An Early-20th-Century Uplift in Southern California

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By ROBERT O. CASTLE, MICHAEL R. ELLIOTT, *and* THOMAS D. GILMORE

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A description of the evolution of an earlier regional uplift in southern California that compared closely with the 1959–76 cycle in both distribution and magnitude

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By Robert O. Castle, Michael R. Elliott, and Thomas D. Gilmore

ABSTRACT

An early-20th-century uplift has been recognized in southern California that compares with the 1959–76 cycle in areal distribution, magnitude, and history. Although the data set used in reconstruction of this earlier event forms but a small fraction of that used in reconstruction of the modern uplift, its distribution and density are such that a generalized representation of the earlier uplift is relatively easily developed. The earlier uplift was characterized by an elongate, double-lobed configuration extending from Point Arguello east-southeastward to the north edge of the Salton Sea. Height changes within the uplift locally exceeded 0.5 m but probably averaged 0.3 to 0.4 m over about half of its nearly 50,000-km^2 areal extent. At or immediately after its culmination, the uplift included most or all of the Transverse Ranges province and parts of the Coast Ranges, San Joaquin Valley, Sierra Nevada, Basin and Range, Mojave Desert, Peninsular Ranges, and Salton Trough provinces. Although the two cycles clearly were similar, the earlier uplift differed from its modern counterpart in its significantly greater penetration southward into the Peninsular Ranges. Although nontectonic displacements may have accompanied the growth and subsequent collapse of the uplift, comparisons with areas of known or suspected fluid extraction indicate that compaction-induced deformation through 1935 was trivial outside of the Los Angeles Basin.

Measured height changes used in the reconstruction of the early-20th-century uplift are based on comparisons between the results of geodetic levelings of differing accuracy. Survey quality ranged upward from wooden-rod, single-run, single-rodded, third-order to Invar-rod, double-run, first-order leveling. Errors associated with signals (height changes) derived from comparisons between the results of surveys of different standards of accuracy presumably were dominated by those identified with the lower order survey; had these signals been but small fractions of their actual values, they could easily have been obscured by the noise. Errors that contributed to inaccuracies in the height determinations and resultant signals can be categorized as blunders, systematic survey errors, random survey errors, errors in the evaluation of the orthometric corrections, and errors associated with intrasurvey movement. A number of blunders, all of which were associated with single-run, single-rodded, third-order surveys, were detected during our reconstruction of the observed-elevation differences identified with specific surveys. Unless both the source and the magnitude of these blunders could be reasonably assessed, those line segments including and extending beyond the blundered portions were discarded in our reconstruction. Comparisons between signal and terrain show that the two are uncorrelated in any significant way and, hence, that height- or slope-dependent systematic errors can be dismissed as equally insignificant. Although conventionally computed estimates indicate that random error could account for as much as 100–120 mm of the signal at the distant ends of several very long lines, redundancy and other evidence suggest that these estimates tend to be exaggerated. All of the orthometric corrections have been based on observed gravity, and the errors associated with this routine geodetic correction can be dismissed as negligible. Intrasurvey movement clearly contaminated the signal along only one line and probably led to a distorted tilt along the south flank of the eastern lobe of the uplift.

Reconstruction of the uplift has been based chiefly on the results of sequentially developed observed-elevation differences referred directly to bench mark Tidal 8, San Pedro. Because Tidal 8 is located adjacent to a tide station that has operated intermittently since the mid-19th century and as a primary station since 1924, its stability is well known. In general, height changes referred to Tidal 8 are biased slightly toward the appearance of subsidence and against the appearance of uplift. Because all the available evidence suggests little, if any, regional deformation during the period 1897–1905, and because an accurate control line was established athwart the uplift in 1902, we have selected 1902 as our reference datum.

The early-20th-century uplift probably evolved largely as two well-defined episodes, the second of which was followed by, or closely associated with, partial collapse. The timing of this second episode is so poorly defined that the partial collapse could have either preceded or accompanied the growth of the eastern lobe—the second major episode of uplift. The first major spasm of uplift began no earlier than spring 1905, probably was largely over by the following spring, and is thought to have included nearly all of the central and western parts of the ultimately uplifted area. Although the evidence is equivocal, uplift may have continued within the central and western parts of the uplift through at least 1914. Partial collapse of the central and western parts of the western lobe began no later than 1925. Uplift of the eastern lobe exceeded 0.5 m; the survey data clearly indicate only that this uplift evolved sometime within the period 1902–28. Although a large section of the central and western parts of the uplift had sustained major tectonic subsidence by 1926, an additional episode of localized collapse, centering on Bakersfield, apparently occurred sometime between 1927 and 1931. Control on the distribution of this later event, which dropped Bakersfield well below its 1902 height, is virtually nonexistent; and we have no evidence indicating that it extended significantly into the already partially collapsed north flank of the uplift.

The growth of the early-20th-century uplift, unlike that of its modern analog, is vaguely correlated with seismicity. A group of medium- to large-magnitude earthquakes just preceded or, less likely, accompanied the first major episode of uplift. Similarly, several relatively large magnitude earthquakes, notably the 1927 Point Arguello $M = 7.5$ shock, closely followed the collapse of the central and western parts of the uplift.

INTRODUCTION

The discovery of regional uplift in southern California that evolved during the period 1959–74 (Castle and others,

1976) stimulated a cursory review of the earlier geodetic record to establish the uniqueness of this event. Examination of the older data (Castle and others, 1976; Castle, 1978; Vaníček and others, 1979; Wood and Elliott, 1979) disclosed an early-20th-century uplift that was remarkably similar to its modern analog. Although the data set that permitted detection of this earlier uplift is very small in comparison with that used in reconstruction of the modern event, the earlier uplift was clearly of a comparable form and magnitude, and similarly divisible into naturally defined eastern and western parts. Uplift in the western part of the early-20th-century uplift probably culminated no later than 1914, but that in the eastern lobe could have peaked as late as 1928.

Our initial description of the early-20th-century uplift (Castle and others, 1976, p. 252–253) is now known to have been significantly flawed. Specifically, this original characterization was based on 1897 leveling between Pacoima and the San Andreas fault (fig. 1) that, contrary to our earlier statement (Castle and others, 1976, p. 252), was single-rodded over this particular reach. Subsequent reconstruction of the field data revealed two large blunders that led to significant errors in the 1897 datum extending northward from Pacoima. In addition, the 1914 double-run field measurements were contaminated by an unusually large rod-calibration error that produced errors of as much as 0.15 m in the resulting heights. This datum has since been corrected through substitution of the results of 1902 double-rodded (precise) leveling between the San Andreas fault and Pacoima that joined with 1897 double-rodded surveys extending southward into San Pedro. The 1914 field measurements have also been corrected through application of recomputed rod-excess values based on repeated field calibrations and a subsequent U.S. Bureau of Standards recalibration of the steel tape used in field calibrations of the wooden rods. Accordingly, the early-20th-century uplift along this line is now known to have been marked by uplift of nearly 0.5 m, followed by a partial collapse that must have occurred no later than 1926. Therefore, there is no longer any basis for concluding that "* * * the 1897/1902–1914 uplift was confined largely and perhaps exclusively to the Transverse Ranges, and that as much as 0.3 m of the uplift that occurred within the northern Transverse Ranges and the western Mojave block is probably specious and attributable simply to systematic error in the 1914 leveling" (Castle and others, 1976, p. 253).

We have since examined the entire recoverable data set that defines the early-20th-century uplift, to describe the evolution of this feature in as much detail as possible. A large part of this effort was devoted to the establishment of a preuplift datum, an even more formidable task than was faced in developing a similar datum for the modern uplift (Castle and others, 1984). An equally large effort has been invested in an assessment of the accuracy of the earlier surveys, a number of which were single run. Because the distribution of the data is relatively fragmentary, we have begun with the assumption that the measurements were biased toward neither the appearance of uplift nor the appearance of subsidence—that they were, in effect, error free. We have attempted to assess the validity of this assumption through examination of misclosures, comparisons between terrain and signal, and so forth, recognizing that our basic premise is unsupportable in detail. For example, where an unbiased normal distribution is assumed, a misclosure of zero will have the highest probability of occurrence; thus, misclosures well below the predicted random-error estimates, whether based on levelings around a circuit or repeated surveys over the same line, are inadmissible evidence of survey accuracy better than the predicted random error—that is, misclosures approaching zero can always be viewed as the products of chance. Nevertheless, the redundancy and coherence

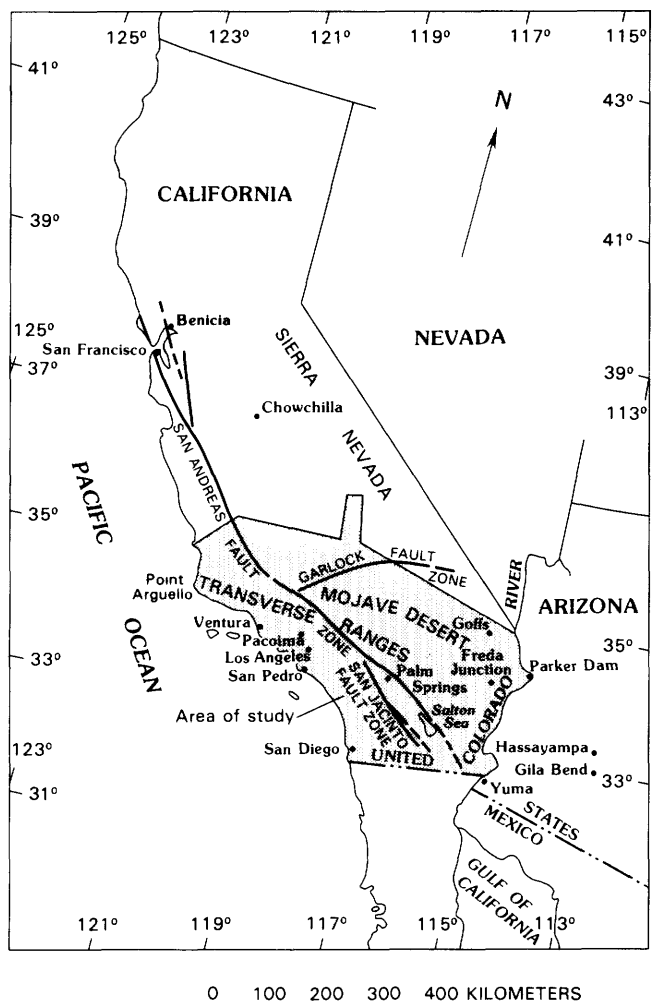

FIGURE 1.—Index map of California, showing location of study area (shaded) including the early-20th-century uplift.

displayed by the data incorporated into our reconstruction are much higher than we would have anticipated from published random-error estimates. This observation suggests to us that the predicted random-error content may be well above the actual values, particularly for the lower order surveys, and, indeed, that these older surveys were remarkably accurate. Although the large number of clearly defined or reasonably inferred blunders uncovered in our analysis of the single-run, single-rodded levelings seemingly militate against this conclusion, these human errors cannot be taken as an index of the accuracy of the measurement system. In the final analysis, the occurrence of the phenomenon we describe in this report can be neither proved nor disproved; in other words, it is always possible to postulate a concatenation of unassessable errors that would refute the existence of this feature. Thus, the conclusions we reach here are necessarily based on the full spectrum of the evidence, which, in our judgment, cannot be cavalierly cast aside.

ACKNOWLEDGMENTS

The geodetic data on which we have based our reconstruction of the early-20th-century uplift have been drawn almost exclusively from levelings by the U.S. Geological Survey and the National Geodetic Survey (formerly a division of the U.S. Coast and Geodetic Survey). The sole exception consists of the results of a 1907 first-order survey (extending northward from Pacoima to the Owens Valley) carried out by the Los Angeles Department of Water and Power.

We are especially indebted to E.I. Balazs of the U.S. National Geodetic Survey for his continuing assistance in the acquisition of many of these older data and for his thoughtful advice on various problems connected with their use. We are equally grateful to J.R. Hubbard of the U.S. National Ocean Survey for sea-level measurements from both the Los Angeles and San Diego tide stations essential to reconstruction of the geodetic data. E.A. Rodriguez and M.E. Wilson of the U.S. Geological Survey provided technical assistance throughout the preparation of this report. J.P. Church, formerly with the U.S. Geological Survey, generously shared his encyclopedic knowledge of the vertical-control record in the Western United States. Finally, we thank R.W. Powell, R.S. Stein, and W.S. Stuart of the U.S. Geological Survey, and Petr Vaníček of the University of New Brunswick, Fredericton, New Brunswick, Canada, for their numerous helpful suggestions and constructive reviews of an earlier version of this report.

GEOLOGIC FRAMEWORK

The area embraced by the early-20th-century uplift lies astride an exceptionally complex section of the North American-Pacific plate boundary. Because the geologic framework is correspondingly complex, this subject is treated largely in simplified map form. The uplifted area includes, in whole or in part, several naturally defined physiographic or tectonic provinces (pl. 1). The Transverse Ranges province (pl. 1) is the only one of these contained almost entirely by the uplift and is, in turn, associated with the more easterly trending section of the San Andreas fault. However, the west half of the very broadly defined Mojave Desert province is also included largely or entirely within the uplifted area. The physiographic lows (pl. 1) generally are at once both depositional basins and actively developing structural troughs that tend to flank the uplifted area. The most significant of these are the southern San Joaquin Valley and the Salton Trough (pl. 1), both of which are closely associated with well-defined, active boundary faults along at least two sides; thus, we may reasonably infer that they have been tectonically decoupled from the adjacent provinces during recent geologic time. It is unclear, however, whether these provinces have been perpetuated owing to the existence of these throughgoing faults or fault systems, or whether the structural integrity of the individual provinces has localized the faulting.

HISTORICAL DEFORMATION

Historical surface deformation in southern California can be classified as tectonic or nontectonic. Nontectonic deformation, in turn, is divisible into naturally and artificially induced movement. Because our purpose here is to describe the vertical-displacement field attributable to generally aseismic tectonic deformation, we have simply disregarded those movements that may be nontectonic in our interpretive reconstructions.

NONTECTONIC DEFORMATION

Compaction of poorly indurated surficial deposits is clearly responsible for nearly all of the nontectonic deformation that occurred in southern California through 1935, which we have taken as the cutoff point for this investigation. Although soil expansion locally has played a role in surface deformation, it is insignificant in the present context. Similarly, naturally or artificially induced free-face movements or landslides, though obviously responsible for the disturbance of the occasional bench mark, have been disregarded in our reconstructions.

ARTIFICIALLY INDUCED DEFORMATION

Artificially induced vertical movements have been historically associated with areas of ground-water withdrawal and oil-field operations. Both processes lead to reduction in fluid pressure, resulting in increases in vertically directed effective stress and consequent production of subsurface compaction and associated surface subsidence (Poland and Davis, 1969). Although increasing fluid pressure has the opposite effect, rebound is limited to expansion within the elastic range of the affected sediments. Moreover, before 1936 there had been little, if any, artificial recharge or repressurization in any of the ground-water basins or oil fields in southern California.

A worst-case scenario characterizing the potential for compaction-induced subsidence through 1935 was given by Castle and others (1984, pls. 3, 4), who showed areas of both fluid-pressure decline and associated subsidence recognized through 1975. With several limited exceptions, however, compaction-related subsidence was generally insignificant before 1936, even in the southern part of the central valley (Poland and Davis, 1969). The chief exceptions to this generalization in southern California are associated with production from several old, but fairly large, oil fields and with head declines within the generally unconfined aquifers in ground-water basins south of the Transverse Ranges.

Although artificially induced compaction before 1936 certainly did not operate on the scale that obtained in later years, production from those oil fields and ground-water basins that had been developed through 1935 (pl. 2) could easily have contributed to at least limited compaction-induced subsidence. The Los Angeles coastal plain and the alluvial valleys extending eastward from Los Angeles to San Bernardino and beyond are believed to be those areas in which ground-water withdrawals were most likely to have produced surface subsidence (Poland, 1959, p. 10–14; Poland and others, 1959, p. 99–110). For example, the Santa Ana area subsided about 0.01 m during the period 1914–20 (USGS summary book A–9349; NGS line 74203) and an additional 0.07 m during the period 1920–32 (NGS lines 74203 and L–386), apparently in response to ground-water withdrawals (Poland, 1959, p. 74). Moreover, measurable subsidence may even have occurred in several basins in which we could have expected very little subsidence before the late 1930's. For example, bench marks in the Lancaster area of the western Mojave Desert are now recognized as having subsided locally about 0.02 m during the period 1929–35 (USGS summary book B–3402; NGS line L–5332). Accordingly, the most conservative interpretation would require that any differential subsidence centering on ground-water basins known or suspected to have sustained significant head declines or over oil fields that had begun to produce before 1936 probably is due to artificially induced compaction.

