

# Experimental Investigation on the Influence of Observation Angle on the Spectral Characteristics of Minerals in the Visible-Near Infrared Range

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**Abstract:** The analysis of the factors affecting the spectral characteristics of rock minerals is the basis of improving the accuracy of quantitative inversion of spectral minerals. Hyperspectral remote sensing has advantages and development potential in the quantitative inversion of minerals, but it is limited by many constraints and influencing factors in the process of remote sensing recognition of rock and mineral spectral information. In practical application, satellite earth observation is affected by terrain fluctuation, which leads to some deviation of observation Angle. At the same time, vertical samples are often used in the experiment to reduce the spectral experimental error. Therefore, the spectral observation Angle plays an important role in determining the composition of rock and ore. In order to study the effect of different observation angles on the reflectance spectra of minerals, the spectral reflectance spectra were analyzed in the visible near-infrared (0.4-2.5 $\mu\text{m}$ ) band to explore the variation rules. First, common quartz, orthoclase and plagioclase minerals were sliced and polished to make block samples with fixed roughness values. The incident Angle of light source was fixed, and the influence of different observation angles on the visible near-infrared spectral characteristics of minerals was analyzed by changing the Angle of emergence and azimuth. Secondly, through the qualitative and quantitative analysis of the results and the mechanism analysis, it can be concluded that the effect of zenith Angle on spectral reflectance is the same under different observation azimuth angles. The observed zenith Angle has a great influence on the spectral reflectance, which is reflected in the fact that the reflectance of mineral samples gradually increases with the increasing of the zenith Angle to reach the peak value within 30°~50°, and then gradually decreases. The spectral reflectance at 0°-360° azimuth is symmetrical, and the spectral reflectance is oscillatory, and the reflectance at 180° azimuth is the highest. The overall situation gradually increases from 0°-180° spectral reflectance, and gradually decreases from 180°-360° spectral reflectance. With the change of observation Angle, the peak and trough of the reflectance of the sample are basically located in the same band position. It is of great significance to realize the accurate division of rock mining area and to exploit mineral resources reasonably and efficiently.

**Keywords:** Massive rock, Visible-near-infrared spectrum, Observation Angle, Spectral reflectance.

## 1. Introduction

In the application of remote sensing geology, spectral recognition, component inversion and content determination of rock and ore are the advantages of hyperspectral remote sensing (Shanjun et al. 2021; Pham-Xuan et al. 2018). Different mineral and rock types have fixed visible near-infrared spectral characteristics (Wang 2009), and the study on the variation of mineral spectral characteristics under different physical and chemical environments will be more and more important in hyperspectral remote sensing geological investigation (Yan et al. 2003). The use of visible-near-infrared spectroscopy can effectively reduce the data amount and data redundancy of hyperspectral data, which lays a foundation for accurate and rapid modeling.

At present, visible near-infrared spectroscopy research in rock and mineral fields mainly focuses on mineral identification and classification. For example, Gilmore M S et al. (Gilmore et al. 2008) developed two automatic detectors that can be used to identify sulphate mineral fragments invisible in the visible-near-infrared spectrum. Both probes have been optimized to help improve the accuracy of on-board data analysis with the Mars visible-near-infrared spectrometer. Cheng, Hao et al. (Cheng et al. 2017) Five phyllosilicate minerals were characterized and distinguished by portable visible-near-infrared spectroscopy, and their bands were associated with their mineral structures. Song

Liang et al. (Pham-Xuan et al. 2018; Song et al. 2017) conducted spectral tests on different coal samples and gangue samples, and found that the spectral characteristics of bituminous coal and lignite in the visible light - near infrared band were significantly different. They proposed a method of coal and gangue differentiation based on the joint analysis of visible light near infrared and thermal infrared spectra to solve the phenomenon of "foreign body in the same spectrum" in a single band. The classification accuracy of the test sample is improved from 90.5% to 100%. Xu Liangji et al. (Xu et al. 2022) selected PCA-SVM, PCA-BP and KPCA-SVM to model coal and rock identification and concluded that the identification accuracy of kernel principal component analysis combined with support vector machine model (KPCA-SVM) was the highest, with the average modeling accuracy of 98.5% and the average verification accuracy of about 95%. It has important reference significance for remote sensing classification of ground objects.

Although the spectral characteristics of rocks and minerals essentially depend on the composition and crystal structure of the material, their external behavior is affected by various factors, and there are many factors affecting the accuracy of mineral spectral inversion, among which the roughness of the rock surface is an important factor affecting the reflectance spectrum. There are relatively few studies on multi-angle observation of rocks and minerals, especially in the visible-near-infrared spectrum, and the observation Angle, as an

important factor affecting the spectral characteristics of ground objects, has not attracted enough attention. Zhao Hu et al. (Zhao Hu 2003, 2004a, 2004b) The most common and important rocks on the surface of the earth, granite, basalt and peridotite, are selected as the research objects, and the influence of observation angles on the reflection spectra of the three representative rocks in  $2\pi$  space is analyzed. The results show that the spatial spectral characteristics of the three representative rocks are different in the vertical direction regardless of the incidence Angle of light. Moreover, the spatial spectrum characteristics of incident light waves at a small Angle show no obvious difference in the spatial horizontal direction, and the different incidence angles of light significantly affect the spatial waveform curve characteristics of the three representative rocks. The difference of waveband mainly affects the reflection spectrum and the energy reflected by polarization reflection spectrum has no significant effect on the characteristics of space waveform curve. Cheng Yinyi et al. (Cheng Yin-Yi 2021) The reflective spectral characteristics of malachite powder under multi-angle conditions were studied, and the Hapke model was used to analyze and interpret the multi-angle spectral characteristics of malachite. It was found that the reflectivity of the test sample was the largest when the sensor was located in the mirror reflection direction, because the test sample had a specular reflection at this position, the reflection effect was strong and the light intensity was the strongest. When the sensor is located in another location, the light intensity gradually decreases. Lu Peng et al. (Peng et al. 2016) The comparison of a variety of minerals shows that when the observation Angle changes, the reflection spectrum of different rock mineral samples will also change, but the reflection spectrum characteristics of different rock minerals at different angles vary in the law and degree of change, with obvious differences. Wang Dong (Dong et al. 2020) The results show that the reflectance spectra of hematite and magnetite are significantly affected by the observation Angle. When the observation zenith Angle increases from  $0^\circ$  to  $20^\circ$ , the spectral reflectance of the samples gradually increases. When the observation Angle of the sample increased from  $20^\circ$  to  $80^\circ$ , the spectral reflectance of the sample showed a slow decrease trend. When the observed zenith Angle increases from  $0^\circ$  to

$80^\circ$ , the reflectance changes up to 10%. Rees et al. (Niclos et al. 2013) The multi-angle spectra of ice and water are studied. It is found that changing the observation azimuth will change the spectral characteristics.

## 2. Experimental Part

### 2.1. Preparation of mineral samples

Because natural rock is a collection of one or more minerals with certain structure and structure, the effect of observation Angle on reflectance of massive minerals is studied by designing different types of observation Angle schemes for mineral end elements, which lays a foundation for studying the effect of observation Angle on spectral reflectance.

Since the spectral information of rocks is jointly affected by many factors, in order to reveal the influence of observation Angle on spectral characteristics of massive rocks and minerals, other influencing factors should be fixed and kept unchanged, and only one factor of observation Angle should be allowed to change, that is, the orthogonal design scheme is adopted. In order to achieve the above purpose, I first thought of using massive rocks. In order to reveal the influence of surface roughness of different minerals on spectral characteristics, it is necessary to polish a fixed roughness of the same rock (to ensure the same mineral composition, the same crystal direction, the same content, etc.) to conduct spectral observation experiments, so as to ensure that the surface of mineral samples is not affected by other factors. However, since the visible near-infrared spectrum is mainly the absorption of charge transition and molecular frequency doubling and harmonic frequency, spectral observation has the characteristics of low signal-to-noise ratio and poor absorption intensity [17]. In order to eliminate the influence of human factors, instrument factors and external environmental factors (temperature, humidity, etc.) on the spectral measurement accuracy, it is necessary to slice the selected rock. The original minerals used in this paper are shown in Figure 1, and the most common rock-forming minerals (quartz, orthoclase and plagioclase) in nature are selected as experimental materials in the experiment. Make the research representative.

