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On the Reactivation of the Pre-Existing Normal Fault

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Abstract

The reactivation of pre-existing faults is a common phenomenon in a basin. This paper discusses the relationship between the pre-existing faults and the newly formed Coulomb shear fractures regarding pore fluid pressures. Based on the Coulomb fracture criterion and Byerlee frictional sliding criterion, an equation relating pore pressure coefficient (λ_e), minimum dip angle (α_e) of the reactive pre-existing fault and the intersection point depth (z) between the pre-existing fault and a newly formed Coulomb shear fault in an extensional basin, is established in this paper. This equation enhanced the understanding on the reactivation of pre-existing faults and can be used to calculate paleo-pore fluid pressures. The bigger the pore fluid pressure in a pre-existing fault is, the less the minimum dip angle for a reactive pre-existing fault will be. The minimum dip angle is less in shallow area than that in deep area. This will be of significance in petroleum exploration and development.

Keywords

Coulomb Criterion, Frictional Sliding Criterion, Pre-Existing Fault, Pore Fluid Pressure, Reactivation

1. Introduction

The reactivation of pre-existing faults is a common phenomenon in a basin [1] (Twiss & Moores, 2007). Pre-existing faults may controlled the geometry and evolution of a rift [2] [3] [4] and after that, pre-existing faults may be abandoned and be cross-cut by newly formed structures [5] [6] to become sealing for oil and gas [7] [8]. In map view, pre-existing faults may reactivate where the stretching direction changes by less than 45˚ between extension events [9]. In cross sections, the minimum angle of a reactive fault and its sealing property for oil and gas has been discussed [8]. However, both the details on reactivation of pre-existing faults and the pore fluid pressures have seldom addressed [1] [10]. Based on the Coulomb fracture criterion (also called the Navier-Coulomb, Mohr-Coulomb or Coulomb-Mohr fracture criterion) [11] and the Byerlee frictional criterion [12], this paper is to discuss the controlling factors of the minimum dip angle of a pre-existing fault thus helping understand the reactivation in pre-existing faults and forecast the paleo fluid pressure in faults.

2. Methodology

Coulomb criterion or frictional sliding criterion is applicable in most of the deformation in the upper lithosphere which always is shown as:

$$\tau = \tau_o + \mu\sigma_n = \tau_0 + \tan\phi\sigma_n \tag{1}$$

where τ_o is cohesion, μ is coefficient of internal friction, ϕ is internal frictional angle and σ_n is effective normal stress [13] [14].

In terms of the principal stresses, the Coulomb criterion for normal faults can be written to be [15]

$$\sigma_1 = \rho gz(1-\lambda) \tag{2}$$

and

$$\sigma_1 - \sigma_3 = \frac{K-1}{K}\rho gz(1-\lambda) + \frac{S}{K} \tag{3}$$

with

$$S = \frac{2\tau_o \sin 2\theta_f}{1+\cos 2\theta_f}, K = \frac{1-\cos 2\theta_f}{1+\cos 2\theta_f} \tag{4}$$

and

$$2\theta_f = 90 + \phi, \mu = \tan\phi \tag{5}$$

where K is a parameter depending on the fracture angle; S is the fracture strength under uniaxial compression with zero confining pressure; θ_f is the fracture angle; ϕ is the internal friction angle and λ is pore fluid pressure coefficient, the ratio of pore pressure to overburden pressure. In a rift basin, the maximum stress is vertical and the pore fluid pressure coefficient is [16]

$$\lambda = \frac{P}{\rho gz} \tag{6}$$

where P is pore fluid pressure, ρ is density of overlying rocks, g is gravity acceleration and z is depth.

For a pre-existing fault, its cohesion is zero and the frictional sliding criterion, for the same rocks becomes to be

$$\tau = \mu\sigma_n = \tan\phi\sigma_n \tag{7}$$

where τ is critical shear stress, μ is frictional sliding coefficient equal to the internal frictional coefficient for a specific rock [17], σ_n is normal stress and ϕ is frictional angle. The frictional coefficient is 0.85 or 0.6 where the confining pressure is less than or larger than 200 MPa in Byerlee's law.

Under the stresses σ_1 and σ_3, corresponding to total stresses σ_1^t and σ_3^t, the pre-existing faults with their normal lines within the ΔOLM (Figure 1) will reactivate where a newly Coulomb shear fracture occurs. In an extensional basin with a vertical maximum principal stress, the reactive pre-existing fault with the minimum dip angle matches point L (Figure 1) and is supposed to be the line AB (Figure 2) with a pore pressure coefficient λ_e.

