U.S. GEOLOGICAL SURVEY CIRCULAR 905

Vertical Crustal Movements in Southern California, 1974 to 1978

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ABSTRACT

An extensive resurvey of most of the first-order leveling network in southern California, known as the Southern California Releveling Program (SCRP), was carried out during the first 5 months of 1978. The primary scientific purpose of these measurements was to rapidly update the vertical control record throughout a recently uplifted region of southern California in order to more thoroughly document the vertical component of tectonic movement and to provide a reliable base for comparison with future levelings. Analyses of historic first-order leveling results have clearly demonstrated that a broad crustal upwarping, largely contained within a region consisting of the Transverse Ranges province and an area along the intervening section of the San Andreas fault system, had developed between about 1959 and 1974. Unfortunately, there is strong evidence that parts of the 1978 SCRP data are contaminated by the effects of intrasurvey tectonic deformation, limited surficial failures, and, less certainly, magnetically induced systematic error associated with the use of automatic levels. However, any distortions in leveling results caused by these or other factors are not so serious as to render the SCRP data useless. In fact, the bulk of these data can be accepted at face value, and most of the remaining data can be incorporated with some caution to augment the more reliable parts of the network. The evaluation of the 1978 leveling is based on a combination of circuit-misclosures, local timing of the field observations, analysis of profiles of apparent height changes derived from comparisons with previous levelings, and an analysis of the position and orientation of the various routes in relation to the regional structural grain and the gradients of differential vertical motion established by previous investigations. Comparisons of the 1978 SCRP results with the latest of the previous surveys along each route retained in the analysis show that all but about one-third of the uplift established by leveling data from 1959 to the combined 1974/76 survey period had relaxed by early 1978 through tectonic subsidence. Subsequent limited relevelings along several of the 1978 routes show that rapid tectonic subsidence probably continued through at least early 1979. Despite the pronounced down-to-the-northeast (northeastward) tilt that developed between 1976 and early 1978, the overall shape of the uplift was well preserved. Results of repeated trilateration surveys since 1971 demonstrate that a remarkably uniform and nearly monotonic negative dilatational strain-change trend reversed abruptly between 1977 and 1979. The change from tectonic uplift to tectonic subsidence is associated with this reversal in horizontal strain accumulation. The reversal in strain trend was expressed as a cessation of the essentially uniaxial north-south contraction, which had been accumulating at about 2×10^{-7}/yr (or 0.2 μstrain/yr), accompanied by onset of uniaxial east-west extension at about 5×10^{-7}/yr (or 0.5 μstrain/yr). Minor earthquakes and occasional swarms of moderate earthquakes were particularly abundant during 1978 and 1979 in conspicuously mobile regions such as the eastern Transverse Ranges and the Salton Trough, areas respectively characterized by nearly complete collapse of the previous maximum uplift and by a dramatic enhancement of the previously identified tectonic subsidence.

INTRODUCTION

A comprehensive resurvey of most of the primary vertical-control network in southern California (fig. 1), funded through the U.S. Geological Survey (USGS) and coordinated by the National Geodetic Survey of the National Oceanic and Atmospheric Administration (NGS/NOAA), was accomplished during the first 5 months of 1978. This multiagency observational effort, known as the 1978 Southern California Releveling Program (SCRP), was conducted by 18 leveling and five gravity teams from NGS and USGS, and by 20 additional leveling teams from Ventura, San Diego, San Bernardino, Riverside, Orange, Los Angeles, and Imperial Counties, the City of Los Angeles, the Los Angeles Water and Power Department, and the Metropolitan Water District of Southern California. During a period of peak effort, 42 teams were simultaneously engaged in SCRP field observations.

The objective of the 1978 regional leveling was to establish a highly precise vertical-control base

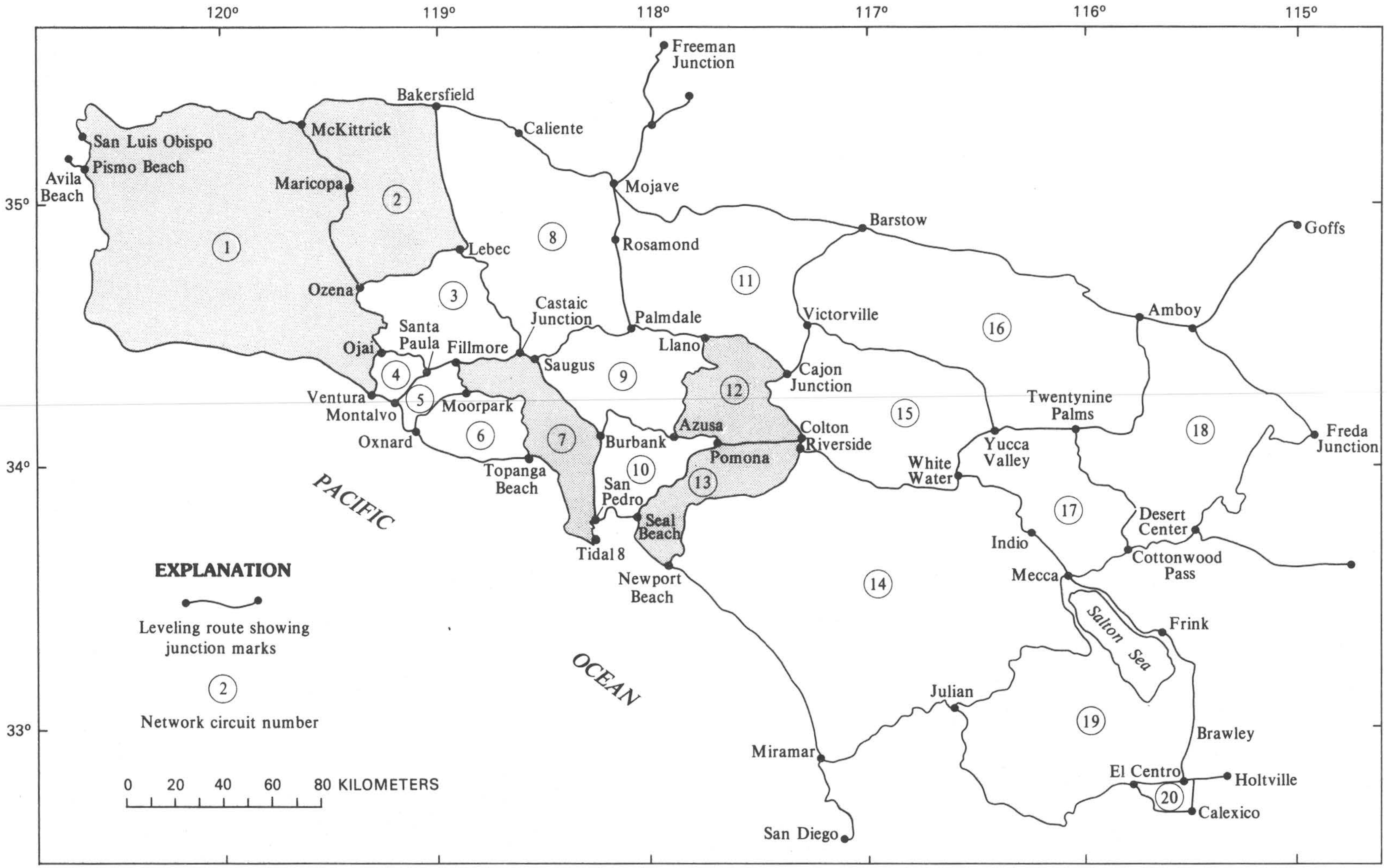


FIGURE 1.—Index map of routes leveled during the Southern California Releveling Program (SCRP) between January and May, 1978. Data on circuit lengths and on observed and orthometrically corrected circuit misclosures presented in table 1 are keyed to numbers shown for network circuits. Shaded areas indicate SCRP circuits with observed misclosures in excess of allowable limits for first-order, class I leveling.

within as short a period as possible, thereby minimizing the effects of possible contemporaneous deformation. Vertical control provided by SCRP was intended to serve as a reliable reference for comparisons with results of both past and future levelings to comprehensively document the vertical component of tectonic movement in southern California. The SCRP measurements were prompted by the discovery of a broad, regional uplift that developed between 1959 and 1974 (fig. 2), as established through comparison and analysis of numerous, yet somewhat scattered, vertical control surveys repeated in parts of the region at various times during the past half century (Castle and others, 1976; Castle, 1978; Castle and others, 1984; National Geodetic Survey, 1978).

Unfortunately, SCRP operations were seriously hampered by weather-related delays. The operation was scheduled for the winter months of 1978 in the hope that generally cool, moderate weather conditions over the entire area would enhance both data quality and the efficiency of its collection. However, from the last few days of January through most of March, southern California was subjected to heavy precipitation, including locally heavy snowfall in the mountains, that constituted the single wettest season during this century. Observations along many of the leveling routes were consequently disrupted, and in several cases leveling was delayed for weeks to months. These delays were particularly damaging in light of the unusual patterns of deformation apparently in progress during the extended field observations (Raleigh and others, 1982; Jachens and others, 1983). It is also possible that errors were introduced by the general destabilizing effect of heavy rainfall on certain bench marks, especially those set in soils or in outcrops of sedimentary rocks either rich in expansive clays or susceptible to slope failure. Weather-related destabilizing effects may have been particularly prevalent in the coastal areas, where generally more susceptible surface materials were subjected to heaviest rainfall.

Despite some uncertainty concerning the reliability of the SCRP results, the data adequately augment and update the documentation of continuing, often rapid vertical movement within the general region of the southern California uplift. This report assesses the quality of the 1978 leveling data and presents the results of a preliminary analysis of vertical displacements that occurred in southern California between about 1974 and 1978.

ACKNOWLEDGMENTS

Suggestions and discussions regarding leveling data and the details and interpretation of features of the southern California uplift shared by Bob Castle were especially helpful. Ross Stein provided unpublished 1979 leveling data and offered several constructive suggestions for improving the manuscript. The manuscript was also improved in response to the critical reviews and suggestions of Mike Elliott and John Tinsley of the U.S. Geological Survey. Emery Balazs of the National Geodetic Survey provided statistical data concerning the quality of the 1978 observations and answered many routine queries concerning other aspects of the leveling data. Several critical questions regarding the field observations were resolved with the help of Bob Wilson and other members of the Office of the County Engineer, Los Angeles County, and Donald Tillman and David Dona of the Bureau of Engineering, City of Los Angeles.