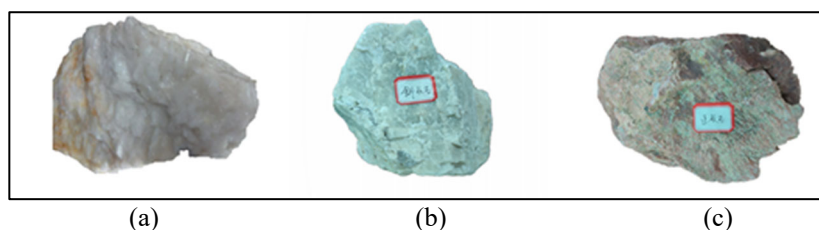


Figure 1. Primitive Mineral. (a) Quartzite. (b) Plagioclase. (c) Orthoclase

### 2.2. Design of observation Angle for mineral samples

In order to study the effect of observation Angle on spectral reflectance, it is necessary to design the observation Angle experiment, that is, to design the orientation of visible near-infrared spectrum observation. First, the influence of geometric observation conditions on spectral reflectance of mineral samples is studied. In the single spectral observation, there are four angles related to the reflectivity of the sample: the incidence Angle of the light source, the exit Angle, the azimuth Angle and the phase Angle. The phase Angle is the

Angle between the incident light and the outgoing light. Through the design, the experiment fixed the indoor light source, the incident Angle was fixed at  $45^\circ$ , and the change of the spatial orientation during the whole observation process was determined by changing the zenith Angle and azimuth Angle observed by the spectrum.

Zenith Angle design: The zenith Angle represents the Angle between the observation direction and the zenith direction (the normal direction of the specimen observation surface). As the field Angle of the ASD spectrometer probe is  $25^\circ$ , the experiment needs to ensure that only the mineral sample to be measured can be observed within the detection

range of the maximum measurement distance of the spectrum measurement, and no other objects except the sample can enter the detection range. Besides, the sample size is limited, and the observation zenith Angle cannot be observed from 0° to 90°. Therefore, the observation zenith Angle is finally set between 0° and 60°. For the observation Angle interval design, the zenith Angle observation of mineral samples was carried out, and the zenith Angle observation Angle was designed to be 10°, which met the research demand of the relationship between the observation Angle and the spectral reflectivity. Therefore, the observation Angle interval of this experiment design is 10°.

**Azimuth design:** In order to understand the distribution law of spectral reflectance in all directions (0°-360°) in geometric space, 12 azimuth angles (30° apart) are designed. The azimuth interval of 30° can meet the research requirements, so the experiment set the azimuth interval of 30°.

### 2.3. Measurement sample size design

In the test equipment used in the multi-angle observation experiment, the test equipment mainly consists of three parts, namely, indoor light source, observation Angle table and ASD spectrometer. In order to meet the test requirements of spectral reflectance of mineral samples, the surface area of the sample should be larger than the theoretical observation area. Since the observation area is determined by the observation Angle and observation distance, the experimental size and observation scheme should be designed. Observation Angle The observation scheme of the sample is designed to keep the fixed position of the sample unchanged, and an observation Angle table is designed to perform spectral tests on the sample by rotating the Angle of the sensor probe of the spectrometer. Ensure that the observation distance from the spectrometer probe to the sample remains unchanged and the incident linear distance from the light source to the sample remains unchanged.

Among them, the designed observation Angle table is a simple rotating table device, which can rotate freely at 0°-360° azimuth, and the detection zenith Angle can also rotate freely at 0°-90°. The device can meet the observation requirements of the observation Angle of 0°-360° and 0°-60° zenith Angle in this experiment, as shown in Figure 2.

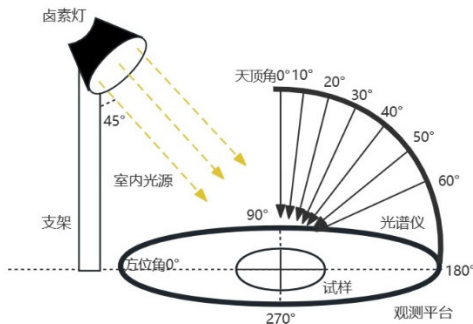


Figure 2. Spectral observations from different observation angles

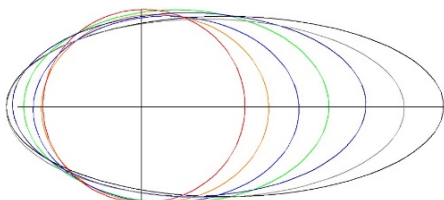


Figure 3. Observation range of different zenith angles

The experimental design uses the method of rotating the spectrometer probe to carry out the spectral test. The theoretical observation area of the experiment is an elliptical region, as shown in Figure 3, that is, an irregular ellipse obtained by a circular light cone being mitered. For ease of expression, the observed surface shape is approximately represented as an ellipse, and the ellipse equation is expressed as follows:

$$ctg^2\left(\frac{a}{2}\right)y^2 = \left(tg^2\theta - ctg^2\left(\frac{a}{2}\right)\right)x^2 + 2tg(\theta)(L \sin \theta)^2 \quad (1)$$

a is the field Angle of the spectrometer;

$\theta$  is the observation zenith Angle of the sample;

L is the distance between the probe of the spectrometer and the center of the observed area of the sample.

For formula 1, let  $y=0$ , solving the equation gives two roots of  $x_1, x_2$ , and the radius of the major semiaxis of the ellipse is  $|x_1 - x_2|/\cos\theta$ . It is calculated that when  $\theta$  is 60°, the length of the theoretical observation range is 4.64cm. Therefore, the diameter of the sample selected in the experiment should be at least greater than 4.64cm, and the surface diameter of the screened mineral sample should be greater than 4.7cm, so as to meet the theoretical requirements.

### 2.4. Spectrum Test

Portable ground object spectrometer ASD FieldSpec 4 was used in the experiment to measure the spectral reflectance in the range of 350~2500nm. Considering the external environment, halogen lamps with uniform illumination were used to simulate the solar light source in the indoor dark environment for the observation Angle series experiments to ensure that the detection range was all on the sample. Ensure that the position relationship between the light source and the probe and the sample is stable, so as to carry out the experiment. Take the probe vertically aligned with the experimental sample detection as an example, the vertical measurement calculation formula:

$$Y = D + 2 * X * \tan\left(\frac{A}{2}\right) \quad (2)$$

Y: diameter;

D: visual distance;

X: the distance of the probe to the measured object;

A: Probe field of view Angle.

The detection height was calculated according to the field of view Angle (Formula 2). During the spectrum measurement, the three experimental samples were observed successively according to the roughness sequence from small to large. The diameter of the measured samples in the field of view of the lens was  $Y=3\text{cm}$ . As calculated by the above formula, the distance X from the probe to the measured object  $=6.76\text{cm}$ . When the observation Angle of the sample changes, X remains at 6.76cm, and the standard whiteboard is used to correct it every 10min.

After the spectral test is completed, the data is pre-processed by ViewSpecPro software, such as mean splicing correction, and error points are removed. All spectral data were smoothed and denoised by Savitzky-Golay filter with window number of 9.

### 3. Results and Discussion

#### 3.1. Zenith Angle observation

##### 3.1.1. Qualitative analysis

First, the spectral reflectance changes with the observed zenith Angle under the premise of constant incident zenith Angle and observed azimuth Angle. When the incident direction is set as the azimuth Angle of  $0^\circ$ , the spectral curve change of the zenith Angle in the range of  $0^\circ$ - $60^\circ$  (the interval is  $10^\circ$ ) is observed. Keep the incident conditions constant.

