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ON TWO ASEISMICALLY CREEPING AND INTERACTING BURIED VERTICAL STRIKE-SLIP FAULTS IN THE LITHOSPHERE

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ABSTRACT

Two aseismically creeping and interacting buried vertical lithospheric strike-slip faults are taken to be situated in a visco-elastic half-space, representing the lithosphere-asthenosphere system. A technique involving the use of Green's functions and integral transforms is used to obtain solutions for the displacements, stresses and strains in the model, in three different cases-the case where no fault is creeping, the case when one fault is creeping and the other is locked, and the case when both the faults are creeping, taking into account the displacements and stresses present initially, and assuming that tectonic forces maintain a constant shear stress far away from the faults. The types of fault creep for which the displacements and stresses are finite everywhere are identified, and the conditions satisfied by these types of fault creep are determined. Detailed computational algorithms are developed and used for the computation of the displacements, stresses and strains. It is found that the influence of fault creep across one fault on the displacements, stresses and strains near the other depends on the distance, dimensions, nature of the creep and the relative positions of the faults. In particular, it is found that, in some cases, including the case in which the faults are of similar dimensions and are at nearly equal depths, creepacross one fault leads to aseismic release of shear stress near the other, thus reducing progressively the possibility of a sudden earthquake generating fault movement. But in some other cases, including the case in which one fault is vertically above or below the other, creep across one fault is found to increase the rate of shear stress accumulation near the other fault, thus increasing the possibility of a sudden seismic fault movement across the other fault, if it is locked. The effect of one creeping fault on another is found to decrease quite rapidly with increase in the distance between the faults. The possible uses of the model in the study of the interaction between neighbouring buried strike-slip faults in the lithosphere and the influence of the interaction on the possibility of earthquakes due to seismic movements across such faults is examined.

Key Words : Aseismic Creep, Strike-slip, Fault, Visco-elastic Half-space, Green's Function, Interaction, Seismic Movements.

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INTRODUCTION

Aseismic surface movements in seismically active regions of the earth during apparently quiet aseismic periods have attracted the attention of seismologists in recent years, and the possibility of utilising them to obtain greater insight into the dynamics of earthquake processes, including accumulation of stress and strain, leading to seismic fault movements, has been recognised [Kasahara (1981)]. Some theoretical models for aseismic surface movements in seismically active regions have been develcped in recent years, and have been discussed by Mukherji et al. (1984) and Cohen et al (1984). In most of these theoretical models, a single locked or creeping fault is considered in models of the lithosphere-asthenosphere system. However, Mukherji et al. (1984) have considered a theoretical model of the lithosphere-asthenosphere system with two surface-breaknig, creeping and interacting faults, and have explained the significance of fault interaction in the process of stress accumulation and release in seismically active regions But no theoretical models of interaction between buried faults have been developed till now. Keeping in view the fact that creep across buried faults is supposed to be occurring in many seismically active regions [Kasahara (1981)], the case of two creeping and interacting buried vertical strike-slip faults, situated in a simple model of the lithosphere-asthenosphere system, has been considered in this paper.

FORMULATION

We consider a simple model of the lithospehre-asthenosphere system consisting of a visco-elastic half space with its material of the Maxwell tvpe. We consider here two long, vertical and interacting strike-slip faults F_1 and F_2 in the half-space across which creep occurs under suitable conditions. We take both the faults to be buried We introduce rectangular Cartesian coordinates (y_1, y_2, y_3) with the free surface as the plane $y_3=0$ and the y_3-axis pointing into the half-space. We take the y_1-axis to be parallel to the planes of the faults. Then we can assume that the displacements, stresses and strains will be independent of y_1. We take the planes of the faults F_1 and F_2 to be given by $y_2=0$ and $y_2=D$ respectively. We take D_1 and D_2 to be the depths of the lower edges of the faults F_1 and F_2 respectively below the free surface $(y_3=0)$, while d_1 and d_2 are the depths of their upper edges below the free surface $(y_3=0)$.

Fig. 1 shows the section of the model by the plane $y_1 = 0$. For the model, since the displacements, stresses and strains are independent of y_1, we find that the displacement component u_1 along the y_1–axis and the stress components τ_{12} and τ_{13} associated with it are independent of the other components of displacement and stress, and satisfy the relation

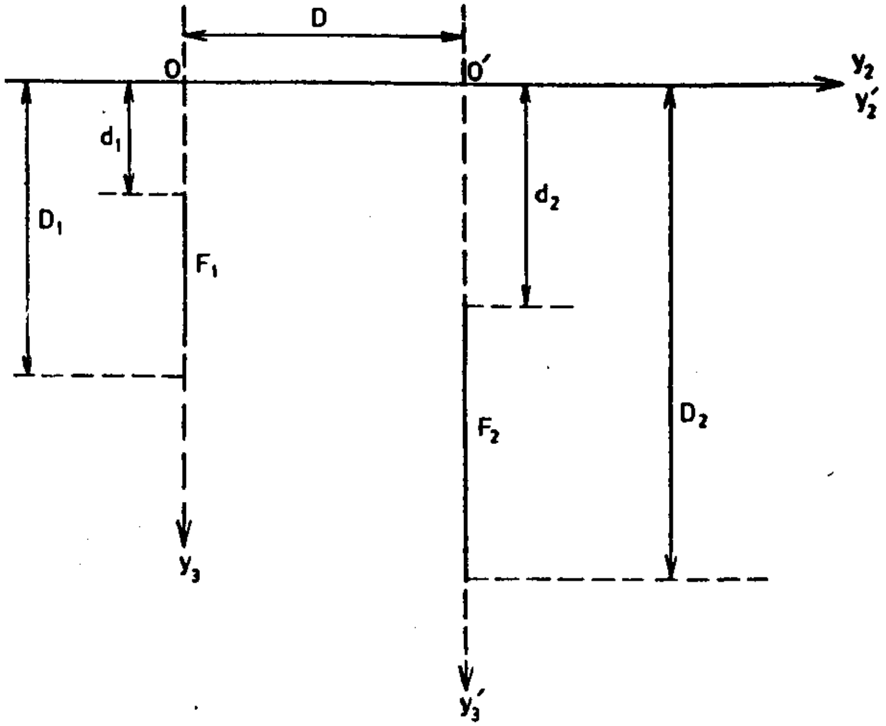

Fig. 1. Section of the model by the plane $y_1=0$

$$\left(\frac{1}{\eta} + \frac{1}{\mu} + \frac{\partial}{\partial t}\right) \tau_{13} = \frac{\partial^2 u_1}{\partial t\, \partial y_3}$$

$$\text{and } \left(\frac{1}{\eta} + \frac{1}{\mu} \quad \frac{\partial}{\partial t}\right) \tau_{12} = \frac{\partial^2 u_1}{\partial t\, \partial y_2} \qquad (1)$$

$$(-\infty < y_2 < \infty,\ y_3 \geqslant 0,\ t \geqslant 0)$$

where μ is the effective rigidity and η is the effective viscosity, as in Mukherji et al. (1984).

We consider the model during aseismic periods leaving out the relatively small periods (if any) following sudden fault movement, when seismic disturbances are present in the model. For the slow, aseismic, quasi-static displacements we consider, the inertial forces are very small and are neglected. Hence the relevant stresses satisfy the relation

$$\frac{\partial}{\partial y_2}(\tau_{12}) + \frac{\partial}{\partial y_3}(\tau_{13}) = 0 \tag{2}$$

$$(-\infty < y_2 < \infty,\ y_3 \geqslant 0,\ t \geqslant 0).$$

From (1) and (2), we find that

$$\frac{\partial}{\partial t}(\nabla^2 u_1) = 0 \tag{3}$$

which is satisfied if $\nabla^2 u_1 = 0$

$$(-\infty < y_2 < \infty,\ y_3 \geqslant 0,\ t \geqslant 0).$$

At the free surface $y_3 = 0$, we have the boundary condition

$$\tau_{13} = 0 \quad \text{on } y_3 = 0 \tag{4}$$

$$(t \geqslant 0,\ -\infty < y_2 < \infty).$$

We assume that tectonic forces maintain a constant shear stress τ_∞ far away from the faults, while stresses near the fault may change with time, due to fault movement (including fault creep). We than have the boundary conditions

$$\tau_{13} \to 0 \text{ as } y_3 \to -\infty \tag{5}$$

$$(\text{for } -\infty < y_2 < \infty,\ t \geqslant 0)$$

and $$\tau_{12} \to \tau_\infty \text{ as } |y_2| \to \infty \tag{6}$$

$$(\text{for } y_3 \geqslant 0,\ t \geqslant 0)$$

DISPLACEMENTS AND STRESSES IN THE ABSENCE OF FAULT MOVEMENT

In the absence of any movement across the faults, the displacements and stresses are continuous throughout the model. In this case, we measure the time t from the instant at which the relations (1) — (6) become valid for the model. Let $(u_1)_0$, $(\tau_{12})_0$, $(\tau_{13})_0$, which may be func tions of (y_2, y_3), be the values of (u_1), (τ_{12}), (τ_{13}) at $t = 0$. $(u_1)_0$, (τ_{12}) $(\tau_{13})_0$ also satisfy the relations (1) — (6).