NATURALLY INDUCED DEFORMATION

Natural compaction associated with slow dewatering and lithification of at least the younger deposits is certainly operating in the major sedimentary basins of southern California, especially in areas of rapid deposition of fine-grained materials during recent geologic time. However, it clearly is very difficult to segregate naturally induced compaction from that attributable to human activities. Regardless, because it is doubtful whether natural compaction is proceeding anywhere in southern California at a rate above 1–2 mm/yr, its contribution can be discounted as insignificant during the period 1897–1935, even in such particularly susceptible areas as the southern San Joaquin Valley and the central Los Angeles Basin (see Castle and others, 1984).

TECTONIC DEFORMATION

The aseismic vertical-displacement field that we are unable to explain as the product of naturally or artificially induced compaction is here classified as tectonic. This is the broadest possible definition applicable to this category of crustal movements, and no specific cause should be inferred. It would include, for example, crustal movements associated with upwelling or collapse of a magma chamber, or epeirogenic movements that many would consider clearly separable from classically orogenic deformation. In short, those vertical movements that cannot be dismissed as the products of compaction are considered tectonic and provide the basis for our reconstruction of the early-20th-century southern California uplift.

VERTICAL-CONTROL DATA

The data on which we have based the reconstructed height changes described in this report consist of the results of repeated level surveys between two or more bench marks. This reconstruction is handicapped by many of the same problems faced in attempting to describe the modern uplift. Use of the results of levelings of significantly different accuracy has additionally complicated the reconstruction; that is, although all of levelings on which this reconstruction is based can be classified as "geodetic," about 15 percent of these surveys consist of the lowest order of geodetic leveling carried out in the United States since the late-19th century.

Vertical-control surveys are divisible into several orders or classes (Vaníček and others, 1980), each of which carries its own procedural and instrumental requirements. These requirements have been strengthened over the years, especially those relating to instrumentation. The procedural requirements changed very little during the period 1897–1935, and relatively few measurement problems of which we are now aware had not been recognized as early as the beginning of the 20th century. Moreover, even though two significant instrumental improvements were made between 1897 and 1936 (with the introduction of a significantly improved level at about the turn of the 20th century, and of the Invar rod in 1916; Vaníček and others, 1980, p. 507), the procedural constraints were sufficiently rigorous during the pre-1916 period that the accuracy of the measurement system probably increased only marginally with this improved instrumentation.

What was formerly identified as "precise" leveling by the U.S. Coast and Geodetic Survey is the equivalent of what is now known as "first-order leveling" (Hayford, 1904, p. 213; Rappleye, 1948, p. 2). However, the "precise" leveling of the U.S. Geological Survey through possibly as late as 1928 was run to two sets of standards, only one of which was the equivalent of the "precise" or "first-order leveling" of the Coast and Geodetic Survey (Hayford, 1904, p. 213; Gannett and Baldwin, 1908, p. 6). Through 1935, first-order or precise leveling (including the higher order work of the Geological Survey) was, by definition, double run over sections of 1 to 2 km. Balanced sights were required by both the Geological Survey and the Coast and Geodetic Survey (U.S. Geological Survey, 1897, p. 228; Wilson, 1898, p. 377; Hayford, 1904, p. 214); the maximum difference between foresight and backsight lengths permitted by the Coast and Geodetic Survey was 10 m (Hayford, 1904, p. 214), whereas it was left unspecified by the Geological Survey. The maximum sight length allowed by the Coast and Geodetic Survey through and beyond 1935 was 150 m, but this "maximum is to be attained only under the most favorable circumstances" or "conditions" (Hayford, 1904, p. 214; Rappleye, 1948, p. 7). The maximum sight length permitted by the Geological Survey never rose above 92 m (300 ft) for any order of leveling (U.S. Geological Survey, 1897, p. 228; Wilson, 1898, p. 377; Birdseye, 1928, p. 132). The section-rejection limit (the maximum permissible divergence between backward and forward runs) for first-order levelings (or the more rigorously defined precise surveys of the Geological Survey) was set at 4 mm $\sqrt{\text{km}}$ (Hayford, 1904, p. 213; Gannett and Baldwin, 1908, p. 6). Procedures for the rerunning of rejected sections during the early years required that "both the forward and backward measures are to be repeated until the difference between two such measures falls within the limits" (Hayford, 1904, p. 213; Bowie and Avers, 1914, p. 9), whereas they were somewhat relaxed by no later than 1948, requiring only that "the leveling shall be repeated until any two runnings in opposite directions agree within the [4 mm/km$^{1/2}$] tolerance" (Rappleye, 1948, p. 8).

All of the second-order leveling (or the approximately equivalent, less rigorously controlled precise work of the Geological Survey) alluded to in this report has been either double run or double rodded. Although single-run second-order surveys were permitted by the Coast and Geodetic Survey, they were otherwise run to first-order specifications (Rappleye, 1948, p. 2); whether double rodded or not, the results of single-run second-order levelings of the Coast and Geodetic Survey have not been incorporated into this investigation. Balanced sights were also required by the Geological Survey for the less rigorous precise (or what we henceforth identify as "second order") leveling, and the maximum sight lengths for explicitly defined second-order surveys were not to exceed 92 m (Birdseye, 1928, p. 151–152). The section-rejection limit for the earlier second-order leveling of the Geological Survey was given as 7.2 mm $\sqrt{\text{km}}$ (Gannett and Baldwin, 1908, p. 6), although a slightly less strict rejection limit (8.4 mm $\sqrt{\text{km}}$) was subsequently adopted by the Geological Survey (Birdseye, 1928, p. 130). To qualify as double-rodded second-order or "precise" leveling, the Geological Survey stipulated that both instruments and rods should be of the highest grade (Birdseye, 1925, p. 1), and it is chiefly in this sense that the double-rodded precise levelings differed from lower order double-rodded control surveys.

Third-order leveling (or what was formerly identified as "primary" leveling by the Geological Survey) was either double or single rodded (U.S. Geological Survey, 1897, p. 228–229). Balanced sights were mandatory, "and no sight over 300 feet [92 m] should be taken excepting under unavoidable circumstances, as in crossing rivers at fords or ferries or in crossing ravines" (U.S. Geological Survey, 1897, p. 228). There was no section-rejection limit as such for third-order work, but circuit closures in feet were "not [to] exceed 0.05 $\sqrt{\text{distance in miles}}$ [12 mm $\sqrt{\text{km}}$]" (U.S. Geological Survey, 1897, p. 229; Wilson, 1898, p. 345). This same rejection criterion remains in force today (Federal Geodetic Control Committee, 1974, p. 9).

ERRORS IN HEIGHT DETERMINATIONS

Errors in measured height differences derived from continuous levelings fall into several clearly separable categories. In practice, however, the assignment of an error to a particular category commonly is very difficult. The major sources of error dealt with here include: (1) blunders or "busts", (2) systematic survey error, (3) random survey error, (4) surface deformation (bench-mark motion) during the course of a given leveling, and (5) imprecisely evaluated orthometric corrections. The magnitudes of error sources 3 and 5 commonly can be closely approximated; the remaining classes of error generally need to be considered on a case-by-case basis, and their clear discrimination may be very difficult, if not impossible. In fact, in comparing the results of any two surveys (and with the exception of certain special situations, such as detectable arithmetic blunders), there is no procedure that categorically discriminates between movement and error. That is, there is no a priori basis whereby tectonic displacement can be forecast in advance of the fact, nor is there any single test that guarantees the accuracy of a particular survey. Therefore, we have based our judgments on the occurrence of survey error on the cumulative evidence, including the predicted error associated with the order and vintage of the leveling.

BLUNDERS

About 15 percent of the vertical-control data available for the reconstruction of the early-20th-century uplift consists of the results of single-rodded third-order (primary) leveling. The potential for blunders clearly is enormously greater in single-run leveling than in either double-run or double-rodded surveys. However, procedures were invoked at least as early as 1897 that tended to minimize, if not eliminate, blunders in single-run leveling. Specifically, the rod readings on which the early single-run levelings were based made use of an attached, movable target, such that the levelman's reading could be made where "the rod is found to be precisely plumb at the same instant that the instrument is level and the horizontal cross-hair bisects the clamped target" (Wilson, 1898, p. 351). Because rod readings could be made by both rodman and levelman, and because the levelman and rodman were required to "keep separate notes and compute differences of elevation immediately" (U.S. Geological Survey, 1897, p. 228), blunders in single-run leveling were kept to a manageable limit.

Various straightforward and generally reliable techniques have been employed in searching for blunders. The most obvious indication of a blunder may lie in the occurrence of large, above-limits misclosures that share at least one common leg, particularly if the misclosures are closely matched by integral multiples of 0.3048 m (1 ft) or 0.1 m. Large misclosures, however, are fallible indices of blunders, even in single-run leveling; and their occurrence commonly can be interpreted as evidence of intrasurvey deformation or, less likely, systematic error (see below). Probably the simplest and least ambiguous approach to the detection of blunders is, where possible, through a direct comparison between the results of old-versus-new leveling over the same line. If large steps appear between adjacent marks in the resulting profile of observed-elevation changes over the indicated line, and particularly if the elevation differences are otherwise conformable, a high probability of blundered measurements or note keeping exists at or between these marks. This is especially true if comparisons of single-run levelings against the results of double-run or double-rodded levelings indicate that the mark-to-mark signal is characterized by values that again approximate integral multiples of 0.3048 or 0.1 m. Finally, large balanced misclosures that share a common leg are a particularly suspicious indication of a blunder in the common segment. Nevertheless, if the bisecting survey is temporally separable from the inclusive loop, these misclosures may be the product of intrasurvey movement.

During the course of our reconstruction of the early 20th-century-uplift, we discovered compelling evidence of 12 major blunders. All of these probable blunders were associated with single-run single-rodded leveling, and all, without exception, were identified with the work of a single levelman, which is at once both disturbing and reassuring. Although the existence of these blunders (involving hundreds, if not thousands, of kilometers of leveling) is hardly a credit to this particular levelman's competence, the restriction of these busts to the work of one man is implied testimony to the skill and adherence to procedures demonstrated by the many other surveyors whose work contributed to this report. Of the 12 identified blunders, we were able to discover the source of the blunder and correct the results (or so we believe) in only 7 cases. Our inability to assess the nature and magnitude of the remaining blunders required that we simply discard otherwise usable data developed from tens or even hundreds of kilometers of leveling.

SYSTEMATIC ERROR

The actual or suspected potential for the occurrence of various types of systematic error has dictated many of the instrumental and procedural requirements used in geodetic leveling. Systematic errors are thought to fall into two categories: those that are detectable through circuit closures and those that are independent of closure. In fact, it is doubtful whether any of the generally recognized sources of systematic error are rigorously independent of closure, a suspicion strongly supported by comparisons between the statistically predicted "random" errors around any given circuit and the actually observed and generally larger misclosures (for example, Hayford, 1904, p. 424–429; Bowie and Avers, 1914, p. 18–19; Vaníček and others, 1980, p. 509). Nevertheless, at least one and, probably, two categories of systematic error can, in theory, be treated as independent of closure. Accordingly, because many of the surveys considered in this report do not close a loop and because large misclosures may be the product of intrasurvey deformation, misclosures in themselves are generally inadequate indices of systematic error in southern California.

Rod error is viewed by many workers as probably the most likely source of significant systematic error in those geodetic levelings where the surveys were based on the use of wooden rods. Our examination of the procedures designed to both control and correct this error, together with the measurements themselves, indicates that systematic error associated with the use of wooden rods was much less than we would have anticipated and, at least in the case of first-order work, only marginally greater than that indicated for measurements that utilized Invar rods. Because this problem is critical to our reconstruction of the early-20th-century uplift, we summarize here both the design features and those calibration and correction procedures that tended to minimize the accumulation of rod error, together with those results which convince us that corrected observed-elevation measurements developed from the use of wooden rods were remarkably accurate. Detailed discussions of this subject can be found in the reports of the U.S. Geological Survey (1897, p. 230; 1913, p. 98), Wilson (1898, p. 345, 358-361), Hayford (1900, p. 415–419; 1904, p. 211–219), Bowie and Avers (1914, p. 7–12, 22–26), Birdseye (1928, p. 129, 146, 155), and Kumar and Poetzschke (1981).

Our own investigations indicate that the wooden rods of both the Coast and Geodetic Survey and the Geological Survey were manufactured exclusively from pine. The several types of wooden rods used by the Geological Survey, whether single piece or extensible, apparently were made from what has been identified only as well-seasoned pine (Wilson, 1898, p. 359), whereas it is stated explicitly that those of the Coast and Geodetic Survey were made from well-seasoned white pine (Hayford, 1900, p. 415, 418–419). The wooden rods used by the Coast and Geodetic Survey before 1899 were single-piece target rods "thoroughly saturated with paraffin for the purpose of making their lengths independent of the hygrometric state of the atmosphere" (Hayford, 1900, p. 415). Those used after 1898 differed chiefly in that they were direct-reading rather than target rods and contained "less than 20 per cent of their original weight of paraffin as contrasted with 72 to 95 per cent in [older] rods P and Q" (Hayford, 1900, p. 419). The single-piece precise rods of the Geological Survey were of approximately similar construction, and, like the later rods of the Coast and Geodetic Survey, they were "paraffined only to a moderate depth, about ⅛ in." (Wilson, 1898, p. 359). Extensible, New York (or Philadelphia) rods apparently were used as late as 1928 in third-order (or primary) surveys of the Geological Survey (Birdseye, 1928, pl. 7), although several now-retired employees of the Geological Survey have indicated that they had been almost entirely supplanted by single-piece yard rods well before 1928.

The instructions for precise leveling contained in the report for 1903 of the Coast and Geodetic Survey include the following requirement:

> At the beginning and end of the season, and at least twice each month during the progress of the leveling, the three-meter interval between metallic plugs on the face of each level rod shall be measured carefully with a steel tape, which shall be continuously kept in the party throughout the season for that purpose. The temperature at the time of each of these measures must be recorded. The purpose of these measures is to detect changes in the lengths of the rods rather than to determine the absolute lengths. The absolute lengths are determined at the Office between field seasons (Hayford, 1904, p. 214–215).

The Geological Survey is known to have emulated these procedures in the southern California area, and presumably elsewhere, in all of its precise surveys and much of its other leveling as well (U.S. Geological Survey, 1913, p. 98). Accordingly, because the coefficients of thermal expansion for both the steel tape and the wooden rods were known, the appropriate rod excess could be computed for any half-month period during the field season. In fact, changes in the lengths of the rods (at the standardized temperature) between successive laboratory calibrations generally were much less than 1×10^{-4} (Bowie and Avers, 1914, p. 31–47), such that modifications of the rod excess based on the field calibrations probably were rarely applied. For example, after a month's storage in a dry environment, two pre-1898 Gurley precise rods used by the Geological Survey were found to have lengthened by 5.5×10^{-5} and 1.8×10^{-5} during the preceding field season (Wilson, 1898, p. 360). Moreover, "after being exposed to a relative humidity of 92% for 45 hours," these same rods showed changes of zero and 2.7×10^{-5}, respectively (Wilson, 1898, p. 360). However, easily measured length changes are known to have occurred over a few weeks or months where wooden rods were brought from a very humid environment into a much dryer climate and vice versa. In the absence of frequently repeated field calibrations that permitted detection of these changes, significant systematic errors could have contaminated the corrected elevation differences. A case in point is the 1914 second-order leveling between Bakersfield and San Pedro, where the rods continued to shorten at a steadily diminishing rate during the first third of the survey, finally stabilizing after 3 or 4 weeks. Accordingly, correction of the field data required that the rod excess for the first third of the survey be computed on a daily basis.

During some unspecified period through at least 1928, rod corrections applied to the results of third-order (primary) levelings using wooden rods were computed in a manner similar to that developed for the first- and second-order surveys of both the Coast and Geodetic Survey and the Geological Survey. Specifically,

> * * * it is very important, particularly for areas where differences of elevation are considerable, that an accurate value for the length of the leveling rod be determined not only from tests by the Bureau of Standards but also from field tests by the levelman. At the beginning of each field season and at least every two weeks thereafter the levelman should make several measurements of each level rod he is using, with an invar test tape or a tested steel tape kept for that purpose, and record in proper order in his notebook the mean of the result to thousandths of a foot for each graduation tested (Birdseye, 1928, p. 129).

