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 tne 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 of aseismic surface movements, in seismically active regions have been developed in recent years, and heve been discussed by Mukherji and Mukhopadhyay (1984, 1986) 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 and Mukhopaday (1984, 1986). have considered theoretical models with two interacting faults, and have explained the significance of fault, interacting in the process of stress accumulation and release in seismically active regions. In these theoretical models, the faults were taken to be both buried or both surface-breaking. Keeping in view the possibility of creep across faults of a fault system with buried as well as surface-breaking faults, a theoretical model of the lithosphere-asthenosphere system, with a surface-breaking fault and a buried fault, has been considered in this paper.

FORMULATION

We consider a simple model of the lithosphere-asthenosphere system consisting of a visco-elastic half space with its material of the Maxwell type. We considered 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 one of the faults (F_1) to be burried. and the other (F_2) is taken to be surface-breaking. We introduce rectangular cartesian co-ordinates (y_1, y_2, y_3) with the free surface as the plan $y_3 = 0$ and the y_3 — axis pointing into the half-space, We take the y_1 —axis to be parallel to the plane of the faults. Then we can assume that the displacements, stresses and strains will be indesendent of y_1. We take the pianes ot the faults F_1 and F_2 be given by $y_2 = 0$ and $y_2 = D$ respectively. Let D_1 be the depth of the lower edge of F_1 below the free-surface. Also let d_2 and D_2 be the depths of the upper and lower edges of the fault F_2 below the free surface. Fig 1 shows the section of the model by the plan $y_1 = 0$ For the model, since the displacements, stresses and strains are independent of y_1, we find that the displacament component u_1 along the y_1 axts 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 relations,

$$\left(\frac{1}{\eta} + \frac{1}{\mu}\frac{\partial}{\partial t}\right)\tau_{13} = \frac{\partial^2 \mu_1}{\partial t\, \partial y_3}$$

and

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

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

where μ is the effective rigidity and η is the effective viscosity, as in Mukherji and Mukhopadhyos (1984, 1986).

We consider the model during aseismic periods, leaving out the relatively small periods (if any) following sudden fault movements, 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

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

$$(-\infty < y_2 < \infty,\ y_3 \geqslant 0,\ t \geqslant 0) \qquad \text{...... (2)}$$

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

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

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

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

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

$$\tau_{13} = 0, \text{ on } y_3 = 0$$

$$(t \geq 0,\ -\infty < y_2 < \infty) \qquad \text{...... (4)}$$

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

$$\tau_{13} \longrightarrow 0 \text{ as } y_3 \longrightarrow \infty$$

$$(\text{for } -\infty < y_2 < \infty,\ t \geq 0). \qquad \text{...... (5)}$$

and

$$\tau_{12} \longrightarrow \tau_\infty \text{ as } y_2 \longrightarrow \infty$$

$$\text{for } y_3 \geq 0,\ t \geq 0) \qquad \text{...... (6)}$$

DISPLACEMENTS AND STRESSES IN THE ABSENCE OF FAULT MOVEMENT

In the absence of any movement across the faults, the displacement 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 functions of (y_2, y_3), be the values of (u_1), (τ_{12}), (τ_{13}) at $t = 0$. $(u_1)_0$, $(\tau_{12})_0$, $(\tau_{13})_0$ also satisfy the relations (1)—(6).

The initial and boundary value problem is solved, following exactly the same method as in Mukherji and Mukhopadhyay (1984, 1986), using Laplace transforms, to obtain

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

As in Mukherji and Mukhopadhyay (1984, 1986), we find from [7), that if the shear stress τ_{12} near the faults, tending to cause strike-slip movements is less than τ_∞ at $t = 0$, then there would be a continuous accumulation of shear stress near the faults for $t > 0$, with $\tau_{12} \to \tau_\infty$ near the faults, as $t \to \infty$.

We assume, as in Mukherji and Mnkhopadhyas (1984, 1986) 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 determind by the values of τ_c, τ_c' and the value of $(\tau_{12})_0$ near tne 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 w:th the following conditions of creep across F_1 and F_2

$$[u_1]_1 = U_1(t_1) f_1(y_3) H(t_1) \quad \ldots\ldots (8a)$$

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

and $$[u_1]_2 = U_2(t_2) f_2(y_3) H(t_2) \quad \ldots\ldots (8b)$$

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

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

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

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

$$[u_1] = 0 \text{ for } t \leqslant T_1.$$

The velocity of creep across F_1 is

$$\frac{\partial}{\partial t}[u_1]_1 = V_1(t_1) f_1(y_2)$$

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

Again $[u_1]_2 = \underset{y_2 \to D+0}{Lt}(u_1) - \underset{y_2 \to D-0}{Lt}(u_1)$

$$(d_2 \leqslant y_3 \leqslant D_2)$$

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

$$\frac{\partial}{\partial t}[u_1]_2 f_2(y_2) = V_2(t_2)$$

where $V_2(t_2) = \frac{d}{dt_2}[U_2(t_2)]$.

T_1 and T_2 ($\geqq 0$) are the times of commencement of creep across F_1 and F_2 respectively. In cause no creep occurs at any time across F_1 or F_2. we simply take

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

or $\quad U_2(t_2) = 0 \quad$ for all $t \geqq 0$,

So that $[u_1]_1 = 0$ or $[u_1]_2 = 0$ for all $t \geqq 0$.

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 :

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

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) :

$$(\tau_{12})_2 \to 0 \text{ as } [y_2] \to \infty \quad (y_3 \geqq 0 \text{ . } t \geqq t_1) \qquad \text{...... (10a)}$$

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) :

$$(T_{12})_3 \rightarrow 0 \text{ as } [y_2] \rightarrow \infty \ (y_3 \geq 0, t \geq T_2) \qquad \text{...... (11b)}$$

In this case, it is clear that the solutions (9) will satisfy (1) - (6), (8a) and (8b). We note that $(u_1)_1$, $(\tau_{12})_1$, $(\tau_{13})_1$ satisfy exactly the same conditions as those satisfied by u_1, τ_{12}, τ_{13} in the absence of fault creep movement. Hence, $(u_1)_1$, $(\tau_{12})_1$, $(\tau_{13})_1$ have the same expressions as those for u_1, τ_{12}, π_{13} given in (7).

