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Deformation of the Mitaka Rhombus: Strain Buildup Following The 1923 Kanto Earthquake, Central Honshu, Japan

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Frequently repeated surveys of a local network near Tokyo provide considerable detail on the horizontal strain changes immediately adjacent to the rupture zone of the $M=8.1$ Kanto earthquake. Changes in the three independent tensor strain components are determined for 35 epochs during 1916-1980 to a precision of about ± 1.5 μstrain. No significant shear or elongational strain changes preceded the earthquake; a change in dilatational strain is marginally significant. Postseismic movements are large, accumulating to 40% or more of the coseismic strain drop. They have at least two time scales. A distinct short-term transient lasting less than a year is explained well by slip or localized deformation that occurs downdip of the coseismic rupture plane and has a time constant of about 3 months. More complex, longer-period postseismic movements continue for at least another 10 years. Their precise duration, as well as the transition to presumably steadier interseismic deformation, is obscured by notable irregularities in the strain buildup at Mitaka. As a result, neither the interseismic strain rate nor the occurrence time of the next Kanto earthquake can be reliably estimated from these observations.

INTRODUCTION

The precise relation between the pattern of strain release in one great earthquake and the subsequent buildup prior to the next event provides important constraints on the process of strain accumulation and can significantly affect earthquake recurrence estimates. Detailed observations of crustal movements at major plate boundaries supply the most critical data on this cyclic buildup and release of strain, and great thrust earthquakes on the Sagami Trough, at the boundary between the Philippine Sea and Eurasian plates, have been carefully studied using both geological and geophysical observations of crustal deformation [*Ando,* 1971, 1974; *Matsuda et al.*, 1978; *Scholz and Kato*, 1978; *Thatcher and Rundle*, 1979; *Shimazaki and Nakata,* 1980]. Extensive geodetic surveys were carried out before and after the most recent Sagami Trough event, the 1923 $M = 8.1$ Kanto earthquake, and the most complete record of crustal movements is at Mitaka, near Tokyo (Figure 1), where a small local network has been resurveyed 35 times since 1916. These data [*Geographical Survey Institute*, unpublished manuscript, 1983] have been analyzed by *Fujita* [1972], whose results have been applied to a number of subsequent studies of the Kanto earthquake [e.g., *Ando,* 1974; *Scholz and Kato*, 1978; *Thatcher and Rundle,* 1979].

The unique value of the Mitaka observations lies in the detail they provide on the evolving strain history since the occurrence of the Kanto earthquake and the relation of this pattern to the coseismic changes of 1923. The purpose of this paper is to analyze the Mitaka data in more detail than has been attempted previously, in particular, determining the survey-to-survey variations in each of the three independent horizontal strain components as well as their observational uncertainties. These results complement those obtained previously by Fujita; where overlap exists, the two independent determinations of strain do not differ in any essential respects. The exercise seems worthwhile because it provides a more complete description of both the large postseismic strain changes and some apparent interseismic fluctuations in strain rate as well as permitting an objective assessment of the significance of both these changes and those preceding the earthquake in 1916-1922, when nine surveys were carried out. In addition, because the Mitaka rhombus supplies only a very local measure of deformation in the South Kanto district, nearby geodetic survey results are examined to assess the degree to which changes at Mitaka may be of more regional extent.

2. OBSERVATIONS AND ANALYSIS

The Mitaka network consists of six lines (Figure 1, inset), five of them nearly 100 m in length that have been measured 35 times during 1916-1980 and a longer east-west line observed 11 times between 1939 and 1980. Distances were measured by invar taping until 1971 (see *Bomford* [1971, pp. 35-45] for procedures), while the 1977 and 1980 observations were made with a Mekometer, a short-range electro-optical distance-measuring (EDM) instrument (any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey). Measurement uncertainties were estimated from year-to-year variations in line length that occurred during 1935-1943, when there was little if any change in the derived strain components (see Figure 2). These variations are randomly distributed about zero with a standard deviation of 1.3 parts per million (ppm) (mean = 0.01 mm, standard deviation = ± 0.13 mm, samples size = 44). Precision was probably lower for the three most recent surveys. The 1971 observations were done in cooperation with students of the Construction College and so may be less accurate. The 1977 and 1980 measurements are more uncertain, not because the EDM length determination is intrinsically less precise than invar taping but because the procedure for centering over each benchmark is not as accurate. Using an invar tape near ground level, centering was repeatable to better than 0.1 mm, but with the Mekometer, mounted on a 1.5-m-high tripod, centering accuracy was several times worse. At the 100-m ranges