This initial and boundary value problem is solved, following exactly the same method as in Mukherji and Mukhopadhyay (1984) using Laplace transforms to obtain,

$$\left.\begin{aligned} u_1(y_2, y_3, t) &= (u_1)_0 + \frac{\tau_\infty y_2 t}{\eta} \\ \tau_{12}(y_2, y_3, t) &= (\tau_{12})_0\, e^{-\mu t/\eta} + \tau_\infty\left(1 - e^{-\mu t/\eta}\right) \\ \tau_{13}(y_2, y_3, t) &= (\tau_{13})_0\, e^{-\mu t/\eta} \end{aligned}\right] \qquad (7)$$

As in Mukherji and Mukhopadhyay (1984), we find from (7), that if the shear stress τ_{12} near the faults, tending to cause strike-slip movement is less than τ_∞ at $t = 0$, then there would be a continuous accumulation of shear stress near the faults for $t > 0$, with $\tau_{12} \rightarrow \tau_\infty$ near the faults as $t \rightarrow \infty$.

We assume,as in Mukherji et.al.(1984),that aseismic creep commences across F_1 and F_2 when τ_{12} reaches critical values τ_c and τ_c' respectively near F_1 and F_2.

If τ_c or $\tau_{c'} < \tau_\infty$, then seismic creep would commence across F_1 or F_2 after a finite time. From (7), we find that the fault across which aseismic creep commences first would be determined by the values of τ_c τ_c' and the values of$(\tau_{12})_0$ near the faults F_1 and F_2. Assuming that τ_c, $\tau_c' < \tau_\infty$, we consider next the situation after aseismic creep commences across F_1 or F_2 or both.

DISPLACEMENTS AND STRESSES AFTER THE COMMENCEMENT OF FAULT CREEP

If fault creep commences across F_1 or F_2 or both, the relations (1)—(6) are still satisfied, together with the following conditions of creep across F_1 and F_2 :

$$[u_1]_1 = U_1 (t_1) f_1 (y_3) H (t_1) \tag{8a}$$

across F_1 ($d_1 \leqslant y_3 \leqslant D_1$, $y_2 = 0$)

and $$[u_1]_2 = U_2 (t_2) f_2 (y_3) H (t_2) \tag{8b}$$

across F_2 ($d_2 \leqslant y_3 \leqslant D_2$, $y_2 = D$).

where $t_1 = t - T_1$, $t_2 = t - T_2$,

$$[u_1]_1 = \underset{y_2 \to 0+0}{\text{Lt}} [u_1] - \underset{y_2 \to 0-0}{\text{Lt}} [u']$$

is the relative displacement across F_1 corresponding to the fault creep and $U_1 (t_1) = 0$ for $t_1 \leqslant 0$ i.e., $t \leqslant T_1$, so that $[u_1]_1 = 0$ for $t \leqslant T_1$.

The velocity of creep across F_1 is

$$\frac{\partial}{\partial t} [u_1]_1 = V_1 (t_1) f_1 (y_3)$$

where $V_1(t_1) = \frac{d}{dt_1} \left[U_1 (t_1) \right]$.

Again,

$$[u_1]_2 = \underset{y_2 \to D+0}{\text{Lt}} (u_1) - \underset{y_2 \to D-0}{\text{Lt}} (u_1), \quad (d_2 \leqslant y_3 \leqslant D_2)$$

is the relative displacement across F_2 corresponding to the fault creep and

$U_2 (t_2) = 0$ for $t_2 \leqslant 0$, i.e., $t \leqslant T_2$, so that

$[u_1]_2 = 0$ for $t \leqslant T_2$

The velocity of creep across F_2 is

$$\frac{\partial}{\partial t} [u_1]_2 f_2 (y_3), = V_2 (t_2)$$

where $V_2(t_2) = \dfrac{d}{dt_2} U_2(t_2)$.

T_1 and T_2 are the times of commencement of creep across F_1 and F_2 respectively. In case no creep occurs at any time across F_1 or F_2, we simply take

$$U_1(t_1) = 0 \quad \text{for all } t \geqslant 0,$$

or

$$U_2(t_2) = 0 \quad \text{for all } t \geqslant 0,$$

so that $[u_1]_1 = 0$ or $[u_1]_2 = 0$ for all $t \geqslant 0$.

Considering the model after the commencement of fault creep, across F_1 or F_2, or both, we try to find solutions for u_1, τ_{12}, τ_{13} in the form

$$\left.\begin{aligned} u_1 &= (u_1)_1 + (u_1)_2 + (u_1)_3 \\ \tau_{12} &= (\tau_{12})_1 + (\tau_{12})_2 + (\tau_{12})_3 \\ \text{and} \quad \tau_{13} &= (\tau_{13})_1 + (\tau_{13})_2 + (\tau_{13})_3 \end{aligned}\right] \tag{9}$$

where $(u_1)_1$, $(\tau_{12})_1$, $(\tau_{13})_1$ are continuous everywhere in the model, satisfy the relations (1)—(6), and have the values $(u_1)_0$, $(\tau_{12})_0$, $(\tau_{13})_0$ at $t = 0$, while $(u_1)_2$, $(\tau_{12})_2$, $(\tau_{13})_2$ are zero for $t \leqslant T_1$, satisfy (1) -(5), (8a) and are continuous everywhere except across F_1, satisfying the following condition which replaces (6) :

$$(\tau_{12})_2 \longrightarrow 0 \text{ as } [y_2] \longrightarrow \infty \quad (y_3 \geqslant 0, t \geqslant T_1). \tag{10a}$$

Again, $(\tau_{12})_3$, $(u_1)_3$, $(\tau_{13})_3$ are zero for $t \leqslant T_2$, satisfy (1)—(5), (8b) and are continuous everywhere except across F_2, satisfying the following condition which replaces (6) :

$$(\tau_{12})_3 \longrightarrow 0 \text{ as } [y_2] \rightarrow \infty \quad (y_3 \geqslant 0, t \geqslant T_2). \tag{11b}$$

In this case, it is clear that the solutions (9) will satisfy (1)—(6), (8a) and (8b).

On substituting $t_1 = t - T_1$, we find that $(u_1)_2$, $(\tau_{12})_2$, $(\tau_{13})_2$ which are functions of (t_1, y_2, y_3) satisfy the following relations, obtained from(1)-(5), (10), (8a) and (8b).

$$\left.\begin{aligned} \left(\frac{1}{\eta} + \frac{1}{\mu}\frac{\partial}{\partial t_1}\right)(\tau_{12})_2 &= \frac{\partial^2 (u_1)_2}{\partial t_1\, \partial y_2} \\ \left(\frac{1}{\eta} + \frac{1}{\mu}\frac{\partial}{\partial t_1}\right)(\tau_{13})_2 &= \frac{\partial^2 (u_1)_2}{\partial t_1\, \partial y_3} \end{aligned}\right] \tag{1a}$$

$$\frac{\partial}{\partial y_2}(\tau_{12})_2 + \frac{\partial}{\partial y_3}(\tau_{13})_2 = 0 \tag{2a}$$

$$\nabla^2 (u_1)_2 = 0 \tag{3a}$$

[(1a), (2a), (3a) being valid for $-\infty < y_2 < \infty,\ y_3 \leqslant 0, \leqslant 0$].

$$(\tau_{13})_2 = 0 \quad \text{on} \quad y_3 = 0 \ (-\infty < y_2 < \infty,\ t_1 \geqslant 0) \tag{4a}$$

$$(\tau_{13})_2 \longrightarrow 0 \quad \text{as } y_3 \longrightarrow \infty \ (-\infty < y_2 < \infty,\ t_1 \geqslant 0) \tag{5a}$$

$$(\tau_{12})_2 \longrightarrow 0 \quad \text{as } y_2 \longrightarrow \infty \ (y_3 \geqslant 0, t_1 \geqslant 0) \tag{6a}$$

$$\left.\begin{array}{ll} & [(u_1)_2] = U_1(t_1)\, f_1(y_3) \text{ across } F_1 \\ & (y_2 = 0,\ d_1 \leqslant y_3 \leqslant D_1,\ t_1 \geqslant 0) \\ & \text{with } U_1(0) = 0 \\ \text{and} & (u_1)_2, (\tau_{12})_2, (\tau_{13})_2 = 0 \text{ for } t_1 \leqslant 0 \end{array}\right] \tag{7a}$$

To obtain solutions for $(u_1)_2$ $(\tau_{12})_2$, $(\tau_{13})_2$ for $t_1 \geqslant 0$, we take Laplace transforms of (1a)—(7a) with respect to t_1.