On substituting $t_1 = t\text{-}T_1$, 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)

$$\left(\frac{1}{\eta}+\frac{1}{\mu}\frac{\partial}{\partial t_1}\right)\left(\mathrm{T}_{12}\right)_2 = -\frac{\partial^2 (u_1)_2}{\partial t_1\, \partial y_2}$$

$$\left(\frac{1}{\eta}+\frac{1}{\mu}\frac{\partial}{\partial t_1}\right)\left(\tau_{13}\right)_2 = -\frac{\partial^2 (u_1)_2}{\partial t_1\, \partial y_3} \qquad \text{......(1a)}$$

$$\frac{\partial}{\partial y_2}\left(\tau_{12}\right)_2 + \frac{\partial}{\partial y_3}\left(\tau_{13}\right)_2 = 0 \qquad \text{.............. (2a)}$$

$$\nabla^2 (u_1)_2 = 0 \qquad \text{....................(3a)}$$

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

$$(\tau_{13})_2 = 0 \text{ as } y_3 = 0 \quad (-\infty < y_2 < \infty,\ t_1 \geq 0) \qquad \text{........... (4a)}$$

$$(\tau_{13})_2 \rightarrow 0 \text{ as } y_3 \rightarrow \infty \ (-\infty < y_2 < \infty,\ t_1 \geq 0) \qquad \text{...........(5a)}$$

$$(\tau_{12})_2 \rightarrow 0 \text{ as } y_2 \rightarrow \infty \ (y_3 \geq 0,\ t_1 \geq 0) \qquad \text{............(6a)}$$

$[(u_1)_2] = u_1(t_1)\, f_1\,(y_3)$ accross F_1
$(y_2 = 0,\ 0 \leqslant y_3 \leq D_1)$.

and ......(7a)

$(u_1)_2$, $(\tau_{12})_2$, $(\tau_{13})_2 = 0$ for $t_1 \leqslant 0$

To obtain solutions for $(u_1)_2$, $(\tau_{12})_2$, $(\tau_{13})_2$ for $t_1 \leqslant 0$, 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 by Mukherji and Mukhopadhyay (1984, 1986). On inverting the Laplace transforms, as in Mukherji and Mukhopadhyay (1984, 1986), we

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

$$(\tau_{12})_2 = H(t-T_1) \left(-\frac{\mu}{2\pi}\right) \int_0^t V_1(\tau) e^{-\frac{\mu(t_1-\tau)}{\eta}} \phi_{11}(y_2, y_3)\, d\tau \quad \text{......(12)}$$

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

$$(y_2 \neq 0) \quad \text{......(13)}$$

where $t_1 = t-T_1$, $H(t-T_1)$ is the Heaviside function, so that $H(t-T_1) = 0$ for $t \leq T_1$ and $H(t-T_1) = 1$ for $t > T_1$

$$\Psi_{11}(y_2, y_3) = \int_0^{D_1} f_1(x_3)\left[\frac{y_2}{(x_3-y_3)^2+y_2^2} + \frac{y_2}{(x_3+y_3)^2+y_2^2}\right]dx_3 \quad \text{......(14)}$$

$$\phi_{11}(y_2, y_3) = \frac{\partial\Psi_{11}}{\partial y_2} = \int_0^{D_1} f_1(x_3)\left[\frac{(x_3-y_3)^2-y_2^2}{\{(x_3-y_3)^2+y_2^2\}^2} + \frac{(x_3+y_3)^2-y_2^2}{\{(x_3+y_3)^2+y_2^2\}}\right]dx_3 \quad \text{......(15)}$$

and $$\phi_{21}(y_2, y_3) = \frac{\partial\Psi_{11}}{\partial y_3} = \int_0^{D_1} 2f_1(x_3)\left[\frac{(x_3-y_3)y_2}{\{(x_3-y_3)^2+y_2^2\}^2} - \frac{(x_3+y_3)y_1}{\{(x_3+y_3)^2+y_2^2\}^2}\right]dx_3 \quad \text{......(16)}$$

$(y_2 \neq 0)$

In (11) — (16), $U_1(t_1)$ and $V_1(t_1)$ vanish for $t_1 \leqslant 0$ i.e., $t \leqslant T_1$. We now consider the functions $(u_1)_2$, $(\tau_{12})_2$, $(\tau_{13})_2$. These functions satisfy the relations (1a) — (6a), with t_1 replaced by t_2, together with the following relation.

$$[u_1]_2 = U_2(t_2)\, f_2(y_3) \text{ across } F_2$$

$$(d_2 \leqslant y_3 \leqslant D_2,\ y_2 = D) \quad \text{...... (7b)}$$

replacing (7a). $(u_1)_3$, $(\tau_{12})_3$, $(\tau_{13})_3 = 0$ for $t_3 \leq 0$.
Now following the sams procedure as in the determination of $(u_1)_2$, $(\tau_{12})_2$ $(\tau_{13})_2$, we obtain the expressions for $(u_1)_3$, $(\tau_{12})_3$, $(\tau_{13})_3$ as follows :-

$$(u_1)_3 = H(t - T_3) \frac{U_3(t_3)}{\pi} \Psi'_{11}(y'_2, y_3')$$

$$(\tau_{12})_3 = H(t - T_3) \left(\frac{\mu}{2\pi}\right) \left[\int_0^{t_3} V_3(\tau)\, e^{-\frac{\mu}{\eta}(t_3 - \tau)} dt\right] \phi'_{11}(y_2', y_3)$$

$$(\tau_{13})_3 = H(t - T_3) \left(\frac{\mu}{2\pi}\right) \left[\int_0^{t_3} V_3(\tau)\, e^{-\frac{\mu}{\eta}(t_3 - \tau)} d\tau\right] \phi_{21}'(y_2', y_3')$$

