EARTH DEFORMATION AND EARTHQUAKE PREDICTION

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1. Introduction

If ten years ago a scientist had been asked to present a paper on this subject he would have shrugged his shoulders and left this field clear to astrologers and doomsday prophets of weird religious sects.

Now, ten years later such an amount of precursory evidence has accumulated that scientists in California, Russia and Japan are confident that, given the facilities for these studies, it will be possible to forecast major earthquakes, which have their epicentres on land, within the next 10-20 years. In fact several successful forecasts have already been made in California.

What is required to forecast earthquakes?

Like a doctor who examines a patient for tell-tale symptoms, and subsequently prescribes particular medication to alleviate and reduce the effects of the illness, so are overseas scientists looking for symptoms, but unlike a doctor they are at present still deciding what <u>are</u> precursory symptoms (changes) and which symptoms are dominant in any particular geological area.

Such precursory changes can be classified broadly into three groups: A. External changes to the earth's crust (earth deformation); B. Internal changes within the rock (geophysical changes) and C. Seismological changes. Of the three groups the first one, that of earth deformation, is the best documented and at present also the most promising approach to the problem.

Throughout history reports of earth deformation prior to earthquakes have been recorded (perhaps the earliest report is that of Moses crossing an arm of the Red Sea), but few can now be verified. Some reliable reports from Japan date back to the 18th and 19th century:

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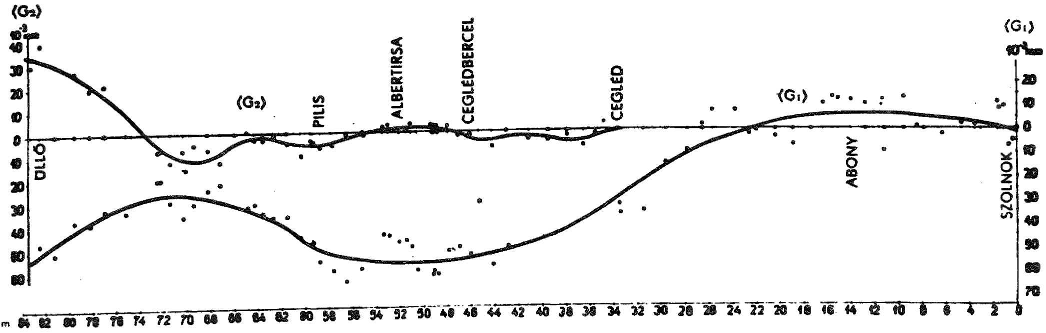
1) Agigasawa EQ of 1793, 3 ft uplift 4 hours before EQ.
2) Sado EQ 1802, 3 ft uplift 4 hours before EQ.
3) Hamada EQ 1872, 6 ft uplift prior to EQ. The last case is particularly spectacular and also reliable.

Professional weather observers at Hamada reported a large rock out to sea, which normally at low tide was separated from the mainland by a depth of 6 ft of water. Shortly before the earthquake this rock could be reached on foot, dry shod.

2. Vertical Deformation

Such events of large vertical deformation immediately prior to earthquakes are obvious even to laymen. Small changes in level can be monitored at any time between earthquakes and are elastic in nature. These changes in level increase as the next earthquake approaches. A striking example was experienced by surveyors in Hungary in 1955, who early that year could not close their levelling circuit; the closing error being ten times the expected and permissible one. As a result a 60 mile long route was relevelled four times at two-month intervals. In April of that year it became clear that elastic sinusoidal deformation was taking place, which increased in magnitude and decreased in wavelength towards the end of that year. On 12th January 1956 an earthquake occurred at Dunaharaszti near Budapest, exactly where the largest amount of elastic deformation was measured in the previous month.



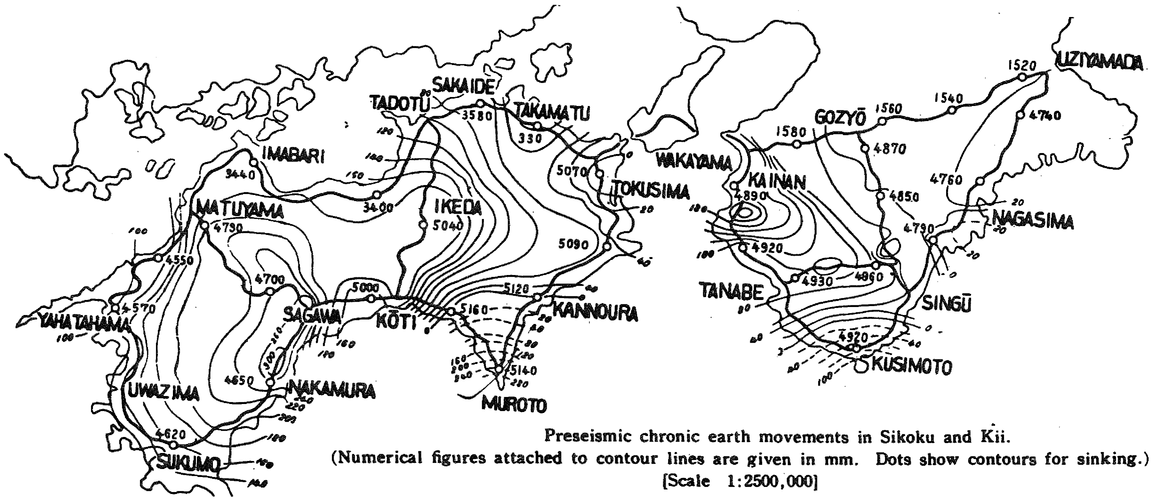
Crustal deformations between Szolnok and Ullö. $[G_1)$ — before, — $[G_2)$ after the earthquake, — $[G_3]$ — in a later point of time.