VERTICAL MOVEMENTS IN SOUTHERN CALIFORNIA DURING THE PERIOD 1959 TO 1974/76

Critical examination and analysis of historical leveling data have established that a broad crustal uplift, ranging between a few tenths to almost half a meter and encompassing nearly 90,000 km^2 of southern California, developed between 1959 and 1974/76[1] (Castle and others, 1976; Castle, 1978; Castle and others, 1984). The shape of the uplift corresponds in several ways to the regional structural grain: from the vicinity of Point Conception west of Santa Barbara, the axis of uplift trends eastward along the north side of the western Transverse Ranges, swings northward to the crest of the Tehachapi Mountains just northwest of the Garlock fault near Mojave, turns southeastward and follows the northeast margin of the San Andreas fault zone through Palmdale to a point near the crest of the San Bernardino Mountains, and then trends eastward along the axis of the eastern Transverse Ranges north of the Salton Trough region (fig. 2). Maximum tilting occurred along the

[1]Dates separated by slashes refer to surveys performed during the stated years. Thus, "1974/76" indicates that leveling done from 1974 through 1976 is combined and considered as a single survey line.

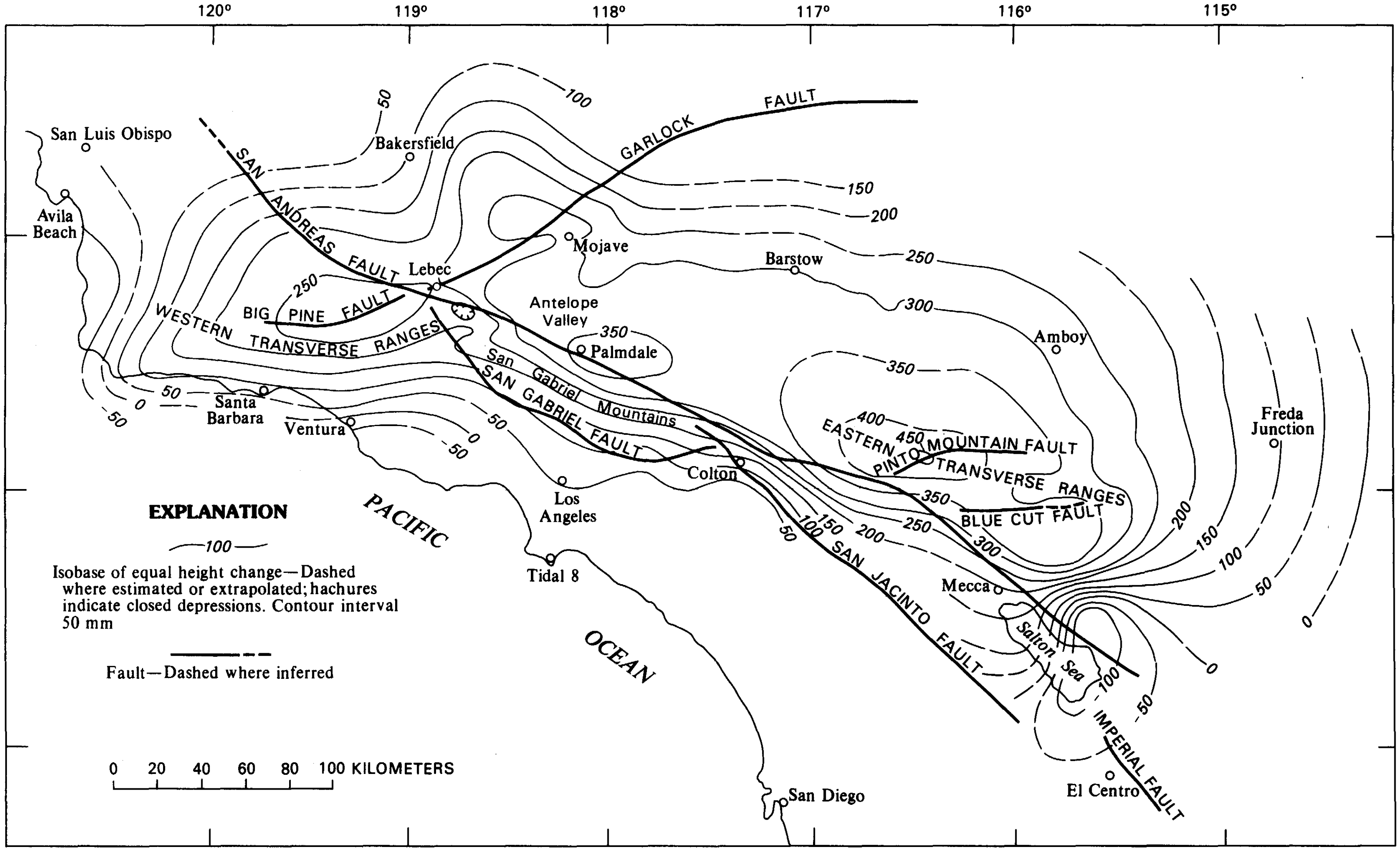


FIGURE 2.—Vertical displacements in southern California between 1959 and 1974 measured with respect to bench mark Tidal 8 adjacent to San Pedro tide station (from Castle and others, 1984, fig. 64).

south-southwest flank of the uplift, which generally coincides with steeper terrain along the south or southwest slopes of the western Transverse Ranges, the San Gabriel Mountains, and the eastern Transverse Ranges. Strong down-to-the-north (northward) tilting also developed at least locally on the north side of the uplift, especially in the vicinity of Bakersfield, and although not as completely documented, it was generally more subdued than the south-southwest tilting along the south flank of the uplift.

EVALUATION OF 1978 LEVELING

Misclosures based on observed elevation differences exceeded the acceptable limits for first-order, class I leveling (defined as 4 mm/km$^{1/2}$ $\times \sqrt{K}$, where K is the circuit length in kilometers) in five of the 20 circuits that compose the SCRP network. These above-limits misclosures are clustered in the south-central and western parts of the network (fig. 1), whereas the rest of the circuits have misclosures that are remarkably low (table 1). It is noteworthy that the mean mis-

TABLE 1.--Lengths and closures of circuits, 1978 SCRP network

CN--Circuit number as given on map of figure 1.
K--Circuit length in kilometers.
S--Circuit-misclosure specifications (allowable limits) for first-order, class I leveling, in millimeters (4 mm/km$^{1/2}$ x$\sqrt{K}$).
OM--Observed circuit misclosures in millimeters (clockwise).
OC--Orthometric corrections for circuit closures in millimeters (clockwise) based on observed gravity.
OCM--Orthometrically corrected clockwise misclosures in millimeters (OCM = OM + OC).
RM--Refraction-corrected orthometric misclosures in millimeters (Holdahl model) (National Geodetic Survey, written commun., Dec. 1981).
D/I--Deterioration or improvement of refraction-corrected misclosure over orthometrically corrected misclosure alone (positive values designate improvement, negative values deterioration).

* Indicates that observed misclosure is in excess of limits specified for first-order, class I leveling.

CN (fig. 1)	K (km)	S (mm)	OM (mm)	OC (mm)	OCM (mm)	RM (mm)	D/I (mm)
1	569.0	±95	-231.7*	+75.2	-156.5	-159.3	-2.8
2	287.9	±68	88.2*	+15.6	103.8	74.3	+29.5
3	275.4	±66	2.1	+2.0	4.1	3.4	+0.7
4	83.5	±37	-2.4	+9.6	7.2	13.6	-6.4
5	109.0	±42	5.9	-9.0	-4.9	-13.9	-9.0
6	148.1	±49	17.5	-1.2	16.3	32.1	-15.8
7	263.6	±65	82.3*	+7.1	89.4	82.4	+7.0
8	374.3	±77	-72.7	+2.0	-70.7	-96.4	-25.7
9	295.6	±69	-38.6	+25.9	-12.7	56.5	-43.8
10	205.9	±57	-30.1	+9.8	-20.3	-28.4	-8.1
11	366.7	±77	-0.7	-9.6	-10.3	-12.3	-2.0
12	255.7	±64	-67.3*	+7.2	-60.1	-82.3	-22.2
13	236.5	±62	-116.5*	+1.3	-115.2	-108.3	+6.9
14	599.7	±98	-20.2	-16.2	-36.4	-31.3	+5.1
15	305.0	±70	-43.7	+20.5	16.8	35.2	-18.4
16	424.6	±82	53.6	-27.5	26.1	16.7	+9.4
17	252.4	±64	56.3	-11.3	45.0	9.4	+35.6
18	407.2	±81	11.8	-17.1	-5.3	0.4	+4.9
19	417.7	±82	26.4	-47.6	-21.2	-20.2	+1.0
20	74.4	±35	14.1	+0.1	14.2	12.7	+1.5
Mean values -----		±67	±49.1		±42.0	±44.0	-52.6 (sum)

closure for all SCRP circuits is only ±49 mm, in comparison with an average tolerance of ±67 mm, and that positive and negative misclosures are approximately balanced throughout the network.

Since misclosures in observed height differences around leveling circuits serve primarily as a field check for the work as it progresses, orthometric corrections based on observed gravity values (Vanicek and others, 1980) have been applied to each of the SCRP circuits in order to convert path-dependent observed elevation differences into uniquely defined true height differences. Orthometric corrections for each of the circuits are presented in table 1, along with the residual, orthometrically corrected misclosures. These corrections reduce the misclosures for all but six of the circuits, and the reductions are especially significant for circuits 1, 9, 10, and 15 through 18. After application of orthometric corrections, the misclosure around circuit 12 is brought to within acceptable limits, and the mean value of the circuit misclosures is reduced to ±42 mm.

Although they are important indicators of survey accuracy, circuit misclosures alone are less than comprehensive indices of the quality or reliability of leveling data over an entire network. For instance, compensating errors in different segments of a circuit might result in an acceptable closure, although such errors occurring on opposite sides of a junction with branching routes would produce distortions in adjacent circuits. Furthermore, excessive closure errors do not necessarily indicate leveling or recording blunders. Instead, they may result from systematic accumulation of height-, slope-, or azimuth-dependent errors, or, in tectonically active regions such as southern California, from contamination of leveling results due to intrasurvey tectonic deformation. The records of repeated levelings in southern California contain a number of well-documented examples of the effects of intrasurvey or intersurvey deformation (Castle and Elliott, 1982; Castle and others, 1983; Jachens and others, 1983), whereas clearly documented cases of significant systematic error are comparatively rare (Mark and others, 1981).