$$(y'_2 \neq 0, \text{ i.e., } Y_2 \neq D) \qquad \ldots\ldots (17)$$

$$\text{where } \Psi'_{11}(y_2', y_3') = \int_{d_3}^{D_3} f_3(x_3) \left[\frac{y_2'}{(x_3 - y_3')^2 + y'^2_2} + \frac{y_2'}{(x_3 + y'_3)^2 + y'^2_2}\right] dx_3 \qquad \ldots\ldots (18)$$

$$\phi'_{11}(y_2', y'_3) = \int_{d_3}^{D_3} f_3(x_3) \left[\frac{(x_3 - y_3')^2 - y'^2_2}{\{(x_3 - y_3')^2 + y'^2_2\}^2} + \frac{(x_3 + y'_3)^2 - y'^2_2}{\{(x_3 + y_3')^2 + y_2'^2\}^2}\right] dx_3 \qquad \ldots\ldots (19)$$

$$\phi'_{21}(y_2', y_3') = \int^{D_3} f_3(x_3) \left[\frac{2y'_2 (x_3 - y_3')}{\{(x_3 - y'_3)^2 + y'^2_2\}^2} - \frac{2y_2' (x_3 + y_3')}{\{(x_3 + y_3')^2 + y_2'^2\}^2}\right] dx_3 \qquad \ldots\ldots (20)$$

$$(y'_2 \neq 0)$$

where $y_2' = y_2 - D$, $y_3' = y_3$.

Hence finally we obtain complete expressions for u_1, τ_{12}, τ_{13} from (9), where $(u_1)_1$, $(\tau_{12})_1$, $(\tau_{13})_1$ have the same expressions as those for u_1, τ_{12}, τ_{13} given in (7), $(u_1)_2$, $(\tau_{12})_2$, $(\tau_{13})_2$ are given by (11) — (16), and $(u_1)_3$, $(\tau_{12})_3$, $(\tau_{13})_3$ are given by (17) — (20).

The shear strain e_{12} is given by

$$e_{12} = \frac{\partial u_1}{\partial y_2} = (e_{12})0 + \frac{\tau\infty\, t}{\eta}$$

$$+ H(t - T_1)\, \frac{U_1(t_1)}{2\pi}\, \phi'_{11}(y_2, y_3)$$

$$+ H(t - T_2)\, \frac{U_2(t_2)}{2\pi}\, \phi'_{11}(y_2, y_3) \qquad \ldots\ldots (21)$$

($t_1 = t - T_1$, $t_2 = t - T_2$, $y_2 = y_2 - D$, $y_3 = y_3$),

The integrals for Ψ_{11}, ϕ_{11}, ϕ_{21}, Ψ'_{11}, ϕ'_{11}, ϕ'_{21} in (14) — (20) can be obtained in closed form if $f_1(y_3)$, $f_2(y_3)$ are polynomials. In particular, if the relative displacement due to creep is independent of depth, so that

$f_1(y_3) = \text{constant} = K$ (say)

$(0 \leqslant y_3 \leqslant D_1)$,

and $f_2(y_3) = \text{constant} = K'$ (say) $\quad (d_2 \leqslant y_3 \leqslant D_2)$.

we find, as in Mukherji and Mnkhopadyay (1984, 1986), that ϕ_{11}, ϕ_{21}, ϕ'_{11}, ϕ'_{21}(and hence τ_{12}, τ_{13}, τ'_{12}, τ'_{13}) have singularities at the lower edge of the surfacebreaking fault and at the upper and lower edges of the buried faults. Following exactly the method mentioned in Mukherji and Mukhopadyay (1984, 1986) we find that the integrals Ψ_{11}, ϕ_{11}, ϕ_{21}, Ψ_{11}, ϕ'_{11}, ϕ'_{21} are finite everywhere in the model, including the edge of faults, for all finite (y_2, y_3, t), provided the following conditions are all satisfied simultaneously by $f_1(y_3)$ and $f_2(y_3)$:

(A) Conditions to be satisfied by $f_1(y_3)$:

(i) $f_1(y_3)$ and $f_1'(y_3)$ are continuous in $0 \leqslant y_3 \leqslant D_1$

(i i) $f_1''(y_3)$ is either continuous in $0 < y_3 < D_1$, or has a finite number of points of finite discontinuity in $0 < y_3 < D_1$.

(iii) either $f_1''(y_3)$ is finite and continuous at $y_3 = 0$ and $y_3 = D_1$ or there exist real finite constant m and n, both < 1, $(y_3)^m f_1''(y_3) \to 0$ or to a finite limite as $y_3 \to 0 + 0$ and $(D_1 - y_3)^n f_1''(y_3) \to 0$ or to a finite limit as $y_3 \to D_1 - 0$. ......(22A)

(iv) $f_1(D_1) = 0$, $f_1'(D_1) = 0 = f_2'(0)$.

These conditions imply that the magnitude of the relative displacement across the fault varies smoothly with depth and approaches zero with sufficient smoothness as $y_3 \to D_1 \to 0$ at the lower edge.

(B) Conditions to be satisfied by $f_2(y_3)$:

(i) $f_2(y_3)$, $f'_2(y_3)$, are continuous in $d_2 \leqslant y_3 \leqslant D_2$

(i i) $f_2(d_2) = f_2(D_2) = f_2'(d_2) = f_2'(D_2) = 0.$

(iii) $f_2''(y_3)$ is either continuous in $d_2 < y_3 < D_2$

or has a finite number of points of finite discontinuity in $d_2 < y_3 < D_2$

and (iv) either $f_2''(y_3)$ is finite and contiuuous at (22B)

$y_3 = d_2$ and and $y_3 = D_2$,

or there exist real finite constants m and n both <1,

such that

$$(y_3 - d_2)^m f_2(y_3) \to 0$$

or to a finite limit as $y_3 \to d_2 + 0$

and $(D_2 - y_3)^n f_2''(y_3) \to 0$

or to a finite limit as $y_3 \to D_2 \to 0$.