(1) As shown in Figure 4, when the observation azimuth is  $0^\circ$ , that is, in the backscattering direction of the incident main plane, the spectral reflectance of the mineral sample increases to a certain extent and then gradually decreases with the increase of the detection zenith Angle. Quartz minerals increase with the increase of zenith Angle in the range of  $0^\circ$ - $40^\circ$ , and decrease with the increase of zenith Angle in the range of  $40^\circ$ - $60^\circ$ . The plagioclase minerals increase with the increase of zenith Angle in the range of  $0^\circ$ - $30^\circ$ , and decrease with the increase of zenith Angle in the range of  $30^\circ$ - $60^\circ$ . Orthoclase minerals increase with the increase of zenith Angle in the range of  $0^\circ$ - $40^\circ$ , and decrease with the increase of zenith Angle in the range of  $40^\circ$ - $60^\circ$ .

(2) As can be seen from Figure 5, at  $90^\circ$  azimuth, the spectral reflectance of mineral samples first increases to a certain extent and then gradually decreases with the increase of detection zenith Angle. The oscillation state of different minerals is also different. Quartz minerals increase with the increase of zenith Angle in the range of  $0^\circ$ - $30^\circ$ , and decrease with the increase of zenith Angle in the range of  $30^\circ$ - $60^\circ$ . The plagioclase minerals increase with the increase of zenith Angle in the range of  $0^\circ$ - $40^\circ$ , and decrease with the increase of zenith Angle in the range of  $40^\circ$ - $60^\circ$ . Orthoclase minerals

increase with the increase of zenith Angle in the range of  $0^\circ$ - $40^\circ$ , and decrease with the increase of zenith Angle in the range of  $40^\circ$ - $60^\circ$ .

(3) When the observation azimuth shown in Figure 6 is  $180^\circ$ , it is the forward scattering in the incident plane, and the spectral variation rule is the same as that shown in Figure 4 (a), which shows that the spectral reflectance of mineral samples increases to a certain extent and then gradually decreases with the increase of the detection zenith Angle. The oscillating states of different minerals are similar, and they all fluctuate greatly. Quartz minerals increase with the increase of zenith Angle in the range of  $0^\circ$ - $30^\circ$ , and decrease with the increase of zenith Angle in the range of  $30^\circ$ - $60^\circ$ . The plagioclase minerals increase with the increase of zenith Angle in the range of  $0^\circ$ - $40^\circ$ , and decrease with the increase of zenith Angle in the range of  $40^\circ$ - $60^\circ$ . Orthoclase minerals increase with the increase of zenith Angle in the range of  $0^\circ$ - $50^\circ$ , and decrease with the increase of zenith Angle in the range of  $50^\circ$ - $60^\circ$ . (3) When the observation azimuth shown in Figure 6 is  $180^\circ$ , it is the forward scattering in the incident plane, and the spectral variation rule is the same as that shown in Figure 4 (a), which shows that the spectral reflectance of mineral samples increases to a certain extent and then gradually decreases with the increase of the detection zenith Angle. The oscillating states of different minerals are similar, and they all fluctuate greatly. Quartz minerals increase with the increase of zenith Angle in the range of  $0^\circ$ - $30^\circ$ , and decrease with the increase of zenith Angle in the range of  $30^\circ$ - $60^\circ$ . The plagioclase minerals increase with the increase of zenith Angle in the range of  $0^\circ$ - $40^\circ$ , and decrease with the increase of zenith Angle in the range of  $40^\circ$ - $60^\circ$ . Orthoclase minerals increase with the increase of zenith Angle in the range of  $0^\circ$ - $50^\circ$ , and decrease with the increase of zenith Angle in the range of  $50^\circ$ - $60^\circ$ .

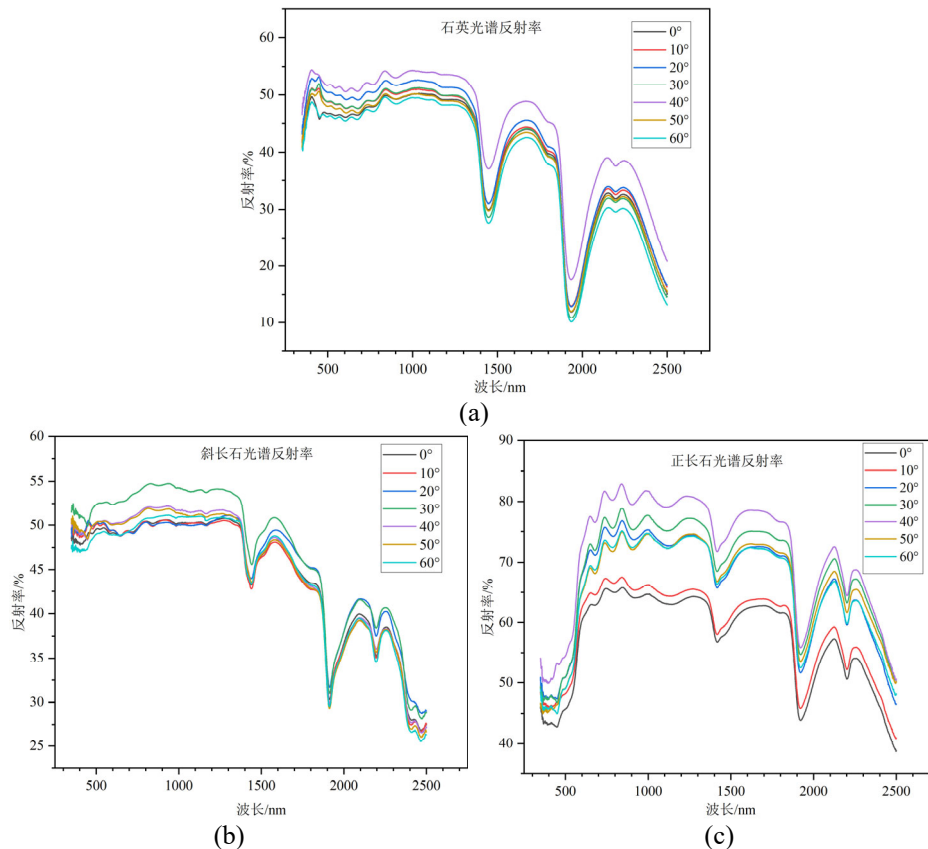
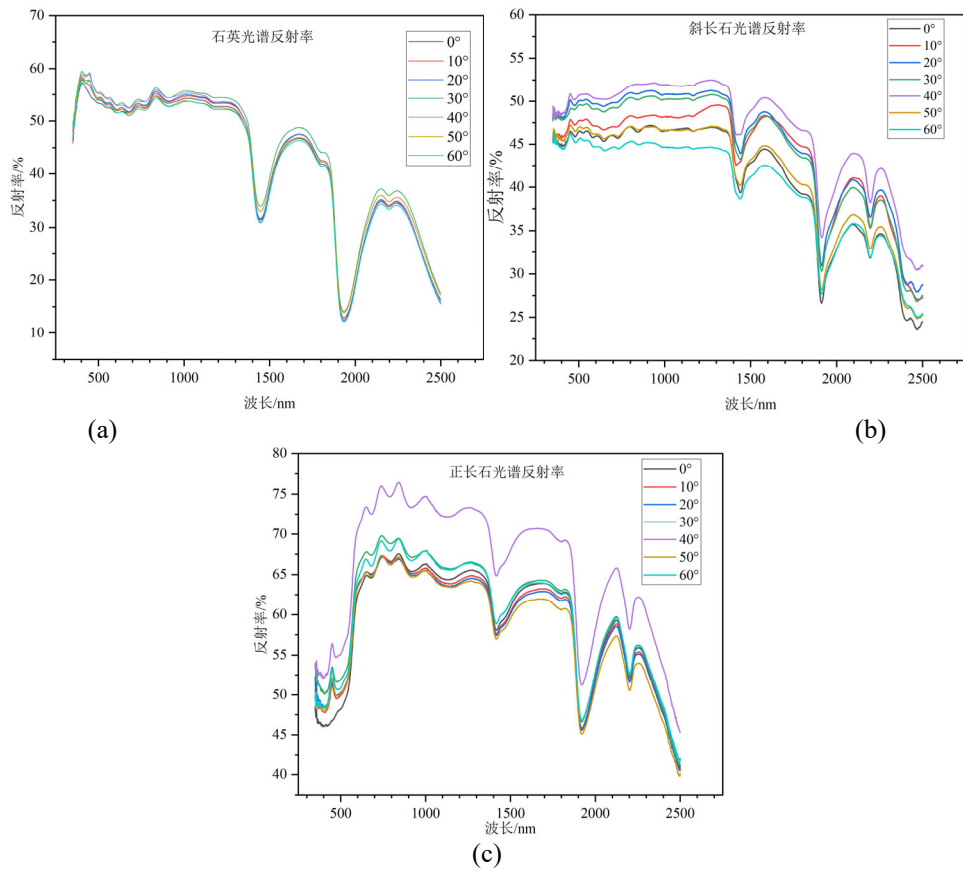
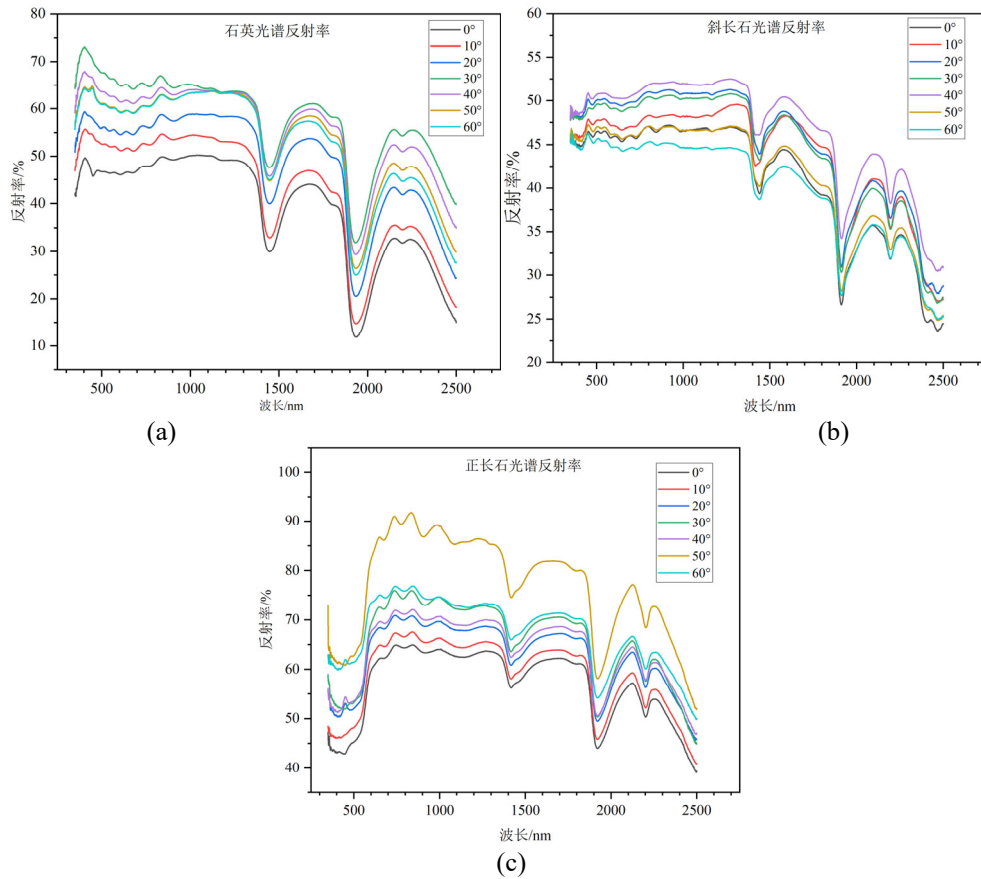


