RECENT VERTICAL MOVEMENTS OF THE CRUST IN THE WESTERN UNITED STATES: REDUCTION AND ANALYSIS OF LEVELING DATA AND ITS INTERPRETATION IN LIGHT OF RELATED SEISMOLOGICAL INFORMATION

Jack E. Oliver

Cornell University
Department of Geological Sciences
Ithaca, New York 14853

USGS CONTRACT NO. 14-08-0001-17625
Supported by the EARTHQUAKE HAZARDS REDUCTION PROGRAM

OPEN-FILE NO.81-444

U.S. Geological Survey
OPEN FILE REPORT

TABLE OF CONTENTS

SUMMARY OF RECENT ACTIVITIES

Introduction

Vertical crustal movement information has been derived from releveling data collected by the National Geodetic Survey (NGS) in the western U.S. Our objective is to determine to what extent this data base can contribute to our understanding of geodynamic phenomena with emphasis on earthquake prediction and seismic hazard evaluation. After critically examining the crustal movement information from a geodetic perspective, the leveling results are interpreted in view of other relevant geophysical and geological data.

This report describes the more significant accomplishments of our research effort, concentrating on results achieved during the past six months. Our most recent work has been directed towards a reevaluation of Southern California releveling observations (because of their importance for the earthquake prediction problem) from the perspective supplied by analysis of leveling throughout the entire U.S. Previous tectonic interpretations of certain leveling measurements in Southern California (including some of those used to define the Palmdale Bulge and preseismic deformation for the 1971 San Fernando earthquake) are significantly in error because they failed to adequately account for spurious influences (ground water effects, systematic errors). Using newly developed techniques and reliability criteria we have identified those southern California observations which appear to reflect tectonic deformation. Because tectonic deformation can often be separated from spurious effects, the releveling data base remains a valuable source of information on neotectonic activity with important implications for earthquake prediction and seismic hazard evaluation.

Recent Results (for details of particular studies see appropriate appendix)

I. Neotectonic Deformation, Near Surface Movements and Systematic Errors in U.S. Releveling Measurements: Implications for Earthquake Prediction

Analyses of U.S. releveling measurements indicate that derivative crustal movement estimates may reflect tectonic deformation, near-surface movements, and/or systematic errors. Discriminating the contributions of these factors is especially crucial for unambiguous geodetic detection of possible precursory seismic deformations. While reliable leveling measurements of co-seismic and post-seismic movements are well documented for some of the larger ($M > 6$) dip-slip earthquakes, leveling evidence for pre-seismic motion is generally sparse and often ambiguous. Subtle earthquake-related motions may be masked by both aseismic movements and systematic errors. For example, deep magma injection and surficial groundwater withdrawal are two mechanisms which have been documented to cause surface movements which, under some circumstances, could be misidentified as seismic-related. Of more concern, perhaps, are systematic measurement errors. Topography dependent errors are an exceptionally troublesome type, perhaps affecting as much as 20% of U.S. leveling. However, other varieties of systematic error also contribute to the uncertainty. Discrepancies between leveling and tide gauge data and within nets of leveling alone suggest large, long baseline accumulations of error. In many cases, aseismic and erroneous contributions cannot be unequivocally determined *ex post facto*. However, a comprehensive examination of the NGS crustal movement data base, representing a large sampling of the entire U.S. Level Net, provides perspective and criteria needed to begin to recognize movement directly related to earthquake activity.

Perhaps the most extensive set of relevant measurements exists in southern California, where much attention has recently been focused. Reevaluation of some of these leveling observations indicates that while some appear to reflect tectonic deformation, others are suspect because of indications of systematic errors and/or near-surface, non-tectonic movements. Specifically, possible preseismic movements reported for the 1971 San Fernando earthquake in the vicinity of the earthquake fault as well as approximately 30 km northwest of the epicenter may be due to systematic errors. Movements near the San Gabriel fault, initially ascribed to the Palmdale Bulge and more recently to preseismic effects of the 1971 San Fernando earthquake apparently reflect near-surface sediment compaction due to water table fluctuations. Similarly, there is strong evidence of contamination by rod calibration errors in the releveling observations used to define the southwestern portion of the "Palmdale Bulge" (Llano to Azusa, California). The reality of the "Palmdale Bulge" itself must be questioned in view of this reevaluation. In contrast, possible tilting southwest of Palmdale between 1961 and 1964 is not easily related to systematic errors or near-surface movements and thus may represent tectonic deformation. Whether this tilt anomaly was due to preseismic effects of the San Fernando earthquake or a mechanically separate tectonic event is presently unknown.

II. Elevation Changes Near the San Gabriel Fault, Southern California

Analysis of repeated leveling observations in the vicinity of the San Gabriel fault in Southern California indicate subsidence immediately south of the fault relative to points to the north, south, and east. These observations were previously interpreted as reflecting tectonic motions associated with either the "Palmdale Bulge" or with preseismic effects of the San Fernando earthquake. Relative subsidence between 1953 and 1964 reaches approximately 9 cm and extends over a distance of more than 20 km.

Subsidence occurs directly above the Saugus aquifer and shows a temporal correlation with the history of water level decline within the aquifer. The degree of subsidence of individual benchmarks is roughly proportional to the product of aquifer thickness and water level decline at the location of the benchmarks. These observations strongly suggest that movements of the surface near the San Gabriel Fault, previously inferred to be of tectonic origin, actually result from near surface sediment compaction within the Saugus basin.

III. Time Behavior of Vertical Crustal Movements Measured by Releveling in North America: A Geologic Perspective

I some areas geodetically determined rates ($\simeq$ mm/yr) are consistent in sign with geologic trends but 10 - 100 times faster. Although the reliability of some of the leveling results is open to question, this "rate paradox" suggests that any real contemporary movements are episodic or oscillatory. In the U.S. midcontinent oscillatory movements with a period of approximately 3000 years are implies. Deformation in the Rio Grande rift (New Mexico and Texas) and at Hegben Lake (Montana) has constant direction and similar rates for the past 50 - 100 yr (excluding the 1959 coseismic movement at Hegben Lake), though geologic evidence indicates transitory behavior in the long term ($\simeq$10,000 years). In Oregon and Washington, 10-50 yr span releveling shows more or less constant-rate landward-tilt of the relatively aseismic coastal ranges that is consistent with the deformation rate of marine terraces (230,000 yr) and underlying strata (36,000,000 yr). In contrast to the 50 - 100 yr span constant rates above, releveling in some seismically active areas (e.g. Alaska and California) suggests rapid rate changes. However the examples presented here suggest that in areas free of major earthquakes, rates from releveling, although high in a geologic sense, can likely be extrapolated for 50 years.

CRUSTAL MOVEMENT STUDIES AT CORNELL*
(numbers refer to index map)

January 1981

(1) Brown, L.D., R.E. Reilinger, S.R. Holdahl, and E.I. Balazs, 1977. Post-seismic crustal uplift near Anchorage, Alaska, J. Geophys. Res., v. 82, no. 23, 3369-3378.

(2) Chi, S.C., R.E. Reilinger, L.D. Brown, and J.E. Oliver, 1980. Leveling circuit closures and vertical crustal movements, Jour. Geophys. Res., v. 85, n. 83, 1469-1474.

(3) Reilinger, R.E., G.P. Citron, and L.D. Brown, 1977. Recent vertical crustal movements from precise leveling data in southwestern Montana, western Yellowstone National Park, and the Snake River Plain, J. Geophys. Res., v. 82, no. 33, 5349-5359.

(4) Reilinger, R.E., and J.E. York, 1979. Relative crustal subsidence from leveling data in a seismically active part of the Rio Grande Rift, Geology, v. 7, 139-143.

(5) Reilinger, R.E., and J.E. Oliver, 1976. Modern uplift associated with a proposed magma body in the vicinity of Socorro, New Mexico, Geology, v. 4, no. 10, 583-586.

(5a) Reilinger, R.E., J.E. Oliver, L.D. Brown, A.R. Sanford, and E.I. Balazs, 1980. New measurements of crustal doming over the Socorro magma body, Geology, v. 8, n. 6, 291-295.

(6) Brown, L.D., R.E. Reilinger, and J.T. Hagstrum, 1978. Contemporary uplift of the Diablo Plateau, west Texas, from leveling measurements, J. Geophys. Res., v. 83, no. B11, 5465-5471.

(6a) Reilinger, R.E., L.D. Brown, and D. Powers, 1980. New evidence for Tectonic uplift in the Diablo Plateau region, west Texas, Geophys. Res. Lett., v. 7, n. 3, 181-184.

(7) Rosepiler, M.J., and R.E. Reilinger, 1977. Land subsidence due to water withdrawal in the vicinity of Pecos, Texas, Engineering Geology, v. 11, 295-304.

(8) Jurkowski, G., J. Ni, and L.D. Brown, 1978. Contemporaneous arching of the Gulf Coastal Plain in Louisiana and Mississippi: Geological Society of America Abstracts, v. 10, no. 7, 430.

(9) Citron, G.P., and L.D. Brown, 1979. Recent vertical crustal movements from precise leveling surveys in the Blue Ridge and Piedmont provinces, North Carolina and Georgia, Tectonophysics, v. 52, 223-236.

(10) Ni, J.F., R.E. Reilinger, and L.D. Brown, 1980. Vertical crustal movements in the vicinity of the 1931 Valentine, Texas, earthquake, Seism. Soc. Am. Bull., submitted.

(11) Reilinger, R.E., 1975. Isostatic uplift of the region of Utah formerly occupied by Pleistocene Lake Bonneville, from precise leveling data, EΦS, Trans. Am. Geophys. Union, v. 56, 349.

(12) Reilinger, R.E., 1977. Recent vertical crustal movements from precise leveling data in the Great Basin of Nevada and western Utah, EOS, Trans. Am. Geophys. Union, v.58, no.12, p.1238.

(13) Schilt, F.S., 1976. Detection of vertical fault displacement by precise leveling; a case study in western Kentucky, Earthquake Notes, v.47, p.3.

(14) Brown, L.D., 1978. Recent vertical crustal movements along the East Coast of the United States, Tectonophysics, v.44, p.205-231.

(15) Lawrence, M.B., and L.D. Brown, 1977. Transcontinental profile of recent crustal movements. Submitted for 1977 Symposium on Recent Crustal Movements, Palo Alto, California.

(16) Reilinger, R.E., and J.E. York, 1978. Tectonic implications of two vertical crustal movement anomalies from NGS releveling data, EOS, Trans. Am. Geophys. Union, v.59, p.330.

(17) Adams, J., 1980. Active tilting of the Midcontinent: geodetic and geomorphic evidence, Geology, v. 8, p. 442-446.

(18) Adams, J., R.E. Reilinger, J.F. Ni, 1980. Active Tilting of the Oregon and Washington Coastal Ranges: EOS, Trans. Am. Geophys. Union, v. 61, p. 371.

(19) Reilinger, R.E., 1980. Elevation changes near the San Gabriel Fault, Southern California, Geophys. Res. Lett., v. 7, p. 1017-1019.

Stippled Area:

Brown, L.D., and J.E. Oliver, 1976. Vertical crustal movements from leveling data and their relation to geologic structure in the eastern United States, Rev. Geophys. Space Phy., v.14, p.13-35.

Jurkowski, G., L.D. Brown, S.R. Holdahl, and J.E. Oliver, 1979. Map of apparent vertical crustal movements for the eastern United States, EOS, Trans. Am. Geophys. Union, v.60, no.18, 315.

Ruled Area:

Ni, J.F., G. Jurkowski, L.D. Brown, S.R. Holdahl, and J.E. Oliver, 1979. Map of apparent elevation change for the southern and southwestern United States, joint project with NGS, in preparation.

Other Cornell Crustal Movement Studies

Brown, L.D., 1978. Large scale deformations of the solid earth, in, Geophysical Predictions, National Academy of Sciences, Washington, D.C., p.19-28.

Brown, L.D., and R.E. Reilinger, 1979. Releveling data in North America: Implications for vertical motions of plate interiors, Report for Working Group 5 of the IUGG, in press.

Brown, L.D., R.E. Reilinger, and G.P. Citron, 1980. Recent vertical crustal movements in the United States, in Earth Rheology, Isostasy and Eustasy. Nils-Axel Morner, Editor. Johy Wiley and Sons, Chichester, p. 389-405.

Brown, L. D., D. L. Miesen, R. E. Reilinger and G. A. Jurkowski, 1980. Geodetic Leveling and Crustal Movement in the U.S., Part I, Topography and Vertical Motion, E⊕S, Trans. Am. Geophys. Union, in press.

Chi, S. C., R. E. Reilinger, L. D. Brown, and G. A. Jurkowski, 1980. Geodetic Leveling and Crustal Movement in the U.S., Part II Non-Tectonic Influences, E⊕S, Trans. Am. Geophys. Union, 1980 Spring Meeting Program, Changes and Corrections, p. 4.

Reilinger, R. E., L. D. Brown, and G. A. Jurkowski, 1980. Geodetic Leveling and Crustal Movement in the U.S., Part III, Tectonic Deformation, E⊕S, Trans. Am. Geophys. Union, v. 61, p. 210.

Reilinger, R. E., and L. D. Brown, 1981. Neotectonic deformation, near surface movements and systematic errors in U.S. releveling measurements: Implications for earthquake prediction, Maurice Ewing Earthquake Prediction Volume, submitted.

Reilinger, R.E., L.D. Brown, G.P. Citron, and J.E. Oliver, 1977. Recent vertical crustal movements associated with intraplate magmatism in North America; evidence from precise leveling, IASPEI/IAVCEI Assembly, Durham, England, p.74. Held August 9-19, 1977.

Reilinger, R.E., G. Jurkowski, L.D. Brown, and J.E. Oliver, 1978. Interpretation of vertical crustal movements as indicated by leveling in intraplate areas, paper presented at Ninth GEOP conference Columbus, Ohio, October 2-5, 1978.

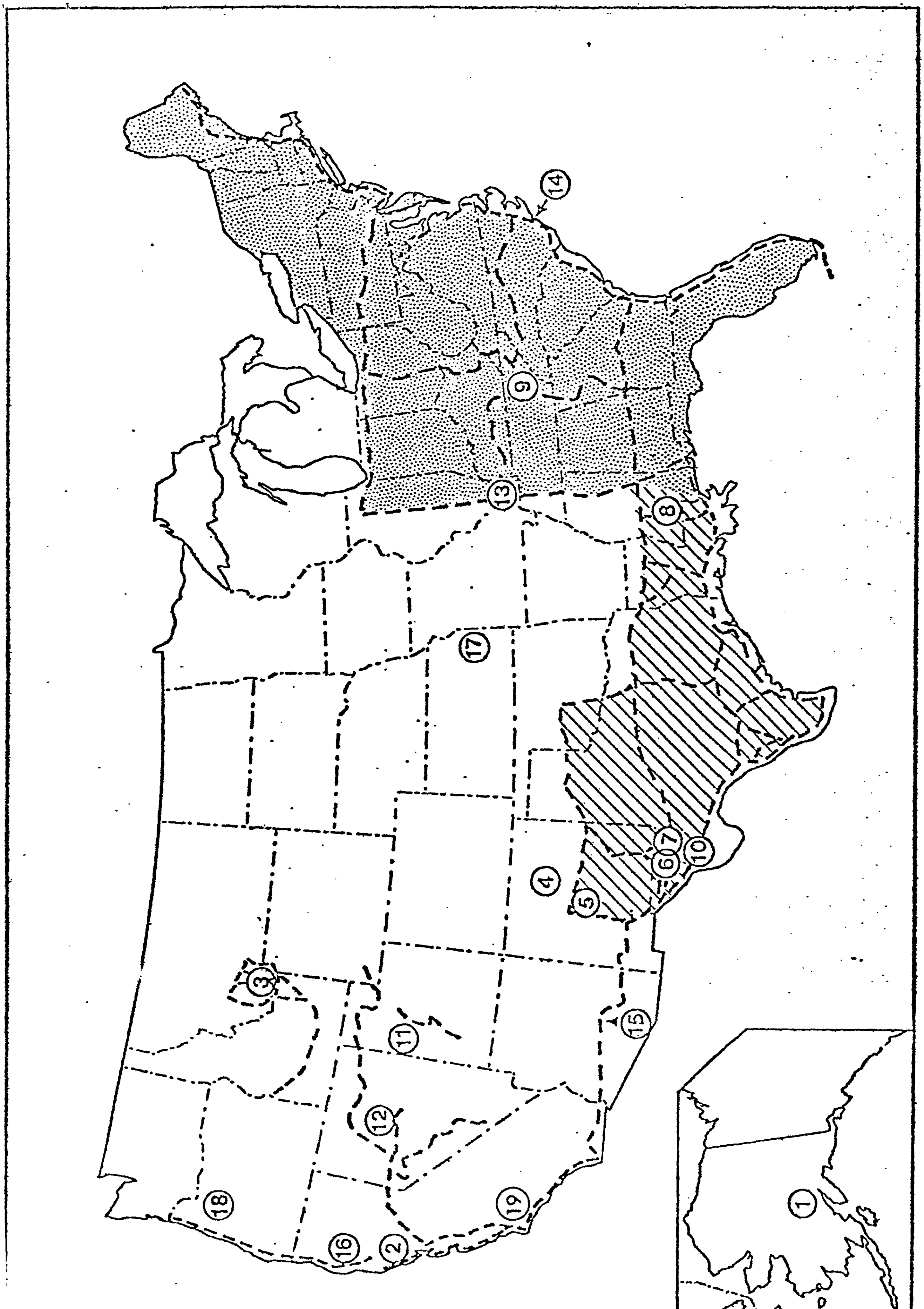
Reilinger, R.E., L.D. Brown, J.E. Oliver, and J.E. York, 1979. Recent vertical crustal movements from leveling observations in the vicinity of the Rio Grande Rift, in: Rio Grande Rift: Tectonics and Magmatism, edited by R.E. Reicker, AGU, Washington, D.C., pp. 223-236.

Adams, J., R.E. Reilinger, and L.D. Brown, 1980. Time behavior of vertical crustal movements measured by releveling in North America: A geologic perspective, (in) Proceedings of International Symposium on Redefinition of North American Vertical Geodetic Networks, Gerard Lachapelle, editor, Ottawa, Canada, p. 327-342.

York, J.E., 1976. Refraction error in leveling: unpublished report.

York, J.E., and J.E. Oliver, 1976. Cretaceous and Cenozoic faulting in eastern North America, Geol. Soc. Am. Bull., v.87, 1105-1114.

* Abstracts cited represent full papers in preparation.



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

CONCLUSIONS AND RECOMMENDATIONS

In spite of laudable progress in developing sophisticated new geodetic methods (e.g., VLBI, Laser Ranging, GPS) releveling measurements continue to be the most accurate (over appropriate distances) and widespread source of information on contemporary vertical movements of the continental crust. As such they constitute an important input to the earthquake prediction problem. Previous investigations clearly demonstrate the potential of the technique for monitoring subtle earth movements. However, it is equally clear that releveling estimates of crustal movement are influenced by near-surface movements and as yet poorly understood systematic errors which can obscure or be mistaken for tectonic deformation. Thus, uncritical interpretation of releveling observations can lead to erroneous tectonic conclusions, which in the case of earthquake prediction could entail serious social ramifications. The checking techniques (e.g., circuit closure analysis) and reliability criteria developed by our group, represent an attempt to quantify specific procedures for evaluating the tectonic significance of particular leveling data sets. Although not foolproof, these procedures have proven effective in a number of cases at discriminating tectonic movements from suspect effects. However, even when spurious effects can be eliminated, relating observed deformation to preseismic mechanisms may be quite difficult because of the limited understanding of precursory phenomena and the general inability to distinguish them from vertical movements due to other causes (e.g., magmatic activity, isostatic movements, orogenic deformations, etc.). Integrating other geophysical and geological information with the leveling results, a major part of our program, is an essential element for proper interpretation.

Substantial progress has been made towards evaluation of releveling evidence for tectonic activity in the U.S. Yet, the implications of many of these measurements remains unclear. Our new techniques for identifying spurious observations and the massive releveling program currently underway by the NGS, hold considerable promise for resolving many of the remaining interpretational problems. Our future effort has been greatly facilitated by the installation of a fully automated leveling data base at the NGS, and development of programs specifically designed for geodynamic analysis at Cornell. The social and scientific importance of understanding contemporary movements of the crust is at least as great now as it was when work on this problem began at Cornell. They require that the remaining uncertainties concerning proper interpretation of releveling observations be resolved so that this information can be effectively applied to earthquake prediction and seismic hazard evaluation.

APPENDIX I

NEOTECTONIC DEFORMATION, NEAR SURFACE MOVEMENTS AND SYSTEMATIC ERRORS IN U.S. RELEVELING MEASUREMENTS: IMPLICATIONS FOR EARTHQUAKE PREDICTION

by

Robert Reilinger and Larry Brown
Department of Geological Sciences
Cornell University
Ithaca, NY 14853

Abstract

Analyses of U.S. releveling measurements indicate that derivative crustal movement estimates may reflect tectonic deformation, near-surface movements, and/or systematic errors. Discriminating the contributions of these factors is especially crucial for unambiguous geodetic detection of possible precursory seismic deformations. While reliable leveling measurements of co-seismic and post-seismic movements are well documented for some of the larger (M > 6) dip-slip earthquakes, leveling evidence for pre-seismic motion is generally sparse and often ambiguous. Subtle earthquake-related motions may be masked by both aseismic movements and systematic errors. For example, deep magma injection and surficial groundwater withdrawal are two mechanisms which have been documented to cause surface movements which, under some circumstances, could be misidentified as seismic-related. Of more concern, perhaps, are systematic measurement errors. Topography dependent errors are an exceptionally troublesome type, perhaps affecting as much as 20% of U.S. leveling. However, other varieties of systematic error also contribute to the uncertainty. Discrepancies between leveling and tide gauge data and within nets of leveling alone suggest large, long baseline accumulations of error. In many cases, aseismic and erroneous contributions can not be unequivocally determined *ex post facto*. However, a comprehensive

examination of the NGS crustal movement data base, representing a large sampling of the entire U.S. Level Net, provides perspective and criteria needed to begin to recognize movement directly related to earthquake activity. Re-examination of certain observations from southern California illustrate both the effectiveness and limitations of this approach. It is clear that more frequent, more extensive, and better constrained observations are needed before leveling achieves its full potential in earthquake prediction research.

Introduction

Vertical movements of the earth's crust are commonly expected to accompany the various phases of strain buildup and release associated with major earthquakes. Observations of vertical co-seismic and post-seismic movements using precise leveling are well-documented. However, reports of preseismic movement in the U.S. are rare and, as will be argued, questionable. Recognition of true pre-seismic motion is complicated by systematic leveling errors, near-surface non-tectonic processes (e.g., fluid withdrawal), the general lack of sufficiently redundant and extensive surveys, and the fact that significant changes in elevation have been identified which are unrelated to earthquakes. Such "noise" could easily hide a pre-seismic signal. Considerable uncertainty exists as to the extent and magnitude of these obscuring "movements". Direct determination of their effects is often extremely difficult. However, some perspective on these problems can be obtained from empirical analyses of existing leveling (Figure 1). Such an analysis forms the basis of this report.

Perhaps, the most extensive set of relevant measurements exists in southern California, where much attention has recently been focused.

Reevaluation of some of these leveling observations in light of empirical criteria developed from broader analysis using most of the available U.S. releveling indicates that while some appear to reflect tectonic deformation, others are suspect because of indications of systematic errors and/or near-surface, non-tectonic movements. Specifically, possible preseismic movements reported for the 1971 San Fernando earthquake in the vicinity of the earthquake fault as well as approximately 30 km northwest of the epicenter may be due to systematic errors. Movements near the San Gabriel fault, initially ascribed to the Palmdale Bulge and more recently to preseismic effects of the 1971 San Fernando earthquake apparently reflect near-surface sediment compaction due to water table fluctuations. The reality of the "Palmdale Bulge" itself has been questioned because of evidence of topography related systematic errors (Jackson and Lee, 1979; Strange, 1980). In contrast, possible tilting southwest of Palmdale between 1961 and 1964 is not easily related to systematic errors or near-surface movements and thus may represent tectonic deformation. Whether this tilt anomaly was due to preseismic effects of the San Fernando earthquake or a mechanically separate tectonic event is presently unknown.