If $f_1(y_3)$ and $f_2(y_3,)$ satisfy the above conditions, in order to facilitate evaluation of the integrals, we carry out integration by parts of the integrals in the expressions for displacement, stress and strain and express the integrals in the following forms:-

$$\Psi_{11}(y_2, y_3) = -\int_{-y_3}^{D_1-y} f_1'(y_3 + y)\tan^{-1}\left(\frac{y}{y_2}\right) dy - \int_{y_3}^{D_1+y_3'} f_1(z - y_3)\tan^{-1}\left(\frac{z}{y_2}\right) dz \quad \ldots\ldots (23)$$

$$\phi_{11}(y_2, y_3) = -\tfrac{1}{2}\left[\int_{-y_3}^{D_1-y_3} f_1''(y+y_3)\log_e(y^2 + y_2^2)\, dy + \int_{y_3}^{D_1+y_3} f_1''(z - y_3)\log_e(z^2 + y_2^2)\, dz\right] \quad \ldots\ldots (24)$$

$$\phi_{21}(y_2, y_3) = -\int_{-y_3}^{D_1-y_3} f_1'(y_3 + y)\tan^{-1}\left(\frac{y}{y_2}\right) dy - \int_{y_3}^{D_1+y_3} f_1'(z - y_3)\tan^{-1}\left(\frac{z}{y_2}\right) dz \quad \ldots\ldots (25)$$

$$\Psi'_{11}(y_2', y_3') = -\int_{d_2-y_3'}^{D_2-y_3'} f_2'(y_3'+y)\tan^{-1}\left(\frac{y}{y'_2}\right)dy$$

$$-\int_{d_2+y'_3}^{D_2+y'_3} f_2(z-y_3)\tan^{-1}\left(\frac{z}{y'_2}\right)dz \qquad \text{...... (26)}$$

$$\phi'_{11}(y_2', y'_3) = -\tfrac{1}{2}\Big[\int_{d_2-y'_3}^{D_2-y_3'} f_2''(y+y_3)\log_e(y^2+y_2^2)\,dy$$

$$+\int_{d_2+y'_3}^{D_2+y'_3} f_2''(z-y'_3)\log_e(z^2+y'^2_2)\,dz\Big] \qquad \text{...... (27)}$$

$$\phi'_{21}(y'_2, y_3') = -\int_{d_2-y'_3}^{D_2-y_3'} f_2''(y'_3-y)\left[\tan^{-1}\left(\frac{y}{y'_2}\right)\right]dy$$

$$-\int_{d_2+y'_3}^{D_2+y'_3} f_2''(z-y_3')\left[\tan^{-1}\left(\frac{z}{y'_2}\right)\right]dz \qquad \text{...... (28)}$$

The primes in $f_1'(y_3+y)$, $f_1''(z-y_3)$, $f_2'(y_3'+y)$, $f_2''(z-y_3)$ etc. denote differentiation with respect to the argument. The intigrals, in (23)-(28) can be expressed in closed form in terms of elementary functions if $f_1(y_3)$, $f_2(y_3)$ are polynomials satisfying (22a) and (22b). Otherwise, they can be evaluated approximately without difficulty by numerical integration if $f_1(y_3)$, $f_2(y_3)$ satisfy (22A) and (22B), but are not polynomials.

DISCUSSION OF THE RESULTS AND CONCLUSIONS :

To study in greater detail the changes of displacements, stresses and strains and strains near the faults with time, and specially the influence of faults creep, we compute the changes of the surface displacement u_1 and surface shear strain e_{12} near the faults, as well as the shear stress τ_{12} near the faults, tending to cause strike-slip movement, for relevant values of the model parameters μ, η, D_1, D_2, D, $\tau\infty$ and for relevant types of creep velocities the faults, Keeping in view the case of shallow strike-slip faults in the lithosphere. we take values for μ in the range (3 to 4) X 10^{11} dynes/cm^2, while D_1, D_2, D d_2 are taken to have values in the range 5 to 40 kms, with $d_2 > D_2$. The computations have been carried out for some simple types of fault creep, where the creep displacements across F_1 and F_2 are given by

$$\left[u_1 \right] = V_1 t_1 \, f_1 (y_3) \, H \, (t - T_1)$$

across F_1

and $$\left[u_1 \right] = V_2 \, t_2 \, f_2 \, (y_3') \, H \, (t - T_2)$$

across F_2,

where V_1, V_2 are constants, so that creep velocities do not change with time, and f_1 (y_3), f_2 (y'_3) are polynomials, satisfying the conditions (22 A) and (22B) for finite displacements, stresses and strains, so that u_1, e_{12}, τ_{12}, J_{12} are finite for all finite (y_2, y_3, t) in the model. In particular, we consider the case in which

$$\left.\begin{aligned} f_1 (y_3) &= 1 - \frac{3y^3_3}{D^2_1} + \frac{2y_3^3}{D^3_1} \\ \text{and} & \\ f_2 (y'_3) &= \frac{16(y_3' - d_2)^2 \; (D_2 - y'_3)^2}{(D_2 - d_2)^4} \end{aligned}\right\} \quad \text{........(29)}$$

For V_1 and V_2, we consider values in the range O to 5 cms/year, which is the range of observed creep velocities on the surface across creeping strike-slip faults in North America. For η, we consider values in the range 10^{21}—10^{22} poise, keeping in view the fact that Cathles (1976) has obtained results on post-glacial uplift and corresponding theoretical results for theoretical models of the lithosphere-asthenosphere system with values of μ in this range. For $\tau\infty$, we consider values in the range 50 to 200 bars, and for $(\tau_{12})_0$ near the faults we consider values in the range O to 100 bars ; with $(\tau_{12})_0 < \tau\infty$ in all cases.

