MOVEMENT ON FAULTS

by Don Tocher*

Abstract

Faulting in large earthquakes is a hazard to works of man that can be avoided completely only by locating structures in the proper place, i.e., not across an active fault. In addition to sudden fault movements, slow movement or creep is known to be taking place on at least two faults in California. The slowly accumulating forces acting on structures affected by fault creep appear to be just as irresistible as those applied suddenly by faulting. Studies of this phenomenon now in progress may well lead to a modification of Henry Fielding Reid's Elastic Rebound Theory by establishing that fault creep as well as earthquakes may serve to relieve the secular accumulation of elastic strain in the vicinity of active faults.

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INTRODUCTION

Sudden disruption of the surface of the earth in an earthquake constitutes a hazard to man-made structures quite distinct from the well-recognized hazards of shaking of the ground. In general, the disruption of the ground by faulting is confined to a narrow linear zone. The number of structures in danger of direct damage from faulting bears a linear relation to the size of the earthquake, whereas the size of the area subject to strong shaking is related more nearly to the second power of the size of the shock. Nevertheless, the dangers of direct damage from faulting are very real in the United States and elsewhere, and can be eliminated only by the proper choice of location of a structure. No man-made structure astride a fault break has yet failed to remain unscathed by the faulting. Fault movement, whether strike-slip or dip-slip, offsets roads, bridges, pipelines, and the like. If it occurs under a building, it either rents the building in twain or, if the building itself is stronger than its attachment to the foundation, the faulting will cause one side of the building to break loose from its foundation and drag along with the part of the building on the opposite side of the fault. For most buildings, this is just as serious as being torn apart. Even broad earthen dams will be disrupted by surface faulting, although if the thickness of the dam is greater than the fault offset, the dam may still act as a barrier for the water behind it.

In the United States, and in California in particular, the perils involved in locating structures in fault zones are well recognized. Although surface faulting had undoubtedly accompanied earlier earthquakes, it was the great San Francisco earthquake of 1906 that brought this point forcibly to the attention of engineers, architects, geologists, and others concerned with the problems of earthquakes. The surface fault break extended 435 kilometers from San Benito county to Humboldt county. The relative movement was largely lateral, and reached its maximum of 21 feet in Marin county, just north of San Francisco. Since 1906, seismologists and geologists in the United States and Canada almost without exception regard sudden fault movement the cause of an earthquake and the ground shaking an effect of the fault movement. Other large earthquakes in the western United States since 1906 have amply supported this view of the cause-effect relation between faulting and shaking, so that today, most are willing also to attribute the shaking of the ground in small earthquakes to fault movements at a great enough depth that the faulting does not extend to the earth's surface.

In recent years slow movements on faults have also been recognized in two places in California. Although intensive study of this phenomenon of fault creep has been carried on only for a relatively short time, enough is now known about it that it must be classed with sudden faulting as an "irresistible force" to be reckoned with in active fault zones.

FAULTING IN EARTHQUAKES

The great San Francisco earthquake of 1906 gave great impetus to the study of earthquakes in the United States. Recognition of the importance of fault movement as the generating mechanism of earthquakes led to a careful study of historical records relating to earlier great earthquakes. A few earlier fault movements had been described by scientific men, and items mentioning a few others were found in old newspapers and diaries. Most had occurred at the wrong time or place to receive the proper attention of geologists. The ground breakage in the Owens Valley earthquake of 1872 east of the Sierra Nevada of California has been mapped and described by more than one geologist, beginning with the head of the State Geological Survey, who visited the epicentral region within a few months of the earthquake. The various accounts of the direction of the horizontal component of the movement are uniformly inadequate. They differ so much that as recently as 1959, a very spirited discussion took place at the annual meetings of the Seismological Society of America on the question of whether the horizontal component of movement in 1872 was right-lateral or left-lateral.

The descriptions of fault breaks since 1906 are in general considerably more complete than those of the 1872 break. A tabulation of surface faulting with a very complete bibliography was given recently by Richter (1958). A number of occurrences of known surface faulting since 1900 are listed in Table 1. Tocher (1958) found that, in contrast to the notion that surface fault breakage is quite rare, every earthquake since 1906 with Richter magnitude greater than $6\frac{1}{2}$ and with epicenter on land in northern California or Nevada has been accompanied by some degree of fault breakage at the surface of the earth. These fault breaks are shown in figure 1, along with epicenters (open circles) of all shocks of magnitude above 6 centered in the map area since 1906.