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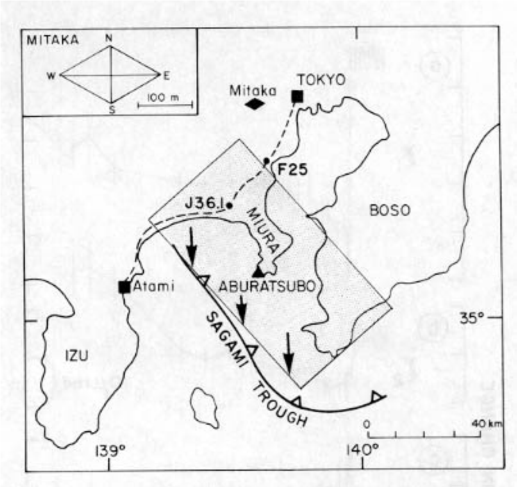

Fig. 1. Location map of South Kanto district. Rectangle shows surface projection of fault plane of $M=8.1$ 1923 Kanto earthquake with arrows indicating slip vectors [*Ando*, 1974], and diamond locates local geodetic network at Mitaka, with its configuration shown in the inset, upper left. Dashed line denotes leveling route between Tokyo and Atami, and solid triangle identifies tidal gage station at Aburatsubo.

measured at Mitaka it is this factor that limits the precision of the 1977 and 1980 observations. Local shifting of a single benchmark sometime during 1958-1971 could have caused further degradation of the post-1971 data, and this possibility is discussed below.

For each measurement epoch, the five (or six) measured line lengths were used to determine the three independent components of the horizontal strain field relative to the 1916 survey by the method of least squares. The procedure is the same as that employed by the U.S. Geological Survey in analyzing repeated laser ranging measurments of line length in tectonically active parts of the western United States [e.g., see *Prescott et al.*, 1979]. Uncertainties in the strain components were estimated in two independent ways: first, by computing the effect of measurement error on the derived strains, and second, by determining the departures of measured lengths from those computed from the least squares fit strain field. For the majority of the data the two error estimates agree, indicating that uncertainties are due largely to random measurement errors. The tensor strain components are uncertain, on average, by about ± 1.5 μstrain; because of the network configuration, the north-south contraction, e_{22}, is slighly more uncertain than this figure, while e_{11} and e_{12} are somewhat better determined.

However, residuals from the computed line lengths are significantly larger than random measurement errors for the surveys of 1931, 1971, 1977, and 1980. Large residuals occur in four of the five lines measured in 1931 and are absent in subsequent surveys, suggesting that observational errors were simply larger for this epoch. However, for the three most recent surveys, the large residuals are confined to only two parallel lines (E-S and W-N, see Figure 1 inset) and reflect an internal inconsistency in their length changes after 1958. While these lengths should change by comparable amounts in a uniform strain field, the changes between 1958 and the three subsequent surveys are significant, ~0.6 mm, but have opposite signs. The other four lines show large changes, ~1 mm or more, during 1958-1971 that are fit well by a uniform strain field, so it seems likely that a significant deformation episode occurred at Mitaka during this time. Inconsistent length changes as large as those occurring after 1958 are absent from the remainder of the data, and a small permanent shift of a single benchmark nearly parallel to either the E-S or W-N line could explain the inconsistency. To indicate the larger uncertainties in strain estimates for these four epochs, error bars in Figures 2 and 3 have been increased proportionally to the root mean square sum of the residuals for each of the four surveys.