Figure 4. Spectral reflections of different zenith angles under different  $0^\circ$  azimuth of different samples (a) Quartzite.(b) Plagioclase.(c) Orthoclase



**Figure 5.** Spectral reflection of different zenith angles observed at 90° azimuth for different samples (a) Quartzite.(b) Plagioclase.(c) Orthoclase



**Figure 6.** Spectral reflections of different zenith angles under 180° azimuth of different samples (a) Quartzite.(b) Plagioclase.(c) Orthoclase

In summary, the observed zenith Angle has a great influence on the spectral reflectance, which is reflected in the fact that the reflectance of mineral samples gradually increases with the increasing of zenith Angle, reaching a peak value in the range of 30°~50°, and then gradually decreasing. When identifying and retrieving minerals based on spectral reflectance, some errors will be caused, which should be paid attention to in satellite remote sensing earth observation. In the process of earth observation, due to the scanning Angle of the sensor and the tilt of the surface, the tilt Angle of the edge pixel of the satellite image reaches or exceeds 60°, which will cause a large error in spectral observation and have a certain influence on the geographical exploration research. Therefore, it is necessary to study the influence of multi-angle observation spectra of samples in order to reduce the identification or inversion errors caused by observation angles.

### 3.1.2. Quantitative analysis

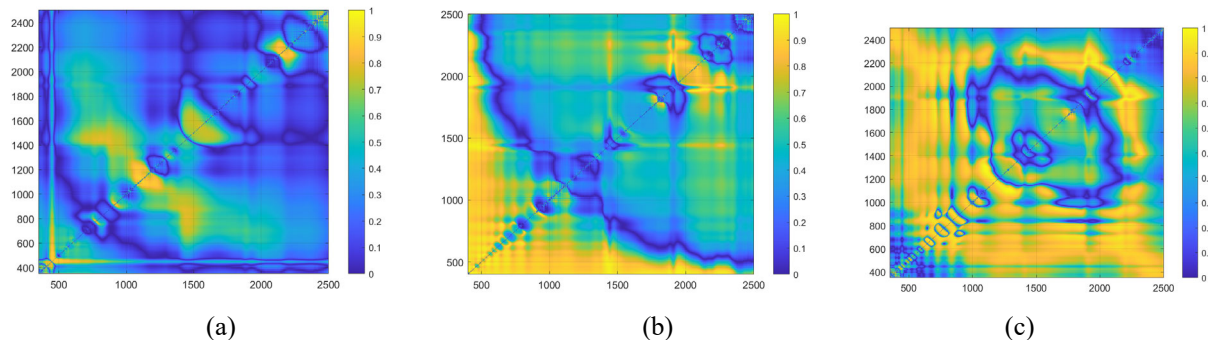
In order to quantitatively analyze the effect of inversion observation zenith Angle on spectral reflectance and explain

the correlation degree between observation zenith Angle and mineral spectral reflectance and sensitive band, spectral index method was used to extract sensitive band.

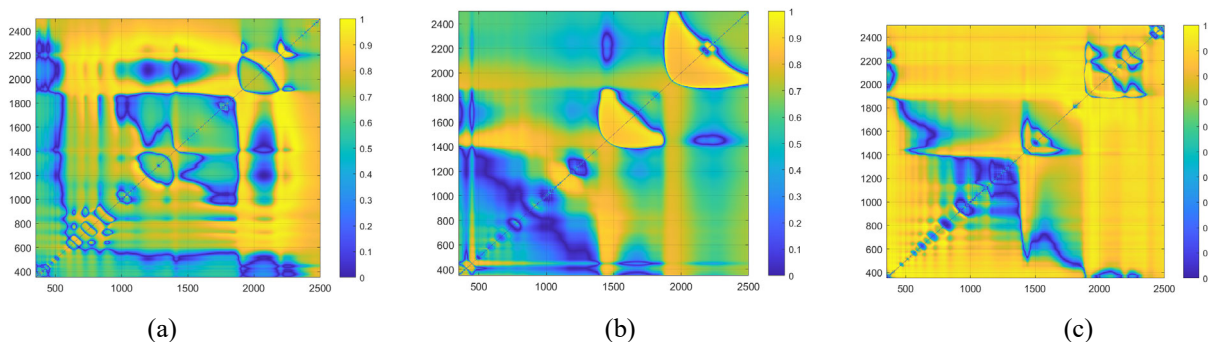
Using MATLAB software programming, the Difference index (DI) and Ratio index (RI) were constructed, and the correlation coefficient of Spears man rank between observation Angle and spectral index was analyzed, so as to select the two bands most significantly correlated with the change of observation Angle of zenith Angle. The correlation between DI and RI and surface roughness is shown in FIG. (7-9). Taking the change of zenith Angle in the direction of exit, i.e., 180° azimuth, as an example, the optimum band (unit /nm) of correlation between DI and RI minerals is shown in Table 1, where the roughness parameter is replaced by Ra. The best fitting curve of the relation between spectral reflectance and surface roughness is calculated. Correlation analysis was carried out between the spectral reflectance of the sample and the zenith Angle of 0°-60°, and the correlation coefficient R was calculated. All R2 were above 0.9 by polynomial fitting, which showed good accuracy, indicating the rationality of the experiment.