This gives a boundary value problem which can be solved by using a suitably modified form of a Green's function technique developed by Maruyama (1966), as explained in Mukherji et. al. (1984). On inverting the Laplace transforms, as in Mukherji et. al. (1984), we obtain,

$$(u_1)_2 = H\ (t - T_1)\frac{U_1(t_1)}{2\pi}\Psi_{11}(y_2, y_3) \tag{11}$$

$$(\tau_{122}) = H\ (t - T_1)\left(\frac{\mu}{2\pi}\right)\int_0^{t_1} V_1(\tau)\ e^{-\mu(t_1-\tau)/\eta}\, d\tau\ \phi_1(y_2, y_3) \tag{12}$$

$$(\tau_{13})_2 = H\ (t - T_1)\left(\frac{\mu}{2\pi}\right)\int_0^{t_1} V_1(\tau)\ e^{-\mu(t_1-\tau)/\eta}\, d\tau\ \phi_{21}(y_2, y_3) \tag{13}$$

where $t_1 = t - T_1$, $H(t - T_1)$ is the Heaviside function, so that $H(t - T_1) = 0$ for $t < T_1$, and $H(t - T_1) = 1$ for $t > T_1$. In (11) — (13),

$$\Psi_{11}(y_2,y_3) = \int_{d_1}^{D_1} f_1(x_3)\left[\frac{y_2}{(x_3-y_3)^2+y_2^2}+\frac{y_2}{(x_3+y_3)^2+y_2^2}\right]dx_3 \quad (14)$$

$$\phi_{11}(y_2,y_3)= \int_{d_1}^{D_1} f_1(x_3)\left[\frac{(x_3-y_3)^2-y_2^2}{\{(x_3-y_3)^2+y_2^2\}^2}+\frac{(x_3+y_3)^2-y_2^2}{\{(x_3+y_3)^2+y_2^2\}^2}\right]dx_3 \quad (15)$$

and

$$\phi_{21}(y_2,y_3)= \int_{d_1}^{D_1} f_1(x_3)\left[\frac{2y_2(x_3-y_3)}{\{(x_3-y_3)^2+y_2^2\}^2}-\frac{2y_2(x_3+y_3)}{\{(x_3+y_3)^2+y_2^2\}^2}\right]dx_3 \quad (16)$$

$(y_2\neq 0)$.

Hence $e_{12} = \frac{\partial u_1}{\partial y_2}$, the shear strain is given by

$$e_{12}+(e_{12})_0+\frac{\tau_\infty t}{\eta}+H(t-T_1)\frac{U_1(t_1)}{2\pi}\phi_{11}(y_2,y_3)$$

In (11) — (16), we note that $U_1(t_1)$ and $V_1(t_1)$ vanish for $t_1<0$. Following exactly the same technique, we obtain expressions for $(u_1)_s$, $(\tau_{12})_s$, $(\tau_{13})_s$ in the following from :

$$(u_1)_s = H(t-T_2)\frac{U_2(t_2)}{2\pi}\Psi'_{11}(y'_2, y'_3) \quad (17)$$

$$(\tau_{12})_s = H(t-T_2)\frac{\mu}{2\pi}\int_0^{t_2} V_2(\tau)\, e^{-\mu(t_2-\tau)/\eta}\, d\tau \;\; \phi'_{11}(y_2,y_3) \quad (18)$$

and $$(\tau_{13})_s=H(t-T_2)\mu/2\pi\int_0^{t_2} V_2(\tau)\, e^{-\mu(t_2-\tau)/\eta}\, d\tau \;\; \phi'_{21}(y'_2, y'_3) \quad (19)$$

$(y'_2 \neq 0$ i. e., $y_2 \neq 0)$,

where $t_2 = t-T_2$, $y'_2 = y_2 - D$, $y'_3 = y_3$, $V_2(t_2) = \frac{d}{dt_2}U_2(t_2)$

and $\Psi'_{11}, \phi'_{11}, \phi'_{21}$ are obtained directly from $\Psi_{11}, \phi_{11}, \phi_{21}$ on replacing $y_2, y_3, D_1, f_1(y_3)$ in $\Psi_{11}, \phi_{11}, \phi_{21}$ by $y'_2, y'_3, D_2, f_2(y'_3)$ respectively, where $\Psi_{11}, \phi_{11}, \phi_{21}$ are given by (14)—(16).

Hence we have after the commencement of fault creep,

$$e_{12}=(e_{12})_0+\frac{\tau_\infty t}{\eta}+H(t-T_1)\frac{U_1(t_1)}{2\pi}\phi_{11}(y_2,y_3)$$
$$+H(t-T_2)\frac{U_2(t_2)}{2\pi}\phi'_{11}(y'_2,y'_3) \tag{20}$$
$$(t_1=t-T_1,\quad t_2=t-T_2,\quad y'_2=y_2-D,\ y'_3=y_3)$$

The integrals for Ψ_{11}, ϕ_{11} and ϕ_{21} in (14) – (16) can be obtained in closed form if $f_1(y_3)$ is a polynomial. In particular, if the relative displacement due to creep is independent of depth, we have,

$$f_1(y_3)=\text{constant}=K\ (\text{say})\quad (d_1\leqslant y_3\leqslant D_1).$$

We find easily,

$$\Psi_{11}(y_2,y_3)=K\left[\tan^{-1}\left(\frac{D_1-y_3}{y_2}\right)+\tan^{-1}\left(\frac{D_1+y_3}{y_2}\right)-\tan^{-1}\left(\frac{d_1-y_3}{y_2}\right)-\tan^{-1}\left(\frac{d_1+y_3}{y_2}\right)\right]$$

$$\phi_{11}(y_2,y_3)=-K\left[\frac{D_1-y_3}{(D_1-y_3)^2+y_2^2}+\frac{D_1+y_3}{(D_1+y_3)^2+y_2^2}-\frac{d_1-y_3}{(d_1-y_3)^2+y_2^2}-\frac{d_1+y_3}{(d_1+y_3)_2+y_2^2}\right] \tag{21}$$

and

$$\phi_{21}(y_2,y_3)=K\left[-\frac{2}{(D_1-y_3)^2+y_2^2}+\frac{y_2}{(D_1+y_3)^2+y_2^2}+\frac{y_2}{(d_1-y_3)^2+y_2^2}-\frac{y_2}{(d_1+y_3)^2+y_2^2}\right]$$

We note that ϕ_{11} and ϕ_{21} (and hence τ_{12} and τ_{13}) have singularities at $[(y_2=0,\ y_3=D_1),\ (y_2=0,\ y_3=d_1)]$.

which are the lower and upper edges of the fault. The integrals for Ψ''_{11}, ϕ'_{11} and ϕ'_{21} can be also obtained in closed form if $f_2(y'_3)$ is a polynomial. Following exactly the method as mentioned in Mukhrji et al. (1984), we find that the integrals Ψ_{11}, ϕ_{11}, ϕ_{21} are finite everywhere in the model including the edges of the faults, provided the following conditions are all satisfied simultaneously by $f_1(y_3)$:

(i) $f_1(y_3)$ and $f'_1(y_3)$ are continuous in $d_1 \leqslant y_3 \leqslant D_1$

(ii) $f''_1(y_3)$ is either continuous in $d_1 < y_3 < D_1$, or has a finite number of points of finite discontinuity in $d_1 < y_3 < D_1$,

(iii) either (a) $f''_1(y_3)$ is finite and continuous at $y_3 = d_1$ & $y_3 = D_1$ (C1)
or (b) there exist constants m_1 and n_1 both >1, such that

$$(y_3 - d_1)^{m_1} f''_1(y_3) \rightarrow 0 \text{ or to a finite limit as } y_3 \rightarrow d_1 + 0$$

and $$(D_1 - y_3)^{n_1} f''_1(y_3) \rightarrow 0 \text{ or to a finite limit as } y_3 \rightarrow D_1 - 0.$$

(iv) $f_1(D_1) = 0 = f_1(d_1)$

$f'_1(D_1) = 0 = f'_1(d_1)$

These conditions imply that the magnitude of the relative creep displacement across the fault varies smoothly with depth and approaches zero with sufficient smoothness as $y_3 \rightarrow D_1 - 0$ and as $y_3 \rightarrow d_1 + 0$ at the upper and lower edges of the fault.

