SECULAR STRAINS IN NE DENVER - 1968

by

Phillip R. Romig, Jr.

A Thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Geophysics.

Signed: Phillip R Romig Jr

Golden, Colorado
Date: 23 May, 1969

Approved: Maurice W. Major
Maurice W. Major
Thesis Advisor

John C. Hollister
Head, Department of
Geophysical Engineering

Golden, Colorado
Date: 23 May, 1969

ABSTRACT

Ten quartz-bar strainmeters within 45 kilometers of NE Denver have been in operation for a minimum of 14 months. Although there are large (5×10^{-6}) seasonal variations in the rock at some sites, tectonic secular strain rates of the order of 3×10^{-5} per year are observed. These can be analyzed only if all three horizontal components are recorded, in which case the data are best displayed as strain ellipses. Strain steps from earthquakes are also recorded and are useful for fault mechanism interpretation.

The secular strain rate in this area varies by two orders of magnitude within 45 kilometers. If characteristic of other areas, this variation implies that first-order geodetic surveys are superior to strainmeters for preliminary regional studies, and that earthquake prediction instruments must be within one half-fault-length of a fault.

The largest earthquakes occurred on right-lateral, strike-slip faults oriented N79W in NE Denver. During the first 9 months of 1968 the right-lateral shear on this fault zone increased steadily. In June 1968 the strain normal to this fault zone and the areal strain both reached maxima in extension. Failure was therefore most likely at this time. A "creep episode" did occur in NE Denver on

24-25 June 1968. These events have not been repeated at any other time.

CONTENTS

ILLUSTRATIONS

ACKNOWLEDGMENTS

Mr. Frank Hamtak, CSM, helped construct and has maintained and operated the strainmeters during the last two years. His work is particularly appreciated. I am also indebted to Mr. R. J. Dorman, who helped construct and maintain the instruments, and to Prof. C. W. Wideman, Montana College of Mineral Science and Technology, for assisting with the heavy construction phase. I especially thank Mr. J. J. Jacobson, CSM, for writing the CDC-8090 computer programs and providing the ellipses used in the movie.

This work was supported by the Environmental Science Services Administration under contracts C-176-65(G) and E-22-90-68(G). Additional financial support was provided by the Texaco and the Mobil Oil Companies in the form of Graduate Fellowships.

INTRODUCTION

Most theories concerning mechanisms for the generation of earthquakes hypothesize that energy is stored in the crust in the form of elastic strain and that an earthquake results from the sudden release of some of this energy by slip on a fracture surface. If this is so, studies of the state of strain of the crust in a seismically active region should contribute to the understanding of earthquake source mechanisms and ultimately to earthquake prediction.

Since 1964 a cluster of ten strainmeters has been constructed within 45 kilometers of a small, seismically active region near Denver, Colorado. No comparable concentration of strainmeters presently exists in North America. This paper is concerned primarily with studies of secular strain during 1968 utilizing data from this network. It will be argued that a significant portion of the deformations observed are indeed real crustal strains of tectonic origin.

The site which experiences the largest secular strain is located directly over the seismically active zone. A relationship probably exists between the secular strains at this site and the earthquakes. Strain step data will be used to deduce fault mechanisms for the three largest earthquakes so that the secular strains can be interpreted in relation to the orientation of, and sense of motion on, the inferred fault zone.

The strain data from this site will be transformed into a coordinate system, one axis of which parallels the fault zone. This will show that during June 1968 the shear strain was increasing and the strain normal to the fault zone reached a maximum in extension. These conditions seem favorable for failure, and coincidentally a creep-like episode was recorded on the Rocky Mountain Arsenal strainmeters on June 24-25. Following this "creep episode" the strain normal to the fault zone went into compression, and no further significant failure has since occurred.

INSTRUMENTATION

Table 1 shows the locations and individual parameters of all strainmeters used in this study.

The seven strainmeters located in NE Denver are shown on Figure 1 (downtown Denver is about 15 kilometers SW of this area). The four instruments on the Rocky Mountain Arsenal (Site RMA-1 and Site RMA-3) were completed during the spring and summer of 1967. A fifth instrument planned for a site (RMA-2) about 1½ kilometers southeast of the Rocky Mountain Arsenal Deep Disposal Well (RMA Well in the figure) was under construction when the first Denver earthquake of Magnitude 5 occurred on April 10, 1967. A preliminary interpretation of the focal mechanism was done (Major and Simon, 1968) using data from the strainmeters at the Cecil H. Green Geophysical Observatory (GOL), located about 45 kilometers WSW of the area shown on the map. The resulting fault orientation is shown on Figure 1. Based on this knowledge concerning the fault, a decision was made to abandon Site RMA-2 and, instead, to construct a three-component site near the fault. The result was the Quimby site (QBY), which was constructed in October 1967 and became fully operational the end of December 1967.

Table 1

Site	Latitude	Longitude	Elevation	Orientation	Base-Length
QBY	39°52'19"N	104°56'39"W	5200 ft	N/S	40 ft
				E/W	40 ft
				NE/SW	40 ft
RMA-1	39°50'04"N	104°51'14"W	5290 ft	N/S	100 ft
				E/W	100 ft
RMA-3	39°51'44"N	104°49'07"W	5190 ft	N17W	100 ft
				E17N	100 ft

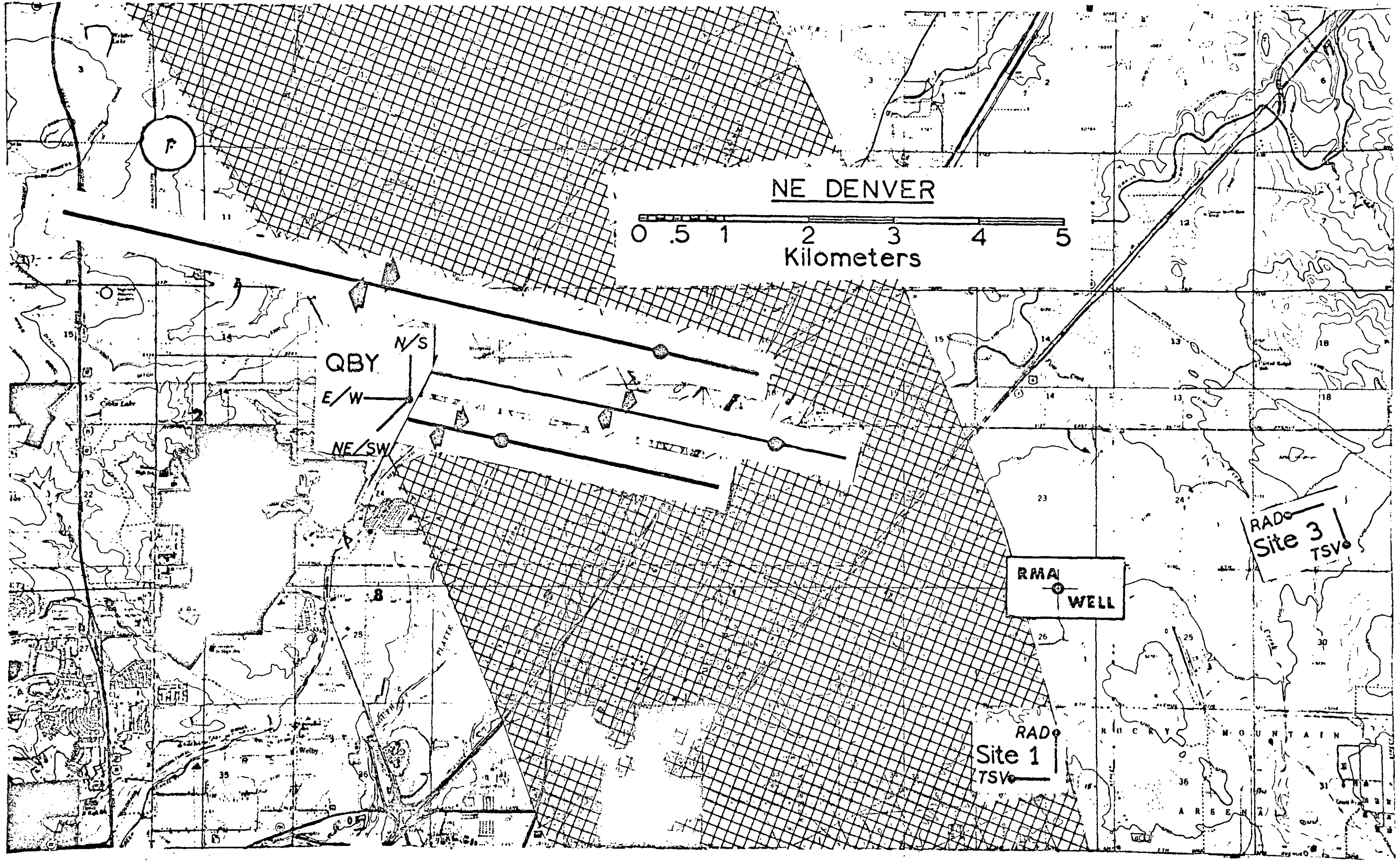

Figure 1. Map of NE Denver showing the locations of the strainmeter sites with respect to the estimated fault planes for the three largest earthquakes. Downtown Denver is about 15 km SSW of this map.

At each site shown on Figure 1 a standard of length, consisting of 10-foot sections of fused quartz tubing shielded by 5-inch-diameter jacket pipe, is buried in a shallow trench with one end fixed to a concrete pier. The sections of quartz are thermally compensated by aluminum compensating elements (Major, 1966). The free end of the quartz extends into a concrete instrument vault which contains a transducer to measure the relative displacement of the quartz with respect to the instrument vault pier. This is a Benioff capacitive transducer modified to include integral micrometer calibration and readjustment (Romig, 1967). Strain is then computed by dividing the apparent displacement by the total base-length.

At QBY the three instruments terminate in one instrument vault; all other instruments have individual vaults. The instrument vault at QBY has two rooms, a lower transducer room 4 feet high and an upper recording room 30 inches high. This upper room is a dead-air space which provides superior thermal insulation for the strainmeters as compared to the single-room vaults used on the other instruments. Figure 2 is a photograph taken during the construction of QBY. The 5-inch jacket pipe and the concrete instrument vault are seen clearly in this picture.

Both RMA sites are located in weathered shale, competent rock not being found near the surface in these areas.

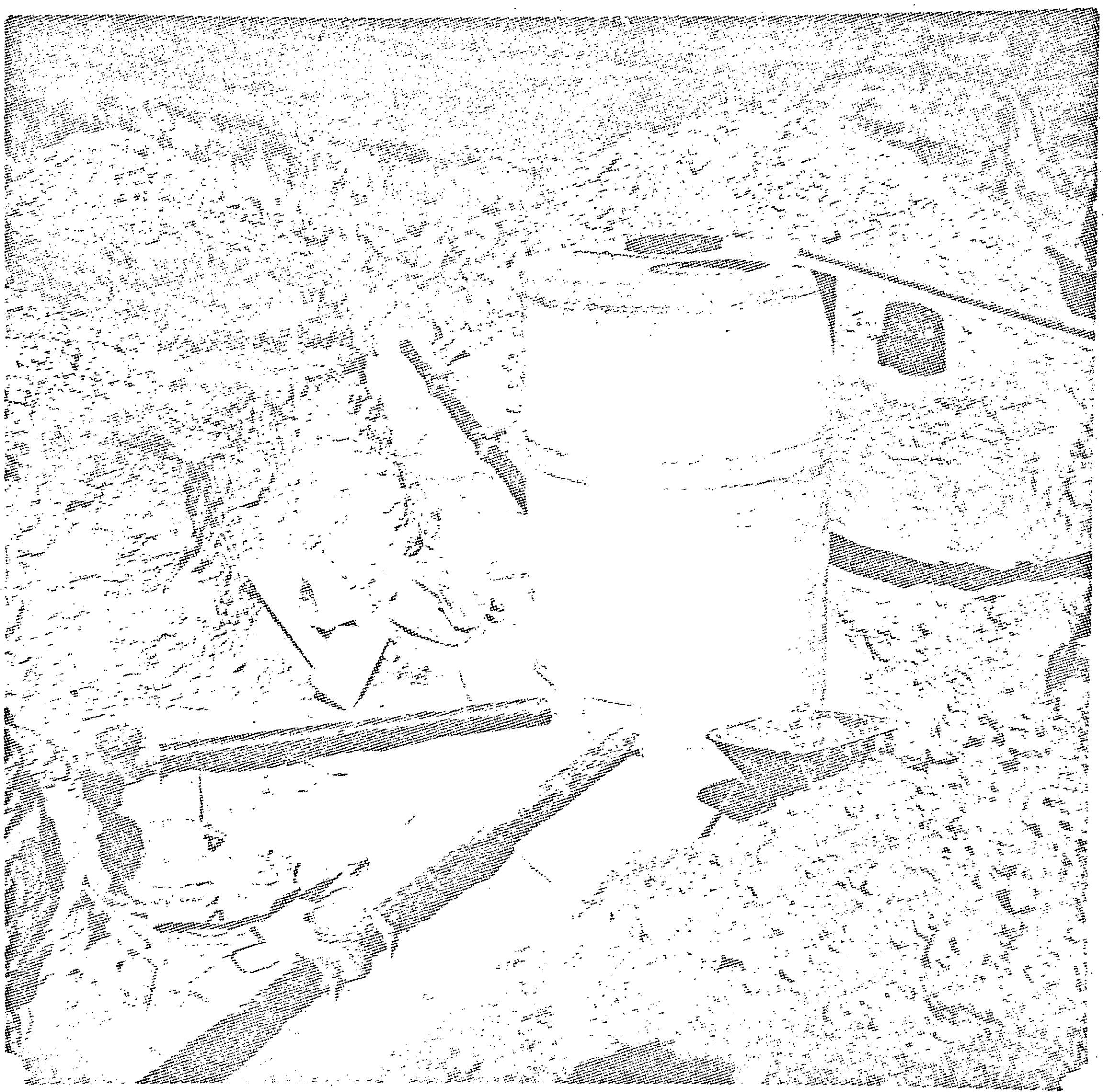

Figure 2. Photograph of QBY during construction showing the concrete instrument vault and the jacket pipe for the three strainmeters.

