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Stable continental region earthquakes due to pressure - weakening of existing faults

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ABSTRACT
Stress conditions for the reactivation of existing thrust faults to rupture have been analytically investigated. The results indicate that the steeply dipping faults at Latur ($\theta r = 45^o$) and at Bhuj ($\theta r = 46^o$) and high angle reverse fault at Jabalpur ($\theta r = 67^o$) cannot be reactivated to rupture due to tectonic stress (σ_1) accumulation alone. Further, the results show that the steeply dipping thrust faults at Latur and Bhuj and the high angle rupture fault at Jabalpur can be reactivated to rupture by pressure-weakening due to near- lithostatic fluid pressures and Supra-lithostatic fluid pressures respectively caused by the fault valve behaviour. We conclude that the deadliest Latur earthquake of 1993, the devastating Bhuj earthquake of 2001 and the Jabalpur earthquake of 1997 were caused due to pressure-weakening of thrust faults due to near-lithostatic fluid pressures and supra lithostatic fluid pressures respectively, caused by fault valve mechanism because of which deposition of valuable ores in the deeper parts of these faults might be taking place during each earthquake cycle.

INTRODUCTION

Recently large earthquakes namely the Latur earthquake of 1993, Jabalpur earthquake of 1997 and the devastating Bhuj earthquake of 2001 occurred in the stable continental region. Fault plane solutions of these earthquakes indicated that they were caused due to rupturing of thrust faults dipping at $\theta_r = 45^0$ (Seeber et al. 1996), 67^0 (Purnachandra Rao et al. 2002) and 45^0 (Mandal et al. 2003) respectively. Can such steeply dipping thrust faults be reactivated to rupture in dry crust without the involvement of fluid pressure in the fault zone? Is it essential that supra-hydrostatic or even supra-lithostatic fluid pressures are required to reactivate such steeply dipping thrust faults in a stable continental region?

REACTIVATION OF DRY THRUST FAULTS DUE TO TECTONIC STRESS ACCUMULATION ALONE

The standard two dimensional equations for shear stress (τ) and normal stress (σ_n) acting on a plane lying at an angle(θ_r) to the major principal stress (σ_1), shown in Fig.1, are given as below:

$$\tau = 0.5 (\sigma_1 - \sigma_3) \text{ Sin } 2\theta_r \qquad (1)$$

$$\sigma_n = 0.5[(\sigma_1 + \sigma_3) - (\sigma_1 - \sigma_3) \text{ Cos}2\theta_r] \qquad (2)$$

where σ_3 is the least principal stress. In a thrust faulting compressional stress regime

$\sigma_3 = \sigma_V$, where σ_V is the vertical stress due to gravitational load of overlying rock (overburden pressure) :

σ_1 = Major horizontal compressive stress

θ_r = Dip of the thrust fault

Hence, in case of a thrust fault,

$$\tau = 0.5 (\sigma_1 - \sigma_V) \text{ Sin } 2\theta r \qquad (3)$$

$$\sigma_n = 0.5[(\sigma_1 + \sigma_V) - (\sigma_1 - \sigma_V) \text{ Cos}2\theta_r] \qquad (4)$$

As σ_V remains constant through loading cycles of an earthquake, Eqs. (3) and (4) reveal that τ and σ_n acting on a thrust fault vary as a function of σ_1 and θ_r only.

Frictional strength (τ_f) of an existing fault is given by the Coloumb criterion:

$$\tau_f = C + \mu \sigma_n \qquad (5)$$

where C is the cohesive or cementation strength of the existing fault and μ is the coefficient of frictional sliding. Combining equation (4) with equation (5) and from equation (3) Gowd (2003) has shown that the frictional strength of the fault as well as shear stress acting on the fault increase by $\Delta\tau_f$ and $\Delta\tau$ respectively when σ_1 increases by $\Delta\sigma_1$, as shown below.

