JOURNAL OF GEOPHYSICAL RESEARCH VOL. 74, NO. 15, JULY 15, 1969

Heat Flow, Stress, and Rate of Slip along the San Andreas Fault, California[1]

JAMES N. BRUNE, THOMAS L. HENYEY,[2] ROBERT F. ROY[3]

Seismological Laboratory, California Institute of Technology
Pasadena, California 91109

The absence of a heat flow anomaly greater than ~0.3 μcal/cm^2/sec associated with the San Andreas fault is used to estimate the upper limit for the steady state or initial shear stress. Under the assumption that the long-term rate of motion along the fault is 5 cm/yr and occurs primarily in the form of creep, this upper limit is about 100 bars. If the motion is primarily accomplished by faulting during large earthquakes and if the frictional stress is equal to the final stress as suggested by E. Orowan (1960), the upper limit is estimated to be about 200 bars. Without Orowan's assumption, the estimation of the upper limit is about 250 bars, based on earthquake energy-magnitude-moment relations. If the long-term rate of motion along the San Andreas fault is only ~2 cm/yr, these results are increased to 250, 350, and 400 bars, respectively.

INTRODUCTION

For the past four years, the California Institute of Technology has been conducting field studies to determine if any detectable heat flow anomaly exists over the San Andreas and other related fault zones in California. The result of these studies has been negative; i.e., no significant heat flow anomaly related to the fault zones has been demonstrated [*Wasserburg et al.*, 1966; *Henyey and Wasserburg*, 1969; *Henyey*, 1968]. A heat flow determination from a hole drilled 3 km from the fault near Hollister [*Henyey*, 1968], along with one from another hole 35 km from the fault drilled by the Granite Rock Company [*Roy et al.*, 1969], suggested that there might be a heat flow anomaly over the fault near Hollister. This possibility was especially intriguing since motion along this portion of the fault is characterized by creep [*Tocher*, 1960; *Whitten*, 1955]. The energy represented by work done during the creep process is practically all converted to heat since no energy is transported away from the fault in the form of elastic waves. Thus, depending upon the magnitude of the shear stress, a frictional heat flow anomaly might be more likely in an area such as Hollister than in regions where creep is occurring.

To investigate the possibility of an anomaly at Hollister, the number of heat flow measurements across the fault was increased. Eight of a proposed total of ten measurements have been completed [*Roy et al.*, 1969]. At the present time, the data suggest a transition from low heat flow in the Salinian block west of the fault to high heat flow in the Diablo block immediately east of the fault, with no frictional anomaly over the fault. This negative result, together with the results of *Henyey and Wasserburg* [1969] and *Henyey* [1968], is used here to estimate an upper limit for the steady state or initial shear stress.

HEAT FLOW FROM FAULT FRICTION

Steady-state frictional heat generation along a vertical strike-slip fault plane in a homogeneous medium will produce a heat flow anomaly that is symmetric and has a maximum directly over the fault. The shape and magnitude of the anomaly in the neighborhood of the fault will depend on the distribution of frictional heat generation with depth (Figure 1). The anomaly caused by frictional heating on the section of the fault shallower than 20 km will become small at distances greater than 20 km from the

---

[1] Contribution 1580, Division of Geological Sciences, California Institute of Technology, Pasadena.

[2] Now at University of Southern California, Los Angeles, California.

[3] Now at University of Minnesota, Minneapolis, Minnesota.

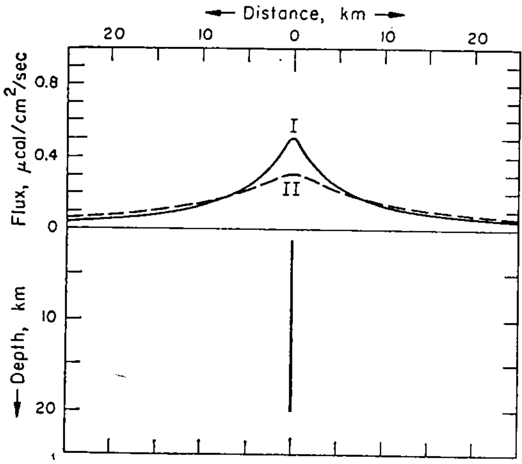


Fig. 1. Surface heat flux from a fault plane source of heat between depths of 1 and 20 kilometers. Case I: Uniform source intensity on fault plane. Case II: Source intensity a linear function of depth. Both cases have been normalized to a total heat production of 1 cal/sec/cm of fault length.

fault trace. The shape of the heat flow anomaly plotted as a function of distance from the fault is fundamental to this study because of the distribution of heat flow measurements across the fault. A single measurement of heat flow at the fault trace, for example, would have little meaning since the observed heat flow could be explained by numerous source distributions, including a very weak source immediately under the point of measurement.