Fig. 1. showing pre-earthshift and post-earthshift deformation in Hungary in 1955 and 1956 (after Bendefy 1966).

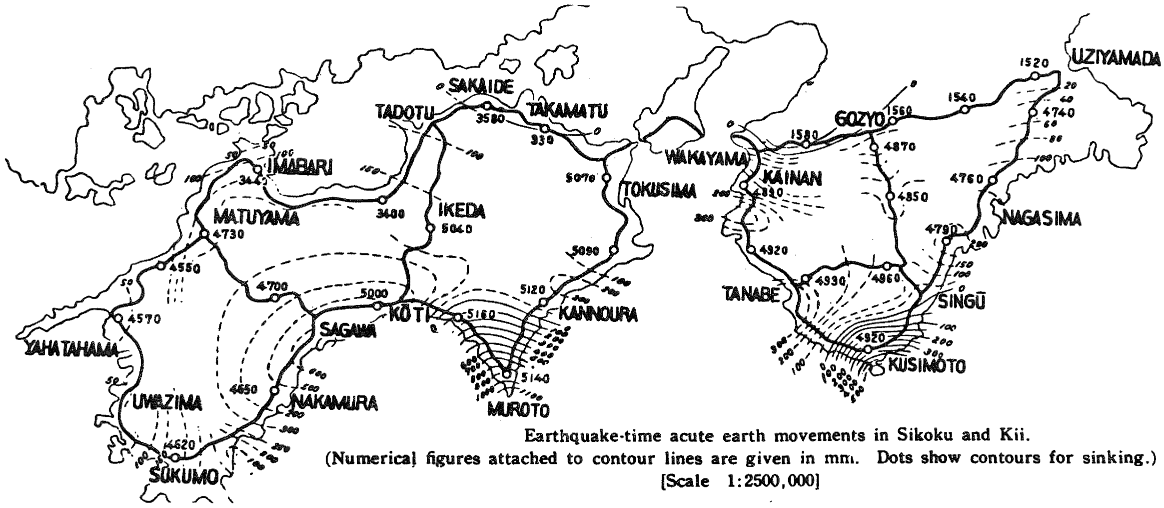
From the result of several repeated precise levellings Bendefy concluded:

1. Earthquakes are introduced by preceding elastic deformation of the crust;
2. The preceding crustal deformation appears in sinusoidal waves;
3. The wave-length decreases while the amplitude increases both in time and place towards the future epicentre. The shortest wavelength and the maximum amplitude appear over the future epicentre.

As precise levelling is a very slow and laborious procedure, it is very unusual to relevel long distances at short-time intervals and instances of detailed monitoring of elastic vertical deformation by this method are rare. In Japan after the 1946 Nankai earthquake it was found that the Sikoku and Kii peninsula had been levelled two and in some parts three times.



Preseismic chronic earth movements in Sikoku and Kii.
(Numerical figures attached to contour lines are given in mm. Dots show contours for sinking.)
[Scale 1:2500,000]



Earthquake-time acute earth movements in Sikoku and Kii.
(Numerical figures attached to contour lines are given in mm. Dots show contours for sinking.)
[Scale 1:2500,000]

Fig. 2. Pre-earthshift and earthshift deformation associated with the 1946 Nankai Earthquake in Japan (after Miyabe 1954).

Analyses of pre- and post-earthquake levellings resulted in the two maps shown here. The upper part shows Sikoku and Kii before the 1946 earthquake where some parts have risen up by 300 mm (1 ft) while other areas have sunk by a similar amount. After the earthquake the situation was reversed, sunken parts rose up to 5 ft while uplifted areas sank by about 2 ft.

Another well-documented case of precursory level changes was that recorded prior to the Tashkent earthquake (1966) U.S.S.R.

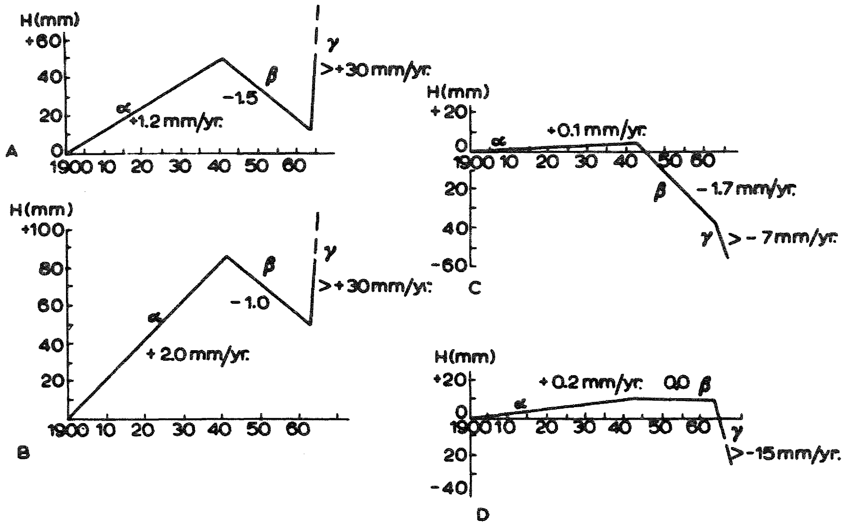


Fig. 3. Changes of heights of four bench marks in the Tashkent area (after Mescherikov 1968).