The piers for QBY are located on relatively fresh, horizontally bedded sandstone. The footings for this site are superior to those for all other sites except the two underground instruments at GOL.

The QBY site is near populous areas of NE Denver; thus the location, along a railroad right-of-way, was influenced by the lack of other available space. A railroad cut near the installation (Figure 3) introduces minor boundary-value effects in the observed strain. It is assumed that this has relatively little effect on regional strains.

Instrumentation of the RMA sites includes telemetry for the strain signal and a telemetry-controlled drive motor on the transducer micrometer. The signals are recorded on 10-inch strip-chart recorders located in the Geophysics Department at the Colorado School of Mines. Calibration and readjustment of the strainmeters are accomplished from the School by means of a telephone dial system. The continuity of data from these instruments is good; very little is lost because of the recorders being off-scale, etc. On the other hand, the QBY instruments record on-site, and readjustment is accomplished manually when the site is visited -- normally once per week. Since this is the area of highest secular strain rate, the recorders are often off scale for long periods of time. For purposes

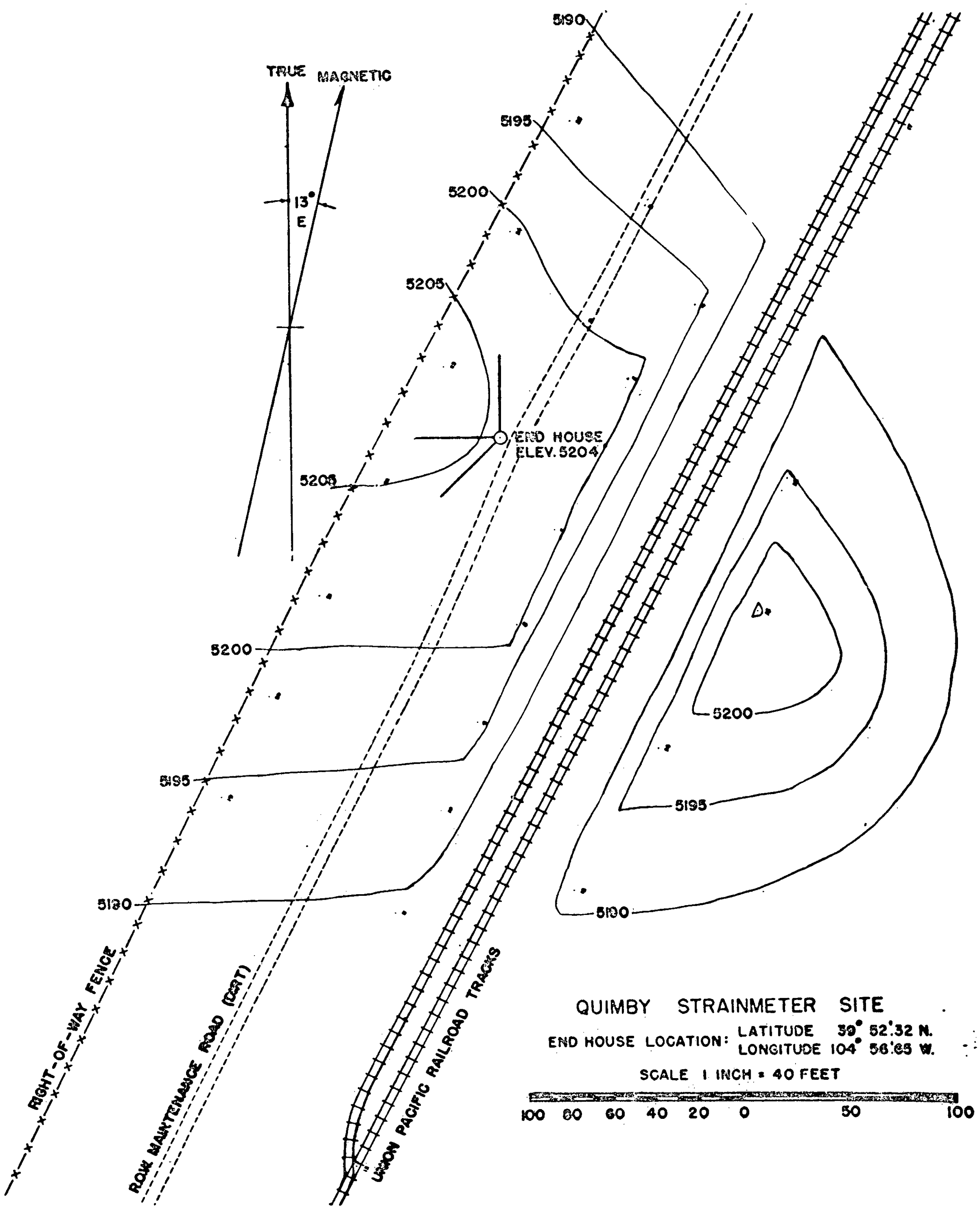

Figure 3. Topographic map of QBY showing the railroad cut.

of secular studies, however, the rebalance numbers provide adequate data.

The RMA instruments were completed during the fall of 1967 and have operated continuously since then. RMA-1 - Radial was not buried until the summer of 1968. Short-period temperature effects are pronounced on that component prior to burial. The QBY site was completed by November 1967, but power was not available until the end of December so three-component records are not available prior to January 1968.

Temperature measurements used in this paper are taken from the monthly ESSA publication "Local Climatological Data." This publication reports measurements made at Stapleton International Airport in E Denver. Since all of the sites in NE Denver are within 10 kilometers of this recording location, these reports provide adequate indication of the surface temperature at these sites.

RELIABILITY OF THE ORIGINAL DATA

All of the micrometers used in the strainmeters are Model DS-501 differential micrometers manufactured by Lansing Research. Three of these have been tested interferometrically and found to be accurate within ± 3% (Smookler, 1968).

Short-period errors are introduced into the data by virtue of the fact that 1) the instruments are not necessarily rebalanced at the same time during the daily cycle, and 2) often the adjustment is sufficient to bring the recorder on-scale but does not balance the instrument to null. Limits on these errors are set by the fact that (1) the daily cycle is less than full scale on the recorder and (2) the readjustment is always sufficient to bring the recorder on-scale. The upper limit of error is thus the full-scale sensitivity of the recorder, or about 2×10^{-7} on the average. At QBY the strainmeters are always adjusted to as near zero as possible; thus the uncertainty is less at that site. These errors are <u>not</u> cumulative, so, for this study, the long-term effects are negligible, i.e., about 1%.

The most important uncertainty in the data pertains to the amount of contamination of the record by non-tectonic environmental changes. Although this uncertainty cannot be calculated, comparison of the plots of the individual components with each other and with known noise sources (e.g. seasonal temperature fluctuations) provides some insight into the reality of the secular data.

Figures 4 and 5 are plots of the original data from the strainmeters at RMA and QBY. An apparent annual variation is seen at all four RMA instruments; it is the largest signal on these records. Since seasonal temperature variations seem the most likely cause of this effect, the mean daily surface temperature at Stapleton Airport (adjoining the RMA) is also plotted on Figure 4. That the annual variation in strain is not solely due to the direct effect of temperature on the instruments is indicated by the following observations:

1) Both instruments at RMA-3 lag the surface temperature by 2 months; instrument RMA-1 Transverse lags RMA-3 by 2 months and the temperature by 4 months. Since all three instruments are identical, this phase difference of 2 months cannot be attributed solely to surface temperature variations.

2) Instrument RMA-1 - Radial was exposed to the air until midsummer 1968. If seasonal temperature variations on the instrument were at fault, there should have been a marked change in the data from RMA-1 - Radial after burial, especially since

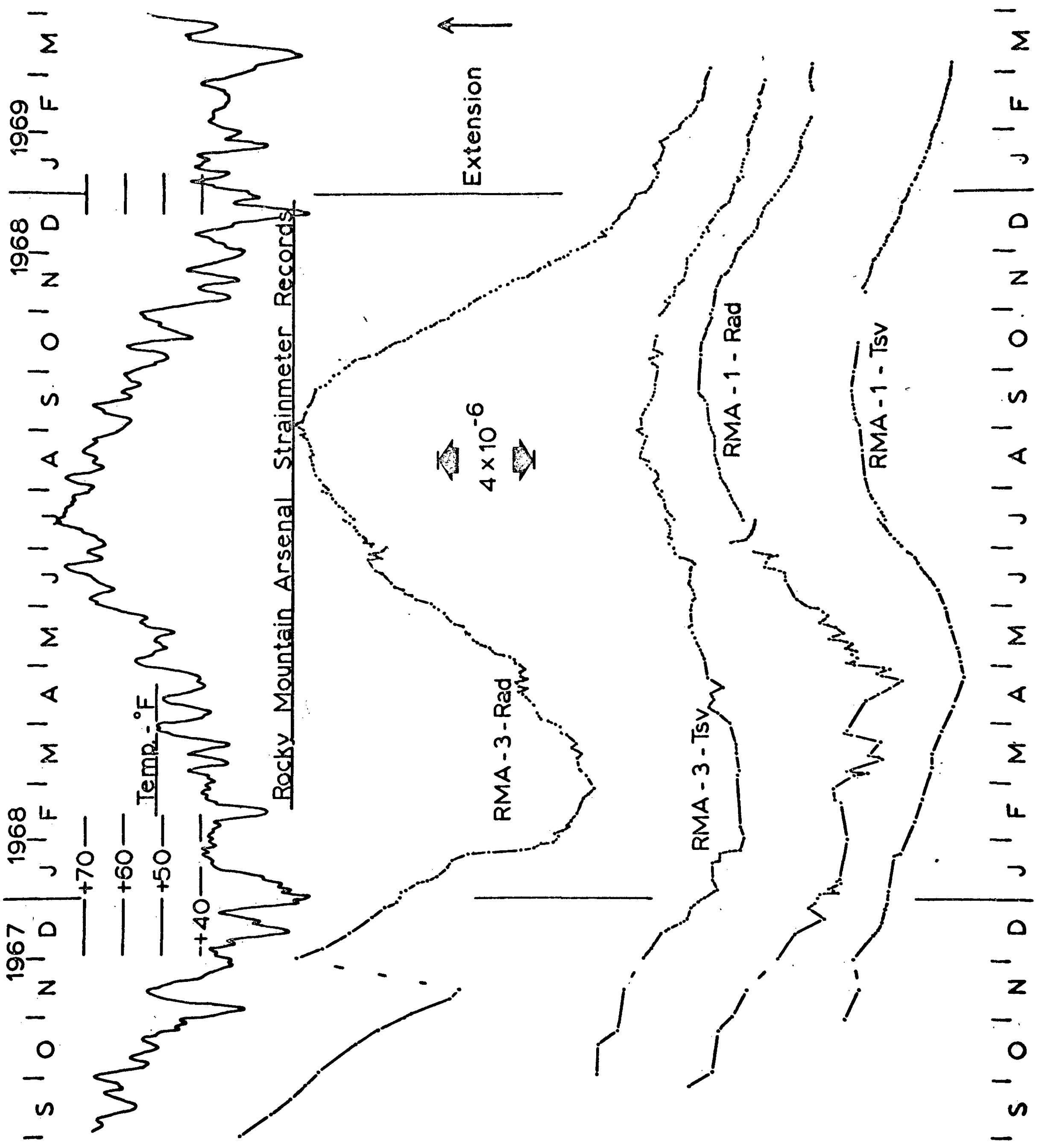

Figure 4. Rocky Mountain Arsenal strain records and surface temperature.