Similarly the integrals Ψ''_{11}, ϕ'_{11}, ϕ'_{21} are finite everywhere in the model including the edges of the faults, provided $f_2(y'_3)$ satisfies conditions (C2) similar to (C1) mentioned above, where for $f_2(y'_3)$, we replace (y_2, y_3, d_1, D_1) by (y'_2, y'_3, d_2, D_2) in these conditions. Hence, after the commencement of fault creep, the displacements and stresses will remain finite everywhere in the model including the edges of the faults provided the above conditions are satisfied by $f_1(y_3)$ and $f_2(y'_3)$. We obtain, in this case, the following solutions for $(u_1, \tau_{12}, \tau_{13}, e_{12})$, which are finite for all finite values of (y_2, y_3, t) and valid for all $t \geqslant 0$ and for all types of fault creep across F_1 and/ or F_2, satisfying (C1) and (C2), when we take $U_1(t_1)$, $U_2(t_2)$, $f_1(y_3)$, $f_2(y'_3)$ in appropriate form, satisfying (C1) and (C2).

$$
\left.\begin{aligned}
u_1 &= (u_1)_0 + \frac{\tau_\infty y_2 t}{\eta} + H(t-T_1)\frac{U_1(t_1)}{2\pi}\Psi_{11}(y_2, y_3) \\
&\quad + H(t-T_2)\frac{U_2(t_2)}{2\pi}\Psi'_{11}(y'_2, y'_3) \\
\tau_{12} &= (\tau_{12})_0 \, e^{-\mu t/\eta_2} \, \tau_\infty \left(1 - e^{-\mu t/\eta}\right) \\
&\quad + H(t-T_1)\left(\frac{\mu}{2\pi}\int_0^{t_1} v_1(\tau)\, e^{-\mu(t_1-\tau)/\eta}\, d\tau\right)\phi_{11}(y_2, y_3) \\
&\quad + H(t-T_2)\left(\frac{\mu}{2\pi}\int_0^{t_2} v_2(\tau)\, e^{-\mu(t_2-\tau)/\eta}\, d\tau\right)\phi'_{11}(y_2, y_3) \\
\tau_{13} &= (\tau_{13})_0 \, e^{-\mu t/\eta} + H(t-T_1)\left(\frac{\mu}{2\pi}\right) \\
&\quad \left(\int_0^{t_2} v_1(\tau)\, e^{-\mu(t_1-\tau)/\eta}\, d\tau\right)\phi_{21}(y_2, y_3) \\
&\quad + H(t-T_2)\left(\frac{\mu}{2\pi}\int_0^{t_2} v_2(\tau)\, e^{-\mu(t_2-\tau)/\eta}\, d\tau\right)\phi'_{21}(y_2, y_3) \\
\text{and } e_{12} &= (e_{12})_0 + \frac{\tau_\infty t}{\eta} + H(t-T_1)\frac{U_1(t_1)}{2\pi}\phi_{11}(y_2, y_3) \\
&\quad + H(t-T_2)\frac{U_2(t_2)}{2\pi}\phi'_{11}(y'_2, y_3)
\end{aligned}\right\} \quad (22)
$$

where

$$
\begin{aligned}
\Psi_{11}(y_2, y_3) &= -\int_{d_1-y_3}^{D_1-y_3} f'_1(y_3+y)\tan^{-1}(y/y_2)\,dy \\
&\quad -\int_{d_1+y_3}^{D_1+y_3} f'_1(z-y_3)\tan^{-1}(z/y_2)\,dz \\
\phi_{11}(y_2, y_3) &= -\tfrac{1}{2}\left[\int_{d_1-y_3}^{D_1-y_3} f''_1(y+y_3)\log_e(y^2+y_2^2)\,dy \right. \\
&\quad \left. + \int_{d_1+y_3}^{D_1+y_3} f''_1 - y_3(\log_e(z^2+y_2^2)\,dz)z \right]
\end{aligned}
\qquad (23)
$$

and

$$
\begin{aligned}
\phi_{21}(y_2, y_3) &= -\int_{d_1-y_3}^{D_1-y_3} f''_1(y_3+y)\tan^{-1}(y/y_2)\,dy \\
&\quad -\int_{d_1+y_3}^{D_1+y_3} f''_1(z-y_3)\tan^{-1}(z/y_2)\,dz,
\end{aligned}
$$

and ϕ'_{11}, Ψ'_{11}, ϕ'_{21} can be obtained from ϕ_{11}, Ψ_{11} and Ψ_{21} by replacing y_2, y_3, D_1, d_1, $f_1(y_3)$ by y'_2, y'_3, D_2, d_2, $f_2(y'_3)$ respectively.

The solutions are valid for all $t \geqslant 0$, for all (y_2, y_3) in the model and for all values of T_1, T_2 ($\geqslant 0$).

We also note that, to obtain u_1, τ_{12}, τ_{13} in the neighbourhood of F_1, we make $y_2 \rightarrow 0+0$, and $y_2 \rightarrow 0-0$ to obtain the limiting values on the right and left of F_1 in Fig. 1. Similarly, to obtain μ_1, τ_{12}, τ_{13} in the neighbourhood of F_2, we make $y_2 \rightarrow D+0$ and $y_2 \rightarrow D-0$ to get the limiting values on the right and left of F_2 in Fig. 1.

If fault creep across F_1 or F_2 starts and stops after some time, the results remain valid on taking appropriate forms of $U_1(t_1)$ and $U_2(t_2)$ in (8a) and (8b). The results will however, be valid only for aseismic periods, and will not be applicable to seismic disturbances in the model due to sudden seismic fault movements, since the inertial terms in the equations of motion cannot be neglected in this case, so that (2) has to be modified.

DISCUSSIONS OF THE RESULTS AND CONCLUSION

To study in greater detail the changes of the displacements, stresses and strains in the model near the fault with time, and specially the influence of fault creep, we compute the changes of the surface displacement $(u_1)_{y_3=0}$ and the surface shear strain $(e_{12})_{y_3=0}$ near the faults, as well as the shear stress τ_{12} near the faults at different depths, tending to cause strike-slip movement, for relevant values of the model parameters $\mu, \eta, d_1, d_2, D_1, D_2, D, \tau_\infty$ and for relevant types of creep across the faults. Keeping in view the case of strike-slip faults in the lithosphere, we take values for μ in the range (3 to 4) X 10^{11} dynes/cm², while d_1, d_2, D_1, D_2, D are taken to have values in the range 5 to 40 Kms. We have carried out computations for creep displacements across F_1 and F_2, commencing at times $t=T_1$, $t=T_2 (T_2 > T_1 > 0)$ having the following form :

$$[u_1] = V_1 t_1 f_1 (y_3) \quad \text{across } F_1,$$

and

$$[u_1] = V_2 t_2 f_2 (y'_3) \quad \text{across } F_2,$$

where V_1, V_2 are constants, and $f_1(y_3)$ and $f_2(y'_3)$ are polynomials, satisfying the conditions (C1) for finite displacement, stresses and strains. In particular, we consider the case,

$$f_1(y_3) = K (y_3 - d_1)^2 (D_1 - y_3)^2 \qquad [K = 16/(D_1 - d_1)^4] \tag{24}$$

and

$$f_2(y'_3) = K' (y'_3 - d_2)^2 (D_2 - y'_3)^2 \qquad [K' = 16/(D_2 - d_2)^4] \, , \tag{25}$$

We have chosen the values of K, K' such that $f_1(y_3)$ has the maximum value 1 at $y_3 = (D_1 + d_1)/2$, at the midpoint of F_1 and $f_2(y'_3)$ has the maximum value 1 at $y'_3 = (D_2 + d_2)/2$, at the midpoint of F_2, so that V_1, V_2 are the maximum creep velocities across F_1, F_2 at their middle points. In this case, the integrals in the expressions for $\Psi_{11}, \phi_{11}, \phi_{21}, \Psi'_{11}, \phi'_{11}, \phi'_{21}$ can be evaluated in closed form. However, the expressions are very long, and are not given here.

For V_1 and V_2, the maximum creep velocities across F_1 and F_2, we consider values in the range 0 to 5 cms. per year, which is the normal range of observed creep velocities across creeping strike-slip faults. For η, we take values in the range 10^{21} to 10^{22} poise, keeping in view the fact that reasonably good agreement between observational data on post-glacial uplift and corresponding theoretical results for theoretical models of the lithosphere-asthenosphere system has been obtained by Cathles (1976) with values of η in this range. For τ_∞, we take values in the range 50 to

200 bars, which is of the same order as the estimated stress-drops in major strike-slip fault movements, and for $(\tau_{12})_0$ near the faults we consider values in the range 0 to 100 bars, with $(\tau_{12})_0$ near F_1 and F_2 less than in all cases.