Frictional heat generation by a strike-slip fault zone of finite breadth will produce a broader heat flow anomaly. The shape and magnitude of the anomaly in this case will depend on the distribution of frictional heat generation with the breadth as well as on the depth of the fault zone, as shown in Figure 2. The details of this calculation are given by *Henyey* [1968]. However, for the San Andreas fault near Hollister and Lake Hughes, we suggest on the basis of geological considerations that the effective fault zone, i.e. the region across which most of the motion occurs, can be represented to a good approximation by a vertical plane. The transition from the granitic rocks west of the fault to the Franciscan sedimentary rocks east of the fault can be observed to take place across a zone less than 2 km wide at many places over a section of the fault a hundred km long [see, e.g., California State Geologic Map, 1959]. For this reason, it is not necessary to discuss broad sources. We will confine our discussion to heat produced in a single vertical plane, the surface projection of which is the present fault trace.

good geological constraint

The mechanism of frictional heat generation assumed here is illustrated in Figure 3. The rate of work done per centimeter of fault length by the fault motion is given by the product of the average shear stress $\bar{\sigma}$ (in the case of creep) or the average frictional shear stress $\bar{\sigma}_f$ (in the case of faulting), the depth of the fault zone *d*, and the average long-term rate of slip $\bar{\dot{u}}$. For example, for a stress of 125 bars, a depth of 20 km, and a slip rate of 5 cm/yr, heat is generated at the rate of 1.0 cal/sec/cm of fault length. The long-term displacement of the fault is assumed to be independent of depth; i.e., the top of the block must move the same as the bottom. At some deeper depth non-elastic flow processes must occur.

As a first approximation, assume that the frictional heat along the fault is liberated by a steady-state line source at a depth *a*, in which case the shape of the anomaly at the surface is determined according to the formula [obtained from equation 7, p. 262, *Carslaw and Jaeger*, 1959].

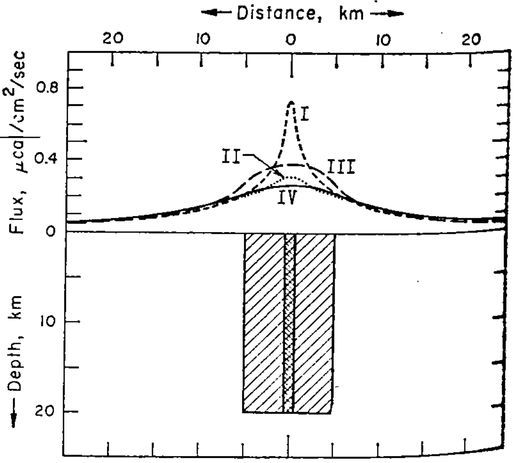


Fig. 2. Heat flux from a fault zone extending to a depth of 20 kilometers. Case I: 1 km wide fault zone with a uniform source intensity. Case II: 1 km wide zone with source intensity a linear function of depth. Case III: 10km wide zone with source intensity a linear function of depth. All cases have been normalized to a total heat production of 1 cal/sec/cm of fault length.

$$Q = \frac{q}{\pi}\left[\frac{a}{x^2 + a^2}\right]$$

In this equation, Q is the surface
anomaly (component normal to the s
is the rate of heat generation per unit
the line source, and x is the horizonta
perpendicular to the surface projecti
line source. Steady-state curves for
10 and 20 km, normalized to a heat p
value of 1.0 cal/sec/cm of fault le
shown in Figure 4. Also shown is a c
resenting the surface heat flow anom
sponding to a transient line source a
of 10 km initiated one million years
solution to which is given by:

$$Q = \frac{q}{\pi}\left[\frac{a}{x^2 + a^2}\right] \exp - \left[\frac{x^2 +}{4\kappa}\right.$$

where κ is the thermal diffusivity and t
since the source was turned on. In this
anomaly maximum is about one ha
steady-state height and somewhat narr