About one-half of the epicenters on figure 1 were at sea, where direct observation of possible surface breakage is not possible. Of the 15 large earthquakes (magnitude above 6) with epicenters on land, 10 definitely developed surface fault trace effects, two almost certainly did not, and no definite information on faulting is available for the other three. During the same period, only one shock of magnitude 6 or less is known to have been accompanied by surface faulting observable by field examination. This was the Herlong earthquake of 1950 ($M = 5\frac{3}{4}$) described by Gianella (1957). Instrumental measurements have recently established that much smaller earthquakes also may be accompanied by small, sudden displacements on faults; these are described in more detail in a later section.

It is not surprising that length of surface breakage roughly increases with earthquake magnitude (see table 1), as it seems to be a reasonable inference that the volume of rock which contributes stored elastic strain energy to an earthquake is somehow related to the magnitude of the shock. Tsuboi (1956) has expressed the view that the elastic energy of an earthquake is dependent mainly on the volume of rock in which the preexisting strain energy has been stored, or, in other words, that the strain of the rock just before an earthquake is not greatly different between small and large shocks. While we might equate length of surface faulting to one of the three linear dimensions of the volume of strained rock, direct measurements of the other two are not available to us. Some understanding of the extent perpendicular to the fault trace and the thickness of the strained zone may eventually come from studies of the distribution of aftershocks of large earthquakes geographically and with depth. To date in California and Nevada, too few sufficiently precise studies of this type are available.

We may, however, investigate the extent of the strain zone perpendicular to the surface faulting indirectly. Under Tsuboi's hypothesis mentioned above, this dimension of the zone of strained rock should be roughly proportional to the displacement of the ground at the fault. The common logarithm of the product lD has been plotted as a function of magnitude in figure 2 for the data of table 1. l is the length in kilometers of the line or zone of observed fault breakage, and D is the maximum observed relative displacement at the fault in centimeters. The solid line in figure 2 is the best straight line fit to the open circles (shocks in northern California and Nevada) by the method of least squares. Its equation is

$$M = 5.22 + 0.53 \log lD \text{ ....(1)}$$

Since equation (1) was first developed (Tocher, 1958), a number of earthquakes accompanied by faulting have occurred elsewhere. Points for three of these (Outer Mongolia 1957, Alaska 1958, and Montana 1959) have been added to figure 2. Although conditions of strength and plasticity probably are not uniform near all the faults involved in the earthquakes listed in table 1, and the thickness of the earth's crust doubtless varies from place to place, these three points representing earthquakes away from northern California and Nevada exhibit no more scatter from the straight line approximation than do the shocks of the more limited region.

We would like to know the relationship between size of strain zone and shock energy. DeNoyer (1959), by a method of seismogram integration, determined the total seismic-wave energy released by eight shocks of magnitudes 6¾ to 8¼. This range of magnitudes nearly coincides with that of the shocks in table 1 which have been accompanied by surface breakage. Over this limited range of magnitudes, the relationship between magnitude and energy may be represented by the approximation

$$\log E = 7.76 + 1.87 M \text{........(2)}$$

in which E is the energy in ergs found by DeNoyer. The fit of the data is not improved significantly by adding a term in M^2.

Combining equations (1) and (2) to eliminate M results in

$$\log E = 17.5 + 1.00 \log lD \text{........(3)}$$

or,

$$E = 3.4 \times 10^{17} \times 1.00\ lD \text{.........(4)}$$

(E in ergs, l in kilometers, D in centimeters.)

From equation (3) we see that shock energy is proportional to the first power of the product of length of surface breakage and the maximum offset at the fault. If the offset is in fact proportional to the dimension of the strain zone normal to the fault, we therefore conclude that the energy released in the larger shallow earthquakes in northern California and Nevada is proportional to the area at the earth's surface of the zone of rock which contributes stored strain energy to the earthquake. Tsuboi's hypothesis of the constancy of the state of strain just before earthquakes then leads to the corollary conclusion that the vertical thickness of the volume of strained rock is approximately the same for all earthquakes large enough to have surface faulting.