The computed values of the displacements, stresses and strains show that, in the absence of fault creep, there is generally a gradual accumulation of the surface shear strain e_{12} and shear stress τ_{12} near the faults, tending to increas the possibility of strike-slip fault movement. The accumulation of shear stress τ_{12} is found to decrease slowly with time, and ultimately if there is no fault creep or sudden fault movement. However, if creep commences across F_1 or F_2 or both, it has a significant influence on the subsequent displacements, stresses and strains near the faults. The magnitude of this effect is found to depend on the following factors :

(a) the creep velocities and spatial distributions across the faults of the relative aseismic creep displacements i. e., v_1, v_2 and f_1 (y_3), f_2 $(y'_3,)$

(b) the depths and dimensions of the faults and the distance between them i. e., d_1, d_2, D_1, D_2 and D,

(c) the shear strees $\tau\infty$ far away from the fault maintained by tectonic forces,

(d) the displacements, stresses and strains present at $t = 0$,

(e) the values of the model parameters μ and η related to the material rheology, and

(f) The relative positions of the faults.

The computations show that when creep across any fault commences, it generally reduces the rate of accumulation of shear stress and shear strain near itself and greater creep velocities result in greater reduction of the rate of accumulation ofshear stress and strain near the fault. For sufficiently large creep velocities across a fault there is a continuous aseismic release of shear stress and strain near the fault, so that the possibility of a sudden fault movement, generating an earthquake, is progressively reduced. The effect of creep across one fault of the model on the shear stress near the other is found to depend on the relative positions of the two faults and on their dimensions and creep velocities. If we consider any particular fault, say F_1, it is found that if the other fault F_2 lies in two particular regions of the model which we call I_1 and I_2, creep across F_1 tends to increase the rate of accumulatian of stress and strain near F_2. But if F_2 lies in two other regions of the model which we call R_1 and R_2, creep across F_1 reduces the rate of accumulation of shear stress and strain across F_2. These regions are shown in Fig. 2. The actual positions of the boundaries of these regions of the model depend on the model parameters d_1, D_1 and f_1 (y_3) for F_1. However, the general from of the regions remain as shown in Fig. 2.

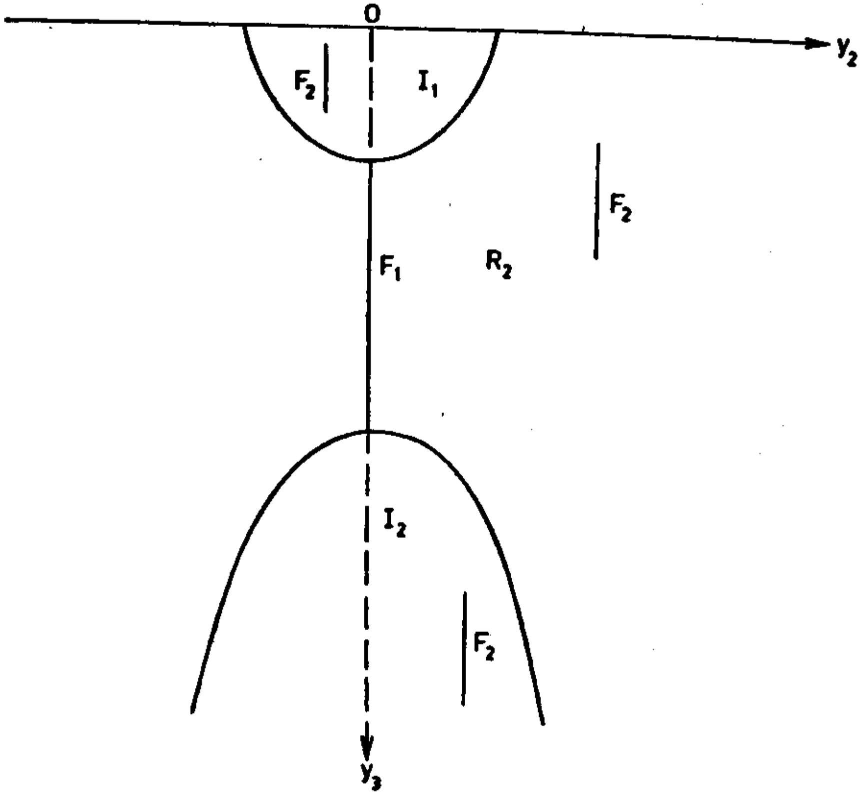

Fig 2 : Creep across F_1—regions of increase in the rate of stress accumulation (I_1, I_2) and decrease in the rate of stress accumulation (R_1, R_2)

Similarly, for creep across F_2, the effect on the shear stress near F_1 depends on the positions of F_2 relative to F°. and we have regions I'_1, I'_2, R'_1, R'_2 of the model such that creep across F_2 increases or decreases the rate of accumulation of shear stress and strain near F° according as F° is in [I'° I'₂] or in [R'_1 R'_1].

These regions are shown in Fig. 3. In particular, if the faults are of similar dimensions and of nearly equal depth, creep across one fault tends

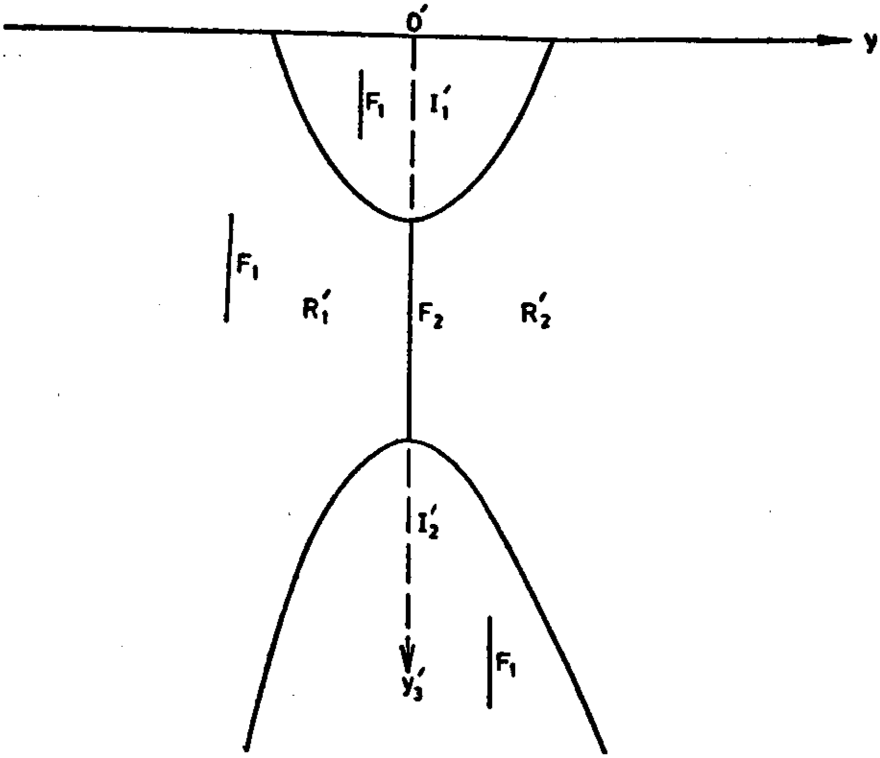

Fig. 3 : Creep across F_2—regions of increase in the rate of stress accumulation (I'_1, I'_2) and decrease in the rate of stress accumulation (R'_1, R'_2)

to release the shear stress and strain near the other, reducing progressively the possibility of a sudden fault movement, generating an earthquake. In this case, the two creeping faults tend to release the shear stress and strain near each other. But if one fault is more or less vertically below or above the other, creep across one fault tends to increase the rate of accumulation of shear stress and strain near the other, so that the possibility of a sudden seismic fault movement across the other fault is increased. In this case, the two creeping faults tend to reinforce the shear stress and strain accumulation near each other.

The influence of one fault on the other is found to decrease quite rapidly with increase in the distance D between them and if $D >> (D_1, D_2)$ then the effect of creep across one fault on the stresses and strains near the other becomes quite small. However, in this case also, creep across any fault generally tends to reduce the rate of shear stress and strain accumulation near itself. Another interesting result is that in the absence of fault creep the rate of accumulation of surface shear strain near the faults is of the order of 10^{-7} per year, which is of the same order of magnitude as the reported rate of surface shear strain accumulation near the locked northern and southern parts of the San Andreas fault.

The influence of creep across one fault (say F_1) on the shear stress and strain near the other and near itself is found to be proportional to the creep velocity across F_1 if the creep velocity does not change with time, i.e., if V_1 (t_1) or V_2 (t_2) is constant. However, the relation is more complex if the creep velocity changes with time, although an increase in creep velocity across one fault still increases its influence on the shear stress and strain near the other fault and near irself.