Although no published instructions have been discovered, our own investigation of the field- and summary-book record indicates that all the rods used in the primary levelings of the Geological Survey, at least as far back as 1897, were laboratory calibrated before their acceptance for field use. Those rods that failed to meet some unstated minimum requirement (presumably based on a comparison between predicted error and the rejection criterion through some stipulated elevation difference over a given distance) were rejected. It is equally clear, however, that field calibrations were not always made; or if they were made, they were not necessarily used. Moreover, although the field data obtained from even the earliest levelings considered in this report commonly were rod corrected, this was not always true, and uncorrected field values occasionally appeared in the summary books and presumably were incorporated as such into any subsequent adjustments. There are two situations in which the utilization of uncorrected field values as the virtual equivalents of rod-corrected elevation differences might have been justified: (1) Where the relief was trivial along any given traverse, the rod corrections would tend to be well below the predicted random error (see below); or (2) if repeated laboratory calibrations indicated that certain rods were characterized by measurably insignificant errors and had apparently stabilized under various atmospheric conditions, rod corrections probably would have improved the field values no more than marginally. Regardless, our examination of circuit closures based on uncorrected, single-run 1901/03/04 primary levelings (involving a mix of rods) in an area of moderate relief in the western Transverse Ranges indicates that the rods used in even these surveys were accurate to well within the stipulated rejection requirement.

Laboratory calibrations during the period 1897–1935 were carried out by two Government agencies. Before 1901, the rods of both the Coast and Geodetic Survey and the Geological Survey were calibrated by the Office of Standard Weights and Measures of the Coast and Geodetic Survey (Wilson, 1898, p. 359–360; Kumar and Poetzschke, 1981, p. 5). Beginning in 1901, this responsibility was passed to the National Bureau of Standards, who continued to calibrate at least some of the rods of the Geological Survey through 1946 (Birdseye, 1928, p. 129; J.P. Church, oral commun., 1980)—after which it was turned over to the Geological Survey. The Coast and Geodetic Survey laboratory resumed calibration of their own rods during the period 1916–22, after which the Bureau of Standards once again took over this task (Kumar and Poetzschke, 1981, p. 6). Calibrations at least as far back as 1897 were never read to less than ± 0.1 mm (Wilson, 1898, p. 360; Bowie and Avers, 1914, p. 31–47; Kumar and Poetzschke, 1981, p. 6–7). The coefficient of thermal expansion of paraffined white pine presumably was determined by the same laboratories and has been given as 0.000004/°C by both Hayford (1900, p. 416; 1904, p. 218) and Bowie and Avers (1914, p. 24). Kumar and Poetzschke (1981, p. 3) contended that this value is too small but failed to state why.

Finally, our review of the results of early levelings based on wooden rods indicates that these levelings generally were no more than trivially contaminated by rod error. We have already shown for example, that even the uncorrected field values obtained from third-order leveling in the western Transverse Ranges suggest that any systematically accumulated rod error generally fell within the predicted noise range. More impressive and certainly more significant evidence is disclosed by an examination of the results of the pre-1912 (pre-Invar) levelings that contributed to the fourth general adjustment (Bowie and Avers, 1914, p. 5, 58—facing, 71–73). Even the worst misclosures identified with the network developed for the fourth general adjustment are relatively good, especially when it is recognized that many of the instruments used on the older surveys were of inferior design and would not be accepted for post-1898 precise (first-order) leveling. If we restrict our consideration to those misclosures based on "C. & G. S. 1899 or later and Geol. Survey 1905 or later" and U.S. Engineers Precise Leveling (Bowie and Avers, 1914, p. 58—facing), nearly all of which involve a mix of rod pairs, the results are especially impressive. Specifically, most of the misclosures based on these more rigorous levelings fall within or below the one or two standard-deviation range. For example, an approximately 7,000-km circuit covering a large part of the Western United States is associated with an orthometrically corrected misclosure of only 238 mm, and misclosures around many of the shorter circuits are equally good (Bowie and Avers, 1914, p. 58—facing). Even the worst of the post-1898 misclosures sums to 407 mm (approx 4 standard deviations) around a 2,664-km circuit. However, the western leg of this particular loop traversed the tectonically active Rio Grande valley between El Paso, Texas, and Belen, New Mexico (Bowie and Avers, 1914, p. 58—facing), such that the likelihood of intrasurvey movement (and any resulting distortion in the height differences) was much greater around this loop than was generally the case in the pre-1912 network.

Atmospheric refraction may, under certain circumstances, contribute to significant systematic errors in geodetic leveling. Moreover, interest in this potential error source, which has been recognized for decades, seems to be enjoying a vigorous revival (Kerr, 1981). "Unequal refraction" (in which the refraction introduced into the foresight is unmatched by that in the backsight) may lead to slope-dependent errors (Bomford, 1971, p. 240–241) that Strange (1981, p. 2823), for example, contended are large enough to effectively negate the presence of the southern California uplift. Although few workers would argue that this postulated error is rigorously predictable, various theoretical considerations suggest that it will, on average, tend to diminish otherwise accurately determined elevation differences (and thus produce "short" mountains).

The likely occurrence of refraction error, whether systematic or not, has dictated many of the procedural requirements stipulated for geodetic leveling. For example, instructions for third-order (primary) leveling dating back to at least as early as 1897 state that these surveys should not be carried out "when the air is 'boiling' badly. During very hot weather an effort should be made to get to work early and remain out late, rather than to work during the midday" (U.S. Geological Survey, 1897, p. 228; Wilson, 1898, p. 377), if for no other reason than to avoid the frustrations associated with excessive scintillation. Similarly, sight lengths were both limited (to 92 m or 300 ft) and balanced—as much, however, to control collimation as refraction errors (U.S. Geological Survey, 1897, p. 228; Wilson, 1898, p. 377). Compulsory resetting of the target on long single-rodded surveys also tended to minimize refraction errors. If the two successive readings differed by more than 0.6 mm (0.002 ft), third-order procedures required that the observation be repeated (U.S. Geological Survey, 1897, p. 229; Wilson, 1898, p. 379). Any thoughtful levelman quickly learned that this procedural constraint could not be met if the sight lengths were excessive under atmospheric conditions (high sensible heat flux) especially conducive to refraction error. Although these attempts to control refraction error were not necessarily aimed at its systematic content, any procedure that minimized the magnitude of the refraction error would reduce this error in both the foresight and the backsight, and thus, in general, reduce the difference between the two (the unequal-refraction error).

The procedures of the Coast and Geodetic Survey in force by 1899, as well as those adopted by the Geological Survey for any of its precise leveling, were much more rigorous than those stipulated for primary leveling. Specifically, because all first-order leveling was double run, these procedures required, in addition to balanced sight lengths,

> * * * that the backward measurement on each section should be made under different atmospheric conditions from those which occurred on the forward measurement. It is especially desirable to make the backward measurements in the afternoon if the forward measurement was made in the forenoon, and vice versa. The observer is to secure as much difference of conditions between the foreward and backward measurements as is possible without materially delaying the work for that purpose (Hayford, 1900, p. 419; 1904, p. 213).

Although we have no assurance that these admonitions were always heeded, to the best of our knowledge these instructions were never relaxed, and at one point they were significantly strengthened (Bowie and Avers, 1914, p. 9, 13, 24; Rappleye, 1948, p. 39). A somewhat subjective requirement that tended to minimize the magnitude of the unequal-refraction error was invoked by the Coast and Geodetic Survey no later than 1903. Hayford (1904, p. 215) observed that

> * * * the required degree of accuracy in double-run leveling will be secured by continually keeping the length of sight such that the percentage of re-running will be from 5 to 15 * * *. The observers have found a convenient rule in fixing the length of sight to be to shorten sights whenever the upper and lower thread intervals subtended on the rod are found to differ by more than a selected limit. Each observer fixes the limit from his own experience by noting the relation between such a limit and the amount of re-running found to be necessary while using it.

Adherence to this rule led the levelman to shorten sights under just that condition where the unequal-refraction error should be most pronounced—namely, high scintillation accompanying intense reradiation of ground heat into the atmosphere. Because the refraction error is ideally proportional to the square of the sight length, the reduction of sight lengths to values that ensured satisfactory section closures would at the same time tend to minimize the magnitude of the refraction error.

The potentially systematic aspect of the refraction error led to the imposition of an explicit Coast and Geodetic Survey procedural requirement that was in force by no later than 1914. Specifically, even though it was believed at the time that "the refraction error on a clear day should be at a minimum during the several hours of the day when the temperature of the air and the surface of the ground are nearly the same," it was also recognized that the unequal-refraction error "may be made small by never letting the line of sight come near the ground" (Bowie and Avers, 1914, p. 22), where the thermal gradient tends to increase (or decrease) very sharply. In practice this goal was thought to be met "if the lower one of the three wires [of the three-wire Fischer level] reads more than 30 centimeters above the ground" (Bowie and Avers, 1914, p. 22; Rappleye, 1948, p. 40)—or if the middle wire reads more than 40 cm above the ground, for example, for sight lengths of about 60 m. Although this requirement could not in itself guarantee the absence of a residual refraction error, when used in conjunction with those requirements designed to minimize section closures or setup rereadings, it is likely, as indicated by the generally tight circuit closures, that this path-dependent error generally did not accumulate to values significantly above measurement noise.

Another category of systematic error that has created varying degrees of concern derives from the possibly systematic rising or settling of rod supports. Hayford (1904, p. 215), for example, believed "that a large steady rate of divergence is in general due to a systematic rising or settling" of these supports. However, because the systematic behavior of this effect is a function of the direction of leveling, it is generally well controlled by double running, whereas it may indeed become a significant systematic contaminant in single-run leveling. Nevertheless, if the footplates (or pins) are properly emplaced or, better yet, if their use can be avoided in favor of a settlement- or heave-resistant turning point, this potential problem may be relatively easily overcome. For example, because much of the Coast and Geodetic Survey leveling has been along railways, beginning in

> * * * 1903 the rail * * * [was] used as the rod support except when a train was known to be approaching, when a pin was used. Since adopting the rail for the rod support, the accumulation of the discrepancy between the two runnings of a line * * * has been within reasonable limits * * *.
>
> Two uncertainties in connection with this method of rod support will occur to anyone who considers it carefully, namely the uncertainty as to whether the rodman holds the foot of the rod for both foresight and backsight on precisely the same point * * * and the uncertainty as to the recovery by the rail of its former elevation after a train has passed over it.
>
> The first of these uncertainties is very small, provided the rodman is careful. No difficulty has been found in marking with chalk or keel the exact spot on the rail in such a way that the mark is recoverable, even after a train has passed over it. Besides, the lines nearly always follow main lines of the railroad where, in general, the roadbed is well constructed and the rails are held firmly to the ties * * *.
>
> With regard to the second objection * * * it should be remembered that it is only occasional (not so much as once each day, if the observer is at all careful) that a train goes over the rod support between the fore and back sights. Besides, each of several observers has reported that tests were made which show that rod readings, with the rod held on the rail, were the same after the passage of a train as before * * * (Bowie and Avers, 1914, p. 12).

Accordingly, although staff settlement remains a potentially significant source of systematic error in single-run leveling (whether double rodded or not), where reasonable care has been taken to minimize this effect, such as using railroad rails as rod supports, it probably no more than competes with random error.

All of the potentially serious sources of systematic error discussed above are, in varying degree, path dependent and thus can be expected to appear in circuit closures (Vaníček and others, 1980, p. 509). Misclosures based on levelings that used the same rod pair around the entire circuit form an obvious exception to this generalization. Moreover, where the leveling has been limited to a single rod or rod pair, if the cumulative error along either or both rods were nonlinearly distributed, the corrected observed-elevation differences might still be systematically biased if the readings were largely confined to a restricted rod interval. Similarly, it is certainly conceivable that the several factors that contribute to the unequal-refraction error may collectively balance around certain loops. Nevertheless, because this error is explicitly path dependent, to the extent that it is, indeed, a significant contaminant, it should in the general case be expressed as an equally significant misclosure. Moreover, even if the support conditions along the survey route vary through some extreme range, systematic error associated with staff settlement can be expected to accumulate around the circuit where the leveling is single run. Thus, although misclosures in themselves do not reveal the physical source of any postulated systematic error, they may still provide an indication of significant systematic error in any given leveling.

The cumulative divergence generated in any double-run leveling commonly is viewed as an index of systematic error. However, because the errors in the forward and backward runnings over any given section are characterized by varying degrees of statistical dependence (Vaníček and others, 1980, p. 509), several of the potentially significant systematic contaminants may not be disclosed in the divergence. Owing to its directional dependency, the cumulative effect of any staff or rod settlement is clearly an exception to this generalization. Large accumulated divergence, particularly if the variation in its accumulation can be closely correlated with any variations in the cumulative difference in the number of setups in the forward and backward directions, is especially suggestive of systematic staff settlement. Nevertheless, because the divergence is generally an expression of cumulative or inclusive survey error only, it has not been particularly helpful in the identification of specific sources of systematic error.

The detection and discrimination of height- and slope-dependent errors, especially where they are thought to be virtually independent of closure, commonly are based on various comparisons between terrain and signal—that is, simply the difference between the results of repeated surveys over the same line. A good correlation between terrain and signal suggests that one or more of these levelings was associated with a height- or slope-dependent error, whereas the absence of any clear correlation invites the opposite conclusion. Nevertheless, all the tests developed to date are fallible, and in no case can any single comparison be considered definitive. For example, if both good and bad rods or rod pairs have been mixed in the same survey (any separately identified leveling), the change in rods from one part of the line to the next could produce a poor correlation between terrain and signal, defined by the results of any two successive surveys—an observation that we would otherwise view as evidence of the absence of significant height- or slope-dependent error in either survey. However, with one exception of no pertinence to this argument—namely, the 1919/20 leveling between Guadalupe and San Pedro—none of the pre-1931 lines referred to in this report were based on more than one rod or rod pair, and the accuracy of all the post-1930 levelings can be independently verified. Similarly, if the repeated surveys bracket a significant seismic event (in both time and space) or if the route traverses an area of compaction-induced subsidence, the absence of any well-defined correlation between signal and terrain cannot be taken as evidence of the absence of significant systematic error. In either of these cases, the magnitude of the signal could be expected to overwhelm any likely survey error and thus obscure the correlation. Finally, correlations between regionally developed tilts and the relatively smooth slopes characterized by graded streams athwart active orogenic belts should not be invoked as unambiguous indications of slope-dependent errors. Because the roads and railroads that mark the routes of many level surveys commonly coincide with these stream valleys, long-wavelength tilts can be reasonably expected to mimic these geomorphically controlled features.

Although direct comparisons between signal and terrain, particularly when used in conjunction with other evidence, are generally useful in searching for the occurrence of height- and slope-dependent systematic errors, several indirect variations of questionable value have been developed during the past several years. Both Chi and others (1980, p. 1473–1474) and Strange (1981, p. 2815–2817, 2819, 2821–2822) simply plotted signal (the height change between surveys) against height to show the degree of correlation between the two. A linear plot is taken as evidence of a height-dependent error, which Strange (1981, p. 2819, 2821–2822), for example, attributed to rod-calibration error. Chi and others (1980, p. 1474) attempted to quantify interpretations of this sort by calculating the correlation coefficients for the two variables. The implication, whether intended or not, is that a large correlation coefficient suggests an "unnatural" relation and thus lends statistical authority to the interpretation of the apparent signal as the product of a height-dependent systematic error.

Stein (1981) approached the problem of expectable correlations between long-wavelength topography and long-wavelength tilt by restricting tilt-slope comparisons to terrains characterized by "rough topography, with large excursions from the mean slope." Moreover, by confining these comparisons to relatively steep slopes, where any unequal-refraction error would tend to be small, this technique effectively limits significant correlations to the discrimination of rod error. Application of a linear least-squares regression of mark-to-mark tilt on slope provides an after-the-fact basis for the calculation of any rod error, especially where the suspect leveling is bracketed by levelings that show no apparent correlation between signal and terrain. Although an element of subjectivity is necessarily introduced into the rejection of those data that would obscure (or dominate) any meaningful correlation, this technique is clearly an improvement over those based on comparisons with smooth topography. It is, however, no more useful in the simple detection of height-dependent systematic error (as opposed to estimating the magnitude of such errors) than a straightforward comparison between terrain and signal. Moreover, accepting the obvious advantage of this approach, various observations (such as tight closures based only in part on the use of presumably aberrant rods, redundant measurements over the same or nearly coincident routes, and the applicable rod calibrations) indicate that this technique is not infallible, even where the terrain conditions are especially suitable. In other words, and for whatever reasons, short-wavelength deformation may closely mimic relatively rough terrain.