This paper reviews some of those factors that must be considered when attempting to extract tectonic information, especially that relevant to earthquake prediction, from historic releveling observations. Evidence for the extent and nature of systematic errors, non-tectonic movements, and tectonic deformation (both earthquake related deformation and tectonic movements unassociated with earthquakes) from U.S. releveling measurements is presented. Specific criteria to help recognize suspect movements are developed and illustrated with their application to a reevaluation of certain southern California leveling results of particular interest to the earthquake prediction problem.

Systematic Errors in Leveling

At the root of much of the current debate regarding leveling-derived estimates of crustal motion is the prevailing uncertainty as to the role of systematic measurement errors. In particular, systematic errors which accumulate with relief have become a central issue in crustal movement research . While errors of this type have been known to geodesists for some time (e.g., Bomford, 1971), their influence has been considered too small to be of concern in most geodetic applications. However, new field experiments carried out by the National Geodetic Survey (NGS: Holdahl, 1980) and empirical analyses (Brown et al., 1980) confirm earlier suspicions (e.g., Savage and Church, 1974; Brown and Oliver, 1976; Citron and Brown, 1979; Jackson and Lee, 1979; Chi et al., 1980) that topography-induced systematic errors are larger and more common than heretofore established and consequently that such errors can be and probably have been misinterpreted as tectonic motions of the crust.

Topography-correlated errors can arise from improperly calibrated leveling rods and from unequal atmospheric refraction of the foresight and backsight readings. The effects of these two sources of error should differ in a number of respects and thus in principle can be distinguished. For example, ficticious movements resulting from rod calibration errors should correlate rather closely with detailed topography, and change magnitude only where rod pairs are changed. In contrast, atmospheric refraction will be independent of the rods used in the survey. Furthermore, refraction errors can be expected to accumulate in a more complex manner because refraction depends on a variety of parameters which may vary significantly during the course of a given survey (e.g., near surface temperature gradients, individual sight lengths, wind, etc.). In addition, because of procedural changes (a tendency towards shorter sight lengths in newer surveys) atmospheric refraction should more often than not result in ficticious movements which show a positive correlation with topography (i.e., high areas will appear to be rising) while errors due to rod miscalibration should have no preference for positive or negative correlations. In practice, these distinctions are not always easy to draw. However, a preliminary survey of NGS releveling estimates of elevation change which correlate with topography indicates that about 75% display positive correlations. Furthermore, the suspected errors seem too large and too common to be attributed to rod miscalibration. For these reasons, refraction appears to be the more pervasive source of elevation correlated error.

The expected magnitude for refraction error is a point of considerable uncertainty. According to one approximation (i.e., Kukkamaki, 1938), this error is proportional to the height difference between benchmarks, the temperature difference between 0.5 m and 2.5 m above the ground, and the square of the sight length used in the observation. Figure 2 shows representative values for refraction error using constants given by Holdahl (1980). For reasonable temperature differences (1-2 degrees C) and sight lengths (25-75 m), errors as large as 30-40 mm or more can easily accumulate over height differences of 100 m (300-400 ppm). Since refraction error will usually have the same sign, its effect should tend to cancel when differencing surveys to compute movement. This rationale has often been used as an argument for ignoring the effect. However, if surveys are conducted using different sight lengths and/or under different micrometeorological conditions, the refraction effect will result in what appear to be movements that correlate with relief.

Examples of apparent movement correlating with elevation are numerous (Brown et al., 1980). Approximately 20% of U.S. releveling observations show visual correlations between apparent movement and topography. The magnitude of the effect often reaches 30-40 mm per 100 m change in elevation. Although, correlation with topography alone is insufficient to warrant rejection of a tectonic interpretation (e.g., see Reilinger et al., 1977), it is clearly grounds for suspicion. For example, Figure 3a shows apparent vertical movements and terrain along the route from Colorado Springs to Leadville, Colorado based on surveys conducted in 1925, 1953, and 1954. The reversal of the 1953-1925 apparent tilt for the period 1954-1953 and the close correlation with terrain (Figure 3b) strongly suggest elevation correlated error. Since elevation-dependent errors may contaminate a significant portion of the NGS releveling data base, the possibility of such errors must always be considered prior to invoking tectonic explanations for apparent movements which correlate with relief.

Topography dependent error is not the only type of systematic error affecting U.S. leveling measurements. Table 1 lists a number of areas where comparison of repeated leveling measurements show large systematic discrepancies which may be due to errors in the observations. These examples occur in areas of generally subdued relief, thus ruling out elevation-correlated errors. If leveling errors are solely responsible for these discrepancies, whatever their cause, they range in magnitude from .3 mm/km to 1 mm/km and remain systematic (i.e., accumulate monotonically) for distances ranging from about 100 km to over 600 km.

Figure 4 shows three different estimates of elevation change (assuming constant rates of movement over the time period between levelings) along the east coast of the U.S. from Maine to Florida: 1) from unadjusted leveling measurements; 2) from tide gauge records (squares); and 3) from the same leveling observations adjusted with standard least squares procedures for consistency with other repeated leveling lines which form circuits extending inland from the coast (tide gauge data were not used in the adjustment, Jurkowski et al., 1979). The leveling measurements span an approximately 30 yr. time interval. The fact that the relative movement between Maine and Florida is substantially reduced through the adjustment and the fact that the adjusted leveling profile is more consistent with tide gauge data (although serious discrepancies still remain) indicate that the regional north-south tilt results from systematic errors in the leveling observations. The error remains more or less systematic over distances of 1000's of kilometers, and on some sections (e.g., 1800-2600 km) reaches .5 mm/km.

Comparison of leveling and tide gauge estimates of crustal movement along the west coast of the U.S. between Astoria, Oregon, and Crescent City, California show similar discrepancies (Brown et al., 1980). Unlike the east coast profile, apparent crustal movements along the west coast were derived from only two surveys and were thus not subject to possible temporal bias due to stringing together segments covering different time intervals. For the west coast profile, the north-south error reaches .3 mm/km and remains systematic over a distance of 380 km.

The cause of the apparent errors in these coastal surveys is presently unknown. The substantial reduction of the apparent tilt indicated by the east coast profile when adjusted with inland data suggests that the error may be related to the proximity of the leveling route to the coast (i.e., the error did not effect, or had less of an effect, on profiles further inland). Alternatively, the predominantly north-south orientation of the coastal profiles may suggest unequal lighting or other factors which are believed to preferentially accumulate primarily on north-south lines (Bomford, 1971).

Suspect movements are not restricted to coastal profiles. For example, consider the large apparent tilt across the U.S. midcontinent identified by Brown and Oliver (1976) from releveling between Davis Junction, Illinois and Willard, Ohio (Figure 5). This tilt is perhaps the largest apparent movement defined by leveling in the eastern U.S. The tilt anomaly shows no relationship to geologic structure and is inconsistent with movements inferred from comparisons of water level gauges in the great lakes (Brown and Oliver, 1976). Figure 5 shows the results of a loop closure analysis (see Chi et al., 1980 for discussion of method) for circuits including the Davis Junction to Willard route. The fact that misclosures are considerably larger when the circuits are closed with the 1967-1969 surveys between Davis Junction and Willard than with the 1930-1947 surveys, even though the remainder of the loop was surveyed more closely in time to the 1967-1969 interval, suggests that the large apparent tilt of the interior plains may/be due to systematic error and not real ground motion. Such an error would have to reach 1 mm/km and remain systematic for distances of well over 500 km.

In both the coastal and interior examples cited above, the discrepancies are characterized by consistent accumulation over large distances. Although the net effect over a profile can be large, the tilt rates involved are rather low, especially when compared with those exhibited by unequivocal examples of real movement. Tilt may therefore be the more diagnostic parameter in evaluating reliability of crustal movement estimates.

Near-Surface Movements

In addition to systematic errors, releveling measurements are influenced by near-surface movements which can mask, or be mistaken for deep-seated tectonic motion. Table 2 lists some near-surface effects which can be important in crustal movement studies. Benchmark instability and surface failure (e.g. mine collapse) are often easily identified or of such local extent that they are not a serious problem for regional tectonic studies. Such effects can, however, complicate local investigations - for example, of movements near earthquake faults. In fact near-surface soil or sediment compaction due to earthquake ground-shaking may be responsible for the predominance of subsidence over uplift near many earthquake faults (Savage and Hastie, 1966). Subsidence due to surface loading and fluid withdrawal is, in general, easily related to human activity. In fact, leveling has proven quite effective at monitoring such movements, with important engineering applications (e.g., Poland and Davis, 1969). However, near-surface movements, and in particular movements due to variations of water levels in aquifers, appear to be more widespread than previously reported. In addition, such effects can be subtle and subsequently misidentified as tectonic deformation.

Figure 6 shows releveling profiles in the U.S. which indicate subsidence relative to surrounding areas and which overlie aquifer systems which have experienced variations in water levels due either to pumping or natural causes. These movements may therefore represent sediment compaction associated with these water level variations, and are consequently suspect as indicators of tectonic motion. It is interesting to note from Figure 6 that these apparently near-surface movements are quite common in southern California, affecting much of the area peripheral to the Palmdale Bulge. Arguments will be presented later suggesting that in at least one case such groundwater subsidence in southern California has been misidentified as tectonic uplift.

A particular example, not previously reported, which illustrates criteria which can be used to recognize near-surface sediment compaction is the relative subsidence of the Los Angeles basin. Figure 7 gives a map of the L.A. Basin showing contours of basement depth and the location of a leveling route traversing the basin. Also shown are the elevation changes along the leveling route and the history of water level decline measured in an observation well near the center of the basin. Subsidence near the center of the basin reaches 15 cm relative to the periphery and extends over a distance of 40 km. The observed subsidence correlates spatially with aquifer geometry and temporally with the history of water level decline. In addition, the magnitude of the effect (i.e., the ratio of subsidence to water level decline) is comparable to observations in other areas (Poland and Davis, 1969). Had the relationship between aquifer geometry and subsidence not been noticed, it is possible that these measurements could have been misinterpreted as tectonic motion.

Vertical Movements and Earthquakes

In spite of the substantial difficulties associated with releveling estimates of crustal movement, some of which have been described in previous sections, the capability of the leveling technique for monitoring tectonic earth movements is well established. In a number of cases, relatively subtle earth movements (i.e., tilts few x 10^{-6} rad and tilt rates few x 10^{-8} rad/yr) have been identified. In this section we briefly review releveling evidence for earthquake related deformation in the U.S. and use specific examples to illustrate some of the criteria employed to identify real tectonic movements.

The best examples of tectonic deformations measured by leveling in the U.S. are those in the vicinity of major earthquakes. Figure 8 and Table 3 review those U.S. earthquakes for which vertical movements have been reported. All of these earthquakes are associated with faults that have a significant component of dip-slip movement (with the possible exception of the 1940 Imperial Valley earthquake). Up to the present, there is no clear evidence from U.S. releveling measurements for permanent vertical deformation associated with purely strike-slip faulting although present observations are not sufficient to rule this out.

The most obvious vertical movements are those accompanying the earthquake (coseismic). Coseismic deformation has been well-documented for several of the larger ($M > 6$) normal and thrust earthquakes which have occurred in areas of preexisting geodetic control (Table 3). Observed movements range in magnitude from a few cm to a few m depending on the size of the earthquake and the proximity of the leveling measurements to the epicentral area. In general, coseismic movements are well explained by elastic dislocation theory (Savage and Hastie, 1966) although complications can arise from such factors as near-surface soil or sediment compaction due to ground shaking.

Post-seismic vertical movements have also been observed by releveling for some of the larger dip-slip earthquakes (see Table 3). These movements are usually smaller than associated coseismic movements; however like coseismic movements they can often be identified by their close spatial and temporal association with earthquakes, and in some cases surface faulting. Where sufficient observations exist, post-seismic deformation rates appear to decrease exponentially from the time of the earthquake. For example, movements near Anchorage following the 1964 Alaska earthquake are shown in Figure 9 (Brown et al., 1977). The Alaska earthquake, one of the largest events ever recorded, occurred where the oceanic Pacific plate is being thrust under the continental North American plate at a rate of over 5 cm/yr (Plafker, 1972). Savage and Hastie (1966) and Hastie and Savage (1970), using a dislocation model of thrust faulting, showed that the coseismic displacements were consistent with low-angle thrusting. Post-seismic movements near Anchorage (Figure 9) amounted to as much as 0.55 m of land uplift at an exponentially decreasing rate during the decade following the earthquake. Additional evidence for deformation following the Alaska earthquake was reported by Prescott and Lisowski (1977) from analysis of detailed leveling arrays on Middleton Island in the Gulf of Alaska. Tilts associated with the Alaska post-seismic movements were on the order of 10^{-5} to 10^{-6} rad. There is still considerable debate as to the mechanism responsible for post-seismic movements, but at least some of the observations appear consistent with after-slip on the fault, or an extension of the fault that ruptured during the earthquake, although other explanations have been proposed (e.g., Nur and Mavko, 1974; Scholz, 1972).

While co-seismic and post-seismic movements are well established for at least some earthquakes, clear evidence for preseismic deformation from U.S. releveling measurements is quite rare. This may be due to a lack of appropriate measurements as opposed to the absence of such movements since it is unusual to have multiple levelings of sufficient proximity prior to an earthquake. Precursory vertical movements have been suggested from leveling measurements for only three U.S. earthquakes: the 1959 magnitude 7.1 Hebgen Lake, Montana, the 1971 magnitude 6.4 San Fernando, California and the 1973 magnitude 6.0 Point Mugu, California earthquakes (see Table 3). The evidence for preseismic movement near Point Mugu is marginal, both because the proposed movements are barely significant relative to random error estimates and because the area was subject to surficial subsidence due to groundwater withdrawal during the period of interest (Castle et al., 1977). The 1971 San Fernando earthquake is exceptional in that significant releveling was available for the epicentral area prior to the earthquake. These observations were analyzed after the earthquake and were interpreted to indicate precursory movements (Castle et al., 1974). However, reevaluation of the relevant leveling observations, described in a later section of this paper, cast some doubts on the reliability of these measurements and hence on their tectonic significance. Reilinger et al. (1977) found evidence for possible precursory uplift throughout a broad region surrounding the area of major co-seismic movement of the 1959 Hebgen Lake earthquake which apparently accumulated at a rate of 3-5 mm/yr (Figure 10). The zone of uplift is defined by five independent elevation change profiles derived from 12 independent surveys. Although three of the five movement profiles show positive correlation with topography (i.e. high areas going up), one shows a negative correlation and one shows no correlation; yet all indicate a consistent sense of movement. This consistency argues strongly against elevation correlated errors as the cause of the observed uplift. The doming stands out distinctly in relation to movements in surrounding areas, and shows a close spatial correlation with the zone of major co-seismic deformation and aftershock activity for the 1959 earthquake (Figure 10). In addition, the geodetically measured deformation is consistent in sign with Cenozoic deformation deduced from geologic structure (Reilinger et al., 1977). Tilts associated with this uplift range from 3 - 7 x 10^{-6} rad with associated tilt rates between 1 - 3 x 10^{-7} rad/yr. Although Reilinger et al. (1977) suggest that doming began prior to the earthquake, because of the limited number of pre-earthquake leveling measurements, it is impossible to prove that the activity was precursory (i.e., doming may have accompanied, and/or immediately followed the earthquake). Brown et al. (1978) suggest a pre-seismic interpretation of uplift in western Texas, although they favor an alternative tectonic explanation. Thus leveling evidence for vertical movements preceding any U.S. earthquake is relatively weak in both quantity and quality.

Other Tectonic Deformation

Recognizing real tectonic deformation from releveling, although necessary, is not sufficient grounds to infer that they are directly relevant to the earthquake prediction problem. Earthquake related movements must be separated from movements due to other deep seated processes, such as isostatic adjustments and magmatic activity. Both of these mechanisms are believed, on the basis of observational evidence, to result in contemporary vertical movements which are sufficiently rapid to be detected by releveling measurements.

Movements due to subsurface magmatic activity are not restricted to volcanically active regions (e.g., Hawaii, Iceland, Japan), having been reported in Yellowstone National Park (Reilinger et al., 1977; Pelton and Smith, 1979), and the Rio Grande rift (Reilinger et al., 1980) as well. Crustal uplift in the Central Rio Grande rift illustrates tectonic deformation which appears to be unrelated to major earthquake activity. The existence of an active magma body beneath the central Rio Grande rift was inferred primarily on the basis of geophysical, and some geological information (Sanford et al., 1977). The magma body is believed to consist of a thin sill at a depth of about 20 km (Figure 11). Elevation change profiles along the routes shown in Figure 11 are given in Figure 12. All three profiles indicate uplift of the area overlying the magma body. The observed uplift is believed to be due to tectonic deformation and not measurement errors or near-surface movements because: 1) uplift is defined by three independent elevation change profiles; 2) while the two east-west profiles show a rough negative correlation with topography near the area of uplift, the north-south profile shows no correlation, thus ruling out elevation-dependent errors as the primary cause of the observed movements; 3) the Belen to Amarillo profile demonstrates that the uplift of the rift is anomalous relative to points to the east; 4) geomorphic evidence for post-Pliocene deformation (Backman and Mehnart, 1978) is consistent in sign with the geodetic observations; 5) anomalous uplift occurs directly above the magma body; and 6) modeling studies indicate that uplift could result from activity within the magma body. If uplift is accumulating more or less continuously as suggested (Reilinger et al., 1980), it is characterized by an average rate of 4 mm/yr, with corresponding tilt rates of 5 to 10 x 10^{-8} rad/yr. If independent evidence for an active magma body beneath the area of uplift were not available, these movements might have been attributed to an impending earthquake.

Reliability Criteria

The selected cases described above demonstrate both the utility and limitations of geodetic leveling to detect tilts of a few x 10^{-6} rad and tilt rates of a few x 10^{-8} rad/yr. Thus while non-tectonic influences (e.g. systematic error) can obscure real earth movement, the technique has clearly proven effective at monitoring relatively subtle tectonic deformation. It is essential, however, that individual releveling observations be examined in detail for possible contamination by systematic errors and near surface movements prior to invoking tectonic explanation. Particularly useful quantitative techniques include comparison of foresight-backsight readings (e.g., Savage and Church, 1974) and loop closure analysis (e.g., Chi et al., 1980). In addition, the following qualitative criteria, some of which were illustrated by the previous examples, have proven useful for evaluating the reliability of particular data sets (Brown et al., 1980): 1) magnitude relative to possible errors (since many errors remain poorly understood this is equivalent to determining whether the movements in question stand out in relation to "background noise"); 2) consistent temporal behavior when multiple levelings are available (e.g., Alaska); 3) relations with independent geophysical or geologic estimates of recent movement (e.g., tide guage, lake levels, tilt meters, horizontal movements, geomorphic evidence, etc.); 4) consistent movements when multiple leveling lines cross a given feature (e.g., Hebgen Lake, Rio Grande rift); 5) correlation with geologic structure and tectonic activity (e.g., Hebgen Lake); 6) lack of correlation with topography ruling out possible elevation correlated errors; 7) lack of relationship to possible near-surface processes (e.g., fluid withdrawal, reservoir impoundment, etc.); 8) lack of relationship between apparent movements and procedural changes (changes in sight lengths, rod or instrument changes); and 9) consistency of inferred mechanism with tectonic setting (e.g., Alaska).

A Case Study: Southern California Releveling Measurements

Much attention has recently been focused on leveling in southern California, where there is both considerable concern about future earthquakes and an abundance of leveling observations. Using the above reliability criteria, developed through analysis of the much broader data base of U.S. releveling, we have reevaluated some of the observations used to deduce preseismic movements for the 1971 San Fernando earthquake as well as the Palmdale Bulge. Our reevaluation, representing a different perspective, suggests that many of the southern California measurements are significantly affected by both topography-dependent errors and near-surface movements. On the other hand, at least some of the observations may reflect real earth movements. Thus, the configuration of the Palmdale Bulge will, at the very least, require revision in light of improved understanding of those factors which can influence releveling measurements. However, since certain spurious effects may be isolated, the southern California releveling data remain an important source of information on contemporary tectonic activity.

In our analysis of southern California releveling observations, data have been displayed in terms of relative movements, or tilts, for sequential time intervals along the pertinent segments of the leveling routes. This contrasts with previous attempts to tie the observations to a tide gauge in order to relate movements to sea level. Analyzing tilts minimizes the effects of systematic errors, which can accumulate to rather substantial amounts over the 100-200 km distance to the tide gauge, and as will be demonstrated, greatly simplifies interpretation of the observations.

Figure 13 shows those leveling routes in southern California for which crustal movement information has been investigated for this study. Possible preseismic movements of the 1971 San Fernando earthquake were reported by Castle et al. (1974) and Strange (1980) in three areas: in the vicinity of the earthquake fault (segment B), 30 km northwest of the epicenter (segment A), and just north of Saugus (along segment A). Vertical movements prior to the 1971 earthquake were also reported in the area south of Palmdale (segment C). Although the movements south of Palmdale were not believed to be precursory to the earthquake (Castle et al., 1974), they subsequently were used in defining the "Palmdale Bulge" (Castle et al., 1976).

The sequence of movements along segment B crossing near the area of surface faulting are shown in Figure 14. Coseismic movement consisting of subsidence south of the San Fernando Fault and uplift north of the fault are clearly indicated for the 1969-1971 interval. These movements are roughly consistent with elastic rebound accompanying thrust faulting (Savage et al., 1975). Possible preseismic tilting up to the north is indicated by the profiles for the time intervals 1955-1961, 1961-1964, and 1964-1965. Apparently no tilt accumulated along this section from 1965-1969. Figure 15a shows relative movements between points near the ends of this profile segment plotted as a function of time. The temporal consistency of these movements is, in itself, normally evidence that the measurements reflect real movements. However, there are two reasons to suspect systematic error, and in particular refraction errors, rather than true ground motion.

Examination of the profiles in Figure 14 indicates that the observed tilting correlates with topography. This correlation, although suggestive, is not sufficient to confirm systematic error because real movements can in some cases correlate with relief (e.g., Reilinger et al., 1977). However, the sequence of apparent tilts between 1955 and 1969 show a systematic relationship to the sight lengths used for different surveys (Figure 15b); a relationship that is consistent with that expected from refraction errors (Holdahl, 1980). The 3°C temperature difference that results in a good fit to the observations, although somewhat high for a daily average, is not unreasonable for the spring and summer months in southern California. In view of the possibility of such refraction errors, the tectonic significance of the sequence of apparent tilts shown in Figure 14 remains ambiguous.

Figure 16 shows profiles of relative elevation change for sequential time intervals crossing the two areas of reported preseismic deformation northwest of the epicenter (Segment A; Figure 13). During the 1953-1964 interval the main deformation consisted of subsidence in the vicinity of Saugus relative to points farther north (ruled area of plot). This movement was originally attributed to the Palmdale Bulge (Castle et al., 1976) and more recently to preseismic effects of the San Fernando earthquake (Strange, 1980). However, analysis of releveling measurements throughout the Saugus Basin indicates that relative subsidence shows a close correlation with the geometry of the Saugus aquifer and the history of water level decline (Reilinger, 1980). This relationship is shown graphically in Figure 17. These observations strongly suggest that subsidence above the Saugus aquifer results from near-surface sediment compaction due to fluctuations of the water level within the underlying aquifer and not from tectonic deformation. This result is particularly important to the current controversy surrounding the "Palmdale Bulge" since, unlike many of the measurements defining the Bulge, those in the Saugus area do not correlate with relief.

The other large possible movements shown in Figure 16 occurred between 1965 and 1968 and between 1968 and 1969. These observations were the primary evidence used to infer pre-earthquake slip at depth on the fault (Thatcher, 1976). The 1965-1968 movements consisted of uplift of the north section relative to the south by about 6 cm. The 1968-1969 movements were, in essence, a reversal of the 1965-1968 movements. The important point is that both sets of apparent movements were dependent upon the 1968 survey. This is illustrated by the bottom-most plot in Figure 16, which shows the general absence of movement for the 1965-1969 interval. Therefore, either we were fortunate enough to catch preseismic deformation at a time of significant deflection (1968), and again when the movements had exactly reversed themselves (1969), or the 1968 survey was in error. While oscillatory movements may have occurred, the possibility of errors in the 1968 survey is at least as likely, particularly in light of the now suspect results south of the epicenter, and similarly suspect trends identified in leveling observations in other parts of the country.

The possibility that refraction errors contaminate leveling measurements south of the epicenter naturally raises the question as to whether this same effect is responsible for the apparent error in the 1968 survey northwest of the earthquake. The steep tilts indicated by the 1965-1968 and the 1968-1969 movement profiles occur where there is a corresponding steep slope in topography (25 to 40 km). However, the topographic slope is so steep (>.04 rad) that only short sight-lengths could be used, making it unlikely that atmospheric refraction coupled to sight-lengths was a significant effect. Unusual near-surface temperature differences at the time of the survey, or other elevation-correlated errors, such as miscalibrated leveling rods (Jackson and Lee, 1979) may have affected these observations.