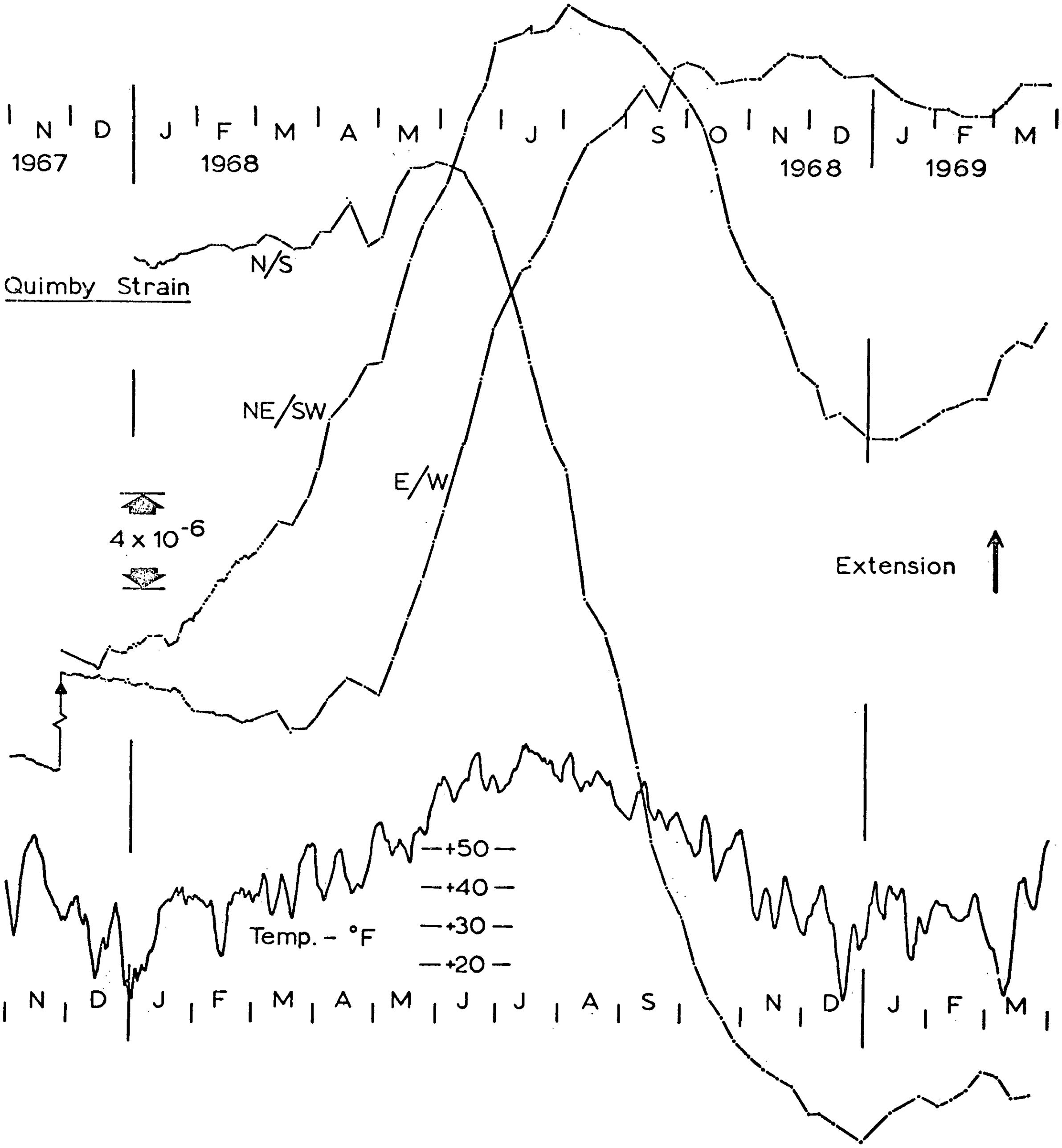

Figure 5. QBY - original strain records plus temperature.

> there was a significant change in the daily cycle, which is almost certainly temperature induced. Since burial, however, RMA-1 - Radial has tracked the previous year almost exactly.

These annual variations at RMA are seasonal effects probably involving variations in rock temperature and soil moisture content complicated by local topography and soil composition near each site. A detailed analysis of this complicated problem is not necessary here because at the end of any given 1-year period there is a permanent change in the state of strain. This indicates the presence of some secular strain in addition to the seasonal variation.

The seasonal variations at QBY, if any (Figure 5), are far less obvious than those at RMA (Figure 4). If the mean straight-line yearly drift is removed, there is some suggestion of an annual period. In each case the time intervals between subsequent peaks and troughs are either 5 or 7 months, not 6 months. Further, the "peak" of the annual variation occurs in June on the N/S, July on the NE/SW, and September on the E/W. Since the three QBY instruments are identical in design and also terminate in the same end house, the existence of these phase differences suggests that, as was concluded for the RMA sites, this annual variation is not a result simply of seasonal temperature change in the instrument. It is obvious that, even if the apparent annual variations are removed, the total "secular" or "residual" strain at QBY is very large, e.g., as large as the step associated with a large earthquake. The E/W, for example, experienced an extension of about 25×10^{-6} during 1968. By comparison, this instrument, as will be discussed later in detail, indicated an extensional strain step of 19×10^{-6} associated with the earthquake of November 27, 1967.

The QBY data will be treated as if there were no seasonal component because it seems insignificant by comparison with the larger secular strains observed.

Long-period noise is significant at many of the sites, so it is pertinent to question whether the residual secular strain is "real" (resulting from a tectonic source) or whether it is simply the result of another, as yet unidentified, type of "noise." The following analyses will attempt to show that there are certain other coincidences and consistencies in the secular strain data which make it unlikely that noise is the cause of the strain.

Wideman and Major (1967) studied the strain "steps" (i.e. elastic rebound) associated with earthquakes at a wide range of epicentral distances and concluded that the rate of decay with distance for these steps is like $R^{-3/2}$. Early theoretical studies using dislocation models predicted a decay with distance like R^{-3} (Press, 1965;

Chinnery, 1961). If the secular strain in the Denver area is a result of deformation within the active zone in NE Denver, it is conceivable that this secular strain might decay with distance according to a similar rule. Figure 6 is a log-log plot of distance from the active zone versus approximate average net yearly secular strain at QBY, RMA-1, RMA-3, and GOL. A source approximately 4 kilometers deep directly under QBY is assumed. All strain data except GOL are the total annual change for each instrument with the instruments at each site averaged together. Long-term data are not available for GOL, so the value used for this point is that determined by Homuth (1968) extrapolated to one year. This strain rate for GOL is probably high, since no attempt has been made to correct for a possible seasonal component to the drift. Decays with distance of R^{-3} and $R^{-3/2}$ are also shown for comparison.

Since the epicentral region is not radially symmetric, the observed strain resulting from movement in this zone will vary significantly with strainmeter orientation and with the azimuth of the strain site from the active area. Since each of the instruments concerned has a different orientation or azimuth, Figure 6 has little value as far as determining a specific rate of decay with distance. It is apparent, however, that in spite of the limitations of the data, all of the points do fall within the area on the

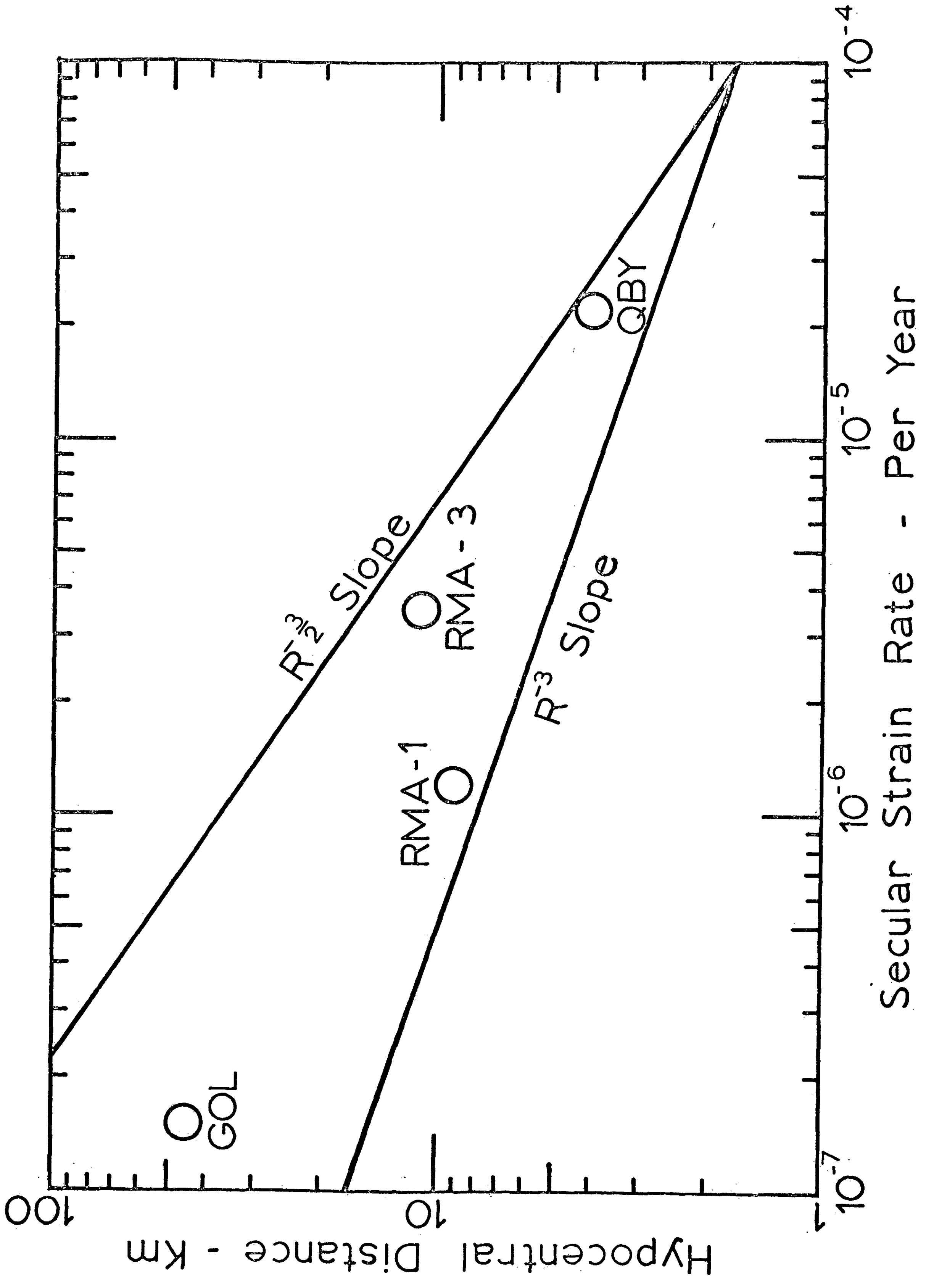

Figure 6. Secular strain rates as a function of distance from the NE Denver active zone to the strainmeter site.

graph bounded by the two limits R^{-3} and $R^{-3/2}$. This tends to support the conjecture that the observed secular strain is a result of real local deformation in the crust, since it seems highly unlikely that purely instrumental drift or fluctuations in surface conditions would produce the observed decay with distance.

It is appropriate now to undertake certain manipulations of the data, specifically to compute the shear strain (e_{12}) and the direction of maximum extension at QBY. The mathematics have either been taken from, or checked by comparison to, Love (1944). There is a basic discrepancy between his definition of shear:

$$e_{12} = \frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2}$$

and that used in this paper:

$$e_{12} = \frac{1}{2} \left(\frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1}\right)$$

This introduces a factor of "2" at various places, which is the only difference between equations given in Love and those used here.

The symbols used throughout the paper are:

p_{ij} -- stress

e_{ij} -- strain $\equiv \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$

θ -- dilation ($e_{11} \not+ e_{22} \not+ e_{33}$)

g_{ij} -- metric (Kronecker delta in this paper)

W -- energy

λ -- principal strain

subscript "1" -- horizontal, East axis

subscript "2" -- horizontal, North axis

subscript "3" -- vertical axis

An orthogonal cartesian coordinate system is assumed.

The original QBY data (Figure 5) are plotted as simple extensional strain in three directions. Shear strain (e_{12}) can be computed by first assuming an E/W - N/S coordinate system, then applying a direction cosine transformation of axes (modified from Love, 1944, p. 43). The expression for the extensional strain in the diagonal direction becomes:

$$e_{NE/SW} = e_{11} \cos^2(\alpha_1) + e_{22} \cos^2(\alpha_2) + 2\, e_{12} \cos(\alpha_1) \cos(\alpha_2)$$

where α_1 and α_2 are the angles between the diagonal direction and the "1" and "2" axes, respectively. Applying this to QBY where the angles are all 45° and the direction cosines are all 0.707, the above equation gives an expression for e_{12} in terms of the three observed extensional strains:

$$e_{12} = e_{NE/SW} - \frac{1}{2} (e_{11} + e_{22})$$

Since extensional strain in the NE/SW direction is contaminated by the presence of N/S or E/W extensional strain, a plot of the shear strain is a more elegant display of this portion of the strain data. It is also significant that any environmental factors affecting all the instruments equally (i.e. temperature, etc.) will be removed by this calculation.

In any strained body there exists one coordinate system where all of the shear terms are zero. When the strain is expressed in terms of this coordinate system, the strain tensor is said to be "diagonalized" (i.e. all off-diagonal terms, or shear terms, are zero) and the non-zero components are the "principal strains." The problem of diagonalizing is one of finding solutions to the equation (McConnell, 1957, p. 274):

$$(e_{ij} - \lambda g_{ij})C^i = 0$$

where C^i is the unit vector of the diagonalized axis in the original coordinate system and λ is the magnitude of the principal strain. This equation is non-trivial only if (from Love, 1944, p. 42):

$$\begin{vmatrix} e_{11} - \lambda & e_{12} \\ e_{21} & e_{22} - \lambda \end{vmatrix} = 0$$

The roots (λ) of this equation (i.e. the eigenvalues) are the principal strains. Once these principal strains are obtained they can be used to solve the previous equation for C^i, thus obtaining the orientation of the principal axes.

The foregoing equations have been programmed for a Wang calculator so that the inputs are e_{11}, e_{22}, and $e_{NE/SW}$, and the outputs are $(e_{11}+e_{22})$, e_{12}, λ_1, λ_2, and Tan $\emptyset$ where $\emptyset$ is the angle between the "1"-axis (E/W) and the direction of the maximum extensional principal strain (λ).