FAULT CREEP

The occurrence of fault creep, or the gradual slipping of one side of a fault relative to the other, was recognized in California more than 30 years ago. For most of that time, however, the recognized economic losses from the phenomenon were relatively small, and the effect was generally regarded more as a curiosity than as an engineering hazard which might eventually cause large losses. Koch (1933), Wilt (1958) and others have described continuing movement on an active thrust fault in the Buena Vista Hills oil field in Kern County, California. Overthrusting movement of one and two-thirds feet has accumulated gradually at an average rate of about 0.8 inch per year on a fault which strikes nearly east-west and dips 20° - 25° to the north. Pipelines crossing the surface trace have been shortened and buckled, and casings of wells drilled through the fault distorted and eventually pinched off.

A second instance of fault creep was recognized as such in April 1956 by Zacher (Pacific Fire Rating Bureau, 1957; Steinbrugge and Zacher, 1960). During the course of a building inspection of the W. A. Taylor and Company winery at Vineyard, seven miles south of Hollister, California, he observed disrupted and offset walls of reinforced concrete, and offset concrete floor slabs. The ground movement causing the building damage cannot be explained by gravity slumping or landsliding, as it is in a direction nearly perpendicular to the gentle slope on which the winery is built. The resultant structural damage is confined to a narrow line across which the building is being sheared slowly into two sections. Columns along the line of creep in one of the storage cellars were racked out of plumb so badly that major reconstruction was undertaken in 1954.

The W. A. Taylor and Company winery at Vineyard is located in the San Andreas fault zone about 10 miles southeast of the southeasternmost point of surface fault breakage in the San Francisco earthquake of April 18, 1906. Like the faulting in 1906, the fault creep is right-lateral, and is taking place along a line parallel to the local strike of the fault zone.

The part of the winery now being torn apart by fault creep was built (in 1948) to replace an earlier structure on the same site. The older building had been torn down because of extensive cracking of the walls and floors. The Hollister region, and particularly the area around Vineyard south of Hollister, has over the years been subjected to far more than its share of earthquakes, so it was only natural that the owners of the older winery building attributed the damage to the accumulated results of earthquakes over a long period of years. It appears likely from descriptions of the damage to the older building that it, too, was largely the result of fault creep rather than earthquakes.

Since 1957, several measuring devices designed to record differential lateral movement of adjacent sections of the concrete floor have been installed in the winery (Tocher, 1960). Table 2 lists two sets of measurements made periodically by means of the micrometer used to calibrate one creep recorder (no. 2) and the dial indicator used to calibrate another (recorder no. 3). During the past twelve months, more than two-thirds of an inch of fault creep has accumulated. The average rate obtained by dividing the total apparent building offset (about 15 centimeters) by the age of the present building (about 12 years) is $1\frac{1}{4}$ centimeters, or one-half inch per year.

The periodic measurements listed in Table 2 have been plotted in figure 3. Although covering an interval of less than two years, these measurements indicate clearly that the rate of creep is not constant at all times. Creep was much more rapid from December 1958 to March 1959, and from November 1959 to April 1960, than it was at other times. So far, the creep seems to exhibit an annual periodicity, but whether or not this continues is a question that can be answered only with time.

The more detailed time history of the creep at Vineyard has been shown best by creep recorder no. 3 operating just inside the north wall of the winery. This recorder is entirely mechanical in its operation: the floor slab on one side of the line of fault creep is connected by a rigid rod to the recording pen of a clock-driven recorder which is firmly attached to the floor slab on the other side of the line. A dial indicator is connected mechanically in series with the recorder to calibrate the recorder, and is read periodically (see table 1). The pen linkage magnifies the relative movement about 15 times, so that a full-scale excursion of the dial indicator gives a full scale excursion on the recorder. The recording-paper drive rate is 40 millimeters per day.

Creep recorder no. 3 has shown the creep to be concentrated in spasms of duration on the order of a week. These periods of creep are separated by intervals of weeks or months during which little or no creep accumulates. During the 402-day period from March 3, 1959, when recorder no. 3 was installed, to April 8, 1960, a total offset of 21.12 millimeters accumulated at recorder no. 3; 19.69 millimeters of that total occurred during five relatively brief periods of rapid creep of total duration just under 42 days. Thus more than 93% of the movement of the 402-day period took place in just over 10% of that time. The remainder of the total accumulated in tiny increments at other times.

