-1 (Figure 5A) and $T_G$ of specimen GSD-1 (Figure 5B), where...
the elastic phase and yield phase can be distinguished. The $K_{cv} - t$ curves manifest monotonic linear rise at the elastic phase, and transform into a complex changing at the yield phase.

Previous studies on the changes of IRT and rock stress had confirmed the linear relations between IRT and uniaxial compressive stress (Wu et al., 2006c; Xu et al., 2015). Here,
the distribution of fitting lines and the data points of IRT $K_{cv}$ and shear force of MHS-1 and GSD-1 are shown in Figure 6. It shows that the relations between IRT $K_{cv}$ and shear force of MHS-1 and GSD-1 before being sheared to fracturing are similar in a rising trend, while the relations between IRT $K_{cv}$ and shear force of MHS-1 and GSD-1 after sheared to fracturing are different. The
difference should be owing to the mechanical properties of marble with plastic deformation and granite with brittle fracturing. The correlation between IRT and shear force \( F_s \) before being sheared to fracturing and after being sheared to fracturing is represented by a regression model \( y = ax + b \). The maximum residual modulus during the process before being sheared to fracturing is \( \Delta \in [9.61 \times 10^{-4}, 2.21 \times 10^{-3}] \), and that during the process after being sheared to fracturing is \( \Delta \in [8.31 \times 10^{-4}, 7.24 \times 10^{-3}] \). IRT change and stress variation are highly correlated, and the fitting effect of \( K_{cv} \) and \( F_s \) is ideal, which indicates that IRT is closely related with shearing stress.

The statistical results of all marble and granite specimens are shown in Table 1.

### Localized Infrared Radiation Temperature Enhancement

In this study, the IRT enhancement, \( \Delta IRT \), is computed as follows:

\[
\Delta IRT = IRT_i - IRT_R,
\]

where \( i \) represents the zone of lifted shear stress, \( IRT_i \) means the value of IRT in zone \( i \), and \( IRT_R \) is the global value of IRT in a standard reference zone with shear stress unchanged.

\[
\xi = \frac{\Delta T}{T_R} \times 100\%,
\]

where \( \xi \) represents the ratio of localized IRT enhancement in zone \( i \).

1) Localized IRT enhancement from thermoelastic effect

As for MHS-1 in period 1,237.91s–1373.04s, the core zone of sheared fracturing increased significantly and experienced shearing stress accumulating, local locking, and delocking in sequence (Figure 7). Zone \( C \) is the stress locking region, and zone \( R \) is applied as a reference region. The IRT data obtained from the thermogram, as in Figure 7, are statistically shown in Table 2. The maximum IR enhancement occurred in the stress locking state, the value of IR enhancement is \( \Delta T = 0.418 K \), and the changing ratio \( \xi \) is up to +0.136%.

2) Localized IRT enhancement from friction sliding

Different kinds of stress or fracturing states (Figures 8–10) have different IRT localized enhancement forms (Table 3), for example, the pre-cracking zones on crack tip have a point-like form (X in Figure 8), the shear fracturing zones are in the form of continuous flocks (P1, P2, and P3 in Figure 9), and the sliding friction zones are ribbon-like (P1, P2, P3, P4, and P5 in Figure 10). The maximum IR enhancement appears at the moment of sliding fracturing; when \( \Delta T \) is up to 10.372K, \( \xi \) is 3.441%.

In Figures 9, 10, the mechanisms of IRT localized enhancements in shearing plane all belong to the friction effect, including frictional heat production (Wu et al., 2004) and emissivity lift (Wu et al., 2018). “L” is the time of local stress focus, and then intergranular dislocation is generated. The mechanism of IRT localized enhancement belongs to frictional heat production; “M” is the time of local stress concentration, and then macroscopic cracks are found. The mechanism of IRT localized enhancement is the friction effect; it includes \( \xi \) increased by frictional heat production and emissivity lift by surface fracturing and grinding behavior; “R” is the time of stress relaxation status, and local stress focus does not exist. The mechanism of IRT localized enhancement is only emissivity lift.