**Table 1.** Difference index of different samples ratio index and its correlation coefficient

Azimuth Angle	Exponent	Quartz	R2	plagioclase	R2	Orthoclase	R2
0°	DI	2455、2456	0.9951	1837、1835	0.9963	1781、1766	0.9981
0°	RI	568、566	0.9895	2158、2160	0.9970	1781、1766	0.9972
90°	DI	912、928	0.9830	473、475	0.9941	2420、2483	0.9969
90°	RI	429、517	0.9895	2077、2052	0.9838	1077、1043	0.9951
180°	DI	2420、2427	0.9918	406、422	0.9975	1102、1305	0.9965
180°	RI	2194、2211	0.9957	405、425	0.9980	2217、1889	0.9913



**Figure 7.** Zenith Angle DI rank correlation heat maps of different samples at 180° azimuth (a) Quartzite.(b) Plagioclase.(c) Orthoclase



**Figure 8.** Zenith Angle RI rank correlation heat maps of different samples at 180° azimuth (a) Quartzite.(b) Plagioclase.(c) Orthoclase

### 3.1.3. Comprehensive analysis

Based on the qualitative and quantitative analysis of the zenith Angle observation experiment, based on the whole series of experimental results and taking the selected sensitive

bands as an example, it is determined that the reflectance increase of different samples from the minimum to the maximum observation Angle is represented by 0°-60° zenith Angle and the spectral reflectance change in unit degree is shown in Table 4.2-4.3:

**Table 2.** Maximum increase of roughness in different sensitive bands

Azimuth Angle	wavelength /nm	Quartzite	wavelength /nm	Plagioclase	wavelength /nm	Orthoclase
0°	2455	8.34%	1837	2.48%	1781	21.88%
	2456	8.34%	1835	2.49%	1766	21.97%
	568	5.33%	2158	2.70%	1782	21.88%
	566	5.33%	2160	2.70%	1751	22.07%
90°	912	0.74%	473	4.81%	2420	13.17%
	928	0.75%	475	4.88%	2483	12.31%
	429	-0.64%	2077	8.16%	1077	16.16%
	517	-0.39%	2052	8.09%	1043	16.57%
180°	2420	7.34%	406	21.41%	1102	24.86%
	2427	7.39%	422	20.78%	1305	26.18%
	2194	6.30%	405	21.48%	2217	25.19%
	2211	6.38%	425	20.73%	1889	22.79%

**Table 3.** Reflectance change rate of unit zenith Angle expressed by different sensitive bands

Azimuth Angle	wavelength /nm	Quartzite	wavelength /nm	Plagioclase	wavelength /nm	Orthoclase
0°	2455	0.14%	1837	0.04%	1781	0.36%
	2456	0.14%	1835	0.04%	1766	0.37%
	568	0.09%	2158	0.05%	1782	0.36%
	566	0.09%	2160	0.04%	1751	0.37%
90°	912	0.01%	473	0.08%	2420	0.22%
	928	0.01%	475	0.08%	2483	0.21%
	429	-0.01%	2077	0.14%	1077	0.27%
	517	-0.01%	2052	0.13%	1043	0.28%
180°	2420	0.12%	406	0.36%	1102	0.41%
	2427	0.12%	422	0.35%	1305	0.44%
	2194	0.10%	405	0.36%	2217	0.42%
	2211	0.11%	425	0.35%	1889	0.38%

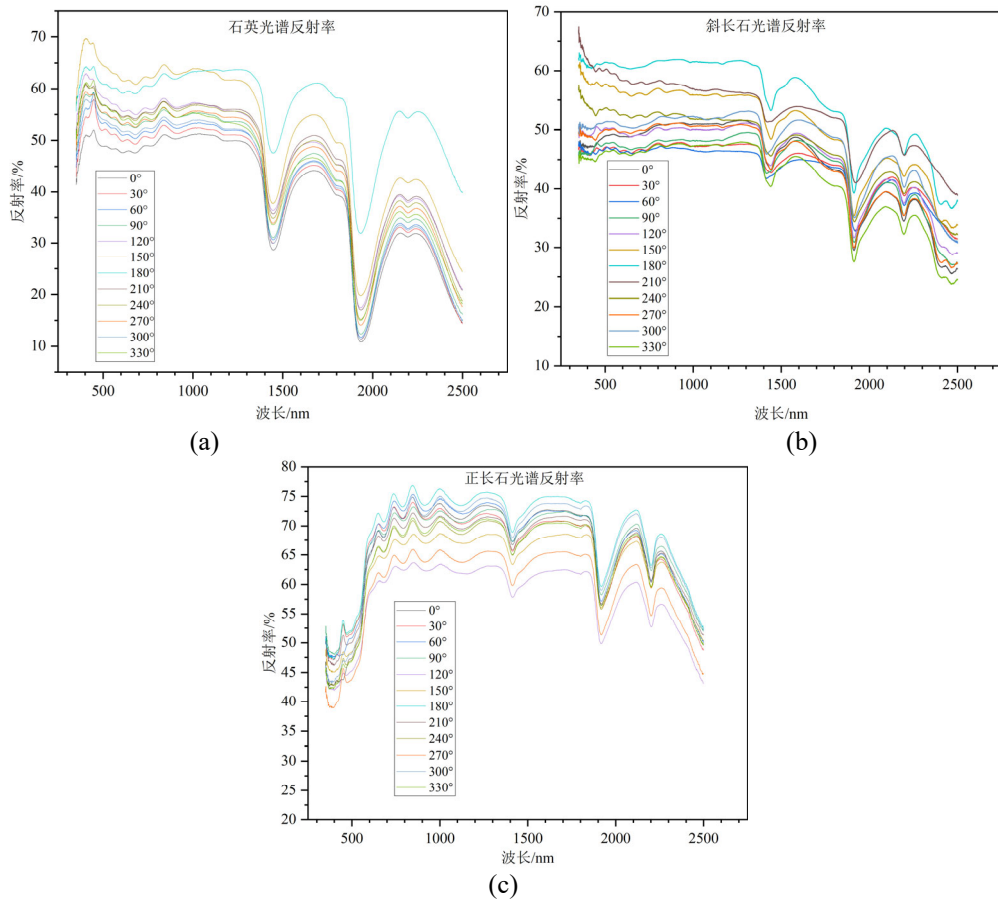
As can be seen from Table 2-3, in the sensitive bands screened by spectral index method, the spectral reflectance of quartz increases by 8.34% at the maximum incidence Angle, and the reflection change rate per unit roughness is 0.14%. The spectral reflectance of plagioclase increases by 21.48% in the exit direction, and the reflection rate per unit roughness is 0.36%. The maximum spectral reflectance of orthoclase increases by 26.18%, and the reflection rate per unit roughness is 0.44%. For different mineral samples, in different sensitive bands and at different zenith angles as a whole, the zenith Angle reflection change rate is relatively obvious, and the unit zenith Angle reflection change rate is different, but the overall difference is not significant, still indicating that the zenith Angle observation Angle has a significant effect on the spectral reflectance.