Tracings of the records from creep recorder no. 3 covering two recent periods of rapid creep are reproduced in figure 4. The scale of movement in figure 3 represents actual lateral displacement of one concrete floor slab relative to the adjoining slab. Downward movement of the trace with increasing time corresponds to movement of the slabs in the right-lateral sense.

Of the periods of creep so far recorded, only that beginning on January 20, 1960 (figure 4b) seems to be directly associated with local seismic activity. The large, sharp jump of the recording pen (corresponding to a sudden right-lateral offset of 3.03 millimeters) occurred at the time of a sharp local earthquake (within the limits of time resolution of the original record -- perhaps plus or minus ten minutes). The elements of the earthquake determined seismographically are:

Origin time -- $03^h\ 25^m\ 53^s$ G.C.T., January 20, 1960
Epicenter -- 36° 47' N, 121° 26' W
Richter magnitude -- 5.0

This location is about six kilometers northwest of Vineyard, and is also in the San Andreas fault zone. The greatest intensity of the shock was at Vineyard: a hollow concrete block chimney at the winery foreman's one-story wood-frame house cracked at the roof line. Objects jumped into the air or overturned in the foreman's house and in an old adobe office building nearby. Large redwood wine tanks (up to 12,000 gallons capacity) in the main winery shifted on their foundations; concrete foundation blocks under some of the tanks were cracked. Settlement of concrete floor slabs (probably on fill) occurred in two storage cellars of the winery. Many 50-gallon wine barrels in racks worked loose from their chocks. Hairline cracks appeared in the asphalt pavement of a road just south of the winery. A buried water pipe broke about on the projection of one of the hairline cracks.

The largest aftershock of the ensuing series (magnitude 3.7) occurred at $03^h\ 47^m\ 51^s$ G.C.T., January 20, 1960. On the creep record, the movement associated with the main shock was followed after approximately 22 minutes by another sharp jump corresponding to 0.03 to 0.04 millimeters additional right-lateral movement. Other smaller jumps can be distinguished on the original creep record during the following sixteen hours, but they do not correspond in time to particular aftershocks. None of these other aftershocks exceeded magnitude $2\frac{3}{4}$.

If the sharp movement on the creep record at about $03^h\ 47^m$ G.C.T. is attributed correctly to the aftershock at that time, it corresponds to the smallest fault breakage by far ever observed. Prior to the shocks of January 20, 1960, the smallest earthquake on record with surface faulting was the Herlong, California earthquake of 1950 (magnitude $5\frac{3}{4}$). The faulting at that time could be measured in inches, and was easily observable in the field.

DISCUSSION AND CONCLUSIONS

Movement on faults, whether slow (fault creep) or sudden (earthquake), represents a serious problem in regions of active faults. The forces causing these movements are many orders of magnitude greater than the strength of the strongest types of man-made structures, and so really present a problem in site selection rather than in engineering design. Once earthquake fault breakage has occurred and been recognized in a given region, the danger to structures that might be built along the line of breakage is evident to all, and any prudent owner of property along the fault might be expected to avoid construction there voluntarily. Unfortunately, some works of man, such as roads, pipelines, fences, and canals must on occasion be built across known active faults. Here the problem is to design and construct in such a way that future movements on the fault will result in a minimum of damage to the facility itself and a minimum of interruption to the service it provides. In the case of roads, a detour usually can be bulldozed across a fault break in a matter of a few hours, so that no lengthy interruption to the flow of vital traffic will result. At the other extreme, the problem of interruption of service can be much more serious in the case of pipelines supplying water to metropolitan areas, as was demonstrated all too clearly in San Francisco in 1906. Here the solution must be to insure that an adequate supply of water is always available in the metropolitan area itself, and to provide in advance for adequate cutoffs and alternate distribution routes in areas where the failure of a single route might prove disastrous.

In the San Francisco Bay region of central California, two major active faults are well known, and surface fault movements have taken place more than once on both of them since the settlement of the area by the Spanish in the eighteenth century. The location of these faults is no secret to anyone, yet regrettably, it appears evident even to the casual observor that the construction of homes and other buildings continues at an accelerating pace on the beautiful hillsides and valleys transected by the Hayward and San Andreas faults. A large new residential subdivision is now well underway in an area a short distance south of San Francisco in which faulting of several feet took place as recently as 1906.