The normal stress on the fault AB is

$$\sigma_n = \sigma_1^t \cos\alpha_e + \sigma_3^t \sin\alpha_e - \sigma_1^t \lambda_e \tag{8}$$

with

$$\sigma_1^t = \rho g z, \sigma_3^t = \frac{1}{K}\rho g z\left(1-\lambda+K\lambda\right) - \frac{S}{K} \tag{9}$$

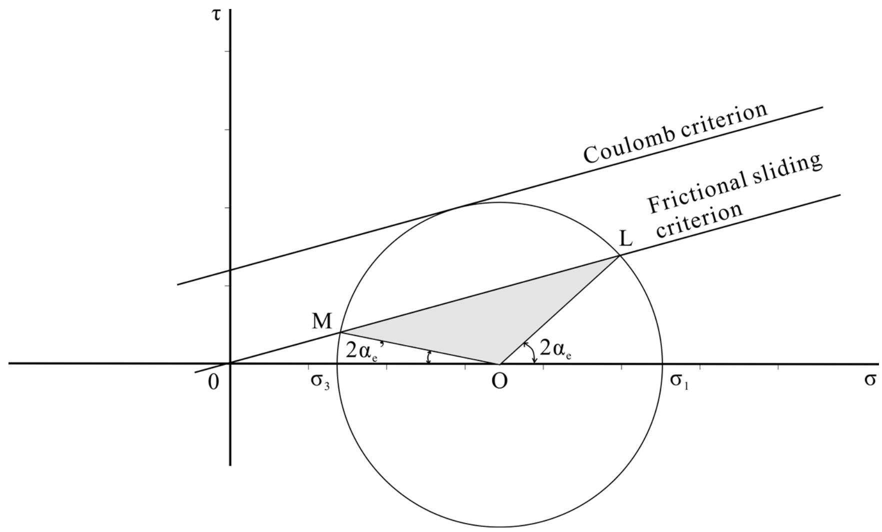

Figure 1. Coulomb fracture criterion and frictional sliding criterion for the same rock.

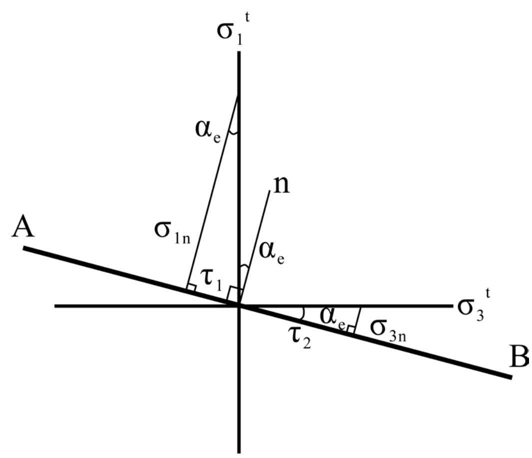

Figure 2. Stress state of a reactive fault AB with the minimum dip angle of α_e. σ_1^t is total maximum principal stress and it is vertical. σ_3^t is total minimum principal stress and it is horizontal. n is the normal line of the fault AB.

The shear stress on the pre-existing fault AB is

$$\tau = \sigma_1^t \sin\alpha_e - \sigma_3^t \cos\alpha_e \tag{10}$$

According to Equation (7), we have

$$\left(\sigma_1^t \sin\alpha_e - \sigma_3^t \cos\alpha_e\right) = \mu\left(\sigma_1^t \cos\alpha_e + \sigma_3 \sin\alpha_e^t - \sigma_1^t \lambda_e\right) \tag{11}$$

Given ρ = 2.7 g/cm^3, ϕ = 30˚, τ = 23 Mpa, g = 10 m/s^2 and λ = 0.413 (a salt water density of 1.073 g/cm^3 is assumed), in terms of the Equations (4) and (5), we get

$$S = 79.67, K = 3 \tag{12}$$

In terms of the Equations (2) and (7), we get

$$\sigma_1^t = 27z \tag{13}$$

and

$$\sigma_3^t = 16.43z - 26.56 \tag{14}$$

where the unit of σ_1^t and σ_3^t is MPa and that of z is km. The depth z is defined to be the depth of the intersection point between a pre-existing fault and a newly formed Coulomb fracture (**Figure 3**).