Careful consideration of all the data used in the preparation of this report indicates that the corrected observed-elevation differences used in the development of the reported height changes probably are no more than trivially contaminated by systematic error. Specifically, the nearly complete absence of any correlation between signal and terrain based on these data argues against the existence of height- or slope-dependent errors significantly above noise level. There is a somewhat greater likelihood that the results of several single-run levelings, consisting of uncorrected field data, may harbor modest height-dependent errors, owing to the use of inaccurate rods. However, the mix of rods, the magnitudes of the pertinent circuit closures, and the general absence of height-correlated signals based on even these lowest-order levelings indicate that any height-dependent systematic errors were generally small and well below the stipulated limits for third-order leveling. Systematic error associated with staff settlement (or heave) would tend to cancel in double-run leveling, but it could have contaminated several single-run surveys. Because this error is independent of slope, it is less easily detected than that associated with rod or refraction error. Moreover, although the randomization or alternation of the direction of running between marks would tend to randomize this error, this procedural control probably was less rigorously enforced than it should have been in the early primary levelings of the Geological Survey. Nevertheless, because misclosures based on these primary levelings (disregarding those including obvious blunders) were generally good, and because, where possible, the practice was to use rails or spikes along railways (where much of the early vertical control was established) as turning points, it is very doubtful that staff settlement contributed to errors that even began to compete with the observed signals.

RANDOM ERROR

Random error generally is assessed through statistical examination of section or circuit closures (Vaníček and others, 1980, p. 507). Double-run procedures are formulated in such a way that any uncorrelated error in the measured elevation difference between any two bench marks a distance L apart is proportional to $L^{1/2}$. Although random error in single-run leveling is less easily determined, it is assumed to be proportional to $L^{1/2}$ and can be approximately evaluated through circuit misclosures.

The higher the order and, in general, the more recent the survey, the smaller the expected random error. Procedures and instrumentation associated with various vintages and orders of geodetic leveling have been so specified that the estimated random error may be expressed as $\sigma L^{1/2}$, where L is in kilometers and σ has ranged as high as about 6 mm/km$^{1/2}$. First-order procedures and instrumentation in use between 1900 and 1916 were such that σ was about 2.0 mm/km$^{1/2}$; between 1917 and 1955 this figure dropped to 1.5 mm/km$^{1/2}$, an improvement that we associate with the introduction of the Invar rod (Vaníček and others, 1980, p. 507). Second-order procedures and instrumentation have been such that σ dropped from about 4.0 mm/km$^{1/2}$ during the period 1901–16 to about 3.0 mm/km$^{1/2}$ between 1917 and 1955 (Vaníček and others, 1980, p. 507–508). The experience of the Geological Survey with third-order leveling carried out before 1956 indicates that σ was as much as 6 mm/km$^{1/2}$. However, even the most permissive specifications invoked since 1897 for all third-order leveling suggest that this estimate almost certainly errs on the conservative side.

In the most general case, $\sigma_{\Delta E}$, or one standard deviation in the measured elevation difference between any two marks based on n combinations of orders of leveling, is given by

$$\sigma_{\Delta E} = \sqrt{[(\sigma_1 L_1^{1/2})^2 + (\sigma_2 L_2^{1/2})^2 + \ldots + (\sigma_n L_n^{1/2})^2]} \qquad (1)$$

$$= \sqrt{[\sigma_1^2 + L_1 + \sigma_2^2 L_2 + \ldots + \sigma_n^2 L_n]}$$

where σ_1, σ_2, and so forth are the estimated standard deviations applicable to each successive segment of length L_1, L_2, and so forth. For example, one standard deviation in the measured elevation difference between the end points of a line consisting of a 100-km 1897 third-order segment joined to a 100-km 1902 second-order segment would be about

$$\sqrt{[(6.0\ \text{mm/km}^{1/2} \cdot 100\ \text{km}^{1/2})^2 + (4.0\ \text{mm/km}^{1/2} \cdot 100\ \text{km}^{1/2})^2]}$$

$$= 72\ \text{mm}.$$

In comparing measured elevation differences based on repeated levelings between any two marks, one standard deviation in the discrepancy between any two determinations of the measured elevation difference, $\sigma_{\delta\Delta E}$, is given by

$$\sigma_{\delta\Delta E} = \sqrt{(\sigma_{\Delta E_1}^2 + \sigma_{\Delta E_2}^2)} \qquad (2)$$

where $\sigma_{\Delta E_1}$ and $\sigma_{\Delta E_2}$ are the calculated standard deviations for each of the separately determined differences. Thus, one standard deviation in the discrepancy between the measured elevation differences based on a comparison between the results of a 1926 first-order survey with those of a 1914 second-order survey over a 200-km line would be about

$$\sqrt{[(4.0\ \text{mm/km}^{1/2} \cdot 200\ \text{km}^{1/2})^2 + (1.5\ \text{mm/km}^{1/2} \cdot 200\ \text{km}^{1/2})^2]}$$

$$= 60\ \text{mm}.$$

ERRORS ASSOCIATED WITH CONTINUING CRUSTAL DEFORMATION

The most enigmatic error source considered in our reconstruction of the early-20th-century uplift stems from possible or probable intrasurvey deformation. Although we start with the assumption that each vertical-control line remained free of movement during the course of any specified continuous or discontinuous leveling, growing evidence has shown that measurable aseismic deformation may occur within months or even weeks (Castle and Elliott, 1982; Jachens and others, 1983).

The way in which movement during the course of any given survey may generate specious elevation differences is easily illustrated by the effects of unrecognized subsidence at a junction mark during a discrete, extended junction interval (fig. 2). Thus, if as shown in figure 2, junction bench mark B subsided Δe with respect to either A or C, during an interruption of Δt_2 duration, continuation of the leveling during the period Δt_3 based on a starting elevation at B equal to that which existed at the end of Δt_1 would produce a set of elevation differences between B and C Δe greater than those that actually obtained during the period Δt_3. Accordingly, although the set of measured elevation differences between A and B and that between B and C are appropriate to the periods Δt_1 and Δt_3, respectively, no set of measured elevation differences exists that is appropriate to either interval over the full length of the line ($\ell_1 + \ell_3$). Were movement to occur during the course of so-called continuous leveling, it could lead to errors of a conceptually similar nature. That is, although the magnitude of the movement that might occur at the mark which defined the end of one segment and the beginning of the next might be barely detectable, the cumulative effect of these otherwise-trivial displacements could lead to significantly distorted elevation differences over the full length of the line. Because we have identified distorted heights associated with both rapid height changes at junction bench marks and apparently continuous deformation accompanying uninterrupted leveling, we are left with showing either that there has been no movement at various junction bench marks or, alternatively, both the sense and magnitude of any movement which may have occurred during a given leveling. Unequivocal demonstration of the second of these two alternatives is particularly difficult.

Various tests can be developed for assessing the relative stability of any specified junction mark during the course of a given survey (for example, Castle and others, 1984). These tests can be classified as either objective or subjective; objective tests are based on redundancy and coherence, whereas subjective tests are based on the recent geologic history, the seismicity, the fluid-extraction record, and so forth. Although none of these tests is infallible, taken together they generally provide a reasonable basis for assessing the stability of a particular junction mark.

ERRORS ASSOCIATED WITH AN INACCURATELY EVALUATED ORTHOMETRIC CORRECTION

Where successive surveys have followed different routes into the same mark(s), a gravity-dependent correction must be applied to the observed elevation data before any comparisons are made between these surveys. Specifically, observed elevation differences are path dependent, whereas true height differences are uniquely defined and thus independent of path (Heiskanen and Moritz, 1967, p. 161–162). Because this correction, though gravity dependent, is relatively insensitive to temporal variations in gravity, any gravity changes that may have occurred between surveys are a negligible consideration (Vaníček and others, 1980, p. 516–517). Thus, height changes over the same level line, based on comparisons between the results of successively developed observed elevation differences, should be virtually identical to those obtained through comparisons between the corresponding height differences.

The orthometric height system presently in use in North America generally has relied on a correction based on a theoretical formulation of the Earth's gravity field (Vaníček and others, 1980, p. 511–512). Use of this correction, developed from theoretical rather than observed gravity values, may introduce errors in the computed height differences that compete with those normally encountered in first-order leveling (Vaníček and others, 1980, p. 513). An earlier examination of this potential error source (Castle and others, 1984) indicated that whereas use of this approximate orthometric correction commonly led to relatively large errors in the resultant height differences, corresponding errors in the height-difference differences (that is, errors in the discrepancies between height differences based on levelings over different routes) generally amounted to no more than a centimeter or two. Nevertheless, even though the errors associated with the use of this inexact orthometric correction are largely dwarfed by the signals described in this report, we have attempted to minimize any errors

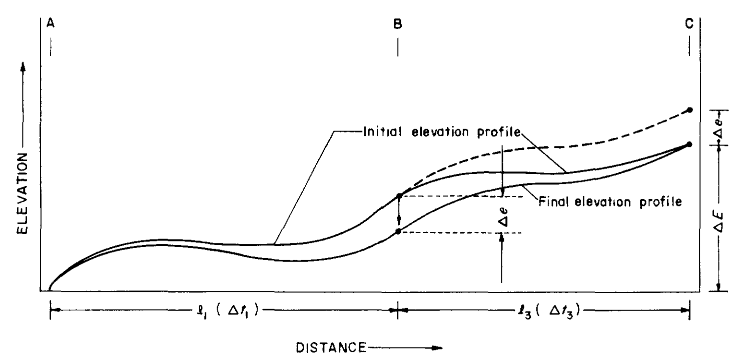

FIGURE 2.—Effect of subsidence, Δe, at junction bench mark B during the period Δt_2 on observed elevations derived from discontinuous leveling along line ABC, where A and C have remained invariant. Dashed-line extension between B and C shows calculated elevations based on leveling between A and B during the period Δt_1 and between B and C during the period Δt_3; solid lines show actual elevations. From Castle and others (1984).

in the reported height changes by basing the orthometric corrections on observed or interpolated gravity values. These corrections have been generated chiefly from the observed (or interpolated) gravity values contained in the machine-readable vertical-control file for California (National Geodetic Survey, 1978). In those relatively few cases where observed gravity values are unavailable, we have used a technique developed by Petr Vaníček, which depends, instead, on Bouguer gravity values (Castle and others, 1984), in calculating the observed-gravity orthometric corrections. The Bouguer values used here were read directly from the new gravity map of California (Oliver and others, 1980).

THE RECONSTRUCTION

Reconstruction of the early-20th-century uplift has been based almost entirely on corrected observed-elevation differences compiled from various sources. Corrections normally applied to the measured (field) elevation differences include (1) a temperature correction designed to compensate for any expansion or contraction of the rod (with respect to the length of the rod at the calibration temperature), and (2) a rod-excess correction intended to compensate for any difference between the actual (calibrated) and nominal length of the rod. Although collimation corrections have been applied to some of the field data, collimation errors generally can be minimized or even nullified through rigorous field procedures. Uncorrected field values have been used in several, specifically identified comparisons; however, the use of rod-corrected data probably would have had little effect on the height changes based on these particular uncorrected observed elevations (see subsections below entitled "The Oxnard-Guadalupe Line," "The San Pedro-Bakersfield Line," and "The Colton-Mecca Line"). Criteria used by the Geological Survey in determining whether rod corrections should be applied to the field differences generated from the earlier, primary (third-order) levelings were never, to the best of our knowledge, formally stipulated. Specifically, the elevation differences listed in the summary books (and, thus, those values used in computing the adjusted published heights) are in several cases identical to those found in the field books. Insofar as we have been able to determine, the results of all the double-rodded primary surveys were nearly always rod corrected. Furthermore, our own experience suggests that the correction criteria in operation at the turn of the century were actually threefold. (1) Where the calibrated lengths departed from the nominal lengths by values conceivably large enough to produce above-limits errors over extreme elevation differences (1,000–2,000 m), the rods were rejected for further use. (2) Where the levelings were carried out under temperate conditions (nearly matching those that obtained during the calibrations) characterized by modest changes in the ambient temperature, the lengths of the rods were assumed to closely match the nominal lengths, provided that the difference between the nominal and calibrated lengths was very small. (3) Where the survey routes were characterized by modest relief (measured in tens of meters), the rod corrections could be expected to fall well below the predicted random-error estimate and were simply ignored.

The computed height changes used in our reconstruction of the early-20th-century uplift are presented chiefly as profiles. Each set of vertical-displacement profiles includes a terrain profile and a bar diagram specifying the inclusive dates of the survey(s), the order of the leveling, and the source of the data (by NGS line number if contained within their files, or by Geological Survey published report, summary book, or field book). Where the starting elevation for any specified survey along a particular line is based on leveling over a route other than the designated primary route, an indicated correction has been applied to this elevation so as to bring it into orthometric compatibility with that which would have been obtained had this leveling followed the primary route.

Bench mark Tidal 8, San Pedro (pl. 3), has been chosen as our primary control point for many of the same reasons that it was selected for this purpose in our study of the modern uplift (Castle and others, 1984). That is, this mark is the only convenient point to which we can relate virtually all of the derived heights over the recognized extent of the early-20th-century uplift. Moreover, by retaining the same control point for both studies, height changes can be easily determined at selected marks or along common lines during the several cycles of uplift and partial collapse described in these two reports. Tidal 8 is, in addition, located adjacent to a primary tide station that has been in continuous operation since 1924. Because this station can also be identified with several secondary occupations during the second half of the 19th century, the position (or changing position) of Tidal 8 with respect to mean sea level is relatively well known (fig. 3). Moreover, because the sea-level history at San Pedro can be compared with that at San Diego (fig. 4), the relative stability of the San Pedro station (and, thus, Tidal 8) is easily assessed. Specifically, sea level at San Diego rose at an average rate of as much as 3.35 mm/yr before 1934 and has since been rising at a rate of about 1.93 mm/yr (fig. 4). The current rate is slightly greater than the average long-period (1940–73) sea-level rise for the conterminous United States of about 1.5 ± 0.3 mm/yr given by Hicks and Crosby (1975) and probably nearly approximates eustatic sea-level rise during the same interval. Thus, San Diego is thought to have remained relatively stable with respect to a tectonically invariant datum, such as the reference ellipsoid. This conclusion is supported by geologic studies which show that over the past 120,000 years the San Diego area has been rising (with respect to present sea level) at a rate of 0.08–0.41 mm/yr (Lajoie and others, 1979). Moreover, according to K.R. Lajoie (oral commun., 1981), no measurably significant vertical displacements have occurred during late Quaternary time within the central San Diego area, where the San Diego tide gauge has operated since 1927. Accordingly, Tidal 8 probably has been rising during historical time at about 2 mm/yr with respect to an "absolute" datum, such that height changes referred to this control point are biased against the recognition of uplift.

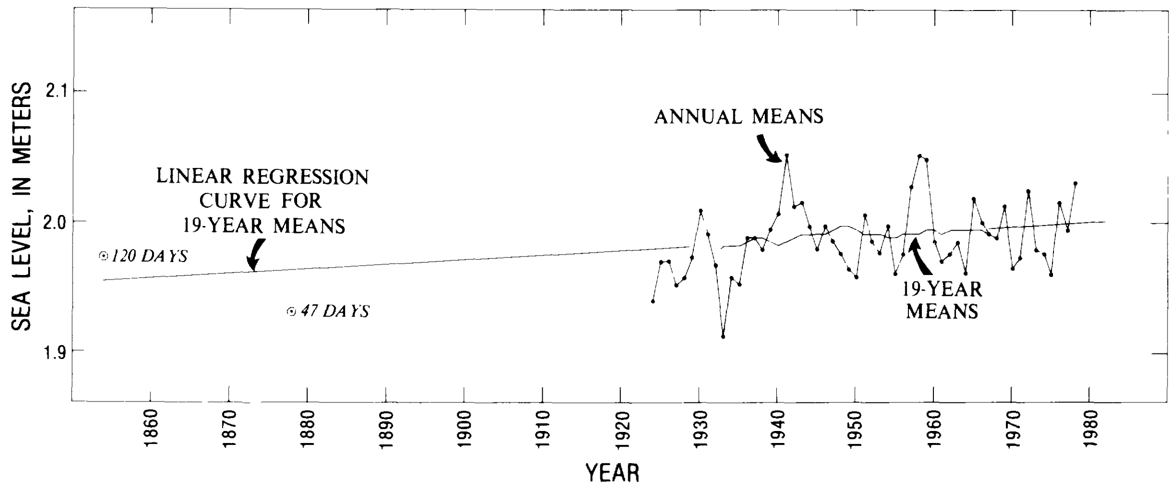

FIGURE 3.—Changes in sea level with respect to bench mark Tidal 8, San Pedro. All elevations are referred to the 1923 tide staff "O" at Berth 60. Number of days indicate durations of two secondary occupations during the middle and late 19th century. From Castle and Elliott (1982, p. 7010).