Again precursory reversals are pronounced and may well have preceded the earthquake by one year or more.

This reversal in trend from pre-earthquake to post-earthquake deformation is typical of most of the 150 cases of precursory deformation recorded.

Other methods of monitoring level changes are tide gauges and tiltmeters which have the advantage of continuous recording but have the disadvantage of recording only for the locality where they are installed.

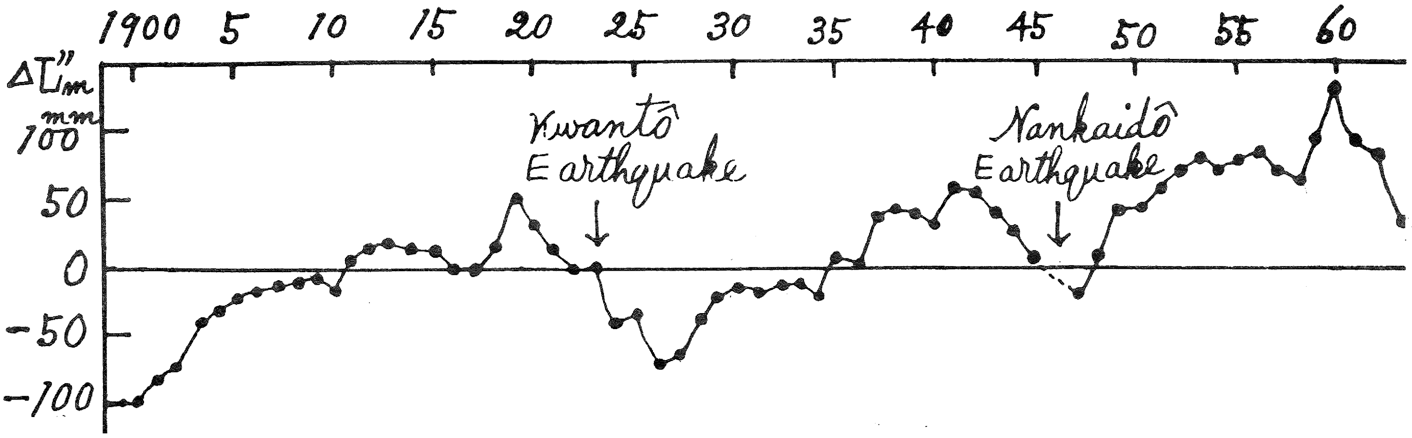


Fig. 4. Yearly mean sealevel at Aburatubo (after Yamaguti 1964).

The yearly mean sealevel curve for Aburatubo (Japan), although concealing elastic deformation changes of less than a year duration, shows clearly the general trend of rising sealevel over 15 or more years to be followed by pronounced reversals which herald the coming earthquakes.

The latest reversal since 1960, however, was not a reversal precursory to an earthquake but was due to a change in ocean currents.

For comparison the reduced sealevels for Wellington have been shown in Fig. 5.

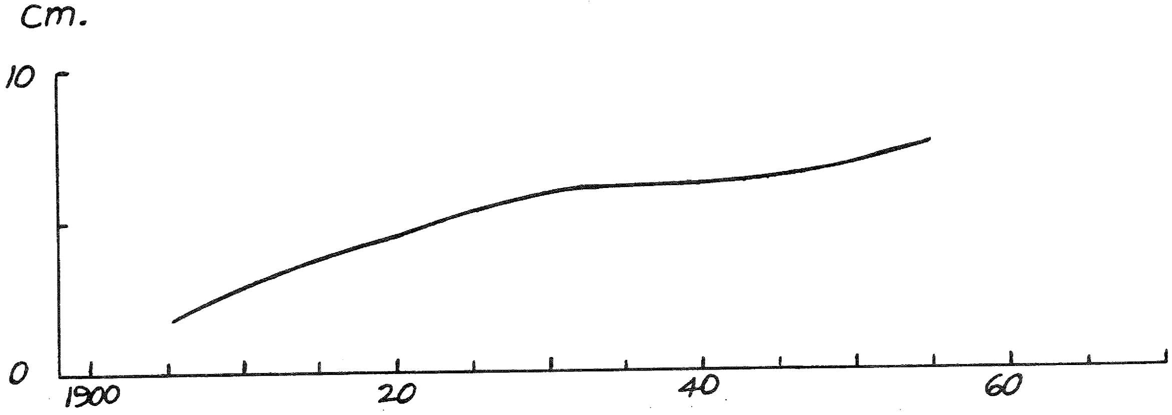


Fig. 5. Reduced sealevels for Wellington. The curve demonstrates a gradual downwarp of land of 7 cm over 50 years. Beyond 1960 the reduced levels are not available and it is therefore not known if this gradual rise has continued or whether a reversal has developed.

3. Horizontal Deformation

So far only vertical deformation has been considered, while in many countries, specially those bordering the Pacific, horizontal deformation is greater than vertical deformation. This type of deformation is more difficult to visualise but the following map (Fig. 6) shows how the 400-mile stretch between Los Angeles and San Francisco is elastically shifting, while the length of arrows show that some areas are shifting faster than others and in time reversals are also taking place.

