Journal of Structural Geology, Vol. 14, No. 8/9, pp. 991 to 998, 1992
Printed in Great Britain

0191-8141/92 $05.00+0.00

The influence of depth on reactivation in normal faulting

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(*Received* 20 *September* 1991; *accepted in revised form* 2 *April* 1992)

Abstract—The study examines the influence of depth on the development of steep normal faults above a gently dipping fault which is reactivated in its deeper part and abandoned in its upper part. The isotropic and anisotropic Mohr–Coulomb–Anderson theory is used to determine the ability of any part of a fault to be reactivated by calculating the difference between the stress deviator necessary to induce reactivation and that required to induce fracturing. When linear depth-dependent properties are assumed, it appears that a new normal fault can branch off a gentle pre-existing fault only if the friction coefficient of the latter is much less than that used by Byerlee, and if the ratio (cohesion of fault/cohesion of intact rock) is non-negligible. For a 30° dip fault, the friction coefficient has to be less than 0.35 (friction angle less than 20°). Neither pore fluid pressure nor constant excess fluid pressure affects the above conditions. When the cohesion of the surrounding rocks increases with depth, steep normal faults can branch off Byerlee faults with dips as gentle as 30°. A low shear strength of the lowest part of the pre-existing fault also increases the chances of reactivation of the deeper part and abandonment of the upper part.

INTRODUCTION

THE origin of many tectonic structures may be strongly influenced by pre-existing weak zones (Bott 1959, McKenzie 1969, Dixon *et al.* 1987). It has been suggested that the gentle dips of many normal faults in an extensional tectonic environment are due to the reactivation of weak pre-existing thrusts (Anderson 1951, Sykes 1978, Bruhn *et al.* 1982, Enfield & Coward 1987). Conversely, the chaos structures described by Dechert (1967) or Wernicke & Burchfield (1982) and the interpretation of the seismic data recorded beneath the Basin and Range lands of the North American Cordillera (Potter *et al.* 1986), or beneath the North Sea (Beach *et al.* 1987), are examples of areas where the pre-existing faults have not been reactivated but are cross-cut by steeper faults.

The marginal stability state between new faulting and reactivation studied by Jaeger & Cook in 1969, has been further developed more recently by Ivins *et al.* (1990) and Ranalli & Yin (1990). Ivins *et al.* (1990) performed a three-dimensional analysis of the marginal stability state, and they non-dimensionalized all quantities having units of stress by the scale factor $1/\sigma_1$. Ranalli & Yin (1990) compared the stress and orientation conditions for reactivation in the normal, thrust and strike-slip faulting regimes.

In this paper, a two-dimensional analysis has been developed more specifically to study the effects of depth on the reactivation of a pre-existing normal fault. The ideal situation is considered where a new fault develops in a shear mode across a homogeneous medium. As tension mode could be important in the shallowest levels and could give rise to the formation of tensile joints (Petit & Barquins 1988), the present analysis is limited to levels where the effective stresses are compressional and to cases where excess fluid pressure in the fault zone does not exceed the effective mean stress in the surrounding rocks. Furthermore it is assumed that the fault plane contains the intermediate stress axis. Relaxation of this condition would introduce further complexities and oblique slip along the pre-existing fault (Gillcrist *et al.* 1987). An analysis is made of the conditions under which a pre-existing gently dipping fault may be reactivated in the brittle domain during extensional tectonic events.

An illustration of this analysis is found in kilometre-scale normal 'short-cut' faults above a gently dipping pre-existing thrust like the Outer Hebrides Fault. This structure (Fig. 1) of the northwest Scottish continental shelf has been studied from widespread exposures of the basement in close proximity to off-shore basins surveyed with a dense network of reflection profiles (Brewer & Smithe 1984, Stein & Blundell 1990). The most recent movement recorded onshore (Lailey *et al.* 1989) is a thrusting event during the Caledonian Orogeny, while the seismic profiles show that the continuation at depth of the Outer Hebrides Thrust is a plane fault that has undergone post-Caledonian extension.

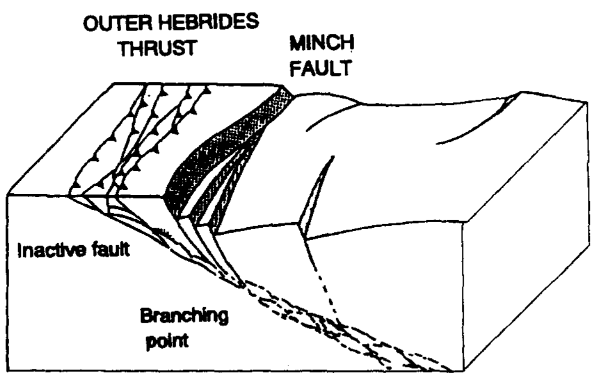

Fig. 1. An isometric sketch showing the partial reactivation of the Outer Isles Fault (Scotland) where the basement fault is reactivated by normal en échelon short-cut faults ('Minch fault') (after Stein & Blundell 1990).