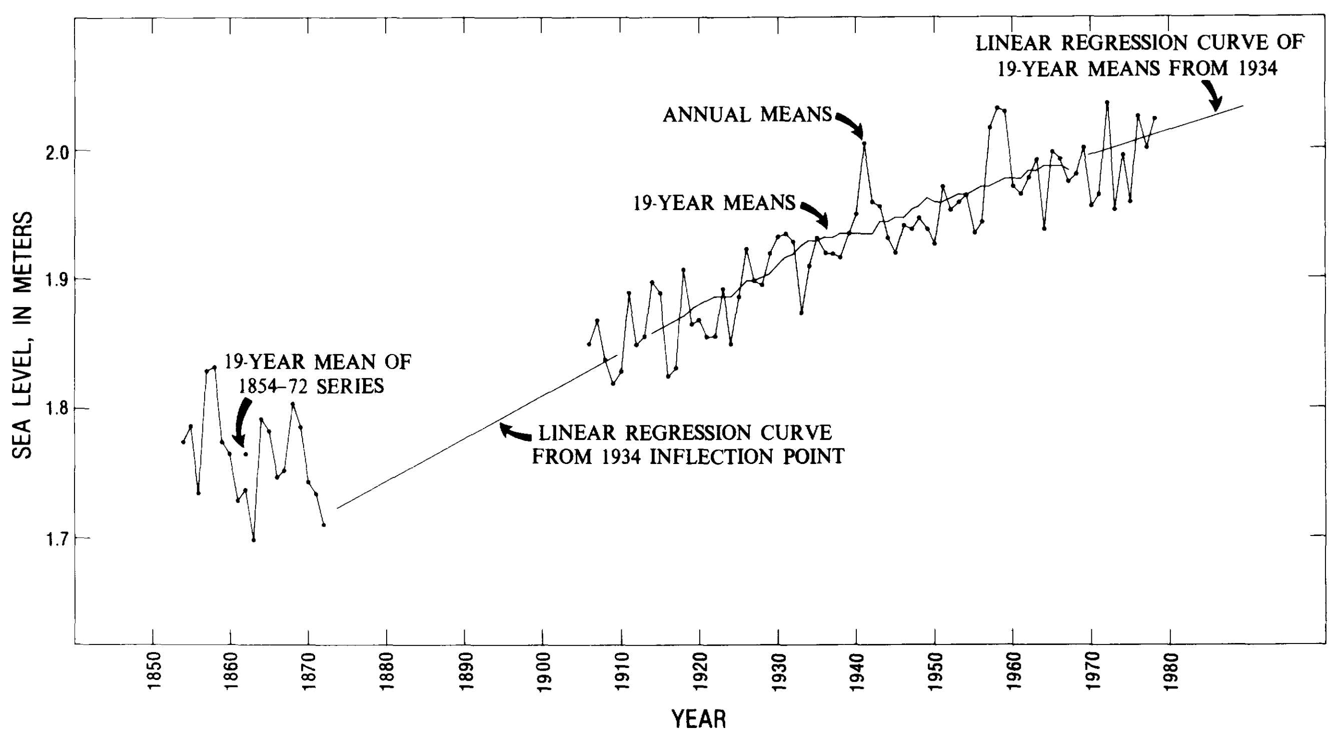

FIGURE 4.—Changes in sea level with respect to adjacent tidal bench marks, San Diego. All elevations are referred to tide staff "O" at the Municipal Pier. 1934 inflection point in 19-year means is interpreted as an effect of the 1926 relocation of the primary tide station (approx 6 km east-northeastward into its present position at the Municipal Pier from its earlier location at the Quarantine Station). From Castle and Elliott (1982, p. 7016).

Although the reconstructed observed elevations used in calculating the height changes described here are all referred to bench mark Tidal 8, Tidal 8 is not known to have been in existence before the 1926 leveling that included this mark. Thus, the several pre-1926 levelings emanating from (or leading into) the San Pedro area can be only indirectly related to the fixed 3.3921-m height of this mark (the published height used both here and in other studies of height changes in southern California).

The height with respect to Tidal 8 of the San Pedro reference mark (BMA) incorporated with the 1897 leveling can be established through a determination of the heights of both these marks with respect to the mean lower low-water tidal datum (MLLW). The record height of BMA above MLLW is given as 7.6779 m (J.R. Hubbard, written commun., 1975). This value, which disregards any changes in sea level during the measurement period, is based on 435 high-water and 435 low-water readings taken in 1853–54, 1878, and 1896–97 and on geodetic ties during the 1890's between BMA and the tidal bench marks to which these highs and lows were referred. The 1933 height of bench mark Tidal 8 above MLLW is given as 4.2398 m; this value is based on the mean of the 1924–42 values recorded at the San Pedro tide station (J.R. Hubbard, written commun., 1975; oral commun., 1982). A linear regression through the 19-yr sea-level means for the San Pedro tide station (fig. 3) indicates that sea level has been rising at this station at an average rate of 0.37 mm/yr, such that the 1897 height of Tidal 8 above MLLW was approximately 13.32 mm greater than in 1933 (or 4.2531 m). Because the 1897 height difference between BMA and Tidal 8 was 3.4248 m, the 1897 height of BMA with respect to the established 3.3921-m height of Tidal 8 is computed as 6.8169 m.

Alternatively, the 1897 starting height of bench mark BMA with respect to Tidal 8 can be developed through a twofold geodetic tie. If we assume that bench mark 30 LA (I 33) remained invariant with respect to Tidal 8 during the period 1920–27 (see below), a 1920 observed elevation for bench mark 7 LA (H 33), Wilmington, can be established with respect to Tidal 8 (NGS lines 74203 and 82656). Similarly, if we further assume that bench mark 7 LA remained invariant with respect to BMA during the period 1897–1920, because the 1897 elevation difference between BMA and 7 LA is known (U.S. Geological Survey, 1898, p. 382), we can obtain an 1897 observed elevation for BMA with respect to Tidal 8. This procedure yields an 1897 value for BMA with respect to Tidal 8 of 6.8022 m. Although the two independently determined 1897 heights for BMA are in remarkably close agreement, we have adopted the first of these values in our reconstruction simply because it avoids assumptions of invariance between bench marks over extended periods.

The height with respect to Tidal 8 of bench mark I 33, the reference mark included with both the 1914 and 1920 levelings in the San Pedro area, can be established through the results of the 1927 leveling that included both these marks (NGS line 82656). The observed elevation difference between these marks is given as 5.7389 m. Because they are only about 2.3 km apart, this 5.7389-m difference between I 33 and Tidal 8—based on first-order leveling (NGS line 82656)—is inferred to have remained invariant during the period 1914–27.

Although the earliest levelings referred to in this report were carried out in 1897, we have adopted 1902 as a reference datum. This choice was governed both by our conviction that 1902 fell within a 6- to 8-year (or greater) period of tectonic quiescence that preceded the inception of the early-20th-century uplift and because 1902 lay approximately midway through a 7-year period of extensive geodetic leveling in southern California. Although, as we show in our detailed reconstruction, localized movement almost certainly occurred between 1897 and the beginning of 1906, evidence of significant regional deformation is minimal before about 1905 and especially before 1902. Specifically, comparison of the results of 1902 double-rodded second-order leveling (USGS summary book 9679) between Pacoima and Lang (pl. 3) against 1897 single-run third-order leveling (U.S. Geological Survey, 1898, p. 390–391) shows that the height difference over this 45-km reach held to within 0.0185 m (expressed as a seemingly down-to-the-north tilt, but actually well within the expected random-error range).[1] Similarly, circuit closures based on sequential levelings extending through the period 1897–1905, particularly in the western Transverse Ranges, generally were well within limits and thus are suggestive of tectonic stability through at least 1905. However, those circuits based on levelings that bracketed the period 1905–07 were characterized by misclosures that were generally above limits and thus are strongly suggestive of major deformation beginning no later than 1907.

Vertical displacements along a series of seven major control lines are described in detail in the following sections. Two of these lines are identified with one or more spurs in which the height changes are related to bench mark Tidal 8 by means of various connections to the primary control lines. Special problems or assumptions

[1] We note that this comparison depends on the recognition and removal of an even 1-ft (0.3048-m) blunder (probably attributable to misreading of the rod or a transcription error) that occurred in the 1897 leveling someplace between bench mark 1076 LA, San Fernando, and a TBM at milepost 460, near the south portal of the Southern Pacific railway tunnel. Compelling evidence of the sense and magnitude of this blunder is shown by the profiled elevation changes that disclose a 0.3049-m offset between the identified marks which seemingly occurred between 1897 and 1902. Although these two surveys continued eastward to Palmdale (fig. 3), we have been unable to unravel the effects of a second blunder in the 1897 leveling that apparently occurred immediately east of Lang.

associated with reconstruction of the observed elevations along particular lines are discussed with the specific reconstruction. Because each successive leveling along any given line commonly has been accompanied by new monumentation and because height changes between levelings might not otherwise be evident, each set of profiles has been reconstructed (where applicable) with respect to a series of progressively younger datums. Presentation of the data in this form tends to diminish any ambiguity, yet still preserves as much detail as possible.

THE OXNARD-GUADALUPE LINE

GENERAL REMARKS

Height changes along the Oxnard-Guadalupe line are based on the results of only two levelings: a join of two third-order surveys completed during the period 1901–03/04[2], and a 1920 first-order survey. Height changes along an adjoining spur extending northward from Ventura to Cuyama are similarly based on a comparison between the results of a 1900/01 third-order survey and a 1934/35 first-order leveling. Although a comparison of the results of the two levelings along the main line, as well as along the Ventura-Cuyama spur, is relatively straightforward, any determination of the height changes along this line is complicated by two problems: the establishment of an accurate contemporary connection between the 1901/03/04 datum and Tidal 8 and an assessment of the accuracy of the third-order leveling that forms the datum along both the main line and the Ventura-Cuyama spur. Three possible approaches can be considered for the establishment of a 1901 starting elevation at Oxnard. We might, for example, simply assume that the height of the reference mark at Oxnard produced by the 1920 first-order leveling is the same as that which would have been produced by 1901 leveling over the same line. Alternatively, a starting elevation at Oxnard could be based on the results of 1898 and 1900 third-order levelings that nearly coincided with the 1920 route extending west-northwestward from Burbank. These surveys, in turn, are easily tied to Tidal 8 through 1897 double-rodded leveling between San Pedro and Burbank. The third option is based on a tie at Ventura with a 1900 spur extending westward from Saugus that is itself connected directly to the results of 1897/1902 double-rodded leveling into San Pedro. The first approach, although it would produce the least uplift along the Oxnard-Guadalupe line (and is, in this sense, the most conservative of the three options), is rejected here simply because it is unnecessarily arbitrary. Even though the second procedure benefits from an approximate coincidence in route between the two levelings into Oxnard, it depends on the use of published (adjusted) height differences over virtually the entire line between Burbank and Oxnard (owing to the physical loss of both summary and field books). It is impaired as well by the detection of two blunders, one of which is imperfectly understood. The third approach, which we have adopted here, also depends on published values over a part of the connecting spur and corrections for two blunders along this line. However, the sense and magnitude of both blunders have been clearly established, and the modest (corrected) misclosure around the circuit involving the published heights indicates that the adjusted height differences closely match the corresponding observed elevation differences. Acceptance of the third option suggests uplift along the Oxnard-Guadalupe line approximately 0.1 m less than that developed from the second approach.

Accepting the validity of the connection between Saugus and Ventura, the accuracy of the 1901/03/04 third-order leveling between Oxnard and Guadalupe is clearly demonstrated by the misclosures that involve the results of this leveling. With relatively few, easily explained exceptions, these misclosures indicate that the levelings that define the Oxnard-Guadalupe datum clearly met third-order standards and were characterized by random error well below the normally estimated value. Similarly, the absence of any correlation between signal and terrain argues convincingly against the existence of height- or slope-dependent error in either of the comparative levelings. Moreover, the field procedures in operation at the beginning of the 20th century suggest that the results of the earlier leveling were not significantly contaminated by systematic error associated with staff settlement.

Comparison of the results of the 1920 leveling against the 1901/03/04 datum shows that uplift along the Oxnard-Guadalupe line increased dramatically westward from about 0.11–0.13 m at Oxnard and Ventura to nearly 0.6 m immediately west of Carpinteria, diminished sharply westward from this maximum to about 0.35 m at Santa Barbara, and held generally above 0.3 m as far as Surf. Northward from Surf it gradually decreased to about 0.15 m at Guadalupe, where the preuplift leveling ends. Although the described uplift could have begun as early as 1904 and subsequently grown more or less constantly, evidence from adjacent areas indicates that it grew spasmodically, probably beginning by no later than 1907.

Because the leveling that defines the datum along the Ventura-Cuyama spur probably is flawed by a major blunder north of Ojai, we show two different interpretations of the 1900/01–34/35 height changes along the Ventura-Maricopa line. Nevertheless, we are skeptical of

[2]Dates separated by slashes refer to surveys performed during the stated years. The convention "1903/04" indicates that leveling done during 1903 and that done during 1904 are combined and treated as a single survey, regardless of whether the levelings were continuous or discontinuous.

both interpretations and show this information simply because we would be remiss in doing otherwise. The 1900/01 starting elevation at bench mark I 30, Ventura, is based on a tie with the 1901 elevation for the nearby mark 13 LA (N 30) on the main line. The 1934/35 starting elevation for I 30 has been developed indirectly from the 1920 observed elevation of bench mark 0 28, Santa Barbara, which can be shown to have remained virtually invariant with respect to Tidal 8 during the period 1920–60.

The 1900/01-34/35 signal along the Ventura-Maricopa spur jumps about 0.4 m between two bench marks in the Ojai area, a jump that is probably, though not certainly, the product of a blunder in the 1900/01 leveling between the two identified marks. The most likely source of this blunder is in either a misreading or transcription error of 0.3048 m (1 ft) in the datum leveling. Our reservation concerning this postulated blunder is based on the effect of the application of a 0.3048-m correction on the circuit that includes this leveling. Specifically, with the introduction of this correction, the clockwise misclosure around the 1900/01 circuit Ventura-Gaviota-Santa Maria-Cuyama-Ojai-Ventura enlarges from +0.07 m to −0.23 m, a value that places it barely within third-order limits. This relatively large, reconstructed misclosure is conceivably the product of yet another compensating blunder that preserved the smaller closure. Nevertheless, it is even more likely that the manufactured 0.23-m misclosure is an expression of blunder-free measurement error around this 430-km loop. The potential for survey error in turn-of-the-century single-rodded third-order leveling is exceptionally high in terrain such as this, which is characterized by relief ranging through more than 1,000 m, primitive roads, and so forth. Thus, this 0.23-m reconstructed misclosure should not be regarded as evidence of especially poor leveling. Therefore, we have adopted, with some reservation, the alternative set of reconstructed height changes along the Ventura-Maricopa spur that allows for a 0.3048-m blunder in the 1901 leveling north of Ojai. This preferred comparison suggests that the 1900/01-34/35 uplift accumulated northward from about 0.06 m to about 0.3 m south of Maricopa, appropriate allowance being made for major random error in the datum leveling. However, because the 1934/35 survey postdated the partial collapse of the early-20th-century uplift, the 1900/01-34/35 signal is assumed to represent residual and presumably lesser uplift than that which obtained at the culmination of this event.

DETAILED RECONSTRUCTION

The Oxnard-Guadalupe line consists of a single vertical-control line that coincides with the Southern Pacific railway west-northwestward from Oxnard to Guadalupe, coupled with a major spur extending northward from Ventura to Cuyama (pl. 3). The 1901 starting elevation at Oxnard is based on a tie through bench mark 13 LA, Ventura, with the results of 1898/1900 leveling along the Saugus-Ventura spur of the San Pedro-Bakersfield line (see subsection below entitled "The San Pedro-Bakersfield Line"). The 1901 observed elevation of 13 LA, based on leveling along the San Pedro-Bakersfield line, has been reduced by 0.0128 m to bring it into orthometric compatibility with that which would have been obtained had this leveling been carried out along the route of the 1920 leveling between San Pedro and Oxnard (pl. 3)—designated here as the primary route. The 1920 starting elevation is based on continuous leveling between San Pedro and Oxnard (NGS line 74203), a 1927 tie between Tidal 8 and bench mark I 33 (NGS line 82656), and a presumption of invariance between these two San Pedro marks during the period 1920–27.

