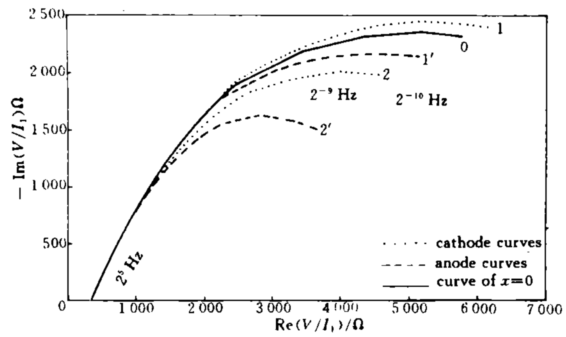


**Fig. 7 Experimental cathode/anode polarization curves of pyrite**

$S = 23.40\text{cm}^2$. $L = 4.2\text{cm}$,

$j_1 = I_1/S = 0.53\mu A/cm^2$

For curve 0, $j_0 = 0\mu A/cm^2$, for curves 1 and 1′, $j_0 = 4.24\mu A/cm^2$;

for curves 2 and 2′, $j_0 = 16.96\mu A/cm^2$

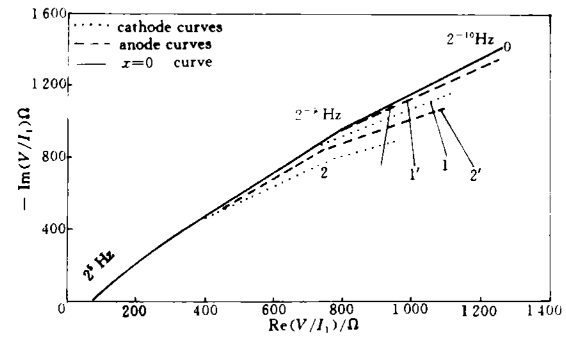


**Fig. 8 Experimental cathode/anode polarization curves of graphite**

$S = 28.50\text{cm}^2$, $L = 3.2\text{cm}$,

$j_1 = I_1/S = 0.85\mu s/cm^2$

For curve 0, $j_0 = 0\mu A/cm^2$,

for curves 1 and 1′, $j_0 = 6.8\mu A/cm^2$;

for curves 2 and 2′, $j_0 = 27.2\mu A/cm^2$

cause the time-constant for graphite is usually much greater than those for the sulfates. This means that the value $x$ for graphite is much greater than those for the sulfates when Re and c are approximately equal for the two kinds of minerals. Thus, $G_1 = (iwx)^c$ would increase with the increase of $x$, and the role played by the nonlinear equivalent admittance $G_2$ becomes weaker relatively. That is why the nonlinear effect of IP for graphite is weaker than that for sulfates. Beacuse $x$ determines the compactive reactance of the double layer structure, which is related closely to the mineral property, The nonlinear effect of IP for different minerals is different.

## 5 CONCLUSIONS

A new equivalent circuit to describe the mineral-electrolyte system has been proposed and the overvoltage response of the circuit induced by any arbitrary current is calculated. The circuit proposed is proved to be reasonable and computing reliable by comparision of theoretically calculated cathode/anode polarization curves of sulfates and graphite with those curves of experiment reuslts. It has been found that the nonlinear effect of IP is different for different minerals. In general, electrode polarization curves for dissolvable minerals are "the cathode polarization dominant", while those for non-dissolvable minerals are "the anode polarization dominant". The nonlinear effect of IP for dissolvable minerals is much greater than that for the nondissolvable minerals usually. Thus, it can be used to evaluate IP anomalies.

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# FRACTURE MECHANICS CONDITIONS OF WALLROCK ALTERATION①

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**ABSTRACT** According to the characteristics of stress field surrounding cracks and by theoretical analyses of fracture mechanics, it was found that the wallrock alteration is controlled by the microcracks developed at crack-tip. The new mode of alteration development controlled by conditions of fracture mechanics was proved by the facts that the variation in regularities of alteration zones and lode-thickness is determined by the extension-length and driving stress of crack.

**Key words** lode structure wallrock alteration rock fracture

## 1 INTRODUCTION

Wallrock alteration is the basic problem of veinlike-deposit research. The discrimination of types, mode of zoning, geochemical environment and formation mechanism of the wallrock alteration have been discussed in detail[1, 2]. In this paper the conditions controlling the intensities of wallrock alteration in ore-vein are discussed in terms of theories of fracture mechanics and some important rules are proposed with examples.