Therefore, the IRT enhancement mechanism and its proportion are calculated as in Table 3, for example, X1 in Figure 8 and L in Figures 8, 9, 10 only belong to frictional heat production, \( FHP\% = 100\% \) and \( EL\% = 0\% \); R in Figures 9, 10 only belong to emissivity lift, \( FHP\% = 0\% \) and \( EL\% = 100\% \); M in Figures 9, 10 have two mechanisms, its proportion on each mechanism calculates by Eq. 6, and (7) as follows:

\[
FHP\% = \frac{\Delta T_M - \Delta T_R}{\Delta T_M},
\]

\[
EL\% = 1 - FHP\% = 1 - \frac{\Delta T_M - \Delta T_R}{\Delta T_M} = \frac{\Delta T_R}{\Delta T_M},
\]

where \( \Delta T_M \) is \( \Delta T \) in M status, \( \Delta T_R \) is \( \Delta T \) in R status.

### Table 1: Statistical information of shear force \( F_s \) and \( K_{cv} \)

| Lithology | Serial number | Before sheared to fracturing | After sheared to fracturing |
|-----------|---------------|----------------------------|-----------------------------|
| Marble    | MHS-1         | 1.67e-7                    | -1.25e-6                    |
|           | MHS-2         | 4.16e-7                    | 2.92e-7                     |
|           | MHS-3         | 3.44e-8                    | 2.67e-7                     |
|           | MHS-4         | 1.77e-7                    | -1.25e-7                    |
|           | MHS-5         | 1.49e-7                    | 6.86e-7                     |
| Granite   | GSD-1         | 1.73e-7                    | 3.63e-6                     |
|           | GSD-2         | 5.43e-7                    | 1.14e-6                     |
|           | GSD-3         | -4.80e-8                   | -1.82e-7                    |
|           | GSD-4         | 9.73e-8                    | 2.81e-7                     |
|           | GSD-5         | 2.23e-8                    | 1.22e-7                     |

\( y = ax + b \) is the regression model, where \( a \) is the slope value and \( b \) is the intercept value.

\( \Delta \) is the maximum residual modulus value.


**DISCUSSION**

**Infrared Radiation Enhancement in the Process of Compressively Sheared to Fracturing and Sliding**

According to infrared detection principles (Rees, 2001), the rock IRT, also called infrared brightness temperature as an index of infrared radiation energy detected by an infrared sensor with particular photoelectric system, is determined by both rock surface emissivity \( \varepsilon \) and physical temperature \( T_d \):

\[
IRT = \sqrt[4]{\varepsilon} \cdot T_d.
\]  

(8)

It illustrates that both the variation of emissivity \( \Delta \varepsilon \) and the variation of physical temperature \( \Delta T_d \) could change the detected IRT of rock specimen as follows:

\[
\Delta IRT = \sqrt[4]{(\varepsilon + \Delta \varepsilon)} (T_d + \Delta T_d) - \sqrt[4]{\varepsilon} \cdot T_d.
\]  

(9)

Accordingly, if \( \Delta T_d \) is less than 0.5 \( K \) or could be ignored, \( \Delta IRT \) is to be computed approximately as (Wu et al., 2018) follows:

\[
\Delta IRT \approx IRT \times \left( \sqrt[4]{1 + \Delta \varepsilon/\varepsilon - 1} \right).
\]

For example, if \( IRT = 300 K \), \( \varepsilon = 0.93 \), and \( \Delta \varepsilon = 0.03 \), the \( \Delta IRT \) will be +2.4 \( K \).
Since thermoelastic effect and friction thermal effect are able to cause local rise of $T_d$, and the surface fracturing and grinding behavior along shearing plane are able to cause local lift of $\varepsilon_\lambda$; all will contribute to localized IRT enhancement. There are many possibilities of $T_d$ rise related with stress, that is, thermoelastic effect, friction thermal effect, and others such as phase transmission (Figure 11). Localized IRT enhancement will occur in some places if one or more than the above mechanisms get functioning in the process of CSFS. The dynamic change of rock surface IRT could be attributed to eight possible situations of stress that happened here and there: overall deformation increasing $f_1$, stress accumulating $f_2$, stress locking $f_3$, stress relaxation $f_4$, pre-cracking zone on crack tip $f_5$, shear fracturing zone $f_6$, sliding fraction zone $f_7$, and others $f_8$.