Movements along the leveling route C in Figure 13 were originally believed to be unrelated to the earthquake. This conclusion was based on the observation that the movements south of Palmdale showed no temporal relationship to the movements which were believed to be preseismic in origin (Castle et al., 1974). The movements south of Palmdale do not appear to be due to either systematic errors or near-surface effects and thus may represent tectonic deformation.

Figure 18 shows the sequence of relative movements along the survey route south of Palmdale. The major tilt event occurred between 1961 and 1964 and amounted to more than 10 cm of relative movement over a distance of 20 km. This corresponds to a tilt of 5×10^{-6} rad. The general absence of movements for the 1955-1961 interval (uppermost movement profile in Figure 18), the 1964-1965 interval and the 1965-1971 interval (bottom two profiles) attests to the reliability of all of these surveys (i.e., comparison of the 55 or 61 surveys with any of the later surveys will give roughly the same result). This implies that the 1961 to 1964 tilt event is in fact defined by five independent surveys. In addition, the tilt anomaly does not show a strong correlation with topography (i.e., the direction of tilting does not reverse where the topographic slope reverses). Furthermore, the sequence of relative movements show no relationship either to changes in leveling rods or to changes in sight lengths. This evidence suggests that the apparent tilting south of Palmdale reflects real crustal movements. Whether the tilt anomaly was a precursor to the San Fernando earthquake or represented a mechanically separate event is presently unknown.

Discussion and Conclusions

In spite of laudable progress in developing sophisticated new geodetic methods (e.g., VLBI, Laser Ranging, GPS) releveling measurements continue to be the most accurate (over appropriate distances) and widespread source of information on contemporary vertical movements of the continental crust. As such they constitute an important input to the earthquake prediction problem. Previous investigations, a few of which have been described here, clearly demonstrate the potential of the technique for monitoring subtle earth movements. However, it is equally clear that releveling estimates of crustal movement are influenced by near-surface movements and as yet poorly understood systematic errors which can obscure or be mistaken for tectonic deformation. Thus, uncritical interpretation of releveling observations can lead to erroneous tectonic conclusions, which in the case of earthquake prediction could entail serious social ramifications. The checking techniques (e.g., circuit closure analysis, foresight-backsight comparisons) and reliability criteria illustrated in this study, represent an attempt to quantify specific procedures for evaluating the tectonic significance of particular leveling data sets. Although not foolproof, these procedures have proven effective in a number of cases at discriminating tectonic movements from suspect effects. However, even when spurious effects can be eliminated, relating observed deformation to preseismic mechanisms may be quite difficult because of our limited understanding of precursory phenomena and our general inability to distinguish them from vertical movements due to other causes (e.g., magmatic activity, isostatic movements, orogenic deformation, etc.). Furthermore, the sparse distribution of leveling surveys in both space and time, even in areas like southern California, makes it highly unlikely that precursory movements for all but the largest earthquakes will ever be detected. In order for leveling to become more than an accidental contributor to earthquake prediction, a systematic leveling program designed for geodynamic rather than geodetic objectives is needed to develop the observational background required to recognize possible preseismic movement.

Acknowledgements

We thank the National Geodetic Survey for supplying the leveling data used for this study. Greg Jurkowski, Christie Chi, and Dave Miesen provided technical assistance. This research was supported by U.S. Geological Survey Grant 14-08-0001-17625, NASA Grant NAG5-40 and USNRC contract AT(49624-0367). Contribution No. 684 of the Department of Geological Sciences, Cornell University.

REFERENCES

Bachman, G.E., and Mehnert, H.H., 1978, New K-Ar data and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico, Geol. Soc. Amer. Bull., v. 89, p. 283-292.

Bomford, G., 1971, Geodesy, third ed., England, Clarendon, Oxford, 226 p.

Brown, L.D., 1978, Recent vertical crustal movements along the East Coast of the United States, Tectonophysics, v. 44, p. 205-231.

Brown, L.D., and Oliver, J.E., 1976, Vertical crustal movements from leveling data and their relation to geologic structure in the eastern United States, Rev. Geophys. and Space Physics, v. 14, p. 13-35.

Brown, L.D., Reilinger, R.E., Holdahl, S.R., and Balazs, E.I., 1977, Post-seismic crustal uplift near Anchorage, Alaska, Jour. Geophys. Res., v. 82, p. 3369-3378.

Brown, L.D., Reilinger, R.E., and Hagstrum, J.R., 1978, Contemporary uplift of the Diablo Plateau, West Texas, from leveling measurements, Jour. Geophys. Res., v. 83, p. 5465-5471.

Brown, L.D., Reilinger, R.E., and Citron, G.P., 1980, Recent vertical crustal movements in the U.S.: evidence from precise leveling, in Earth Rheology, Isostasy and Eustasy, ed. N.A. Morner, John Wiley and Sons, p. 389-405.

Brown, L.D., Miesen, D.L., Reilinger, R.E., and Jurkowski, G.A., 1980, Geodetic leveling and crustal movement in the U.S.: Part I, Topography and vertical motion, EOS, Trans. Am. Geophys. Union, 1980 Spring Meeting Program, Changes and Corrections, pg. 4.

Burford, R.O., Castle, R.O., Church, J.P., Kinoshita, W.T., Kirby, S.H., Ruthven, R.T., and Savage, J.C., 1971, Preliminary measurements of tectonic movement, in The San Fernando, California Earthquake of February 9, 1971, U.S. Geol. Surv. Prof. Pap., 733, p. 80-85.

Castle, R.O., Alt, J.N., Savage, J.C., and Balazs, E.I., 1974, Elevation changes preceding the San Fernando earthquake of February 9, 1971, Geology, v. 2, p. 61-66.

Castle, R.O., Church, J.P., and Elliott, M.R., 1976, Aseismic uplift in Southern California, Science, v. 192, p. 251-253.

Castle, R.O., Church, J.P., Elliott, M.R., and Savage, J.C., 1977, Preseismic and coseismic elevation changes in the epicentral region of the Point Mugu earthquake of February 21, 1973, Bull. Seismol. Soc. Am., v. 67, p. 219-231.

Chi, S.C., Reilinger, R.E., Brown, L.D., and Oliver, J.E., 1980, Leveling circuits and crustal movements, Jour. Geophys. Res., v. 85, p. 1469-1474.

Chi, S.C., Reilinger, R.E., Brown, L.D., and Jurkowski, G.A., 1980, Geodetic leveling and crustal movement in the U.S., Part II, Non-tectonic influences, EΘS, Trans. Am. Geophys. Union, v. 61, p. 210.

Citron, G.P., and Brown, L.D., 1979, Recent vertical crustal movements from precise leveling surveys in the Blue Ridge and Piedmont provinces, North Carolina and Georgia, Tectonophysics, v. 52, p. 223-236.

Hastie, L.M., and Savage, J.C., 1970, A dislocation model for the Alaska earthquake, Bull. Seismol. Soc. Amer., v. 60, p. 1389-1392.

Holdahl, S.R., 1980, An assessment of refraction error and development of methods to remove its influence from geodetic leveling, Final Technical Report Contract 14-08-0001-17733, USGS, 18 p.

Jackson, D.D., and Lee, W.B., 1979, The Palmdale Bulge - An alternate interpretation, EΘS, Trans. Am. Geophys. Union, v. 60, p. 810.

Jurkowski, G. Brown, L.D., Holdahl, S.R., and Oliver, J.E., 1979, Map of apparent vertical crustal movements for the eastern United States, EΘS, Trans. Am. Geophys. Union, v. 60, p. 315.

Kaariainen, E., 1953, On recent uplift of the earth's crust in Finland, Suom. Geodeettisen Laitoksen Julka, v. 42, p. 1-106.

Kukkamaki, T.J., 1938, Uber die nivellitsche refraktian, Publication of the Finnish Geodetic Institute, No. 25, 48 p.

Lofgren, B.E., 1966, Tectonic movement in the Grapevine Area, Kern County, California, U.S. Geol. Surv. Prof. Pap. 550-B, p. B6-B11.

Lofgren, B.E., 1979, Changes in aquifer-system properties with groundwater depletion, in ed., S.K. Saxena, Evaluation and Prediction of Subsidence, American Society of Civil Engineers, New York, New York, p. 26-46.

Miller, R.W., Pope, A.J., Stettner, H.S., and Davis, J.L., 1970, Crustal movement investigations, Operational data report, U.S. Department of Commerce, Coast and Geodetic Survey, DR-10.

Myers, W.F., and Hamilton, W., 1964, Deformation accompanying the Hebgen Lake earthquake of August 17, 1959, U.S. Geol. Surv. Prof. Paper 435, p. 55-98.

Ni, J.F., Reilinger, R.E., and Brown, L.D., 1980, Vertical crustal movements in the vicinity of the 1931 Valentine, Texas, earthquake, Seism. Soc. Am. Bull., in press.

Nur, A., and Mavko, G., 1974, Postseismic viscoelastic rebound, Science, v. 181, p. 204-206.

Parkin, E.J., 1948, Vertical movement in the Los Angeles region, 1906-1946, Trans. Am. Geophys. Union, v. 29, p. 17-26.

Pelton, J.R., and Smith, R.B., 1979, Recent crustal uplift in Yellowstone National Park, Science, v. 206, p. 1179-1182.

Pitt, A.M., Weaver, C.S., and Spence, W., 1979, The Yellowstone Park earthquake of June 30, 1975, Bull. Seismol. Soc. Am., v. 69, p. 187-205.

Sanford, A.R., and others, 1977, Geophysical evidence for a magma body in the crust in the vicinity of Socorro, New Mexico, in Heacock, J.E., ed., The Earth's Crust, AGU Monograph 20, p. 385-403.

Savage, J.C., and Hastie, L.M., 1966, Surface deformation associated with dip slip faulting, Jour. Geophys. Res., v. 71, p. 4897-4904.

Savage, J.C., and Church, J.P., 1974, Evidence for postearthquake slip in the Fairview Peak, Dixie Valley, and Rainbow Mountain fault areas of Nevada, Bull. Seismol. Soc. Am., v. 64, p. 687-698.

Savage, J.C., Burford, R.O., and Kinoshita, W.T., 1975, Earth movements from geodetic measurements, Calif. Div. Mines and Geol. Bull., v. 196, p. 175-186.

Savage, J.C., and Church, J.P., 1975, Evidence for afterslip on the San Fernando fault, Bull. Seismol. Soc. Amer., v. 65, p. 829-834.

Savage, J.C., Lisowski, M., Prescott, W.H., and Church, J.P., 1977, Geodetic measurements of deformation associated with the Oroville, California earthquake, Jour. Geophys. Res., v. 82, p. 1667-1671.

Scholz, C.H., 1972, Crustal movement in tectonic areas, Tectonophysics, v. 14, p. 201-217.

Strange, W.E., 1980, The impact of refraction correction on leveling interpretations in California, EOS, Trans. Am. Geophys. Union, v. 61, p. 367-368.

Terzaghi, K., and Peck, R.B., 1967, Soil Mechanics in Engineering Practice, John Wiley and Sons, New York, 729 p.

Thatcher, W., 1976, Episodic strain accumulation in Southern California, Science, v. 194, p. 691-695.

Whitten, C.A., 1957, The Dixie Valley-Fairview Peak, Nevada, earthquakes of December 16, 1954: geodetic measurements, Bull. Seismol. Soc. Am., v. 47, p. 321-325.

Plafker, G., 1969, Tectonics of the March 27, 1964 Alaska earthquake, U.S. Geol. Surv. Prof. Pap. 543-I, p. 1-74.

Plafker, G., 1972, Alaskan earthquake of 1964 and Chilean earthquake of 1960: Implications for arc tectonics, Jour. Geophys. Res., v. 77, p. 901-925.

Poland, J.F., and Davis, G.H., 1969, Land subsidence due to withdrawal of fluids, in Reviews of Engineering Geology II, p. 187-269.

Prescott, W.H., and Lisowski, M., 1977, Deformation at Middleton Island, Alaska, during the decade after the Alaska earthquake of 1964, Bull. Seismol. Soc. Am., v. 67, p. 579-586.

Reilinger, R.E., 1980, Elevation changes near the San Gabriel Fault, Southern California, Geophys. Res. Lett., in press.

Reilinger, R.E., and Oliver, J.E., 1976, Modern uplift associated with a proposed magma body in the vicinity of Socorro, New Mexico, Geology, v. 4, no. 10, p. 583-586.

Reilinger, R.E., Citron, G.P., and Brown, L.D., 1977, Recent vertical crustal movements from leveling data in southwestern Montana, western Yellowstone National Park, and the Snake River Plain, Jour. Geophys. Res., v. 82, p. 5349-5359.

Reilinger, R.E., Oliver, J.E., Brown, L.D., Sanford, A.R., and Balazs, E.I., 1980, New measurements of crustal doming over the Socorro magma body, New Mexico, Geology, v. 8, p. 291-295.

Rinehart, E.J., Sanford, A.R., and Ward, R.M., 1979, Geographic extent and shape of an extensive magma body at mid-crustal depths in the Rio Grande rift near Socorro, New Mexico, (in) Riecker, R.E., ed., Rio Grande Rift: Tectonics and Magmatism, Washington, D.C., American Geophysical Union, p. 237-251.

TABLE AND FIGURE CAPTIONS

Table 1. Magnitude of systematic discrepancies between levelings in areas of subdued relief.

Table 2. Near surface effects on leveling estimates of crustal movement.

Table 3. Earthquakes for which vertical crustal movements have been reported from releveling observations. Maximum amplitude of observed movements, and typical dimension of area effected are also given.

Figure 1. Leveling routes for which crustal movement information has been obtained in the U.S.

Figure 2. Magnitude of refraction error (R_ε) normalized by height difference (ΔH) versus sight length (L) for various temperature differences. Based on relationship and theoretically determined constant given by Holdahl (1980).

Figure 3. a) Profiles of apparent elevation change and topography from Colorado Springs to Leadville, Colorado. Reversal of apparent tilt and correlation with topography strongly suggest elevation correlated error.

b) Apparent elevation change versus elevation difference for 1954-1953 profile in Figure 3a. Correlation coefficient (r) and regression slope (magnitude of error) are also shown.

Figure 4. Elevation change profiles along east coast of U.S. (map at right). Unadjusted profile based on observed elevations from leveling assuming constant velocity movement (modified from Brown, 1978). Adjusted profile is same data adjusted by other leveling lying inland from coast (tide gauge data not used in adjustment). Squares show similar profile derived from tide gauges.

Figure 5. Leveling loops used to investigate apparent tilting between Davis Junction, Illinois and Willard, Ohio. Elevation change profile and topography along Davis Junction to Willard route shown at right. Misclosures are also given.

Figure 6. Location of elevation change profiles which indicate subsidence possibly due to groundwater effects. Shaded areas represent previously published cases of near surface subsidence.

Figure 7. Map of Los Angeles basin. Contours indicate depth to basement (Ft), heavy dashed lines are faults, stippled areas are bedrock outcrops, heavy solid line (San Pedro to Los Angeles) is leveling route - crustal movements for period 1955-1964 shown below map. Asterisk shows location of observation well for which water level history is shown at right.

Figure 8. Locations of U.S. earthquakes for which releveling evidence of crustal movement has been reported. Numbers refer to Table III.

Figure 9. Elevation changes and topography between Anchorage and Whittier following 1964 Alaska earthquake (modified from Brown et al., 1977). Profiles are tied to sea level at Anchorage. Elevation change versus time for benchmark near center of uplift is shown at right. Note exponentially decreasing uplift.

Figure 10. Contours of elevation change (1 mm/yr and 5 mm/yr contours shown) for doming of Hebgen Lake region.

Figure 11. Locations of leveling routes and benchmarks (dots) in Soccoro-Albuquerque, New Mexico area. Outline of mid-crustal magma body is also shown (from Rinehart et al., 1979).

Figure 12. Profiles of elevation change and topography used to infer uplift above Soccoro magma body. Dates of leveling are indicated at the top of each plot.

Figure 13. Leveling routes in Southern California for which crustal movements have been investigated in this study. 1971 San Fernando earthquake epicenter (*) and surface fault are shown along with contours of Palmdale Bulge as reported by Castle et al., 1976.

Figure 14. Relative movements for sequential time intervals and topography for route B in Figure 13.

Figure 15. a) Relative movement between benchmarks near ends of profile shown in Figure 14 plotted versus time.

b) Relative movement [$\Delta(\Delta H)$] indicated by profile in Figure 14 normalized by height difference between these points (ΔH) for different time intervals plotted versus difference in square of sight length for corresponding leveling surveys. The straight lines represent the expected relationship from refraction error for a range of temperature differences (from relationship given by Holdahl, 1980).

Figure 16. Relative movement for sequential time intervals and topography for route A in Figure 13.

Figure 17. Plot of subsidence versus change in potentiometric surface (i.e., water level: ΔP) times aquifer thickness (T) for benchmarks in and immediately adjacent to aquifer (from Reilinger, 1980). Different symbols refer to different releveled segments: circles-Saugus to North (1953-1964); squares-Saugus to South (1955-1964); triangles-Saugus to East (1955-1961). The three circled points lie in the southeastern part of the aquifer and may reflect either different sediment characteristics or some effect other than sediment compaction in this area.

Figure 18. Relative movement for sequential time intervals and topography for route C in Figure 13.

MAGNITUDE OF SYSTEMATIC DISCREPANCIES

AREA	MAGNITUDE (MM/KM)	MAGNITUDE (10^{-8} YR^{-1})	DISTANCE (KM)	AVERAGE RELIEF (M)
EAST COAST U.S.	0.5	1.6	650	<5
WEST COAST U.S.	0.3	3.3	380	<10
MIDCONTINENT U.S.	1.0	2.6	140	<100

QUOTED LIMIT FOR SYSTEMATIC ERROR <0.2 MM/KM (BOMFORD, 1971)

NEAR SURFACE EFFECTS

I. BENCH MARK INSTABILITY
   - A. FROST HEAVE
   - B. SOIL MOISTURE AND TEMPERATURE
   - C. HUMAN DISTURBANCE

II. SURFACE FAILURE
   - A. LAND SLIDES
   - B. MINE AND CAVERN COLLAPSE

III. LOADING
   - A. RESERVOIR IMPOUNDMENT
   - B. BUILDING SETTLEMENT

IV. FLUID WITHDRAWAL (WATER, OIL, GAS)

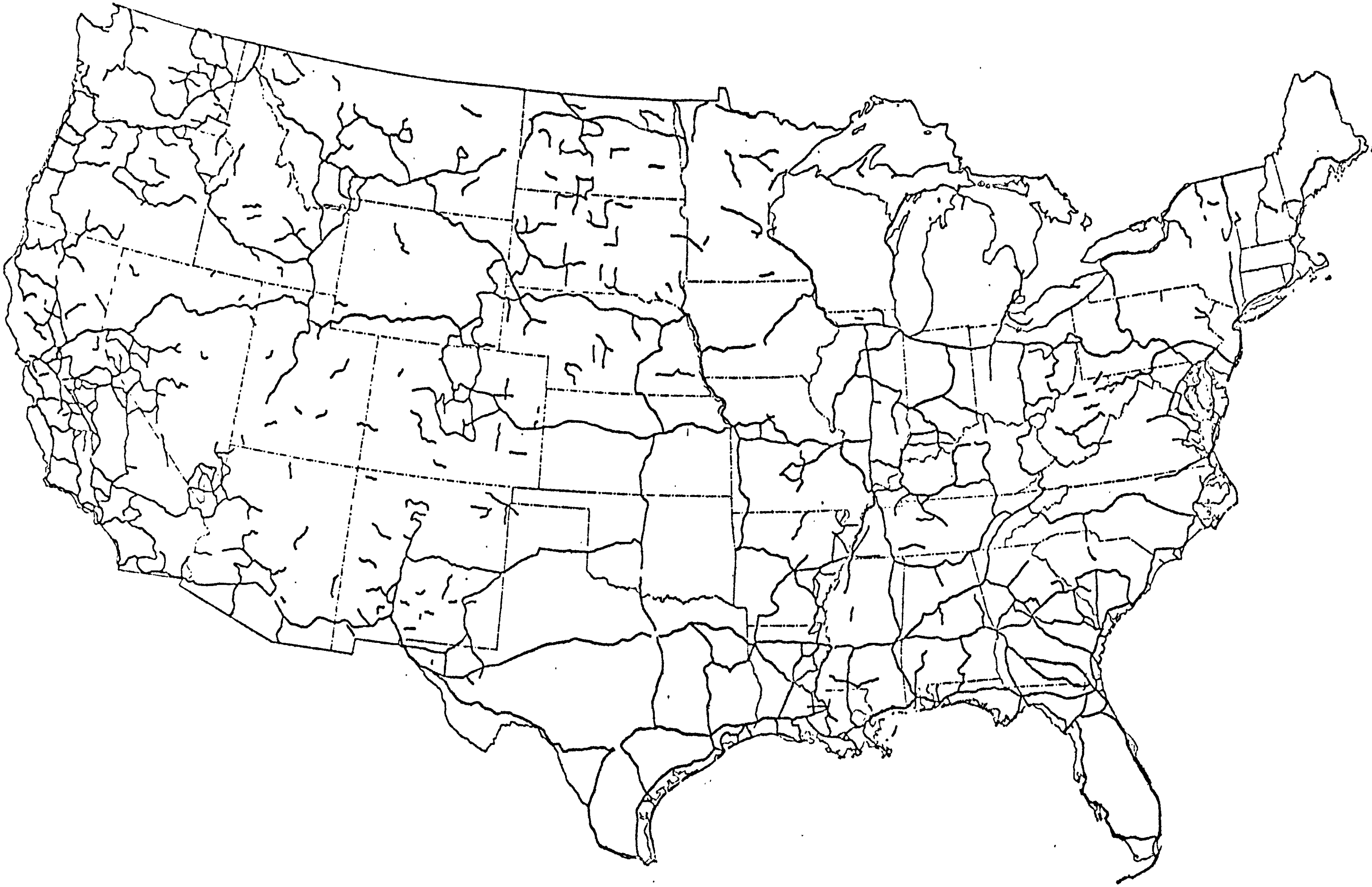
TABLE III

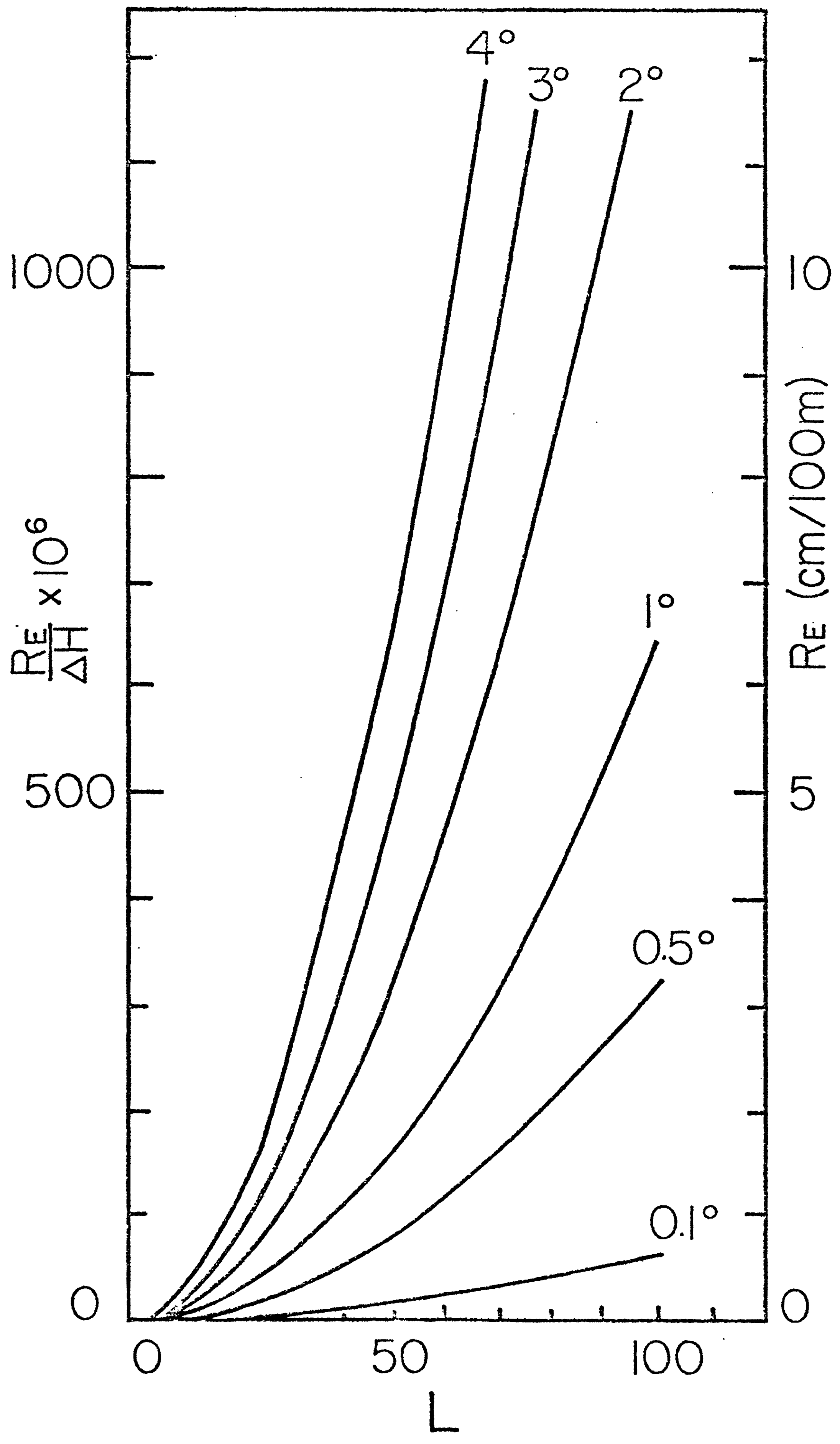
Earthquakes for Which Vertical Movements Derived from Leveling have been Reported.