3. Strain History

The three independent components of the tensor strain field are plotted in Figure 2, and the two parameters needed to specify the engineering shear strain, γ_1 and γ_2, are shown at the top of Figure 3. The tensor strains are relatively stable during 1916-1922, show a sharp coseismic offset in 1923, and exhibit considerable variability thereafter, even after about 1935, when at least the largest postseismic transients had died out. During 1923^{+}-1958, after the 1923 earthquake, the maximum compressive strain axis varies in orientation by no more than a few degrees from N5°W relative to the 1916 survey, indicating that the chosen coordinate system, oriented north-south and east-west, is close to the principal axis reference frame. However, after 1958 the e_{12} component changes significantly, corresponding to a clockwise rotation of more than 20° in the principal strain axes. The two independent shear strain components (Figure 3) show the same temporal variability as the three tensor components, indicating that the unexpectedly large changes after 1923 cannot be attributed to small undetected survey-to-survey scale errors, since such a bias would contaminate the elongational strains but leave the shear components unaffected.

Coseismic deformation at Mitaka involved a nearly uniaxial north-south extension of 36 μstrain roughly parallel to the slip vector of the 1923 earthquake (see Figure 1). *Ando* [1974] has

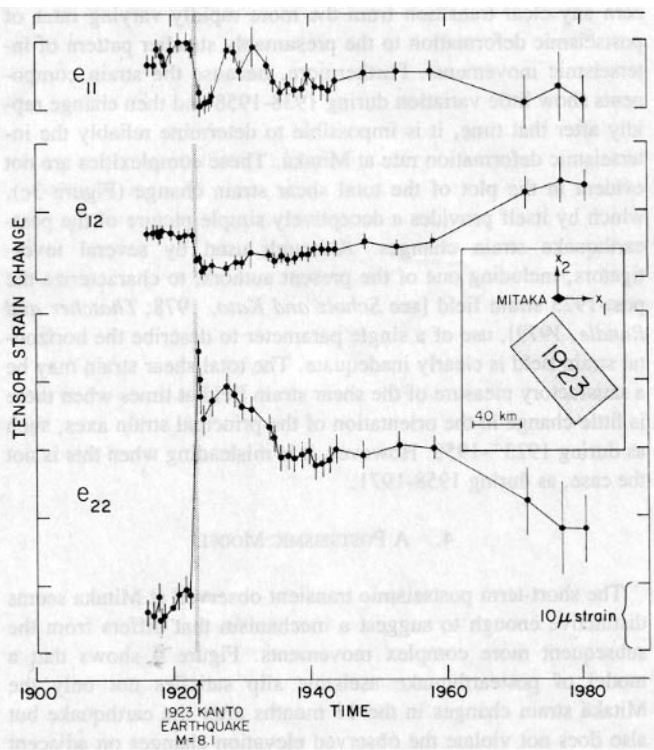

Fig. 2. Time history of the three independent horizontal strain components at Mitaka. Vertical bars are one standard deviation error estimates. Extension is positive upward for the elongational strains e_{11} and e_{22}; left-lateral shearing is positive for e_{12}. Strains are referred to a cartesian coordinate system in which the x_1 axis is directed to the east and the x_2 axis to the north. Inset, middle right, shows location of Mitaka relative to 1923 fault plane.

shown that the observed strain changes agree well with the movements predicted by an independently constrained dislocation model of the earthquake, indicating that despite the small size of the network, tectonic strain changes of regional extent were nonetheless faithfully recorded at Mitaka.

Whether significant strain changes preceded the earthquake is uncertain. The shear components exhibited negligible change, and elongational strain changes of several parts per million are only marginally significant. During 1916-1922 the areal dilatation, Δ, increased by 4.6 ± 2.1 μstrain, a change which may have been significant. However, survey-to-survey fluctuations within the pre-earthquake period approach this magnitude (see Figure 3*d*), and with only these data it does not seem possible to decide clearly whether these dilatational strain changes represent true tectonic deformation or mere statistical scatter in the strain field determinations.

Although complicated in detail, the postseismic deformation is separable into a transient of very short duration and a longer-term, more complex sequence of movements. The immediate postseismic transient involves nearly uniaxial north-south compression that decays rapidly during the year following the earthquake. Changes in the e_{22} strain component during the 11 months after the earthquake are matched well by an exponential decay function with an amplitude of 10 μstrain and a time constant of 3 months (Figure 4*a*). Subsequent movements cannot be fit to this simple functional form, and changes clearly occur more slowly. They include both elongational strain components, involve at least one reversal in the sense of straining, and persist until at least 1935. During 1923^+-1935 the cumulative change in e_{22} was 15 μstrain, about 40% of the coseismic strain drop.