Figure 5 presents theoretical steady-s
flow anomalies for some more realistic
tions of stress and heat generation on t
20 km of the fault plane. These were c
by superimposing line sources to give th
distribution of heat sources with dept
cases, the surface stress is zero and
with depth. The stress below 20 km is
to be zero, and the rate of slip is assum
5 cm/yr over the entire fault plane f
surface to 20 km. In case I, the stress is
a depth of 1 km, at which point it incr
250 bars, remaining constant to a dept
km; thus, the heat production per ce
of fault for this model is about 2 cal/sec

why?

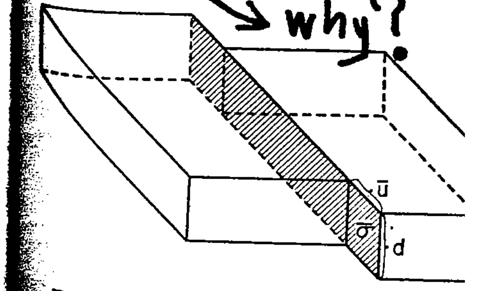
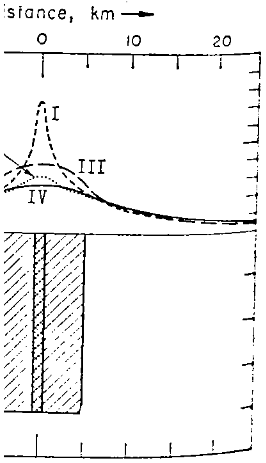


Fig. 3. Assumed model of heat genera
strike-slip faulting. $\bar{\sigma}$ is the average shea
$\bar{u}$ the average rate of slip, and *d*, the d
faulting.

Geologic Map, 1959]. For
necessary to discuss broad
ine our discussion to heat
vertical plane, the surface
the present fault trace.

frictional heat generation
ated in Figure 3. The rate
timeter of fault length by
ven by the product of the
(in the case of creep) or
shear stress $\bar{\sigma}_f$ (in the case
of the fault zone d, and
rate of slip $\bar{\dot{u}}$. For example,
, a depth of ~~20 km, and~~ a
heat is generated at the
~~of fault~~ length. The long-
~~he fault~~ is assumed to be
i.e., the top of the block
as the bottom. At some
stic flow processes must

tion, assume that the fric-
fault is liberated by a
e at a depth a, in which
nomaly at the surface is
o the formula [obtained
62, *Carslaw and Jaeger*,



a fault zone extending
ters. Case I: 1 km wide
n source intensity. Case
source intensity a linear
II: 10km wide zone with
function of depth. All
ed to a total heat pro-
fault length.

$$Q = \frac{q}{\pi}\left[\frac{a}{x^2 + a^2}\right]$$

In this equation, Q is the surface heat flow anomaly (component normal to the surface), q is the rate of heat generation per unit length by the line source, and x is the horizontal distance perpendicular to the surface projection of the line source. Steady-state curves for depths of 10 and 20 km, normalized to a heat production value of 1.0 cal/sec/cm of fault length, are shown in Figure 4. Also shown is a curve representing the surface heat flow anomaly corresponding to a transient line source at a depth of 10 km initiated one million years ago, the solution to which is given by:

$$Q = \frac{q}{\pi}\left[\frac{a}{x^2 + a^2}\right] \exp - \left[\frac{x^2 + a^2}{4\kappa t}\right]$$

where κ is the thermal diffusivity and t the time since the source was turned on. In this case, the anomaly maximum is about one half of its steady-state height and somewhat narrower.