The potential for contamination of geodetic leveling by height- or slope-dependent systematic error has been recognized since the 1890's and has been explored in depth by a number of investigators (Bomford, 1971; Vanicek and others, 1980). It is the recognition or suspicion of potential systematic errors that has dictated many of the rigorous procedural requirements stipulated for geodetic leveling and has also encouraged a progressive tightening of these standards through time (Department of Commerce, Coast and Geodetic Survey Special Publications Numbers 18, 39, and 239; Federal Geodetic Control Committee, 1974; Vanicek and others, 1980, fig. 2). Rigorous analyses show no clear or compelling evidence for systematic error in the 1978 data of the magnitude necessary to account for the larger misclosures (Stein, 1981, fig. 10; Mark and others, 1981), despite various allegations that such errors contaminated certain of the pre-1974 measurements (Jackson and others, 1980; Strange, 1981).

A potential for serious systematic error unrecognized until very recently arises from an apparent interaction between the Earth's magnetic field and the pendulum compensators in modern, automatic levels. At present the full potential for magnetically induced errors is poorly understood. The magnetic response has been demonstrated by laboratory experiments and attempted calibrations of certain instruments (National Geodetic Survey, 1982), but it is not yet clearly established that laboratory test results are strictly applicable to the results of field surveys. The magnetic response of pendulum compensators is not only azimuth dependent, but seemingly also varies with instrument design, and it is both instrument specific and time dependent. Since there may be significant drift in the susceptibility of each instrument, it is doubtful that results of a laboratory calibration obtained in 1982 for a particular instrument should be applied to data acquired with that instrument during the period from 1974 through 1978. Given the mix of instruments involved, including a wide variety of both automatic and spirit levels, the SCRP misclosures are generally so small as to preclude major or pervasive contamination by magnetically induced systematic error. A similar conclusion is reached when results of levelings partially based on suspected instruments are compared with results of independent strain and gravity monitoring (Jachens and others, 1983, fig. 2). Thus, although a number of pendulum-type instruments, doubtless having various levels of potential vulnerability, were deployed in the SCRP and earlier levelings, detailed records of where these instruments were used and what their individual susceptibilities might have been at the time are not considered in this report.

A more serious problem is the fact that height differences determined from the 1978 SCRP leveling along the coastal route show significant discrepancies when matched against height differences established by previous levelings and against steric (oceanographic) determinations of mean sea level at Avila Beach, San Pedro, Newport Beach, and San Diego. Acceptance of the 1978 leveling data along the entire coastal route at face value implies extraordinarily rapid changes in an apparently stationary sea slope that probably has persisted for several decades (Castle and Elliott, 1982). In addition, a sharp break in the 1974 to 1978 height-change profile along the southwest side of the Palos Verdes peninsula west of San Pedro probably is attributable to measurement error, especially since the associated circuit misclosure is of about the same size. In addition, similar uncertainties are raised regarding a succession of abrupt steps in the 1974 to 1978 height-change profile along the coastal route from Newport Beach southeastward to San Diego. Possible errors in either or both of the two surveys compared could have been incorporated because of either misidentification of bench marks, effects of intrasurvey surficial movement (for example, soil slump or landslide slope failure), or observational blunders. The latter source is considered much less likely than the others, because gross blunders are rendered all but impossible by current observational procedures specifying the use of dual-scale leveling rods and programmed recording methods. However, because the coastal leveling was an NGS effort based on automatic levels and almost exclusively (95 percent of the route) on the Zeiss[2] Ni 1, the instrument now considered most susceptible to magnetic error, there is increased likelihood that the large misclosures of certain circuits involving the coastal route and other described discrepancies along the coast may be the product of magnetically induced systematic errors.

The possibilities of contamination of the SCRP leveling results by intrasurvey deformation (warping or tilting) in the tectonically active southern California region were greatly increased by extended delays in the work, caused by inclement weather, during a time of conspicuous change in the pattern of strain accumulation (Raleigh and others, 1982). Leveling along virtually all routes was delayed to some extent. Particularly susceptible to such contamination are the generally north-south level lines across the Transverse Ranges and the San Gabriel Mountains, not only because of delays experienced there during the period of heavy snow cover at the higher elevations, but also because these routes generally are nearly perpendicular to the axis of the 1959-1974/76 uplift, which tends to follow the regional tectonic grain (see figs. 2 and 4). Presumably, leveling along routes at high angles to the structural grain would be more subject to intrasurvey distortions, produced by any continuation or reversal of the established pattern of deformation, than leveling along routes that follow the regional structure (that is, routes nearly parallel to isobases of regional tilting). Possible tectonic movement during long delays at several places along the coastal route may have contributed to discrepancies between geodetic leveling results and independent mean sea-level determinations, as well as to the excessive circuit misclosures. This possibility is especially critical in areas of known high activity such as in the coastal mountains just west of Ventura, where rapid vertical deformation is well documented by large signals developed between earlier leveling surveys (Buchanan-Banks and others, 1975) and by studies of uplifted marine terraces that have established long-term uplift rates near Ventura as great as 10 mm/yr during at least the past 40,000 years (Lajoie and others, 1979; Lajoie and others, 1982, p. 47-48).

The possibility that the excessive circuit misclosures and other discrepancies may have resulted largely from intrasurvey tectonic deformation is also suggested by comparison of repeated leveling within at least two short sections observed before and after long delays. Specifically, the leveling across steep, high terrain of the San Gabriel Mountains between Azusa and Llano (fig. 1) was delayed for 87 days because of heavy snowfall, and the subsequent releveling of an 830-m-long section showed that the initial elevation difference had increased by nearly 4 mm ($\sigma = \pm 1.4$ mm), equivalent to a northward tilt of 4.8 ± 1.7 μradians. Another long delay, between January 11 and April 13 (92 days), hampered the leveling about 15 km north of Ozena (fig. 1). Subsequent releveling detected a 4.5-mm ($\sigma = \pm 1.7$ mm) increase in the elevation difference between endpoints of the 1.35-km-long section, equivalent to a northward tilt of 3.3 ± 1.3 μradians. These probable indications of intrasurvey tectonic deformation during the course of the SCRP leveling, although conceivably related instead to rainfall-induced instabilities of bench

[2]Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

marks, are further reinforced by observations of continued northward tilting on several of the north-south routes that were releveled during 1979 as part of a regional tilt-monitoring project (Jachens and others, 1983).

Despite excessive closure errors within four of the network circuits (table 1) and independent indications of continuing deformation during the period of observations, the precision of the 1978 SCRP leveling was generally good, although somewhat less than the conventionally estimated ± 0.512 mm/km random error expected on the basis of first-order, class I specifications (Federal Geodetic Control Committee, 1974). A set of standard-deviation determinations based on comparisons of observed elevation differences obtained for forward and backward leveling runs on each section between bench marks, normalized to a 1-km section length, averaged ± 0.71 mm for the network as a whole and ranged from ± 0.54 to ± 1.07 mm for a subset of 15 segments from several of the leveling routes separately evaluated (table 2).

Evidence from other networks has been cited to suggest that a systematic (statistically dependent or correlated) error in section misclosures may increase circuit misclosures above the tolerance limits by as much as 30 percent, a figure based on the predicted accumulation of conventionally estimated random error (Remmer, 1975; Vanicek and others, 1980). However, the large residual misclosures for four of the SCRP circuits, which after orthometric corrections still range between 38 percent and 86 percent above the conventionally estimated misclosure tolerances (fig. 1, table 1), are not readily explained as the product of statistically dependent errors associated with section misclosures.

The relatively high precision of section closures, as contrasted with the excessive residual misclosures of isolated circuits, suggests that the circuit misclosure problem is attributable to intrasurvey tectonic deformation. Castle and Elliott (1982, p. 6989) conclude, for example, that "Geodetic leveling is the inherently accurate measurement system that it has been thought to be. However, it is flawed in application in one significant respect—it is time consumptive." In the case of the 1978 SCRP data, intrasurvey tectonic deformation remains as the most likely cause of otherwise inexplicably large circuit misclosures because the in-

TABLE 2.--Statistical evaluation of selected parts of SCRP network

N--Number of sections used in the test.
S--Standard deviation of double-run sections within the test segment, normalized to a 1-km length, in millimeters per kilometer.
R--Percentage of sections within the test segment initially rejected for excessive misclosure (sections partially or wholly reobserved at least once).

Line No.	Description of test segment	N	S	R
All lines	Entire SCRP Network---------------	6484	± .709	5.9
L24301.1	Pismo Beach to Ventura------------	272	± .61	3.9
L24301.1	Topanga Beach to San Pedro--------	165	± .63	4.1
L24301.1	San Pedro to Seal Beach-----------	56	± .54	3.4
L24301.1	Seal Beach to Newport Beach-------	49	± .70	3.9
L24301.1	Newport Beach to San Diego--------	269	± .68	4.1
L24301.2	Pismo Beach to McKittrick---------	191	± .77	9.5
L24301.2	McKittrick to Ozena---------------	262	± .56	2.8
L24301.2	Ozena to Ojai---------------------	112	± .90	5.9
L24301.13	Colton to near Cajon Pass---------	182	± .71	5.0
L24301.16	Colton to Newport Beach-----------	179	± .75	6.0
L24301.24	Yucca Valley to Whitewater--------	36	± .48	5.3
L24301.28	Mecca to Cottonwood Pass----------	29	±1.07	13.6
L24301.13	Burbank to Colton-----------------	200	± .64	5.0
L24301.23	Amboy to Twentynine Palms---------	86	± .67	9.0
L24301.18	El Centro to Mecca----------------	153	± .80	15.7

dividual section closures were rapidly completed within hours or days, whereas the large circuits were not completed for weeks or months and, as a consequence, were much more susceptible to the effects of continuing or frequent episodes of vertical deformation. On the basis of strong evidence for dramatic, short-term pulses of aseismic deformation in the southern California region (Jachens and others, 1983) and the data concerning aseismic slip on various parts of the San Andreas fault system in other regions (Goulty and others, 1978; Schulz and others, 1982), it is not unreasonable to expect short-term differential vertical movements in southern California on the order of 10 mm due to episodes of local to regional aseismic deformation lasting from a few days to a few months.

COMPARISON OF 1978 LEVELING WITH SURVEYS COMPLETED BETWEEN 1972 AND 1976

In light of the reservations concerning possible contamination of the 1978 SCRP data by intrasurvey deformation and possible systematic errors, perhaps the most reliably determined height changes are those obtained along the generally east-west leveling routes (figs. 1, 3). For the purpose of constructing a framework of connected routes to compare the 1974 and 1978 levelings, height changes along the east-west routes were tied to height changes along the frequently releveled route from San Pedro through Saugus and Palmdale to Mojave (figs. 1, 3). Wherever compatible, the results obtained along other north-south routes and parts of the coastal route were incorporated to augment the coverage. The east-west inland routes were combined primarily with connecting routes that form smaller, well-closed circuits to provide 1978 coverage that can be compared most confidently with the results of earlier surveys to obtain a preliminary set of recent height-change values.