Substituting Equations (13) and (14) into Equation (11) and considering μ = tan 30˚ = 0.577, we get

$$\lambda_e = 2.03\cos\alpha_e - 1.14\sin\alpha_e - \frac{1.71\cos\alpha_e + 1.03\sin\alpha_e}{z} \tag{15}$$

3. Implication of the Equations

According to Equation (15) we know that there is a specific relationship between the pore fluid pressure (λ_e) and the minimum dip angle (α_e) in a reactive pre-existing fault and the intersection depth (z) between the pre-existing fault and a newly formed Coulomb shear fault. The pore pressure coefficient is rational in the range of 0 to 1 and the minimum dip angle is rational in the range of 0˚ - 60˚. For a typical rock with an inner frictional angle of 30˚, the dip angle of a normal fault, a Coulomb shear fracture with a maximum vertical stress and a minimum horizontal stress, is 60˚. As shown in **Figure 4**, the relation between λ_e and α_e is close to linear. We can get one of the three parameters like z, λ_e and α_e in terms of the Equation (15) or **Figure 4**.

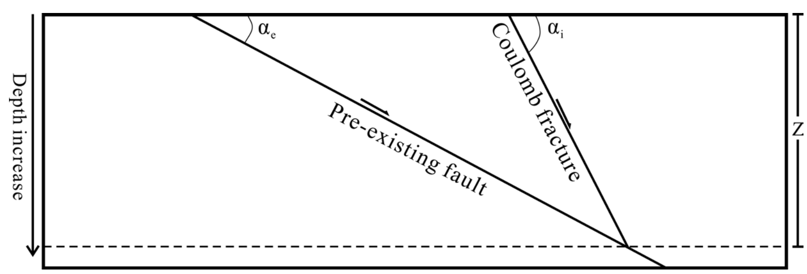

Figure 3. A reactive pre-existing fault with minimum dip angle and a newly formed Coulomb shear fracture with a dip angle α_i that is $\alpha_i = 45^\circ + \dfrac{\phi}{2}$.

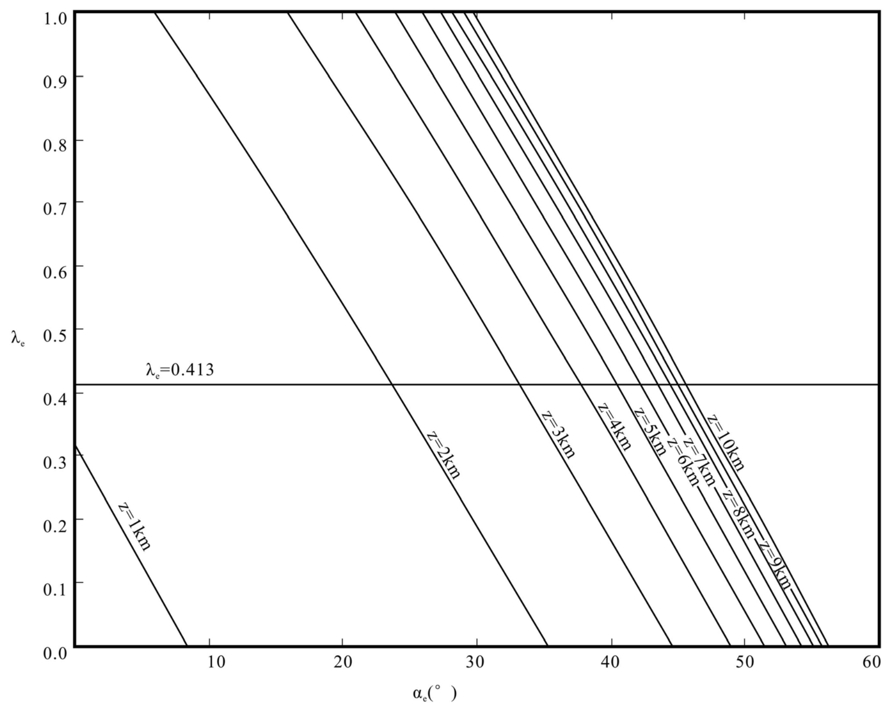

Figure 4. Coefficient of pore fluid pressure vs. minimum dip angle for pre-existing fault for various depthes.

For the cases with the same intersection depth of z, the pore fluid pressure coefficient in a reactive pre-existing fault will decrease with the increase of the minimum dip angle for the pre-existing fault (**Figure 4**). The less the minimum dip angle of a reactive pre-existing fault is, the bigger the pore fluid pressure coefficient in a reactive pre-existing fault is.