An assessment of the accuracy of the 1901/03/04 single-rodded single-run levelings (Gannett and Baldwin, 1908, p. 76–77, 81, 83, 85) on which we have based the datum along the main line (pls. 3, 4) rests on various tests and comparisons. It is very unlikely that the results of either of the indicated third-order levelings are contaminated by blunders. Blunders would appear in the profiled height changes (pl. 4) as steps or offsets rather than smoothly defined warps. Even though the height changes shown on plate 4 indicate remarkably abrupt, mark-to-mark uplift northwestward from Ventura into bench mark 21 LA, uplift into the same mark accumulated smoothly eastward from Guadalupe. Thus, it would be difficult to dismiss the signal between 13 LA and 21 LA as the product of a survey blunder. The spike at bench mark 57 LA, near Gaviota (pl. 4), is almost certainly an expression of bench-mark disturbance between the two surveys, probably associated with unstable fill (Yerkes and others, 1981). However, the spike identified with the culmination of the uplift at bench mark 52 LA (pl. 4) is less reasonably dismissed as bench-mark disturbance, if only because single-mark uplift is less easily explained than comparable subsidence commonly associated with local settlement or free-face movement. Moreover, because this particular mark is spatially associated with the currently active Red Mountain fault (Yerkes and others, 1981), we have interpreted the uplift centered on 21 LA as an expression of movement on this fault rather than bench-mark disturbance. Similarly, because bench mark 291 LA lies within a youthful, locally elevated and apparently recently uplifted terrane associated with continuing seismicity (Woodring and Bramlette, 1950, p. 10–12, 113–114; Real and others, 1978), it is not unlikely that this spike (pl. 4) is also the product of tectonic movement rather than bench-mark disturbance between surveys.

Significant contamination of the 1901/03/04 levelings by systematic error is very unlikely, even though the resulting elevation differences are based on field values. Specifically, the trivial relief and the absence of any correlation between terrain and signal, other than that associated with the apparent uplift at Casmalia (pl. 4), effectively rules out any significant height- or slope-dependent systematic error. For example, were we to appeal to rod error in the datum leveling to explain the 240-mm signal at Gaviota with respect to Ventura (pl. 4), it would require an average rod error of more than 5×10^{-3} (5,000 ppm). Alternatively, we might attempt to explain this signal by invoking Holdahl's (1982, p. 9376; 1983a, p. 126; 1983b) approximate formulation for estimating the correction for the unequal-refraction error:

$$R' = CL^2\Delta t\Delta h, \qquad (3)$$

where R' = the refraction correction (in meters),
$C = -5.17\times10^{-8}{}^\circ C^{-1}m^{-2}$,
L = the sight length (in meters),
Δt = the temperature at 0.5 m less that at 2.5 m above the ground surface (in °C),
and Δh = the elevation difference (in meters).

If we assume the use of maximum permitted sight lengths of 92 m throughout the earlier survey and zero sight lengths for the 1919/20 survey, it would require a Δt value of approximately -22.0 °C in the datum leveling to explain the 240-mm signal. This argument, of course, is based on the assumption that simplistic relations of the sort given in equation 3 have any validity when applied to the results of normally constrained geodetic leveling. Because there is significant evidence which indicates that they do not (Castle and others, 1983), we are convinced that direct comparisons between terrain and signal provide a much better, albeit qualitative index of slope-dependent error. Furthermore, we have no reason at this time to believe that the indicated variables included in equation 3 are the only nonnegligible "primary physical parameters" (Strange, 1981, p. 2811) that affect the refraction error in those geodetic levelings constrained to no better than third-order standards. However, even though height- or slope-dependent systematic error is reasonably precluded, because this leveling was single run, there is a somewhat greater likelihood that it may have been contaminated by systematic error associated with staff settlement. Nevertheless, both the generally good network closures (see below) and the leveling practice of the day along railways, which called for holding the rod directly on the rail, suggest that any systematic staff settlement must have been measurably insignificant. Moreover, because the apparent uplift of Guadalupe with respect to the east end of the line was only about 0.04 m (pl. 4), attribution of any large fraction of the indicated signal to staff settlement in the 1901/03/04 surveys would require that this postulated error accumulated to almost exactly the same degree from opposite ends of the line. This same observation invites a corollary conclusion: In the absence of any intervening marks between Oxnard and Guadalupe, the excellent correspondence between the results of the two successive surveys could be viewed as equally excellent evidence of an accurately defined datum.

The generally high quality of the 1901/03/04 single-rodded single-run third-order leveling between Oxnard and Guadalupe (pl. 4) is further demonstrated by the network misclosures involving the results of these levelings (fig. 5). Although we have dropped the results of one of the surveys included in the original network (specifically, a 1903 line that bisects the circuit Las Cruces-Lompoc-Los Alamos-Los Olivos-Las Cruces; see fig. 5), this particular line contains an as-yet-unresolved blunder (USGS summary book A-5271). Alternatively, what we interpret as a blunder in this line is conceivably the product of differential movement between the end points sometime between the beginning of 1902 and 1903 (see below). Similarly, the line between Santa Barbara and Wasioja (fig. 5) has been purged of a probable 0.3048-m (or even 1 ft) blunder detected through a comparison of the results of a 1948 survey (NGS lines L-12638, L-12641) against those of the original 1901/02 survey (USGS summary books 9200, 9203) that extended between bench marks 43 LA, Goleta, through Santa Barbara to 842 LA (fig. 5). The observed-elevation differences used in this analysis are otherwise identical to those contained in the indicated summary books (fig. 5).

All but two of the circuit closures shown in this network (fig. 5) are well within third-order limits, and even the larger of the acceptable misclosures are relatively small, given the potential for error. For example, even though the misclosures around the circuits Santa Barbara-Gaviota-Los Olivos-Los Alamos-Santa Maria-Wasioja-Santa Barbara and Santa Barbara-Wasioja-Ozena-Ojai-Ventura-Santa Barbara are given as -0.0821 m and $+0.1553$ m, respectively (fig. 5), these values are only modestly above the estimated random errors predicted for these loops. Moreover, if we consider the inclusive circuit Santa Barbara-Gaviota-Los Olivos-Los Alamos-Santa Maria-Wasioja-Cuyama-Ozena-Ojai-Ventura-Santa Barbara, the misclosure drops to 0.0732 m, an especially impressive figure, considering the more than 1,500 m of relief traversed by this 430-km survey through the western Transverse Ranges. The largest misclosures involving the coastline leveling, two of which are above third-order limits, occur between Gaviota and Guadalupe (fig. 5). The two above-limits misclosures, Gaviota-Surf-Lompoc-Las Cruces-Gaviota and Surf-Harris-Los Alamos-Lompoc-Surf, are approximately balanced, indicating that the survey "error" is probably identified with the common line between Surf and Lompoc (fig. 5). Accordingly, the results of the coastline leveling that define the 1901/03/04 datum over the reach between Gaviota and the point opposite Harris probably are about as accurate as could be expected for leveling of this vintage. The somewhat smaller 0.0950-m misclosure associated with the circuit Guadalupe-Santa Maria-Harris-Purisima Point-Guadalupe is balanced against the 0.1295-m misclosure on the south (fig. 5), a relation suggesting that this smaller misclosure may also be largely the product of an error in the common line between these two loops and, thus, supports the accuracy of the coastal leveling. This possibility implies that the 0.1295-m misclosure would be markedly reduced in the absence of this postulated error (of whatever source) in the survey extending westward from Harris.

Because the 1901/03/04 datum is based on the results of a splice between 1901 and 1903/04 levelings at bench mark 94 LA, Gaviota (pl. 4), we have attempted to identify any movement within this general area during the full survey period. Possibly the most compelling evidence of deformation during the period 1901–03/04 consists of the two above-limits, balanced misclosures northwest of Gaviota (fig. 5), even though, as we have already indicated, they could be explained by nothing more than survey error in the Surf-Lompoc line. Specifically, earthquakes were recorded in the Los Alamos-Lompoc area during the period July 27-31, 1902, and were followed by still another earthquake at Los Alamos on December 12, 1902 (Coffman and von Hake, 1973, p. 162). Thus, the Lompoc area conceivably sustained coseismic deformation characterized by intersurvey uplift with respect to both

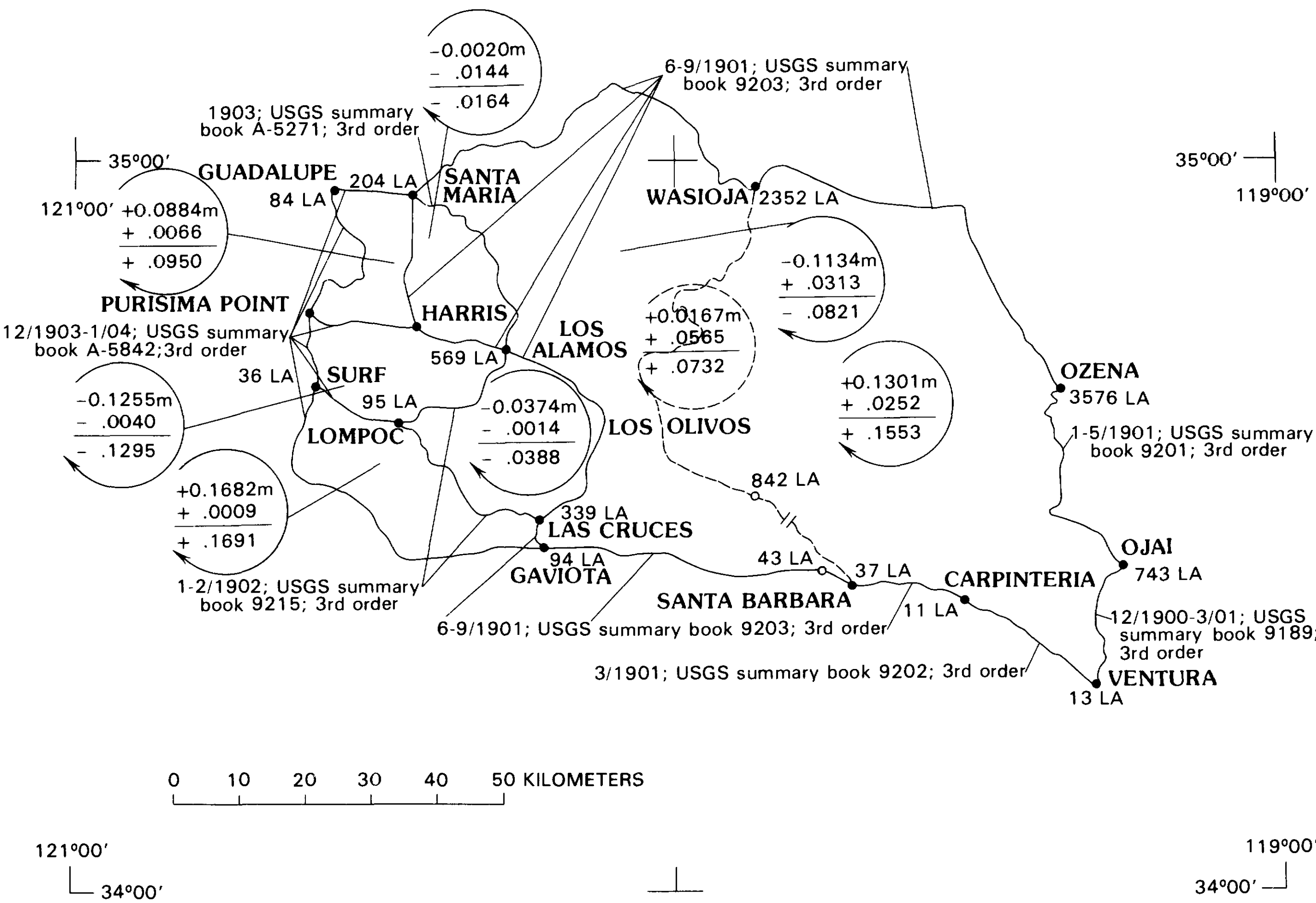

FIGURE 5.—Misclosures around various circuits in the western Transverse Ranges, based on the results of levelings carried out during the period 1900–04. Dashed-line misclosure is algebraic sum of the two adjoining misclosures, each of which depends on the dashed-line survey. Conventions adopted here are used throughout this report: (1) All summations are clockwise, (2) upper figure is the summation of observed-elevation differences around the circuit, (3) figure on the second line is the summation of orthometric corrections around the same circuit, and (4) sum of the two preceding figures is shown on the bottom line and forms the orthometrically corrected misclosure around the indicated circuit. Dots denote junction bench marks. Inclusive dates of leveling, data source (USGS summary or field book, U.S. National Geodetic Survey line number, or other source), and survey order are indicated for each line segment. Approximate location of blunder is shown as interruption in survey line. Orthometric corrections are based on observed gravity.

Gaviota and Surf. Moreover, the misclosure based on the 1901 leveling between Santa Maria and Gaviota via Los Olivos and on the 1903/04 leveling between Gaviota and Santa Maria via Guadalupe sums to only 0.0958 m (fig. 5), well below third-order limits. This observation further suggests that any deformation during the period 1901-03/04 was localized inland from the coast.

Sylvester (1980) and Sylvester and Voors (1981) have argued that correction for a previously unrecognized 387-mm (1.271 ft) arithmetic blunder in the 1903 leveling between Santa Maria and Guadalupe so degenerates the entire network used in our analysis (fig. 5) that it becomes virtually useless. The thrust of their argument is that this "correction" propagates throughout the network, enlarging the misclosures to values that indicate that none of the earlier leveling would be suitable for comparative purposes. In fact, various lines of evidence indicate that the alleged blunder identified by Sylvester (1980) and Sylvester and Voors (1981) is nothing more than a misinterpretation of the original field notes. However, because Sylvester (written commun., 1982) has since repudiated his earlier analysis, we need not detail the evidence that compels this repudiation.

The accuracy of the 1919/20 leveling (pl. 4) is assumed to match that characteristic of first-order leveling of this vintage (Vaníček and others, 1980, p. 507). Moreover, the accuracy of this particular survey is independently verified by the results of a tie between the San Francisco and San Pedro tide stations, based on the results of this leveling. If allowance is made for compaction-induced subsidence measured at the San Jose junction mark during a 1912-19/20 junction interval, the 1920 leveling into San Pedro produces a closure of −0.0241 m on an extrapolated value of mean sea level at San Pedro with respect to measured mean sea level at San Francisco (Castle and Elliott, 1982, p. 7002, 7006–7007).

It is impossible to categorically define the magnitude of the error in the signal developed along the Oxnard-Guadalupe line (pl. 4). Nevertheless, with respect to Tidal 8, the estimated random error in the discrepancy between the results of the 1901/03/04 and 1920 surveys at Guadalupe is approximately 120 mm. In fact, because the height changes at Oxnard and Guadalupe so nearly agree (pl. 4), even this 120-mm value probably is well above the actual error in the signal at Guadalupe—or, in effect, we have overestimated σ for the third-order work. In any case, there is a less than 1 percent chance that the indicated signal can be dismissed entirely as an artifact of the measurement system. This conclusion is based on the probable absence of any significant systematic error and on the likelihood that neither survey has been seriously contaminated by intrasurvey movement.

The indicated height changes along the Oxnard-Guadalupe line are surprisingly large, even if allowance is made for probable errors in the baseline leveling. However, the peak signal—namely, the 574.4-mm uplift at 52 LA (pl. 4)—should be disregarded in considering the regionally developed uplift, which ranged through maxima of 0.3–0.4 m (pl. 4). We cannot dismiss the possibility that the 1901/03/04–20 uplift could have begun as early as 1903/04 and subsequently grown at a more or less uniform rate through the full period between the inclusive surveys. However, comparisons between the results of successive levelings and various misclosures based on leveling completed during the period 1902–14, largely within the area east of the Oxnard-Guadalupe line, indicate that uplift along this line probably grew spasmodically, chiefly during the period 1905–07 (see subsection below entitled "The San Pedro-Bakersfield Line").