The most recent prior surveys along most of the 1978 SCRP routes were completed during 1973 and 1974 (fig. 3). Additional control from observations completed in adjoining parts of the network during 1972, 1975, and 1976 generally produce satisfactory circuit closures in combination with the 1973/74 levelings, except around the easternmost circuit. With that one exception, the circuit closures based on combinations of 1973/74 data with results of 1972 and 1976 levelings indicate that these selected parts of the region showed no significant tilting and thus were relatively stable between 1972 and 1976 (table 3; fig. 3). Relative height changes for all bench marks that were common to both the 1972/76 and the 1978 surveying periods were computed by direct comparison along each of the routes shown in figure 3. Bench mark Tidal 8, adjacent to the San Pedro tide station, was held fixed as the primary reference point for all comparisons.

Results from several of the releveled segments suspected to be contaminated were omitted before proceeding with the final analysis. Apparent height changes along the coastal route from San Pedro to Topanga Beach were rejected because the height-change value at Topanga Beach was inconsistent with the value determined along the route passing through Burbank, Saugus, and Oxnard (fig. 3). The results of additional 1978/79 leveling by Los Angeles City and County along four ties crossing the area enclosed by circuit 7 (fig. 1) of the 1978 network isolates an error in the coastal segment between San Pedro and Topanga Beach comparable to the 1978 misclosure (Robert Wilson, written commun., 1979). Results from Newport Beach inland to Cajon Junction were set aside because of inconsistencies in height-change values at Colton and Cajon Junction in comparison with results for routes from San Pedro through Burbank and Pomona to Colton, and through Saugus and Palmdale to Cajon Junction. Thus, the framework of comparable, repeated levelings along the routes shown in figure 3 (less the three sections omitted) provides the basis for a preliminary comparison of 1972/76 and 1978 heights. Although the available coverage actually consists of two separate networks connected only by the single line between Mojave and Amboy, the validity of the connection is supported by the remarkable stability of this segment (absence of significant tilting) determined by comparisons with other recent levelings; the only exceptions are the apparent coseismic effects associated with the 1952 Kern County earthquake and the westward tilting along the route from Boron to Barstow between 1972 and 1974 (Castle and others, 1984).

Several critical assumptions were introduced into the analysis of 1972/76 to 1978 height changes in order to interpolate or extend the pattern of vertical deformation between and beyond the areas of directly comparable survey control shown in figure 3. Because contamination of SCRP results along the coastal route is suspected as a conse-

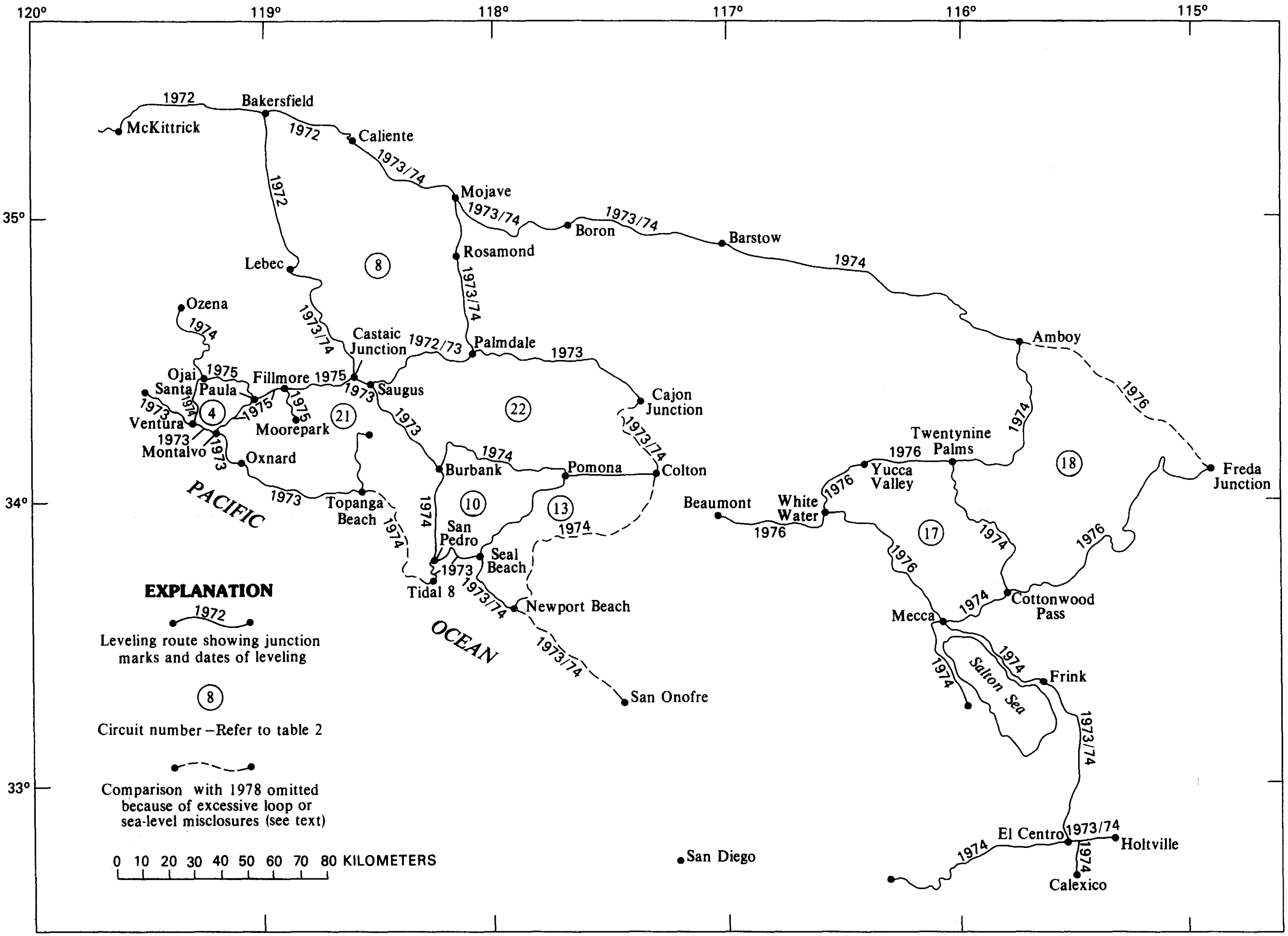


FIGURE 3.—Index map of routes leveled between 1972 and 1976 that are common to the 1978 SCRP network. Circuits that were included in the 1978 SCRP network are identified by the same numbers given in table 1 and figure 1. Data on circuit lengths and on observed and orthometrically corrected misclosures for levelings completed between 1972 and 1976 are presented in table 3.

quence of instrumental errors or intrasurvey displacements, a comparison of the 19-year sea-level means for the San Pedro, Avila Beach, and San Diego tide stations is included in the analysis. This comparison independently indicates that these tide stations have remained relatively stable with respect to one another, thus providing a reliable basis for extending the control for vertical motion from San Pedro to the two outlying points (Castle and Elliott, 1982). In addition, relative stability or a minimal eastward tilt of the northern Peninsular Ranges east of San Diego is assumed on the basis of a nearly perfect match between the 1956, 1968, and 1978 height determinations along the route between San Diego and Julian (Mark and others, 1981, fig. 12). This assumption, if true, would constrain a zone of steep eastward tilting to within the region between Julian and a point near Campo, about 65 km east of San Diego, near the end of the 1974 and 1978 comparison west of El Centro (see figs. 3 and 5). Finally, a partial collapse and westward tilt between 1976 and 1978 of the terrain covered by the easternmost circuit of the network (circuit 18) is assumed to be well represented by an unconstrained height-change profile between Cottonwood Pass and Freda Junction obtained through comparison of 1976 and 1978 levelings (fig. 4).

Although this final assumption is seemingly arbitrary, the basis for it is provided in the following detailed assessment of the complicated nature of deformation between 1974 and 1978 in the vicinity of circuit 18. The area within the eastern Transverse Ranges north of the Salton Sea has undergone intense, relatively complex deformation in recent geologic time that has continued to the present, as indicated by high seismicity, steep and rugged terrain, complex patterns of faulting, and the distribution of vertical movement that accumulated between 1959 and 1974 (fig. 2). Thus, the complexity of deformation (fig. 5) determined by comparisons of 1974, 1976, and 1978 leveling surveys around circuits 17 and 18 (figs. 3, 4) comes as no surprise. Unfortunately, the temporal distribution of leveling in the area is insufficient for a complete and unambiguous resolution of the details of post-1974 deformation.