Figure 5 presents theoretical steady-state heat flow anomalies for some more realistic distributions of stress and heat generation on the upper 20 km of the fault plane. These were computed by superimposing line sources to give the proper distribution of heat sources with depth. In all cases, the surface stress is zero and increases with depth. The stress below 20 km is assumed to be zero, and the rate of slip is assumed to be 5 cm/yr over the entire fault plane from the surface to 20 km. In case I, the stress is zero to a depth of 1 km, at which point it increases to 250 bars, remaining constant to a depth of 20 km; thus, the heat production per centimeter of fault for this model is about 2 cal/sec and the average stress about 250 bars. In case II, the stress increases linearly from zero at the surface to 400 bars at 10 km and remains constant to a depth of 20 km. The heat production for this model is about 2½ cal/sec/cm of fault, and the average stress is 300 bars. In case III, the stress increases linearly to a value of 800 bars at a depth of 20 km, the heat production being about 3 cal/sec/cm of fault and the average stress 400 bars. The assumption that the stress is zero below 20 km is not critical. An average stress of 125 bars from 20 to 40 km would only increase the heat flow at the fault by 0.1 μcal/cm^2/sec. The heat flow resulting from stresses below 40 km could not be resolved by the present distribution of heat flow locations in the vicinity of the fault, i.e., it could not be distinguished from a regional increase in heat flow.

why?

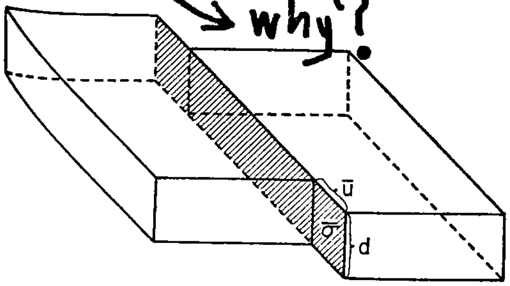


Fig. 3. Assumed model of heat generation by strike-slip faulting. $\bar{\sigma}$ is the average shear stress; $\bar{u}$ the average rate of slip, and d, the depth of faulting.

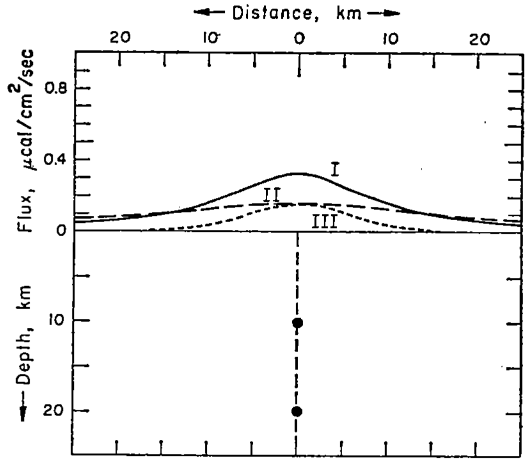


Fig. 4. Heat flux from line sources at depths of 10 and 20 km. Case I: Steady-state line source at 10 km. Case II: Steady-state line source at 20 km. Case III: Source at 10-km depth which has existed for last 1 m.y. All cases have been normalized to a heat production rate of 1 cal/sec/cm of fault length. Diffusivity is taken as $\simeq$ 0.01.

Considering the various curves in Figures 4 and 5, we conclude that, for slip rates of 5 cm/yr, a heat flow anomaly of about 1 μcal/cm^2/sec at the fault trace will be produced by a stress that averages about 300 bars in the upper 20 km of the fault plane.

DISCUSSION

The results of the study of *Roy et al.* [1969], indicate that if any frictional heat flow anom-

perhaps Little contribution below.

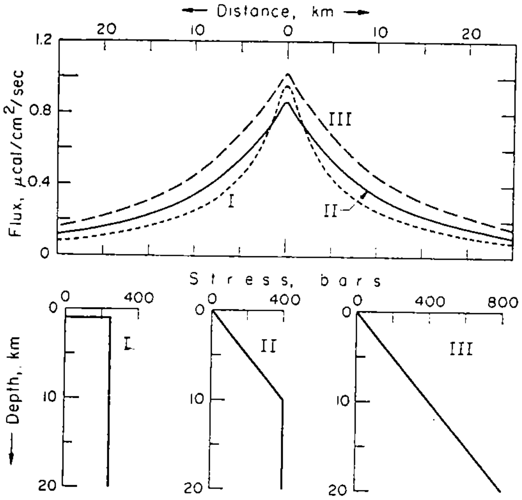


Fig. 5. Heat flux from fault planes having three different stress distributions. The stress distributions for the three cases are shown. The curves have been calculated using the technique described by *Henyey* [1968].

aly is present in the flow profile at Hollister, its amplitude is less than 0.3 μcal/cm²/sec in the neighborhood of the fault. Likewise, heat flow determinations across the fault near Lake Hughes in southern California [*Henyey and Wasserberg*, 1969] suggest that in this region, where the stress has historically been released by large earthquakes (e.g. the 1857 Fort Tejon earthquake) a symmetric component is essentially absent (<0.1 μcal/cm²/sec). Their results also indicate no heat flow anomaly greater than 0.3 μcal/cm²/sec associated with heat production along other major faults in southern California. Using these observations, we may establish an approximate upper limit to the product of the average stress and the average rate of slip.