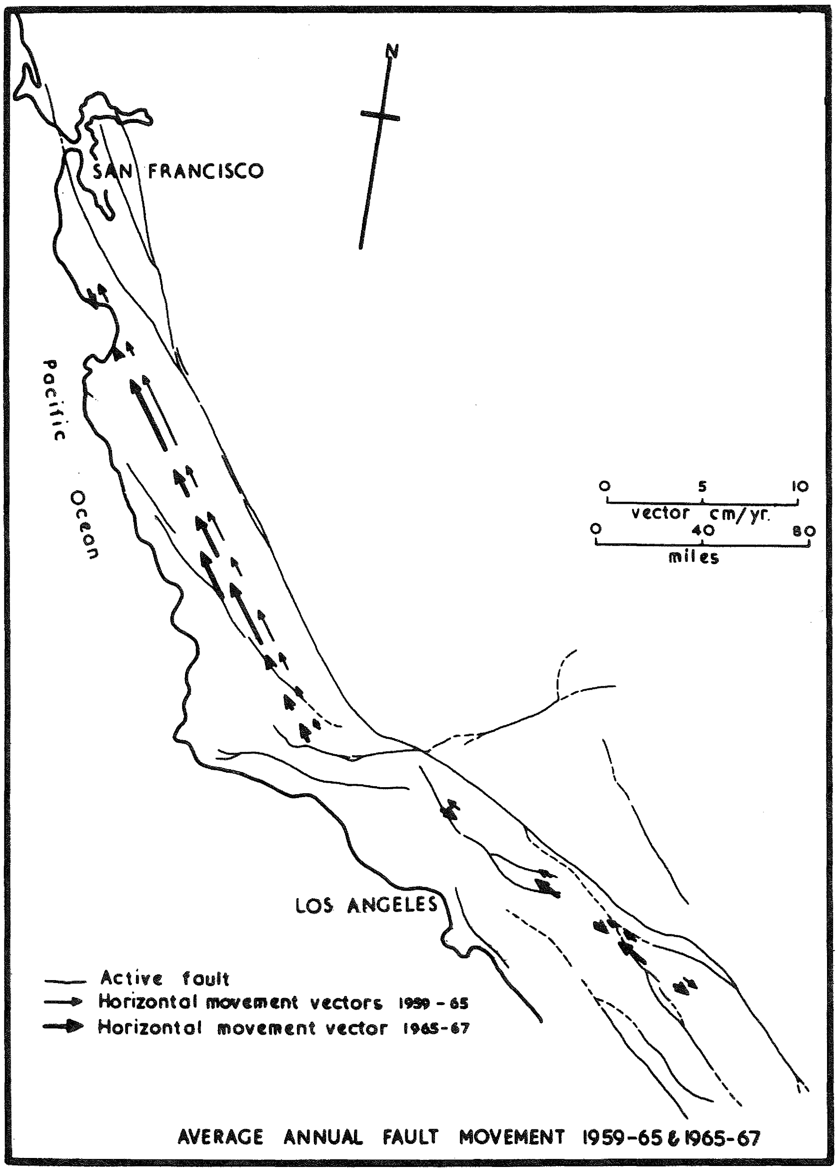


Fig. 6. Pre-earthshift and earthshift deformation in California after Hofmann 1968).

As a result of the 1906 San Francisco earthquake when a 20 ft horizontal offset along the San Andreas Fault was measured, Reed compared two pre-1906 triangulation surveys with a subsequent triangulation and found that elastic deformation had occurred in between major earthquakes. This discovery resulted in his theory of "elastic rebound". Since then parts of California have been re-triangulated repeatedly and evidence of horizontal deformation has accumulated steadily.