THE MARGINAL STATE ANALYSIS

The competition between potential new faults and misorientated pre-existing structures forms the basis of the stability analysis (Ivins *et al.* 1990, Ranalli & Yin 1990).

Fault geometry

In the following text the three branches of the faults are referred to, respectively, as: (A) the abandoned fault; (B) the reactivated fault; and (C) the new normal fault. The branching fault pattern is defined by the following parameters (Fig. 2):

— H : depth of the branching point,

— α : angle between the vertical line and the reactivated fault. Close to the branching point, this angle is the same as the angle between the vertical line and the abandoned thrust,

— α' : angle between the vertical line and the new fault. An antithetic (in reference to the early thrust fault) new normal fault is shown in Fig. 2(a), but the following analysis applies also to a synthetic fault.

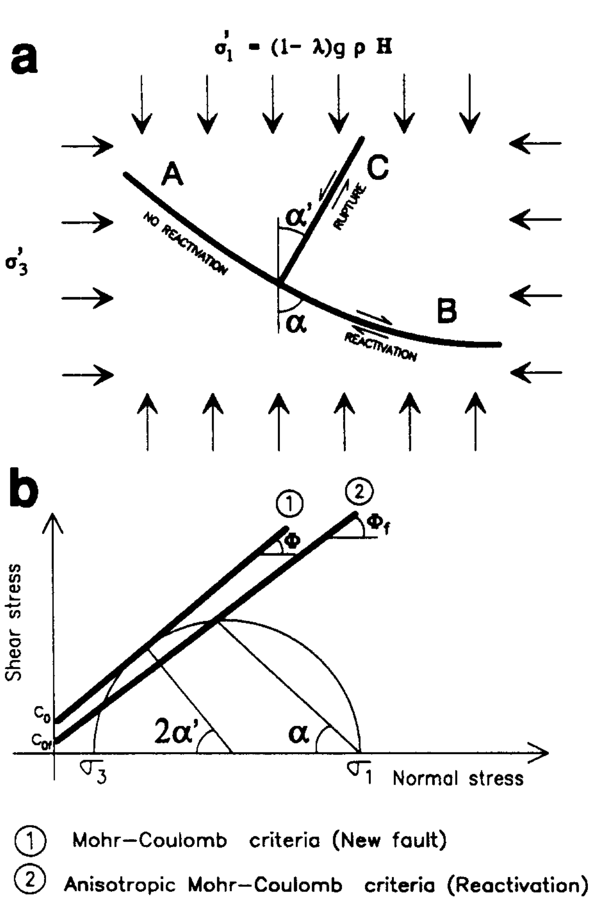

Fig. 2. (a) A sketch of the branching of a new normal fault on a previous fault and boundary conditions around the branching point. A, Abandoned thrust; B, pre-existing fault reactivated as normal fault; C, new fault; H, depth of the branching point. σ_1' and σ_3', principal components of the effective stress tensor. α and α' are, respectively, the angles between σ_1' and the pre-existing fault and the new fault (b). The Mohr diagram for the marginal stability state between reactivation and fracture propagation in the brittle domain. C_o and C_{of} are, respectively, the apparent cohesion of the surrounding rock and the fault cohesion. ϕ and ϕ_f are, respectively, the internal friction angle and the fault friction angle.

State of stress around the branching point. The analysis presented here applies to the small volume of rocks surrounding the branching point at the time of the propagation of the new normal fault. In this small volume, a constant stress tensor is assumed, and in accordance with the Anderson theory (Anderson 1951), a vertical maximum principal direction for the stress tensor is also assumed (Fig. 2a). The value of the effective vertical stress applied on a horizontal surface is:

$$\sigma_1' = (1 - \lambda)\Sigma \mathbf{g} \cdot \rho_i \cdot z_i, \tag{1}$$

where λ, $\mathbf{g}$, ρ_i and z_i are, respectively, the pore fluid ratio (pore fluid pressure/overburden pressure) defined by Hubbert & Rubey (1959), the gravitational acceleration, the density and the thickness of the different lithologies.