Unfortunately, strain changes after 1935 are too erratic to discern any clear transition from the more rapidly varying rates of postseismic deformation to the presumably steadier pattern of interseismic movements. Furthermore, because the strain components show little variation during 1938-1958 and then change rapidly after that time, it is impossible to determine reliably the interseismic deformation rate at Mitaka. These complexities are not evident in the plot of the total shear strain change (Figure 3*c*), which by itself provides a deceptively simple picture of the post-earthquake strain changes. Although used by several investigators, including one of the present authors, to characterize the post-1923 strain field [see *Scholz and Kato,* 1978; *Thatcher and Rundle,* 1979], use of a single parameter to describe the horizontal strain field is clearly inadequate. The total shear strain may be a satisfactory measure of the shear strain field at times when there is little change in the orientation of the principal strain axes, such as during 1923^+-1958. However, it is misleading when this is not the case, as during 1958-1971.

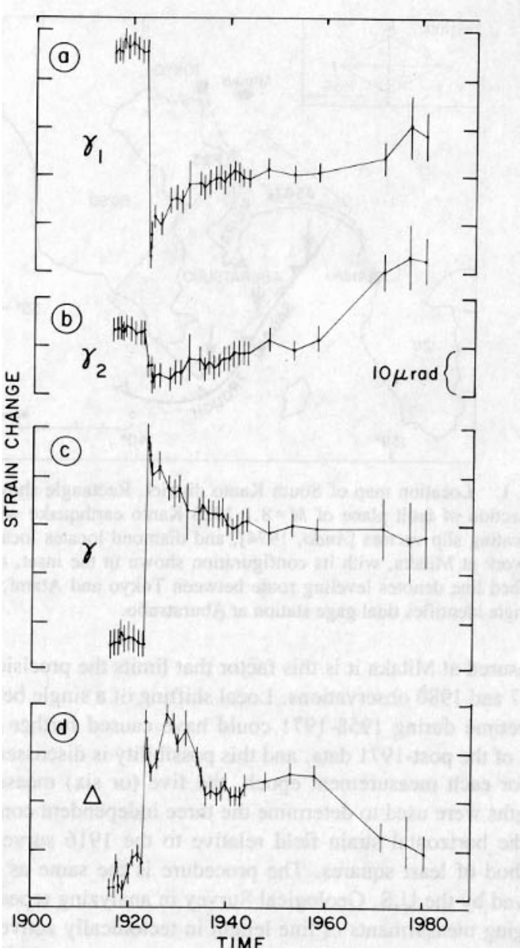

Fig. 3. Horizontal strain parameters versus time. (*a*) Shear strain ($\gamma_1 = e_{11} - e_{22}$). (*b*) Shear strain ($\gamma_2 = 2e_{12}$). (*c*) Total shear strain ($\gamma = \sqrt{\gamma_1^2 + \gamma_2^2}$). (*d*) Areal dilatation ($\Delta = e_{11} + e_{22}$).

4. A POSTSEISMIC MODEL

The short-term postseismic transient observed at Mitaka seems distinctive enough to suggest a mechanism that differs from the subsequent more complex movements. Figure 4 shows that a model of postearthquake aseismic slip satisfies not only the Mitaka strain changes in the 11 months after the earthquake but also does not violate the observed elevation changes on adjacent portions of the Tokyo-Atami leveling route. The model fault has 0.90 m of right-lateral strike-slip and 0.45 m of reverse dip-slip motion across a plane 30 km wide and 85 km long that dips 30° NE and lies on the downdip extension of the coseismic fault. The 2:1 ratio of strike-slip to dip-slip motion is the same at that required by *Ando* [1971, 1974] to satisfy the coseismic deformation. A comparison of the observed and computed principal strains, Figure 4*b*, shows excellent agreement.