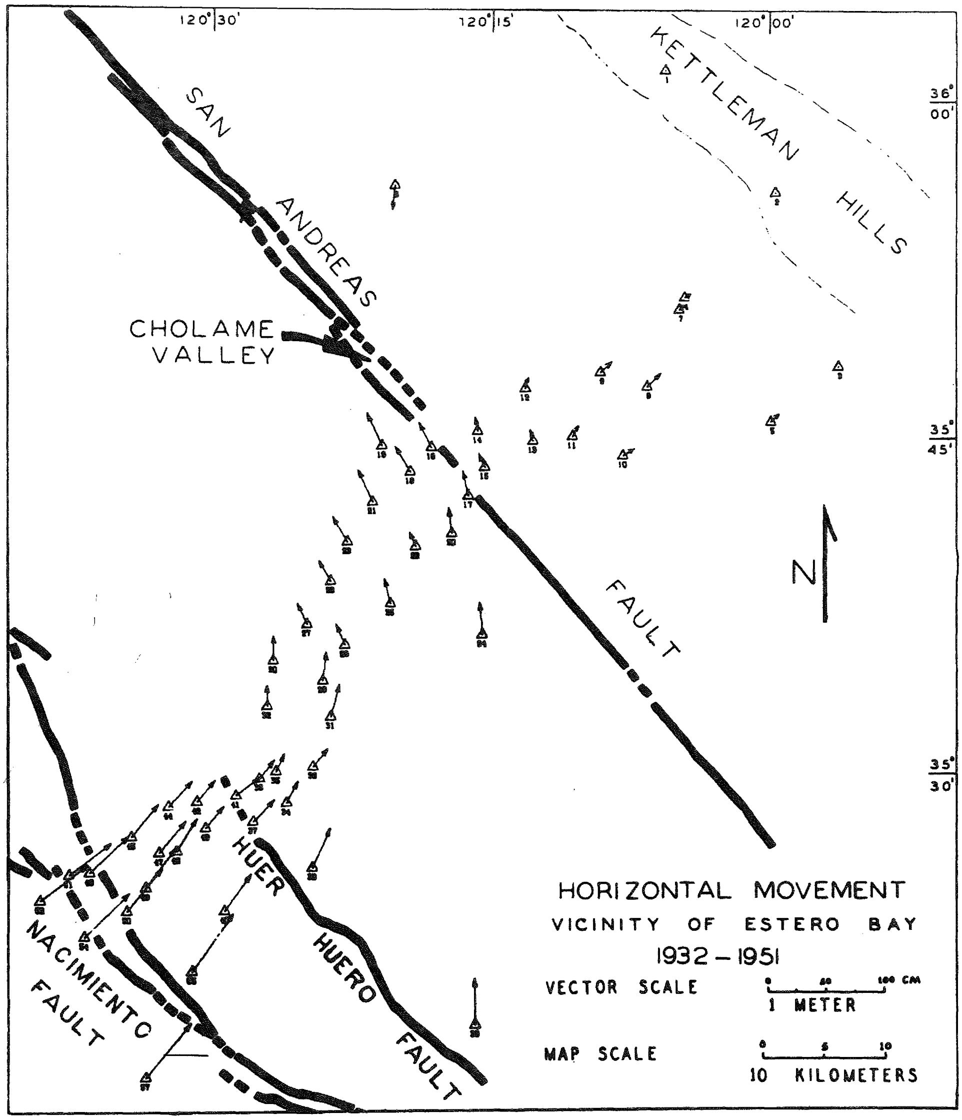


Fig. 7. A portion of a retriangulation in California showing the trends of horizontal movement of stations during the interval between 1932 and 1951 (after Burford 1966).

Fig. 7 shows horizontal displacement relative to a baseline in the Kettleman Hills with station 2 as origin. The general trend is toward the northeast relative to Kettleman Hills except in the vicinity of the San Andreas Fault where the direction of movement changes gradually from north-east to north and finally to north-west adjacent to the fault. Comparison of the vectors on both sides of the fault gives about 32 cm maximum differential displacement across the fault in dextral sense (about 1.7 cm/year).

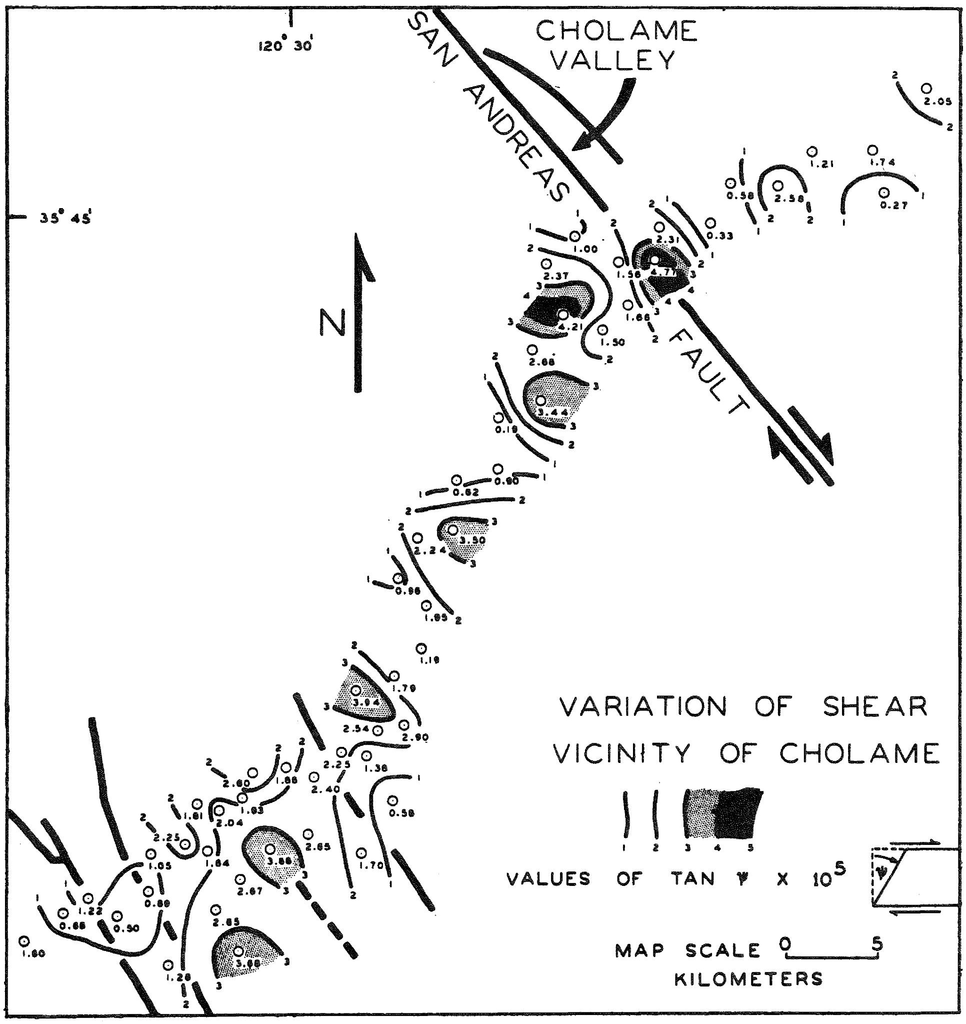


Fig. 8. Pattern of shear strain based on relative horizontal movement shown in Fig. 7 (after Burford 1966).

Based on such data principal strain axes can be computed and a variation of shear for the region shown in Fig. 8 results. Areas of maximum horizontal shear are located on the San Andreas fault and also approximately 5 kilometers to the southwest on subsidiary faults within the zone (not shown). The largest shear of 4.77×10^{-5} is about half that on the San Andreas Fault further to the north.