## 3.2. Analysis of mineral reflectance variation with relative azimuth Angle

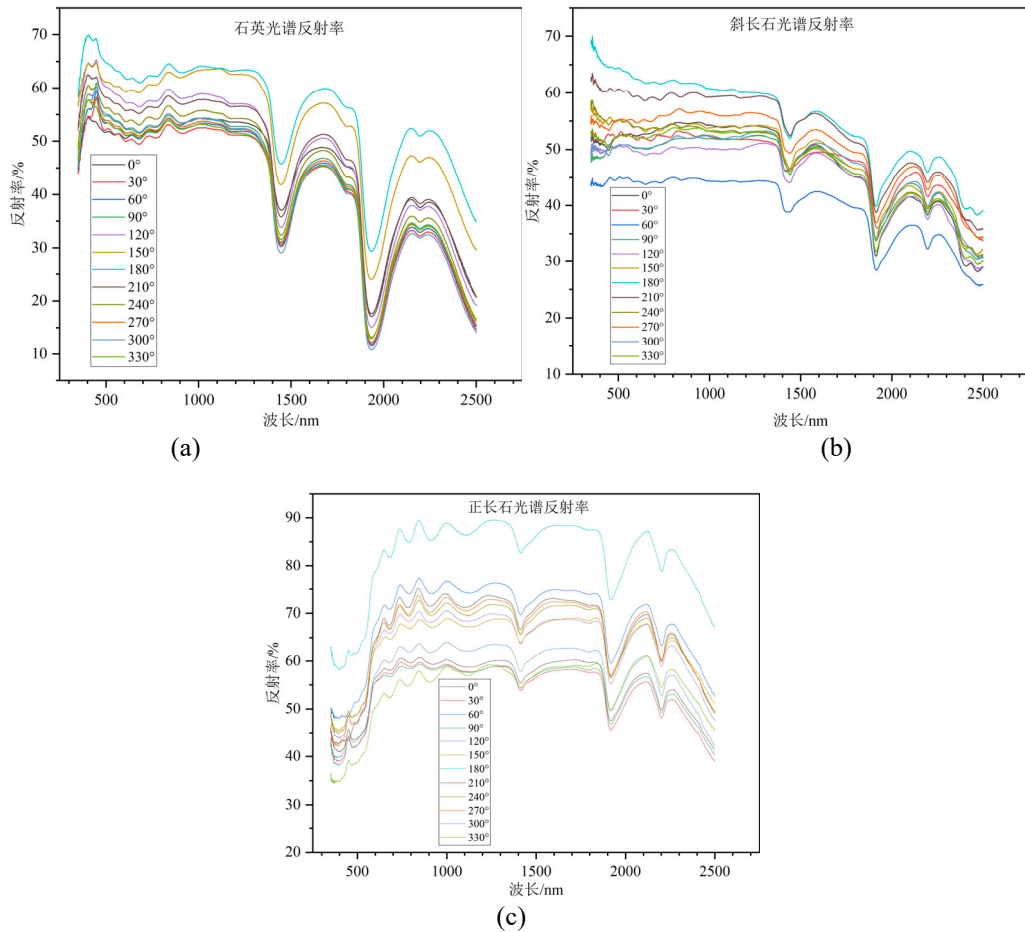
### 3.2.1. Qualitative analysis

In the process of studying the spatial distribution law of

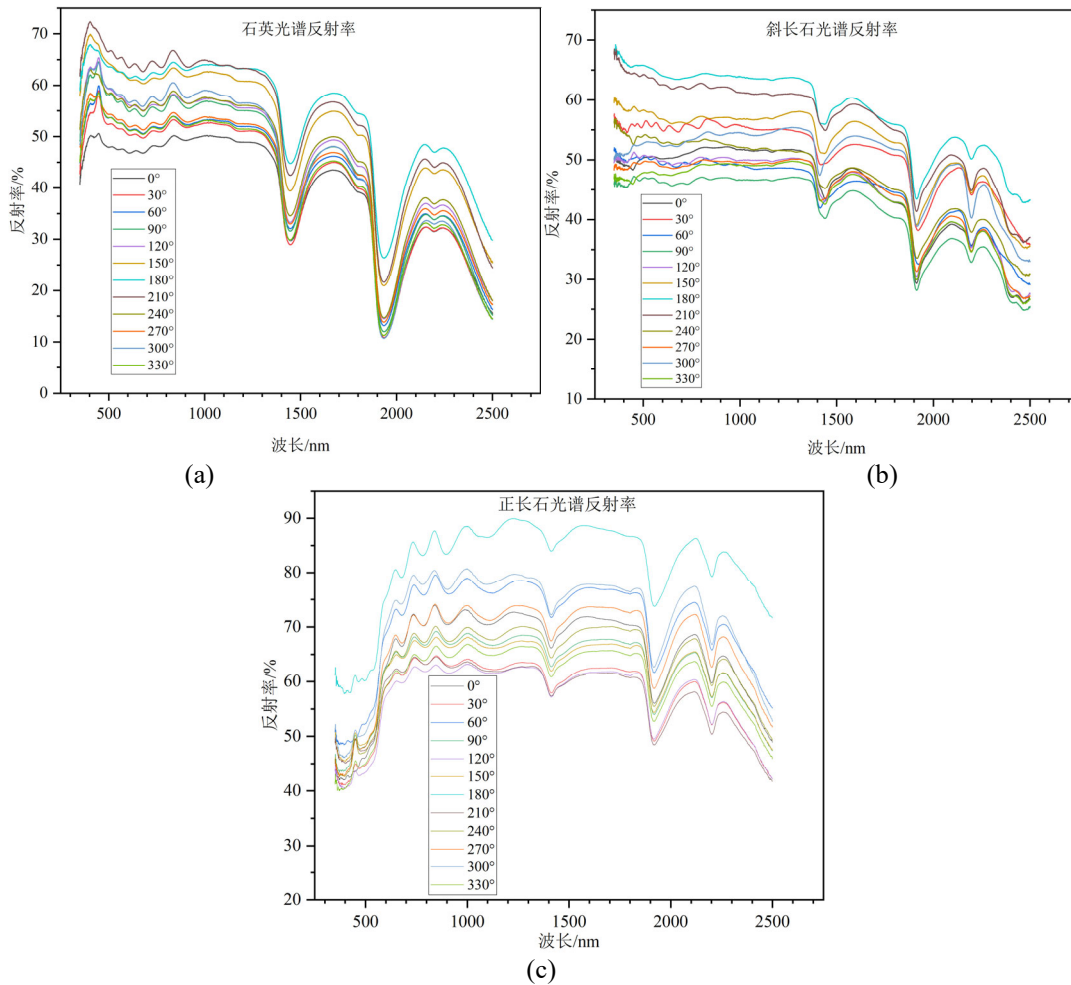
spectral spectra of different rocks and minerals from observation angles, the spatial distribution characteristics of reflectance of different mineral samples in the visible near-infrared band as a whole rather than in a fixed band are analyzed, which makes the experiment more intuitive as a whole. The spectral observation experiment results of different relative azimuth observation angles of different mineral samples are shown in Figure 9-11. From the following three figures, it can be clearly found that the distribution of reflectance of different minerals is similar when the azimuth changes clockwise. It can be concluded that the spectral reflectance in the 0-2 $\pi$  azimuth changes in an oscillatory manner with the change of the outgoing azimuth, and the spectral reflectance turns out to be the highest value in the 180° direction. The reflectance has no obvious change regularity. With the increase of zenith Angle (30°-50°), it can be seen that the reflectivity rises rapidly at the azimuth Angle of 90° to 180° and 270° to 180°.



**Figure 9.** Spectral reflection of different samples observed at azimuth Angle under 30° zenith Angle (a) Quartzite.(b) Plagioclase.(c) Orthoclase



**Figure 10.** Spectral reflection diagram of azimuth observation under 40° zenith Angle for different samples (a) Quartzite.(b) Plagioclase.(c) Orthoclase



**Figure 11.** Spectral reflection diagram of azimuth observation under 50° zenith Angle for different samples (a) Quartzite.(b) Plagioclase.(c) Orthoclase

### 3.2.2. Quantitative analysis

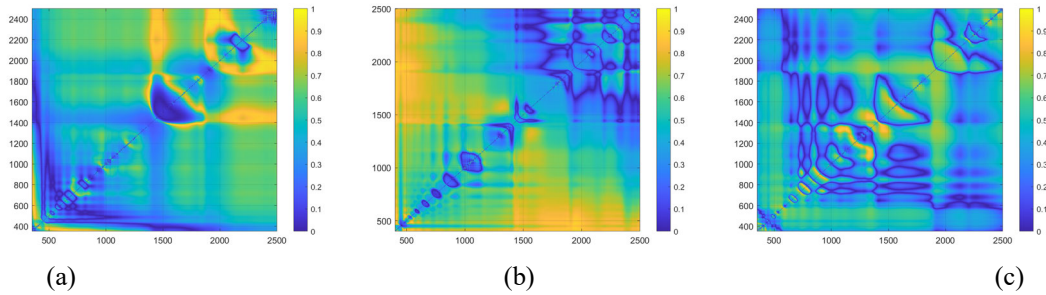
In order to quantitatively analyze the effect of inversion observation on spectral reflectance and explain the correlation degree between the observation azimuth and mineral spectral reflectance and the sensitive band, the spectral index method was used to extract the sensitive band.