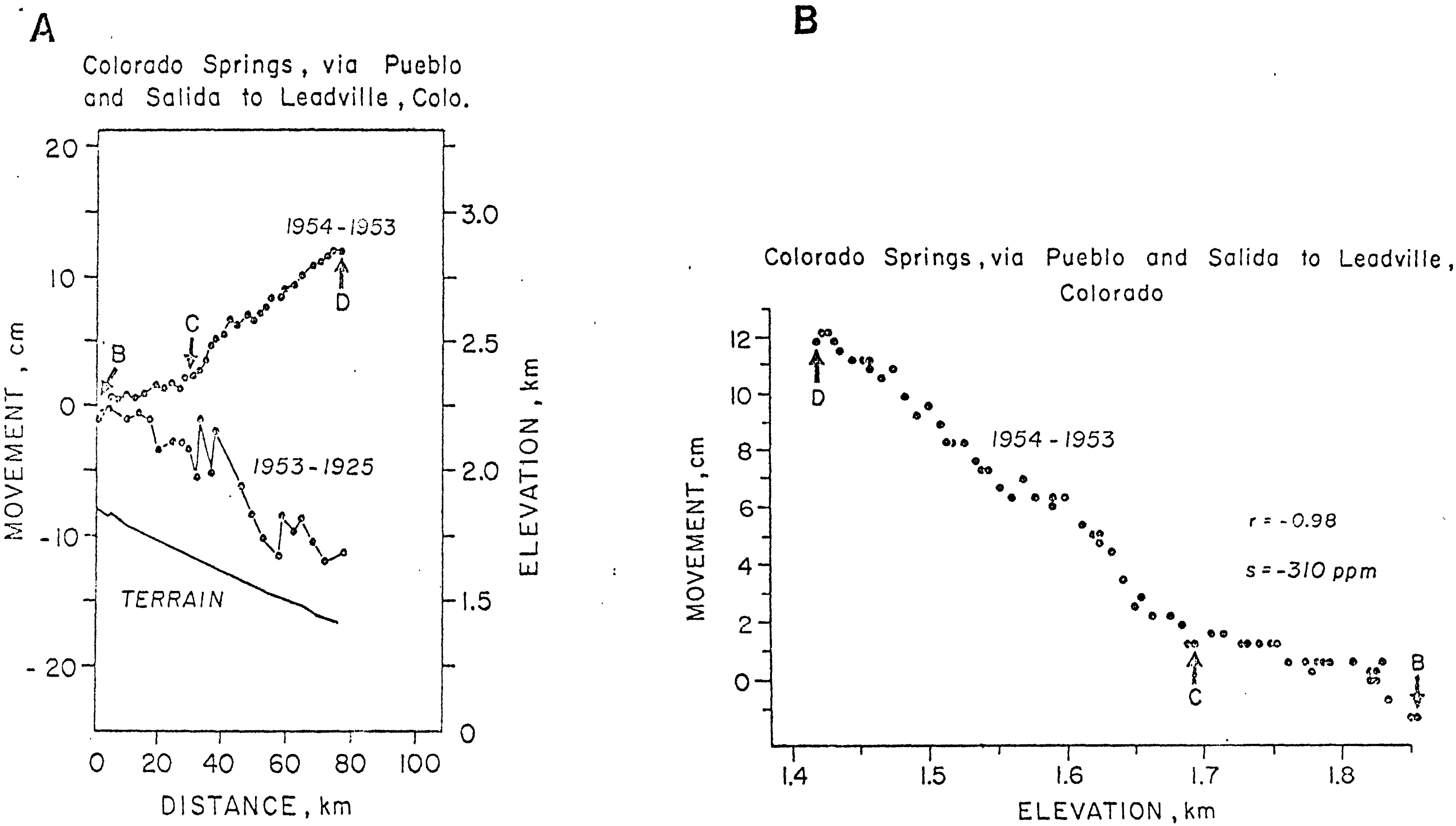
Maximum Observed Deformation and Typical Dimension of Effected Area are also Civen. Numbers refer to Figure 9.

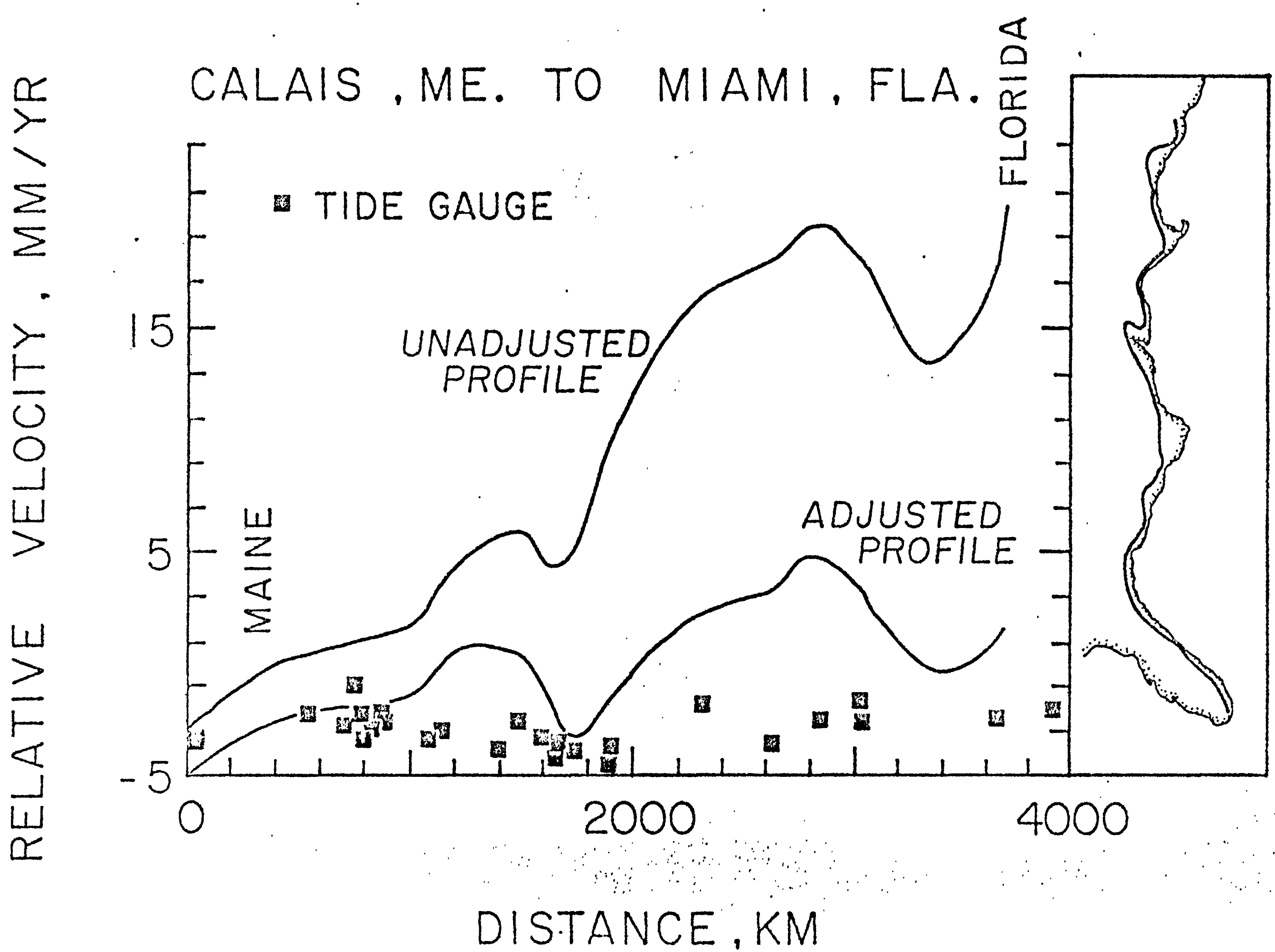
Earthquake	Movement (cm)	Dimensions (km)	Comments	Reference
1931 Valentine, Texas M∼6.1 coseismic	10	30	Observed movements could include possible preseismic and/or postseismic deformation	Ni et al., 1980
1933 Long Beach, California; M∼6.3 coseismic	20	15	Complicated by effects of fluid withdrawal	Parkin, 1948
1940 Imperial Valley, California; M∼ coseismic	20	25	Complicated by possible near-surface compaction	Miller et al., 1970
1952 Kern County, California; M∼7.7 coseismic	60	30		Lofgren, 1966
1954 Western Nevada series of earthquakes; M∼6.6 to M 7.1				
coseismic	100	35		Whitten, 1957
postseismic	7	8		Savage and Church, 1974
1959 Hebgen Lake, Montana; M∼7.1			Movements interpreted as preseismic could include coseismic and postseismic effects	
preseismic	20	100		Reilinger et al., 1977
coseismic	700	35		Myers and Hamilton, 1964

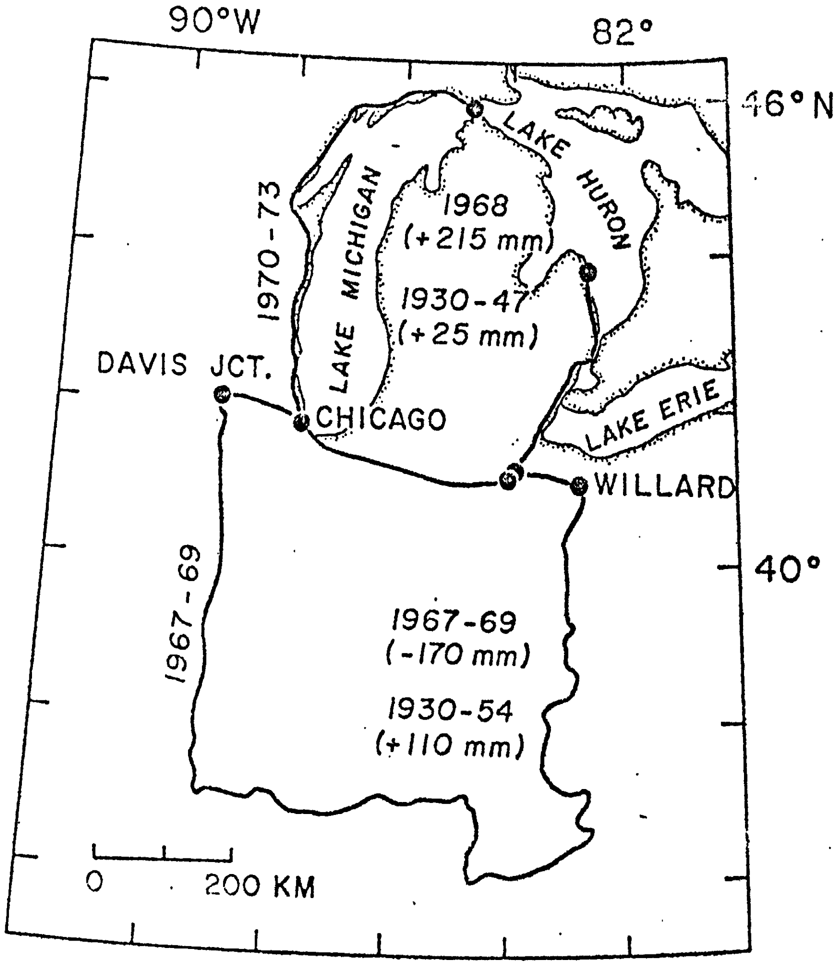
Earthquake	Movement (cm)	Dimensions (km)	Comments	Reference
1964 Alaska; M∿8.4				
coseismic	600	400		Plafker, 1969
postseismic	55	100		Brown et al., 1977
1971 San Fernando, California; M∿6.4			Preseismic movements questionable - see text	
preseismic	20	30		Castle et al., 1974
coseismic	230	30		Burford et al., 1971
postseismic	6	10		Savage and Church, 1975
1973 Point Mugu, California; M∿6.0			Complicated by subsidence due to groundwater effects	
preseismic	4	50		Castle et al., 1977
coseismic	3	50		
1975 Oroville, California; M∿5.7				
coseismic	18	20		Savage et al., 1977
postseismic	3	20		
1975 Yellowstone, Wyoming; M∿6.0 coseismic	6	8	Complicated by possible postseismic movements of 1959 Hebgen Lake earthquake	Pitt et al., 1979

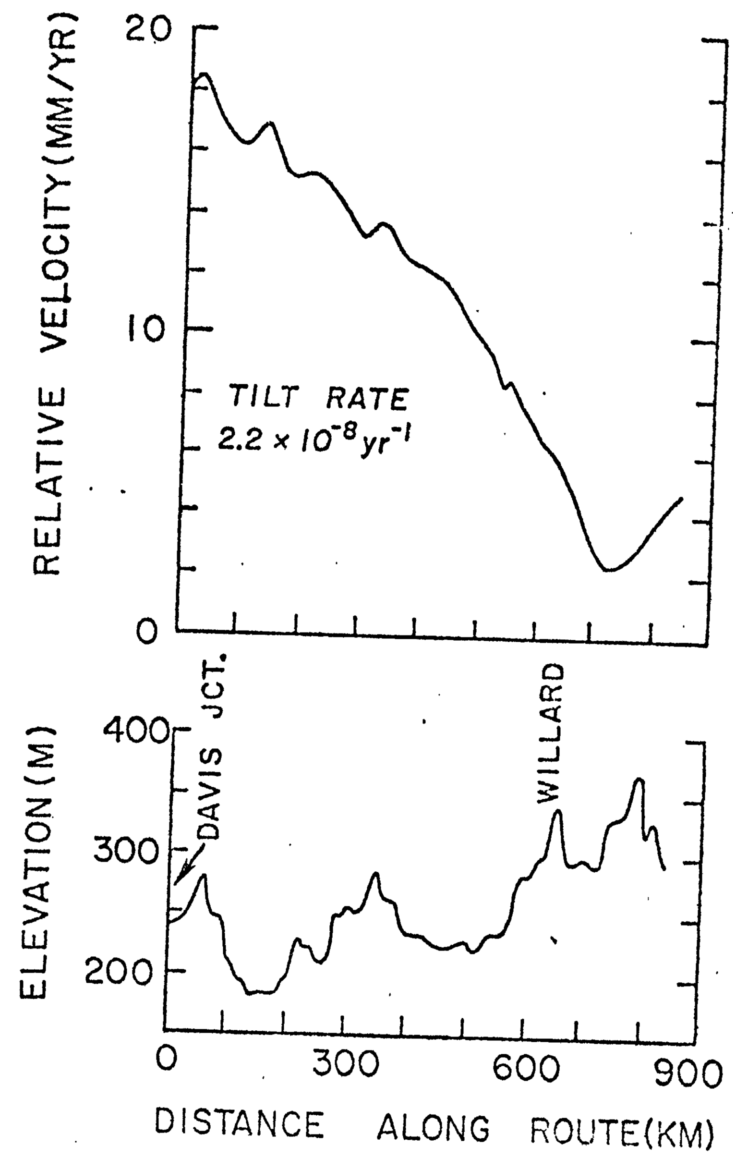


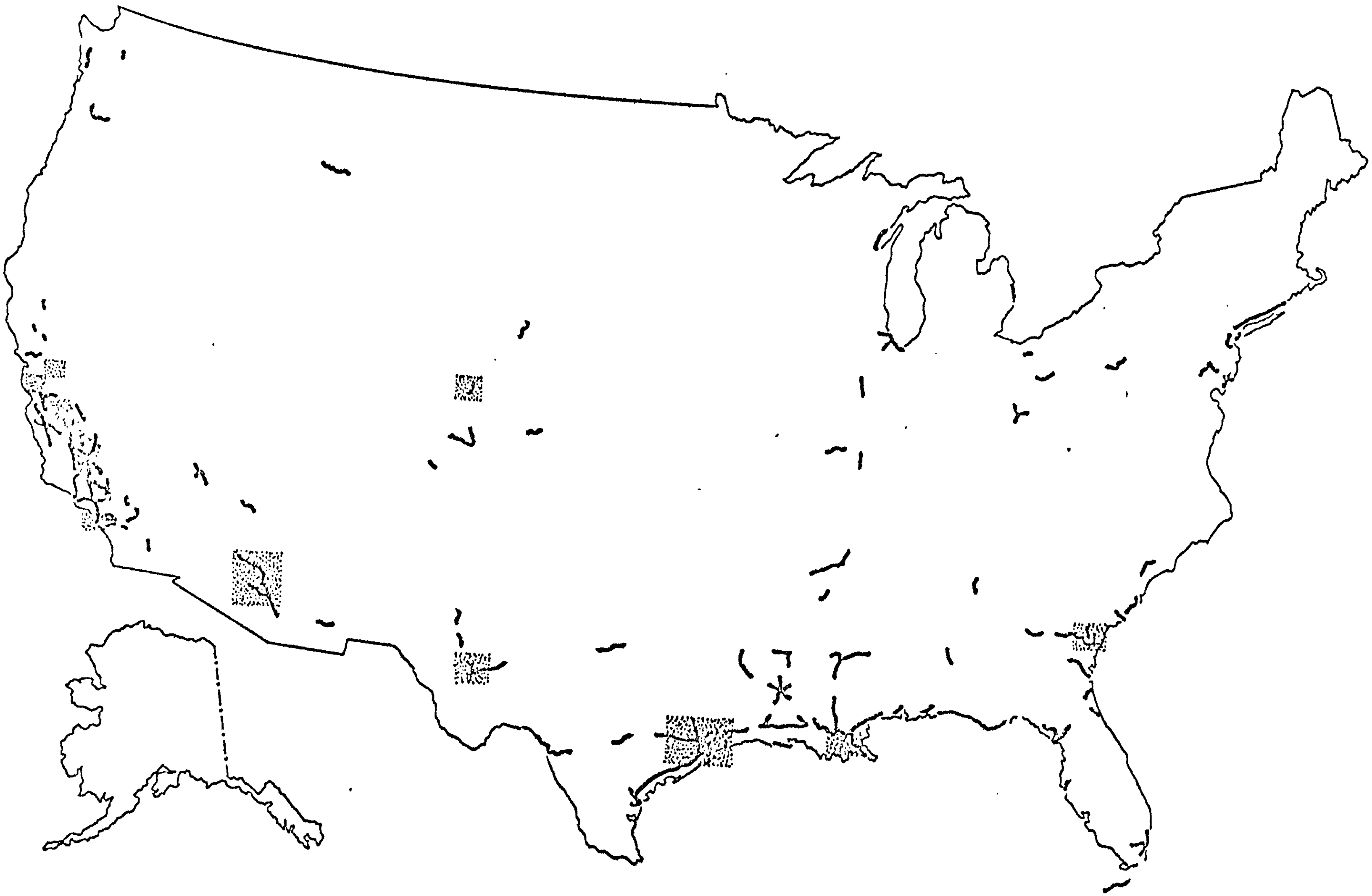

4°
3°
2°
1°
0.5°
0.1°
1000
500
0
10
5
0
0
50
100
L
$\frac{R_E}{\Delta H} \times 10^6$
R_E (cm/100m)

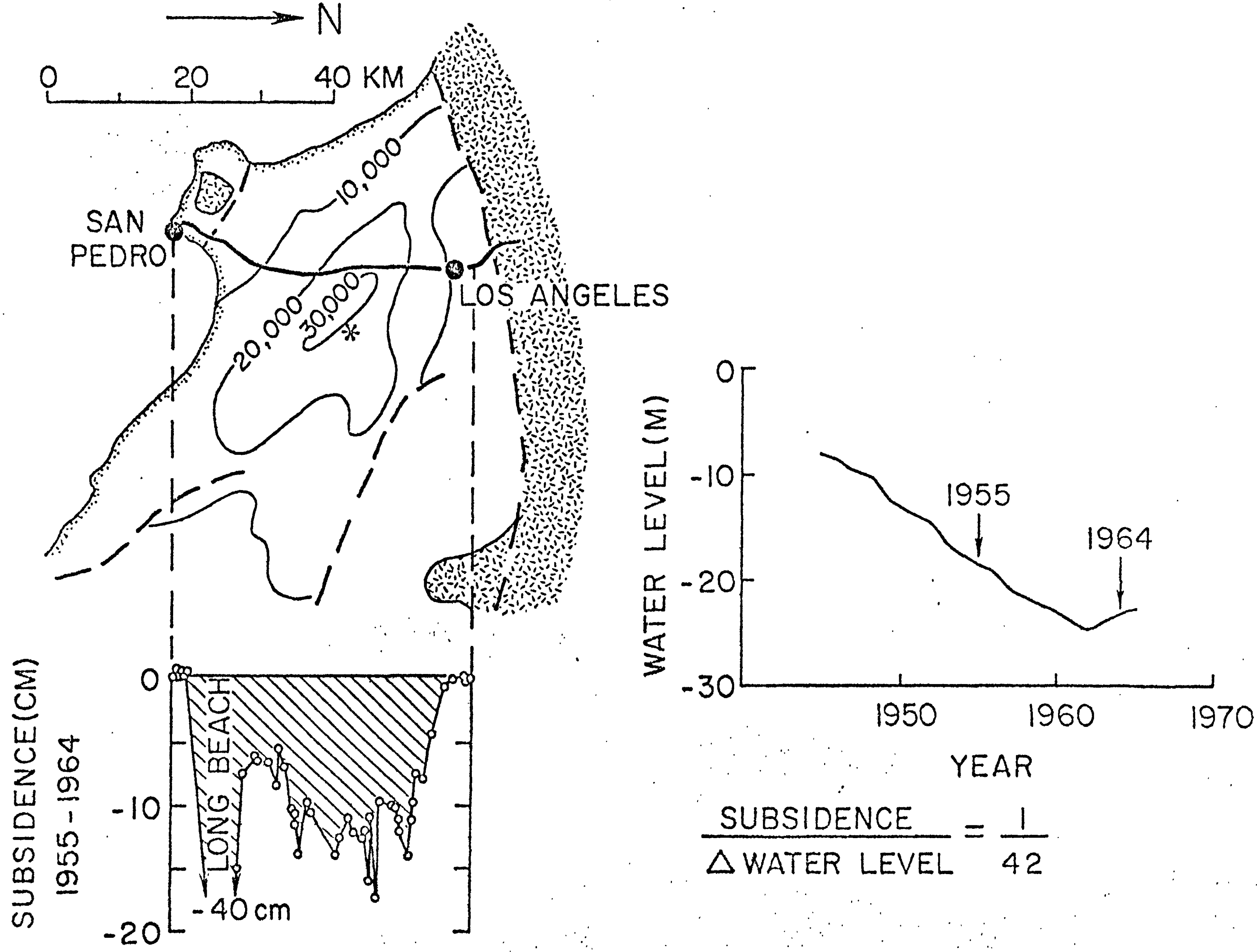

A
Colorado Springs, via Pueblo and Salida to Leadville, Colo.
MOVEMENT, cm
ELEVATION, km
DISTANCE, km
1954-1953
1953-1925
TERRAIN
B
C
D
20
10
0
-10
-20
3.0
2.5
2.0
1.5
0
20
40
60
80
100
B
Colorado Springs, via Pueblo and Salida to Leadville, Colorado
MOVEMENT, cm
ELEVATION, km
1954-1953
r = -0.98
s = -310 ppm
D
C
B
12
10
8
6
4
2
0
1.4
1.5
1.6
1.7
1.8