## 2 VARIATION CHARACTERISTICS OF THICKNESS OF WALLROCK-ALTERATION ZONE IN ORE-VEINS

The wallrock alteration flanking the lodes generally shows zonal distribution. At the same site of an ore-deposit the relationship between lode-thickness and alteration-zone thickness is one of the markers indicating the lode-controlled alteration intensity. The results through measurement on some veinlike deposits, however, show variable features of positive and negative correlations between the thicknesses of the alteration-zone and the ore-vein[3, 4]. Such phenomena reveal that the factors affecting the development of alteration-zone are rather complicate. Fig. 1 illustrates the projections of relationship between thickness of ore-vein and wallrock alteration-zone statistically measured at Xihuashan tungsten mine of Jiangxi, Xiangxi gold mine of Hunan and Xinjinchang gold mine of Gansu.

As shown in Fig. 1, the ratio of thickness between ore-vein and alteration-zone for all deposits just mentioned decreases with increasing lode-thickness. The range of variation in corresponding lode-thickness is large when the ratio is small, but small when the ratio increases. The ore-bearing solution according to general theory of wallrock alteration replaces the wallrock by two processes, i. e. permeation and diffusion. Such replacement is affected by the composition of ore-bearing solution, the nature of wallrock, the hydrothermal channel-way and the physicochemical environment. In some deposits, such conditions mentioned above are consistent everywhere, therefore, the greater lode-thickness is more favourable for chemical reaction during metasomatosis-alteration. An inhomogeneous stress field formed surrounding a lode which is actually a crack, however, can efficiently change the porosities of wallrock, thus

① Supported by the National Natural Science Foundation of China; Received Feb. 8, 1995

affecting the hydrothermal channel-way which is an important factor for alteration.

## 3 CHARACTERISTICS OF FRACTURE STRESS-FIELD AND ITS CONTROL ON THE WALLROCK ALTERATION

The crack filled by ore-bearing solution generally belongs to brittle fracture. The linear elastic fracture-mechanics is appropriate to be used for studying the two-dimensional crack configuration as shown in Fig. 2. Using methematical model of crack the stress field is derived from the stress function, and the equations expressing stress field surrounding the crack under homogeneous loadding are:

$$\sigma_{11} = \sigma_{11}^{r} + \Delta\sigma_{I}[rR^{-1}\cos(\theta - \Theta) - 1 + a^{2}rR^{-3}\sin\theta\sin\varepsilon 3\Theta] + \Delta\sigma_{II}(a^{2}rR^{-3}\sin\theta\cos 3\Theta \quad (1)$$

$$\sigma_{22} = \sigma_{22}^{r} + \Delta\sigma_{I}[rR^{-1}\cos(\theta - \Theta) - 1 - a^{2}rR^{-3}\sin\theta\sin 3\Theta] + \Delta\sigma_{II}(2rR^{-1}\sin(\theta - \Theta) - a^{2}rR^{-3}\sin\theta\cos 3\Theta] \quad (2)$$

$$\sigma_{12} = \sigma_{12}^{r} + \Delta\sigma_{II}[rR^{-1}\cos(\theta - \Theta) - 1 - a^{2}rR^{-3}\sin\theta\sin 3\Theta] + \Delta\sigma_{I}(a^{2}rR^{-3}\sin\theta\cos 2\Theta) \quad (3)$$

where $\sigma_{11}$ and $\sigma_{22}$ are normal stresses, $\sigma_{12}$ the shear stress, $\sigma^{r}$ the remote loading, $\sigma^{c}$ the fluid-pressure within cracks, $\Delta\sigma_{I} = \sigma_{11}^{r} - \sigma_{11}^{c}$ and $\Delta\sigma_{II} = \sigma_{12}^{r} - \sigma_{12}^{c}$ are driving stress, $r$ and $\theta$ are polar coordinates, $R = (r_1, r_2)^{1/2}$, $\Theta = (\theta_1 + \theta_2)/2$, $a$ is the semi-length of crack, $x_1$ and $x_2$ are perpendicular and parallel to the crack respectively. The model I of tension fracture is merely considered as the major mechanical feature of ore-vein[4], then taking $\Delta\sigma_{II} = 0$. In order to express the general characters of stress-field surrounding crack, assumed $\Delta\sigma_{I} = 1$ MPa and abandoned the remote term, the stress components are calculated from equations (1) ~(3), and principal stresses are plotted after transformation[5] (Fig. 3). In Fig. 3(a), the maximum principal strsses are compressive in the central part of the crack close to the latter, but there are all tensile stresses in the remaining parts of the crack with greater ones at crack-tip. In the region of tensile stress, potential tensile microcracks are considered to be parallel to the minimum principal stress trajectories, but in the region of compression potential tensile microcrack is considered to be absent. In Fig. 3(b), the minimum principal stresses at crack front are tensile locally, and