The deformation demonstrated by retriangulation is the result of both pre-earthshift and earthshift that took place over that 19-year period, the long time interval between observations preventing separation of pre-earthshift from earthshift.

It was not until the last decade, however, when electronic-optical distance measuring instruments were improved to sufficient accuracy that frequent close monitoring across active faults produced detailed evidence of precursory elastic deformation which may lead to earthquake prediction.

As an example the Corralitos earthquake of 1964 and the associated elastic deformation heralding this earthquake is given in Fig. 9.

On the left the San Andreas Fault runs from San Francisco southwards through California. The arrows indicate the direction of horizontal displacement along this fault. Lines obliquely across the fault will either shorten or lengthen depending whether they run from bottom left to top right or top left to bottom right respectively. The lower inset on the right shows line C to shorten between 1960 and 1962 by 6 cm ($2\frac{1}{4}$ inch). The next measurement shows a reversal and the line had lengthened by 8 cm (3 inches) since 1962. This reversal was on the 15th November followed by the Corralitos earthquake. Line B as expected lengthened slightly between 1960 and 1963 and shortened subsequently. The amounts of change are less than for line C which was closer to the future epicentre.

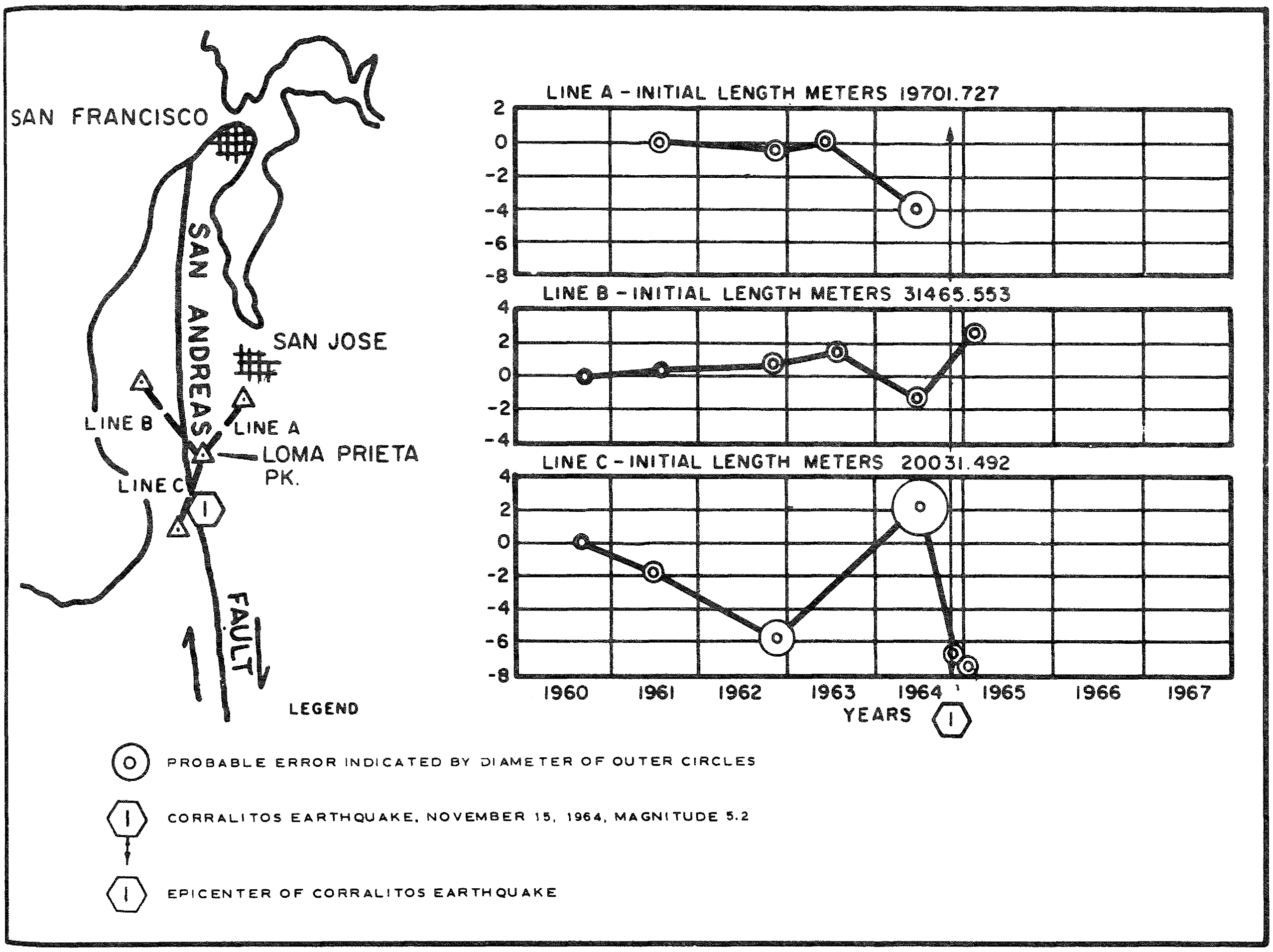


Fig. 9. Precursory elastic crustal movement and 1964 Corralitos Earthquake (after Hofmann 1968).

Note that the earthshift position virtually lies on the line extrapolated from the 1960-1962 positions.

Although reversals and increased rate of elastic deformation appear to be diagnostic if monitored at yearly intervals, to measure the actual rate of deformation at which the elastic limit is reached would require virtually continuous monitoring and this has not been achieved as yet. However, one instance of a series of measurements on a line length with an earthquake occurring within the sequence of measurements has been recorded.