Applying the above calculations to the QBY data results in Figure 7, which displays the cumulative areal strain $(e_{11}+e_{22})$ and cumulative shear strain (e_{12}) and the incremental variation in the direction of maximum extension from week to week.

Several features of this plot are of interest:

1) The areal strain shows an extremely sudden reversal near the end of June. It is difficult to attribute such a sharp discontinuity in slope to environmental noise.

2) Although the observed components of strain varied radically during 1968, the computed shear strain showed a straight-line increase from mid-January until mid-September. Since there was such radical variation in the individual observed components of strain, it seems unlikely that this linearity was accidental. This suggests that the QBY area was being subjected to a real shear during this time. In the full 14-month plot of shear there is a suggestion of some cyclic variation around a

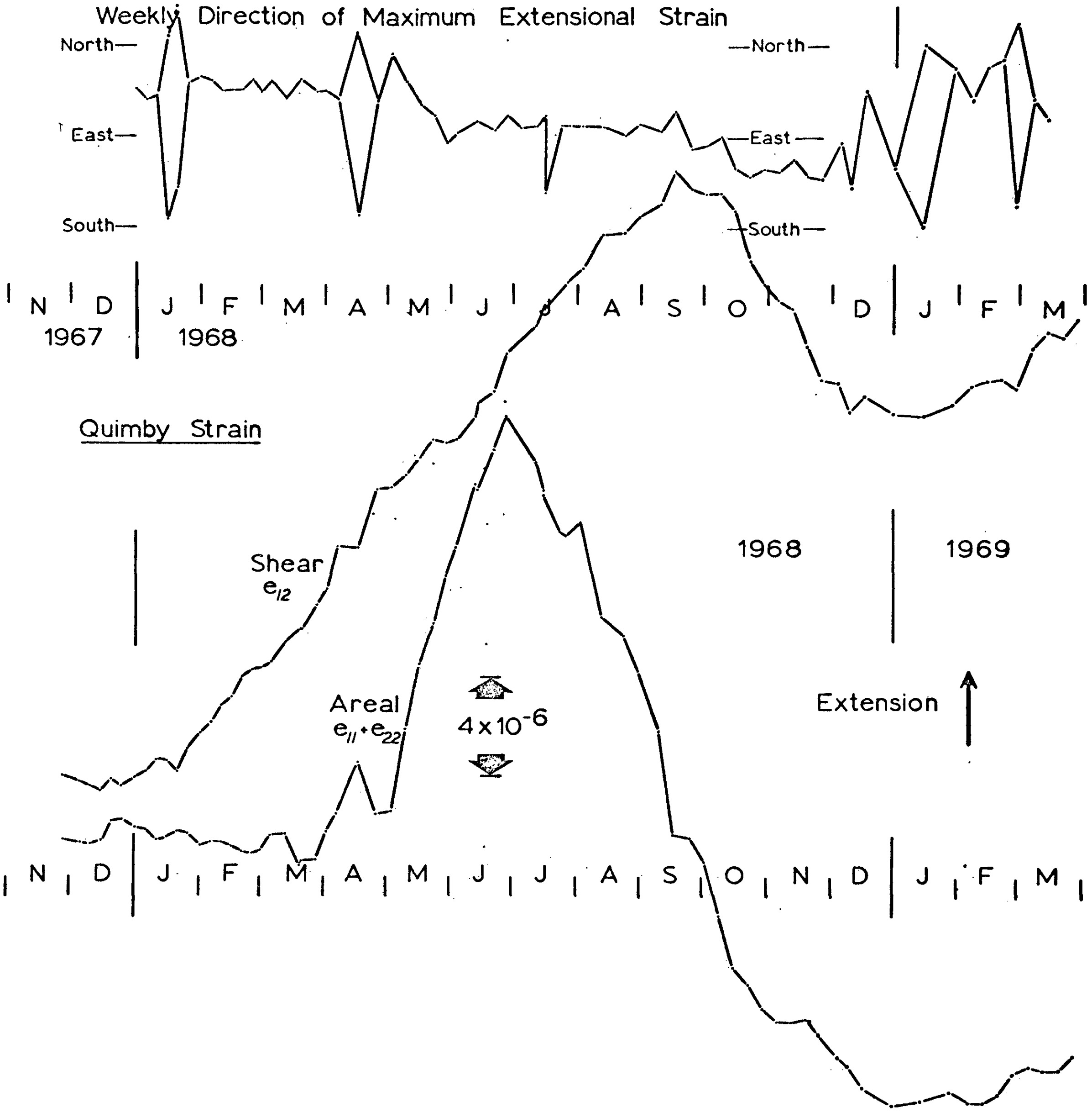

Figure 7. QBY - calculated cumulative areal and shear strains and the incremental direction of maximum extension.

steadily increasing mean. Since the calculation of shear removes atmospheric effects in the instruments, any "seasonal" source for this variation must be a seasonal deformation of the ground. The alternative interpretation, that the variation is not seasonal, is preferred because the shape of this variation is very unlike the smooth 1-year sine wave shown by the RMA instruments.

3) The direction of maximum extension shows short-period noise as might be expected in view of the fact that it is an incremental plot. If the short-period changes (i.e. those associated with only one point) are ignored, 80% of the points fall within 20 degrees of a constant clockwise drift at the rate of 10 degrees per month. If due to environmental conditions, it might be expected that the strain would show a change in one direction for 6 months, then as the seasons reverse, the strain change should similarly reverse. Under these conditions the direction of maximum extension should have one orientation for 6 months, then rotate 90 degrees for the other 6 months. The fact that this pattern is not apparent in the QBY strain again suggests that there is little seasonal component.

Since the occurrence of an earthquake is generally considered to represent the release of strain energy which was previously stored in the ground, it is pertinent to consider the energy stored or released by the secular strain. Since all components of strain are included in the computation, this one scalar quantity gives some information about the overall state of strain in the area.

The total energy stored in the form of elastic strain may be computed from (after McConnell, 1957, p. 280):

$$W = \frac{1}{2} \iiint p_{ij}\, e_{ij}\, dV$$

Since the QBY strain is recorded at a single point only, the integration can be eliminated to give:

$$2W = p_{ij}\, e_{ij}$$

Applying Hooke's Law and assuming homogeneity and isotropy:

$$2W = \lambda\theta^2 + 2\mu\, e_{ij}\, e_{ij}$$

Further assuming that $\lambda = \mu$, and that the surface of the ground is a free surface (i.e., $p_{i3} = 0$ where the subscript "3" refers to the vertical axis) an equation involving only the three horizontal components of strain can be derived:

$$\frac{W}{2\mu} = \frac{2}{3}\,(e_{11} + e_{22})^2 + e_{12}{}^2 - e_{11}e_{22}$$

This agrees with the equation shown by Love (1944, p. 102).

For an incremental change in the state of strain of a body, the corresponding change in the potential energy depends upon the stress level at which this change took place, as is obvious from the first equation above. This implies that in order to quantitatively compute the true energy relationships from the QBY data, it is necessary to know the in-situ stress in effect for at least one point on the curve. This quantity is not known; however, if it is assumed that the absolute strain did not pass through zero during the interval of observation, it is possible to determine the gross shape of the strain-energy curve during that interval. Under the assumed condition the shape of the energy curve varies slowly with change in the zero strain level chosen. Of course no quantitative results can be obtained using this assumption, not even the sign of any change.

It is common to plot strain release from earthquakes as the square root of energy release (Richter, 1958, p. 366). The resulting formula is:

$$\mathrm{Log}(E^{\frac{1}{2}}) = 4.45 + 0.95\ M_L - 0.012\ M_L{}^2$$

where M_L is the magnitude derived from Wood Anderson seismograms in the original manner. The equivalent <u>secular</u> strain release can be similarly computed by taking the square root of the result of the energy calculation outlined earlier.

It is useful to attempt to scale the earthquake strain release to the secular strain release at QBY by using data from the Derby earthquake of November 27, 1967, to relate strain release (strain steps) to Magnitude. The result of this approach is shown in Figure 8. In this figure, strain release (the positive vertical axis) during 1968 is the sum of the secular strain observed at QBY plus the local earthquake data. The order-of-magnitude similarity between the slopes of the secular strain data and the earthquake data provides further evidence for the "reality" of the secular strain observations.

There is an inherent difficulty in attempting to interpret the total strain field by use of such line plots. It is impossible to interpret the meaning of the variations in any particular curve unless all other components of strain are also considered simultaneously. For example, at Quimby during the period September to October 1968, the areal strain went through zero and the shear term began decreasing. At first glance this might suggest that a relaxation in the strain field was taking place. On the contrary, it will be shown that the crust in this region was being subjected to continuously increasing strain during this time.

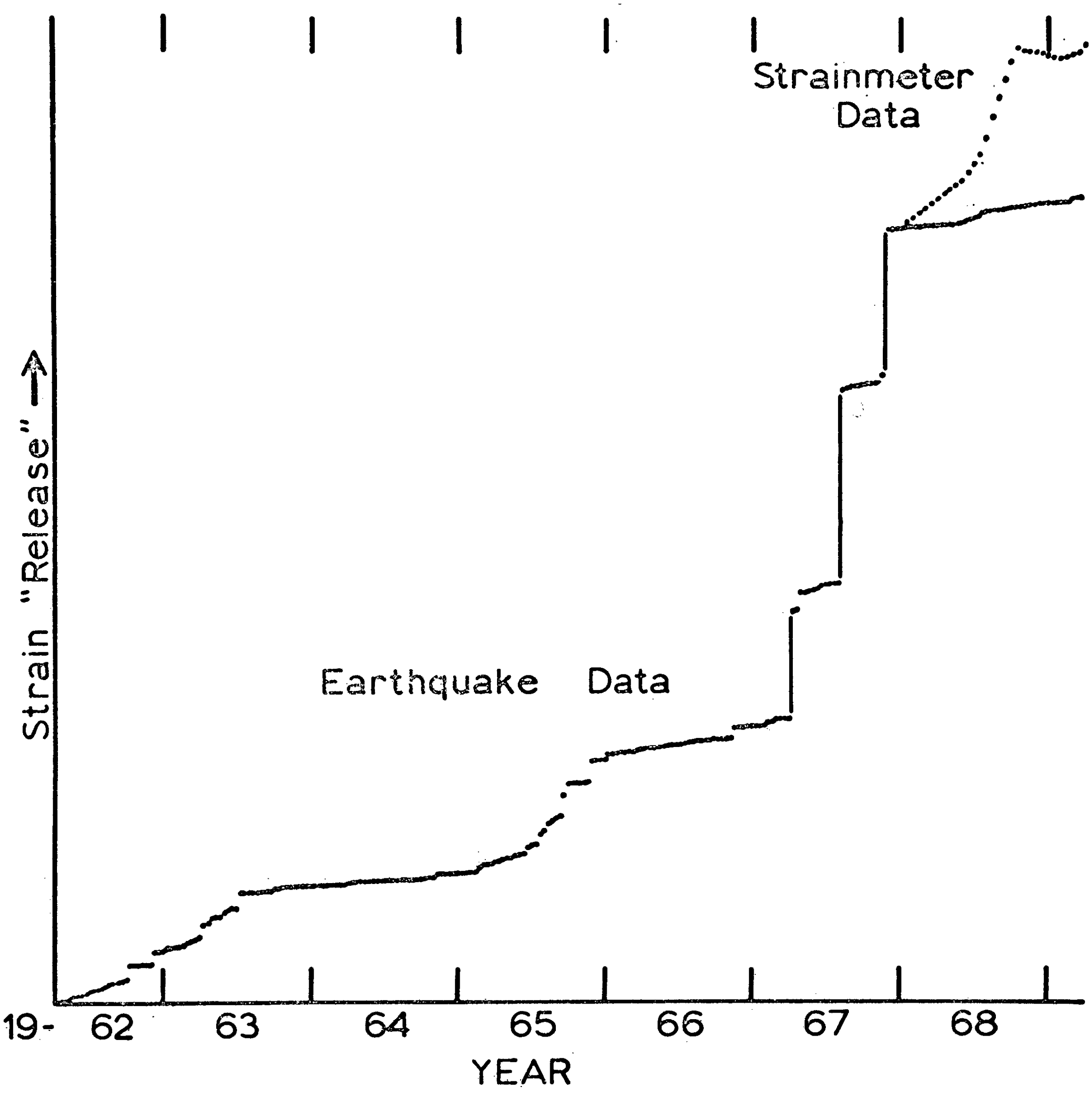

Figure 8. Earthquake "strain release" in NE Denver compared to secular "strain release" at QBY.

A superior method of presenting any two dimensional strain data is to produce the strain ellipse, representing the shape which a circle would assume if subjected to the strain observed.

The Wang program mentioned earlier for "diagonalization" has been adapted to the CDC 8090 computer. The resulting principal cumulative strains were exaggerated by a factor of about 15,000 and then used to specify the orientation and magnitude of the axes of an ellipse. Since this large exaggeration factor was required to make the strains visible, the areal strain was grossly distorted. For example, if one of the principal strains becomes -1/15,000, the magnitude of that axis of the ellipse becomes zero. The strain ellipse then deteriorates into a straight line of finite length, which has no area regardless of what the original areal strain was.