$$\Delta\tau_f = 0.5 \mu (\Delta\sigma_1 - \Delta\sigma_1 \cos 2\theta_r \qquad (6)$$

$$\Delta\tau \;\; = 0.5 - \Delta\sigma_1 \sin 2\theta_r \qquad (7)$$

Frictional instability on a thrust fault can occur if $\Delta\tau$ increases faster than $\Delta\tau_f$ during pre-seismic period. In other words, frinctional instability on a thrust fault cannot occur if $\Delta\tau < \Delta\tau_f$. Since $\Delta\tau$ and $\Delta\tau_f$ are a function of θ_r , they will increase at equal rate due to tectonic stress accumulation ie. increase in σ_1 when a thrust fault dips at a specific angle θ_l only. We can find θ_l by differentiating equation (6) and (7) with respect to θ_r and by equating them ie.

$$\frac{d\,\Delta\tau_f}{d\,\theta_r} = \frac{d\Delta\tau}{d\theta_r} \qquad (8)$$

By solving equation (8), we find that

$$\theta_l = \;\; 2\theta^\star = \tan^{-1} 1/\mu \qquad (9)$$

$$\theta_l = 53^o \;\; \text{for} \;\; \mu = 0.75$$

This shows that accumulation of shear stress ($\Delta\tau$) on a thrust fault and increase in its shear strength ($\Delta\tau_f$) in response to increase ($\Delta\sigma_1$) in the maximum horizontal compressive tectonic stress (σ_1) will be equal if the dip of a thrust fault is 53^o. It is obvious that the equal rate of increase of τ and τ_f i.e. $\Delta\tau_f$ / $\Delta\sigma_1 = \Delta\tau/\Delta\sigma_1$ during pre-seismic period cannot lead to frictional instability of thrust faults which dip at 53^0 since τ_f is always higher than τ during the pre-seismic period. This shows that thrust faults dipping at $\theta_r{}^3\ \theta_l = 53^0$ cannot be reactivated to rupture in dry crust and they remain locked up even if σ_1 increases to any level for the simple reason that $\frac{\Delta\tau}{\Delta\sigma_1} \leq \frac{\Delta\tau_f}{\Delta\sigma_1}$ in the case of such high angle reverse faults. Hence we conclude that the high angle reverse fault at Jabalpur ($\theta_r = 67^0$) remains locked-up in dry crust and it can never be reactivated to rupture in dry crust due to tectonic stress accumulation alone.

However reactivation of thrust faults in dry crust can be possible due to increasing tectonic stress (σ_1) alone if $\frac{\Delta\tau}{\Delta\sigma_1}$ is higher than $\frac{\Delta\tau_f}{\Delta\sigma_1}$, say at least 1.25 times. This condition is satisfied when $\theta_r = \theta_s \approx 47^0$, for $\mu = 0.75$. This shows that thrust faults dipping at 47^0 (θ_s) or less can be reactivated to rupture in dry crust due to increasing tectonic stress alone, if other conditions, if any, are satisfied. Sibson (1985) and Gowd, Sri Rama Rao & Chary (1996) derived a criterion for frictional reactivation of a cohesionless fault in terms of $R = \sigma_1/\sigma_3$ i.e. the ratio of maximum to minimum principal stress and found that the most favourable (optimal) orientation $\theta^\star$ for fault reactivation is given by $\theta^\star = 0.5 \tan^{-1} 1/\mu$, when R has a minimum positive value of 4.0 and $\theta^\star$ is about 27^0 for $\mu = 0.75$ (Sibson 1985) and pore fluid pressure requirement is minimum for $\theta^\star$ (Gowd, Sri Rama Rao & Chary1996). Sibson (1985) also showed that the favourably oriented thrust faults (dip $\theta_r = 10^0 - 44^0$) can be reactivated at R ranging from 4.0 to 6.0. In a stable continental region, where strain accumulation rate is extremely low, it is expected that attaining such high stress ratios of 4 to 6 in the Indian shield is a remote possibility. In view of this, we conclude that the thrust faults at Latur ($\theta_r = 45^0$) and Bhuj ($\theta_r = 46^0$) could not have been reactivated to rupture in dry crust due to tectonic stress accumulation alone even though these faults are favouably oriented with σ_1 for facilitating $\Delta\tau$ to be 1.25 times $\Delta\tau_f$.