Height changes along the Ventura-Cuyama spur (pls. 3, 4) are based on the results of only two levelings, the earlier of which probably was barely up to third-order standards. Reconstruction of the observed elevations that define the 1900/01 datum is based on a 1901 starting elevation for bench mark I 30 obtained from the 1920 leveling between I 30 and 13 LA (N 30), Ventura (NGS line 74203), and on an assumption of invariance between these marks during the period 1901–20. The 1901 elevation of 13 LA is based, in turn, on the same reconstruction used in the development of the orthometrically compatible observed elevation for this mark that permitted the reconstruction of the 1901/03/04 datum along the main line (see above). The 1934/35 starting elevation for bench mark I 30 is based on the 1920 leveling out of San Pedro into bench mark D 29, Carpinteria (NGS line 74203), the 1939 leveling backed into I 30 from D 29 (NGS line L–8470), and an assumption of invariance at I 30 during the period 1934–39. Because D 29 remained virtually fixed with respect to bench mark 0 28, Santa Barbara, during the period 1920–42 (NGS lines 74203, L–9449) and because the height of 0 28 held to within a centimeter with respect to Tidal 8 during the period 1920–60 (NGS lines 74203, L–17847, L–17850), the reconstructed 1939 elevation of D 29 is very close to that which would have been obtained had the 1939 leveling been propagated directly out of Tidal 8.

The 1900/01 datum and, thus, the 1900/01–34/35 signal along the Ventura-Cuyama spur is based on two different reconstructions (pl. 4). The first reconstruction accepts the field values given in USGS summary book 9189 as both accurate to third-order standards and free of blunders. However, because the 1900/01–34/35 signal between bench marks 743 LA and 955 LA jumps by about 0.4 m (pl. 4), the 1901 leveling between these marks probably was contaminated by a major blunder. The magnitude of the seemingly increased signal between 743 LA and 955 LA suggests a 0.3048-m (even 1 ft) reading or transcription error. Accordingly, the second (dashed-line) reconstruction is based on the introduction of a 0.3048-m increase in the 1901 observed-elevation difference between bench marks 743 LA and 955 LA. The effect of this manufactured elevation difference is twofold: (1) It reduces the signal northward from Ojai to values that more closely accord with those obtained elsewhere within the area of the early-20th-century uplift (see subsections below entitled "The San Pedro-Bakersfield Line" and "The San Diego-Barstow Line"), and (2) it enlarges the misclosure around the circuit Ventura-Gaviota-Santa Maria-Wasioja-Cuyama-Ojai-Ventura from +0.0732 m (fig. 5) to −0.2318 m, barely within third-order limits. Because the misclosure around this circuit (fig. 5) is more than tripled with the introduction of a 0.3048-m correction between bench marks 743 LA and 955 LA, the occurrence of a compensating blunder elsewhere around the circuit is reasonably possible. Coupling of the results of the 1920 leveling against the 1901/03/04 datum between the end points of the main line (pl. 4) with the adjacent misclosures clockwise around this circuit between Ojai and Santa Maria (fig. 5) indicates that this section of the circuit probably is free of blunders. Thus, this postulated compensating blunder would have to have been localized somewhere between Santa Maria and Ojai around the north half of the circuit. Were a compensating blunder of the same magnitude (0.3048 m) made between Santa Maria and Wasioja, correction for its occurrence would enlarge the misclosure around the circuit Wasioja-Santa Barbara-Gaviota-Santa Maria-Wasioja from −0.0821 m (fig. 5) to +0.2227 m. Similarly, if this presumed blunder were located east of Wasioja, the corrected −0.1485-m misclosure around the circuit Wasioja-Cuyama-Ojai-Ventura-Santa Barbara-Wasioja (which allows for the 0.3048-m increase in the 1901 elevation difference between bench marks 743 LA and 955 LA) would enlarge slightly to the value shown in figure 5 (+0.1553 m). Thus, the introduction of an equal but opposite correction designed to balance the blunder between bench marks 743 LA and 955 LA would degrade the misclosures around one or the other of the two circuits that combine to form the larger circuit identified with the corrected −0.2318-m misclosure.

The most likely explanation for the magnitude of the corrected misclosure around the circuit Ventura-Santa Maria-Wasioja-Cuyama-Ojai-Ventura is in the generally diminished accuracy of the leveling between Santa Maria and Ojai. There are several reasons for believing that the noise level alone would rise significantly with turn-of-the-century single-rodded third-order leveling through relief of over 1,000 m, even in the absence of any rod error. For example, over much of its course this survey followed what was, at best, a poorly maintained wagon road, and the likelihood that the level sustained accelerated wear and tear or even damage was much greater than might otherwise be expected. If the instrument was slightly out of collimation and the sights were poorly balanced—much more likely under these conditions than had the survey followed a railway—the random error could be expected to increase markedly. Moreover, this area is characterized by intermittent gusty winds, and rod and instrument vibration could be expected to increase with a corresponding reduction in reading accuracy. Similarly, because the leveling was single run, at least a degree of systematic error associated with staff settlement could be reasonably anticipated in this terrain—unless great care were taken to ensure that the direction of running was randomized. However, height- or slope-dependent systematic error is, in our judgment, an unlikely explanation for more than a small fraction of the signal disclosed by the results of the 1934/35 leveling against the 1900/01 datum (pl. 4). The signal shown by the preferred (dashed-line) reconstruction accumulated largely between Ozena and Cuyama (pl. 4). To explain this signal as a result of rod error, the average error in the presumably less accurate rods used in the datum leveling would have to have been about 5.2×10^{-4} (520 ppm)—about that expected in an ordinary ruler. Attempts to attribute this signal to the operation of the unequal-refraction error are even less supportable. If we again assume an average sight length of 92 m for the datum leveling over the Ozena-Cuyama reach—a sight length that would be difficult or impossible to obtain over this 1-percent grade—and a zero average sight length for the 1934/35 leveling, and if we adopt the same value for C used earlier (equation 3), the presumed error would compel a Δt value of $+1.2°C$. In other words, in this worst-case situation (92- versus 0-m sight lengths), the sign of Δt is the reverse of that expected during daylight hours. Moreover, had we chosen a more realistic average sight length for the 1900/01 leveling of about 60 m, it would more than double the Δt value to $+2.8°C$. Accordingly, although we cannot dismiss the possibility of a compensating blunder or intrasurvey deformation, the conditions under which this single-run single-rodded third-order survey was carried out indicate that the manufactured −0.2318-m misclosure around the Ventura-Gaviota-Santa Maria-Cuyama-Ojai-Ventura circuit (fig. 5) probably is an expression of generally lower accuracy than that which characterized the baseline leveling elsewhere within the southern California network.

Disregarding the specifics, the preceding interpretation should not be categorically dismissed as the more unreasonable of the two likely alternatives. The estimated random error alone, with respect to Tidal 8, in the discrepancy between the two levelings leading into bench mark 2180 LA is given as 110 mm. To suggest that the actual error may have matched or even exceeded this value is certainly far from preposterous, even though the accumulated 1901 survey error may have been concentrated largely east of bench mark 2180 LA.

If we accept the second (dashed line) reconstruction as the more likely of the two alternatives considered here (pl. 4), the cumulative 1900/01–34/35 uplift along the Ventura-Cuyama spur increased gradually northward from less than 0.1 to about 0.3 m immediately south of Maricopa. However, the 1934/35 leveling postdated the partial collapse detected east of this line (see next subsection). Assuming that the uplift shown here is a residual signal following partial collapse along this line, the maximum precollapse uplift could easily have approached 0.5 m or more. Furthermore, even though we suspect that the datum survey probably is the least accurate of any of those used in our reconstruction of the early-20th-century uplift, the magnitude of this presumably residual signal (pl. 4) is compatible with that observed along the nearly parallel San Pedro-Bakersfield line and thus is believed to be a fairly good approximation of the actual residual uplift that obtained in 1934/35 along the Ventura-Cuyama spur.

THE SAN PEDRO-BAKERSFIELD LINE

GENERAL REMARKS

Computed height changes based on the results of repeated levelings along the San Pedro-Bakersfield line, together with its several spurs, form one of the two least assailable records considered in this report. The three successive sets of observed elevations developed along the full length of the main line are based on generally continuous and rapidly propagated levelings, such that errors attributable to intrasurvey movement can be dismissed as small or even negligible. Moreover, the accuracy of two of these three surveys is independently verifiable, and the third was run to exceptionally high standards. However, height changes along the five spurs included with this line are believed to be generally less accurate, owing chiefly to the use of less accurately defined datums along three of these five spurs and a questionable assumption of stability at the north end of the Mojave-Olancha spur.

The reference datum along the main line is based on a combination of the results of 1897 double-rodded leveling extending northward from San Pedro to Pacoima and of 1902 double-rodded leveling between Pacoima and Bakersfield. Because the 1897 and 1902 observed-elevation differences northward from Pacoima were virtually identical at least as far as Lang, it is unlikely that this general area sustained any significant regional deformation during the period 1897–1902. Accordingly, the results of the 1897 leveling are treated as the equivalent of those that would have been obtained had this leveling been carried out in 1902. Similarly, because the levelings that define all but one of the datums along the spurs off the San Pedro-Bakersfield line were completed during the period 1897–1902, they too can be treated as the equivalents of those that would have been obtained had they been run in 1902. Although the baseline leveling along the major (Mojave-Olancha) spur was carried out in 1905, it is especially likely that this survey also predated any regional deformation associated with the early-20th-century uplift.

The chief problem in the reconstruction of heights along the San Pedro-Bakersfield line centers on detection and correction for blunders or other errors in the recorded observed-elevation differences. The baseline levelings that define the reference datums in three of the four minor spurs contain one or more blunders, all of which we were able to correct through comparisons against the results of subsequent levelings. A more or less systematic error attributed to the use of imprecisely formulated values for a changing rod excess in the pair of wooden rods used in the 1914 leveling along the main line led to exaggerated observed-elevation differences. The original field observations have since been corrected, using successively computed values for the rod excess based on the full series of field calibrations.

Comparisons against the 1897/1902 datum indicate that uplift during the period 1902–14 accumulated steadily and remarkably uniformly northward from San Pedro. Uplift apparently culminated within the reach between Saugus and Palmdale at nearly 0.5 m, held at about 0.4 m northward to Tehachapi, and finally dropped precipitously to less than 0.3 m at Bakersfield. Uplift during the period 1905–07 increased uniformly to 0.35 m southward from Freeman Junction to Mojave; we can only assume that Mojave rose at a lesser average rate during the period 1907–14. Although the data are ambiguous in part, the results of the 1905 and 1907 surveys between Freeman Junction and Mojave put the most explicit constraints on spasmodic growth of the uplift along the San Pedro-Bakersfield line. Moreover, misclosures based on the results of 1910 leveling on both the preuplift datum and the 1914 survey support the conclusions that the uplift must have begun by or before 1910 and conceivably achieved its maximum growth during the same year.

Beginning no later than 1926 and possibly as early as 1925, the uplift along the San Pedro-Bakersfield line had begun to collapse. Regrettably, all of the postuplift leveling along two of the four minor spurs off the main line followed this period of partial collapse. Thus, the magnitude of the uplift along these two spurs is, in effect, an expression of the residual uplift that survived the collapse.

DETAILED RECONSTRUCTION

The San Pedro-Bakersfield line consists of a primary vertical-control line between San Pedro and Bakersfield, together with a major spur extending northward from Mojave to Olancha and four minor spurs (pls. 3, 5). These four minor spurs include one between Florence and Santa Ana, a second between Los Angeles and Moorpark, and two others that extend westward and northward from Saugus to Ventura and Gorman, respectively. Although all but two of the subsequent sets of observed elevations along the San Pedro-Bakersfield line were based on more or less continuous levelings completed during relatively short periods, the datum is pieced together from the results of levelings that extended over the period 1897–1905. This situation has required that assumptions of stability at the several junctions that define the datum be tested as completely as the data permit.

The several starting heights at San Pedro are based on both direct and indirect ties with bench mark Tidal 8. The 1897 starting height is based on the height of bench mark BMA with respect to Tidal 8, developed through a comparison of the 1897 heights of these two marks with respect to the MLLW tidal datum (see section above entitled "The Reconstruction"). The 1914, 1920, and 1926 starting heights are based on the 1927 height of bench mark I 33 with respect to Tidal 8 (NGS line 82656), coupled with an assumption of stability between these two marks during the period 1914–27.

The 1897/1902 datum along the main line consists of a join between the results of 1897 and 1902 levelings at Pacoima (pl. 5) and an assumption of stability at the Pacoima mark during the 5-year junction interval. This assumption is strongly supported by the conformity between the 1897 and 1902 observed-elevation differences extending northward from Pacoima to Lang (see section above entitled "The Reconstruction"). Moreover, had any regional tilting occurred between 1897 and 1902, we could expect to have seen it expressed as a break at the junction mark in the otherwise-smooth 1897/1902–14 profile between Los Angeles and Ravenna—disregarding the spike at 1171 LA, which is clearly attributable to benchmark disturbance between 1907 and 1914 (pl. 5). This presumed stability is somewhat less convincingly supported by the 1897/1902/1906 misclosure around the circuit Los Angeles-Saugus-Palmdale-Mojave-Barstow-Highgrove-Los Angeles (see subsection below entitled "The Los Angeles-Riverside Line"). Nevertheless, because we suspect that the 1906 leveling between Barstow and Mojave (as well, possibly, as that between Highgrove and Barstow) postdates the first major pulse of the early-20th-century uplift (see subsection below entitled "The Mojave-Barstow Line"), this relatively large, but still-within-limits, misclosure (−0.1357 m) probably would have been somewhat smaller had Mojave not sustained significant uplift between 1902 and the 1906 leveling into Barstow and (or) the still-later 1906 leveling between Barstow and Mojave. Indirect but fairly compelling circumstantial evidence of the accuracy of the combined 1897/1902 leveling between San Pedro and Bakersfield and, by implication, the 1897–1902 stability of the Pacoima junction mark is based on the results of the 1897/1901/1902 leveling over a 900-km route between the San Francisco and San Pedro tide stations. This leveling, which includes the 1897/1902 leveling between Bakersfield and San Pedro and involved the use of at least three sets of rods, produces a closure on an extrapolated value for mean sea level at San Pedro, with respect to measured mean sea level at San Francisco, of +0.2435 m (Castle and Elliott, 1982, p. 7008–7009). This value, moreover, is reduced to +0.2167 m where allowance is made for coseismic movement during the 1897–1901 junction interval at Benicia, and disagrees by only 0.1992 m with the up-to-the-south stationary sea slope predicted from oceanographic investigations (Castle and Elliott, 1982, p. 7000–7002, 7006–7007). We view this 1897/1901/1902 tie between the San Francisco and San Pedro tide stations as exceptionally impressive support for the accuracy of the 1897/1902 leveling between Bakersfield and San Pedro—which was double rodded or double run over the entire line, but to only third-order standards between Pacoima and San Pedro (Gannett and Baldwin, 1908, p. 68).

Because the 1914 leveling between San Pedro and Bakersfield (pl. 5) was completed within 3 months (USGS summary book A–9349), it is unlikely that the results of this survey were distorted by intrasurvey movement. However, even though this leveling was double run to second-order (precise) standards, the utilized rods shortened almost asymptotically over time during the course of the survey. Nine field calibrations against two standardized tapes, coupled with a subsequent calibration of these rods at the end of the field season by the Bureau of Standards, clearly indicated that a single rod excess could not be reasonably applied to the field observations obtained during the full survey. Accordingly, a set of rod corrections was developed from three "averaged" rod-excess values that were in turn applied to the field measurements obtained during the corresponding time-frames (USGS summary book A–9349). Although this procedure should have led to trivial errors in areas of modest relief, because this survey traversed a route identified with height differences in excess of 1,200 m, the rod corrections were recomputed in connection with the present study. This recomputation was achieved by fitting a curve to the measured values for the rod excess plotted against time. This somewhat more rigorous approach produced a discrete rod excess for each day's work that was then applied to the corresponding field values. The results of this recomputation reduced the corrected observed-elevation differences with respect to Tidal 8 by as much as 0.059 m.

The main line of the 1920 leveling extended southeastward through Los Angeles into Santa Ana, with a spur into San Pedro from Florence (pls. 3, 5)—about 10 km south of Los Angeles (NGS line 74203). We infer that a short junction interval occurred between the completion of the main line and the tie between Florence and San Pedro. Nevertheless, both the accuracy of this first-order leveling (which was carried out after the introduction of the Invar rod) and the likely absence of any significant vertical displacement during the junction interval at Florence (at bench mark M 33) are strongly supported by the results of the tie between the San Francisco and San Pedro tide stations based on the results of this leveling (see subsection above entitled "The Oxnard-Guadalupe Line").