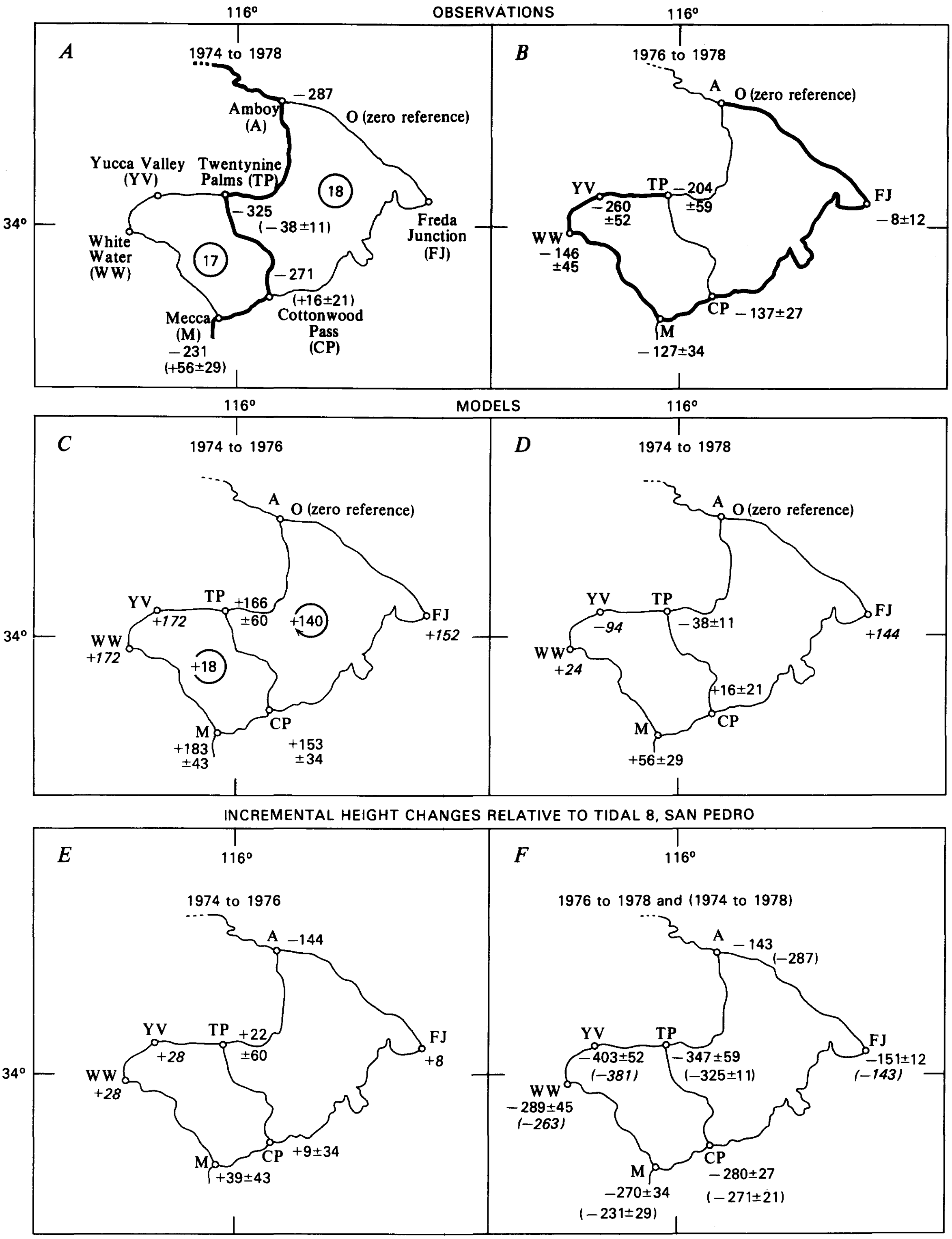
The only leveling done during 1974 in the eastern Transverse Ranges was along the route from Barstow to Frink, via Amboy, Twentynine Palms,

TABLE 3.--Lengths and closures of circuits, 1972/1976 network

CN--Circuit number as given on map of figure 3.
K--Circuit length in kilometers.
S--Circuit misclosure specifications in millimeters (allowable limits) for first-order, class I leveling ($4\ mm/km^{\frac{1}{2}} \times \sqrt{K}$).
OM--Observed circuit misclosures in millimeters (clockwise).
OC--Orthometric corrections for circuit closures in millimeters (clockwise) based on observed gravity.
OCM--Orthometrically corrected clockwise misclosure in millimeters (OCM = OM + OC).

* Indicates that observed circuit misclosure is in excess of limits specified for first-order, class 1 leveling

CN (fig. 1)	K (km)	S (mm)	OM (mm)	OC (mm)	OCM (mm)
4	83.5	±37	-33.0	+9.6	-23.4
8	374.3	±77	20.8	+2.0	22.8
10	205.9	±57	-12.9	+9.8	-3.1
13	236.5	±62	56.0	+1.3	57.3
17	252.4	±64	29.5	-11.3	18.2
18	407.2	±81	156.8*	-17.1	139.7
21	324.1	±72	-25.7	-3.1	-28.8
22	349.1	±75	19.2	+33.1	52.3
Mean values -----		±66	±44.2		±43.2


OBSERVATIONS
116°
A
1974 to 1978
Amboy (A)
−287
O (zero reference)
Yucca Valley (YV)
Twentynine Palms (TP)
18
−325
(−38±11)
17
White Water (WW)
Freda Junction (FJ)
−271
(+16±21)
Cottonwood Pass (CP)
Mecca (M)
−231
(+56±29)
34°
B
1976 to 1978
A
O (zero reference)
YV
TP
−204
±59
−260
±52
WW
−146
±45
FJ
−8±12
CP
−137±27
M
−127±34
MODELS
C
1974 to 1976
A
O (zero reference)
YV
+172
TP
+166
±60
+140
FJ
+152
WW
+172
+18
M
+183
±43
CP
+153
±34
D
1974 to 1978
A
O (zero reference)
YV
−94
TP
−38±11
FJ
+144
WW
+24
+16±21
CP
M
+56±29
INCREMENTAL HEIGHT CHANGES RELATIVE TO TIDAL 8, SAN PEDRO
E
1974 to 1976
A
−144
YV
+28
TP
+22
±60
FJ
+8
WW
+28
M
+39±43
CP
+9±34
F
1976 to 1978 and (1974 to 1978)
A
−143
(−287)
YV
−403±52
(−381)
TP
−347±59
(−325±11)
FJ
−151±12
(−143)
WW
−289±45
(−263)
M
−270±34
(−231±29)
CP
−280±27
(−271±21)

Cottonwood Pass, and Mecca (figs. 3, 4*A*). Circuits 17 and 18 were closed against the north-south 1974 route by 1976 levelings to the west through White Water and Yucca Valley and to the east through Freda Junction (fig. 4*B*). The route between Cottonwood Pass and Mecca was also releveled during 1976. Combining the 1974 and 1976 levelings around circuit 17 results in an orthometrically corrected misclosure of only +18 mm (table 3), which suggests that the junction marks at Twentynine Palms and Mecca were very nearly stable or moved uniformly during 1974 to 1976 (fig. 4*C*). Nevertheless, the large, orthometrically corrected misclosure of +140 mm for circuit 18 (table 3) produced by linking the 1974 survey at Amboy and at Cottonwood Pass with the 1976 survey (through Freda Junction) indicates that deformation was in progress, at least between the two junctions, sometime during the same period. Specifically, the Cottonwood Pass junction must have been uplifted about 140 ±34 mm with respect to Amboy sometime after the 1974 leveling along the north-south route but before completion of the 1976 leveling along the route through Freda Junction (fig. 4*C*). The comparison of relative heights at Cottonwood Pass with respect to Amboy, as determined by separate, unconstrained surveys in 1974 and 1976, and by the 1978 network results, suggests an uplift of about 153 mm at Cottonwood Pass between 1974 and 1976. Approximately the same amount of uplift relative to Amboy is assumed for the same period at Freda Junction.

The apparent stability between 1974 and 1976 of the junction marks at Twentynine Palms and Mecca (or Cottonwood Pass) indicates that about the same amount of relative movement occurred at all three junctions with respect to Amboy. The effect of arbitrarily distributing the 287-mm collapse of Amboy with respect to San Pedro equally between the two periods 1974-76 and 1976-78 (about −143 mm during each 2-year period) suggests that a general collapse of the previous uplift in the eastern Transverse Ranges area may have started in the north (1974-76) and then proceeded southward (1976-78), perhaps leaving Freda Junction relatively high (fig. 4*E*, *F*). Thus by the time of the 1978 leveling, the maximum rate of collapse may have already shifted southward to a center near Yucca Valley, the site of previous maximum uplift (fig. 2). The assumption that Freda Junction moved upward 152 mm during 1974-76 (fig. 4*C*) to keep pace with the upward movement of Cottonwood Pass (with respect to Amboy) has the effect of closing off the 1974-78 vertical deformation rapidly toward the Colorado River to the east, a feature of the general deformational history suggested by several other lines of evidence (Gilmore and Castle, 1983).

The pattern of relative height changes from 1974/76 to 1978 (figs. 5, 6) is dominated by pervasive eastward to northward tilting throughout most of the region, modified by local tectonic warping in the Transverse Ranges east of Ventura, in the San Joaquin Valley south of Bakersfield (after removal of the estimated effects of artificially induced subsidence), in the Imperial Valley area from the Salton Sea southeastward, and north of the Little San Bernardino Mountains near Yucca Valley (between Barstow and Mecca). Height changes shown in figure 5 include the effects of nontectonic subsidence attributable to removal of underground fluids in at least two well-defined regions of extensive pumping, one south of Bakersfield and the other in the Antelope Valley

FIGURE 4.—Compilation of height changes (in millimeters) at major junctions for circuits 17 and 18 in the eastern Transverse Ranges area of southern California, based on discrepancies in leveling results along different routes observed (*A*) between 1974 and 1978 and (*B*) between 1976 and 1978. (*C*) Height changes at Cottonwood Pass, Mecca, and Twentynine Palms relative to Amboy, indirectly determined by comparison of height values established by 1974 and 1976 surveys along different routes (except for the common link between Cottonwood Pass and Mecca), are augmented by assumed height changes (numbers in italics) at Freda Junction (+152 mm), and at White Water and Yucca Valley (+172 mm). Aside from assumed changes, these values are obtained by subtracting the 1976-78 height changes relative to Amboy (as shown in *B*) from the 1974-78 changes (as shown in parentheses in *A*). (*D*) The model of 1974-78 height changes relative to Amboy is derived by adding the height changes shown in *B* and *C*. Italicized numbers indicate values based on the assumed changes shown in *C*. Incremental changes (1974-76, 1976-78, and 1974-78) with respect to the prime reference bench mark Tidal 8 at San Pedro are based on an assumption that the 287-mm downward movement at Amboy accumulated at an approximately constant rate between 1974 and 1978: about −144 mm (relative changes in *C* minus 144 mm) from 1974 to 1976 (*E*), and another −143 mm (relative changes in *B* minus 143 mm) between 1976 and 1978 (*F*). Values in parentheses in *F* designate the long-term changes between 1974 and 1978 given by the observed and assumed relative changes in *D* minus 287 mm.