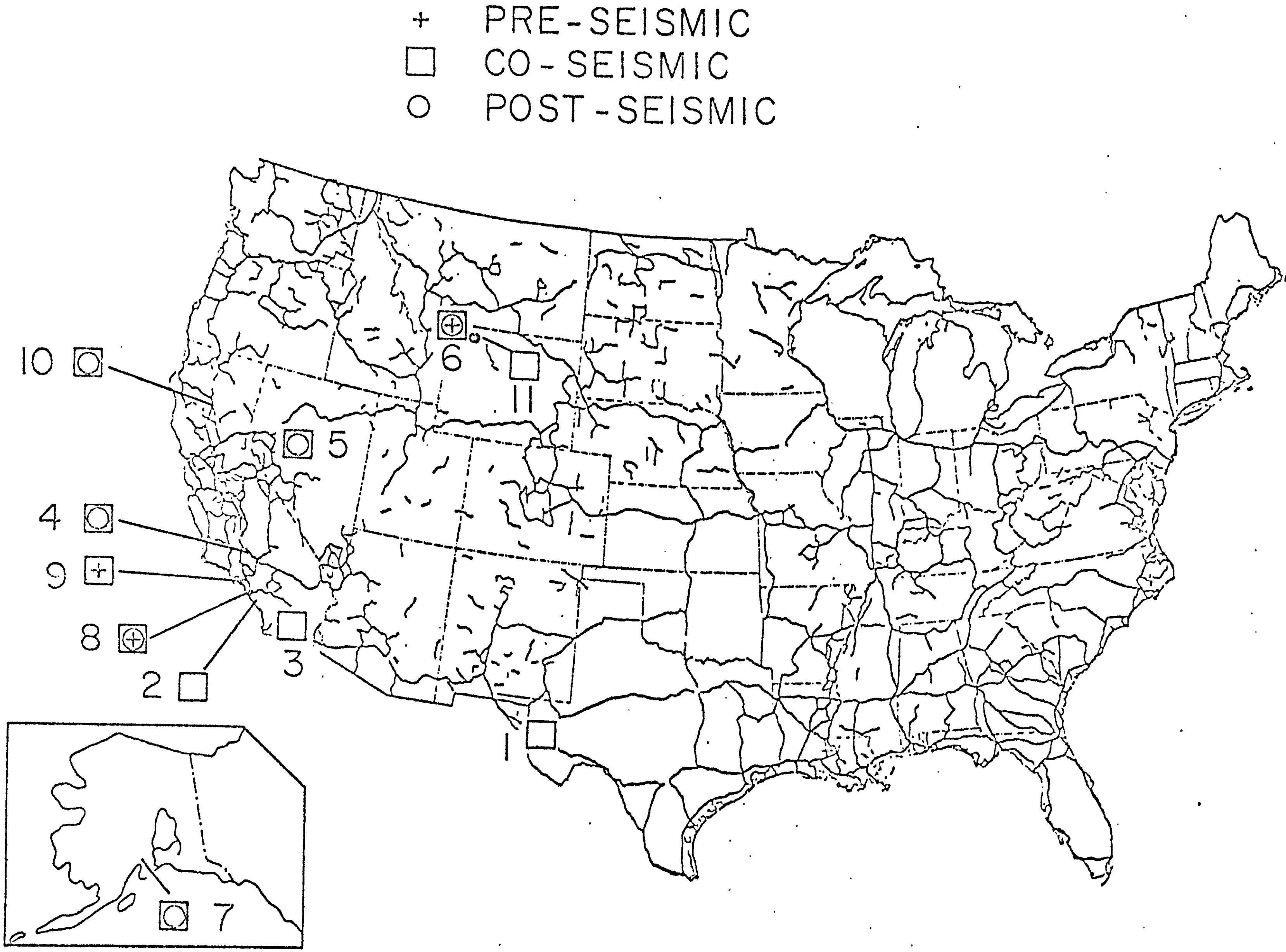

CALAIS, ME. TO MIAMI, FLA.
TIDE GAUGE
FLORIDA
UNADJUSTED PROFILE
ADJUSTED PROFILE
MAINE
15
5
-5
0
2000
4000
RELATIVE VELOCITY, MM/YR
DISTANCE, KM

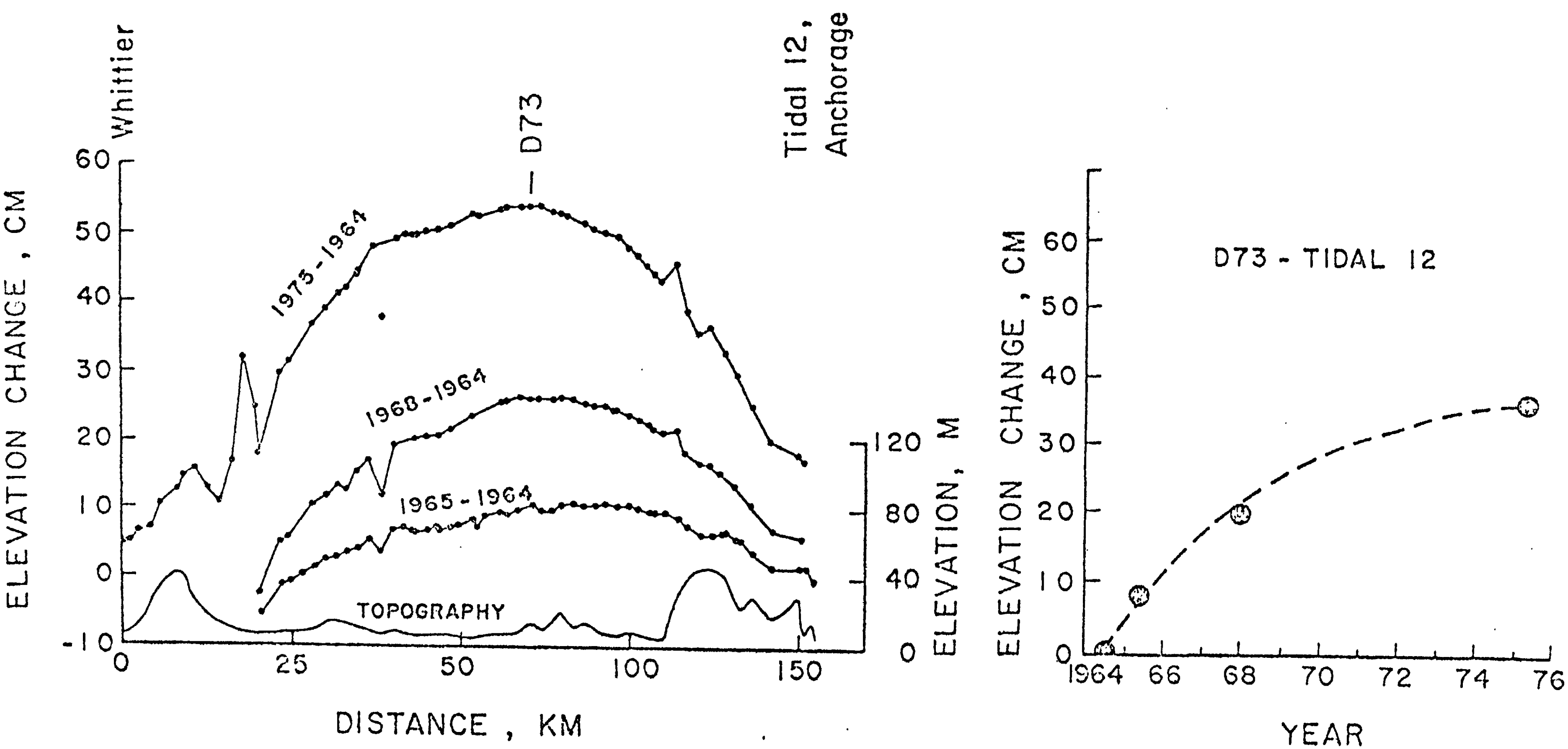

90°W
82°
46°N
40°
LAKE HURON
LAKE MICHIGAN
LAKE ERIE
1970-73
1968
(+215 mm)
1930-47
(+25 mm)
DAVIS JCT.
CHICAGO
WILLARD
1967-69
1967-69
(-170 mm)
1930-54
(+110 mm)
0
200 KM

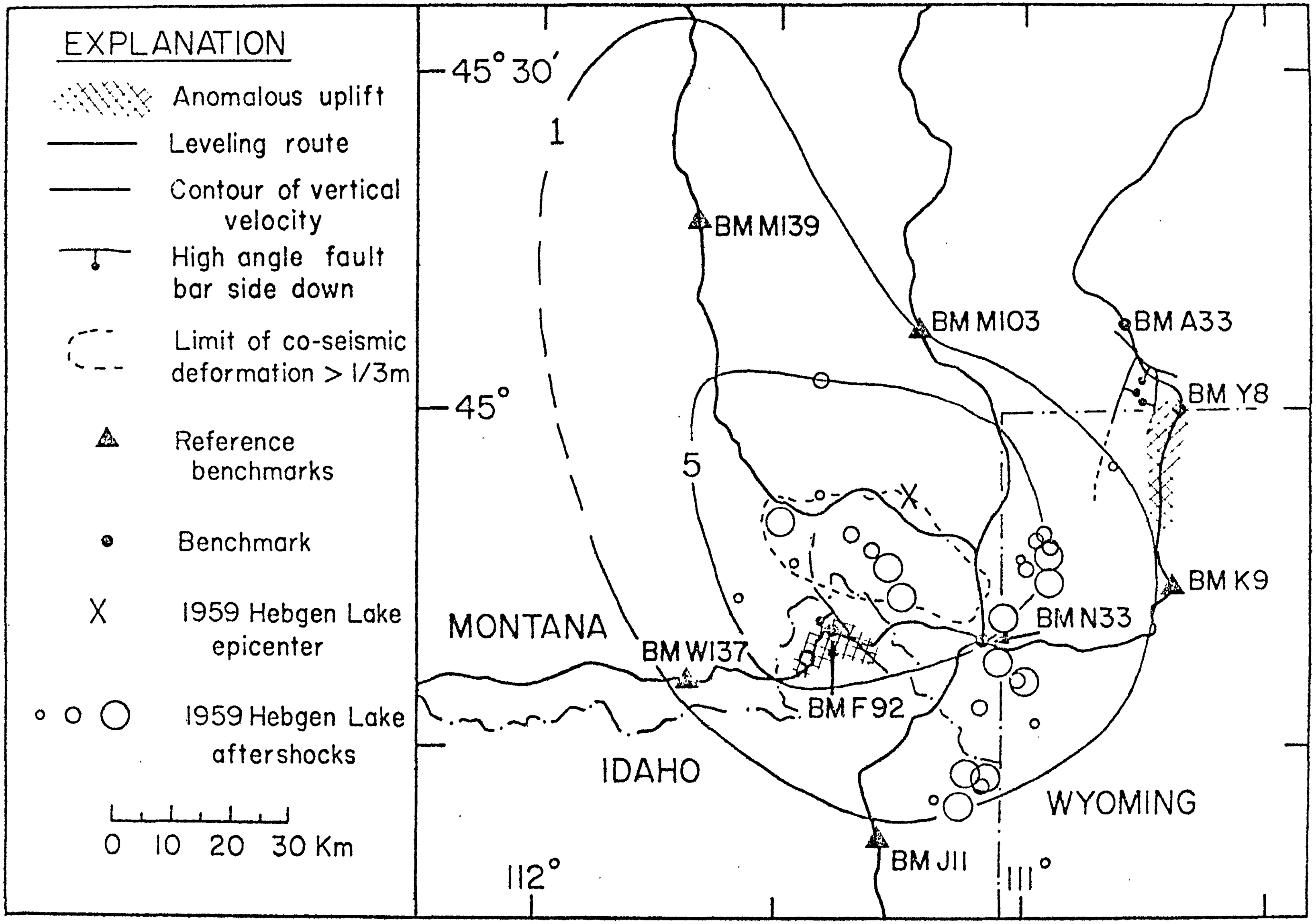

RELATIVE VELOCITY (MM/YR)
20
10
0
TILT RATE
2.2 × 10^-8 yr^-1
ELEVATION (M)
400
300
200
DAVIS JCT.
WILLARD
0
300
600
900
DISTANCE ALONG ROUTE (KM)

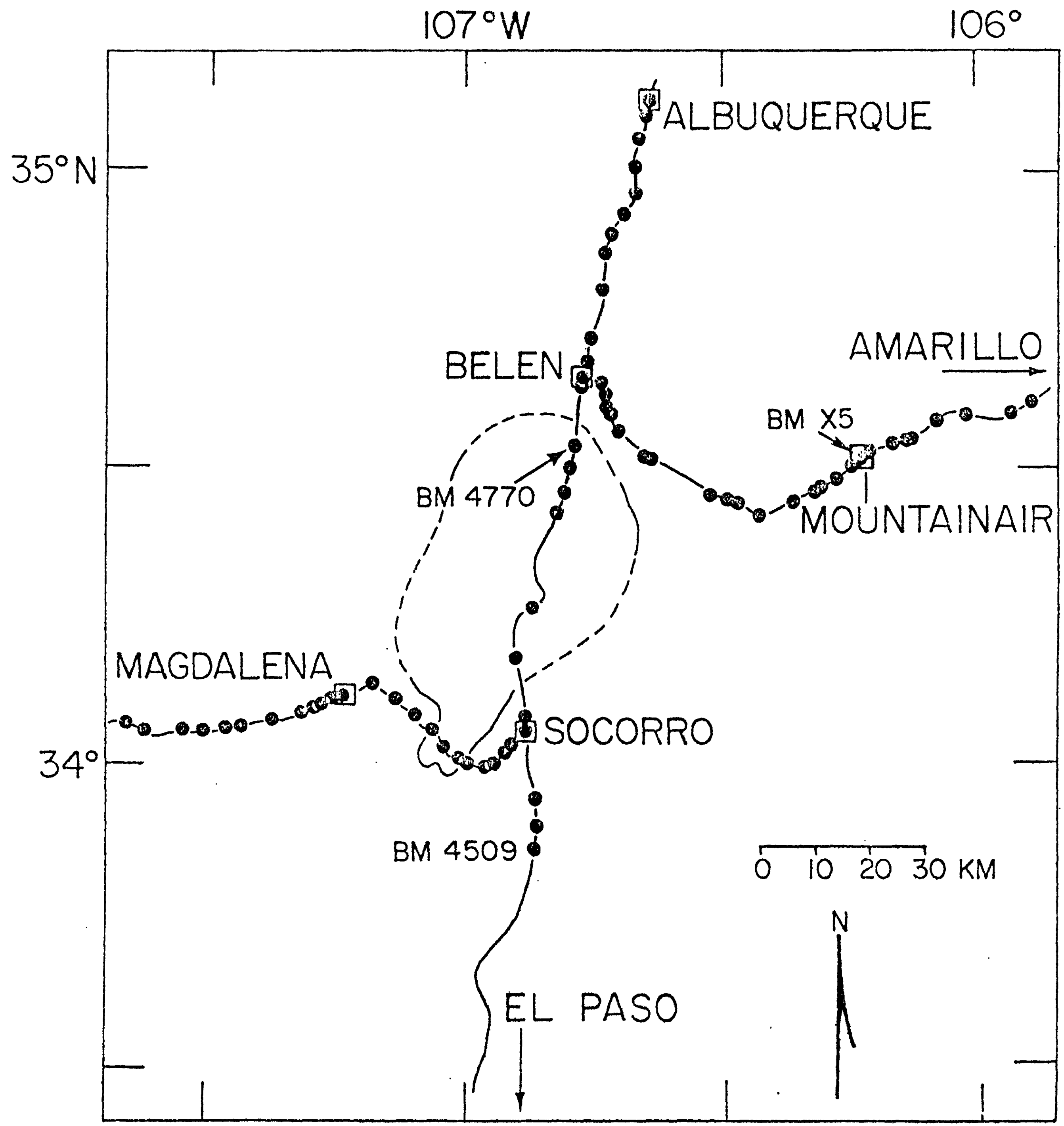


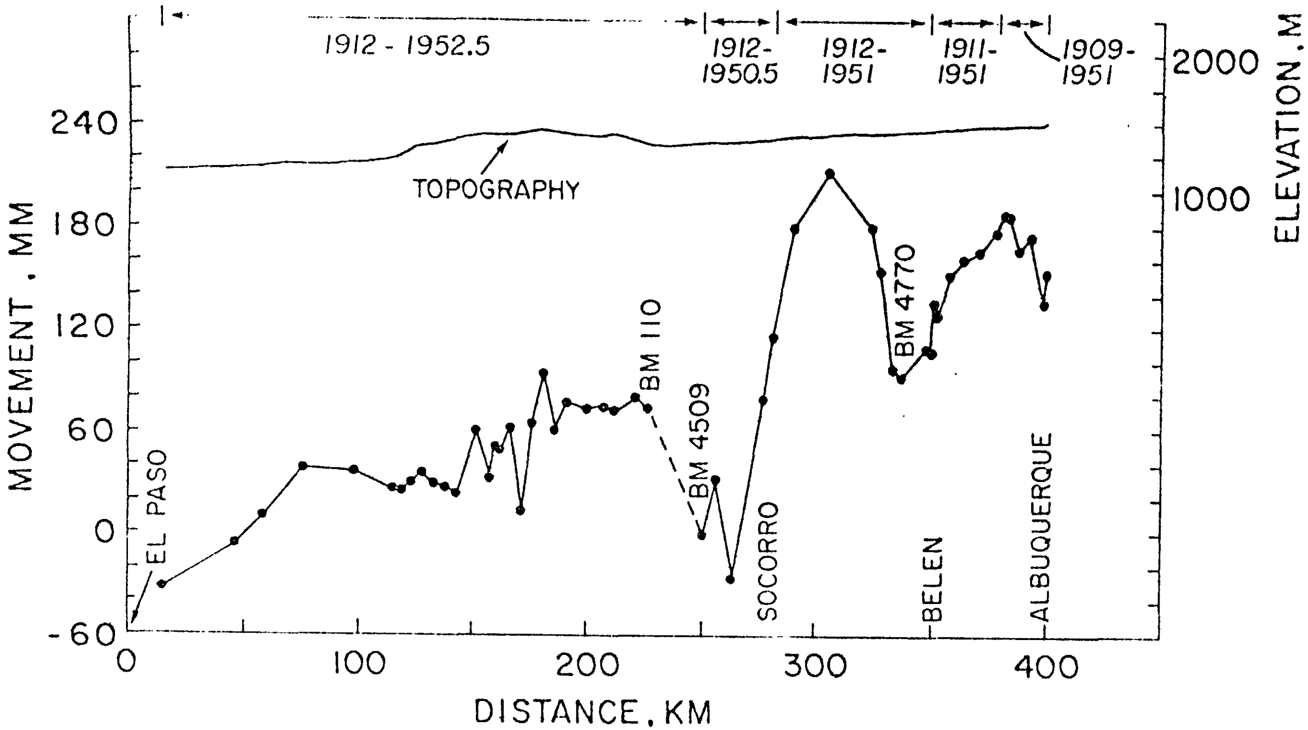

N
0
20
40 KM
10,000
20,000
30,000
*
SAN PEDRO
LOS ANGELES
LONG BEACH
-40 cm
SUBSIDENCE(CM) 1955-1964
0
-10
-20
WATER LEVEL(M)
0
-10
-20
-30
1955
1964
1950
1960
1970
YEAR
SUBSIDENCE / Δ WATER LEVEL = 1 / 42

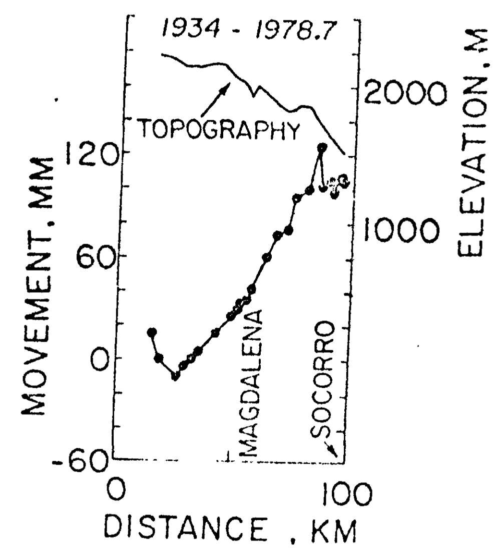

+ PRE-SEISMIC
□ CO-SEISMIC
○ POST-SEISMIC
1
2
3
4
5
6
7
8
9
10
11

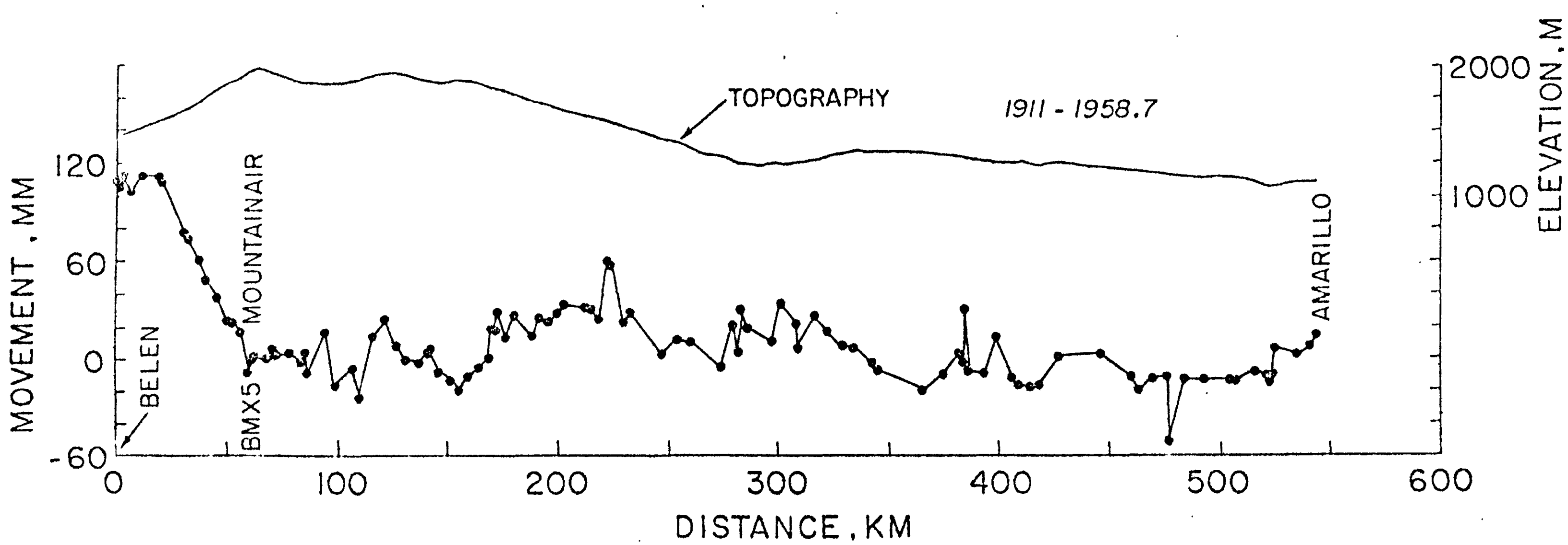

Whittier
D73
Tidal 12,
Anchorage
ELEVATION CHANGE , CM
60
50
40
30
20
10
0
-10
1973-1964
1968-1964
1965-1964
TOPOGRAPHY
0
25
50
100
150
DISTANCE , KM
120
80
40
0
ELEVATION, M
D73 - TIDAL 12
ELEVATION CHANGE , CM
1964
66
68
70
72
74
76
YEAR