The isotropic Mohr–Coulomb criterion. The propagation of the new normal fault implies that the stress tensor reaches the strength of the 'intact' (isotropic) rocks. Its value is predicted by the Mohr–Coulomb criterion:

$$\tau = C_o + \mu\sigma_n, \tag{2}$$

where τ, σ_n, C_o, μ are, respectively, the shear stress, normal stress, apparent cohesion and coefficient of internal friction ($\tan^{-1}\mu$ is the angle of internal friction Φ). The Mohr–Coulomb criterion predicts (Jaeger & Cook 1969) the following value for the angle α' between the new fault and the maximum principal stress direction:

$$\alpha' = \frac{90 - \Phi}{2} \tag{3}$$

and the following relation between the effective maximum stress component and the deviatoric component at the time of fracture development:

$$\frac{\sigma_1 - \sigma_3}{2} = \frac{C_o \cos\Phi + \sin\Phi\sigma_1'}{1 + \sin\Phi}. \tag{4}$$

The Mohr–Coulomb criterion is appropriate for shear fractures only if the effective stress is compressional (Jaeger & Cook 1969). Consequently the following study is restricted to depths where ($\sigma_3' > 0$):

$$H > \frac{2C_o \cos\Phi}{\rho\mathbf{g}(1 - \lambda)(1 - \sin\Phi)}. \tag{5}$$

The anisotropic Mohr–Coulomb criterion. The anisotropic Mohr–Coulomb criterion predicts the conditions that lead to the reactivation of a pre-existing fault (Jaeger & Cook 1969):

$$\tau = C_{of} + \tan\Phi_f\sigma_n, \tag{6}$$

where C_{of} and Φ_f are, respectively, the cohesion and the angle of friction on the reactivated fault plane.

If the pre-existing fault has an extra amount of fluid pressure (δP) above that of the surrounding rocks (P), then the effective normal stress applied on the pre-existing fault surface is (Ivins *et al.* 1990):

$$\sigma_{nf}' = \sigma_{nf} - P - \delta P. \tag{7}$$

For any pre-existing fracture, at an angle α from the maximum principal stress direction, the deviatoric component that delimits the domains of reactivation and non-reactivation is calculated by (adapted from Jaeger 1959, equation 7):

$$\frac{\sigma_1 - \sigma_3}{2} = \frac{C_{of} \cos \Phi_f + \sin \Phi_f(\sigma_1' - \delta P)}{\sin(2\alpha + \Phi_f) + \sin \Phi_f}. \quad (8)$$

The anisotropic Mohr–Coulomb criterion is appropriate only if the compressive effective stress around the fracture is greater than the excess fluid pressure along the pre-existing fault. Otherwise, tensile mode propagation gives rise to tensile joints (Petit & Barquins 1988).

Given a stress state, two pre-existing faults are at the marginal stability state for reactivation. The fault selected for this study is more gentle than the potential new fault.

Transition between brittle reactivation and fracturing

The marginal stability state of a pre-existing planar fault is studied by examining the ratio (Ranalli & Yin 1990) or the difference between the deviatoric stress necessary to induce reactivation (equation 8) and that necessary to induce fracturing (equation 4). The difference is expressed as P_f, a function depending on six parameters:

$$P_f = A(C_{of}, C_o, \delta P, \Phi, \Phi_f, \alpha) + B(\phi, \phi_f, \alpha)\,\sigma_1' \quad (9)$$

with

$$A = \frac{\cos \Phi_f}{\sin(2\alpha + \Phi_f) + \sin \Phi_f} C_{of} - \frac{\cos \Phi}{1 + \sin \Phi} C_o - \frac{\sin \Phi_f}{\sin(2\alpha + \Phi_f) + \sin \Phi_f} \delta P$$

$$B = \frac{\sin \Phi_f}{\sin(2\alpha + \Phi_f) + \sin \Phi_f} - \frac{\sin \Phi}{1 + \sin \Phi}.$$

The function P_f, referred to hereafter as the function of fracturing ability, can be used to examine the conditions of reactivation of any portion of a pre-existing fault (Fig. 3a). It cannot be reactivated if its fracturing ability P_f is positive. In this case, when σ_1 reaches the strength of the rocks, there is failure and a new fault appears. It can be reactivated if its fracturing ability P_f is negative. Its reactivation prevents σ_1 reaching the strength of the surrounding rocks, and there is no new fracturing.

CONDITIONS FOR REACTIVATION AT DEPTH AND NEW FAULTING AT SHALLOW LEVELS

Reactivation of a plane fault in a homogeneous medium

Beneath the depth boundary (equation 5) where the effective stress is compressional, the only depth dependent factor in the fracturing ability function is σ_1'. If