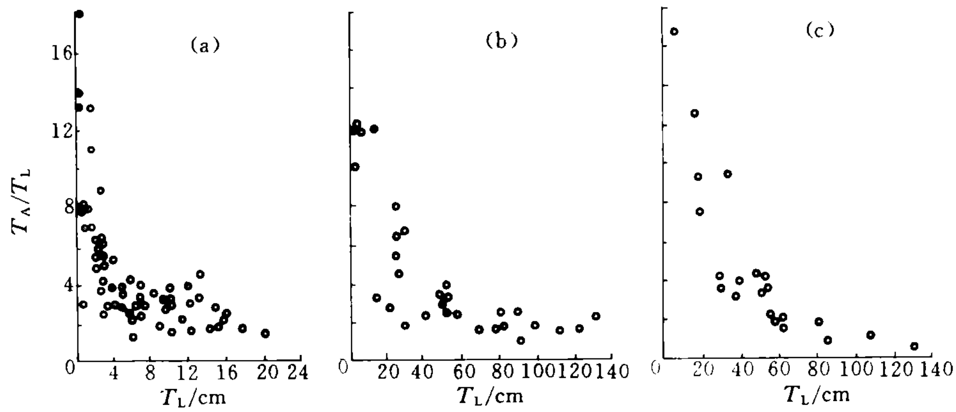


**Fig. 1 Projections of ratio of practically measured thicknesses between alteration-zone and lode from the three deposits**

(a)—Xihuashan tungsten mine, 60 measurements; (b)—Xiangxi gold mine, 31 measurements; (c)—Xinjinchang gold mine, 21 measurements; $T_A$ —thickness of alteration-zone; $T_L$ —thickness of lode in the remaining parts of crack are all compressive, which increase as closing to the crack-middle. In the region of compression, potential buckles are considered to be parallel to the maximum principal stress trajectories. The distinguishing features of superposition of these two principal stresses exhibit a tensile stress field at the crack front and a compressive one in remaining parts surrounding the crack, with a transitional zone between these fields.

From the features mentioned above, thus it can be seen that a large stress gradient is established in the wallrock between crack-front and central part of the crack, and dense tensile microcracks are formed at the crack front, but the pores and earlier formed tensile microcracks in the central part of the crack may be sealed. Such difference in microcracks provides the driving force and channel-way for crack-filling ore-bearing solution to permeate and diffuse into the wallrock at crack-tip, and is favourable for the formation of strong metasomatosis-alteration zone. In contrast, the wallrock flanking the crack may arrest the ore-bearing solution to enter into it, and unfavourable for chemical reaction of metasomatosis-alteration. The wallrock alteration of ore-vein, therefore, possesses a particuluar "alteration-mechanism of crack-tip".

## 4 DEVELOPMENT PROCESSES OF CRACK AND WALLROCK ALTERATION

In the processes of crack-growth and crack-extension, the alteration-zone at the earlier formed crack-tip will later transpose to the compressive stress field flanking the crack, and display the action of metasomatosis-alteration gradually diminished and even ceased, then this action during crack-extension will take place in the fresh (unaltered) wallrock at the newly formed crack-tip. The interchange of these two processes, namely generation and transposition of alteration in wallrock, creates a distinct wallrock alteration-zone distributed along the flank of a crack (Fig. 4).