According to Eq. 6, the IR enhancement, $\Delta IRT$, caused by $\varepsilon_\lambda$ and $T_d$ changes during the CSFS experiments, could be expressed as follows:

$$\Delta IRT = \begin{cases} 
    f_1 (\Delta T_d), & \text{I} \\
    f_1 (\Delta T_d) + f_2 (\Delta T_d) + f_3 (\Delta T_d) + f_4 (\Delta T_d), & \text{II} \\
    f_1 (\Delta T_d) + f_2 (\Delta T_d) + f_3 (\Delta T_d) + f_4 (\Delta T_d) + f_5 (\Delta T_d) + f_6 (\Delta T_d) + f_7 (\Delta T_d) + f_8 (\Delta \varepsilon_\lambda), & \text{III} 
\end{cases}$$

where $\Delta T_d$ represents $T_d$ change and $\Delta \varepsilon_\lambda$ is $\varepsilon_\lambda$ change. I is the compressively loaded phase, II is the compressively shearing loaded phase, and III is the frictional sliding phase.

**Significance of the Localized Infrared Radiation Enhancement**

Localized IRT enhancement is related to the stress concentration phenomenon in space–time aspects, and the different enhancement mechanisms correspond to different IR enhancement forms. Thermoelastic effect is often expressed as a regional type of IRT enhancement, for example, elliptic or circular type (C in Figure 7). Friction thermal effect is expressed as a point-like form (X in Figure 8), a
continuous flake form (P1, P2, and P3 in Figure 9), or a ribbon-like form (P1, P2, P3, P4, and P5 in Figure 10) of IRT enhancement. In our research, \( \Delta \text{IRT} \) caused by the thermoeelastic effect is 0.418 K, and \( \Delta \text{IRT} \) caused by the friction effect, which is a coupling of frictional heat production and emissivity lift, reaches up to 10.372 K.

Generally, an earthquake results from tectonic motion or crustal stress field alteration (Liao et al., 2003; Yohei et al., 2010), and the satellite infrared observation has been proven effective to monitor seismicity and the seismogenous process. The features of IR localized enhancement revealed in this study have at least two aspects relevant to satellite observation on crustal stress field alteration and the seismogenous process: 1) time aspect: \( \Delta \text{IRT} \) represents the stress evolutions, and 2) space aspect: the location of localized IRT enhancement tells the place of stress concentration. Different types of localized IRT enhancement
correspond to different stress patterns, which could be identified from IRT monitoring, for instance, the area C of MHS-1 (Figure 7); areas P1, P2, and P3 of marble MHS-4 (Figure 9); and areas P1, P2, P3, P4, and P5 in granite MHS-1 (Figure 10).

Nevertheless, the localized IRT enhancement of a ground target would be affected by multiple environmental factors, such as sunlight reflecting, surface moisture, geoidal heights, viewing angle, and vegetation cover. Further experimental studies for different surface situations are demanded, even including different wavelength of electromagnetic wave for satellite observations. Detecting the infrared radiation anomaly related to earthquakes remains to be conquered due to multiple influencing factors. It is possible to extract the localized IR enhancement caused by crustal stress alteration from satellite observations, but it is especially challenging.

CONCLUSION

1) Localized IRT enhancement of rock specimen in the process of CSFS develops with stress variations, for example, a bright spot reflects local stress locking, a point-like form and continuous flecks reflect the sheared fracturing, and a ribbon-like form reflects the frictional sliding.

2) The $K_{csfs}$ of IRT and shear force displays a linear relationship before and after the rock being compressively sheared to fracturing. There exists a close correspondence between IRT and stress in wave length 3.7–4.8 µm.

3) Different mechanisms lead to different IRT enhancement ($A_{IRT}$) in quantity in the process of rock CSFS. By the thermoelastic effect, $A_{IRT} = 0.418K$ and $\xi = 0.136\%$, while by the friction effect, $A_{IRT} = 10.372K$ and $\xi = 3.441\%$, which is about 25 times to the former.

This experimental study provides new evidence and physical interpretation for imaging monitoring rock fracturing in the engineering scale and satellite remote sensing crustal stress field alteration in the regional scale with detection of infrared radiation brightness temperature. There are still some difficulties and challenges in the field of crustal stress monitoring by satellite infrared; further investigations are encouraged.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

LX, WL, ZY, and MW participate in the test of compressively sheared to fracturing and sliding (CSFS).

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