The computed values of displacements stresses and strains show that, in the absence of fault creep, there is a gradual accumulation of the shear strain e_{12} and the shear stress τ_{12} near the faults, increasing the possibility of a strik-slip fault movement. The rate of accumulation of τ_{12} decreases slowly with time, and ultimately $\tau_{12}\tau\infty$ if no fault creep occurs. But if creep occurss F_1 or F_2 or both, it has a significant influence on the displacements, stresses and strains near F_1 and F_2, where the nature of the effect of fault creep depends on the following factors :-

(a) the creep velocities and their variation with depth [i.e., V_1, V_2, $f_1(y_3)$, $f_2(y_3')$]

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

(c) the relative positions of the faults,

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

(e) the displacements, stresses and strains present at t=O,

(f) the shear stress τ_{00} far away from the faults, maintained by tectonic forces.

From the computed values, it is found that, when the creep across a fault commences, it reduces the rate of accumulation of surface shear strain and shear stress near itself. For sufficiently large creep velocities across a fault, there is a continuous aseismic release of shear stress near the fault under suitable circumstances, so that the possibility of a sudden fault movement, generating an earthquake is reduced continuously.

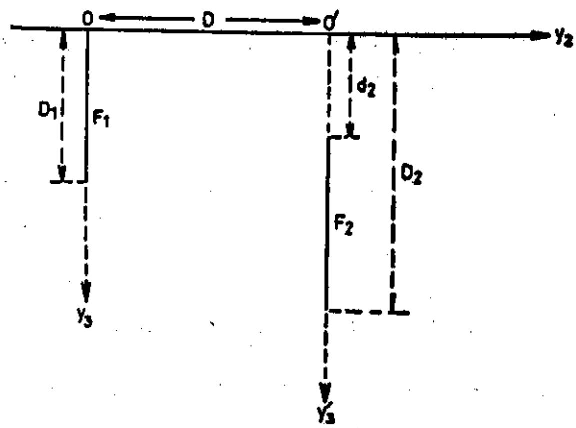

Fig. 1. Section of the model by the plane y_1=0

The effect of creep across one fault on the shear stress and strain near the other depends significantly on the relative positions of the faults and also on their depths and dimensions and the distance between them. Considering the effect of creep across F_1 or F_2, we find that if F_2 lies in a perticular region of the model, which we call f_1, creep across F_1 increase the rate of accumulation of shear stress near F_2. But if F_2 lies in two others regions of the model which we call R_1 and R_2, the creep across F_1 reduces the rate of accumulation of shear stress near F_2 These regions are shown in Fig. 2.

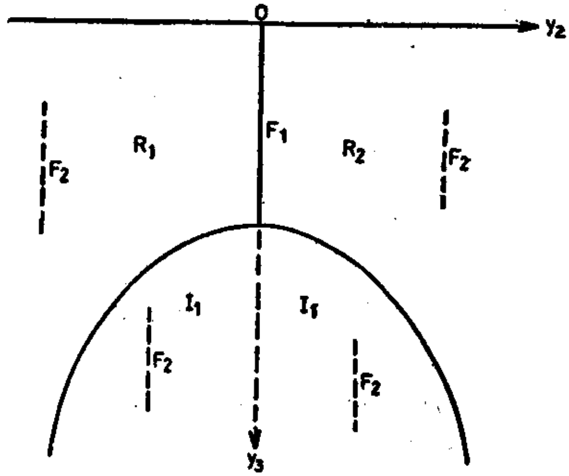

Fig. 2. Creep across F_1—regions of increase in the rate of shear stress accumulation (I_1) and decrease in the rate of shear stress accumulation (R_1, R_2).

If F_1 and F_2 are more or less at the same level, then creep across any one fault reduces the rate of accumulation of shear stress and shear strain near the other, so that creeping faults tend to release shear stresses and strain near each other, thus reducing the possibility of a sudden seismic fault movement. But if one fault is more or less vertically below the other then creep across one fault tends to increase the rate of accumulation of shear stress and strain near the other, increasing the possibility of a sudden seismic fault movement. In this case, the faults tend to reinforce the accumulation of shear stress and strain near each ather.

The influence of one fault on the other is found to decrease quite rapidly with increase in the distence between them, and if $D >> (D_1, D_2)$, the effect of creep acioss one fauit on the shear stress and strain near the other becomes small. However, in this case also, creep across a fault reduces the rate of accumulation of shear stress and strain near itself.

In the absence of fault creep, the rate of accumulation of shear strain on the surface near F_1 and F_2 is found to be of the order of 10^{-7} per year, which is of the same order of magnitude as the observed rate of surface shear strain accumulation near the locked northern and southern parts of the San Andreas fault.

If the creep velocity across F_1 and F_2 does not change with time [i.e.,

$V_1(t_1)$, $V_2(t_2)$] are constants the magnitude of the effect of fault creep across F_1 and F_2 on the shear stresses are found to be proportional to the creep velocities. If the creep velocities change with time, the relation is more complex. But, in this case also, an increase in the creep velocity across a fault leads to an increase in the magnitude of the effect of creep on the shear stresses near the fault itself and near the other fault.

On computing the surface shear strain, whose changes with time can be monitored by repeated geodetic surveys and instrumental observations, we find that, in our model, fault creep has a significant effect on the surface shear strain $(e_{12})\ y_3=0$. For the surface breaking fault F_1, it is found that fault creep across F_1 reduces the rate of accumulation of surface shear strain in the regions above F_1 and F_2. But for the buried fault F_2, it is found that creep across F_2 results in increase in the rate of accumulation of the surface shear strain $(e_{12})\ y_3=0$ in a region $E_1'E_2'$ vertically above F_2, and in its reduction outside this region, which is shown in Fig.3. The width of $E_1'E_2'$ pepends on the fault paremeters d_2, D_2 and f_2 (y_3') for F_2, and $E'_1E'_2$ is symmetrical obout the line on the surface $y_3=0$ vertically above F2.