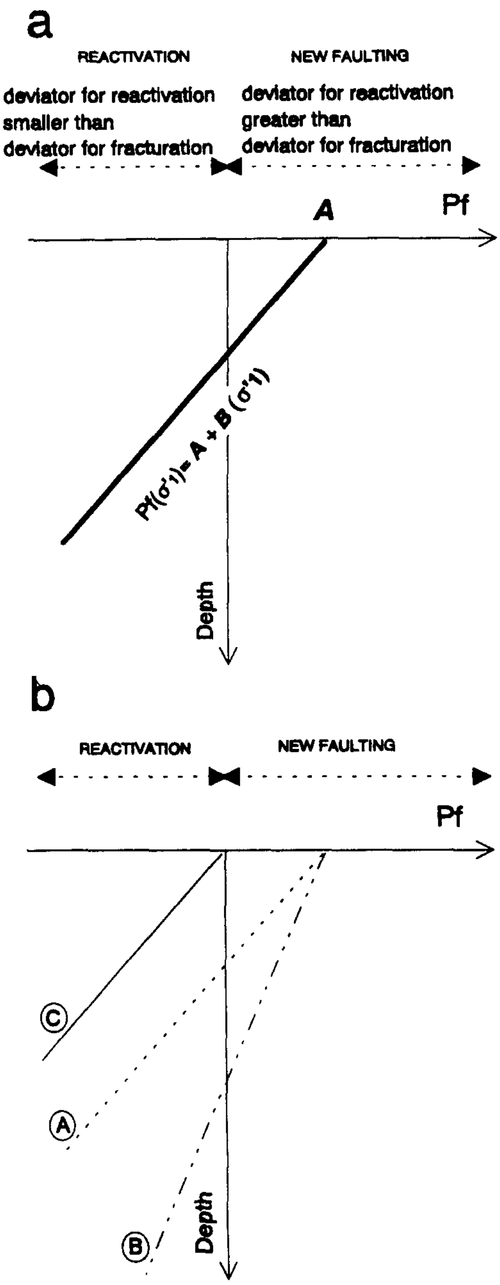

Fig. 3. The evolution over depth of the reactivation ability function (P_f). (a) New fault domain is located at shallower levels than the reactivation domain if $A > 0$ and $B < 0$ (see text for the discussion). (b) The effect of fluids: line Ⓐ no fluids ($\lambda = 0$ and $\delta P = 0$); line Ⓑ the effect of pore fluid pressure ($\lambda = 0.5$ and $\delta P = 0$); line Ⓒ the effect of excess fluid pressure ($\lambda = 0.5$, and δP determined from equation 10). The left-lateral translation induced by this excess fluid pressure, and vertical dilatation induced by any pore fluid pressure do not depend on the value of the other four parameters.

reactivation is harder than new faulting at levels shallower than the transition level, i.e. if the depth gradient of the fracturing ability function B is negative and A is positive (Fig. 3a), then the upper part of the pre-existing fault could be abandoned while the lower part remained active. Conversely, the lower part of the pre-existing fault would be abandoned if reactivation occurred more easily than new faulting at levels shallower than the transition level; i.e. if B is positive, and A is negative.

Figure 4(a) shows the domain of the solutions where $B > 0$. To simplify graphical presentation, $\delta\phi = \phi - \phi_f$

has been used. B is negative in the space to the left of the grid surface representing the solution of $B = 0$. For faults with a dip more gentle than 30° ($\alpha > 60°$), B is negative only if the friction angle on the fault is less than 23° and the difference between the internal friction angle and the friction angle along the fault is more than 20°.

In cases where $\delta P = 0$, Figs. 4(b) & (c) emphasize the influence of the cohesion ratio C_{of}/C_o and show the solutions of $A > 0$ and $B > 0$, respectively, for $\phi_f = 40°$ and $\phi_f = 1°$. These values can be considered as the two extreme cases, respectively, for strong fault zones and weak fault zones. The grid surface delimits the sign domains of A, and A is positive in the space above the grid surface. The vertical hatched surface delimits the sign domains of B. Figure 4(b) shows that $B < 0$ and $A > 0$ only for steep faults and $C_{of}/C_o > 0.5$. The extreme case of $\phi_f = 1°$ must also be studied to determine the effect of increasing ϕ_f (Fig. 4c). The domain of solutions where $A > 0$ and $B < 0$ becomes larger. This situation could be inferred in the case of 'fault-normal' compression (Zoback *et al.* 1987), where the fault shows activity even though supporting a very small shear stress.

The effects of pore fluid and excess fluid pressures

Pore fluid pressure P in the intact rocks has considerable influence on the depth gradient B. An increase of pore fluid ratio λ would make the transition level between new faulting and reactivation deeper (Fig. 3, curve Ⓑ).

Excess fluid pressure δP in the fault zone has no effect on the depth gradient B, but decreases the value of A in the fracturing ability function. Any excess fluid pressure would make the transition level shallower when the reactivation domain is located beneath it, and would allow reactivation to reach the surface if (Fig. 3, curve Ⓒ):

$$\delta P > \frac{C_{of}}{\tan \Phi_f} - \frac{\cos \Phi \left((\sin (2\alpha + \Phi_f) + \sin \Phi_f\right)}{(1 + \sin \Phi) \sin\Phi_f} C_o \cdot \quad (10)$$

Therefore, neither the pore fluid nor the excess fluid pressure would change the relative position of the fracturing and reactivation domains.