We now consider, in greater detail, the effect of fault creep on the surface shear strain (on the free surface) in the region near the faults, whose changes with time can be monitored observationally by repeated geodetic surveys and instrumental observations, and changes in the shear stress near the faults, which may be expected to influence fault creep and sudden seismic fault movements across the faults. We consider two cases.

In the first case, represented by Fig. 4, the two faults F_1, F_2 are at the same level. In the second case, represented by Fig. 5, onefault is vertically above or below the other.

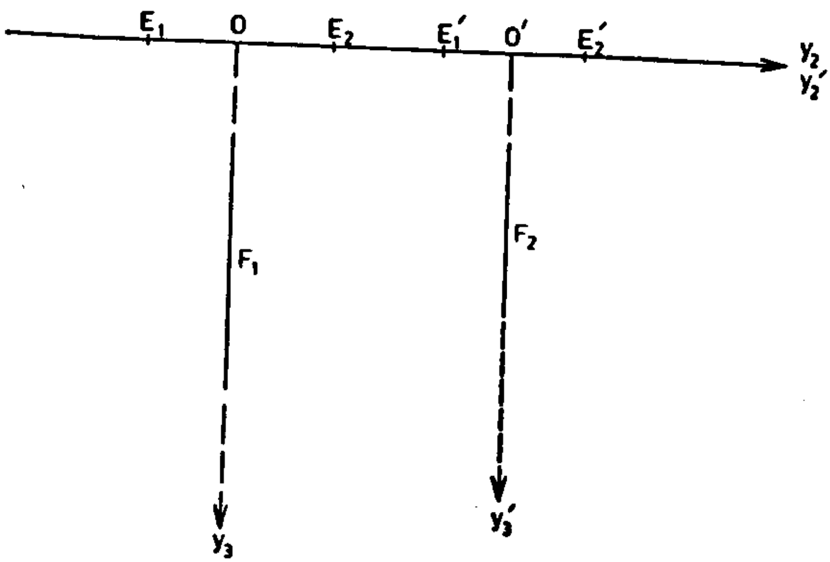

Fig. 4 : Faults F_1, F_2 approximately at the same level.

On computing the shear strain e_{12} on the free surface $y_3=0$, it is found that, in both the cases, creep across F_1 or F_2 results in an increase in the rate of accumulation of shear strain e_{12} over regions E_1E_2 for F_1 and $E'_1E'_2$ for F_2, shown in Fig. 4 and Fig. 5. These regions are symmetrical about the lines vertically above F_1 and F_2 on the free surface. But outside these regions, creep across F_1 or F_2 results in a decrease in the rate of accumulation of the shear strain e_{12} on the surface. The widths E_1E_2 and $E'_1E'_2$ of the regions of increasing strain accumulation on the surface depend on the fault parameters for F_1, F_2 including d_1, d_2, D_1, D_2, $f_1(y_3)$, $f_2(y'_3)$.

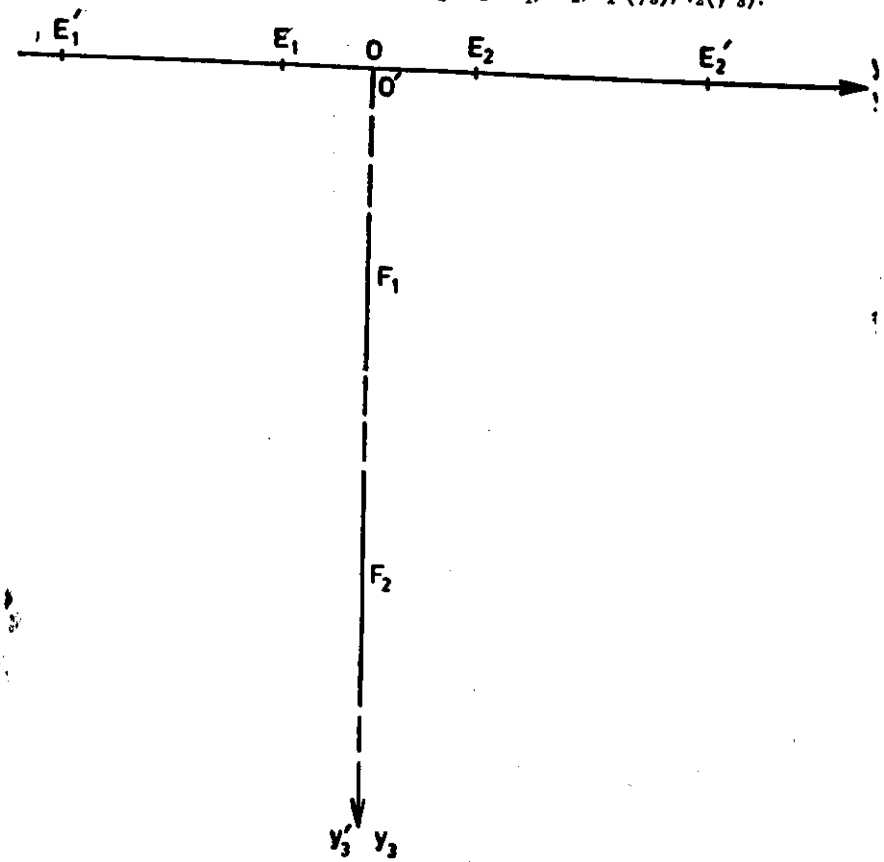

Fig. 5 : F_1 vertically above F_2

We show in some detail the changes of the shear strain on the surface above the faults and the shear stress τ_{12} near the faults, tending to cause strike-slip movement, for some typical values of the model parameters, taking $\eta=10^{22}$ poise, $\mu=3\times10^{11}$ dynes/cm², $\tau_\infty = 100$ bars, $(\tau_{12})_0=25$ bars in the region of the faults, $[f_1(y_3), f'_2(y'_3)]$ given by (24) and (25) and V_1, V_2 in the range 0 to 5 cms/year. The reasons for such choice of the model parameters have been explained earlier in the paper here, and also by Mukhopadhyay et al. (1978a, b, 1979a, b, c, d and 1980a, b). Fig 6 shows the variations in the quantity

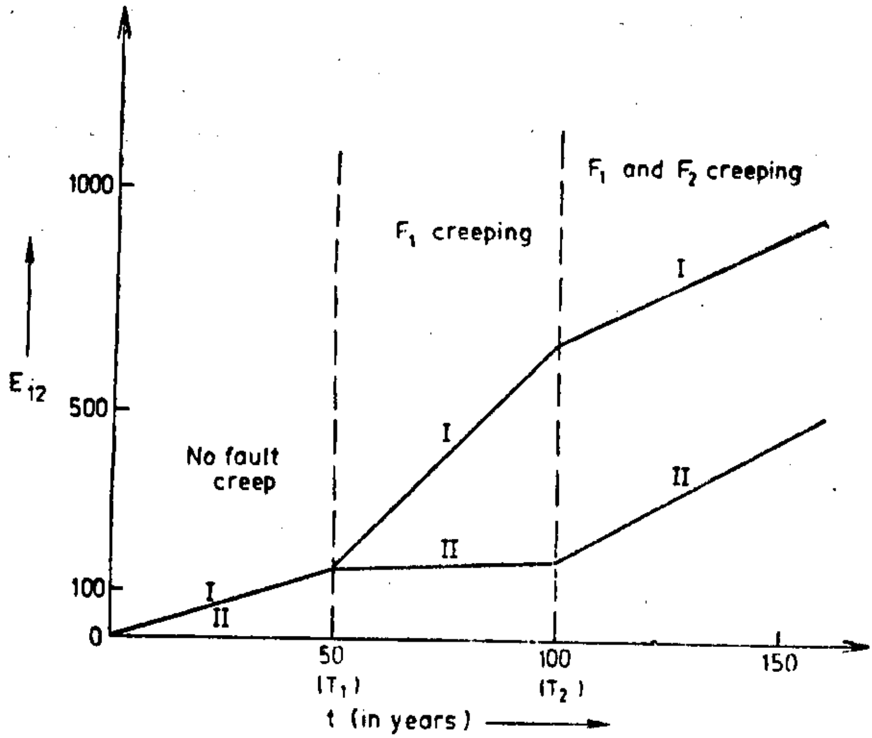

Fig. 6 : Changes in the surface shear strain with time above F_1 and F_2 which are at the same level.

$$E_{12} = [e_{12} - (e_{12})_0]_{y_3 = 0} \times 10^7$$

(= change in surface shear strain X 10^7)

with time, at points vertically above F_1, F_2 in the situation shown in Fig. 4, where F_1, F_2 are parallel and at the same depth, with

$d_1 = d_2 = 5$ kms, $D_1 = D_2 = 15$ kms,

$V_1 = V_2 = 2$ cms/year,

$T_1 = 50$ years,

$T_2 = 100$ years,

and D = 10 kms.