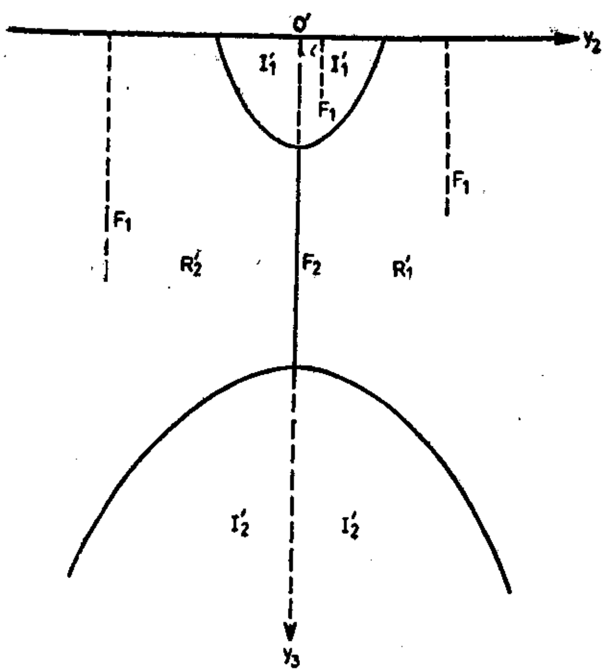

Fig. 3 : Creep across F_2-region of increase in the rate of shear stress accumulation (I'_1, I'_2) and regions of decrease in the rate of shear stress accumulation (R'_1, $R'2$)

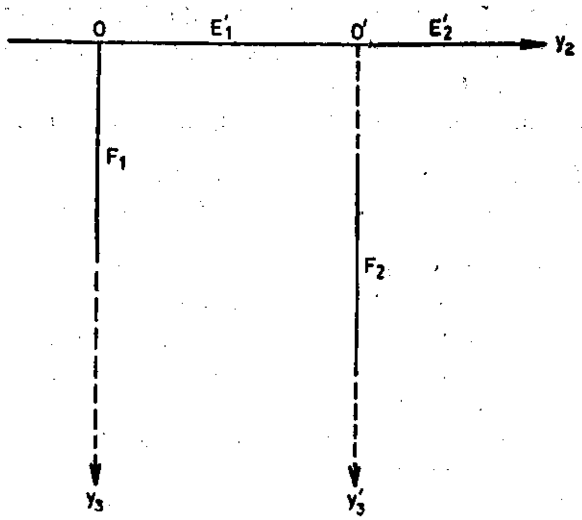

Fig. 4 : Region E'_1, E'_2 of increase in the rate of accumulation of surface shear strain due to creep across F_2

Fig. 4 shows the changes in the shear strain e_{12} on the surface above the faults and the shear stress τ_{12} near the faults, tending to cause strike-slip fault movements, for some typical values of the model parameters, which are given as follows :-

$\eta = 10^{22}$ poise,

$\mu = 3 \times 10^{11}$ dynes/cm^2,

$(\tau_{12})_0 = 25$ bars in the region of the faults,

$[u_1] = v_1 t_1 f_1 (y_3') H(t - T_1)$ across F_1

and $[u_1] = v_2 t_2 f_2 (y_3') H(t - T_2)$ across F_2,

where $f_1 (y_3)$, $f'_2 (y_3^1)$ are given by (29), and V_1, V_2 are in the range 0 to 5 cms/year In the first situation, F_1 and F_2 are in different parallel planes, and have similar dimensions The configuration is shown in Fig. 5. In the second situation, F_1 is vertically above F_2 This configuration is shown in Fig 6. Fig 7 shows the changes with time of the quantity.

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

(=change in surface shear strain X 10^7), at points vertically above F_1 and F_2, in the different planes as in Fig. 5,

with $D_1 = D_2 = D = 15$ Kms,

and $d_2 = 5$ kms,

$T_1 = 50$ years,

$T_2 = 100$ years,

$V_1 = V_2 = 2$ Cms/year.

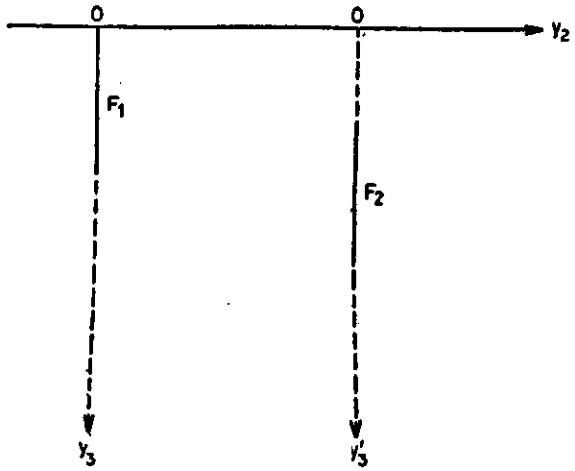

Fig. 5 : F_1 and F_2 in different parallel planes with approximately similar dimensions and at levels which do not differ appreciably.