Sharing the same dip angle, the bigger the intersection depth of z is, the bigger the pore fluid pressure coefficient is. Similarly, when pore pressure coefficient keeps the same, the minimum dip angle for reactivating a pre-existing fault will increase with the increase in the intersection depth z (**Figure 4**). This can be further explained based on **Figure 5**. The maximum principal stress in vertical direction will increase with increasing depths, which mean increasing confining pressures. In turn, the differential stress needed to form a Coulomb shear fracture will increase with increasing depths or confining pressures. The minimum reactive dip angles (α_{e1}) of pre-existing faults in less confining pressure is less than those (α_{e2}) in higher confining pressure.

4. Discussion

Rock deformation in the upper lithosphere is governed by Coulomb behavior, and the brittle fracture [18] or frictional sliding [12] apply for most the deformation in the upper lithosphere [19] [20]. The occurrence of fractures in cohesion rocks is obeyed by Coulomb fracture criterion, and the subsequent movement of the two walls is obeyed by frictional sliding after the occurrence of fractures because the cohesion was missed [1]. Where there are pre-existing faults, the

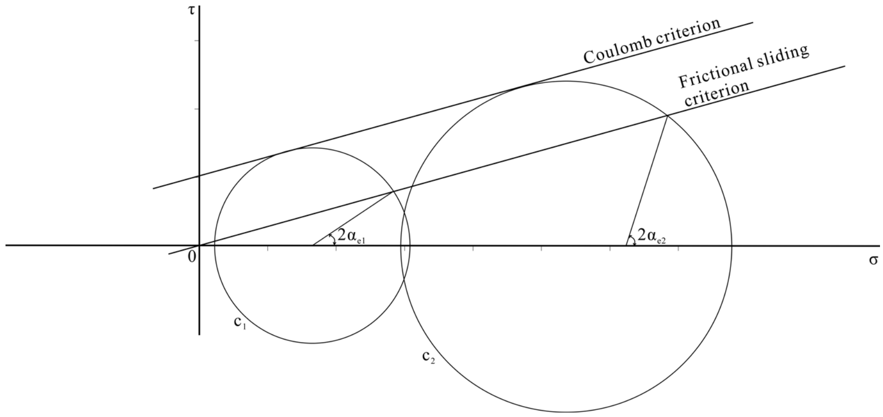

Figure 5. Coulomb shear fractures and reactive pre-existing faults with increasing confining pressure or depth in an extensional basin. α_{e1} and α_{e2} are minimum reactive dip angles of pre-existing faults in less confining pressure and higher confining pressure. $\alpha_{e1} < \alpha_{e2}$.

occurrence of new Coulomb fractures will be accompanied by reactivation of pre-existing faults to form fluid flowage paths [8] [10] [21]. However, the Coulomb fracture criterion cannot explain the normal faults with dip angles less than 45˚ in an extensional basin with a vertical maximum principal stress (σ_1). The angle relationship between the fault dip and the maximum principal stress (σ_1) is not involved in the Byerlee frictional sliding criterion. Seldom work has been addressed on the effect of pore fluid pressures [1] [10] [20] [22] [23]. Furthermore, little has been addressed on the dip change of a reactive pre-existing fault with increasing depth.

In terms of the Equation (15) and based on the analysis in section of implication of the equations, the effect of pore fluid pressures on the reactivations of pre-existing faults can be addressed. A high pore fluid pressure will decrease the minimum dip angles of reactive pre-existing faults. Paleo fluid pressure would be calculated and this will be helpful in determining fault sealing property. On the other hand, the minimum dip angles of reactive pre-existing faults will increase with the increasing depth in an extensional environment where the maximum principal stress is vertical (**Figure 5**). Both the confining pressures and differential stresses needed to form Coulomb shear faults will increase with depths. This will explain both the increasing dip angles upward the pre-existing faults and the fault branching downward the pre-existing faults.

5. Conclusion

Given certain rocks in a basin, a quantitative relationship between the pore fluid pressure (λ_e), the minimum dip angle (α_e) in a reactive pre-existing fault and the intersection depth (z) can be established. The intersection depth (z) refers to the depth of the intersection point between the pre-existing fault and a newly formed Coulomb shear fault. This relationship will help us understand both the reactivation of pre-existing faults and the pore fluid pressures in the pre-existing faults. Two improvements have been made on the reactivation of pre-existing normal faults. The first is that the pore fluid pressures affect the reactivations of pre-existing faults. A high pore fluid pressure will decrease the minimum dip angles of reactive pre-existing faults. This is of significance in petroleum exploration. The second is that the minimum dip angles of reactive pre-existing faults will increase with the increasing depth in an extensional environment. This is of significance in explaining some downward branching faults and some upward steepening faults.

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