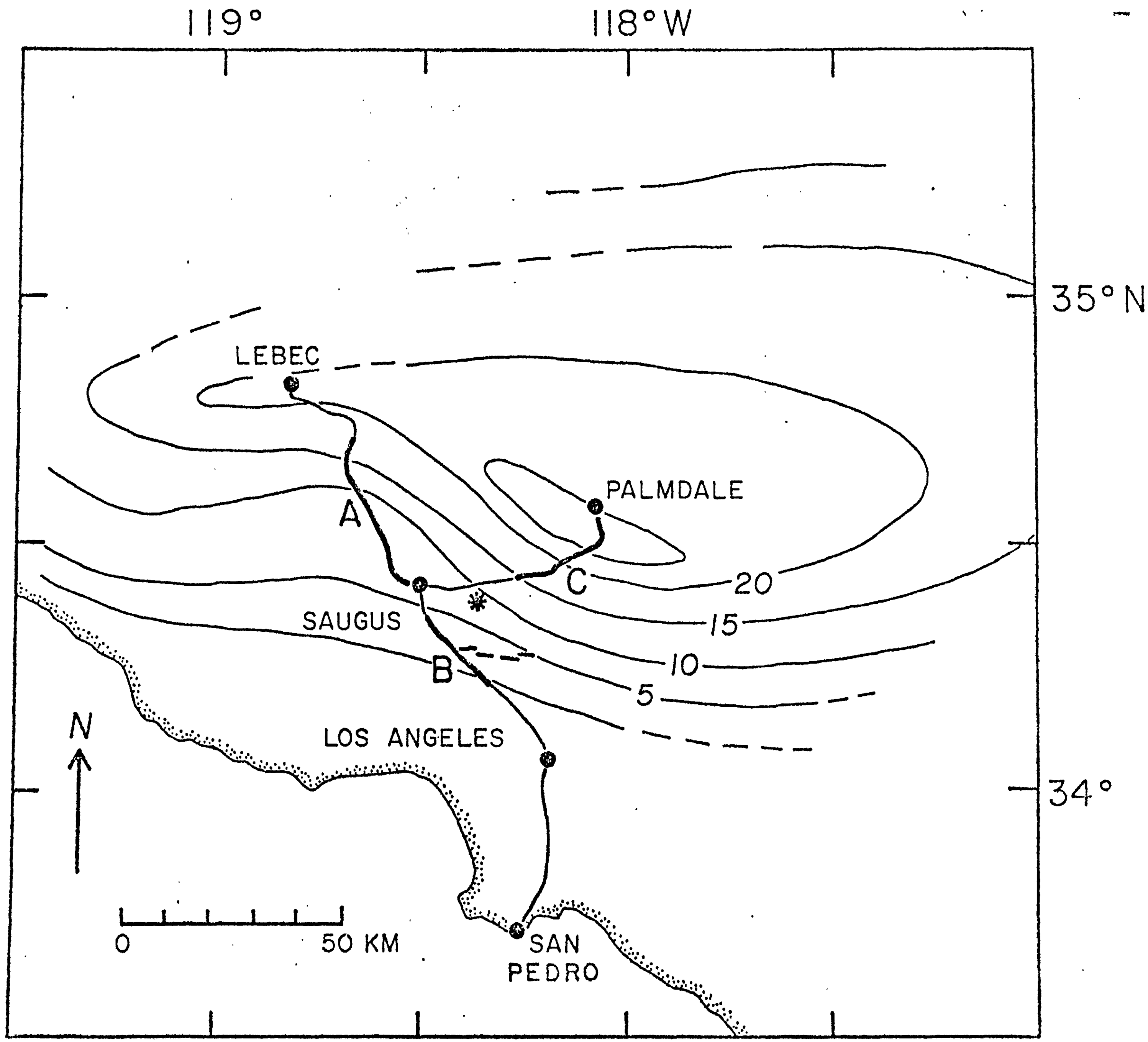

EXPLANATION
Anomalous uplift
Leveling route
Contour of vertical velocity
High angle fault bar side down
Limit of co-seismic deformation > 1/3m
Reference benchmarks
Benchmark
1959 Hebgen Lake epicenter
1959 Hebgen Lake aftershocks
0 10 20 30 Km
45° 30′
45°
112°
111°
1
5
BM M139
BM M103
BM A33
BM Y8
BM K9
BM N33
BM W137
BM F92
BM J11
MONTANA
IDAHO
WYOMING

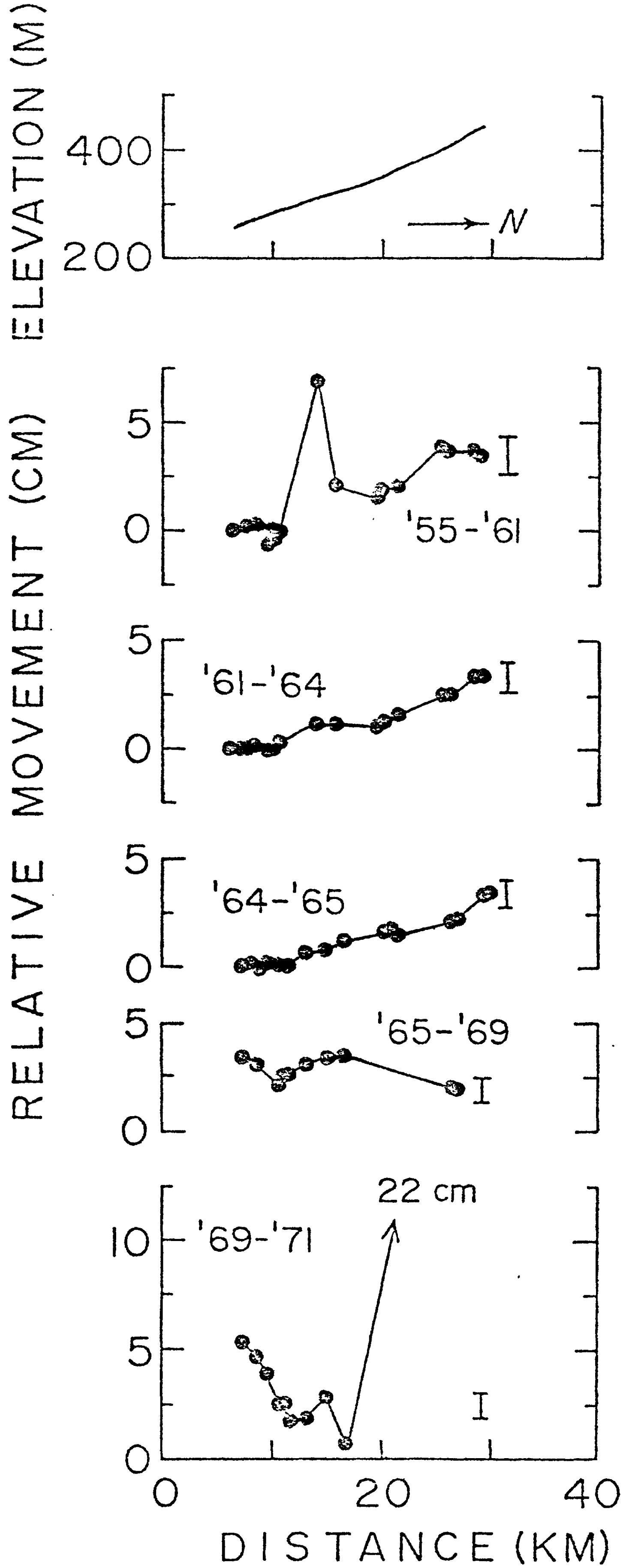

107°W
106°
35°N
34°
ALBUQUERQUE
BELEN
AMARILLO
BM X5
MOUNTAINAIR
BM 4770
MAGDALENA
SOCORRO
BM 4509
0 10 20 30 KM
N
EL PASO

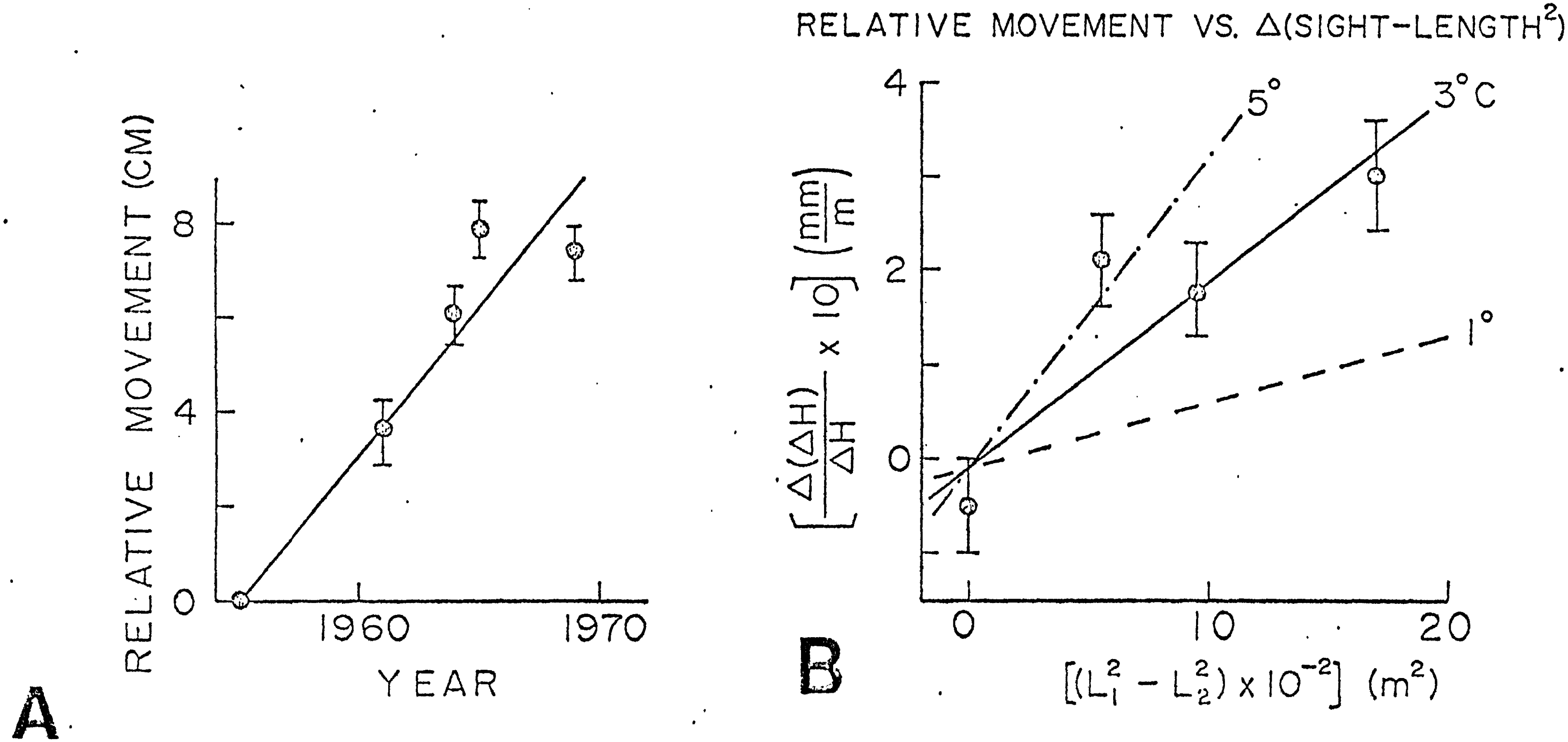

1912 - 1952.5
1912-
1950.5
1912-
1951
1911-
1951
1909-
1951
TOPOGRAPHY
EL PASO
BM 110
BM 4509
SOCORRO
BM 4770
BELEN
ALBUQUERQUE
MOVEMENT, MM
ELEVATION, M
DISTANCE, KM

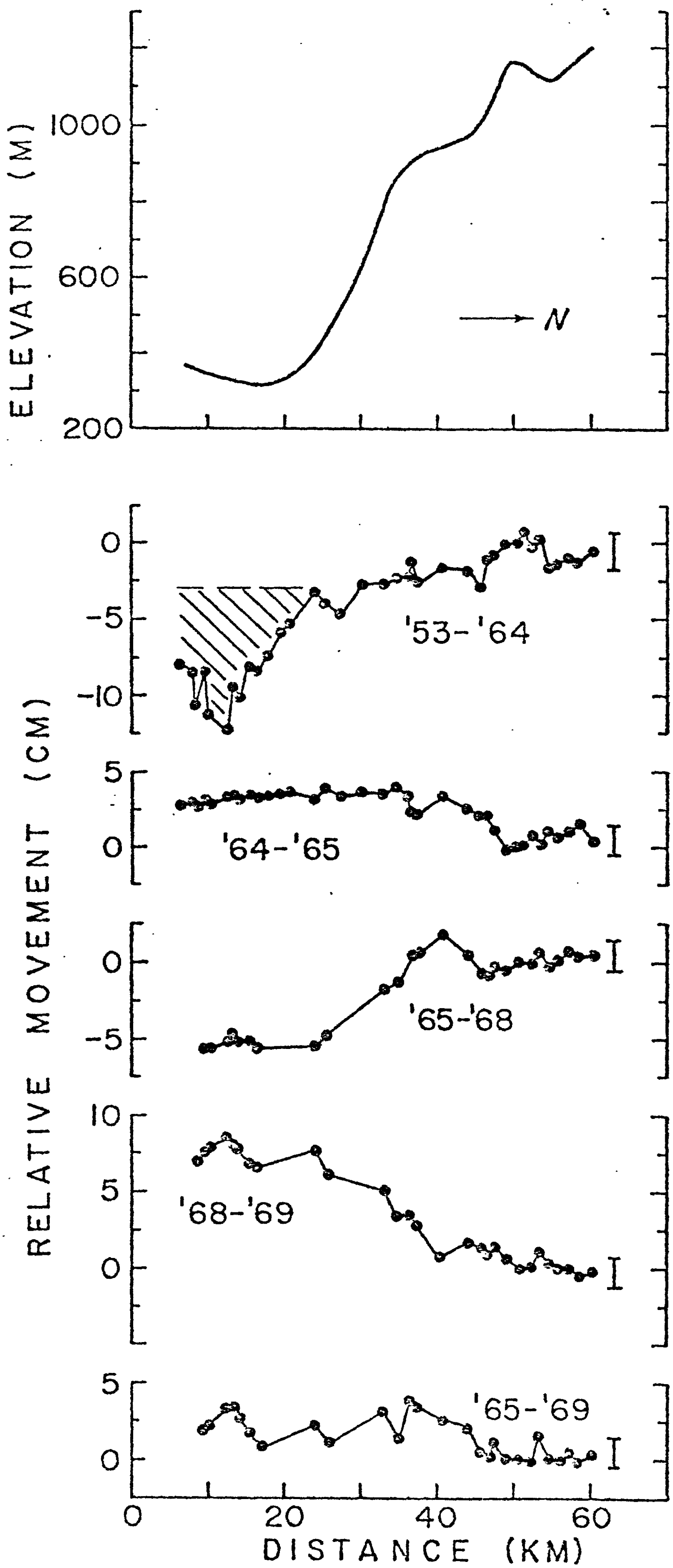

1934 - 1978.7
TOPOGRAPHY
MAGDALENA
SOCORRO
MOVEMENT, MM
ELEVATION, M
DISTANCE, KM

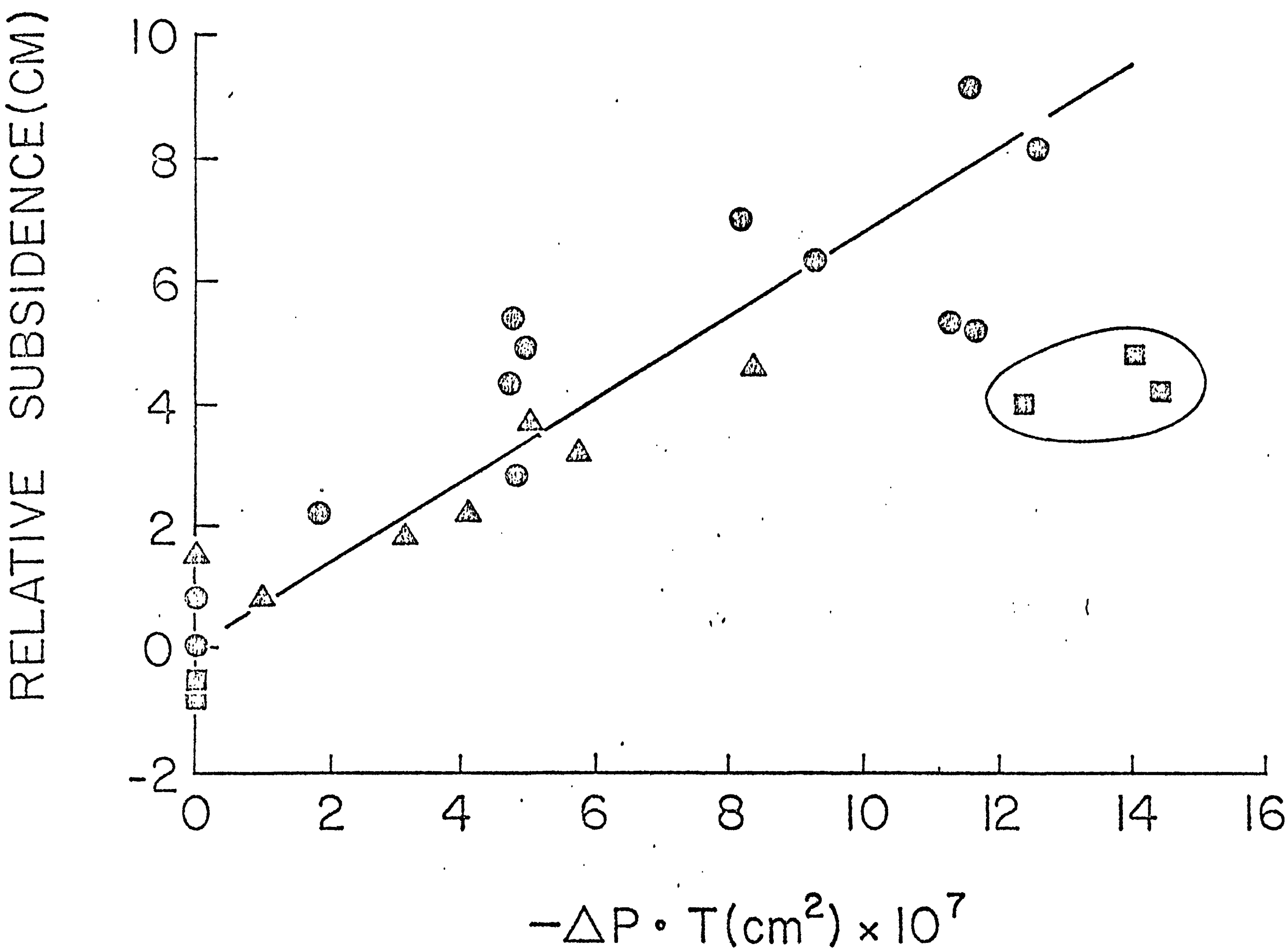

TOPOGRAPHY
1911 - 1958.7
BELEN
BMX5
MOUNTAINAIR
AMARILLO
MOVEMENT, MM
ELEVATION, M
DISTANCE, KM

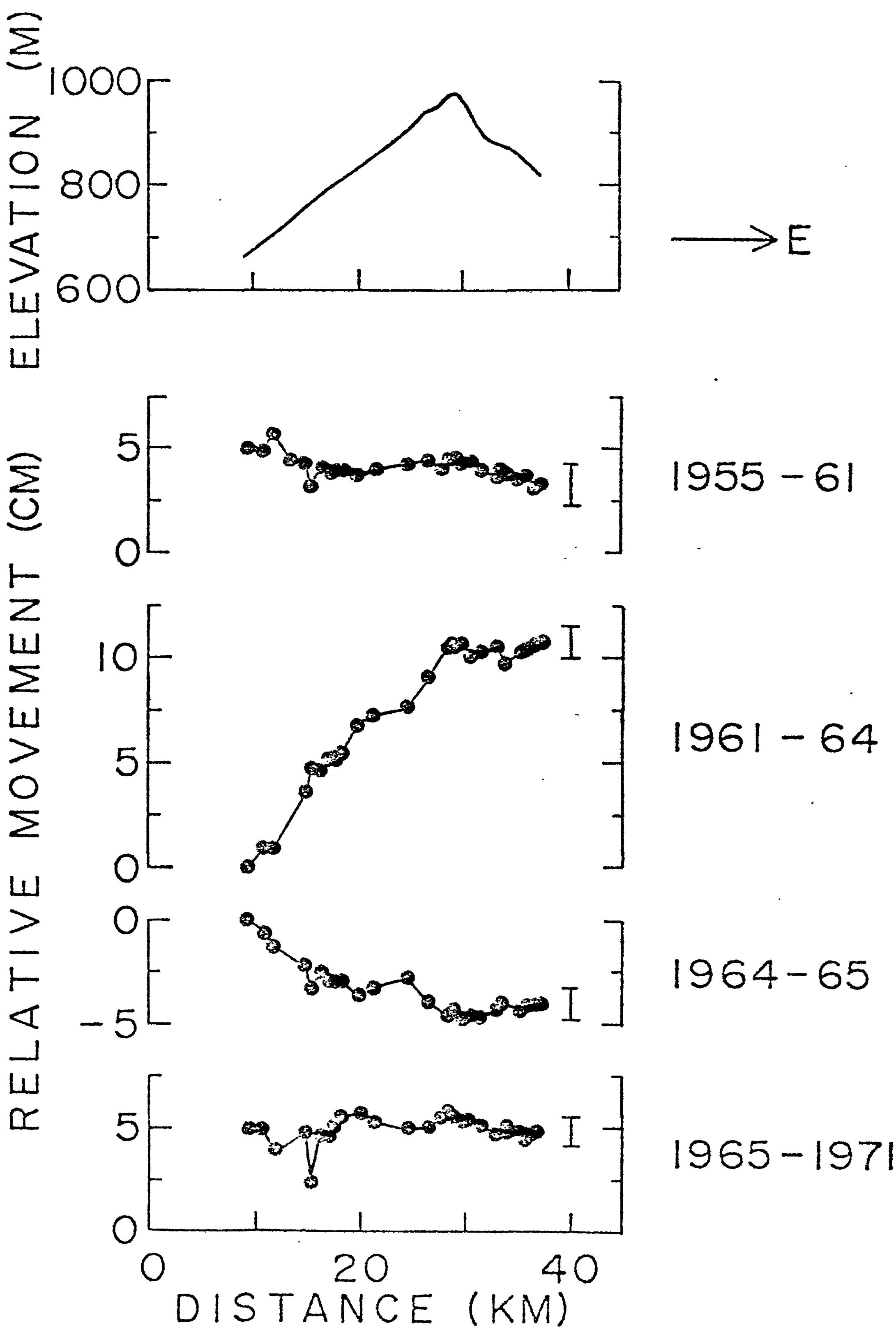

119°
118°W
35°N
34°
LEBEC
PALMDALE
SAUGUS
LOS ANGELES
SAN PEDRO
A
B
C
20
15
10
5
N
0
50 KM


ELEVATION (M)
400
200
N
RELATIVE MOVEMENT (CM)
5
0
'55-'61
'61-'64
'64-'65
'65-'69
'69-'71
22 cm
10
0
20
40
DISTANCE (KM)


RELATIVE MOVEMENT (CM)
0
4
8
1960
1970
YEAR
A
RELATIVE MOVEMENT VS. Δ(SIGHT-LENGTH²)
[Δ(ΔH)/ΔH x 10] (mm/m)
0
2
4
5°
3°C
1°
0
10
20
[(L₁² − L₂²) x 10⁻²] (m²)
B


ELEVATION (M)
200
600
1000
N
RELATIVE MOVEMENT (CM)
0
-5
-10
'53-'64
5
0
'64-'65
0
-5
'65-'68
10
5
0
'68-'69
5
0
'65-'69
0
20
40
60
DISTANCE (KM)


RELATIVE SUBSIDENCE(CM)
10
8
6
4
2
0
-2
0
2
4
6
8
10
12
14
16
−ΔP • T(cm²) × 10⁷


ELEVATION (M)
1000
800
600
E
RELATIVE MOVEMENT (CM)
5
0
1955 - 61
10
5
0
1961 - 64
0
-5
1964-65
5
0
1965-1971
0
20
40
DISTANCE (KM)

APPENDIX II

GEOPHYSICAL RESEARCH LETTERS, VOL. 7, NO. 11, PAGES 1017-1019, NOVEMBER 1980

ELEVATION CHANGES NEAR THE SAN GABRIEL FAULT, SOUTHERN CALIFORNIA

Robert Reilinger

Department of Geological Sciences, Cornell University

Ithaca, N.Y. 14853

Abstract. Analysis of repeated leveling observations in the vicinity of the San Gabriel fault in Southern California indicate subsidence immediately south of the fault relative to points to the north, south, and east. These observations were previously interpreted as reflecting tectonic motions associated with either the "Palmdale Bulge" or with preseismic effects of the San Fernando earthquake. Relative subsidence between 1953 and 1964 reaches approximately 9 cm and extends over a distance of more than 20 km. Subsidence occurs directly above the Saugus aquifer and shows a temporal correlation with the history of water level decline within the aquifer. The degree of subsidence of individual benchmarks is roughly proportional to the product of aquifer thickness and water level decline at the location of the benchmarks. These observations strongly suggest that movements of the surface near the San Gabriel Fault, previously inferred to be of tectonic origin, actually result from near surface sediment compaction within the Saugus basin.