In the case of steady-state creep, the motion along the fault occurs in a continuous or episodic manner at rates sufficiently slow that no significant energy is carried away from the fault as elastic waves (i.e. earthquakes). Thus, essentially all the work done by steady-state creep is released as heat in the neighborhood of the fault.

The long-term steady-state creep rate along the San Andreas fault at Hollister is not known with certainty but is probably of the order of a few centimeters per year. *Tocher's* [1960] data indicate that the creep rate at the Hollister Winery has an average value of about 1.5 cm/yr. The triangulation results of the U.S. Coast and Geodetic Survey [*Whitten*, 1955], indicate a motion of 5 cm/yr for points 20 km from the fault on either side. Geologic studies suggest long-term rates of motion along the San Andreas fault of the order of a couple of centimeters per year [*Hill and Dibblee*, 1953; *Crowell*, 1962; *Dickinson and Grantz*, 1968]. Recent measurements of magnetic anomaly offsets in the southern Gulf of California [*Larson et al.*, 1968] indicate a rate of slip of about 6 cm/yr for the last 4 million years. It is important to note that in discussing surface heat flow due to frictional heat generation on a fault plane, one is concerned with the long-term rates of motion (over approximately the last 5 million years) since the thermal time constants are typically of the order of several million years for this problem (see Figure 4). Of course present rates of motion may reflect short-term variations in slip rates [*Crowell*, 1962].

Previous studies of stress along the San Andreas fault have been inconclusive as far as initial or steady-state stress is concerned. Stress drops inferred for large earthquakes along the San Andreas fault are usually greater than 10 bars and less than 100 bars [*Chinnery*, 1964; *Brune and Allen*, 1967; *King and Knopoff*, 1968]; therefore, we expect initial stresses of about 50 bars or greater (initial stress must be greater than or equal to the stress drop). Chinnery [1964] concludes that the strength of the crust along faults is about 100 bars. Rupture strengths of rocks indicated by laboratory studies at pressures corresponding to depths of the order of 10 km and indicated by theoretical calculations [*Jeffreys*, 1959] are more than an order of magnitude greater, but it may be that the conditions along actual faults might lead to the low rupture strengths inferred in our study and in other studies of faulting. Repeated faulting may produce fault gouge of relatively low strength. The presence of serpentine along the fault zone might decrease the strength [*Allen*, 1968; *Byerlee and Brace*, 1968]. Also, fluids with high pore pressure can reduce the strength of rock [*Hubbert and Rubey*, 1959; *Rubey and Hubbert*, 1959; *Byerlee*, 1967]. Stable sliding may occur even at high pressures [*Scholtz et al.*, 1969]. We further suggest that the inferred high temperatures on the east side

---

of the fault near Hollister may in pa
sponsible for the apparent low streng
rocks. However, we admit that none
explanations is completely established.

The negative result obtained in the s
a heat flow anomaly over the San Andı
establishes an approximate upper lim
product of steady-state creep rate and
heat flow anomaly of about 0.3 μcal
will be produced by a steady-state cree
5 cm/yr at a stress of about 100 bars.
aly greater than 0.3 μcal/cm²/sec
would have been detected.

Alternatively, if motion of 5 cm/yr
lister and other locations along the San
fault is primarily accomplished by rap
ing during earthquakes, we may esta
approximate upper limit of 100 bars
frictional stress operating during faulti
the work done against friction goes i
Orowan [1960] has suggested that
stress during faulting be equated to
stress after faulting. If this is so, the
heat flow anomaly at Hollister and ot
along the San Andreas fault indicate
proximate upper limit to the initial
100 bars plus the stress drop. Since stre
are less than 100 bars along the San
fault [*Brune and Allen*, 1967; *Chinner*
an approximate upper limit for the init
under these conditions is 200 bars. At
Hughes profile, the upper limit to a
heat flow anomaly may even be less
Hollister; thus the upper limit on th
stress may be considerably lower than
This would imply a seismic efficienc
[*King and Knopoff*, 1968] near unity
earthquakes.