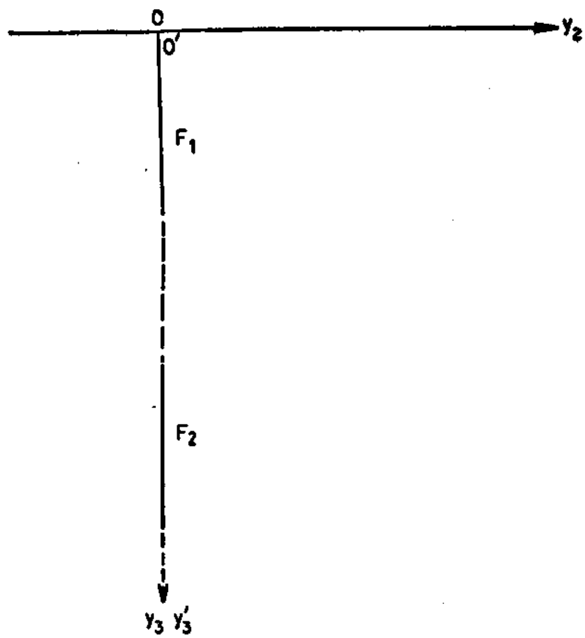

Fig. 6 : F_1 vertically above F_2

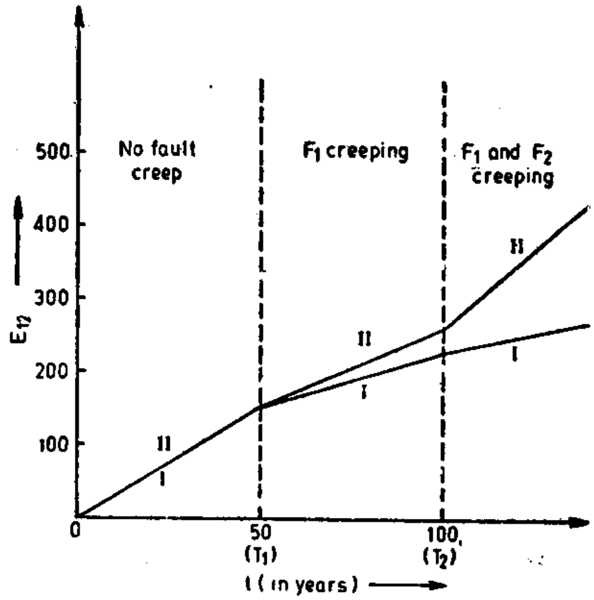

Fig. 7 : Changes in the surface shear strain with time above F_1 and F_2 which are in different parallel planes as in Fig. 5. The lines I and II correspond to points vertically above F_1 and F_2 respectively.

The lines I and II show the changes in E_{12} with the time t at surface points vertically above F_1 and F_2 respectively. Creep across F_1, which starts earlier in this case, is found to decrease the rate of accumutation of surface shear strain near F_1 itself, and to a lesser extent, above F_2 Subsequent creep across F_2, in this case, is found to increase the rate of accumulation of surface shear strain vertically above F_2 itself, while decreasing further the rate of accumulation of surface shear strain above F_1.

Fig 8 shows the variations in the same quantity E_{12} with time, in the case in which F_2 is vertically above E_2, as in Fig 6 with $D_1=15$ kms, $d_2=20$ kms, $D_2=35$ kms, $D=0$, $V_1=V_2=2$ cms/year, $T_1=50$ year, and $T_2=100$ years, on the surface $y_3=0$ vertically above F_1 and F_2 It is found, in this case, that creep across F_1 decreases the rate of accumulation of surface shear strain above F_1 and F_2. But subsequent creep across F_2 again increases the rate of accumulation of surface shear strain above F_1 and F_2, although this compensates only partially for the effect of creep, across F_1, which tends to decrease this rate.

Fig. 9 shows the variations of the quantity

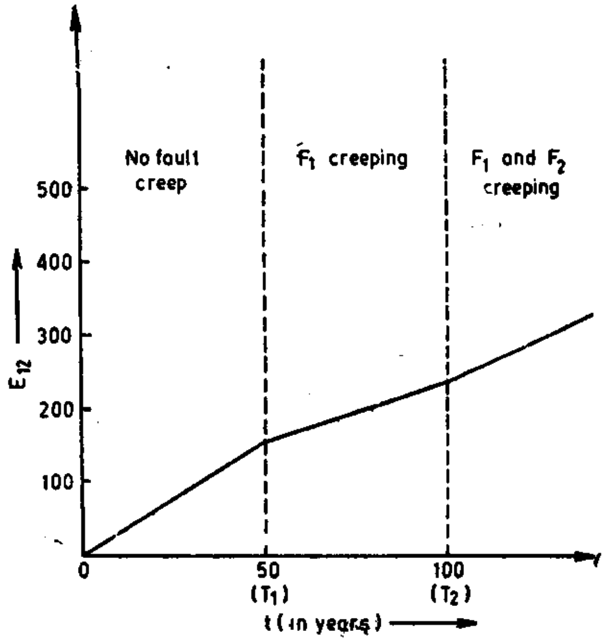

Fig. 8 : Changes in the surface shear strain above F_1 and F_2 with time in the case in which F_1 is veritically above F_2 as in Fig. V. 6

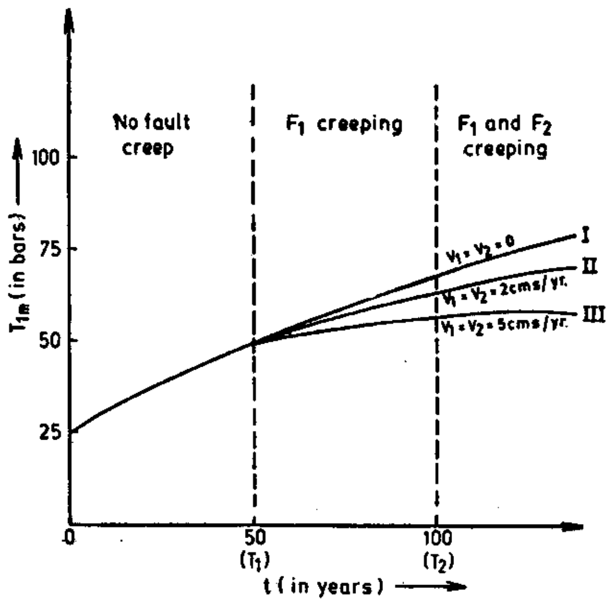

Fig 9 : Changes in T_{1m}, the maximum shear stress near F_1, with time, where F_1 and F_2 are in different parallel planes, as in Fig. 5.

T_{1m}=max $[(\tau_{12})y_2 \to 0, O \leqslant y_3 \leqslant D_1)]$
with time, in the case in which F_1 and F_2 are in different parallel planes, with $D_1=D_2=D=15$ kms, $d_2=5$kms, $T_1=50$ years and $T_2=100$ years.

The curves I, II and III in Fig. 9 corresponds to $V_1=V_2=0$ (no fault creep),
$V_1=V_2$ cms/year and
$V_1=V_1=5$ cms/year respectively.