The feature of stress-field at lode-tip will

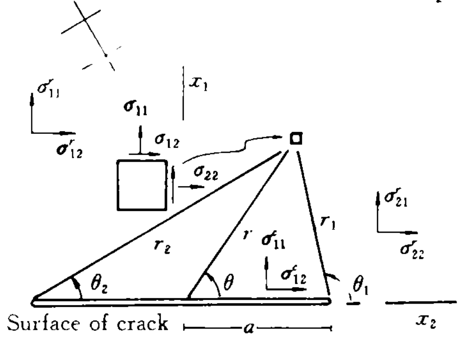


**Fig. 2 Relation of parameters calculated from stress field surrounding the crack[3]**

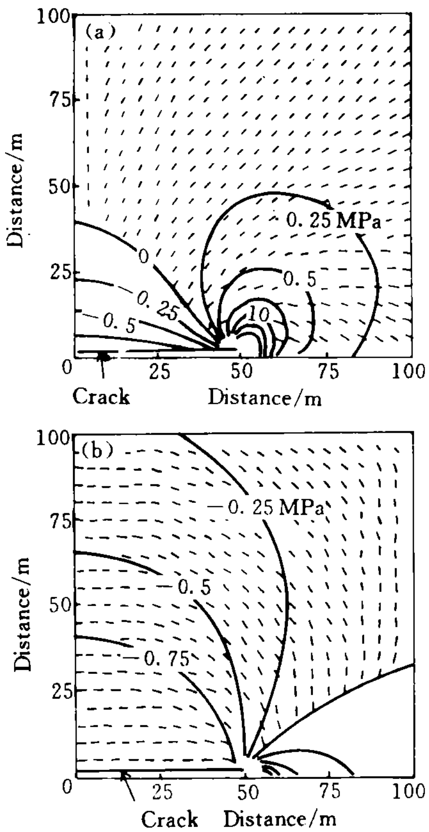


**Fig. 3 Isoplethes and trajectories of principal stress surrounding the crack[5]**

(a)—Isoplethes of maximum principal stress and trajectories of minimum principal stress; (b)—Isoplethes of minimum principal stress and trajectories fo maximum principal stress; Solid line—isopleth of principal stress; Dash line—trajectories of principal stress

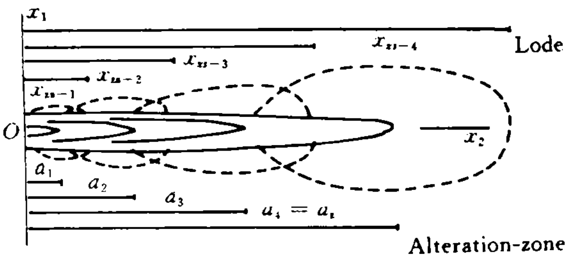


**Fig. 4 Schematic diagram illustrating the characteristics of wallrock alteration at the extension-front of ore-vein**

$a_i$ —lode-length; $i = 1 \sim 4$ the stages of crack-extension; $a_I$ —final lode-length; $x_{2si}$ —the range of alteration-zone corresponding to each stage of crack-extension( $i = 1 \sim 4$ stages)

be continuously changed during propagating process of the lode, and only the characteristics of stress on the prolonged line of along $x_2$ coordinate will be considered for simplicity in discussion. From equation (1), we have[3]

$$\sigma_{11} = \Delta\sigma_I [x_{2s}(x_{2s}^2 - a_i^2)^{-\frac{1}{2}} - 1] \quad (4)$$

Putting $\sigma_{11}/\Delta\sigma_I = 1$, the above equation becoming $x_{2s}^2 = 1.33\, a_i^2$, desplays linear relation of crack-length to the position $x_{2s}$ of stress point, the driving stress of which is equal to that at the crack-front. The relationship between lode-thickness and lode-length is expressed as follows[3]:

$$\mu\Delta U_I/2(1-\nu) = \Delta\sigma_I(a_z^2 - x_{2i}^2)^{1/2} \quad (5)$$

where $\Delta U_I$ is the distance between two walls of lode, $\nu$ the Poisson's ratio, $\mu$ the elastic modulus coefficient. When driving stress $\Delta\sigma_I$ is fixed, the length-thickness ratio shows a simple and directly proportional relation. Taking $\Delta\sigma_I = 20\,\mathrm{MPa}$, according to the mean tensile strength of rock, the formation of microcrack in wallrock may be ensured when $\sigma_{11} \geqslant \Delta\sigma_I$. Putting the lode-length $a_i$ in equation (4) equal to the coordinate $X_{2i}$ in equation (5) and establishing a simulataneous equation by combining equations (4) and (5), we have