If we do not invoke Orowan's argu
garding the equivalence of the frictio
final stress, it is still possible to esti
upper limit for the initial stress for larg
quakes along the San Andreas fault.
assume that the total energy release
equal to the sum of the seismic (E_s) a
tional (E_f) energies (no other significa
of energy release), i.e.

$$E_t = E_s + E_f$$

it follows that

$$\bar{\sigma} = \eta\bar{\sigma} + \bar{\sigma}_f$$

of the fault near Hollister may in part be responsible for the apparent low strength of the rocks. However, we admit that none of these explanations is completely established.

The negative result obtained in the search for a heat flow anomaly over the San Andreas fault establishes an approximate upper limit to the product of steady-state creep rate and stress. A heat flow anomaly of about 0.3 μcal/cm^2/sec will be produced by a steady-state creep rate of 5 cm/yr at a stress of about 100 bars. An anomaly greater than 0.3 μcal/cm^2/sec probably would have been detected.

Alternatively, if motion of 5 cm/yr at Hollister and other locations along the San Andreas fault is primarily accomplished by rapid faulting during earthquakes, we may establish an approximate upper limit of 100 bars for the frictional stress operating during faulting, since the work done against friction goes into heat. *Orowan* [1960] has suggested that frictional stress during faulting be equated to the final stress after faulting. If this is so, the lack of a heat flow anomaly at Hollister and other areas along the San Andreas fault indicates an approximate upper limit to the initial stress of 100 bars plus the stress drop. Since stress drops are less than 100 bars along the San Andreas fault [*Brune and Allen*, 1967; *Chinnery*, 1964], an approximate upper limit for the initial stress under these conditions is 200 bars. At the Lake Hughes profile, the upper limit to a frictional heat flow anomaly may even be less than at Hollister; thus the upper limit on the initial stress may be considerably lower than 200 bars. This would imply a seismic efficiency factor [*King and Knopoff*, 1968] near unity for large earthquakes.

If we do not invoke Orowan's argument regarding the equivalence of the frictional and final stress, it is still possible to estimate an upper limit for the initial stress for large earthquakes along the San Andreas fault. If we assume that the total energy release (E_t) is equal to the sum of the seismic (E_s) and frictional (E_f) energies (no other significant form of energy release), i.e.

$$E_t = E_s + E_f$$

it follows that

$$\bar{\sigma} = \eta\bar{\sigma} + \bar{\sigma}_f$$

where $\bar{\sigma}$ is the total average stress operating during fault slippage, $\bar{\sigma}_f$ is the average frictional stress and η is the seismic efficiency. Using the equation [after *Aki*, 1966; *Brune*, 1968]

$$\eta\bar{\sigma} = \mu(E_s/M_0)$$

where μ is the rigidity and M_o is the seismic moment, the apparent seismic stress $\eta\bar{\sigma}$ is estimated to be about 100 bars for the 1906 San Francisco earthquake (assuming the validity of the Gutenberg-Richter magnitude energy relation and the source moment given by *Brune and Allen* [1967]). Similar values would be obtained for other earthquakes. Thus we have

$$\bar{\sigma} \simeq 100 + \sigma_f \qquad \text{bars}$$

From above we have

$$\bar{\sigma}_f \leq 100 \qquad \text{bars}$$

Thus

$$\bar{\sigma} \leq 200 \qquad \text{bars}$$

Now we can write the average stress as

$$\bar{\sigma} = (\sigma_1 + \sigma_2)/2$$

where σ_1 and σ_2 are the initial and final stresses, respectively. Thus

$$(\sigma_1 + \sigma_2)/2 \leq 200 \qquad \text{bars}$$

or $\sigma_1 \leq 400$ bars $- \sigma_2$. In addition, we have the constraint that the stress drop, $\sigma_1 - \sigma_2 \leq 100$ bars for large earthquakes. Hence

$$\sigma_1 \leq 250 \qquad \text{bars}$$

Thus an upper limit of about 250 bars can be placed on the initial stress by assuming the Gutenberg-Richter energy versus magnitude relationship and the source moment indicated by field evidence. Again an average long-term rate of slip of 5 cm/yr is assumed.