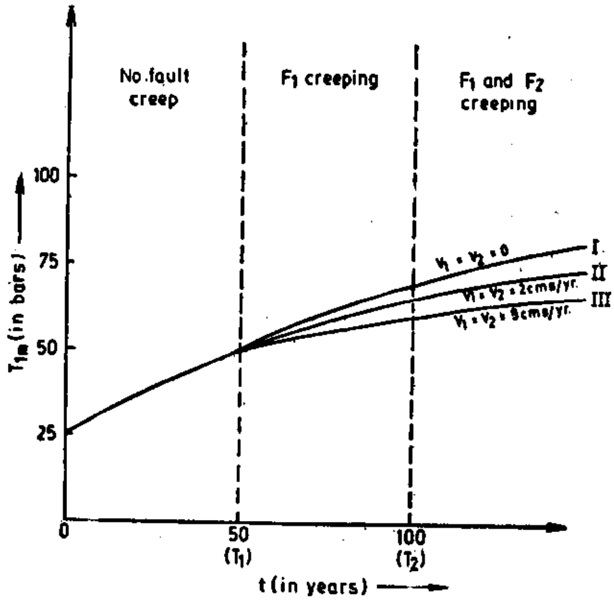

Fig. 10 . Changes in T_{2m}, the maximum shear stress near F_2, with time, where F_1 and F_2 are in different parallel planes, as in Fig. 5.

Fig. 10 also corresponds to exactly the same model, with the same alues of D_1, D_2, D, d_2, T_1 and T_2, and it shows the variation of time of T_{2m}=max $[(\tau_{12})y_2' \to 0, d_2 \leqslant y'_3 \leqslant D_2]$.

In Fig. 10, the curves I, II and III corresponds to $V_1=V_2=0$, $V_1=V_2=2$ cms/year and $V_1=V_2=5$ cms/year respectively. Here T_{1m}, and T_{2m} which are functions of t, represent at any time t the maximum values of the shear ress τ_{12} near the faults E_1 and F_2 respectively at that time. Fig. 9 and Fig. 10, we find that, in the absence of fault creep, there is a steady accumulation of shear stress near F_1 and F_2. The rate of increase oftshear stress falls off slowly with time. This accumulation of shear stress increases the possibility of a student seimic fault movement. Creep acaoss each fault reduces the rate of accumulation of shear stress near itself, and to a lesser extent near the other fault, in the case considered here. For the case $V_1=V_2=5$ cms/year, when both the faults are creeping for $t > T_2$, the cumulative effect of creep acro s the two faults is found to lead to a steady aseismic release of the maximum shear stress near F_1 and F_2, so that the possibility of a sudden seismic fault movement is progressively reduced. The model to which Fig 9 and Fig. 10 corresponds is the same as the model for which Fig. 7 shows the variations of the surface shear strain above F_1 and F_2, with the same values of the model parameters.

In Fig. 11 and Fig. 12, we have shown the variations with time of the quantities T_{1m} and T_{2m} respectively, defined earlier, in the case in which F_1 is vertically above F_2, as in Fig. 6 with $D_1=15$ kms, $d_2=20$ kms, $D=35$ kms, $D=0$, $T_1=50$ years and $T_2=100$ years. In this case, creep across F_1 or F_2 tends to release the shear stress τ_{12} near the fault itself, but tends to increase the rate of shear stress accumulation near the other neighbouring fault.

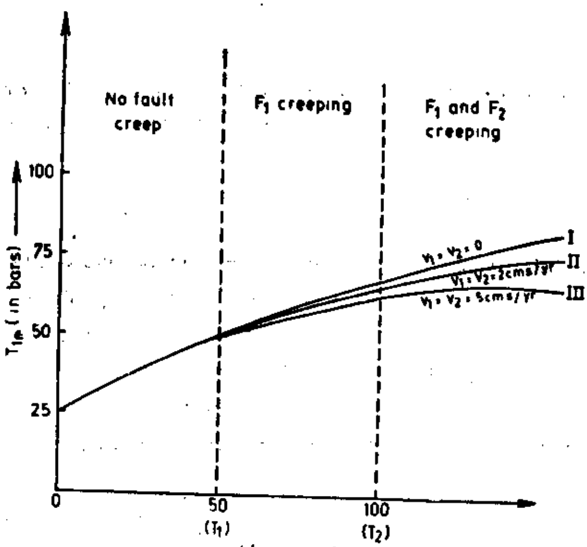

Fig. 11 ; Changes with time of T_{1m}, the maximum shear stress near F_1, with F_1 vertically above F_2, as in Fig. 6.

In conclusion, we may say, that we find that the effect of fault creep on a fault system consisting of a buried fault and a surface-breaking fault depeneds significantly on the relative positions of the faults, and may lead

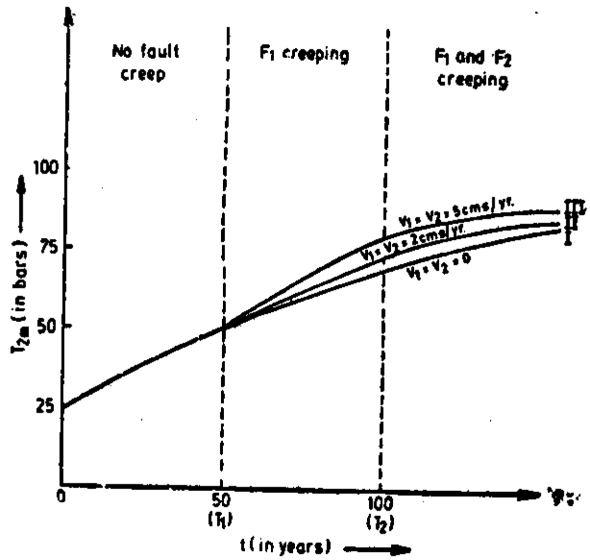

Fig. 12 : Changes with time of T_{2m}, the maximum shear stress near F_1 is vertically above F_2, as in Fig. V, 6.

to aseismic stress accumulation or stress release depending on their mutual positions, as well as other model parameters, including creep velocity.

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