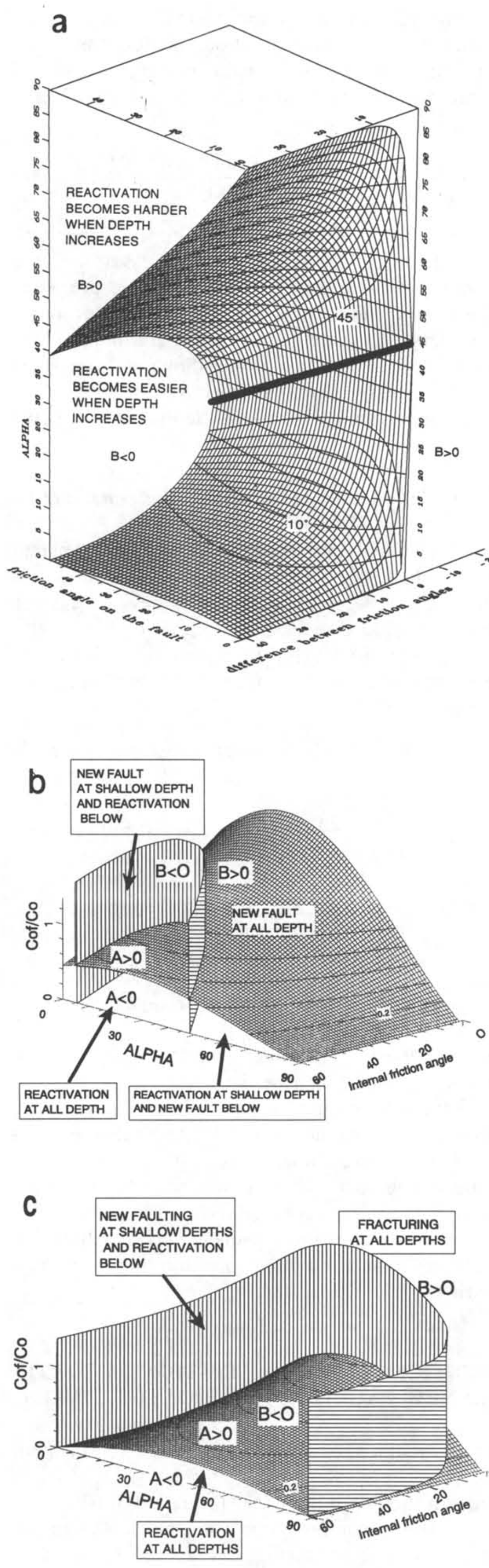

Fig. 4. Influence of the parameters on the depth of the reactivated domain and the fracturing domain (see text for discussion). (a) The influence of the difference between the internal friction angle of the intact rocks and the friction angle on the fault. Reactivation at deeper levels than fracturing requires $B < 0$. ($B < 0$ in the half-space located to the left of the grid surface depicting a half funnel.) (b) The influence of the cohesion ratio C_{of}/C_o ($\phi_f = 40°$, $\delta P = 0$). $A > 0$ above the grid surface, $B > 0$ to the right of the vertical wall. Four domains are defined: (1) reaction at all levels if $A < 0$ and $B < 0$; (2) new fault at all levels if $A > 0$ and $B > 0$; (3) the reactivation domain is deeper than the fracturing domain if $A > 0$ and $B < 0$; and (4) reactivation is predicted at shallower levels than fracturing, if $A < 0$ and $B > 0$. (c) The influence of the cohesion ratio C_{of}/C_o ($\phi_f = 1°$, $\delta P = 0$).

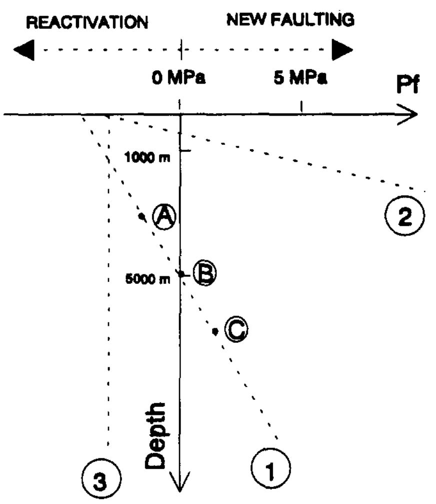

Fig. 5. Depth domains of reactivation for a plane fault according to Byerlee's law in a homogeneous medium. ①, ② and ③ are the fracturing ability functions for the three sets of parameters of Table 1. Ⓐ, Ⓑ and Ⓒ represent three states of stress at three different levels for the first set of parameters of Table 1. In Ⓐ, reactivation is favoured, in Ⓒ new faulting is favoured, and Ⓑ is the marginal stability state.