The normal procedure is to take a series of 5-6 measurements during one night and the mean value is used as the length determination.

The Hollister Earthquake of January 1960 occurred while such a series of measurements was under way and the measurements are shown in Fig. 10.

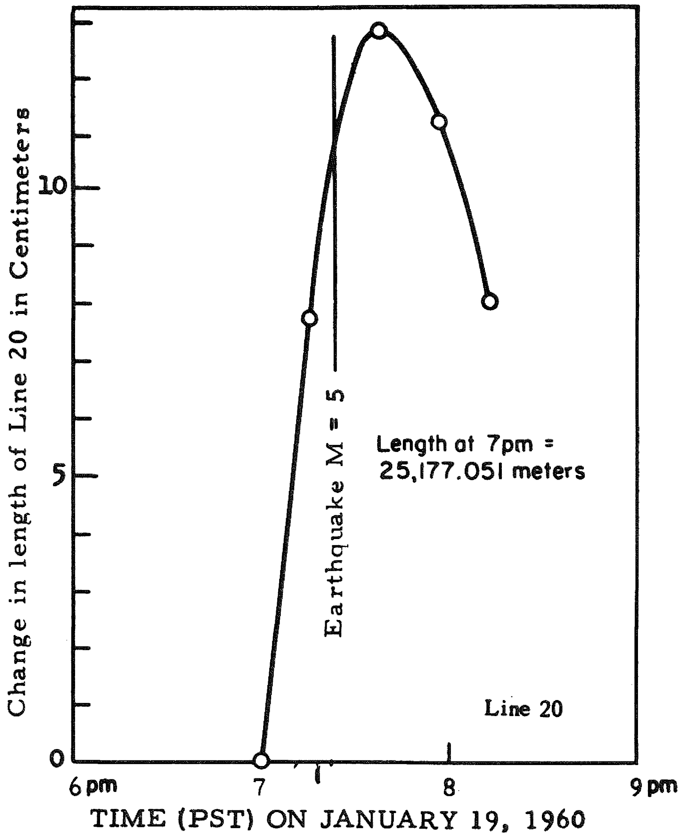


Fig. 10. Short-range anomaly demonstrating rate of deformation immediately prior and after the Hollister 1960 Earthquake (after Hofmann 1968).

The rate of 8 cm in 20 minutes (time interval between first and second observation) is extremely high and as the third observation took place after the earthquake the actual curve between observation 2 and 3 may have been far steeper with its apex well beyond the 13 cm mark. Such high rates of deformation a few hours or minutes prior to an earthquake may provide an effective criterion for short-range earthquake warnings.

4. Phases and Nature of Earth Deformation

The study of present-day earth deformation is still nearly in its infancy, although systematic research has started in several countries, notably Japan, Russia and California. It indicates that not all deformation takes place during fault movement and suggests that the type of deformation changes with time over the period between and during sudden movements associated with earthquakes.

The author (Lensen 1968a) has recognized four phases in one cycle of earth deformation - secular, pre-earthshift, earthshift and post-earthshift, the first two phases being of elastic nature while the remaining two phases are non-elastic.

Secular long-term, slow-deformation occurs in the interval between two sudden earth movements on a fault at any one locality. The interval may be 900 years or longer (Lensen 1968b). At the end of this phase rates and magnitudes increase (pre-earthshift deformation) until finally the elastic limit of the earth's crust is reached and an earthshift occurs in the form of faulting, folding, tilt, warp of drape and the crust has yielded non-elastically (brittle or plastic). This phase is followed by a period of further adjustments and often ends with a small reversal (post-earthshift deformation).

The nature of earth deformation in the vertical plane would appear to be of sinusoidal transverse nature (Bendefy 1966, Fig. 1, and Miyabe 1958, Fig. 2).

The nature of horizontal deformation can be gleaned from Fig. 6 where the length of arrows indicate the magnitude of displacement vectors along the San Andreas fault. If one vector indicates a displacement of 4 cm, while the preceding one indicates a displacement of 1 cm, then the area in between them must have shortened by 3 cm (compression). Similarly, an area can become lengthened (dilatation). Plotting the amount of compression and dilatation along the length of the San Andreas fault (400 miles) the following two curves in Fig. 11 result -