Slip on the model fault produces very little vertical displacement on the Tokyo-Atami level line, predicted movements being nowhere greater than 25 mm (Figure 4*c*). Observed displacements on the route are comparably small except near Atami, where they depart significantly from the model curve. This disagreement is mirrored in the coseismic deformation, which shows uplift near Atami, where a simple northeastward dipping fault model would predict subsidence to occur. However, as *Ishibashi* [1976] and *Scholz and Kato* [1978] point out, thrust motion on a subsidiary westward dipping fault located offshore of the Izu peninsula would reproduce the observed coseismic deformation, and aseismic slip downdip of this fault could account for the postseismic uplift near Atami.

The postseismic slip model proposed here differs in several respects from that suggested previously by *Thatcher and Rundle* [1979]. Our model fault has the same dip and downdip width and the slip magnitudes are comparable, but the fault length is 50 km less. In addition, Thatcher and Rundle chose to fit strain data for the entire 1923^+-1935 time interval and did not explicitly compare the predictions of their postseismic slip model with the available leveling data. By shortening the fault and considering only the first year after the earthquake we are able to show better agreement between model predictions and observations than was obtained by Thatcher and Rundle: both the magnitudes and orien-

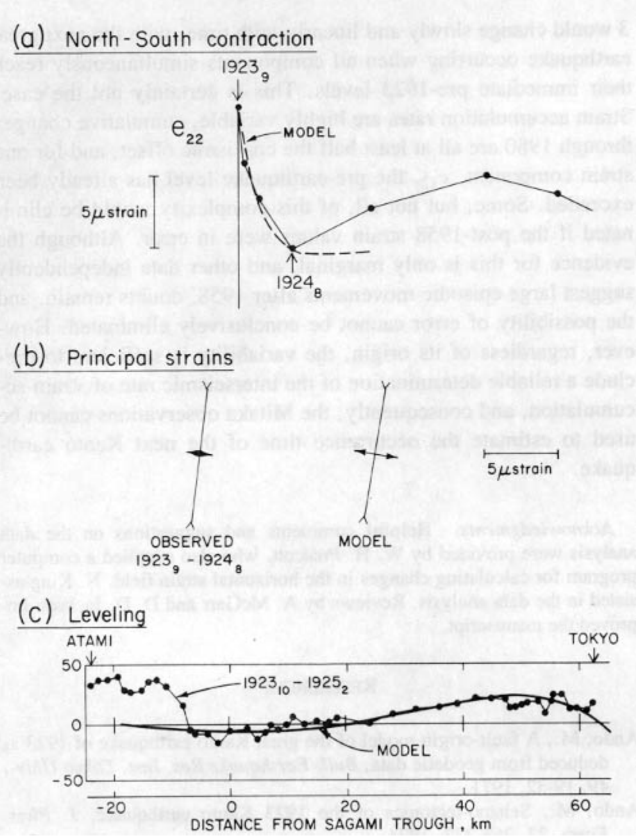

Fig. 4. Observed short-term postseismic deformation and predicted movements for a model of aseismic fault slip described in the text. Absolute level of observed elevation changes in Figure 4*c* is unknown and has been arbitrarily shifted to produce the best match with the model curve. Subscript on dates refers to month of year.

tations of the principal strain changes are matched significantly better, and we also show that computed elevation changes do not disagree with observed movements during 1923^{+}-1925.

However, the postseismic slip model does not account for strain changes observed at Mitaka after late 1924. Thatcher and Rundle showed that post-1924 leveling and tidal gage data from the South Kanto region were consistent with deformation expected from a model of postearthquake asthenospheric relaxation, and the longer time scale strain changes observed at Mitaka during 1925-1935 might be explained in the same way. However, since the relevant computational results for horizontal strain have not thus far been derived, we are as yet unable to test this possibility.

5. COMPARISONS WITH OTHER DATA

Because the irregularity in strain buildup at Mitaka is surprising, it seems worthwhile to determine whether or not other deformation measurements in the region show evidence of similar variability. The leveling route between Tokyo and Atami has been surveyed six times since the Kanto earthquake, and elevation changes for five successive time intervals are plotted in Figure 5. After 1931, the absolute level of each profile is tied to changes recorded at Aburatsubo, a tidal station at the tip of Miura peninsula (Figure 1). During 1923-1931, datum uncertainties are comparable to observed elevation changes; rather than apply a poorly constrained correction, the top two profiles in Figure 5 are plotted assuming that the Tokyo benchmark remained fixed.