An alternative approach is to make the eccentricity a constraint on the ellipse and then adjust the size of the ellipse to agree with the observed areal strain. This was done by solving two simultaneous equations:

1) One equation specifying the ratio of the two major axes of the ellipse, and

2) a second equation requiring that the area of the ellipse be equal to that obtained by applying the same exaggeration to the original areal strain.

This approach provides a good picture of the general shape (ellipticity) and magnitude (areal strain) of the total strain, so this latter method was used in this paper. The disadvantage is that this method distorts the actual components of strain as measured in any direction from the strain ellipse. The purpose of this section, however, is to develop an accurate mental picture of the temporal development of the strain at QBY, for which the latter display is superior to the former.

All of the ellipses (one for each data point from QBY) were photographed on 16mm movie film at a time rate of 6 frames per day, thus producing a time-lapse motion picture of the deformation in NE Denver. This movie is Enclosure "A" attached to the back cover of this publication.

The special advantage of presenting the data in this manner is the simple and coherent picture it provides of the overall total strain. The example mentioned previously concerning the difficulty of interpreting the QBY areal and shear strains during October and November is an excellent illustration; the strain ellipses clearly show the deformation that is taking place: an initial elongation in the NE direction; further NE elongation and a growth of the entire ellipse during May and June; increased ellipticity, shrinking of the area, and rotation of the ellipse to a nearly E/W long axis through October; relative quiescence following October. There is no question of ambiguity or misunderstanding in this mental picture. Construction of the strain ellipses seems to be the only effective way of producing this result.

When the QBY secular strain data are viewed in this manner, the dominant impression is of a progressive secular deformation of the region. If there is a seasonal variation, it is too small to be apparent in this presentation.

In summary, the secular strain measurements at the Rocky Mountain Arsenal exhibit a significant seasonal variation. This is due, however, to environmental effects on the ground directly; the effect of temperature on the instrument itself is insignificant. The measurements at QBY may have a similar annual component; if so, it is small compared to the secular strain and will be neglected until enough data are available so that it can be better estimated.

All of the instruments indicate varying amounts of permanent secular strain. Although it is not possible to prove conclusively that this secular strain is <u>not</u> due to instrumental drift, the foregoing analyses have produced a number of factors which suggest that the secular strain is real crustal deformation:

1) The phenomenon of a "decay with distance" for the secular strain rate demonstrates an internal consistency in all of the strain data. It is highly improbable that drift or noise would produce this consistency.
2) The sudden discontinuity in slope in the areal strain at QBY about June 25, 1968 is significant. It is difficult to imagine a noise source that would produce such a sharp change in the middle of a long period of otherwise smooth data.
3) The remarkable straight-line increase in the shear at QBY (in view of the radical variations in the individual components) implies a coherence between the individual components of strain such as would result if there were a single regional mechanism producing this strain.
4) A seasonal variation would oscillate in some manner about a "zero-level" straight line. At maxima or minima in this variation there is a reversal of the direction of drift. Such a reversal of drift in strain (i.e., changing from a compression to an extension) would produce a sudden 90-degree rotation of the instantaneous direction of maximum extension. This effect does not occur in the QBY data.

5) The slope of the secular "strain release" curve is of the same order as the slope of the earthquake "strain release" curve for the previous 5 years. If the secular strain were just noise, it is improbable that these slopes would match so well.

EARTHQUAKE MECHANISMS

It has been pointed out that there is an apparent relationship between the secular strain in 1968 and the earthquakes of the preceeding 5 years. It is therefore pertinent to consider the mechanisms of the earthquakes before investigating this relationship further. Since almost all of the energy was released by the three largest earthquakes, these will be considered in detail in this section.

Wideman and Major (1967) demonstrated the existence of "strain steps" (permanent residual changes in the strain field) associated with earthquakes. Although most of their data were recorded at teleseismic distances, they suggested the presence of much larger strain steps in the area immediately around an earthquake.

This result had been predicted by Chinnery (1961) and Press (1965), who published maps of the strain and displacement fields associated with basic dislocation models. The existence of a large number of strainmeters near the NE Denver active zone provides one of the first opportunities to use the results of Press and Chinnery in fault interpretation.

Of the hundreds of earthquakes occurring in NE Denver during the last 7 years, most of the energy has been released by three of Magnitude 5 or greater: April 10, 1967 (M = 5.0), August 9, 1967 (M = 5.3), and November 27, 1967 (M = 5.1). The first of these was recorded on the strainmeters at GOL only (Fig. 9), the second was recorded on all the strainmeters at RMA, and the third was recorded on all instruments used in this report.

The hypocentral location for the April event was computed using arrival-time-difference charts for GOL and three other short-period stations. These charts were constructed from travel-time charts for the Denver Basin computed by Wang (1965). The location was checked against one computed using a short-period network on the Rocky Mountain Arsenal operated by the U.S. Geological Survey (U.S.G.S.). The latter location (Hoover, 1967, personal communication) agrees within 1 kilometer horizontally and 2 kilometers vertically.

The August event was not recorded by the U.S.G.S. network, but the time-difference charts produced a good fit using all 6 short-period stations operated by the Colorado School of Mines. This location should also be accurate within 1 kilometer horizontally and 2 kilometers vertically.

The November earthquake was not well recorded by the CSM short-period network; however, a good location was obtained by use of data from the U.S.G.S. network. Their

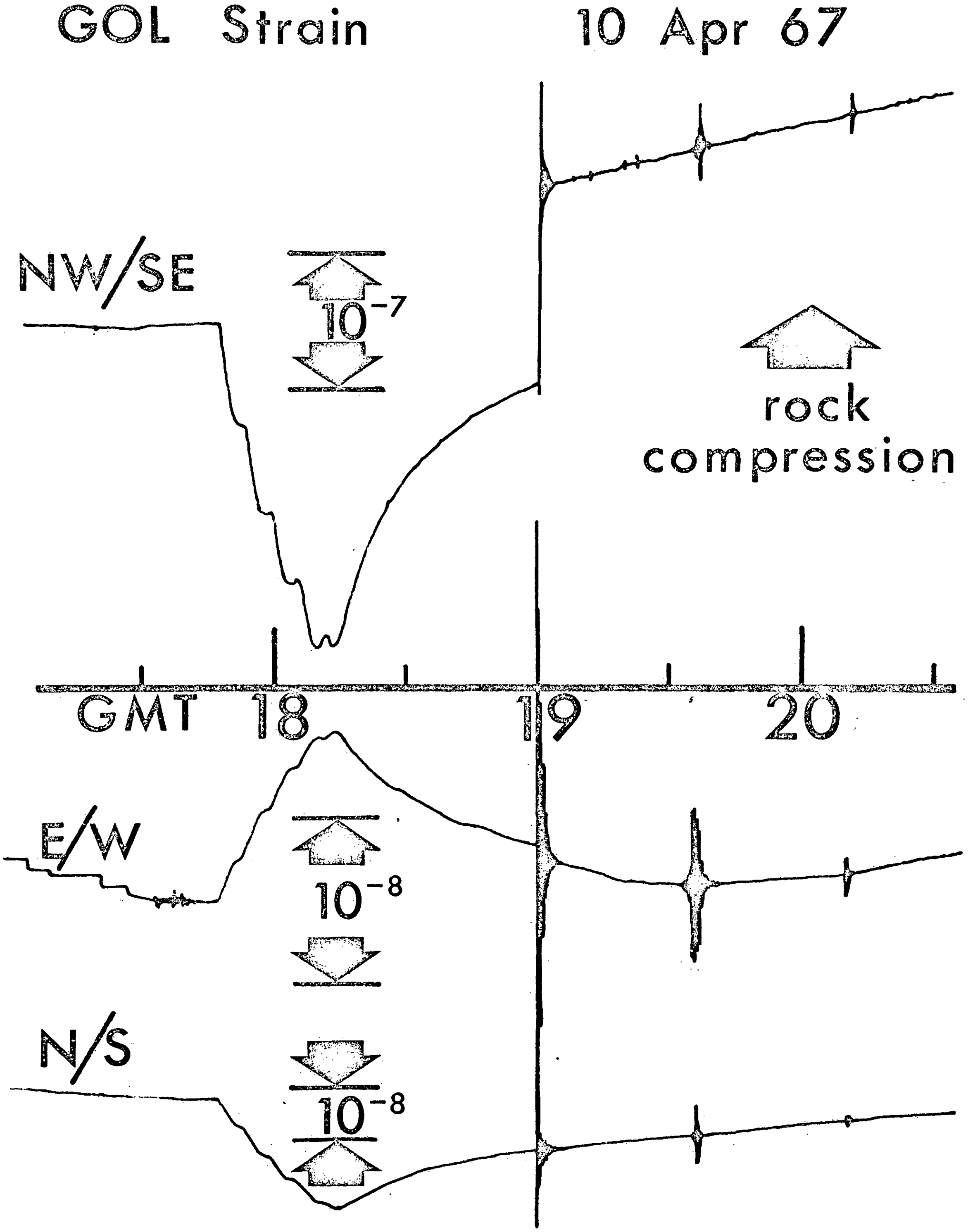

Figure 9. Sample strainmeter records from GOL showing the strain steps associated with the NE Denver earthquake (M=5.0) of April 10, 1967.

result is used in this paper (Hoover, personal communication).

The epicenters are shown by the black dots on Figures 10 through 12. The strain steps recorded for these events are shown in the figures. Also included in the figures are reproductions, properly oriented, of the records from a network of Wilmot Seismoscopes installed in NE Denver. Following the August earthquake, a number of persons in NE Denver were interviewed and Modified Mercalli Intensity ratings were assigned to their experiences. These intensities resulted in the contours on Figure 11.

A preliminary report on the first two earthquakes has already been made by Major and Simon (1968). The following discussion will refine their results and present additional data now available.

April 10, 1967 ($t_o = 19^h00^m33.6^s$GMT, M = 5.0)

Given a fault length of 10 kilometers for a Magnitude 5 earthquake (Wideman and Major, 1967) the GOL installation is located about nine half-fault-lengths W27S from the epicenter. Press' maps were used by Major and Simon (1968) to compute the components of strain at GOL for various fault orientations, and the resultant best fit was a right-lateral strike-slip fault oriented about N70W.

The theoretical decay with distance derived by Press is at considerable variance with that observed by Wideman and

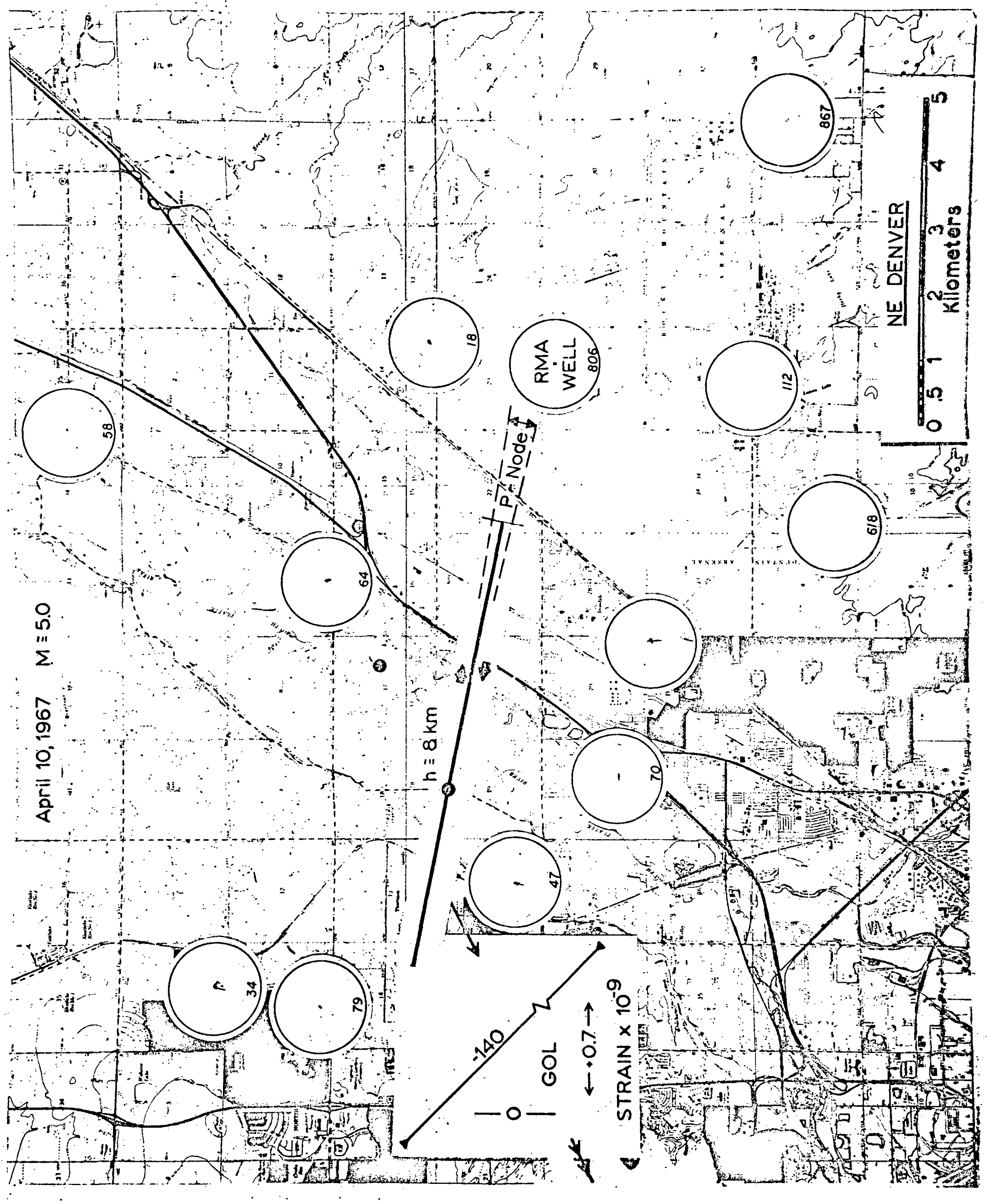

Figure 10. Fault mechanism interpretation - NE Denver earthquake of April 10, 1967 (M=5.0).