Using MATLAB software programming, the Difference index (DI) and Ratio index (RI) were constructed to analyze the Spears man rank correlation coefficient of observed surface roughness and spectral index, so as to select the two bands most significantly correlated with observed azimuth Angle. The correlation between DI and RI and the observed

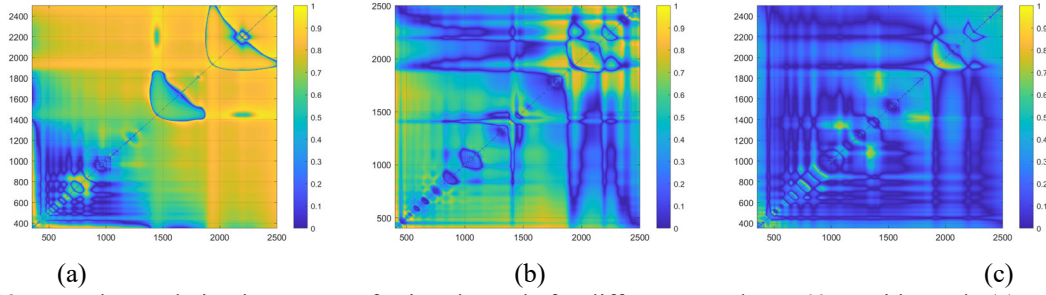
azimuth is shown in Figure 12-13. Taking the change of azimuth at 40° zenith Angle as an example, the best band (unit /nm) of correlation between DI and RI minerals is shown in Table 4, where the roughness parameter is replaced by Ra, and the best fitting curve of the relationship between spectral reflectivity and surface roughness is calculated. The correlation analysis was conducted between the spectral reflectance of the sample and the roughness parameter Ra, and the correlation coefficient R was calculated. All R2 was basically above 0.9 by polynomial fitting, and the accuracy of orthoclase sample at 40° zenith Angle was 0.857, indicating the overall accuracy was good, indicating the rationality of the experiment.

**Table 4.** Difference index of different samples ratio index and its correlation coefficient

Zenith Angle	Exponent	Quartzite	R2	Plagioclase	R2	Orthoclase	R2
30°	DI	1811、1815	0.9137	490、554	0.9357	496、491	0.9101
30°	RI	2190、2214	0.310	1923、1892	0.9744	481、504	0.9468
40°	DI	2460、2472	0.9829	489、546	0.9031	2072、2075	0.9324
40°	RI	1382、1594	0.9553	2033、2034	0.9222	1941、1938	0.8570
50°	DI	434、463	0.9480	485、548	0.9242	1110、1112	0.9230
50°	RI	2221、2185	0.9634	1960、1943	0.9405	2356、2358	0.9631



**Figure 12.** Rank-dependent heat maps of azimuth DI for different samples at 40° zenith Angle (a) Quartzite.(b) Plagioclase.(c) Orthoclase



**Figure 13.** RI rank correlation heat maps of azimuth Angle for different samples at 40° zenith Angle (a) Quartzite.(b) Plagioclase.(c) Orthoclase

### 3.2.3. Comprehensive analysis

Based on the results of the whole series of experiments, taking the selected sensitive bands as an example, it is determined that the increase of the reflectance of different

samples in a period from 0° to 360° in the azimuth Angle with a fixed zenith Angle is expressed in degrees and the reflectance changes per unit azimuth Angle, as shown in Table 5-6:

**Table 5.** Maximum increment of azimuth in different sensitive bands

Zenith Angle	wavelength /nm	Quartzite	wavelength /nm	Plagioclase	wavelength /nm	Orthoclase
0°	1811	18.92%	490	15.11%	496	8.34%
	1815	18.98%	554	14.68%	491	8.40%
	2190	23.12%	1923	12.60%	481	8.49%
	2214	23.21%	1892	13.01%	504	8.35%
	2460	20.94%	489	15.12%	2072	30.72%
90°	2472	20.91%	546	14.73%	2075	30.76%
	1382	13.68%	2033	12.95%	1941	27.37%
	1594	14.30%	2034	12.96%	1938	27.32%
180°	434	20.89%	485	19.21%	1110	24.99%
	463	19.55%	548	18.25%	1112	25.03%
	2221	15.56%	1960	15.42%	2356	30.01%
	2185	15.50%	1943	15.31%	2358	30.05%

**Table 6.** Reflectance change rate per unit azimuth Angle expressed by degrees of different sensitive bands

Zenith Angle	wavelength /nm	Quartzite	wavelength /nm	Plagioclase	wavelength /nm	Orthoclase
0°	1811	0.05%	490	0.04%	496	0.02%
	1815	0.05%	554	0.04%	491	0.02%
	2190	0.06%	1923	0.03%	481	0.02%
	2214	0.06%	1892	0.04%	504	0.02%
	2460	0.06%	489	0.04%	2072	0.09%
90°	2472	0.06%	546	0.04%	2075	0.09%
	1382	0.04%	2033	0.04%	1941	0.08%
	1594	0.04%	2034	0.04%	1938	0.08%
180°	434	0.06%	485	0.05%	1110	0.07%
	463	0.05%	548	0.05%	1112	0.07%
	2221	0.04%	1960	0.04%	2356	0.08%
	2185	0.04%	1943	0.04%	2358	0.08%

It can be seen from Table 5-6 that in the sensitive bands screened by spectral index method, the spectral reflectance of

quartz increases by 23.21%, and the reflection change rate per unit azimuth Angle is 0.06%. The spectral reflectance of

plagioclase increases by 19.21%, and the reflectance change rate per unit azimuth is 0.05%. The spectral reflectance of orthoclase increases by 30.76%, and the reflectance change rate per unit azimuth is 0.09%. For different samples, in different sensitive bands, the unit azimuth reflection change rate is similar, indicating that the azimuth Angle has a significant effect on the spectral reflectance.

### 3.3. Mechanism analysis of experimental results

The experimental results show that in addition to the key factors such as mineral composition, crystal structure and chemical composition, the observation Angle also has an impact on the spectral characteristics of minerals. In the visible and near infrared bands, the spectral reflectance of rocks will also have different changes with the change of the observation Angle of minerals. The effect of zenith Angle on spectral reflectance is the same under different observation azimuth. The observed zenith Angle has a great influence on the spectral reflectance, which is reflected in the fact that the reflectance of mineral samples gradually increases with the increasing of the zenith Angle to reach the peak value within 30°~50°, and then gradually decreases. The spectral reflectance at 0°-360° azimuth is symmetrical, and the spectral reflectance is oscillatory, and the reflectance at 180° azimuth is the highest. The overall situation gradually increases from 0°-180° spectral reflectance, and gradually decreases from 180°-360° spectral reflectance. The mechanism of this phenomenon is discussed in this study.

This phenomenon can be explained from the perspective of Kirchhoff's approximation theory and masking effect. Kirchhoff approximation, KF(Marston et al. 2016; Gunderson, Smith, and Marston 2014)The theory applies to a microwave-like rough surface, where the average level is large compared to the wavelength. Kirchhoff's approximation postulates that if an incident wave is projected onto an infinite plane tangent to the point, the plane interface will be reflected at any point on the surface. According to Fresnel's reflection law, the total field strength at any point on the tangent plane can be calculated. To study the surface reflection characteristics by statistics, the following conditions must be met. In the horizontal direction, the relative length  $l$  of roughness must be greater than the length of the incident wave. In the vertical direction, the roughness root-mean-square height  $Rq$  must be small enough to ensure that the average curvature radius is greater than the length of the electromagnetic wave. The mathematical expression of the above restriction is,

$$kl > 6 \quad (4.4) \quad l > 2.76Rq\lambda \quad (3)$$

$k$  is the wave number;

$\lambda$  is the incident wavelength;

$l$  is the surface correlation length.