The recognition of fault creep is not an easy matter, nor do we yet even know how common a phenomenon it is. Geologists usually have no trouble determining the location of an active fault even though surface faulting may not have occurred within historic times at the spot under investigation. But so far, slow creep on faults has been recognized only by its effects on rigid structures. The fault creep in the Buena Vista Hills makes necessary periodic repairs to roads, pipelines, and well casings, and will continue to make them necessary as long as the oil field remains in active production. At Vineyard, the only permanent solution to the creep damage short of tearing down the winery would be to reconstruct the present building into two separate structures, each free to go its own way independently of the other.

Thus far in California only two isolated areas are known to be sustaining losses from fault creep. Damage to structures directly caused by faulting has thus far been relatively slight alongside the great damage that has resulted from the strong shaking of the ground. The current population explosion in California, with consequent accelerated development along known active faults, suggests that both types of movement on faults will assume greater importance in the years to come.

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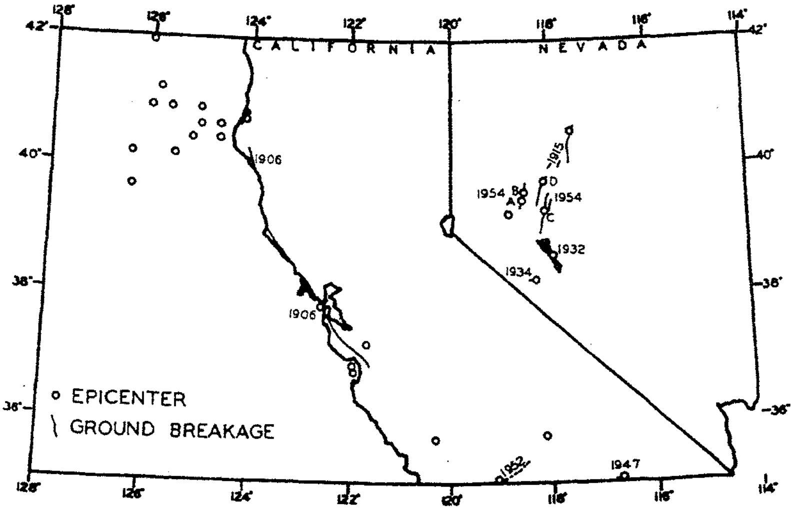

Figure 1. Epicenters and surface fault breakage of earthquakes of magnitude above 6 in northern California and Nevada, 1906 - 1960.

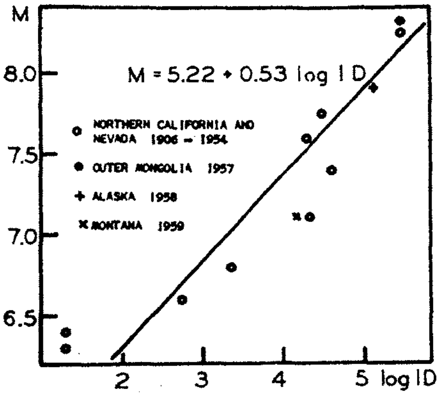

Figure 2. Plot of log lD versus M for surface fault breakage. l = length (in kilometers) of line or zone of breakage. D = maximum reported relative displacement (in centimeters). Solid line is best straight line through open circles by method of least squares.

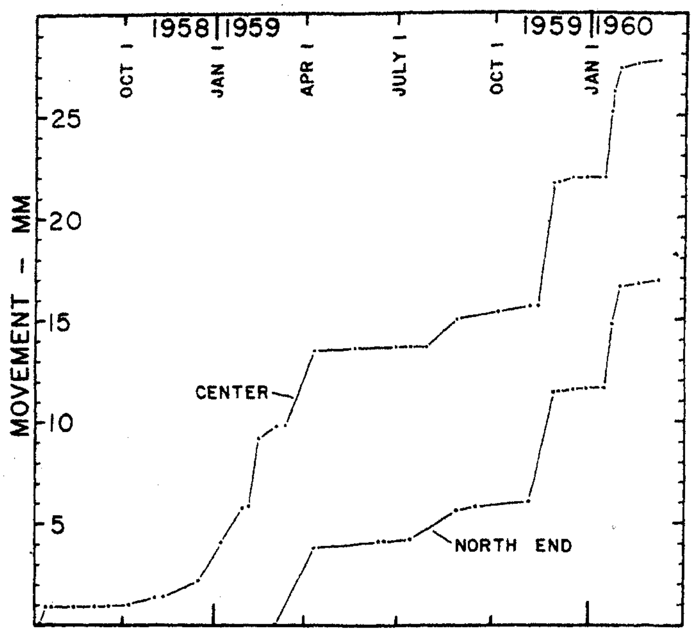

Figure 3. Right-lateral movement of floor slabs in W. A. Taylor winery, Vineyard, California. Center of winery, since July 9, 1958. North end of winery, since March 3, 1959.