Introduction

Releveling estimates of crustal movement may reflect tectonic deformation, nontectonic motion, or systematic measurement errors. Proper interpretation of releveling measurements entails descriminating between these effects. The releveling measurements in Southern California which are presented here were initially interpreted as representing tectonic movements associated with the "Palmdale Bulge" (Castle et al., 1976). More recently, Strange (1980) has sug-

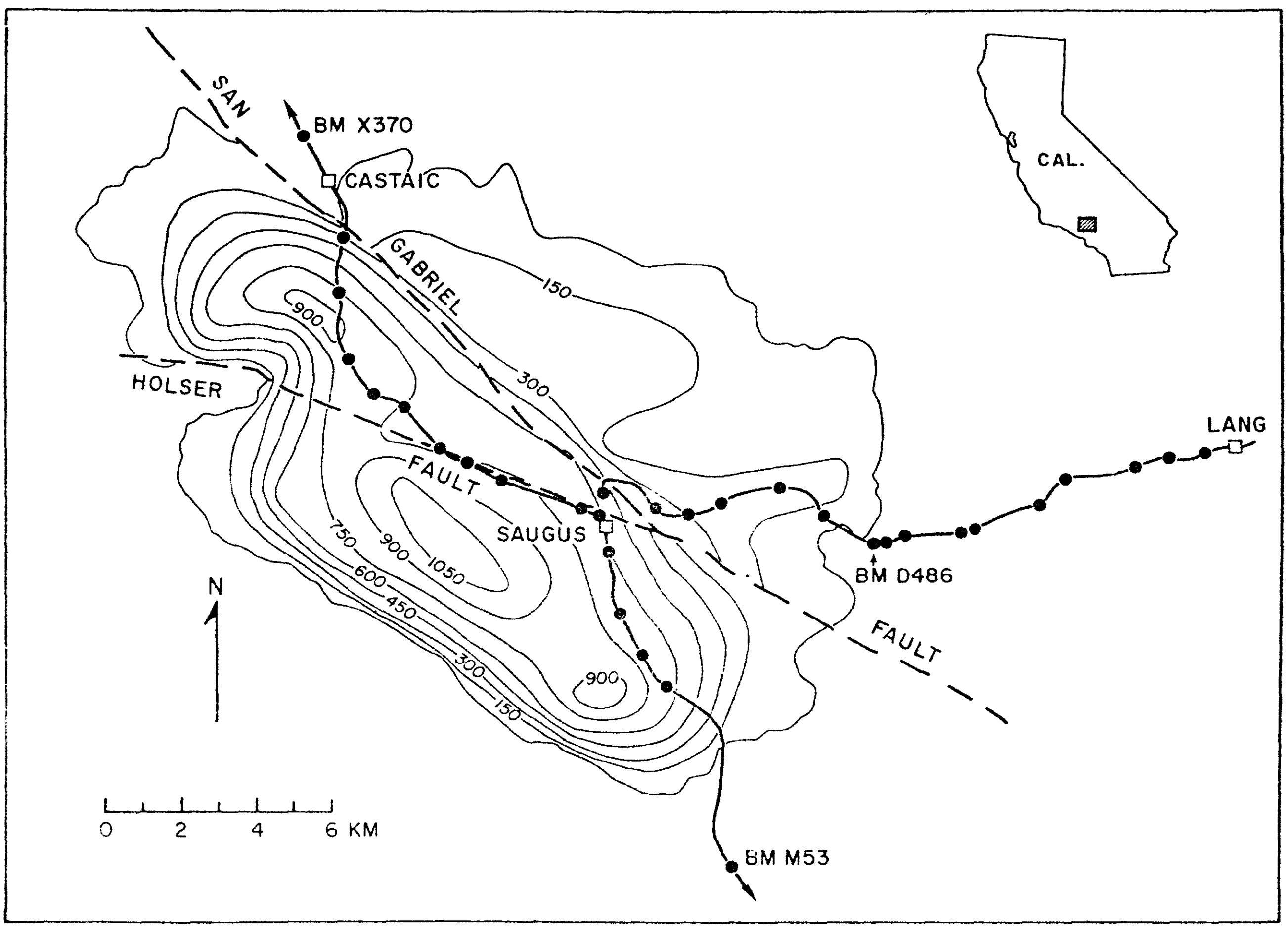


Fig. 1. Contours (meters) showing thickness of the Saugus aquifer (Robson, 1972). Leveling routes and benchmarks (dots) crossing the basin are also shown. Dashed lines are faults.

Paper number 80L1439.
0094-8276/80/0080L-1439$01.00

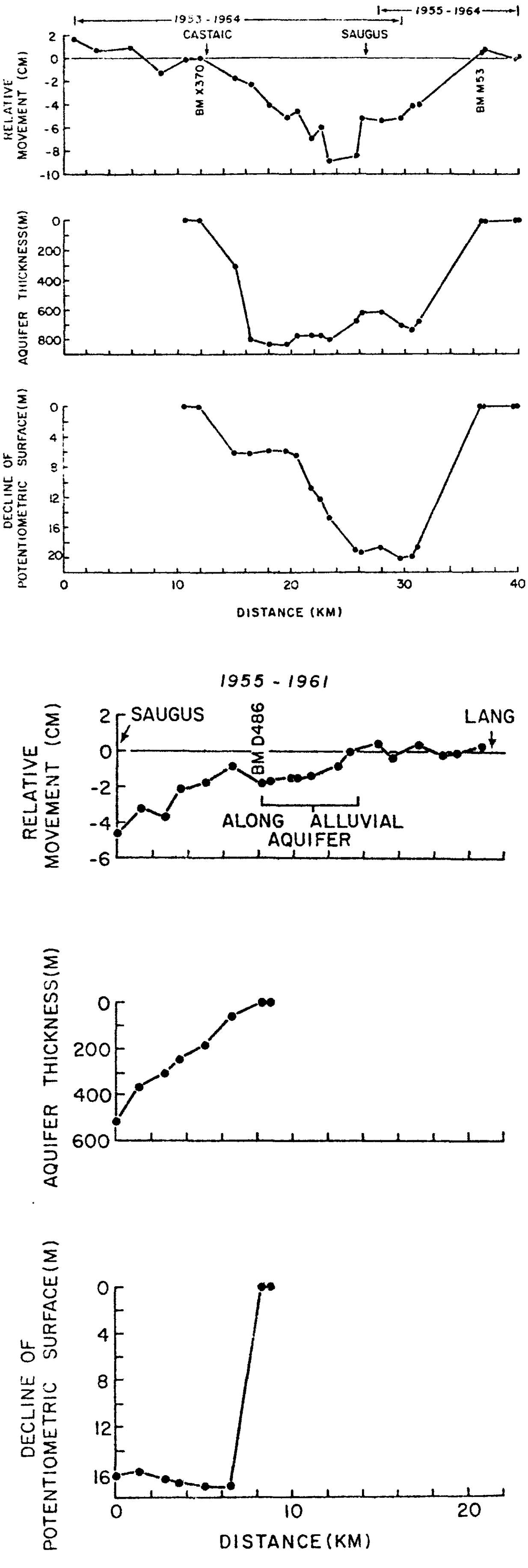


Fig. 2. A) Top: Movement of benchmarks along approximately North-South route plotted versus distance along route. BMX370 on northern periphery of aquifer assumed stable. Years of leveling surveys shown at top. Middle: Profile of thickness of Saugus aquifer along leveling route (from Robson, 1972). Bottom: Profile of decline in potentiometric surface (water level) as of 1963 relative to 1945 surface (from Robson, 1972). B) Profiles along route from north of Saugus to Lang (see Fig. 1). Same format as A.

gested that these measurements reflect preseismic deformation associated with the 1971 San Fernando earthquake. In this study, evidence is presented which strongly suggests that movements of the ground surface south of the San Gabriel fault in Southern California result, for the most part, from near surface sediment compaction due to fluctuations of the water level within the Saugus aquifer and not from tectonic activity. Although these crustal movements most likely are not tectonic in origin, they do represent real surface movements and in this sense further demonstrate the ability of precise leveling to detect relatively subtle deformation.

Data

Figure 1 shows contours of the thickness of the confined Saugus aquifer (Robson, 1972) with leveling lines and benchmarks superimposed. Profiles of elevation change, aquifer thickness and estimated change in potentiometric surface (water level) along the survey routes are shown in Figure 2a,b. The elevation change profile from north of Castaic through Saugus is plotted assuming stability for benchmark X370 immediately adjacent to the aquifer. This benchmark is chosen as a reference since it lies outside of the aquifer and appears generally stable relative to benchmarks further north. The elevation change profile from Saugus to Lang is plotted assuming stability near Lang since the benchmarks immediately adjacent to the Saugus aquifer occur within the alluvial aquifer of the Santa Clara River and appear to have subsided themselves. The change in water level shown in Figure 2a,b represents the calculated decline as of 1963 relative to the steady state level estimated to have existed around 1945 (Robson, 1972). This decline was due to pumping from the Saugus aquifer as well as overlying alluvial aquifers, and to an extended drought (Robson, 1972, pp. 8, 40). Because the water level was already below the steady state at the time of the first leveling survey (1953), the decline in

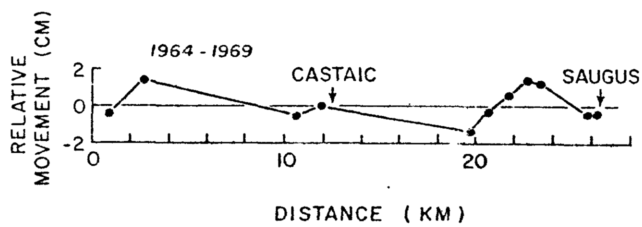


Fig. 3. Profile of elevation change for period 1964 to 1969 along route from north of Castaic to Saugus (see Fig. 1 for location).

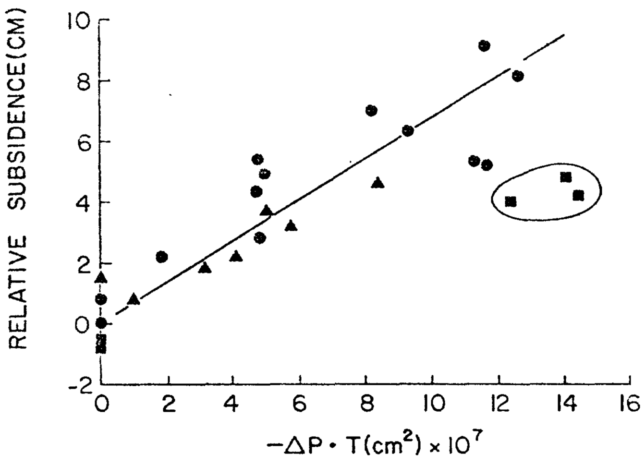


Fig. 4. Plot of subsidence versus change in potentiometric surface times aquifer thickness for benchmarks in and immediately adjacent to aquifer. Different symbols refer to different releveled segments: circles-north of Castaic to Saugus (1953-1964); squares-Saugus to South (1955-1964); triangles-Saugus to Lang (1955-1961).

water level shown in Figure 2a,b is somewhat larger than the actual change between leveling surveys. However, water levels declined more or less continuously up to 1963 (Robson, 1972).

Figure 2a,b indicate a reasonable spatial correlation between subsidence, aquifer thickness and change in water level. In addition, the water level within the Saugus aquifer stabilized after 1963 and began to recover around 1968 (Robson, 1972). Examination of post-1964 elevation changes across the northern part of the basin indicate a general absence of subsidence of the basin (Figure 3). Thus, the observed elevation changes correlate spatially with aquifer geometry and temporally with the history of water level decline.

In the ideal case, the amount of compression (subsidence) of a sediment layer is proportional to the thickness of the layer and the increase in effective pressure (grain to grain pressure) on the sediments (Terzaghi and Peck, 1967; p. 278). Lowering the water level produces a proportional reduction in the buoyant force between grains and hence causes an increase in the effective pressure on the underlying sediments (Terzaghi and Peck, 1967; p. 584). Assuming uniform sediment characteristics throughout the aquifer (constant compressibility), to a first approximation the amount of compaction (subsidence) at a particular location will be roughly proportional to the product of water level decline and aquifer thickness. Figure 4 gives a plot of relative subsidence versus the product of the change in water level and aquifer thickness for benchmarks in and immediately adjacent to the Saugus aquifer. Considering the uncertainties in aquifer parameters and probable spatial variations in aquifer compressibility, the observations fit the simple linear relationship quite well. The three circled points on the right side of the plot lie in the southeastern portion of the aquifer (Figure 1) and may reflect either different sediment characteristics or possibly tectonic movement in this area. The slope of the straight line in Figure 4 is an estimate of the average compressibility of the Saugus aquifer. Although the compressibility can vary through at least two orders of magnitude depending on sediment type, stress level, and stress history, the value obtained from Figure 4 ($\approx 7 \times 10^{-8} cm^{-1}$) is quite comparable to those reported for other confined aquifers in California (Lofgren, 1979, p. 35).

Conclusions

Repeated leveling surveys conducted between 1953 and 1964 indicate subsidence of the Saugus Basin relative to benchmarks on its periphery. Subsidence extends over a distance of about 20 km with maximum relative subsidence near the center of the basin reaching 9 cm. The spatial correlation between the area of relative subsidence and the Saugus aquifer, the temporal correlation with the history of water level decline, and the parameter dependence indicated in Figure 4, strongly suggest that movements in the Saugus Basin, previously inferred to be associated with either the "Palmdale Bulge" or preseismic effects of the 1971 San Fernando earthquake, result from near-surface sediment compaction. This study demonstrates the need for caution when applying tectonic interpretations to releveling observations in areas of unconsolidated sediments. On the other hand, the fact that the leveling measurements accurately detected real surface movements under actual field conditions demonstrates the potential of this technique for monitoring crustal deformation.

Acknowledgements. I am grateful to the National Geodetic Survey for supplying the leveling data used in this study, and to Jack Oliver and Larry Brown for helpful comments. This research was supported in part by U.S. Geological Survey Grant 14-08-0001-17625, and N.A.S.A. Grant NAG5-40. Cornell Department of Geological Sciences Contribution No. 679.

References

Castle, R.O., J.P. Church, and M.R. Elliott, Aseismic uplift in Southern California, Science, 192, 251-253, 1976.

Lofgren, B.E., Changes in aquifer-system properties with ground-water depletion, (in) ed., S.K. Saxena, Evaluation and Prediction of Subsidence, American Society of Civil Engineers, New York, New York, 26-46, 1979.

Robson, S.G., Water-resources investigation using analog model techniques in the Saugus-Newhall area, Los Angeles County, California, U.S.G.S. Open File Report 5021-04, 58, 1972.

Strange, W.E., The impact of refraction correction on leveling interpretations in California, EOS, Trans. Am. Geophys. Union, 61, 367-368, 1980.

Terzaghi, K, and R.B. Peck, Soil Mechanics in Engineering Practice, John Wiley and Sons, New York, 729, 1967.

(Received September 3, 1980; accepted September 22, 1980.)

APPENDIX III

Time Behavior of Vertical Crustal Movements Measured by Relevelling in North America: A Geologic Perspective

by

John Adams* and Robert Reilinger
Cornell University, Dept. of Geological Sciences
Ithaca, N.Y. 14853

* Now at Earth Physics Branch
Dept. Energy, Mines and Resources
Ottawa, Ontario K1A 0Y3, Canada

ABSTRACT

In some areas geodetically determined rates (~ mm/yr) are consistent in sign with geologic trends but 10 - 100 times faster. Although the reliability of some of the levelling results is open to question, this "rate paradox" suggests that any real contemporary movements are episodic or oscillatory. In the U.S. midcontinent oscillatory movements with a period of approximately 3000 years are implied. Deformation in the Rio Grande rift (New Mexico and Texas) and at Hegben Lake (Montana) has constant direction and similar rates for the past 50 - 100 yr (excluding the 1959 coseismic movement at Hegben Lake), though geologic evidence indicates transitory behaviour in the long term (~ 10,000 years). In Oregon and Washington, 10-50 yr span relevelling shows more or less constant-rate landward-tilt of the relatively aseismic coastal ranges that is consistent with the deformation rate of marine terraces (230,000 yr) and underlying strata (36,000,000 yr). In contrast to the 50-100 yr span constant rates above, relevelling in some seismically active areas (e.g. Alaska and California) suggests rapid rate changes. However the examples presented here suggest that in areas free of major earthquakes, rates from relevelling, although high in a geologic sense, can likely be extrapolated for 50 yrs.

SOMMAIRE

Dans certaines régions, les variations (~ mm/an) évaluées par méthode géodésique sont consistantes (en signe) avec les tendances géologiques tout en étant de 10 à 100 fois plus grandes. Même si la fiabilité de certaines fondées sur le nivellement peut être mise en question, ce "paradoxe de variations" implique que les mouvements actuels sont épisodiques ou oscillatoires. Au centre des Etats-Unis, ceci implique des mouvements oscillatoires ayant une période d'environ 3,000 ans. Les déformations dans la région de la fissure du Rio Grande (Nouveau-Mexique et Texas) et au Hegben Lake (Montana) ont des directions constantes et des variations similaires depuis 50 à 100 ans (à l'exception d'un mouvement survenu en même temps qu'un séisme au Hegben Lake en 1959) même si, à long terme (~ 10,000 ans), un comportement transitoire semble prévaloir. Dans les états d'Oregon et de Washington les nivellements espacés de 10 à 50 ans révèlent que, pour la zone côtière où l'activité séismique est nulle, les variations d'inclinaison en direction du continent sont plus ou moins constantes et consistantes avec les variations de déformation des plates-formes marines (230,000 ans) et des couches servant d'assises à ces plates-formes (36,000,000 ans). En opposition aux périodes de variations constantes de 50 à 100 ans mentionnées ci-dessus, les travaux de renivellement dans certaines régions actives au sens séismique (par ex. l'Alaska et la Californie) impliquent des changements de variations rapides. Cependant, les exemples analysés dans cette étude permettent de penser que, dans les régions exemptes de séismes majeurs, les variations impliquées par les renivellements, bien que grandes au sens géologique, peuvent être probablement extrapolées pour 50 ans.

1. INTRODUCTION

Understanding vertical movements of the earth's crust has important implications for geodetic as well as geologic research. Awareness of vertical movements and their time behavior is necessary in order to provide accurate instantaneous heights from levelling observations made at different times. In addition, information on the temporal behavior of crustal movements is useful for deducing their causes and can contribute to our understanding of a variety of geophysical phenomena such as earthquakes, aseismic strain buildup and release, magma migration, and plate tectonic interactions.

Levelling observations in tectonically active areas, while in some cases poorly understood, are often accepted as geologically significant because they can be associated with likely causative mechanisms. By analogy, similar observations in "stable" plate interiors have been interpreted as indicating substantial vertical motion, although tectonic activity is generally unexpected and plausible mechanisms are difficult to identify (e.g. *Mescherikov 1959; Brown and Oliver 1976*). The latter group of observations especially has raised some fundamental questions concerning the reliability of levelling estimates of vertical movement (at least in some cases), the time behaviour of any real movements, and the nature of the neotectonic forces which may be currently deforming plate interiors (*Brown and others 1980*).

In some areas the trends of geodetically measured movements are consistent with trends in the geologic record, although contemporary rates of movement (several mm/yr) are ten to one hundred times faster than average rates estimated from geomorphic and geologic evidence for the past 1 to 100 m.y. Similar observations have been made in many intraplate areas where levelling measurements have been examined in detail (e.g. USSR), and the apparent contradiction termed the "rate paradox". The paradox has lead to the hypothesis that contemporary movements are episodic or oscillatory with relatively short periods (~ 10,000 years). Clear examples of episodic movements are those associated with earthquakes. Oscillatory movements may result from magmatic activity (i.e. inflation and deflation). However these mechanisms do not appear to be applicable to observations in many (? most) intraplate areas. Besides the lack of identified mechanisms there are other problems with the hypothesis since 1) present rates appear high almost everywhere, an abnormal situation if the rates are real and episodic, and 2) oscillatory movements have rarely been unambiguously identified.

Long wavelength tilts on the order of 0.5 mm/km which give rise to large absolute movements are likely to be due to systematic error, as evidenced by discrepancies between levelling and tide gauge measurements along the east coast of the U.S. (*Brown 1978*). In addition, elevation correlated errors (atmospheric refraction, rod miscalibration) may be responsible for many of the apparent movements deduced from levelling in "stable" plate interiors (*Brown and others 1980*). As geologic structure often controls topographic relief, elevation correlated errors may account for the observed relationship between geodetically measured apparent movements and geologic structure. It is quite possible that large absolute movements of plate interiors are not as widespread as suggested by previous analyses of levelling observations.

In this paper we discuss studies that characterize the time behaviour of some localized vertical crustal movements in nine parts of North America (Fig. 1). While there is evidence for continuous, for episodic, and for oscillatory behaviour in various places, we infer that in areas free from large earthquakes the contemporary rate can likely be extrapolated for 50 years.

2. CASE STUDIES

2.1 Eastern United States

In that part of the United States east of the Mississippi, Brown and Oliver (*1976*) assembled four large levelling circuits by assuming constant rate and so justifying the joining together of line segments levelled at different times. The tilt rates calculated from the circuit misclosures were an order of magnitude smaller than most tilts shown by the levelling data and thought significant, and they were also smaller than the propagated random error.

Brown (*1978*) analysed a profile along the east coast that was assembled in the same way. Although there is a major disagreement between the very large north-south tilt shown by the levelling and the much smaller tilt shown by tide gauge records, some localized features appear to correlate with major geologic/tectonic structures. The deformation across these structures is occuring too fast to continue for very long, and so if these are real, some as yet not identified, episodic or oscillatory causative mechanism must be involved.

2.2 Eastern United States (Map)

In the same general area of the eastern United States studied by Brown and Oliver (*1976*), an attempt has been made by Jurkowski and others (*1979; in prep.*) to fit a velocity surface to a sparse, extensive network of 252 selected benchmarks. The selected benchmarks were those considered representative of the velocity of "nearby" (up to 40 km distant) bench marks. The velocity surface (potentially a map of relative vertical crustal movement rates) was constrained by tide-gauge data. To include all the data, the rate of movement at each benchmark was assumed constant between 1888 and 1974. While poorly constrained by the available data, the misclosure statistics were acceptable, and hence the assumption of constant rate seemed appropriate as a first approximation.

Although the statistics were acceptable, it is still possible that certain systematic errors may have distorted the velocity surface. However if some terrain-correlated error was responsible for the broad uplift shown along the Appalachians, it would need to be systematic not only with topography (e.g. refraction error or rod miscalibration), but also systematic with time, since many levellings done at many times fit together acceptably (*Holdahl 1979*). One explanation is the systematic change in sight length that has occurred with time (shorter in newer surveys) and which results in smaller refractive error in newer surveys. Given normal near-surface temperature gradients, the change in sight length produces a positive correlation of height change with topography that is of the correct magnitude to explain the apparent movement between surveys (*Reilinger 1980*).

For these and other reasons, the velocity surface should only be considered a map of "apparent" crustal uplift. The high rates (+ 2 and -6 mm/yr) relative to sea level are probably not real, but more localized features may represent real movements. If any of the apparent movements are real, they must be episodic or oscillatory in the long-term, because geologic evidence indicates rates one hundred times slower.

2.3 Midcontinent United States

Some evidence for oscillatory as opposed to episodic movements comes from an analysis of levelling results in the United States midcontinent between Iowa and Tennessee (*Adams 1980a*). Despite the high tilt rates (as large as 10^{-7} rad./yr) and rapid relative uplifts (several mm/yr), the observations do appear to represent real crustal movements.

The level lines follow large rivers, and there is a remarkably high correlation between tilt shown by the levelling and downstream changes in the river sinuosity (Fig. 2). Along north-south lines, the slope of the correlation suggests that the present tilting would need to have started several hundred years ago and to have continued at the present rate to account for the downstream changes in river sinuosity. Along east-west lines, the correlations appear to imply that the measured tilting will destroy the present sinuosity pattern only if it continues at the present rate for the next few hundred years. Taken together, the correlations suggest that the midcontinent is being deformed by oscillatory tilting with a period of about 3,000 years. Even without the above interpretation, the correlations provide good evidence that present tilting has continued in the same direction as measured for the last 80+ yr, and if the periodicity of 3,000 yr is even approximately correct, the assumption of constant rate for the 100-yr-span seems justified.