Although the infrequent surveys on this route do not always neatly bracket major movement episodes at Mitaka, useful comparisons are nonetheless available. First of all, the data indicate that a one-to-one correlation between strain and tilt should not always be anticipated: while coseismic strains at Mitaka were comparable to tilts on adjacent portions of the Tokyo-Atami route (see, for example, *Thatcher and Rundle* [1979, Figure 13]), postseismic strain changes during 1923-1925 exceeded corresponding tilts by about a factor of 10 (Figure 4). Figure 5 also shows that tilt rates during 1950-1967 were significantly greater than those in 1967-1980, and the post-1950 Mitaka deformation is at least roughly consistent with this temporal behavior.

Better temporal resolution is provided by level changes on the northern half of the Tokyo-Atami route, which has been surveyed 25 times since 1923. Figure 6 compares the e_{22} strain component at Mitaka with elevation changes between two stable benchmarks on this frequently surveyed route segment. Vertical displacements at Aburatsubo are shown as well [*Coastal Movements Data Cen-*

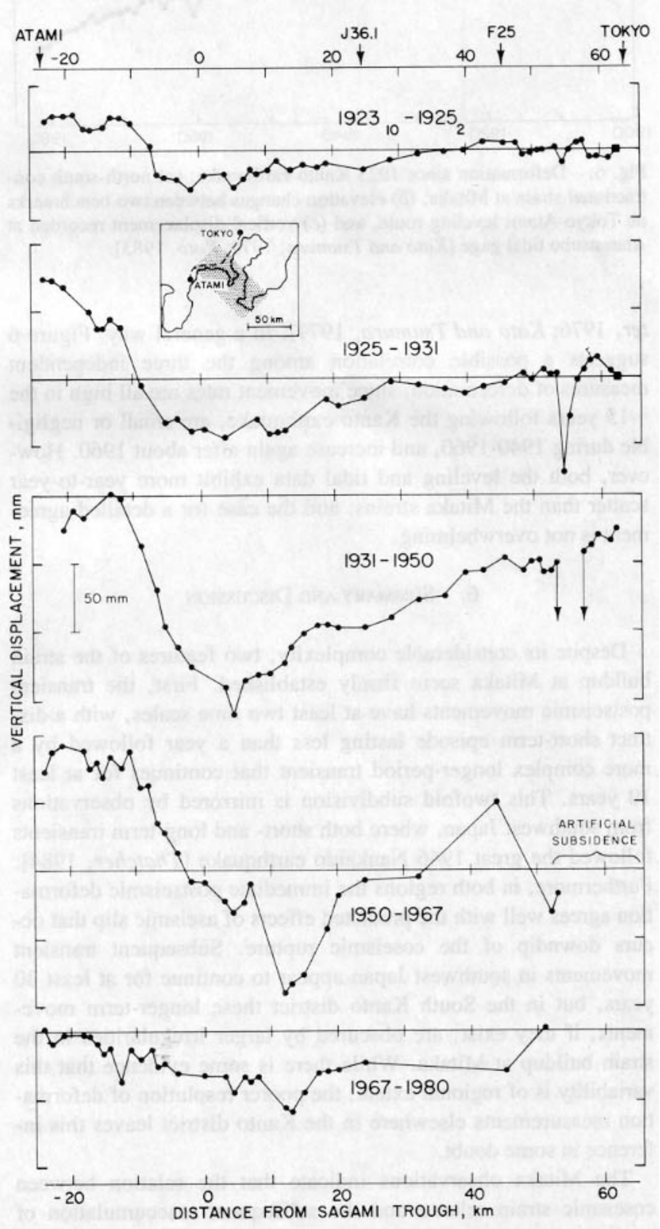

Fig. 5. Elevation changes between Tokyo and Atami (level route shown dashed on inset, upper right), plotted against perpendicular distance from Sagami Trough.