If the long-term rate of slip along the San Andreas fault is only ~ 2 cm/year [see *Dickenson and Grantz*, 1968] the upper limit on $\bar{\sigma}_f$ is increased to about 250 bars. This increases the upper limits on initial stress estimated above to 250, 350, and 400 bars, respectively. The last two estimates are critically dependent on the energy versus magnitude relationship of Gutenberg and Richter, which is somewhat uncertain. If the energy output of large earthquakes is much greater than indicated by this relationship, then the upper limits on initial stresses are increased. Verification of the energies radiated by large earthquakes awaits further study; however we feel that extreme value for energy could not increase the upper limit on initial stress to greater than 1000 bars and that the most probable value for average initial stress is about 100 to 200 bars.

CONCLUSION

Under the assumption that the long-term average rate of slip is 5 cm/yr for the San Andreas fault and that the heat flow anomaly is 0.3 μcal/cm^2/sec, then the following may be concluded about tangential stress along the upper 20 km of the fault:

1. If almost all the 5 cm/yr of fault motion at Hollister is accomplished by creep, the lack of a frictional heat flow anomaly greater than 0.3 μcal/cm^2/sec establishes an upper limit of about 100 bars for the average steady-state stress over the last several million years.
2. If most of the fault motion is accomplished by periodic earthquakes, the lack of an anomaly both at Hollister and other locations along the San Andreas fault, establishes an upper limit of about 100 bars for the average frictional stress operating during faulting. If we assume after Orowan that the frictional stress is equal to the final stress after faulting, and if we further assume that stress drops along the San Andreas fault are less than 100 bars, an upper limit to the average initial stress of about 200 bars is indicated.
3. Without Orowan's assumption, an upper limit of about 250 bars can be deduced for the initial stress by estimating values for the stress drop, the source moment, and the energy release. In this case the upper limit is primarily determined by the energy of large earthquakes, which is uncertain by a factor of at least 2. If the Gutenberg-Richter energy relation gives an estimate of energy too low by a factor of 2, the upper limit on initial stress might be raised to about 500 bars.

If the long-term rate of slip along the San Andreas fault is only about 2 cm/yr, the upper limits derived above will all be increased by 250 bars. On the other hand, if the upper limit for the frictional heat flow anomaly is lower, say 0.1 μcal/cm^2/sec as indicated near Lake Hughes, then the upper limits above will be decreased. Considering all the uncertainties involved we think that for extreme values, if all uncertainties act to increase the stress, the average initial stress could be as high as a kilobar, but the data strongly suggest that it is about 100 to 200 bars.

Acknowledgments We are indebted to Mr. Tom Baldwin who assisted in much of the field work and to Prof. Gerald Wasserburg who participated in helpful discussion.

This research was supported by the NSF under NSF grant GA 715 (Heat Flow).

REFERENCES

Aki, K., Generation and propagation of *G* waves from the Niigata earthquake of June 16, 1964, 2, Estimation of earthquake moment, released energy, and stress-strain drop from the *G* wave spectrum, *Bull. Earthquake Res. Inst. Tokyo Univ., 44,* 73, 1966.

Allen, C. R., The tectonic environments of seismically active and inactive areas along the San Andreas fault system, in *Proceedings of Conference on Geologic Problems of San Andreas Fault System,* edited by W. R. Dickenson and A. Grantz, Stanford University Publications, Stanford, California, 1968.

Brune, James N., Seismic moment, seismicity, and rate of slip along major fault zones, *J. Geophys. Res., 73,* 777–784, 1968.

Brune, J. N., and C. R. Allen, A low stress-drop, low-magnitude earthquake with surface faulting: The Imperial Valley, California earthquake of March 4, 1966, *Bull. Seismol. Soc. Am., 57,* 501–514, 1967.

Byerlee, J. D., Frictional characteristics of granite under high confining pressure, *J. Geophys. Res., 72,* 3639–3648, 1967.