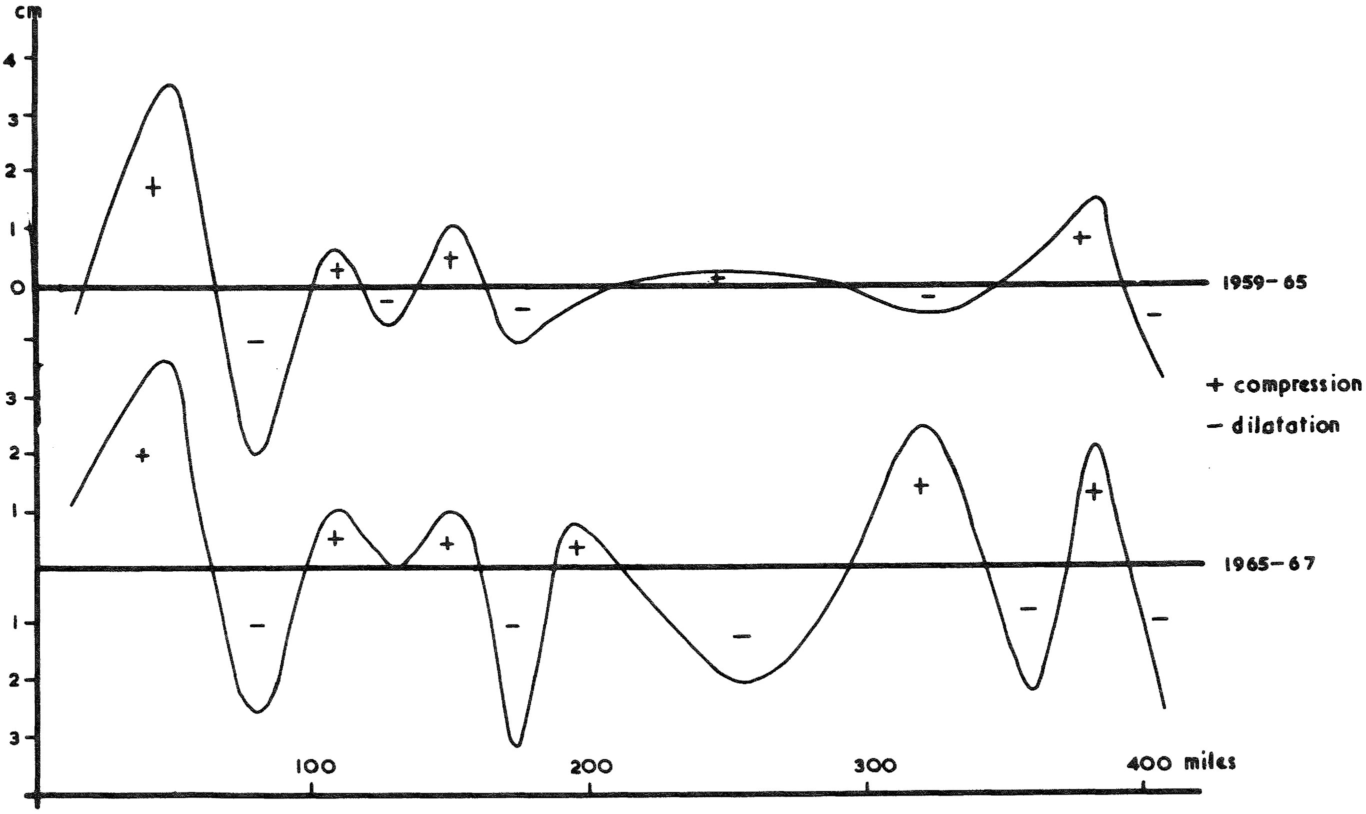


Fig. 11. Distribution of compression and dilatation along the San Andreas fault, both in space and time.

In the top curve on the left-hand side (northern part of the San Andreas fault) areas of compression and dilatation follow each other in rapid succession with varying amplitudes. In the middle of the San Andreas fault little activity can be found while to the right (southern part of the fault) a succession of a compressional and a tensional area reappear.

Over the next two years (bottom curve) the northern part of the fault has remained very much the same except that the amplitudes have changed somewhat. To the right along the southern part of the fault a second compressional and a second dilatational zone have developed while the middle part has markedly changed.

It would appear that both curves represent a longitudinal wave-train. The southern part of the second curve suggests this wave-train to travel in northerly direction. This is consistent with the earthshifts on the San Andreas fault where the Pacific side moves northwards relatively to the eastern side.

Thus it would appear that the crust of the earth is in constant motion at a roughly uniform rate (secular). This motion appears as a transverse wave pattern in the vertical plane and as a longitudinal wave pattern in the horizontal plane. Suddenly amplitudes increase, wave-lengths decrease and reversals take place (pre-earthshift) until an earthshift occurs, to be followed by post-earthshift deformation which finally settles down again to secular deformation of the next cycle.

5. Earthquake Prediction

Based on the evidence shown before, scientists in California have succeeded in predicting earthquakes, using changes in rates of length changes of lines obliquely across the San Andreas Fault. In their report (Hofmann 1968) prediction is specifically defined both in space and time:

> "Earthquakes are shown to be predictable within a time accuracy equivalent to the current interval between measurements (usually a year or somewhat more) and a dimensional accuracy near that of the length of geodimeter lines affected (usually about 20 miles on the earth's surface)."

Using a computer program for earthquake warnings Hofmann and associates have in the last few years succeeded in forecasting 8 out of 11 earthquakes that occurred of magnitude 4.5 or larger. The three earthquakes that were not predicted had insufficient measurements or too long a time interval between measurements (32 months). But in addition a further 17 earthquakes were predicted that did not eventuate. Considering that the earthquakes that occurred were only of moderate magnitude (4.5-5.6) and also considering that earthquakes with epicentres more than 20 miles distant from their lines were programmed to be discounted as having been predicted, about a 50% success has been claimed.

This result compares favourably with that of tsunami (earthquake generated "tidal" waves) warnings which are now universally accepted, but only one out of 10 warnings is followed by significant wave action.

Additional logic to the computer programme, more lines and closer monitoring, together with continuous monitoring by means of strain gauges and other geophysical methods will be required to obtain evidence of precursory changes in greater detail and thereby improve earthquake prediction.

While earthquakes of moderate magnitude show precursory symptoms within one year of the event, evidence from Russia suggests that for large earthquakes precursory pre-earthshift deformation may start up to five years before the major event. If this is indeed the general case, it would provide government and local bodies with considerably more time to remedy their most serious earthquake hazards.

Concluding, the present state of knowledge of the problem of earthquake prediction compared with that of one decade ago shows that major advances have been made and that, given the facilities for these studies, such prediction may be possible, provided basic data, which may take 10-20 years to collect, are available.

6. References

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