The lines I and II show the changes in E_{12} with time t at surface points vertically above F_1 and F_2 respectively. In this case, creep across F_1 or F_2 increases the rate of accumulation of surface shear strain above the fault itself. But creep across F_1 or F_2 reduces the rate at points vertically above the other faults. The surface shear strain above F_1 (or F_2) is influenced to a greater extent by creep across F_1 (or F_2). The effect of creep across the other fault F_2 (or F_1) is smaller, but still appreciable. In particular, during the period $T_1 < t < T_1$, when F_1 creeps and F_2 is locked, the rate of accumulation of surface shear strain above F_2 is almost reduced to zero.

Fig. 7 shows the variation of the same quantity E_{12} with time in the case corresponding to Fig. 5, where F_1 is vertically above F_2, taking $d_1 = 5$ Kms, $D_1 = 15$ Kms, $d_1 = 20$ Kms, $D_2 = 30$ Kms, $D = 0$, $V_1 = V_2 =$ 2 cms/

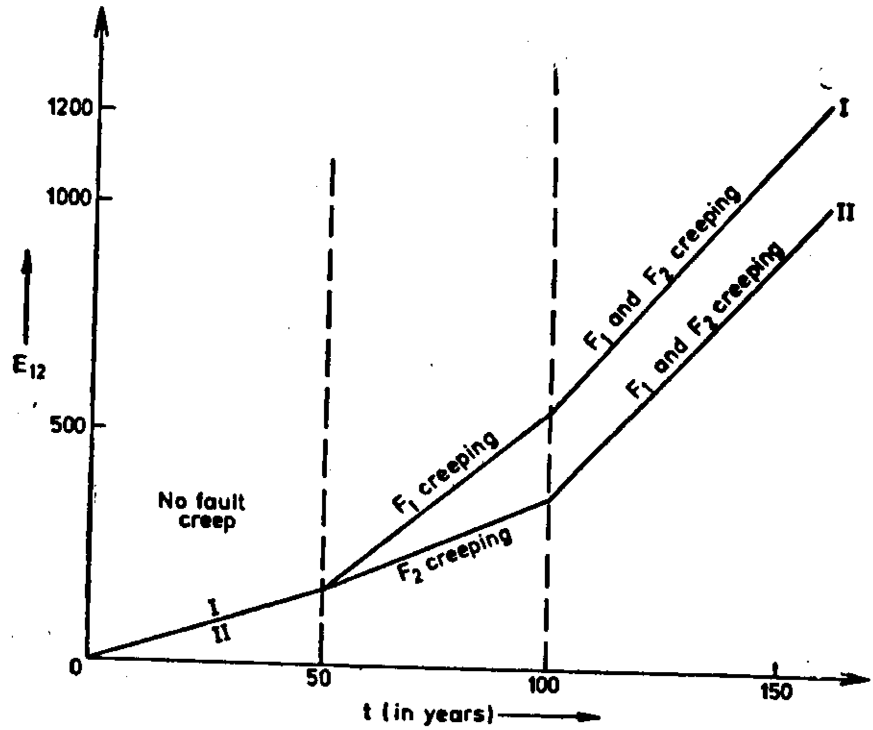

Fig. 7 : Changes in the surface shear strain with time above F_1 and F_2, with F_1 vertically above F_2.

year. In this case, as shown in Fig. 7, creep across F_1 and F_2 both increase the rate of accumulation of surface shear strain above F_1 and F_2 ($y_2=y_3=0$). But the effect of creep across F_2, which is at a greater depth below the surface, is much less pronounced. The line I corresponds to the case in which $T_1=50$ years and $T_2=100$ years so that F_1. starts creeping first and F_2 starts creeping later, and the line II corresponds to the case in which $T_1=100$ years and $T_2=50$ years, so that F_2 starts creeping first and F_1 starts creeping later.

Fig 8 shows the variations with time of the quantity

$T_1m = \max [(\tau_{12})_{y_2} \longrightarrow 0, d_1 \leqslant y_3 \leqslant D_1]$,
in the case in which the two faults F_1, F_2 are parallel to each other and at the same level, as in Fig. 4, with $d_1 = d_2 = 5$ Kms, $D_1 = D_1 = 15$ Kms, $T_1 = 50$ years, $T_2 = 100$ years, and $D = 10$ Kms. The curves I, II and III in Fig. 8 correspond to $V_1 = V_2 = 0$ (the case of no fault creep), $V_1 = V_2 = 2$ cms/year and $V_1 = V_2 = 5$ cms/year respectively.

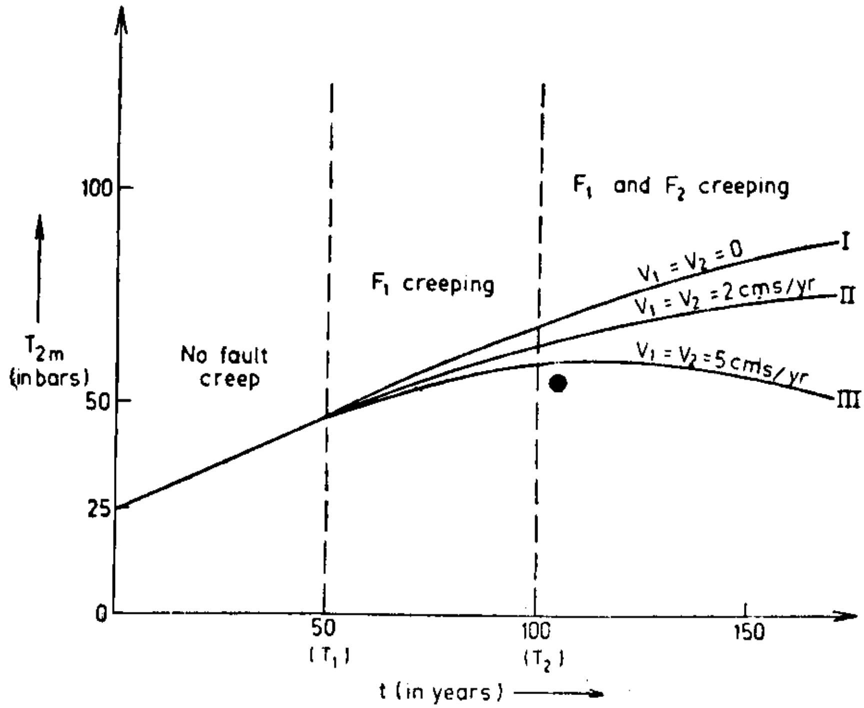

Fig. 8 : Changes in the maximum shear stress near F_1 with time (F_1 and F_2 at the same level)

Fig. 9 also corresponds to exactly the same model; with F_1, F_2 parallel and at the same level, and it represents the variation with time of the quantity

$T_2m = \max [(\tau_{12})_{y'_2} \longrightarrow 0. d_2 \leqslant y_3 \leqslant D_2]$,
with the same values of the model parameters as in Fig 8. As in Fig 8, the curves I, II and III in Fig. 9 correspond to $V_1 = V_2 = 0$, $V_1 = V_2 = 2$ Cms/year and $V_1 = V_2 = 5$ Cms/year. We note that T_1m and T_2m, which are functions of t, represent, at any time t, the maximum values of the shear stress τ_{12} near the faults F_1 and F_2 respectively at that time. Fig. 8 and Fig 9 show that, in the absence of fault creep, there is a steady accumulation of shear tress near the faults, leading to an increasing possibility of a sudden