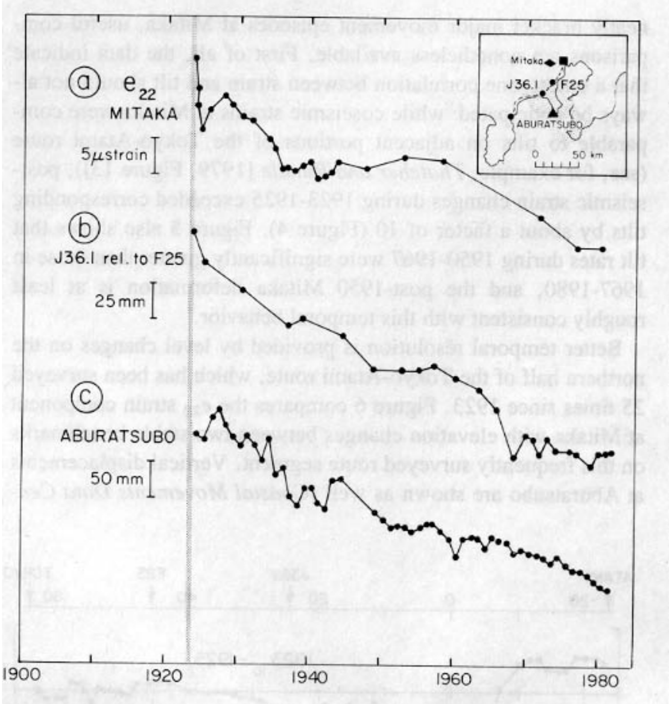

Fig. 6. Deformation since 1923 Kanto earthquake: (*a*) north-south contractional strain at Mitaka, (*b*) elevation changes between two benchmarks on Tokyo-Atami leveling route, and (*c*) vertical displacement recorded at Aburatsubo tidal gage [*Kato and Tsumura*, 1979; *Kato*, 1983].

ter, 1976; *Kato and Tsumura*, 1979]. In a general way, Figure 6 suggests a possible correlation among the three independent measures of deformation, since movement rates are all high in the ~15 years following the Kanto earthquake, are small or negligible during 1940-1960, and increase again after about 1960. However, both the leveling and tidal data exhibit more year-to-year scatter than the Mitaka strains, and the case for a detailed agreement is not overwhelming.

6. SUMMARY AND DISCUSSION

Despite its considerable complexity, two features of the strain buildup at Mitaka seem firmly established. First, the transient postseismic movements have at least two time scales, with a distinct short-term episode lasting less than a year followed by a more complex longer-period transient that continues for at least 10 years. This twofold subdivision is mirrored by observations from southwest Japan, where both short- and long-term transients followed the great 1946 Nankaido earthquake [*Thatcher*, 1984]. Furthermore, in both regions the immediate postseismic deformation agrees well with the predicted effects of aseismic slip that occurs downdip of the coseismic rupture. Subsequent transient movements in southwest Japan appear to continue for at least 30 years, but in the South Kanto district these longer-term movements, if they exist, are obscured by larger irregularities in the strain buildup at Mitaka. While there is some evidence that this variability is of regional extent, the poorer resolution of deformation measurements elsewhere in the Kanto district leaves this inference in some doubt.

The Mitaka observations indicate that the relation between coseismic strain release and the subsequent reaccumulation of strain is not simple. Ideally, one might expect that after a brief postseismic phase, each of the strain components in Figures 2 and 3 would change slowly and linearly with time, with the next great earthquake occurring when all components simultaneously reach their immediate pre-1923 levels. This is certainly not the case. Strain accumulation rates are highly variable, cumulative changes through 1980 are all at least half the coseismic offset, and for one strain component, e_{12}, the pre-earthquake level has already been exceeded. Some, but not all, of this complexity would be eliminated if the post-1958 strain values were in error. Although the evidence for this is only marginal, and other data independently suggest large episodic movements after 1958, doubts remain, and the possibility of error cannot be conclusively eliminated. However, regardless of its origin, the variability is sufficient to preclude a reliable determination of the interseismic rate of strain accumulation, and consequently, the Mitaka observations cannot be used to estimate the occurrence time of the next Kanto earthquake.

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