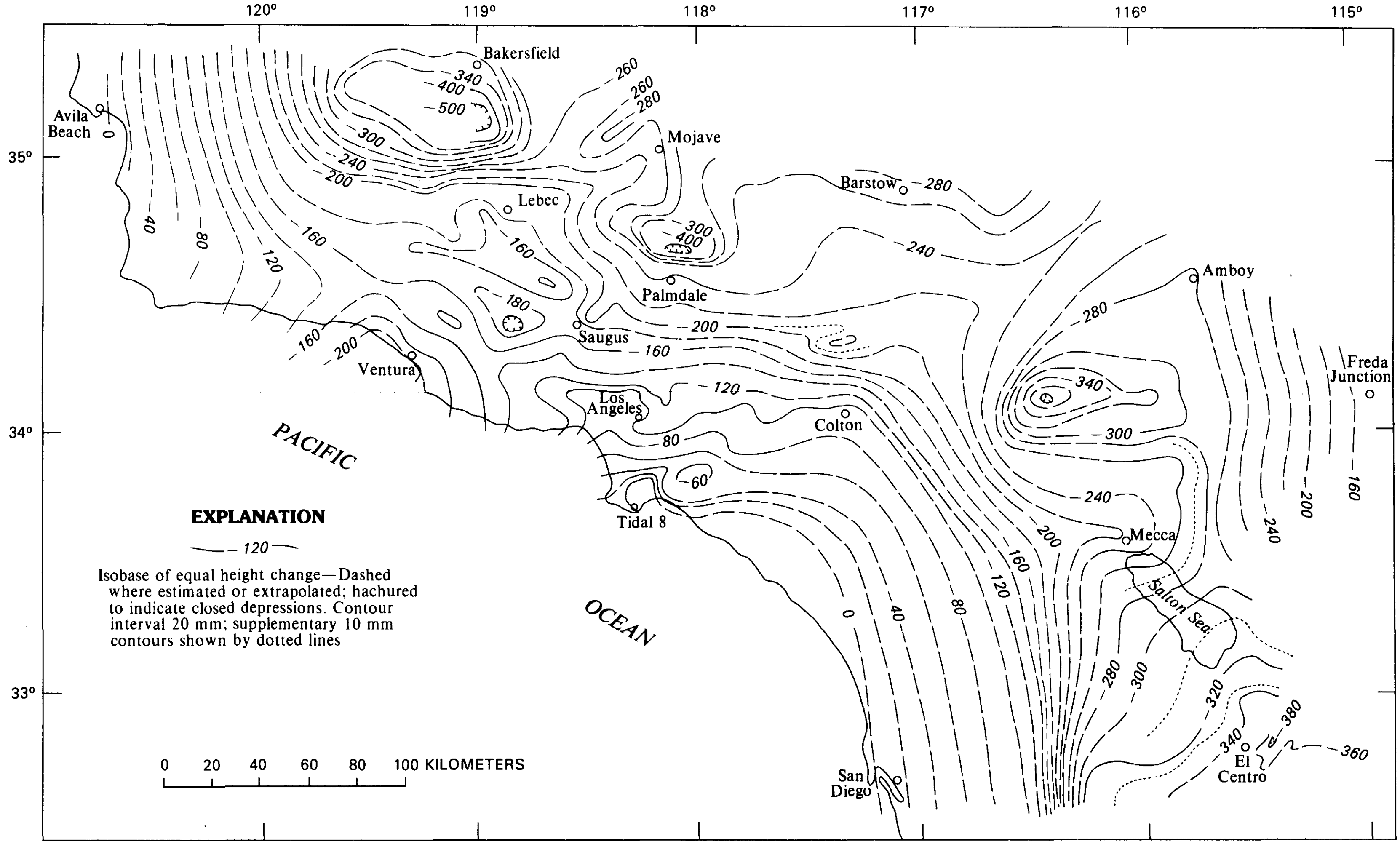


FIGURE 5.—Map showing changes in heights in southern California relative to bench mark Tidal 8 adjacent to the San Pedro tide station, based on comparisons between the results of 1972/76 and 1978 levelings. Closed depressions south of Bakersfield and north of Palmdale represent areas of major subsidence associated with withdrawal of underground fluids.

north of Palmdale. Bench marks in Bakersfield, however, appear to be situated in an area free of the effects of artificially induced subsidence, as indicated by the nearly stable 1972/74 to 1978 height-change profile between McKittrick and Mojave that passes through Bakersfield. Moreover, comparisons between several earlier surveys demonstrate consistently stable conditions at Bakersfield (Castle and others, 1976; Castle, 1978). Although downward movement in the vicinity of Ventura occurs in an area of high-volume oil production, the breadth of the downwarp and the intervening occurrence of several strong earthquakes in that area suggest tectonic deformation.

Excluding areas of artificially induced subsidence, the maximum north to northeastward tilting occurred within a narrow zone that coincides with the southern boundary of the Transverse Ranges province, a belt of generally steep terrain characterized by strong south to southwestward tilting during the 1959-74 uplift. The 1972/76-1978 pattern of height changes is related to the patterns of major faulting and of minor to moderate earthquake occurrences during 1974 through 1978 (fig. 6*B*); regions of pronounced tilting or warping are also commonly characterized by much more frequent occurrences of minor to moderate earthquakes than the surrounding, relatively quiescent regions. For example, the nearly total collapse of the previous maximum uplift in the vicinity of Yucca Valley and Twentynine Palms occurred in an area of frequent earthquake activity, including occasional swarms of moderate shocks. Along the south side of the local downwarp, east-west lineations in the pattern of earthquake epicenters and similar orientations in the height-change contours (fig. 6*A*) concide with active east-west oriented fault traces, as represented by the Pinto Mountain and Blue Cut faults (figs. 2, 6*B*).

TIMING AND NATURE OF THE REVERSAL IN VERTICAL MOVEMENT SUGGESTED BY OTHER OBSERVATIONS

Large, correlated changes in local gravity, elevation, and strain values recorded between 1977 and 1981 near Lebec, Palmdale, and Cajon Junction (fig. 1; Jachens and others, 1983) strongly support the conclusions that aseismic tectonic deformation can occur rapidly and that such changes may not always be smooth and progressive. Each of the three monitoring sites was subjected to short period (1 to 2 yr), high amplitude (100 to 150 mm) relative elevation changes that were accompanied by local changes in both gravity and horizontal strain (plane dilatation). Changes in each parameter were consistent with the concept that vertical bulging, indicated by increases in elevation ($\delta e>0$) and corresponding decreases in observed gravity ($\delta g<0$), is likely associated with negative changes in plane dilatational strain ($\delta\Delta<0$), and vice versa for tectonic subsidence. Stable conversion constants (scale factors) were derived from the three correlated data sets. The scale factor relating gravity and elevation changes for these data ($\delta g/\delta e = -0.2$ μgal/mm) is the same as that established by studies of coseismic deformation associated with the 1964 Alaskan and 1971 San Fernando earthquakes (Jachens and others, 1983, fig. 2 and p. 1216).

The derived scale factor relating changes in elevation and horizontal strain for the 1977-81 southern California data ($\delta e/\delta\Delta = -100$ mm/μstrain) seemingly requires that the vertical strains associated with elevation changes be distributed through an elastic plate 200 to 300 km thick, assuming a Poisson's ratio of 0.25 to 0.30 (Jachens and others, 1983, p. 1216). Despite some uncertainty and skepticism regarding this result, this scale factor, in conjunction with the long-term, negative strain-change trend of about -1.7×10^{-7}/yr (Savage and others, 1981), predicts a regional average uplift rate in southern California of about 17 mm/yr during the strain-monitoring period between 1971/72 and 1977/79. This period was characterized by a nearly steady, regional accumulation of north-south contraction at 2 to 3×10^{-7}/yr with little or no significant east-west extension.

If we assume that the 1971/72 through 1977/79 negative strain-change trend was actually established in the late 1950's at about the onset time of the most recent southern California uplift, then an average regional uplift of about 320 mm would have been produced at that rate by the late 1970's, a close match for the general uplift value based on repeated leveling (fig. 2). Thus, the uplift value predicted from backward extrapolation of the strain trend strongly supports the reliability of the leveling results. The apparent onset of the uplift in about 1959 came a few years after a period of high seismicity (1952-55) that was dominated by the 1952 Kern County earthquake sequence (main shock of $M_L = 7.7$). The end of high seismicity in

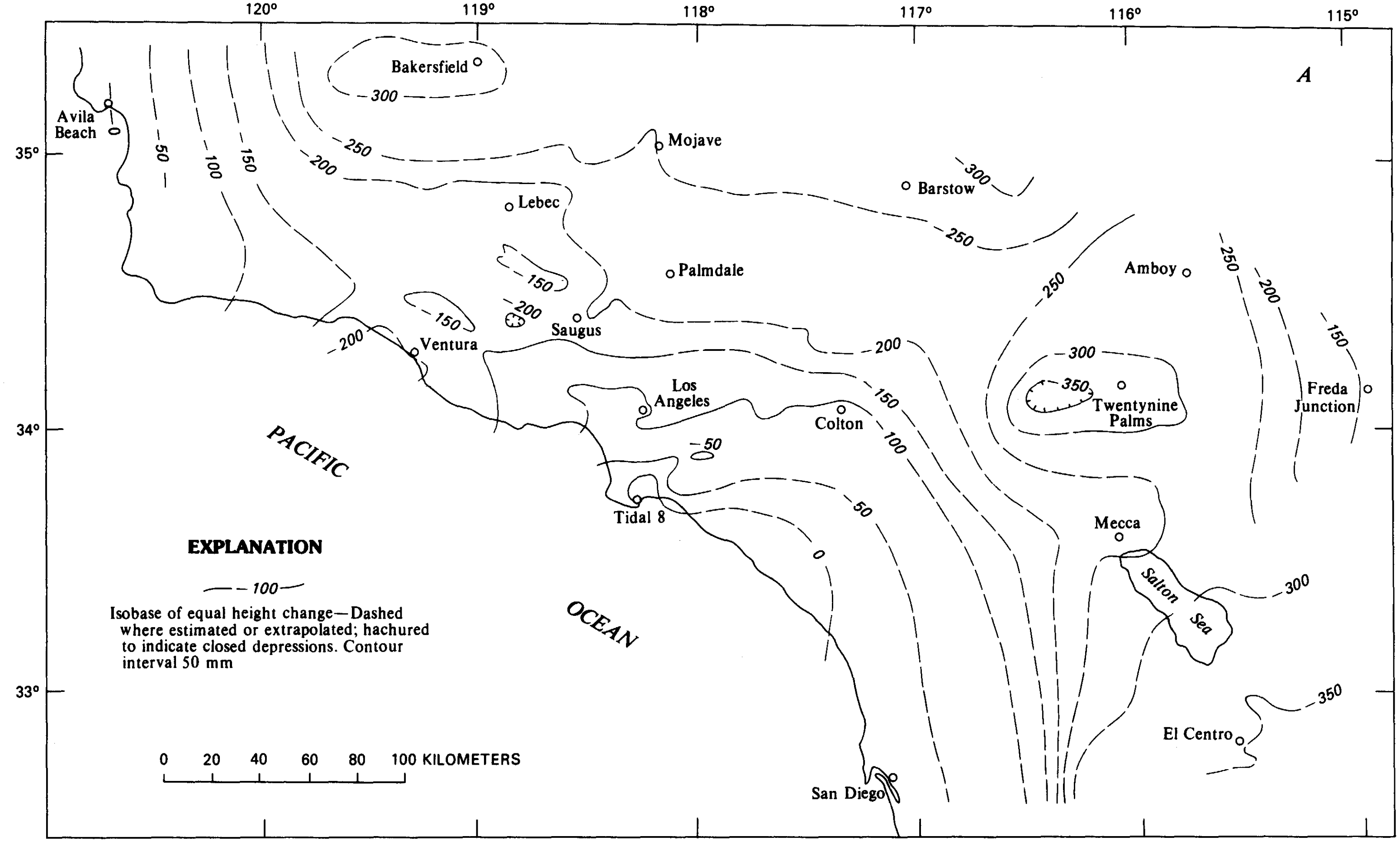


FIGURE 6.—(*A*) Changes in heights in southern California, based on comparisons of 1972/76 and 1978 leveling results along the routes indicated in figure 3 after removal of estimated nontectonic height decreases in known subsidence areas. (*B*) Epicenters of southern California earthquakes recorded from January 1, 1974, through December 31, 1978. Trends of major faults in the region are also shown.