$$[\mu\Delta U_I/2(1-\nu)]^2 - 300x_{2s}^2 = 400a_z^2 \quad (6)$$

where $a_z$ is the final lode-length taken as constant. The relationship of $x_{2s}$ and $\Delta U_I$ is an elliptical curve. The theoretical reference value of alteration-zone thickness is obtained (Fig. 4) by substracting the lode-length $a_i$ at the corresponding instant from $x_{2s}$, and its relation to lode-thickness is shown in Fig. 5(a). For the lode with length $a_z$, its alteration-zone thickness $x_{2si} - a_i$ increases with decreasing lode-thickness $\Delta U_I$, and exhibits negative correlation. The rate of variation in lode-thickness in the central part of lode is higher than that at lode-tip. For those lodes with same thickness $\Delta U_I$, the greater the $a_z$ and $\Delta U_I$, the greater the alteration-zone thickness is, and the relationship of thickness between lode and alteration-zone displaying positive correlation (Fig. 5 (a)), therefore, is depended on two factors, the position and final length of the lode.

Using the absolute value of lode-thickness calculated from elastic constant of rock, the curves exhibiting the thickness-ratio between alteration-zone and lode are plotted in Fig. 5b, the feature of which is as follows: the curves corresponding to different lode-length manifest convergent with increasing thickness-ratio, and divergent with decreasing one. This is the result of increase in range of lode-thickness variation caused by increasing the total lode-length. The similarity of configurations between the theoretical curves in Fig. 5 (b) and the projections of practical measurement in Fig. 1 indicates that the development regularity of wallrock-alteration intensity in ore-vein is controlled by the evolution of fracture mechanics conditions in the process of crack-extension. According to the principle of alteration at the crack-tip, provided that the rate of chemical reaction of wallrock-alteration is lower than that of propagation-transfer of crack-front, the wallrock at crack-tip may transpose more quickly into the compressive field flanking the crack with its alteration zone hindered from fully developing. However, it is possible that the crack and the wallrock alteration may simultaneously propagate by the action of stress corrosion.

## 5 CONCLUSIONS

The relationship of thickness between

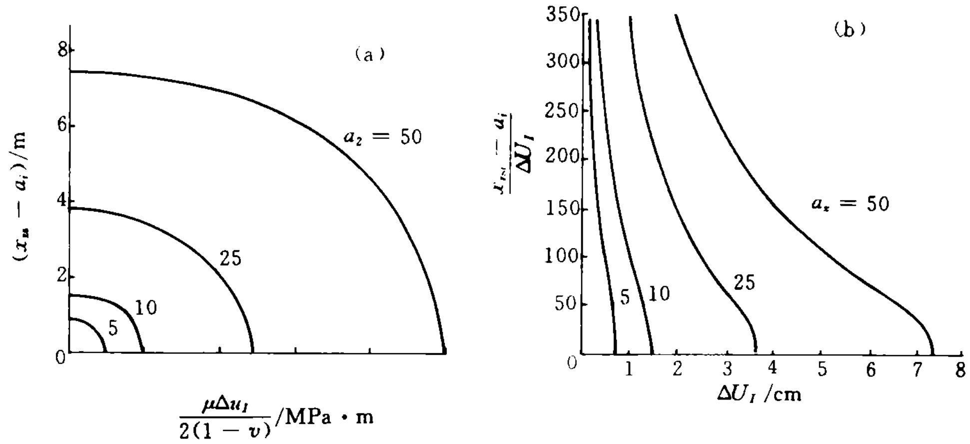


**Fig. 5 Relationship of thickness-alteration between lode and alteration-zone**

(a)—Relationship of ellliptical curve between the thickness of lode and alteration-zone;
(b)—Variation relation of the ratio between thickness of alteration-zone and lode to the lode-thickness; taking $\nu = 0.25$, $\mu = 5 \times 10^4$ MPa

wallrock alteration and lode reflects the characteristics of development intensity in wallrock alteration controlled by the conditions of fracture mechanics. Only the lode situated at crack-tip possesses the superiority to produce wallrock alteration, and the lode-extension may cause the wallrock alteration at its front tending to enhance, thus it can be decided that the relationship between the development intensity of wallrock alteration and the lode-thickness shows a regularity of negative correlation. The new mechanism of wallrock alteration just mentioned provides a new idea in deep understanding of genesis and regularity about the types of alteration and its zoning, the variation in vein composition and the enrichment of ore-forming elements, etc.

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