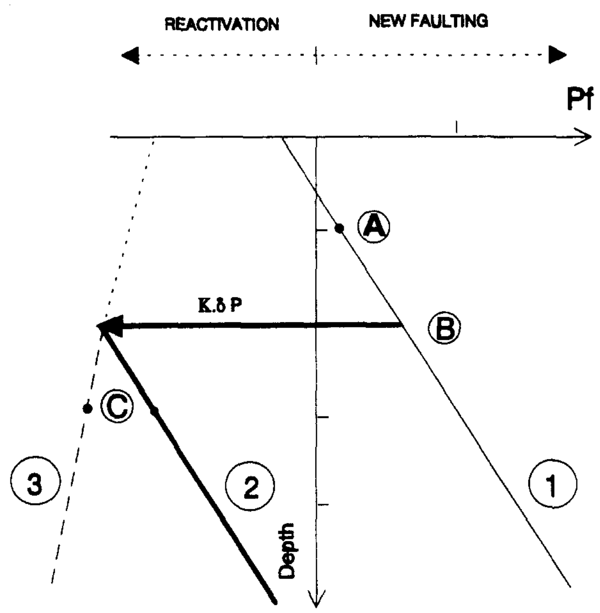

Fig. 6. Stress domains of reactivation and non-reactivation for a plane fault with a weakness zone located in the deeper part of the fault. A sketch of three fracturing ability functions: ① no weakness; ② excess fluid pressure at depth; ③ decrease of Φ_f at depth. Ⓐ, Ⓑ and Ⓒ represent three states of stress at three different depths. In Ⓐ new faulting is favoured, in Ⓒ reactivation is favoured, and Ⓑ is the marginal stability state.

Cases where a thrust is reactivated at depth but abandoned in its upper part

If material parameters are within a range of reasonable values, the above analysis shows that solutions where the reactivation domain is located at deeper levels than the fracturing domain are rather difficult to envisage. For example, if the values of the parameters proposed by Byerlee (1978) are used ($\Phi_f = 40°$ and $C_{of} = 0$), the above analysis predicts that reactivation becomes easier when depth increases ($B < 0$) only if the pre-existing structure has a dip ranging between 43° ($\alpha <$ 47°) and 65° (dip of the potential new formal fault from equation 4). In these conditions, the pre-existing fault is reactivated at all levels since ($C_{of} = 0$) implies $A < 0$.

Byerlee's values may therefore be disregarded in this case. It would seem that Byerlee's law cannot be considered as a paradigm for the properties of faults in the brittle domain (Hickman 1991, Rutter & Brodie 1991), and any example of a new normal fault that branches on a thrust which is partly abandoned suggests two possibilities.

Table 1. Parameters for fracturing ability; see Fig. 5

Curve	①	②	③
Parameters			
ϕ_f	40°	40°	40°
ϕ	37°	45°	45°
α	38°	60°	38°
α'	26°	22°	22°
$\rho g(1-\lambda)$	25 MPa km^{-1}	25 MPa km^{-1}	25 MPa km^{-1}
C_o	8 MPa	8 MPa	8 MPa
C_{of}	0 MPa	0 MPa	0 MPa
δP	0 MPa	0 MPa	0 MPa
P_f evolution			
A	−4 MPa	−3 MPa	−3 MPa
$\delta P_f/\delta z$	0.8 MPa km^{-1}	6 MPa km^{-1}	0 MPa

(1) The ratio (cohesion of fault/cohesion of intact rocks) is non-negligible and leads to the abandonment of the upper part of the pre-existing fault, while the cohesion C_o is small and allows fracturing in shear mode beneath a shallow domain of tensile fracturing.

(2) The linear depth-dependent properties of the rocks and faults have to be disregarded. In the following section, several cases where mechanical properties change with depth are examined.

SOME POSSIBLE ORIGINS OF REACTIVATION AT DEPTH AND NEW FAULTING AT SHALLOW LEVELS

Weakness along the fault zone below a given depth

The above analysis has been developed for a homogeneous medium. If the mechanical properties are depth-dependent, then the situation may be different. It has been observed that hydrothermal alteration of silicate bonds (Bruhn *et al.* 1982) or the presence of specific minerals such as montmorillonite (Byerlee 1978) or anhydrite (Muller & Briegel 1980) along a pre-existing fracture decreases its strength and increases the likelihood of its reactivation. When this weakness is located in the deeper part of the fault (Fig. 6, state of stress Ⓒ), its ability to be reactivated changes abruptly. In this case, the deeper part of the pre-existing fault may be reactivated, while the upper part would not be, and a new normal fault would branch from the top of the weakness (Fig. 6, curve ③).