Byerlee, J. D., and W. F. Brace, Stick-slip, stable sliding, and earthquakes, *J. Geophys. Res., 73,* 6031–6039, 1968.

California State Geologic Map, Santa Cruz Sheet, Olaf D. Jenkins edition, California State Division of Mines, 1959.

Carslaw, H. S., and J. C. Jaeger, *Conduction of Heat in Solids,* 497 pp., Oxford University Press, London, 1959.

Chinnery, M. A., The strength of the earth's crust under horizontal shear stress, *J. Geophys. Res., 69,* 2085–2089, 1964.

Crowell, J. C., Displacement along the San Andreas fault, California, *Geol. Soc. Am. Spec. Paper 71,* 61 pp., 1962.

Dickinson, W. R., and A. Grantz (Eds.), *Proceedings of Conference on Geologic Problems of San Andreas Fault System,* vol. 11, Stanford University Publications, Geological Sciences, 374 pp., Stanford, 1968.

Henyey, T. L., Heat flow near major strike-slip faults in central and southern California, Ph. D. thesis, California Institute of
1968.

Henyey, T. L., and G. J. Wasserburg
near major strike slip faults in C
press, *J. Geophys. Res.,* 1969.

Hill, M. L., and T. W. Dibblee, San A
lock, and Big Pine faults, Californi
of the character, history, and tect
icance of their displacement, *Geol*
Bull., 64, 443–458, 1953.

Hubbert, M. K., and W. W. Rubey, M
fluid-filled porous solids and its
to overthrust faulting, *Geol. Soc.*
70, 115–166, 1959.

Jeffreys, H., *The Earth,* 420 pp.,
University Press, 1959.

King, C. and L. Knopoff, Stress dro
quakes, *Bull. Seismol. Soc. Am.,*
1968.

Larson, R. L., H. W. Menard, and S.
Gulf of California: A result of
spreading and transform faulting, *S*
781–784, August 1968.

Orowan, E., Mechanism of seismic fau
Soc. Am. Mem., 79, 323–345, 1960.

D. thesis, California Institute of Technology, 1968.

Henyey, T. L., and G. J. Wasserburg, Heat-flow near major strike slip faults in California, in press, *J. Geophys. Res.*, 1969.

Hill, M. L., and T. W. Dibblee, San Andreas, Garlock, and Big Pine faults, California—A study of the character, history, and tectonic significance of their displacement, *Geol. Soc. Am. Bull., 64,* 443–458, 1953.

Hubbert, M. K., and W. W. Rubey, Mechanics of fluid-filled porous solids and its application to overthrust faulting, *Geol. Soc. Am. Bull., 70,* 115–166, 1959.

Jeffreys, H., *The Earth,* 420 pp., Cambridge University Press, 1959.

King, C. and L. Knopoff, Stress drop in earthquakes, *Bull. Seismol. Soc. Am., 58,* 249–257, 1968.

Larson, R. L., H. W. Menard, and S. M. Smith, Gulf of California: A result of ocean-floor spreading and transform faulting, *Science, 161,* 781–784, August 1968.

Orowan, E., Mechanism of seismic faulting, *Geol. Soc. Am. Mem., 79,* 323–345, 1960.

Roy, R. F., J. N. Brune, and T. L. Henyey, A heat flow transition near Hollister, California, in preparation, 1969.

Rubey, W. W., and M. K. Hubbert, Overthrust belt in geosynclinal area of western Wyoming in light of fluid-pressure hypothesis, *Geol. Soc. Am. Bull., 70,* 167–205, 1959.

Scholz, C. H., M. Wyss, and S. W. Smith, Seismic and aseismic slip on the San Andreas fault, *J. Geophys. Res.*, in press, 1969.

Tocher, Don, Creep rate and related movements at Vineyard, California, *Bull. Seismol. Soc. Am., 50,* 396–404, 1960.

Wasserburg, G. J., R. Kovach, T. Henyey, and R. Roy, Heat flow in the vicinity of the San Andreas fault (abstract), *Trans. Am. Geophys. Union, 47,* 181, 1966.

Whitten, C. A., Measurements of earth movements in California, *Calif. Div. Mines Bulletin, 171,* 75–80, 1955.

(Received December 18, 1968;
revised March 17, 1969.)