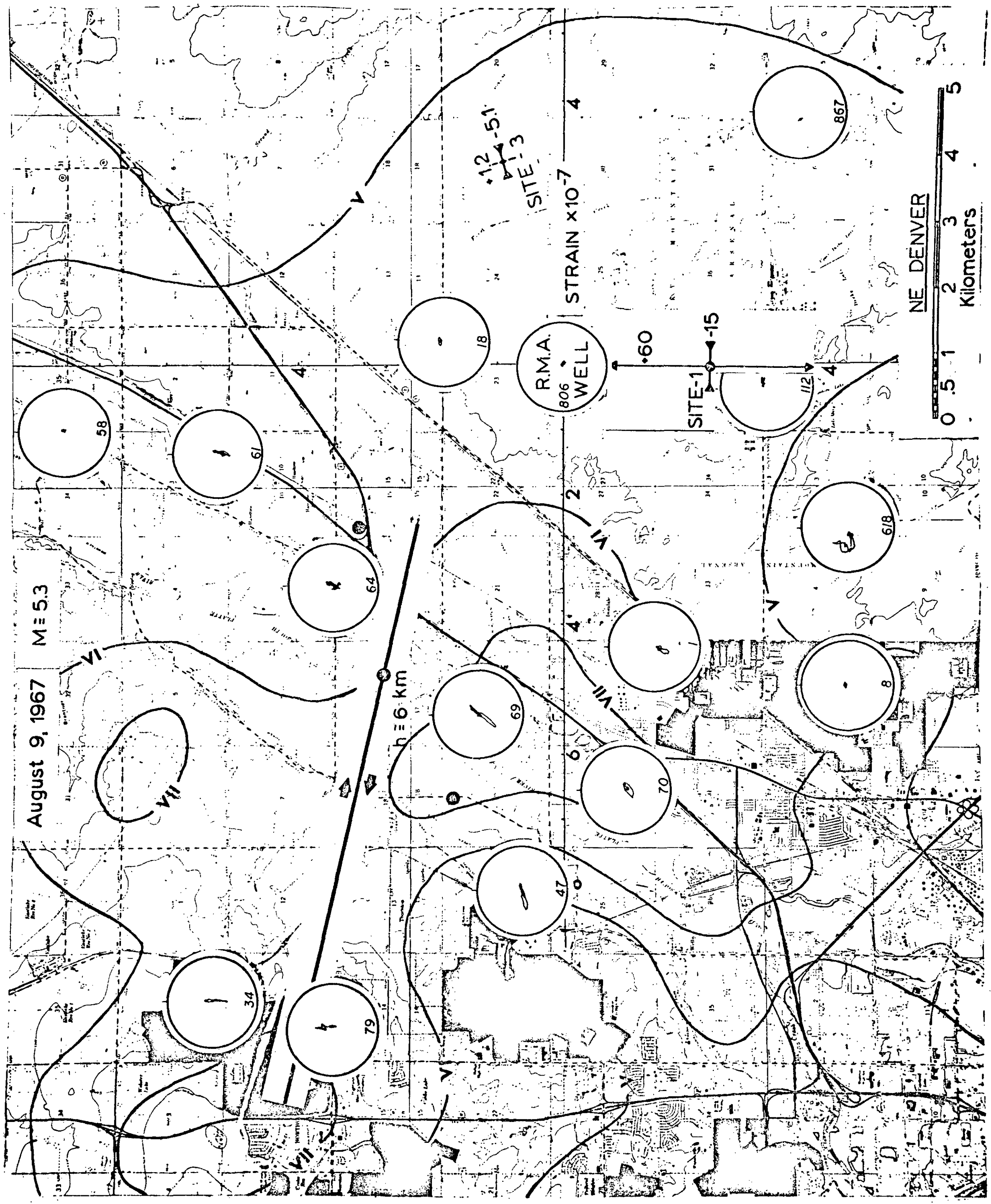

Figure 11. Fault mechanism interpretation - NE Denver earthquake of August 9, 1967 (M=5.3).

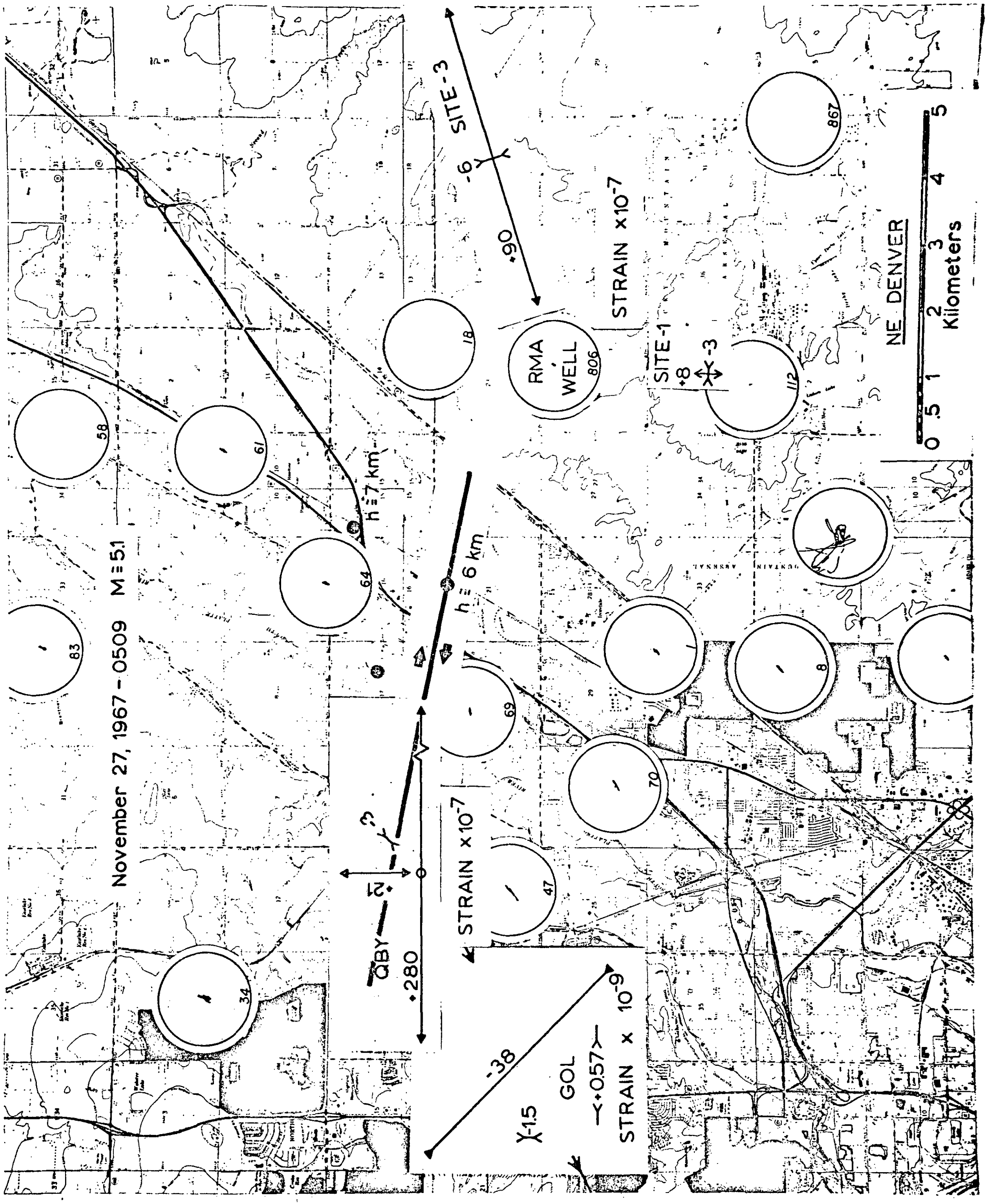

Figure 12. Fault mechanism interpretation - NE Denver earthquake of November 27, 1967 (M=5.1).

Major (1967). The actual strain step amplitudes at GOL differ significantly from those predicted by Press. Since the direction of maximum extension is independent of the amplitude decay with distance, this direction was computed for GOL and for each 10 degrees of arc on Press' maps. Utilizing this approach, the best fit was obtained for a right-lateral strike-slip fault oriented N79W. This orientation agrees well with the nodal plane for P-waves as recorded by the U.S.G.S. network, as indicated by the dotted line on Figure 10 (Hoover, personal communication).

There is the possibility that the motion on the fault is dip-slip; however, the foregoing analysis would require a dip-slip fault plane orientation of either N45E or N9E. This is not consistent with first motion data from P-waves. There is also a 90-degree ambiguity in the use of Press' strike-slip maps: the same result would also be obtained from a left-lateral, strike-slip fault oriented N11E.

Although the seismoscope data do little else than illustrate the complexity of the ground motion, the similarity of the excursions on numbers 1 and 47 does tend to eliminate the ambiguity in the choice of strike-slip fault plane orientation.

<u>August 9, 1967</u> ($t_o = 13^h 25^m 30.0^s$, $M = 5.3$)

This event was not recorded on the underground strainmeters at GOL as they were out of commission. It was recorded at RMA and Regis. Comparison of these records with Chinnery's (1961) vertical and horizontal displacement maps suggests a strike-slip fault plane oriented N77W for right-lateral motion or N13E for left-lateral motion. All strain steps are consistent with this interpretation.

The seismoscope data again suggest a preference for the N77W fault orientation, since numbers 34 and 79 would be too large if the other orientation were used. The predominant motion indicated by the seismoscopes is largely normal to the strike of the N77W fault. That this agrees with observations of the Parkfield, California, earthquake of 1966 (strike-slip motion, vertical fault plane, $M = 5.6$) further supports the choice of fault plane shown.

The felt-report intensity contours show two highs trending WNW and SSW from the epicenter. The southward trending high is probably associated with the Platte River bottom. There is no comparable explanation for the westward trending high unless this orientation is chosen for the fault.

<u>November 27, 1967</u> ($t_o = 05^h09^m31.3^s$, $M = 5.1$)

This event was recorded on all instruments in the area. The strain field at GOL was almost identical to that for the April earthquake; thus a similar interpretation results. The RMA data is consistent with a right-lateral, strike-slip fault oriented about N79W with the exception of the record from RMA-3 - Radial. This component recorded a very large step whose sign is opposite that expected for the fault orientation shown. There is, at present, no explanation for this anomalous observation. The QBY site is within the region outlined by projecting the fault zone up through the sediments; thus it is not possible to place it precisely on Chinnery's map. The QBY data are not, however, inconsistent with the interpretation shown.

The displacement and strain maps of Chinnery and Press are useable in predicting the general sense and orientation of displacements or strains associated with earthquakes similar to the models. There are severe constraints on the models, though, which limit their usefulness as a source of quantitative information. This problem is particularly noticeable when the observation is made within one fault length of the epicenter.

As interpreted here, the three faults are within 2 kilometers of each other and are oriented within 2 degrees of the same direction. The uncertainties in location are at least 1 kilometer for each hypocenter and the uncertainty in orientation is more like 10 degrees. Given these uncertainties, it is quite possible that the three earthquakes occurred on a single fault zone buried in the basement.

Even if they did not occur on the same "fault," it is probable, from the proximity of the faults, that there is a zone of weakness oriented about N80W. This control over the orientation and location may be due to a pre-existing fracture pattern or may be the result of imposition of regional stress on a random fracture pattern.

From the foregoing it is probable that the three largest NE Denver earthquakes occurred on the same fault zone in the Precambrian basement under the Denver Basin. This zone strikes approximately N80W, is near-vertical, and the sense of motion is right-lateral strike-slip.

INTERPRETATION OF THE SECULAR STRAIN AT QUIMBY

Since the fault zone orientation is apparently well defined by the previous analysis, it is possible to interpret the secular strain with some prior knowledge as to where failure might most likely occur.

The secular strains at QBY are recorded in a N/S-E/W coordinate system. By means of the direction cosine transformation of axes mentioned earlier (Love, 1944, p. 43), it is possible to compute e'_{11}, e'_{12}, and e'_{22} where the "1'"-axis is oriented parallel to the fault. In this coordinate system, shear strain (e'_{12}) is associated with a strike-slip type of movement between the two sides of the fault, e'_{11} is extensional strain parallel to the fault, and e'_{22} is the extensional strain normal to the fault. These three strains are plotted in Figure 13, along with the areal strain ($e'_{11} + e'_{22}$). A positive change in the shear plot is associated with right-lateral deformation in this particular coordinate system.

Two factors should control movement on the fault: shear strain indicates a tendency to slip and the strain normal to the fault is related to how strongly the fault is held together or "locked up." An extension normal to the fault, indicating a pulling apart of the surfaces on each side of the fault, should be a prerequisite for failure.