Excess fluid pressure located below a given depth

Excess fluid pressure in the fault zone decreases its apparent strength (Hubbert & Rubey 1959, Sibson 1981, 1985, for example). When this excess fluid pressure is located below a given depth, this also results in an apparent weakness located at depth, and increases the likelihood of a reactivation at depth (Fig. 6, curve ②).

Increase in cohesion of the surrounding rocks

It is known, mostly qualitatively, that cohesion varies with lithology and porosity, and some data (Hoshino *et al.* 1972, Karig 1986, Jones & Preston 1987) suggest that cohesion could increase exponentially when porosity decreases. As sediment compaction commonly induces an exponential decrease in porosity with depth (Athy

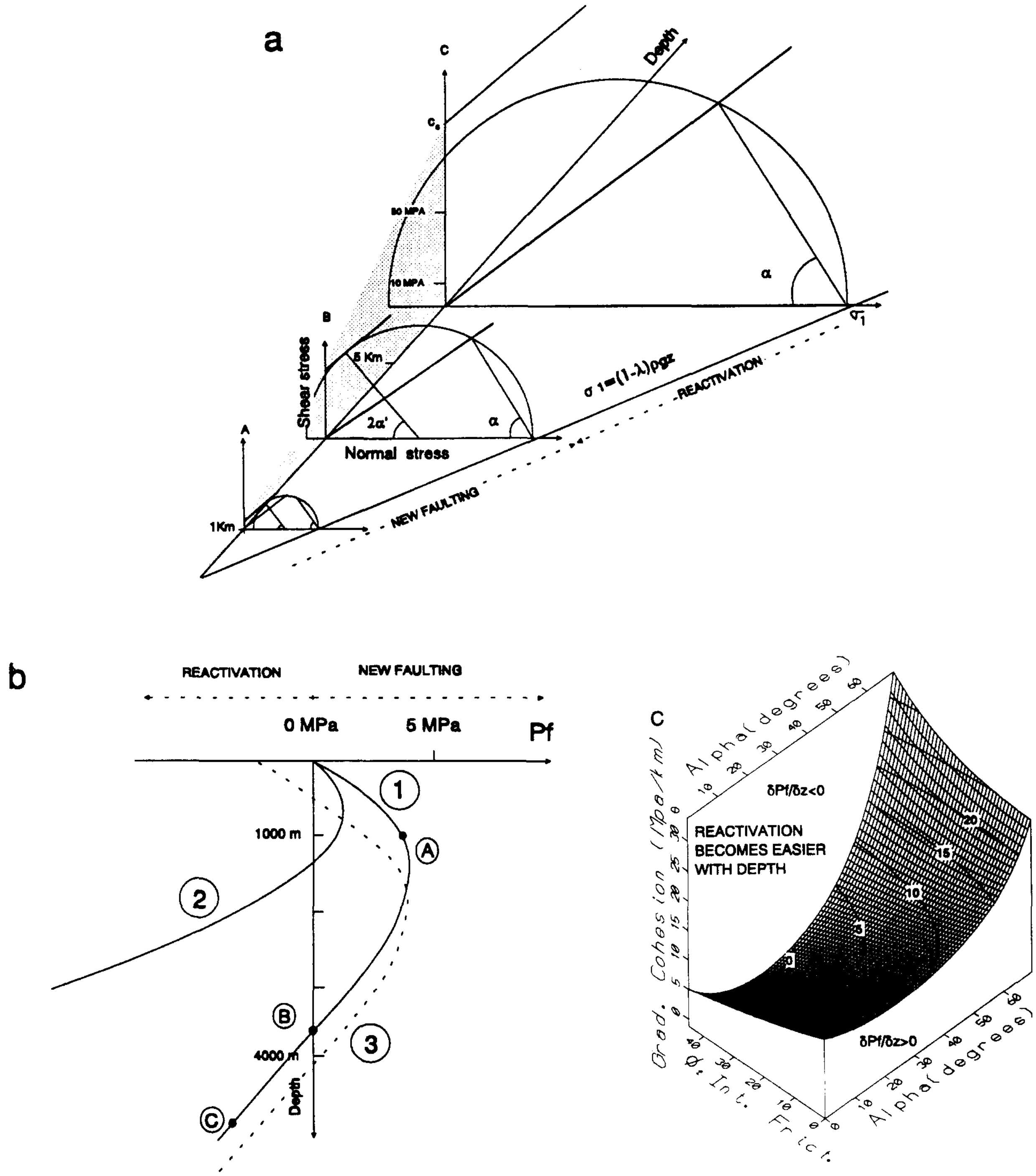

Fig. 7. Stress domains of reactivation and non-reactivation for an increase in cohesion with depth. (a) Mohr diagrams. A, B and C represent three states of stress at three different depths for an increase in cohesion of the intact rocks (shown by the shaded area) and the following set of parameters: $\varphi_f = 40°$, $C_{of} = 0$, $\alpha = 60°$, $\Phi = 37°$, $\lambda = 0$, $\delta P = 0$. (b) The fracturing ability function; curve ①, same paramaters as (a); curve ②, same parameters except a pore fluid ratio $\lambda = 0.4$; curve ③, same parameters except $C_o\ (0) = 5$ MPa. (c) The influence of the parameters on the evolution of reactivation with depth. Reactivation at deeper levels than fracturing requires $\delta P_f/\delta z < 0$ (see text for discussion); this domain is located in the half-space above the grid surfaces, solution of equation (12) for $\varphi_f = 40°$, and $\lambda = 0$.