Through calculation and analysis, the surface of the sample meets the Kirchhoff approximation condition. Based on the above conditions, the analytical solution of reflection is further obtained, and two methods are often used at present: Stataionary phase approximation, also known as steady phase method, which is suitable for surfaces with large root-mean-square value of surface elevation. By solving Holmoltz integral equation with phase stabilization method, the scattering field is represented, and then the average scattering field is calculated from the average stable points per unit area and the average contribution of each point, and then the

average reflected power is obtained. Scalar approximations are suitable for surfaces with medium or small root-mean-square height values. The Kirchhoff approximation is suitable for cases of small incidence angles (usually less than 30°) and reflection angles, and for medium incidence angles (30° to 60°) and large incidence angles (generally greater than 60°), the influence of masking effects needs to be considered. The masking functions include Hapke masking function, the masking function proposed by Smith, and the masking function proposed by Wagner for Kirchhoff theory. The shielding effect is affected by the incidence Angle. The larger the incidence Angle is, the more obvious the shielding effect is. When incident at 0°, the reflection decreases from 0° to 90°. With the increase of the incidence Angle, the value of the reflection at 0° gradually decreases, and with the increase of the reflection Angle, it still decreases to 0 at 90°.

Since Kirchhoff's approximation considers only a single reflection and is only suitable for explaining the reflection at a small Angle, further consideration of multiple reflection effects and masking effects can be used to explain the medium and large Angle reflections. However, further theoretical and experimental studies are needed, but it shows that the directional reflectance is the result of the reflectance of smooth surface, multiple scattering and masking effects. The interpretation of the effects of roughness and observation Angle on spectral reflectance is not completely separate, but mutually integrated.

The parameters of Kirchhoff approximation also change with the change of roughness. Similarly, surface scattering and volume scattering will also change with the change of observation Angle, and the reflection times of the cavity will also be different. In practical work, aiming at the influence of observation Angle on quantitative inversion of rock and ore, the observation Angle of mineral end elements should be consistent with that of mineral samples. When mineral samples are tested for reflectance spectrum, the main optical axis of the spectrometer lens should be kept perpendicular to the surface of the sample, so as to ensure the consistency of the observation Angle between the mineral end element and the mineral sample, so as to avoid the influence of the observation Angle on the experimental results.

## 4. Conclusions

In this paper, the influence of different types of observation angles on the visible near-infrared spectral characteristics of three mineral samples was studied. Through qualitative and quantitative analysis, the results showed that:

(1) The effect of zenith Angle on spectral reflectance is the same under different observation azimuth. The observed zenith Angle has a great influence on the spectral reflectance, which is reflected in the fact that the reflectance of mineral samples gradually increases with the increasing of the zenith Angle to reach the peak value within 30°~50°, and then gradually decreases.

(2) The spectral reflectance at 0°-360° azimuth is symmetrical, and the spectral reflectance is oscillatory, and the reflectance at 180° azimuth is the highest. The overall situation gradually increases from 0°-180° spectral reflectance, and gradually decreases from 180°-360° spectral reflectance.

(3) There are sensitive bands for the effect of observation azimuth on spectral reflectance. With different spectral index band combinations, further qualitative and quantitative analysis shows that for different samples, in different

sensitive bands, the reflection change rate of unit observation Angle is relatively similar, indicating that the azimuth Angle has a significant influence on the spectral reflectance.

## References

- [1] Cheng, Hongfei, Riwa Hao, Yi Zhou, and Ray L. Frost. 2017. "Visible and near-infrared spectroscopic comparison of five phyllosilicate mineral samples." *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* 180:19-22. <https://doi.org/10.1016/j.saa.2017.02.043>.
- [2] Cheng Yin-Yi, ZHOU Kefa, Wang Jin-Lin, et al. 2021. "Multi-angle spectral characteristics analysis of malachite based on Hapke model." *Geological science and technology information*.
- [3] Dong, Wang, Liu Shanjun, Li Hengyu, and Qi Yuxin. 2020. "Study on the influence of grade on reflectance spectral characteristics of Anshan type iron ore." *Spectroscopy and Spectral Analysis* 40 (10):3193-3198.
- [4] Gilmore, Martha S., Benjamin Bornstein, Matthew D. Merrill, Rebecca Castaño, and James P. Greenwood. 2008. "Generation and performance of automated jarosite mineral detectors for visible/near-infrared spectrometers at Mars." *Icarus* 195:169-183. <https://doi.org/10.1016/j.icarus.2007.11.025>.
- [5] Gunderson, Aaron M., Anthony R. Smith, and Philip L. Marston. 2014. "Kirchhoff approximation for spheres and cylinders partially exposed at flat surfaces and application to the interpretation of backscattering." *The Journal of the Acoustical Society of America* 136 (4):2087-2087.
- [6] Marston, Philip, L., Gunderson, Aaron, and M. 2016. "Kirchhoff approximation for backscattering from a partially exposed rigid sphere at a flat interface." *Journal of the Acoustical Society of America*.
- [7] Niclos, Raquel, Carolina Dona, Enric Valor, and Mar Bisquert. 2013. "Thermal-infrared spectral and angular characterization of crude oil and seawater emissivities for oil slick identification." *IEEE Transactions on Geoscience and Remote Sensing* 52 (9):5387-5395.
- [8] Peng, Lu, Chen Shengbo, Cui Tengfei, Zhou Chao, and Yang Qian. 2016. "Experimental study on bidirectional reflection characteristics of minerals on lunar surface." *Acta petrologica* 32 (01):107-112.
- [9] Pham-Xuan, V., D. Trinh, H. De Gerssem, and C. Brennan. 2018. "Novel Iterative Algorithm for the Solution of Electromagnetic Scattering From Layered Random Rough Surfaces." *IEEE Transactions on Antennas & Propagation*:1-1.
- [10] Shanjun, LIU, WANG Dong, MAO Yachun, SONG Liang, DING Ruibo, and LIU Haiqi. 2021. "Intelligent Spectrum Sensing Technology and Research Progress of Rock and Ore in Intelligent Mine." *Metal Mine(in chinese)*. <https://doi.org/10.19614/j.cnki.jsks.202107001>.
- [11] Song, L., S. J. Liu, M. L. Yu, Y. C. Mao, and L. X. Wu. 2017. "A Classification Method Based on the Combination of Visible, Near-Infrared and Thermal Infrared Spectrum for Coal and Gangue Distinguishment." *Spectroscopy and Spectral Analysis* 37 (2):416-422. [https://doi.org/10.3964/j.issn.1000-0593\(2017\)02-041607](https://doi.org/10.3964/j.issn.1000-0593(2017)02-041607).
- [12] Wang, Runsheng. 2009. "Spectral Identification and Inversion of Composition and Component of Objects with Hyperspectral Remote Sensing." *Journal of Geo-information Science(in Chinese)* 11 (03):261-267.
- [13] Xu, L. J., X. Y. Meng, R. Wei, and K. Zhang. 2022. "Experimental Research on Coal-Rock Identification Method Based on Visible-Near Infrared Spectroscopy." *Spectroscopy and Spectral Analysis* 42 (7): 2135-2142. [https://doi.org/10.3964/j.issn.1000-0593\(2022\)07-2135-08](https://doi.org/10.3964/j.issn.1000-0593(2022)07-2135-08).
- [14] Yan, Shouxun, Bing Zhang, Yongchao Zhao, Lanfen Zheng, Qingxi Tong, and Kai Yang. 2003. "Summarizing the VIS-NIR Spectra of Minerals and Rocks." *Remote Sensing Technology and Application(in Chinese)* (04):191-201.
- [15] Zhao Hu, YAN Lei, ZHAO Yunsheng. 2003. "Multi-angle polarization reflection spectra of basalt." *Geography and geographic information science* (04):81-83+112.  
2004a. "Multi-angle polarization reflection spectra of granite." *Mineral rock* (02):9-13. <https://doi.org/10.19719/j.cnki.1001-6872.2004.02.003>.  
2004b. "Multi-angle polarization reflection spectra of peridotite." *Geology and exploration* (02):51-54.