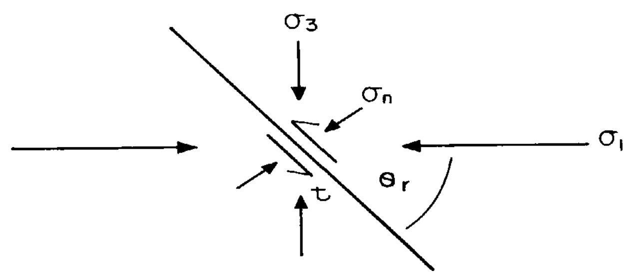

Figure 1. Normal stress (σ_n) and Shear stress (τ) affecting the stability of a fault plane lying at angle (θ_r) to the maximum principal compressive stress (σ_1); σ_3 is the least principal stress

PRESSURE-WEAKENING OF STEEPLY DIPPING THRUST FAULTS BY FAULT–VALVE MECHANISM

Gowd, Sri Rama Rao & Chary (1996) showed that thrust faults dipping at 45^0 can be reactivated to rupture when fluid pressure within the fault zone becomes near-lithostatic and high angle thrust faults dipping at $>50^0$ can rupture at supra-lithostatic fluid pressure only. This shows that high angle thrusts can rupture due to pressure-weakening of faults only and not due to tectonic stress accumulation. According to Sibson (1990) high angle reverse faults are reactivated to rupture by a mechanism termed by him as fault – valve behavior.

It is well understood that the seismogenic regime occupies the upper continental crust and is the zone of unstable frictional sliding. Larger shocks (M >5.5), according to Sibson (1990) tend to nucleate at the bottom of this seismogenic zone. The base of the seismogenic zone marks the gradual transition from unstable frictional faulting to quasi-plastic aseismic shearing. Above the base, shear resistance is pressure dependent and increases with depth and below the base, shear resistance is temperature dependant and decreases with depth. It is therefore inferred that the peak shear resistance occurs near the base of the seismogenic zone and as a result larger shocks tend to nucleate at the base of the seismogenic zone.

Permeability barrier develops at the base of the seismogenic zone due to hydrothermal cementation and sealing of the base (Sibson 1990) Suprahydrostatic pressures develop beneath the barrier from a variety of causes including progressive metamorphic dehydration enhanced by any accompanying plutonism. Permeability barrier is breached, when the frictional strength condition is satisfied through the accumulation of fluid pressure and or shear stress within the over pressured zone. As a result, fluids are discharged along the fault from the over-pressured zone until the fault reseals. The sharp drops in fluid pressures accompanying discharge is responsible, according to Sibson (1990), for much hydrothermal deposition along the deeper portions of the crustal fault zones. This is how fault-valve behaviour operates and causes rupture of high angle thrust faults and plays an important role in the development of much fault-hosted mineralisation such as mesothermal gold-quartz lodes hosted in high- angle reverse shear zones.

Sarma et al. (1994) observed from magnetotelluric data that there exists a fluid- filled body at 6.0 to 7.0 km depth in the epicentrral zone of the Latur earthquake of 1993. Focal depth of 6.0 km estimated by Grad et al.(1997) for this earthquake suggests that the fluid-filled body exists in the focal region possibly at the base of the seismogenic zone. Mandal et al. (2003) detected a low velocity zone at the hypocentral depth of the 2001 Bhuj earthquake (18-25 km), which was inferred by them to be a fluid-filled (trapped aqueous fluid resulted from metamorphism) fractured rock mass. Presence of the fluid filled bodies in the focal region of these two earthquakes indicates the possibility of reactivation of the thrust faults at Latur and Bhuj by the fault-valve mechanism. Hence we suggest that the steeply dipping thrusts at Latur and Bhuj ($\theta_r = 45^0$) and high angle reverse fault at Jabalpur ($\theta_r = 67^0$) were reactivated to rupture by pressure-weakening due to near–lithostatic fluid pressures and supra-lithostatic fluid pressures respectively, caused by the fault – valve mechanism. In the light of the above discussion we conclude that the recent devastating earthquakes at Latur, Jabalpur and Bhuj were caused due to fault-valve mechanism only and as a result deposition of valuable ores might be taking place in the deeper parts of these faults during each earthquake cycle.

CONCLUSIONS

It has been inferred that the steeply dipping and high angle thrust faults at Latur and Bhuj, and Jabalpur area were reactivated and ruptured by pressure-weakening of the faults caused by what is termed as fault-valve mechanism because of which valuable ores are being deposited in the deeper parts of these fault zones during each earthquake cycle.

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