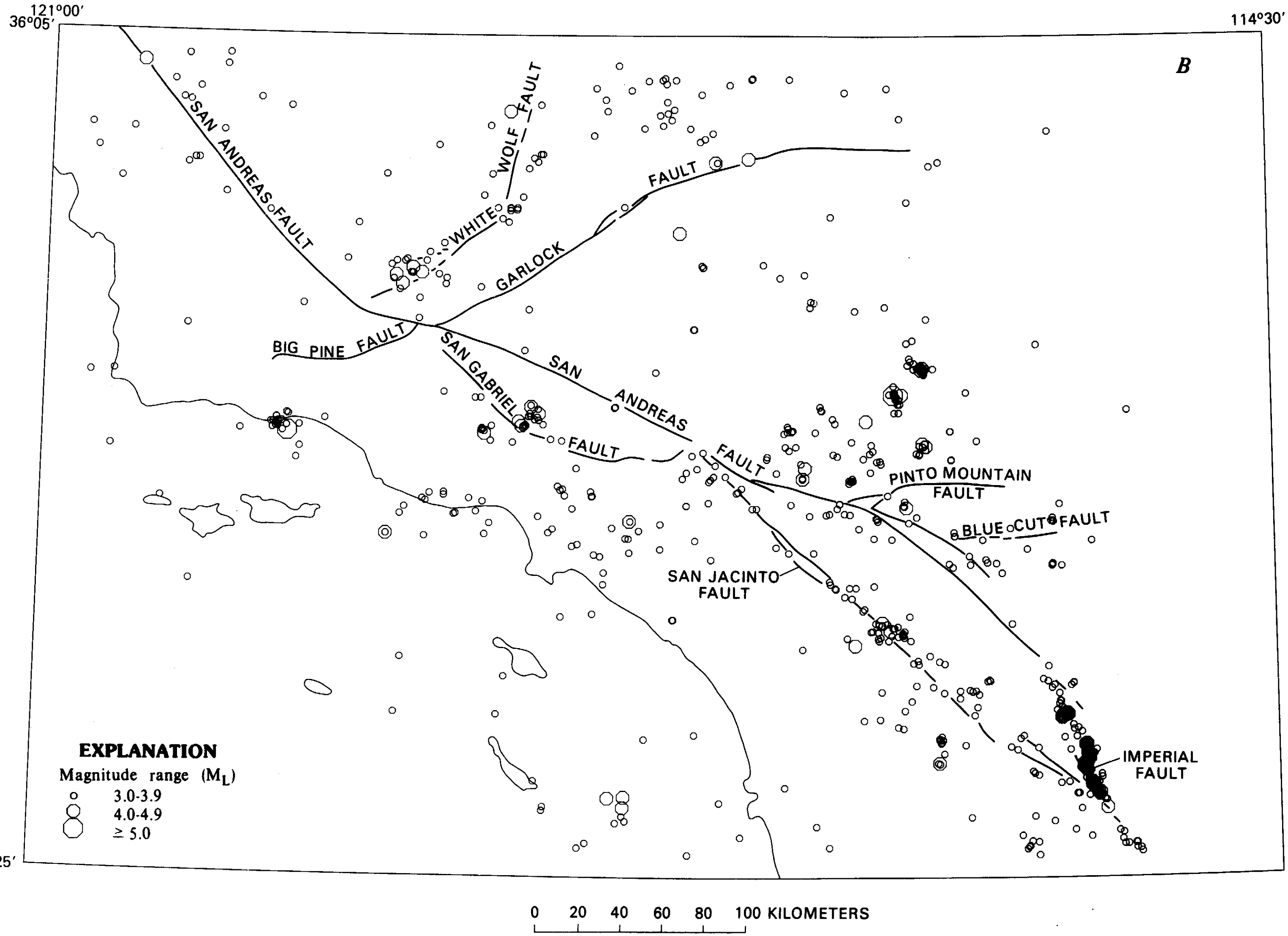


FIGURE 6.—Continued

about 1955/56 marked the onset of a period of relative quiescence, somewhat interrupted by the 1971 San Fernando shocks, but more positively terminated by the occurrence of moderate to major earthquakes in 1978/79.

As emphasized by Raleigh and others (1982, figs. 7 and 8), the recent increase in seismic activity (1978/81) was associated with a dramatic reversal of the 1971/72 to 1977/79 negative strain trend (onset of regional east-west extension with little to no significant north-south strain). While the reversal occurred as early as late 1977 or early 1978 in the Salton Sea and Anza areas, and as late as the beginning of 1979 in the Palmdale area, the change was essentially coherent over the broad southern California region within a 1.2-year time span with a mean reversal time of about April 1978. Thus, the change in regional deformational pattern from tectonic uplift to subsidence, which according to results of repeated levelings seems to have had an onset sometime after 1976 but before 1978 and a definite continuation during 1978 and 1979, is closely associated with the change in the pattern of horizontal strain accumulation. The average rate of positive dilatational strain was about 0.5 μstrain/yr during 1978 and 1979, consistent with a rapid partial collapse of the previous uplift at a rate of about 50 mm/yr.

CUMULATIVE VERTICAL DISPLACEMENTS DURING THE PERIOD 1959 TO 1978

Preliminary results of the comparison of 1972/76 and 1978 levelings indicate a partial collapse of the southern California uplift with little substantial change in its shape and relatively modest reduction in its areal extent. This result can be most readily demonstrated by superimposing values of 1972/76-1978 height change on the pattern of 1959-74 uplift contours to produce a map of 1959-78 cumulative (residual) height changes (fig. 7). Despite local complexities in the pattern of the more recent height changes and the strongly developed north to northeastward tilting, the prime features of the 1959-74 uplift clearly persist in the pattern of cumulative vertical movement, albeit at substantially lower amplitudes (compare figs. 2, 7). The major axis of the residual uplift follows nearly the same trend as that developed between 1959 and 1974. West of Lebec, the axis follows a nearly east-west trend, parallel to that of the western Transverse Ranges. The axis turns southeastward at Lebec and follows the trend of the San Andreas fault zone to the Little San Bernardino Mountains, where it turns eastward and continues along the trend of the eastern Transverse Ranges. Residual height-change values along the primary axis of uplift range from less than 100 to more than 150 mm relative to bench mark Tidal 8, roughly one-third of the peak values attained by 1974.

Several secondary features of local warping associated with the 1959-74 uplift were sharply accentuated by the continuing deformation. A local tectonic depression, between 50 and 100 mm in amplitude, centered on the San Andreas fault about 20 km southeast of Lebec and clearly defined in the pattern of vertical movement between 1959 and 1974, was enlarged to an elongate, northwest-trending troughlike downwarp. A lobe of the 1959-74 uplift centered just north of Cottonwood Pass, which was flanked on the south by a steep gradient of southeast tilting and on the north by a slight downwarp, subsequently developed into a more elongate east-west-oriented residual upwarp with steep southeastward tilt on the south and a more pronounced east-west elongate depression on the north. The center of 1959-74 tectonic subsidence near Frink, in the Salton Sea area, had by 1978 apparently shifted about 20 km to the south, and the subsidence increased. The initial differential height change of 450 to 500 mm between Cottonwood Pass and this center of subsidence apparently increased by 50 mm or so, even though a roughly 250-mm collapse occurred in the Cottonwood Pass area during the continuing deformation. In addition to the general decrease in uplift amplitude and the almost complete collapse of the previous maximum uplift near Yucca Valley and Twentynine Palms, the most significant changes in the cumulative (residual) pattern since 1974 were the development of an east-west-trending downwarp of more than 200 mm along the south flank of the uplift which cuts across the coastline just south of Ventura and may extend westward into the Santa Barbara Channel, a remarkable deepening of the tectonic depression in the southeast end of Salton Sea, and the enhancement of an east-west-trending residual upwarp running from about 20 km north of Mecca eastward along the crest of the Eagle Mountains.