2.4 Diablo Plateau

Across the Diablo Plateau of New Mexico-Texas, three-fold levelling indicates uplift of an area 120 km wide (*Reilinger and others 1980; Brown and others 1978*). Observations in 1934, 1943/1958, and 1977 indicate uplift (as fast as 4 ± 1 mm/yr relative to surrounding areas) at a nearly constant rate (Fig. 3), at least during the time-scale of the observations (~ 20 yr). The progressive deformation indicated by the relevelling measurements, the large magnitude relative to possible levelling errors, and the spatial dimensions of the uplifted area rule out systematic errors or near-surface effects as an explanation and favour a tectonic origin. Crustal magmatic activity or some form of preseismic deformation appear to be the most reasonable explanation in view of the tectonic setting (eastern branch of Rio Grande rift). Contemporary deformation is consistent in sign with

with Cenozoic displacements, but the Cenozoic rates are likely to have been far slower than the present rate, suggesting that episodic movements occur in the long-term.

2.5 Socorro

In the Rio Grade Rift north of Socorro, levelling lines show contemporary doming above an active magma body that has been inferred from the high level of microearthquake activity, seismic reflection studies, high heat flow, and some weak seismic Pn phases (*Reilinger and Oliver 1976; Reilinger and others 1980*). The observed uplift rates at Socorro can be explained by inflation of the magma body. Uplift at the centre of the dome is more than 3.9 mm/yr relative to the sides. The fit of nearby level lines, relevelled at different times, suggests that the observed doming has been at a constant rate for the last 80 yr.

Post-Pliocene tilt rates (averaged over the last few million years) are about 30 times slower than present rates, although they do have the same direction. On the southern side of the dome, the inferred geodetic tilt rate is 13×10^{-8} rad./yr, down to the south. In the same area, Pliocene sands of the ancestral Rio Grande River are tilted 0.0067 rad. down to the south (*Bachman and Mehnert 1978, p. 288*). If the doming occurred at the presently measured rate, then the sands would have had the same downstream slope as the Rio Grande only 50,000 years ago. At the magma flow rates of 1 to 2×10^{-2} km^3/yr required to account for the present doming (*Reilinger and others 1980*), the entire magma body (a sill 1700 km^2 in area and assumed to be 0.5 km thick) would be formed in 40,000 to 90,000 yr. Thus there is a general consistency between the present magma flow rates, the volume of the magma chamber, and the total tilt as shown by the Pliocene sands. If present activity represents the only activity in the last few million years, then the Socorro body could have been inflated and the sands tilted in the last 100,000 years or less. Alternatively the tilt of the sands may represent the cumulative effect of several magma injections with intervening periods of quiescence or even backtilting.

2.6 Montana-Idaho-Yellowstone

Levelling in southwestern Montana and Idaho suggests a steady doming extending over an area of 8000 km^2 with a peak rate of 3 to 5 mm/yr (*Reilinger and others 1977*). The doming apparently preceeded and continued after the Hegben Lake earthquake. The general high regional altitude suggests that the area is being broadly uplifted, and the doming may have continued for hundreds of thousands of years. The cause of the regional uplift is unclear, but the high rates suggest some mechanical cause (possibly magma injection), since the rates are too high to be attributed to thermal effects. The consistency between many lines levelled at different times from 1923 to 1967 and the steady movements of some bench marks (*Reilinger and others 1977, figure 6*) suggest that uplift has been at a more or less constant rate (excluding the 1959 coseismic movement) for the last 40 yr or more.

To the east of the area studied by Reilinger and others (*1977*), two-fold levelling in the vicinity of Yellowstone National Park has revealed an elongate dome, 50 km long and 40 km wide within the caldera rim (*Pelton and Smith 1979*). At its centre, the dome is rising at about 14 mm/yr relative to the rim. Yellowstone Lake extends across the rim toward the centre of the dome, but a terrace 18 to 20 m above lake level has been imperceptably tilted. Thus the present uplift cannot be older than a few hundred years, and episodic deformation related to periodic magma injection is suggested.

2.7 Oregon-Washington Coastal Ranges

Tilted and uplifted marine terraces of Oregon and Washington show progressive landward tilting of the coast ranges at about 4 to 7 degrees per m.y. for the last 0.25 m.y. (*Adams and others 1980; in prep.*). The tilting is almost certainly due to the subduction of the Juan de Fuca plate beneath the coast ranges, and as such is likely to have continued for the last few million years. Seven resurveyed levelling lines (two described by *Ando and Balazs 1979*) running inland from the coast indicate contemporary landward tilt rates of about 1 to 9 x 10^{-8} rad. yr^{-1} (0.6 to 5 degrees per m.y.) averaged over periods of from 10 to 40 years (Fig. 4). The levelling lines traverse, and the terraces cut across, dipping Cenozoic strata: Pleistocene (dips to 3^{0}), Mio-Pliocene (dips to 30^{0}) and Eocene (dips to 60^{0}). At least four places (Cape Blanco, Bandon, Cape Arago, and Siuslaw River) are characterized by geodetic or terrace dips that have the same direction as the underlying stratal dips.

A constant tilt-rate can be deduced from the geodetic and terrace observations. If extrapolated to the stratal dips, the tilt rate suggests that deformation began some 7 m.y. ago. Alternatively, the average rate indicated by the deformation of the Eocene strata (~ 36 m.y. old) is one quarter the present rate, so that if deformation began when the strata were first deposited, it must have been episodic with a period greater than 0.25 m.y.

2.8 Isostatic uplift, North America

In the northern United States and eastern Canada, postglacial rebound following the removal of ice load dominates present vertical crustal movement. From Milwaukee, Wisconsin 700 km north-east to Lake Superior, lake gauges indicate 5 mm/yr of relative uplift (*Walcott 1972*) with a down-to-the-southeast tilt of about 0.7×10^{-8} rad./yr. The best evidence that most of the uplift occurs at constant-rate is pairs of lake gauges (e.g. *Moore 1948, figure 2*) which show steady, progressive differences with time. If unsteady uplift is occurring, it is likely to be averaged out over periods of 10 to 15 years.

Thus in these areas, where the absolute uplift rates are large (but tilt rates are still relatively small), uplift probably occurs at a constant-rate, and once regional rates are deduced, observations made at any one time may be adjusted to them. However, suggestions of isostatic block-movements superposed on the regional trends (e.g. *Moore 1948, p. 706*), postglacial faults and folds in some places (*Adams 1980b*), and other, non-isostatic block-movements elsewhere in the continental interior (*Adams 1980a*), suggest that caution will still be needed in the adjustments.

2.9 Seismically active areas, western North America

In contrast to the above examples where approximately constant rates seem to characterize the 50-100 yr span, relevelling measurements in other areas of the U.S. suggest rapid changes in deformation rates within a few years. Crustal uplift following the 1964 Alaska earthquake was characterized by exponentially decreasing rates with a time constant of <10 yrs (*Brown and others 1977, figure 3*). The uplift can best be described by down-dip creep on the fault plane, and in time the postseismic deformation will presumably decay to zero and be replaced by a phase of strain accumulation. Recognition of earthquake strain-accumulation phases in levelling results has important implications for earthquake prediction.

Aseismic movements near Palmdale in southern California have apparently undergone rapid changes in direction and rate over periods of a few years or less (*Vanicek and others 1979*), although the reliability of the measurements defining this feature have recently been questioned (*Jackson and Lee 1979*). Such rapid changes are to be expected in these seismically active areas in view of the episodic nature of certain earthquake related deformation. Relevelling measurements in such areas must be frequent and rapidly accomplished if their results are to be meaningful.

3. CONCLUSIONS

In most areas there are not sufficient multiple relevellings to allow for the development of a clear picture of the short-term temporal behavior of vertical crustal movements. In addition, where multiple relevellings are available the apparent temporal behavior is often quite complex. In many cases it is not presently known whether this complex behavior is due to actual crustal movements or to survey errors.

Circuit analysis is one method that can demonstrate survey errors in relevelling data (*Chi and others 1980*). Misclosures around the circuits analysed should be smallest for the circuit with the most temporally-homogeneous data. For example, circuit analysis has shown that an apparent uplift on the San Andreas Fault north of San Francisco is probably due to an error in one survey, rather than to real crustal movements. The development of this and similar techniques may resolve many presently ambiguous survey results.

With the continuing support of geologic and especially geomorphic information on the long-to medium-term deformation rates of the North American continent, the interpretation of the short-term rates measured by levelling will become more certain. If the examples described here are generally applicable, they suggest that in areas free of major earthquakes, movement rates deduced from relevelling observations spanning tens of years, although fast in a geologic sense, can likely be extrapolated for 50 yr with some degree of assurance. The degree of assurance in any one place will depend on local studies like those above, and on a regional synthesis of vertical crustal movement rates, styles and causes.

4. ACKNOWLEDGMENTS

We thank the National Geodetic Survey for supplying the levelling data. This research was supported in part by USGS grant 14-08-0001-17625, NASA grant NCC5-4 and NRC grant 04-76-376. Cornell University Department of Geological Sciences contribution number 674.

REFERENCES

ADAMS, J. (1980a) *Active tilting of the midcontinent: geodetic and geomorphic evidence.* Geology, in press.

ADAMS, J. (1980b) *Postglacial Faulting in eastern Canada.* Report prepared for Atomic Energy of Canada Limited, March 1980, 62 pp.

ADAMS, J., R. REILINGER and J. NI (1980) *Active tilting of the Oregon and Washington Coastal ranges.* EOS, Trans. Am. Geophys. Union, Vol. 61, No. 17, pp. 371.

ANDO, M., and E.I. BALAZS (1979) *Geodetic evidence for aseismic subduction of the Juan de Fuca Plate.* Journal of Geophysical Research, Vol. 84, pp. 3023-3028.

BACHMAN, G.E. and H. H. MEHNERT (1978) *New K-Ar data and the late Pleistocene to Holocene geomorphic history of the central Rio Grande region, New Mexico.* Geological Society of America, Bulletin, Vol. 89, pp. 283-292.

BROWN, L.D. (1978) *Recent vertical crustal movements along the East Coast of the United States.* Tectonophysics, Vol. 44, pp. 183-189.

BROWN, L.D. and J.E. OLIVER (1976) *Vertical Crustal movements from levelling data and their relation to geologic structure in the eastern United States.* Reviews of Geophysics and Space Physics, Vol. 14, pp. 13-35.

BROWN, L.D., R.E. REILINGER, S.R. HOLDAHL and E.I. BALAZS (1977) *Postseismic crustal uplift near Anchorage, Alaska.* Journal of Geophysical Research, Vol. 82, pp. 3369-3378.

BROWN, L.D., R.E. REILINGER and J.T. HAGSTRUM (1978) *Contemporary uplift of the Diablo Plateau, west Texas, from levelling measurements.* Journal of Geophysical Research, Vol. 83, pp. 5465-5471.

BROWN, L.D., R.E. REILINGER, and G.P. CITRON (1980) *Recent vertical crustal movements in the U.S.: evidence from precise levelling.* In Morner, N.A. (ed.) *Earth rheology, isostasy, and eustasy.* John Wiley & Sons, New York, pp. 389-405.

CHI, S.C., R.E. REILINGER, L.D. BROWN and J.E. OLIVER (1980) *Levelling circuits and crustal movements.* Journal of Geophysical Research, Vol. 85, pp. 1469-1474.

HOLDAHL, S.R. (1979) *Report on the North American Subcommission on recent crustal movements.* Paper presented at the International Symposium on Recent Crustal Movements, Canberra, Australia, Dec. 2-15th.

JACKSON, D.D. and B.L. WOOK (1979) *The Palmdale Bulge - an alternate interpretation.* EOS, Trans. Am. Geophys. Union, Vol. 60, No. 46, p. 810.

JURKOWSKI, G., L.D. BROWN, S.R. HOLDAHL and J.E. OLIVER (1979) *Map of apparent vertical crustal movements for the eastern United States.* EOS, Trans. Am. Geophys. Union, Vol. 60, No. 18, p. 315.

MESCHERIKOV, Y.A. (1959) *Secular crustal movements of the East European plain and associated problems.* Bull. Geod. Vol. 52, pp. 69-75.

MOORE, S. (1948) *Crustal movement in the Great Lakes area.* Geological Society of America Bulletin, Vol. 59, pp. 697-710.

PELTON, J.R. and R.B. SMITH (1979) *Recent crustal uplift in Yellowstone National Park.* Science, Vol. 206, pp. 1179-1182.

REILINGER, R.E. (1980) *Apparent uplift preceding the 1971 San Fernando, California Earthquake: Probable artifact of systematic errors in levelling.* Submitted to Science, May 1980.

REILINGER, R.E. and J.E. OLIVER (1976) *Modern uplift associated with a proposed magma body in the vicinity of Socorro, New Mexico.* Geology, Vol. 4, pp. 583-586.

REILINGER, R.E., G.P. CITRON and L.D. BROWN (1977) *Recent vertical crustal movements from precise levelling data in Southwestern Montana, western Yellowstone National Park, and the Snake River Plain.* Journal of Geophysical Research, Vol. 82, pp. 5349-5359.

REILINGER, R.E., J.E. OLIVER, L. BROWN, A. SANFORD and E. BALAZS (1980) *New measurements of crustal doming over the Socorro magma body.* Geology (in press).

REILINGER, R.E., L. BROWN and D. POWERS (1980) *New evidence for tectonic uplift in the Diablo Plateau region, west Texas.* Geophysical Research Letters, Vol. 7, pp. 181-184.

VANICEK, P., M.R. ELLIOTT and R.O. CASTLE (1979) *Four-dimensional modelling of recent vertical movements in the area of the Southern California Uplift.* Tectonophysics, Vol. 52, pp. 287-300.

WALCOTT, R.I. (1972) *Late Quarternary vertical movements in eastern North America: Quantitative evidence of glacio-isostatic rebound.* Reviews of Geophysics and Space Physics, Vol. 10, pp. 849-884.

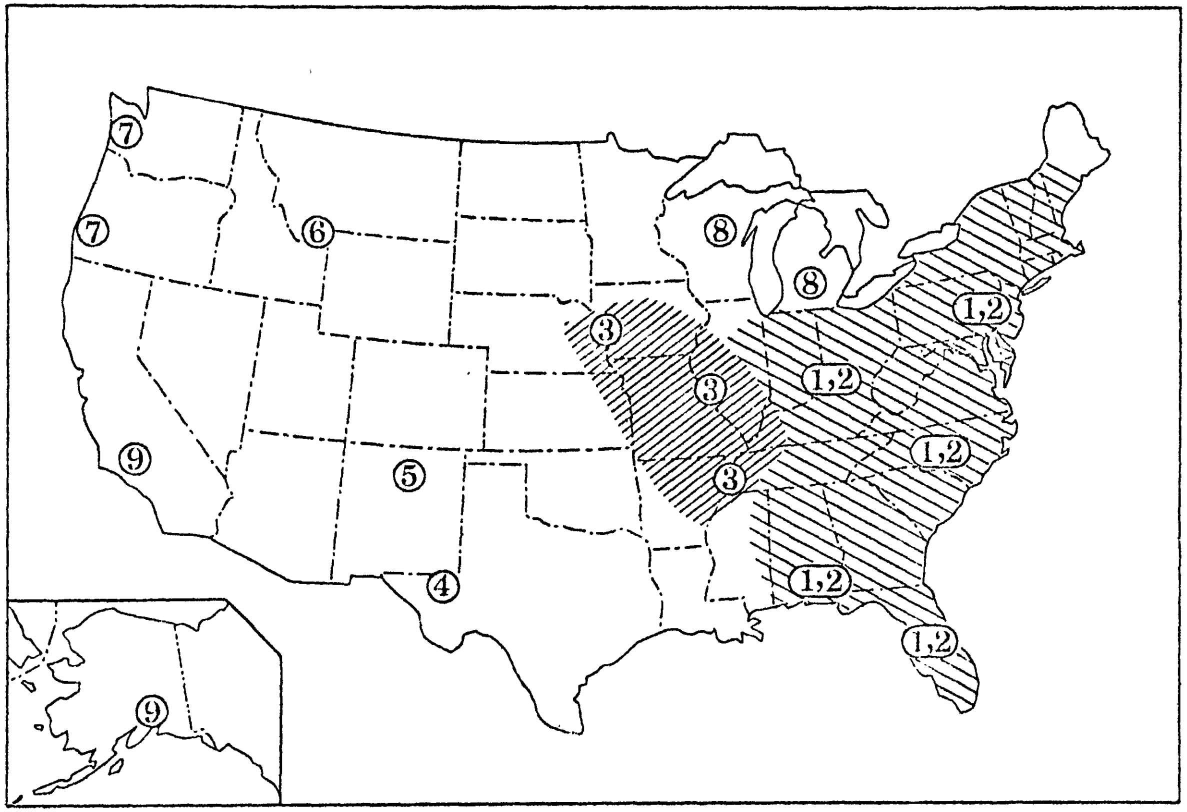
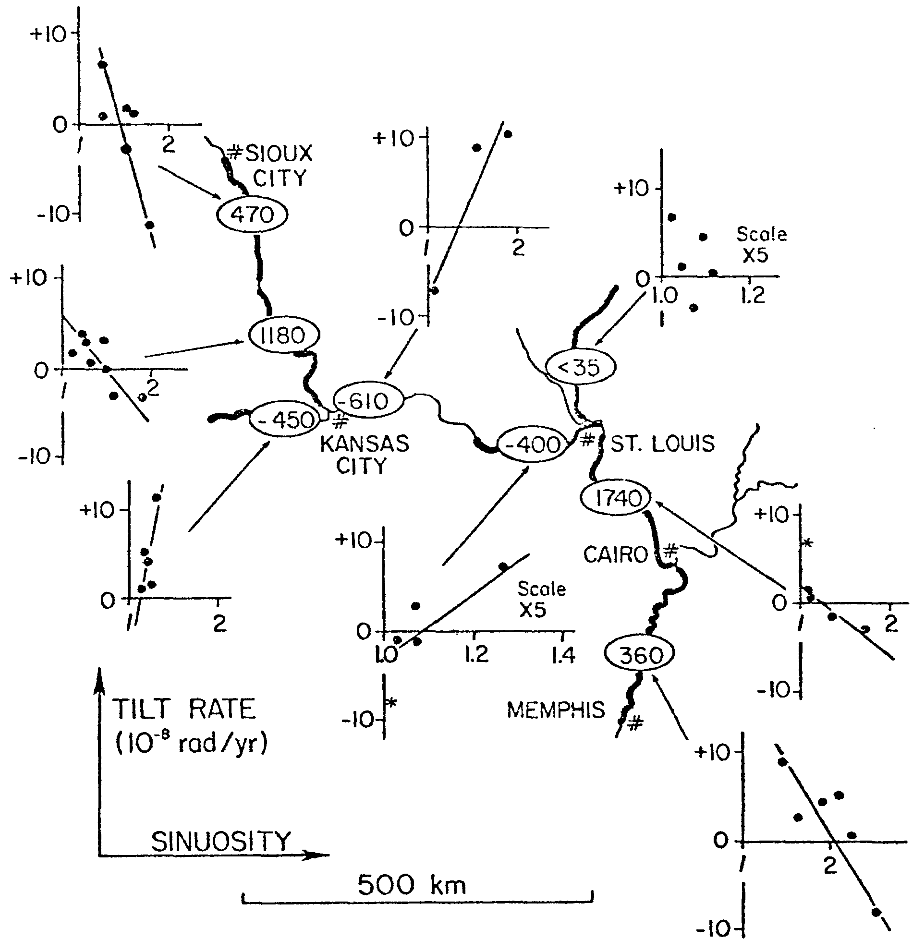


FIGURE 1: LOCATION MAP FOR CASE STUDIES. NUMBERS REFER TO SECTIONS IN THE TEXT.



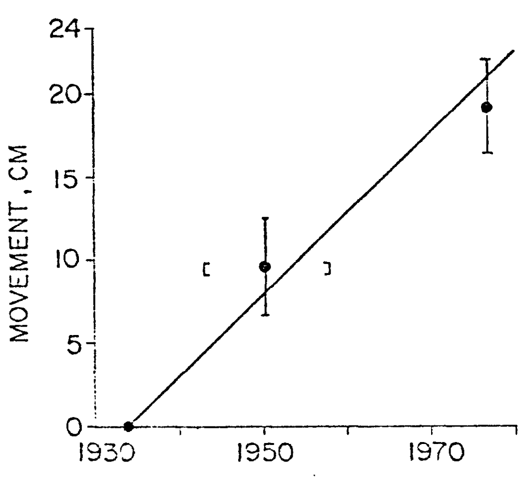


FIGURE 2: (ABOVE) RELATIONSHIP BETWEEN RIVER SINUOSITY AND GEODETIC TILT IN THE MIDCONTINENT. NUMBERS IN OVALS GIVE AGE OF TILTING IN YEARS.

FIGURE 3: MOVEMENT OF BENCHMARK BULT 53, NEAR CENTRE OF DIABLO PLATEAU UPLIFT.

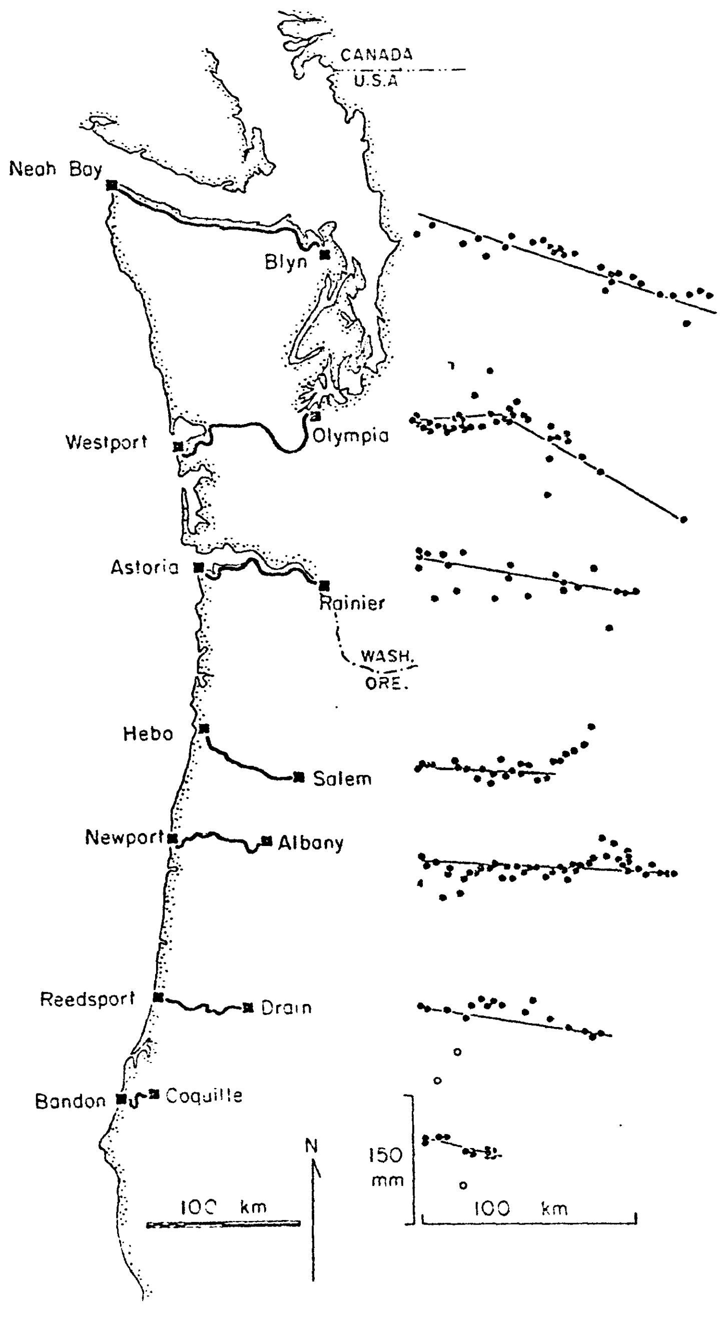


FIGURE 4: EAST-WEST LEVELLING ROUTES (LEFT) IN THE PACIFIC NORTHWEST THAT SHOW (RIGHT) LANDWARD TILT OF THE COASTAL RANGES.