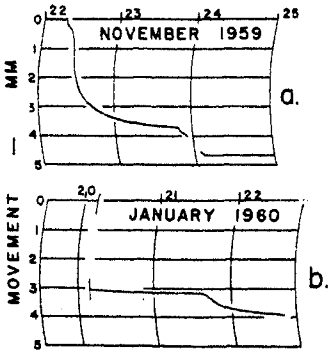

Figure 4. Tracings of records from creep recorder no. 3, W. A. Taylor winery, Vineyard, California. Time lines are at 0^h G.C.T. of indicated date. a: Rapid fault creep beginning 06^h G.C.T. November 22, 1959. b: Sharp movement of earthquake (03^h 25^m G.C.T. January 20, 1960) followed by fault creep.

Table 1

Examples of surface faulting

Date	Location	M	l (km.)	D (cm.)	Reference
1903	Wonder	?	19?	?	Slemmons et al. (1959)
1906	San Francisco	8 1/4	435	640	Lawson et al. (1908)
1915	Pleasant Valley	7 3/4	65+	460	Jones (1915); Ferguson, Roberts, and Muller (1951, 1952)
1932	Cedar Mountain	7.2	61	?	Gianella and Callaghan (1934)
1934	Excelsior Mountains	6.3	1.5	13	Callaghan and Gianella (1935)
1947	Manix	6.4	4 ±	5 ±	Buwalda and Richter (1948); Richter (1958)
1952	Kern County	7.6	65	310	Oakeshott (1955)
1954A	(July 6) Fallon	6.6	18	31	Tocher (1956)
1954B	(August 24) Fallon	6.8	30	76	Tocher (1956)
1954C	(December 16) Fairview Peak	7.4	59	700	Slemmons (1957)
1954D	(December 16) Dixie Valley	7.1	62	370	Slemmons (1957)
1957	Outer Mongolia	8.3	275	1000±	Treskov and Florensov (1958)
1958	Alaska	7.9	200	655	Tocher and Miller (1959)
1959	Montana	7.1	22	640	Anonymous (1959)

Table 2

Periodic measurements of fault creep at Vineyard, California
(Increase with time denotes right-lateral movement)

Date	Recorder No. 2 (mm.)	Recorder No. 3 (mm.)
1958		
July 9	0	
July 16	0.90	
July 22	0.94	
Aug. 13	0.94	
Sept. 3	0.95	
Sept. 17	0.95	
Oct. 7	1.08	
Nov. 3	1.41	
Nov. 11	1.43	
Dec. 16	2.19	
1959		
Jan. 7	4.08	
Jan. 28	5.75	
Feb. 3	5.84	
Feb. 13	9.19	
Mar. 3	9.79	0
Mar. 12	9.82	
Apr. 10	13.47	3.81
May 20	13.60	
June 13		4.13
June 19		4.14
June 30	13.65	
July 14	13.67	4.26
July 29	13.66	
Aug. 27	15.02	5.65
Sept. 15		5.86
Oct. 5	15.37	
Nov. 4	15.65	6.07
Nov. 12	15.67	
Nov. 27	21.74	11.45
Dec. 2	21.76	11.48
Dec. 16	21.96	11.57
Dec. 29	21.97	11.65
1960		
Jan. 15	21.97	11.65
Jan. 20	25.16*	14.84
Jan. 22	26.11	
Jan. 30	27.31	16.67
Feb. 17	27.57	16.79
Mar. 8	27.73	16.96
Mar. 12		16.96
Mar. 26		17.04
Mar. 29	27.80	
Apr. 2		18.35
Apr. 6	29.79	
Apr. 8	31.69	21.12

* Recorder no. 2 out of service for repairs January 15-20, 1960. Movement during that period assumed equal to movement measured by recorder no. 3.