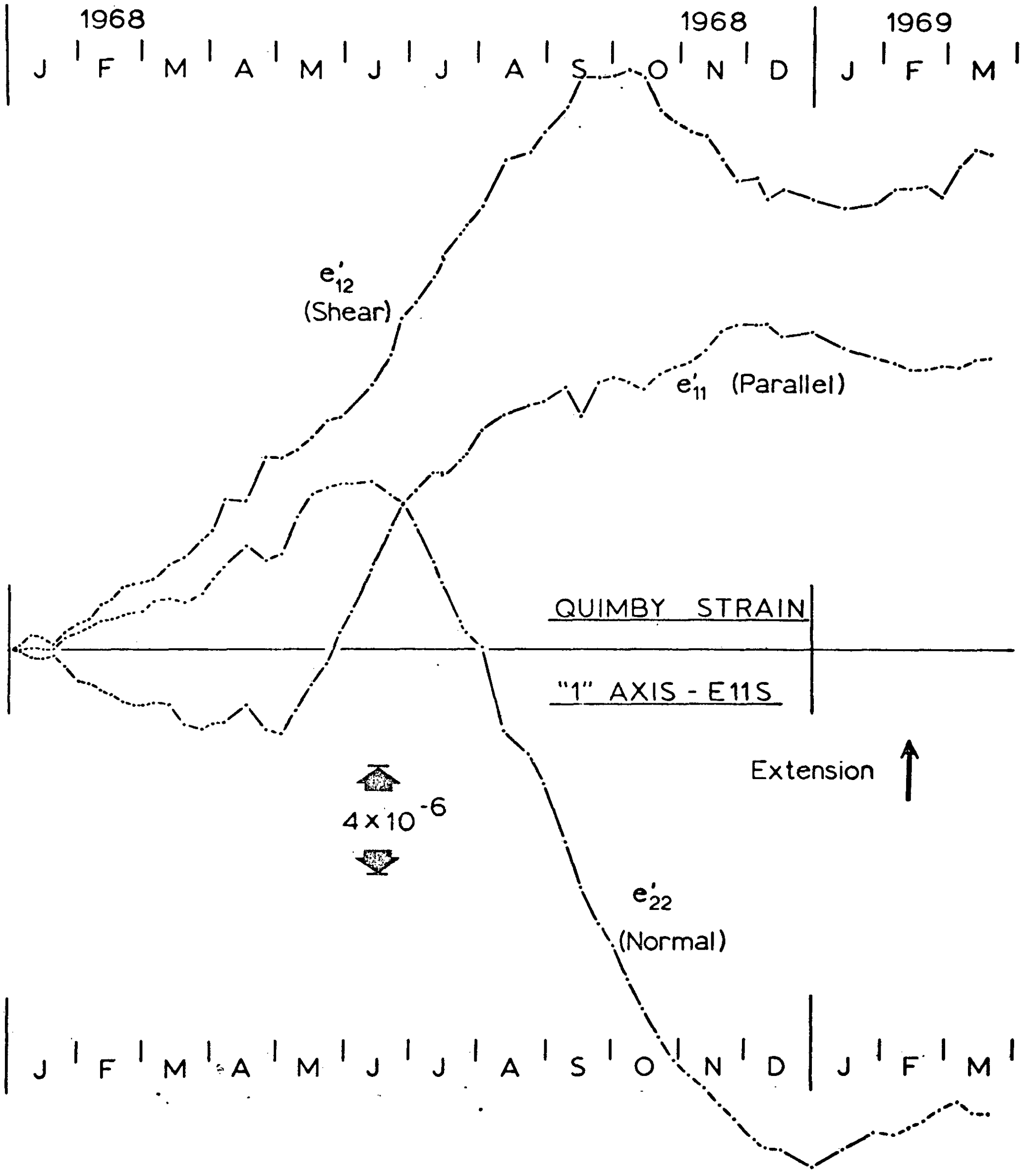

Figure 13. QBY strain data transformed so that the "1" axis is parallel to the estimated fault orientation.

Figure 13 shows that the shear strain increased (with a right-lateral sense) steadily during the first nine months of 1968, with an increase in the slope in June. The strain normal to the fault increased in extension until June, after which it went into compression for the remainder of the year. The situation in June was characterized by a steadily increasing shear on the fault coupled with a maximum of extension normal to the fault. If further failure were to occur on this fault, the optimum conditions appear to exist during June 1968.

The areal strain is more dramatic (Figure 7). After relative quiescence through April, the area expands rapidly during May and June. An extremely sharp peak is reached within a few days of June 27, after which the area contracts rapidly.

Rocks appear to fail in tension, with tensional fractures opening normal to the least compressive stress just prior to failure. The volume of the rock sample expands rapidly just prior to failure as these fractures open. In this context the rapid increase in areal strain at QBY may be analagous to volume increase prior to failure. This may imply that during 1968, that failure was most likely to occur at the peak of the areal strain -- i.e., within a few days of June 27.

Evidence from the rock mechanics laboratory indicates that, under conditions of high confining stress and long time, failure occurs on a plane oriented at 45 degrees to the principal stresses (Silverman, 1957). In the Derby case the fault orientation has been previously established by other factors. The experimental results imply that failure is most probable when the principal stresses (or strains) are oriented at 45 degrees to the Derby fault plane.

The principal strains coincide with the major and minor axes of the ellipses shown previously in the movie. Twelve of these ellipses are shown in Figure 14 at monthly intervals during 1968. This figure illustrates that the principal extension was initially oriented NNE, and that during the year it rotated clockwise to ENE. The rate of rotation was a maximum during June, and the direction of cumulative principal extension was oriented E34N on June 27, 1968. This orientation is 45 degrees off the E11S strike of the fault plane, thus further establishing late June as a time when failure might be most likely to occur.

A unique event which may be associated with the secular strain did occur beginning about 22^h45^m GMT on June 24, 1968. This transient, which occurred in two phases about twenty minutes apart, was particularly well recorded at site RMA-3 (Figure 15). At site RMA-1 the Transverse instrument did not show a recognizable transient; the Radial instrument (not yet buried at that time) had drifted, in extension, beyond the range of the transducer by 22^h00^m; thus the

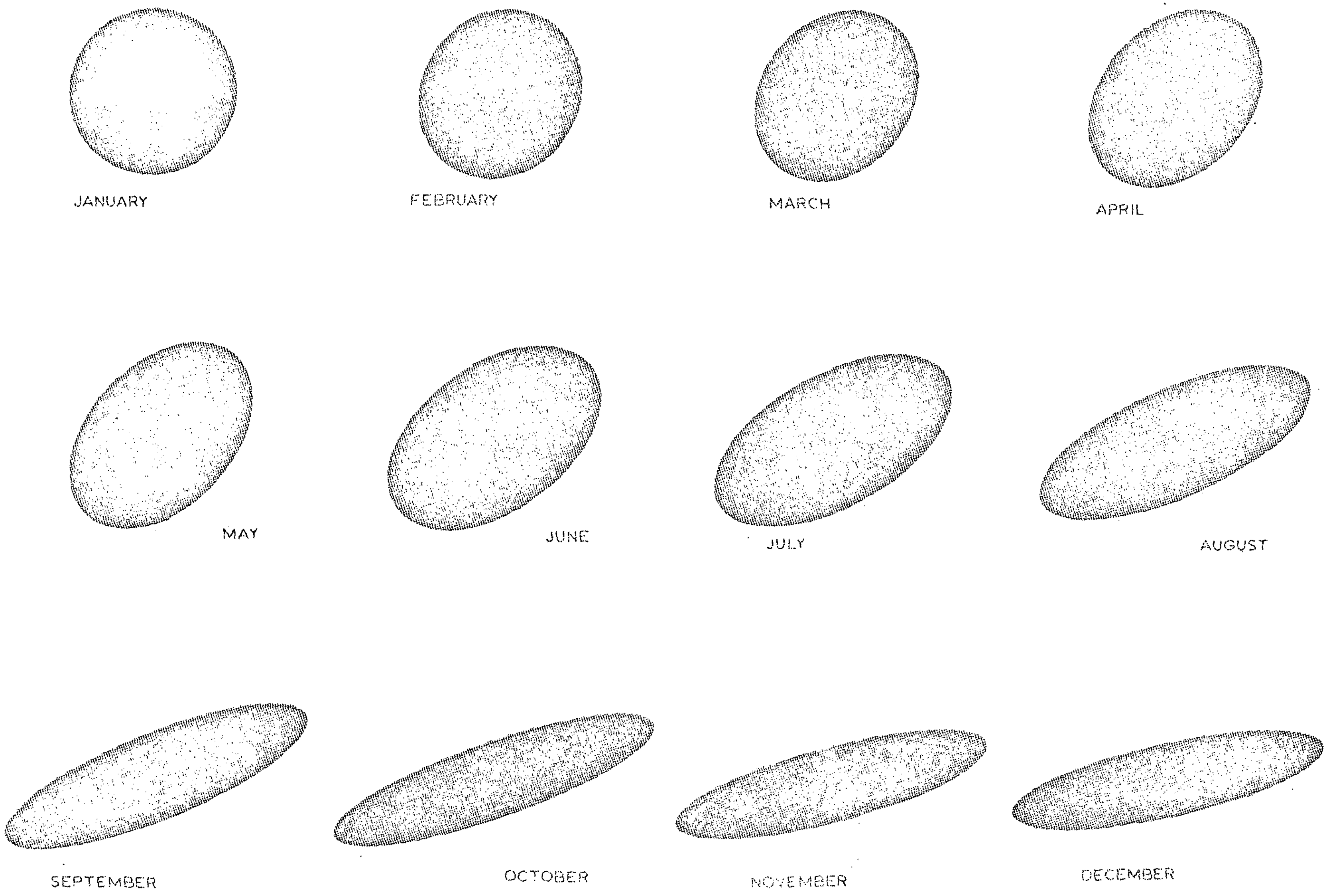

Figure 14. QBY strain ellipses for 1968 at monthly intervals.

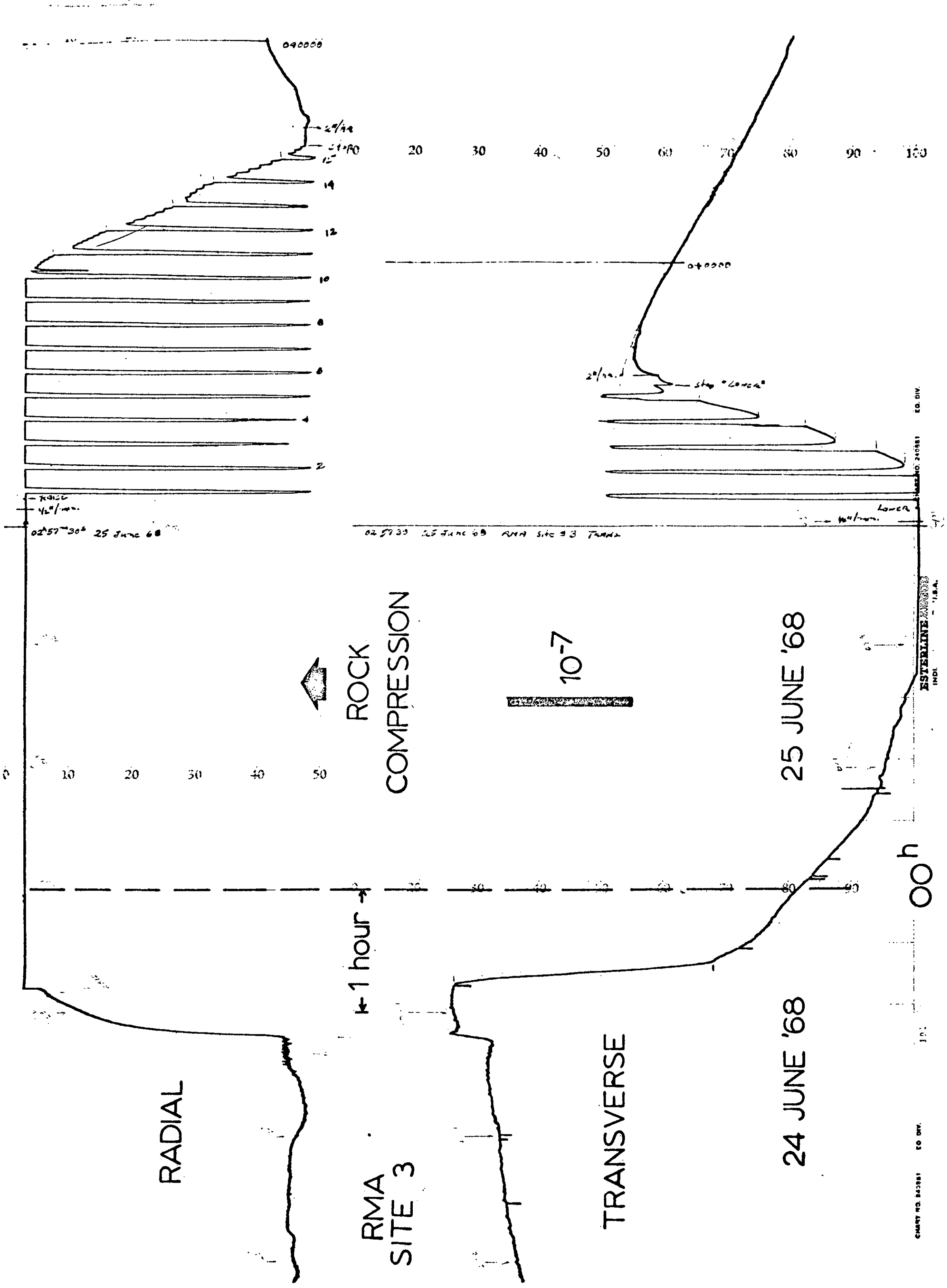

Figure 15. RMA-3 strain records for 24-25 June 1968, showing the creep-like event.

first portion of the transient was not recorded. This (Radial) instrument did record a compressional transient which reached approximately 1 x 10^{-6} by 0300^{hm} GMT on 25 June. The spikes beginning about $03^{h}00^{m}$ on both RMA-3 records are indicators of micrometer movement during remote rebalance: each spike represents 50 micro-inches movement of the "fixed" capacitor plates. As indicated by this rebalance data, 4 hours after the beginning the transients at RMA-3 were about 1 x 10^{-6} compression on the Radial instrument and about 0.5 x 10^{-6} extension on the Transverse instrument.