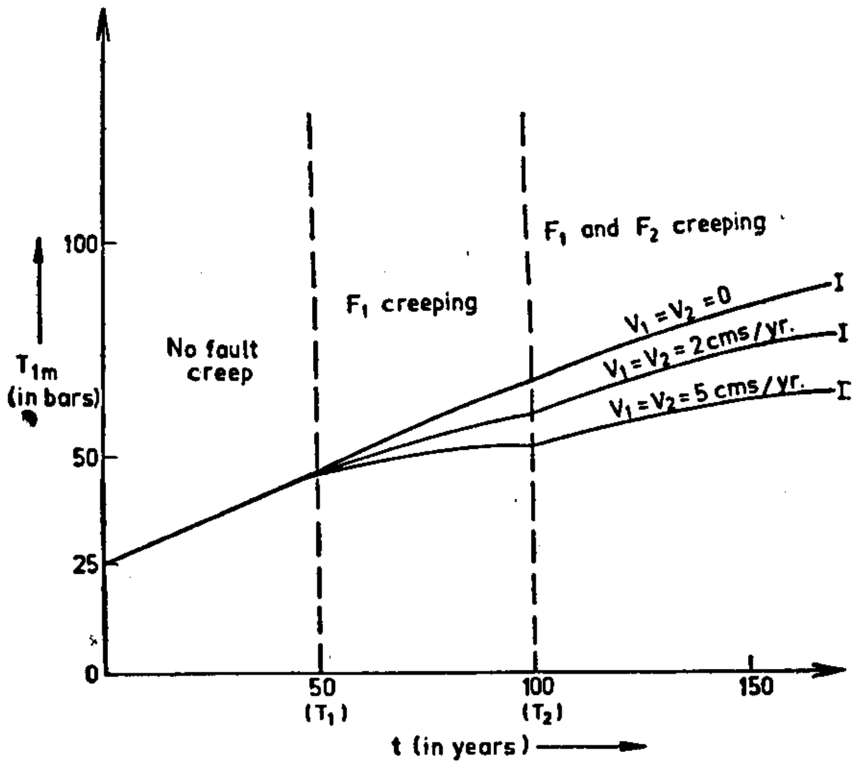

Fig. 9 : Changes in the maximum shear stress near F_2 with time (F_1, F_2 at the same level)

seismic faults movement. Creep across either fault reduces the rate of accumulation of shear stress near itself and, to a smaller extent near the other fault, and in the case $V_1 = V_2 = 5$ cms / year; the cumulative effect of fault creep when both the faults are creepig (for $t > T_2$), leads to a steady aseismic release of shear stress near the faults, reducing progressively the possibility of a seismic fault movement generating an earthquake. This effect is qualitatively similar to the effect of two creeping surface-breaking strike-slip faults on each other, discussed by Mukherji & Mukhopadhyay (1984) We note here that Fig 8 and Fig. 9 show the changes with time in the shear stress τ_{12} near F_1 and F_2 for the same model for which Fig. 6 shows the variations with time of the surface shear strain above F_1 and F_2 Fig. 10 and Fig. 11 correspond to the situation in Fig.5, with F_1 vertically above F_2 and with $d_1 = 5$ Kms, $D_1 = 15$ Kms, $d_2 = 20$ Kms, $D_2 = 30$ Kms and $D = 0$. As in Fig. 8 and Fig 9, the curves I, II and III correspond to $V_1 = V_2 = 0$, $V_1 = V_2 = 2$ cms/year and $V_1 = V_2 = 5$ cms/year respectively.

Fig. 10 and Fig. 11 show the variations of the quantities T_{1m} and T_{2m} defined earlier. We note that, in this case, the effect of creep across one fault on the shear stress near the other is significantly different. Creep across one fault, in this case, reduces the rate of stress accumulation near itself, and increases the rate of accumulation of shear stress near the other fault, which is vertically above or below. As a consequence of this effect, even in the case $V_1 = V_2 = 5$ cms/year, there is no release of shear stress even when both the faults are creeping, upto t = 160 years. In fact, as shown is Fig. 10, while creep across F_1, starting at t = T_1, reduces the rate of accumulation of shear stress near F_1, the rate is again increased after t = T_2, when F_2 also starts creeping. Fig. 11 shows that after t = T_1,

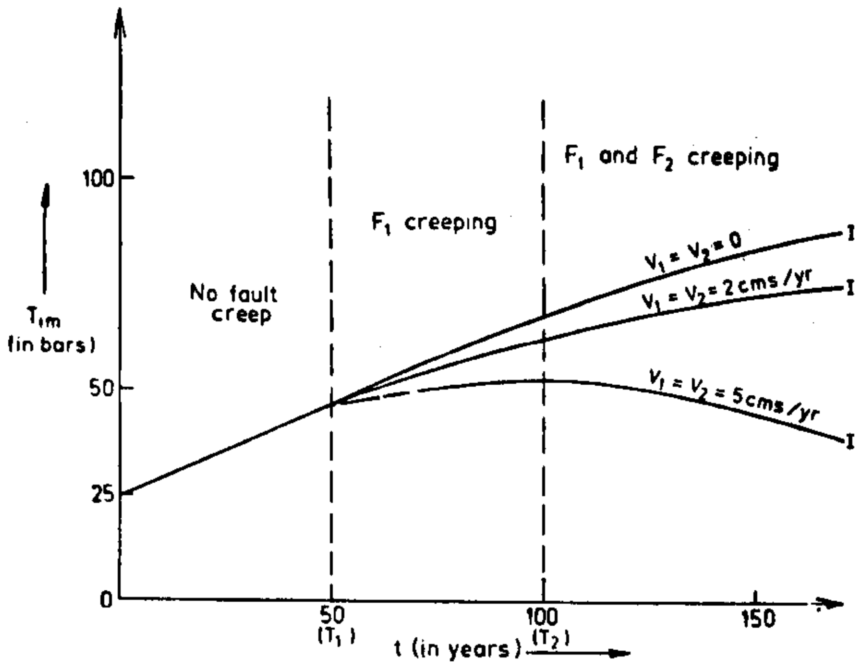

Fig. 10 : Changes in the maximum shear stress near F_1 with time (F_1 vertically above F_2)

creep across F_1 increases the rate of accumulation of shear stress near F_2. But the rate is reduced after t = T_2, when F_2 also starts creeping. We note that Fig. 10 and Fig. 11 correspond to the same model for which Fig. 7 shows the variations with time of the surface shear strain above F_1 and F_2. We finally note that, in this case, with one fault vertically above or below the other, interaction between the faults results in increasing accumulation of shear stress near them, increasing the possibility of a sudden seismic fault movement, generating an earthquake. However, in this case, in which the faults are parallel and at the same level, as in Fig. 4, interaction results in aseismic release of shear stress, so that the possibility of a sudden seismic fault movement, generating an earthquake is progressively reduced. This shows that the effect of fault creep in system of buried and interacting

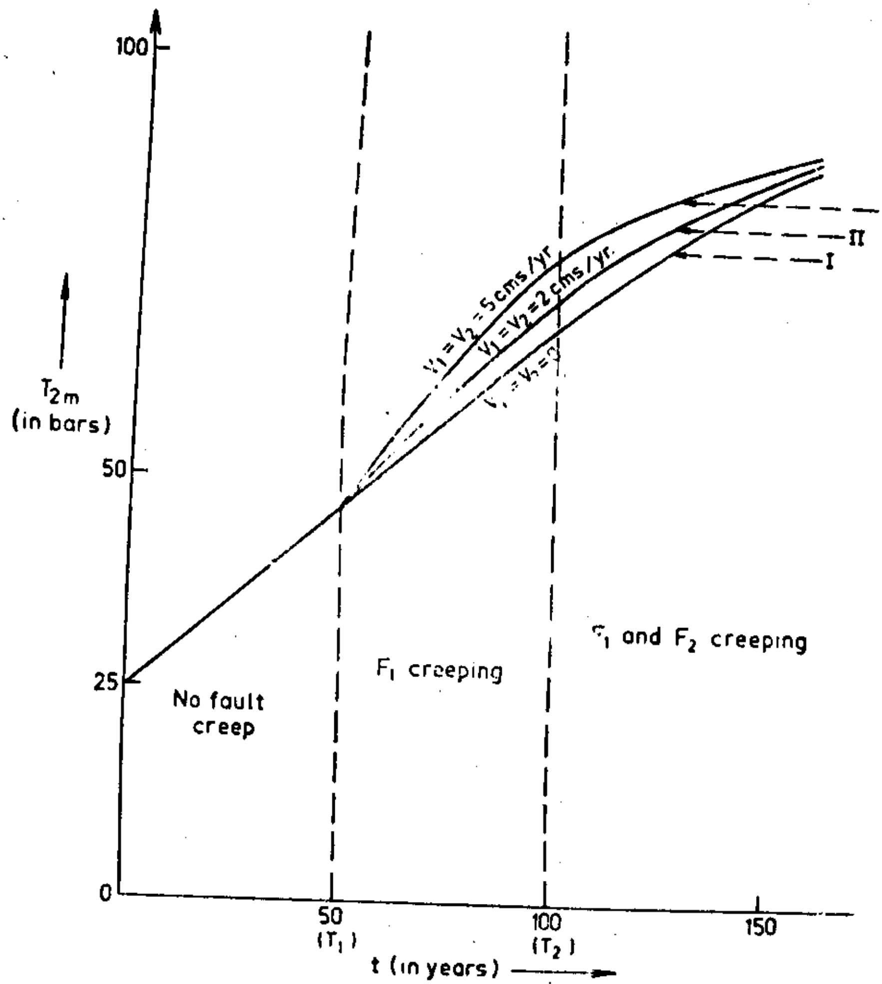

Fig. 11 : ***Changes in maximum shear stress near F_2 with time (F_1 vertically above F_2)***

faults depends significantly on the relative positions of the faults, and may lead to aseismic stress accumulation or release, depending on their relative positions.

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