1930), the increase of cohesion with depth is probably an important feature in the evolution of sedimentary basins (Zaho *et al.* 1986). When it is assumed that the only depth-dependent parameter is the cohesion C_0, the tangent of the P_f function can be expressed by:

$$\frac{\delta P_f}{\delta z} = g\rho(1-\lambda)B - \frac{\cos\phi}{1+\sin\Phi}\frac{\delta C_o}{\delta z}. \quad (11)$$

Increasing cohesion of the surrounding rocks at depth may increase the chances of the reactivation of gently dipping pre-existing fault planes when the depth gradient of the fracturing ability function is negative, and $\delta P_f/\delta z < 0$ when:

$$\frac{\delta C_o}{\delta z} > \frac{(1+\sin\Phi)\, g\rho(1-\lambda)B}{\cos\phi}. \quad (12)$$

Figure 7(c) gives solutions of this inequality. A cohesion gradient $\delta C_o/\delta z$ of 5–20 MPa km^{-1} has been suggested by Zaho *et al.* (1986) and can be inferred for the first few kilometres of a sedimentary basin. Greater values seem unrealistic, thus excluding, in Fig 7(c), reactivation of faults with a less than 30° dip. For faults with dips ranging between 60° and 30°, a slightly convex depth evolution of cohesion ($\delta^2 C_o/\delta_z^2$) would allow reactivation in the deepest domain (Fig 7a, state of stress C) below a fracturing domain (Fig. 7a, state of stress A), as this evolution would imply that P_f is positive in the upper part where the cohesion gradient is too small (Fig. 7b, point Ⓐ) and that it decreases in the deeper domain (Fig. 7b, point Ⓒ) until reaching a negative value.

If increasing cohesion in the deep part of sedimentary basins increases the chances of the reactivation of faults with dip as gentle as 30° and values as high as those proposed by Byerlee, this situation should obviously not exist in the basement.

CONCLUSION

Beneath the shallowest domain of the tensile fracturing mode, the linear Mohr–Coulomb–Anderson criterion predicts extensional reactivation of a planar fault at deep levels and fracturing at shallower levels, when the difference between the internal friction angle of the intact rocks and the friction angle along the fault exceeds 20°, the ratio (cohesion of fault/cohesion of intact rocks) is non-negligible, and excess fluid pressure along the fault is limited. If the cohesion of the fault is negligible and friction angle along the fault is larger than 23°, reactivation would only involve the upper part of a fault. A greater pore fluid pressure ratio would deepen the transition between new faulting and reactivation but would not change the location of the reactivation domain with respect to the new fault domain. Nonetheless, if the material is heterogeneous and shows a change in mechanical properties with depth, the chances of the propagation of new normal faults above a pre-existing fault may be increased. An increase with depth of the cohesion of the intact rocks allows the propagation of normal faults above a reactivated Byerlee fault which may have a dip as gentle as 30°. If a weakness zone or excess fluid pressure along the pre-existing fault is located at deeper levels, then a new fault would develop from the upper part of this heterogeneity.

When the mechanical properties of a gentle pre-existing fault allow its reactivation at levels deeper than the transition level, its progressive exhumation would result in new steeper faults cutting across it. In an area which has been progressively buried by sedimentation, these relationships would not be found. As normal fault systems are most frequently buried in basins beneath sediments, it is tempting to use the field observations made in extensional uplifted areas like the Basin and Range lands (Wernicke & Burchfield 1982) to define rules concerning normal faulting in the upper crust. Earthquakes and seismic profile analysis (Jackson & White 1988) suggest that some rules apply whatever the geodynamic context. Nonetheless, the present study, by outlining the influence of depth on the extent of the respective areas of fault reactivation and new faulting, suggests that the cross-cutting relationships between normal faults may be different in an eroded area from those in a subsiding area.

Acknowledgements—We wish to thank B. Célérier, G. Ranalli and J.-P. Petit for very constructive criticisms, which substantially improved the scientific aspect of the manuscript. J. P. Gratier and G. Mascle made helpful suggestions about an earlier version of this work. Acknowledgement is made to Elf Petroland b.v. for providing seismic data which partly form the basis of this research.

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