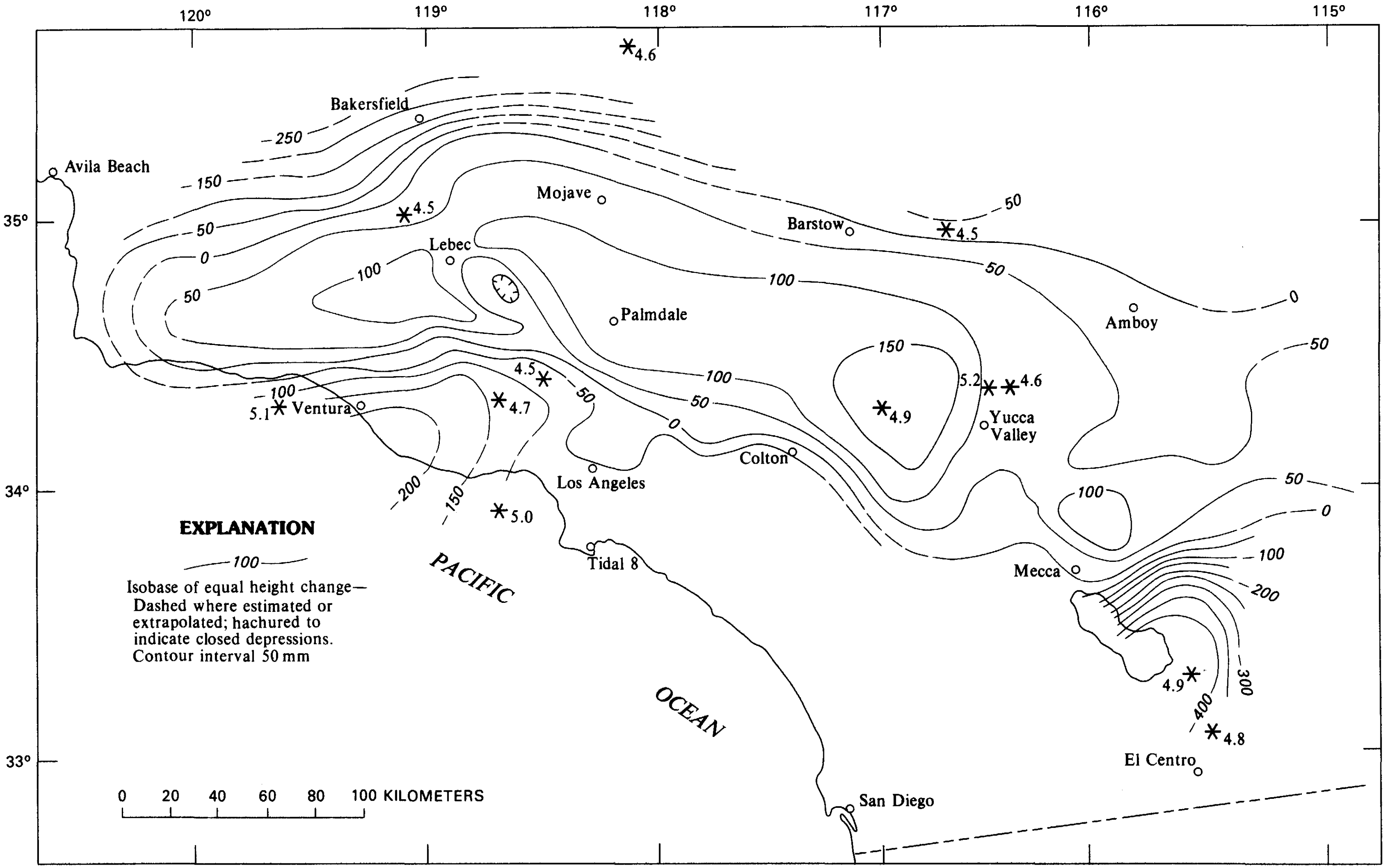


Figure 7.—Pattern of residual height changes (1959-78) relative to bench mark Tidal 8 at San Pedro obtained by superimposing 1972/76-1978 height changes indicated in figure 5 on the contours of 1959-74 vertical movement shown in figure 2. Epicenters of earthquakes ($M_L \geq 4.5$) that occurred between July 1, 1974, and August 31, 1978, are indicated by asterisks.

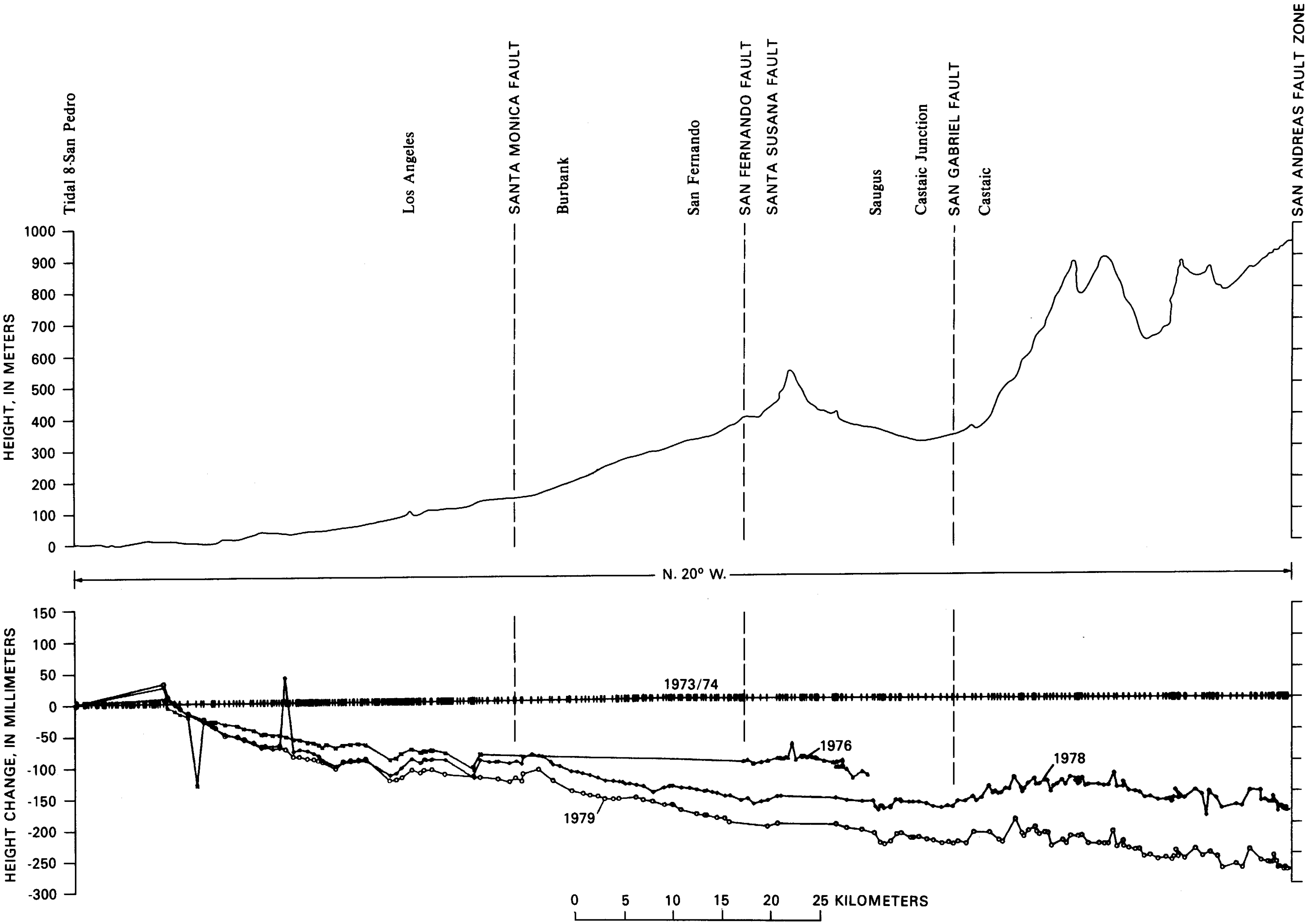


Figure 8.—Profiles showing heights and height changes since 1973/74 along the route from San Pedro via Burbank and Saugus to the position of the San Andreas fault zone near Lebec for 1976, 1978, and 1979 levelings.

CONTINUED NORTHWARD TILTING AFTER THE 1978 LEVELING

Comparisons of 1976, 1978, and 1979 leveling results with a 1973/74 leveling baseline along the route from bench mark Tidal 8 at San Pedro northward through Burbank and Saugus to the position of the San Andreas fault zone near Lebec (fig. 8) demonstrate that a substantial northward tilt developing since 1974 continued during 1978 and 1979. Furthermore, the resulting displacement profiles suggest that the zone of maximum tilting gradually migrated northward, passing through the southern section of the route (San Pedro to Burbank) between 1973/74 and 1976, through a central section (Burbank to Castaic) between 1976 and 1978, and finally through a 12-km-long section north of Castaic from 1978 to 1979. The ends of these tilted sections appear to coincide with the traces of the Santa Monica, San Fernando (or the fault trend defined by the Red Mountain, Oakridge, Santa Susana, and San Fernando faults), and San Gabriel faults. Consequently, it appears that the major faults may serve as hinge lines, essentially decoupling the tilting induced across large, fault-bounded crustal blocks by the passage of a deep-seated, northward-sweeping wave of down-to-the-north tilting. Preliminary analyses of 1978-79 height changes along at least two additional north-south routes, from Ventura to just south of Maricopa and from Azusa to Islip Saddle, 25 km north of Azusa in the San Gabriel Mountains, also indicate continuing northward tilting of a similar magnitude (Jachens and others, 1983).

CONCLUSIONS

Two important implications of the 1974-79 leveling data for the southern California region are very clear: (a) the 1978 releveling was carried out during an active period of tectonic deformation that almost certainly contributed to some distortion of the reference surface during the 5-month period of its establishment, and (b) this deformation consisted primarily of north to northeastward tectonic tilting over much of the area of the southern California uplift, starting as early as 1976 and continuing at least through the period of 1979 monitoring.

Other conclusions based on the 1972/76 and 1978 data comparison, the continued northward tilting during 1978 and 1979, and the results of independent strain and gravity monitoring are:

(1) The shape and extent of the southern California uplift of 1959-74 were only slightly altered during the subsequent deformation, despite the occurrence of pervasive northward to northeastward tilting that reduced the uplift to about one-third its previous maximum value.

(2) Major modifications of the 1959-74 uplift pattern, aside from the general decrease in amplitude, include the almost complete collapse of the region of maximum uplift in the eastern Transverse Ranges, a substantial increase in the tectonic subsidence of the central Salton Trough, and the development of a prominent tectonic downwarp within the Ventura Basin that may extend westward into the Santa Barbara Channel.

(3) Deformation in southern California apparently accumulates in distinct pulses perhaps associated with episodic adjustments within crustal blocks to deep-seated subcrustal movement. At times the shallow deformation seems to be expressed as a rocking motion of large tectonic blocks which are separated and mechanically decoupled by major faults.

(4) The last third of the period of tectonic uplift (1971-76) is associated with the well-documented accumulation of negative plane dilatational strain (north-south contraction) at about -1.7×10^{-7}/yr. While tectonic subsidence in isolated areas may have begun as early as 1976, the regional collapse is clearly associated in time, space, and by mechanism with a conspicuous change in the pattern of strain accumulation (aseismic strain release?) marked in 1977/79 by the cessation of north-south contraction and the onset of east-west extension at a rate of about 5×10^{-7}/yr.

(5) Numerous minor earthquakes and occasional moderate shocks occurred throughout the region of the southern California uplift during its partial collapse, but earthquake activity was particularly common in the eastern Transverse Ranges area and in the Salton Trough region, where crustal downwarping and rapid subsidence were accompanied by several swarms of moderate earthquakes that dominated the 1974-77 pattern of seismic-energy release (Fuis and others, 1977; 1978).

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