As mentioned previously, telemetry is not available for QBY; thus during periods of high drift the recorders are often off-scale within a few days after manual rebalance. This was unfortunately the case on June 24, 1968 for all QBY strain instruments.

Instrumental malfunctions (water drops on the capacitor plates, electronic failure, etc.) are normally step-like or erratic in shape, not smooth curves as shown in Figure 15. Moreover, that anomalous instrumental malfunctions should occur at three separate instruments at precisely the same time is so improbable that it may be eliminated as a possible explanation.

The only equipment common to the RMA sites are the telemetry power supplies at each end of the telephone line.

Any transient in the power supplies would have affected all four instruments. The fact that instrument RMA-1 - Transverse did not indicate any transient eliminates the possibility of power supply fluctuations being at fault.

The shape of the transients at Site 3 is remarkably similar to that of the creep episodes recorded on the San Andreas fault as reported by Tocher (1960). Part of Toucher's Figure 9 is reproduced here as Figure 16 to illustrate this similarity, which suggests that the event at RMA might be a similar "creep episode." Tocher has also reported that many creep episodes on the San Andreas exhibit the "two phase" nature shown in both Figures 15 and 16.

The amplitudes of the strain changes associated with this episode are intermediate between those of the strain steps associated with the earthquakes of August 9 and November 27, 1967 ($M = 5.3$ and 5.1 respectively). This episode also signalled an abrupt change in the long-term characteristics of the secular deformation. It is therefore tentatively concluded that a "creep episode" occurred in NE Denver beginning 22^h45^m GMT on June 24, 1968, and that this creep represented slow movement in the fault zone, which produced an amount of strain release that might otherwise have been associated with an earthquake of the order of Magnitude 5.

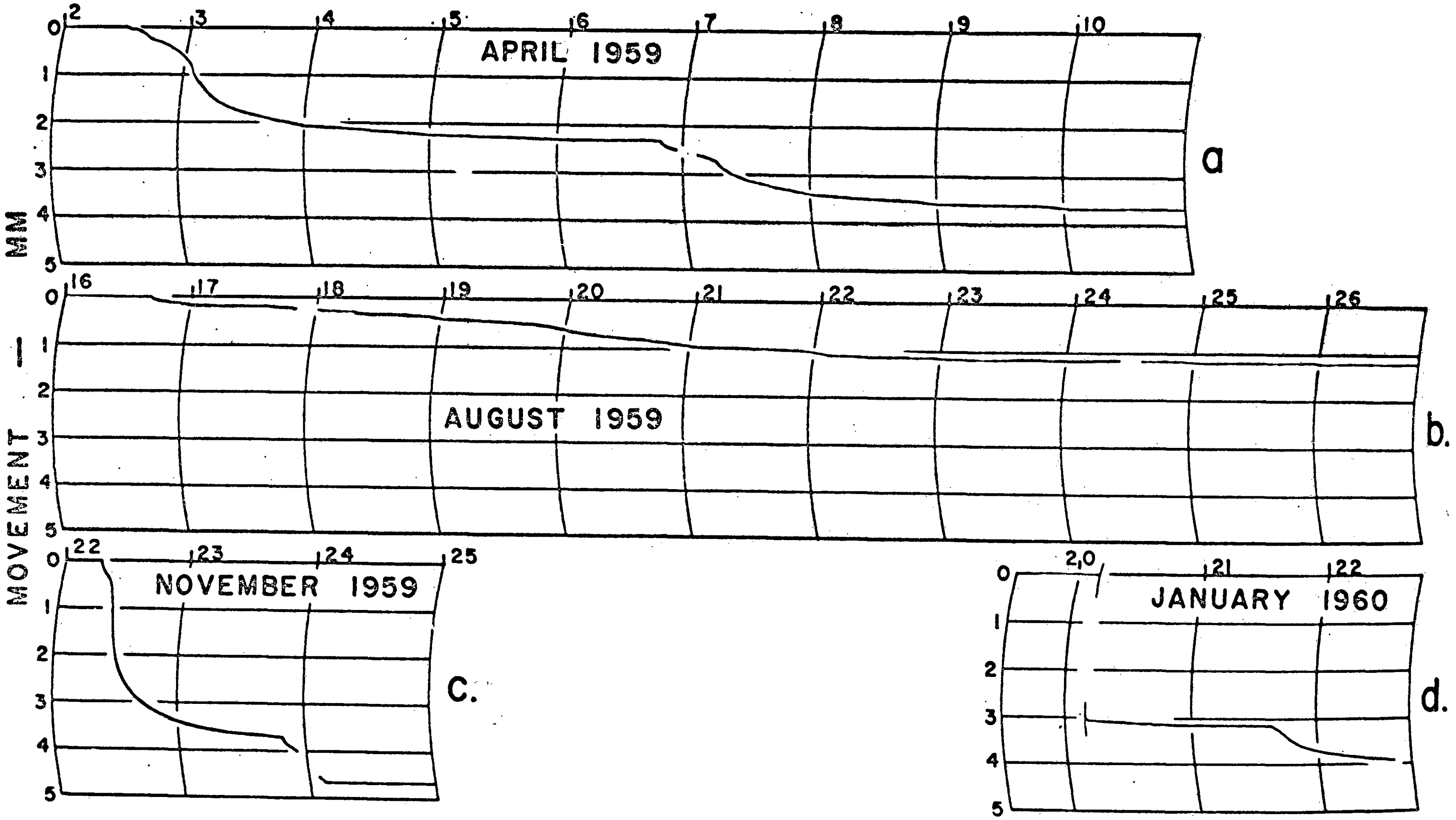

Fig. 9. Records from creep recorder no. 3. Time lines at 0 h GCT of indicated date.

Figure 16. Published creep records from the San Andreas Fault near Hollister, California.

CONCLUSIONS

The existence of a cluster of entrenched strainmeters in NE Denver provides a unique opportunity to study secular strains in a seismically active region. Analysis of data collected from this network since the fall of 1967 has resulted in some general conclusions concerning secular strain measurements:

1) Annual variations averaging about 5×10^{-6} are apparent on some instruments. These are seasonal fluctuations in the rock, not just temperature variations in the strainmeters.

2) Secular strain rates, of a tectonic origin, are of the order of 3×10^{-5} per year in the NE Denver active zone. These are readily observable in spite of the seasonal variations.

3) All three components of horizontal strain must be observed in order to perform certain necessary analyses of the data.

4) The most comprehensible method of displaying the complete horizontal secular strain is by construction of strain ellipses. Temporal variations in the ellipses are conveniently illustrated by use of a time-lapse motion picture.

5) Strainmeters operating in an active zone will also record strain steps associated with local earthquakes. These strain steps are useful in interpreting local fault mechanisms, upon which the interpretation of local secular strain is based.

Secular strain rates in the Denver area vary radically with distance from the active zone. Two orders of magnitude difference are observed within 45 kilometers of NE Denver where earthquakes with fault lengths of 10-15 km have occurred. If this result is applicable to other regions, two conclusions follow:

1) Widely-spaced strainmeter networks are not suitable for preliminary regional secular strain studies. Detailed first-order surveys are probably preferable.
2) Only instruments within approximately one half-fault-length of a fault will contribute to the prediction of earthquakes on that fault.

Fault mechanisms in NE Denver were deduced using strain step data, and the secular strain was then analyzed in a coordinate system, one axis of which was oriented parallel to the resultant fault zone. It is concluded that:

1) The three largest ($M \geq 5$) Denver earthquakes occurred on right-lateral, strike-slip faults oriented N79W.
2) During the first nine months of 1968 the right-lateral shear in this coordinate system increased

steadily. In June 1968, both the strain normal to the fault and the areal strain reached maxima in extension that have not since been duplicated. Failure was therefore most probable during June.

3) On June 24-25, 1968, a "creep episode" occurred in NE Denver. No other similar event has ever been recorded.

4) Since the conditions observed during June 1968 do not presently exist in NE Denver, no major failure is anticipated in the immediate future.

APPENDIX A -- ORIGINAL DATA

Following is a tabulation of the cumulative strain at QBY. The numbers are the total displacement of the "free end" of the quartz in micro-inches, positive values signifying rock extension. Strain is computed by dividing this displacement by the base-length (approximately 40 feet).

Date		E/W	N/S	NE/SW
December 1967	31	1150	0	-1760
January 1968	5	1170	-45	-1660
	10	1105	-200	-1520
	15	1060	-90	-1520
	20	1070	0	-1680
	25	940	100	-1230
	31	620	170	-1040
February	5	600	265	-790
	10	560	295	-440
	15	520	260	-320
	20	440	235	40
	25	350	280	150
	28	400	300	210
March	5	500	500	500
	12	600	425	910
	19	157	229	853
	20	227	249	914
	27	227	289	1424
April	1	483	588	1998
	6	842	588	3056
	16	1300	1188	3546
	25	1126	318	4202
May	2	1000	493	4258
	9	1717	1419	5339
	16	2537	1916	6348
	23	3311	1948	7110
	29	4175	2048	7519
June	3	4799	2011	7867
	12	6219	1837	8969
	13	6219	1736	9180
	21	7574	1196	9837
	27	8607	637	10817

Date		E/W	N/S	NE/SW
July 1968	3	9127	-126	10898
	11	9827	-1335	11007
	15	10010	-2072	11155
	15 (EQ)	9931	-2090	11030
	23	10537	-3390	11076
	26	10819	-3750	11172
August	2	11616	-4296	11572
	12	12419	-7000	11292
	23	12739	-7700	11142
	30	13019	-8690	11092
September	9	13599	-10490	10752
	16	13099	-12050	10392
	24	13959	-13000	9982
October	1	14079	-13600	9642
	8	13969	-14560	9120
	15	13669	-15280	8270
	22	13740	-15700	7080
	29	13760	-16180	6370
November	5	13780	-16460	5910
	12	14050	-16750	5650
	19	14280	-16930	4910
	26	14220	-17080	4150
December	5	14220	-17650	3800
	10	14040	-17630	3140
	17	13810	-17830	3230
	31	13830	-18190	2710
January 1969	14	13340	-17610	2710
	28	13150	-17240	3040
February	6	13140	-17430	3310
	13	12990	-17300	3410
	20	12980	-17130	3530
	27	12990	-16740	3540
March	6	13270	-16840	4450
	13	13630	-17280	4730
	20	13630	-17280	4620
	27	13630	-17000	5100

BIBLIOGRAPHY

Chinnery, M. A., 1961, The deformation of the ground around surface faults: Seis. Soc. America Bull., v. 51, n. 3, p. 355-372.

Homuth, E. F., 1968, Earth Strains: tidal and secular, observed near Bergen Park, Colorado: Colorado School Mines Graduate Thesis T-1218.

Love, A. E. H., 1944, A treatise on the mathematical theory of elasticity: New York, Dover Pub., 643 p.

Major, M. W., 1966, Strainmeters, in ESSA Symposium on earthquake prediction: Washington, U.S. Govt. Printing Office, p. 69-71.

Major, M. W., and Simon, R. B., 1968, A seismic study of the Denver (Derby) earthquakes: Colorado School Mines Quart., v. 63, n. 1, p. 9-55.

McConnell, A. J., 1957, Applications of tensor analysis: New York, Dover Pub., 318 p.

Press, Frank, 1965, Displacements, strains, and tilts at teleseismic distances: Jour. Geophys. Research, v. 70, n. 10, p. 2395-2412.

Richter, C. F., 1958, Elementary seismology: San Francisco, W. H. Freeman and Co., 768 p.

Romig, P. R., 1967, A millimicron displacement transducer with mechanical calibration: Colorado School Mines Graduate Thesis T-1123.

Silverman, I. K., 1957, Behavior of materials and theories of failure: Colorado School Mines Quart., v. 52, n. 3, p. 3-17.

Smookler, S., 1968, A continuously recording interferometer in the calibration of strainmeters: Colorado School Mines Graduate Thesis T-1164.

Tocher, Don, 1960, Creep rate and related measurements at Vineyard, California: Seis. Soc. America Bull., v. 50, n. 3, p. 396-404.

Wang, Yung-liang, 1965, Local hypocenter determinations in linearly varying layers applied to earthquakes in the Denver area: Colorado School Mines Graduate Thesis T-1027.

Wideman, C. W., and Major, M. W., 1967, Strain steps associated with earthquakes: Seis. Soc. America Bull., v. 57, n. 6, p. 1429-1444.