Although the 1926 leveling along the San Pedro-Bakersfield line consisted of generally uninterrupted surveys, it was associated with several junction intervals of as long as 2 years (pl. 5). Because two of the interruptions in the "1926" leveling occurred within the San Fernando Valley (at Burbank and immediately north of San Fernando, pl. 5), subsidence associated with ground-water withdrawals (pl. 2) could have led to a change in the elevation difference between the junction marks during the period 1924–26 (pl. 5). Nevertheless, the relative stability between the Burbank and San Fernando marks during the period 1924–26 is clearly demonstrated by the history of bench mark J 52, Saugus, with respect to Tidal 8 during the period 1926–64 (Castle and others, 1984). That is, a comparison of the results of repeated surveys between Tidal 8 and J 52 shows that J 52 subsided 0.0243 m between 1926 and 1955, a value almost precisely half the predicted uplift of Tidal 8 with respect to the San Diego tide station during the 29-year interval between these surveys (figs. 3, 4). Because San Diego has remained remarkably stable, this apparent subsidence is more reasonably attributed to the uplift of Tidal 8 than the collapse of J 52. Moreover, the results of the 1961 and 1964 levelings between Tidal 8 and J 52 indicate almost perfect conformity with the 1926 results (Castle and others, 1984). This exceptionally good agreement is excellent evidence of both the accuracy of the 1926 leveling and the absence of any intrasurvey distortion during the course of the 1926 leveling through the San Fernando Valley into Saugus. This conclusion is forcefully supported by the vertical-displacement history of bench mark 3219 USGS (fig. 6), which shows that this mark subsided about 0.01 m during the period 1926–55. Finally, even though the 1926 leveling over the San Pedro-Bakersfield line was carried out during a period of probable tectonic collapse, the misclosure around the 1926 circuit Saugus-Lebec-Bakersfield-Mojave-Palmdale-Saugus (fig. 7) is persuasive evidence of relative stability along this line during the course of the 1926 leveling.

Even though our analysis of the results of all the surveys along the main line indicate that they were generally accurate and clearly free of both significant distortion associated with intrasurvey movement and blunders of any sort (pl. 5), both systematic and random error have undoubtedly contaminated all of these levelings in varying degree. Nevertheless, comparisons against both the 1897/1902 and 1914 datums indicate that signal and terrain are uncorrelated (pl. 5)—in other than the grossest sense. Thus, it is unlikely that height- or slope-dependent systematic errors have significantly affected the results of any of these surveys. Rod error can be dismissed as a trivial contaminant with respect to the indicated height changes, not only because of the absence of any persistent correlation between terrain and signal, but also because of the unrealistically large magnitude of the postulated error. For example, because the results of the 1914 and 1926 levelings closely agree between San Pedro and San Fernando (pl. 5), we might argue that the apparent signal between Tidal 8 and 1013 LA is reasonably explained as the product of rod error in the 1897

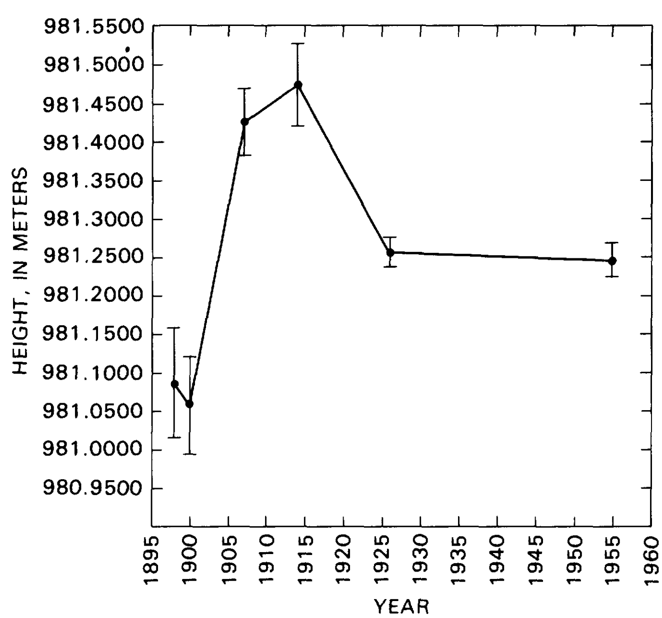

FIGURE 6.—Changes in orthometric height at bench mark 3219 USGS, Vincent, with respect to bench mark Tidal 8, San Pedro. "1898" height is based on an assumption of invariance between Lang and Vincent during the period 1897–1902. 1907 height is based on assumptions of the stability of Olancha with respect to Tidal 8 during the period 1905–07 and of an invariant height difference between Mojave and Vincent during the period 1907–14. Orthometric corrections are based on observed gravity. Error bars show conventionally estimated random error only.

survey. Acceptance of this argument would compel a rod error of 1×10^{-3} (1,000 ppm) in the 1897 leveling—or 2×10^{-3} (2,000 ppm), if we consider the line only as far north as Los Angeles. Alternatively, we might assume that the apparent signal between San Pedro and San Fernando (pl. 5) is attributable to refraction error in the datum leveling only. Resorting to equation 3 and again assuming that the average sight length in the baseline (1897) leveling matched the maximum permissible figure of 92 m, attribution of the 1897–1914 signal to operation of the unequal-refraction error would require an average Δt term of $-2.3°C$. Because the measured Δt values obtained from the field experiment of Stein and others (1982) averaged $-1.07°C$, this estimate seems excessive. Regardless, we have obtained the actual sight lengths for the 1897, 1914, and 1926 surveys as far north as 1013 LA, and for the 1914 and 1926 surveys into 3219 USGS (table 1), near the crest of the grade. Given this information, we can compute the theoretical values for the Δt term (equation 3) required to produce the 1897–1914 uplift at 1013 LA, where it is assumed (1) that the average Δt term is the same for both surveys, or (2) that the average Δt term for the 1914 survey was 1°C less than that associated with the 1897 survey. Where we incorporate the same value for C (equation 3) used above, the average value for Δt based on the first assumption emerges as

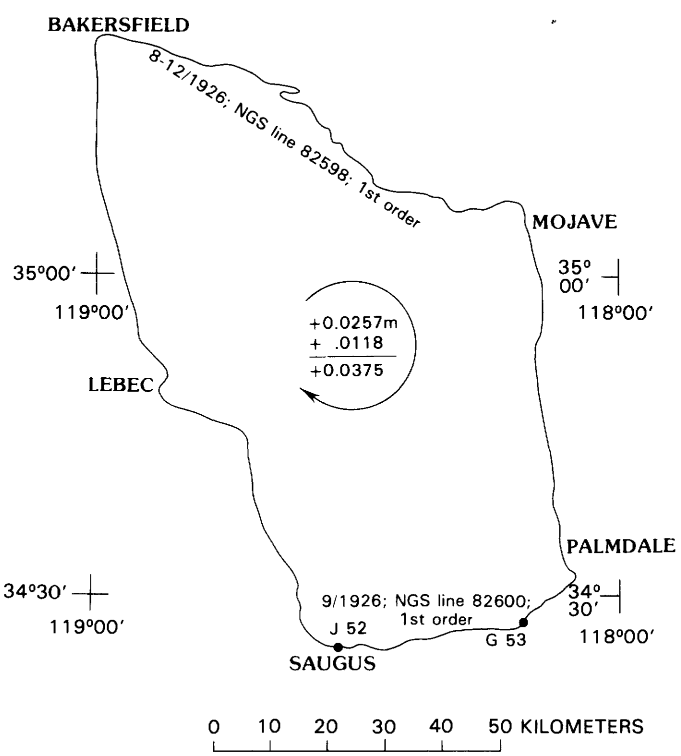

FIGURE 7.—Misclosure around circuit Saugus-Lebec-Bakersfield-Mojave-Palmdale-Saugus, based on leveling carried out during 1926. See figure 5 for explanation of symbols and adopted conventions.

TABLE 1.—*Average sight lengths over selected parts of the San Pedro-Bakersfield line*

[Average sight lengths from U.S. Geological Survey field books 5744, 5746, 5749, U.S. Geological Survey summary book A-9349, and NGS lines 82466, 82583, 82598, and 82600]

Survey period	Average sight length (m)	
	San Pedro to 1013 LA (70.2 km)	San Pedro to 3219 USGS (142.2 km)
	1897	
July 30-Aug. 2 Aug. 27-Sept. 6 Oct. 7-20	68.69	([1])
	1914	
June 9-July 14	67.86	69.30
	1926	
Aug. 16-19 [2]Aug. 23-25 Sept. 7-22 Dec. 3-6	[3]74.84	68.42

[1]The 1902 field books containing setup data over the reach between 1013 LA and 3219 USGS were destroyed by fire.
[2]Though included within the indicated seasonal time frame, this 6-km segment (between Burbank and Pacoima) was actually run in 1924.
[3]Sight-length data are unavailable from the NGS machine-readable file for a 40-km segment between Compton and Burbank (NGS line 82583).

$-173.5°C$. If, however, the Δt value associated with the 1914 survey is assumed to have been 1°C less than that associated with the 1897 survey, the corresponding values for Δt are computed as -173.9 and $-172.9°C$ for the 1897 and 1914 surveys, respectively. Moreover, direct inspection (table 1) indicates that the seasonal correspondence and the average sight lengths for the 1914 and 1926 surveys leading into 3219 USGS are such that it would be fatuous to suggest that the 1914–26 subsidence at 3219 USGS could be attributed to the systematic accumulation of refraction error. Finally, with respect to Tidal 8, the estimated random error at Bakersfield in the discrepancies between successive surveys are given as 113 mm in comparing the 1897/1902 and 1914 levelings, 92 mm in comparing the 1897/1902 and 1926 levelings, and 76 mm in comparing the 1914 and 1926 levelings.

The Florence-Santa Ana spur consists of a very short line extending southeastward into Santa Ana from Florence (pl. 3) and incorporates the results of only two levelings, both of which postdated the first major surge of uplift (pl. 5). This spur is included here in spite of its very limited extent simply because it provides some in-sight into the magnitude and sense of the vertical-displacement field around the south margin of the uplift.

Both the 1914 datum and the results of the 1920 leveling along the Florence-Santa Ana spur have been developed from direct ties with the main line through bench mark 123 LA (M 33) (USGS summary book A-9349; NGS line 74203). Because the results of both levelings are the products of more or less continuous surveys emanating directly out of San Pedro, we can disregard intrasurvey movement as a significant error source. Moreover, the double running of each of these surveys, coupled with the profiled height changes and comparisons between these changes and the terrain profile, precludes the existence of blunders or significant systematic error in either leveling. With respect to Tidal 8, the estimated random error in the discrepancy between the results of the 1914 and 1920 levelings at Santa Ana is given as 36 mm.

Although the Los Angeles-Moorpark spur is redundant between Los Angeles and Burbank, we have begun this line in Los Angeles simply because the Burbank mark was not recovered during the 1920 postuplift leveling. Reconstruction of the observed elevations that form the 1900 datum is based on a tie with the results of the 1897 double-rodded leveling into 563 LA from San Pedro (pls. 3, 5) and the presumed stability of this mark during the period 1897–1900. The 1920 observed elevations along the Los Angeles-Moorpark spur are based on the results of uninterrupted 1920 leveling between Moorpark and Los Angeles (or San Pedro) (pls. 3, 5). Because the route of the 1900 leveling nearly coincided with the 1920 line between Burbank and Moorpark, any differences in the orthometric corrections applicable to these two lines are certainly very small and thus are disregarded here.

Development of the 1897/1900 datum is based on published, adjusted elevations between Burbank and Moorpark and a correction for a −0.3048-m (even 1 ft) blunder in the 1900 leveling that occurred somewhere between 563 LA, Burbank, and 961 LA, Santa Susana (pls. 3, 5). The Geological Survey summary book for this line was destroyed in a fire. Nevertheless, because the published elevation differences over this short spur probably differ only slightly from the observed values, a reconstruction based on the use of these adjusted values (Wilson and others, 1901, p. 174–175, 177, 180) should nearly match that which would have been generated from the observed values. The identification of the blunder west of Burbank ultimately rests on a seemingly contradictory combination of a satisfactory misclosure that includes this line (fig. 8) and a calculated discrepancy in the 1897/1900 and 1920 elevation differences between bench marks 306 LA and 961 LA of 0.3118 m. Because bench mark 563 LA was not recovered in the 1920 leveling and because 432 LA appears as a spike in the 1897–1920 profiled height changes (pl. 5), we have been forced to back off to bench mark 306 LA in order to establish the comparison, even though the blunder must have occurred somewhere between 563 LA and 961 LA.

Although the only recognized blunder in the Los Angeles-Moorpark spur has been removed and even though there is little likelihood that the results of either of the utilized surveys have been affected by intrasurvey displacements, systematic and random error probably have contaminated both levelings to at least some degree. However, comparison of the results of the 1920 leveling against the 1897/1900 datum indicates that terrain and signal are again uncorrelated (pl. 5) and suggests that neither height- nor slope-dependent systematic errors have contributed significantly to the error budget of either survey. The spike at Moorpark (bench mark 511 LA) is interpreted as the product of a local disturbance between surveys and thus neither supports nor refutes the existence of any height- or slope-dependent error. Disregarding our use of adjusted values in the construction of the 1900 datum between Burbank and Moorpark, the estimated random error in the discrepancy between the 1897/1900 and 1920 levelings into Moorpark from Tidal 8 is given as 63 mm.

The Saugus-Ventura spur (pls. 3, 5) provides the basis for both a datum tie between the San Pedro-Bakersfield line and the Oxnard-Guadalupe line and a measure of the postcollapse, residual uplift over this reach. Because one line of evidence indicates that the junction mark at Saugus, 1171 LA, was disturbed between the 1897 and 1902 surveys into this mark, the 1900 starting elevation at 1171 LA is based on an 1897 (single-rodded) observed-elevation difference between 1171 LA and bench mark 1273 LA, Newhall (U.S. Geological Survey, 1898, p. 391), and the 1897/1902 (double-rodded) observed elevation given for 1273 LA (pl. 5). The 1935 starting elevation at Saugus is based on a tie with the 1926 observed elevation of bench mark J 52 (NGS lines 82466, 82583, 82598).

The 1900 datum is again based in part on published, adjusted elevations, coupled with observed-elevation differences westward from Fillmore into Ventura. The 1900 datum is also identified with two blunders, one of which is clearly a 0.3048-m (even 1 ft) error, whereas the other is much more ambiguously defined and only indirectly related to the actual leveling between Saugus and Ventura. The elevation difference between Saugus and 599 LA (pl. 3) has been taken directly from Wilson and others (1901, p. 178–179) and corrected for the 0.3048-m (even 1 ft) blunder between 1171 LA and Castaic Siding (fig. 8). Moreover, indirect evidence indicates that the adjusted elevation difference between bench marks 599 LA and 469 LA (which was destroyed before the 1935 leveling and through which we must make our tie between the adjusted and observed values along this line) is even more seriously and complexly flawed. Specifically, the 1935 observed-elevation difference between bench mark 599 LA and 501 LA is given as 28.9107 m (NGS line L–5266), whereas that based on the 1900 adjusted elevation difference between 599 LA and 469 LA (Wilson and others, 1901, p. 178) and the 1900 observed difference between 469 LA and 501 LA (USGS summary book 9189) is 29.5925 m, a discrepancy of 0.6818 m. Similarly, the adjusted elevation difference between 501 LA and the top of the north rail at Fillmore is given as 10.3898 m (U.S. Coast and Geodetic Survey line 140 Calif., 1954), whereas the elevation difference between these same two points based on the observed difference between 501 LA and 469 LA (USGS summary book 9189) and the adjusted difference between 469 LA and the top of the north rail (Wilson and others, 1901, p. 178) is 9.5570 m, a 0.8328-m discrepancy that seems to localize the problem around bench mark 469 LA. In fact, both of these discrepancies are the product of the propagation of two 0.3048-m (even 1 ft) blunders in the 1900 leveling extending westward from Burbank through Moorpark and Oxnard and back into bench mark 469 LA (figs. 8, 9). That is, because of these two blunders, the observed elevation of 469 LA came in 0.6096 m lower than would have been the case had these errors not been introduced into the indicated leveling. The misclosures associated with the two blundered, adjoining loops considered here (figs. 8, 9) are both balanced and reasonably tight. In other words, the adjustment corrections must have been very small, indicating that the adjusted elevation differences are virtually identical with the observed values from which they were produced. To establish a tie

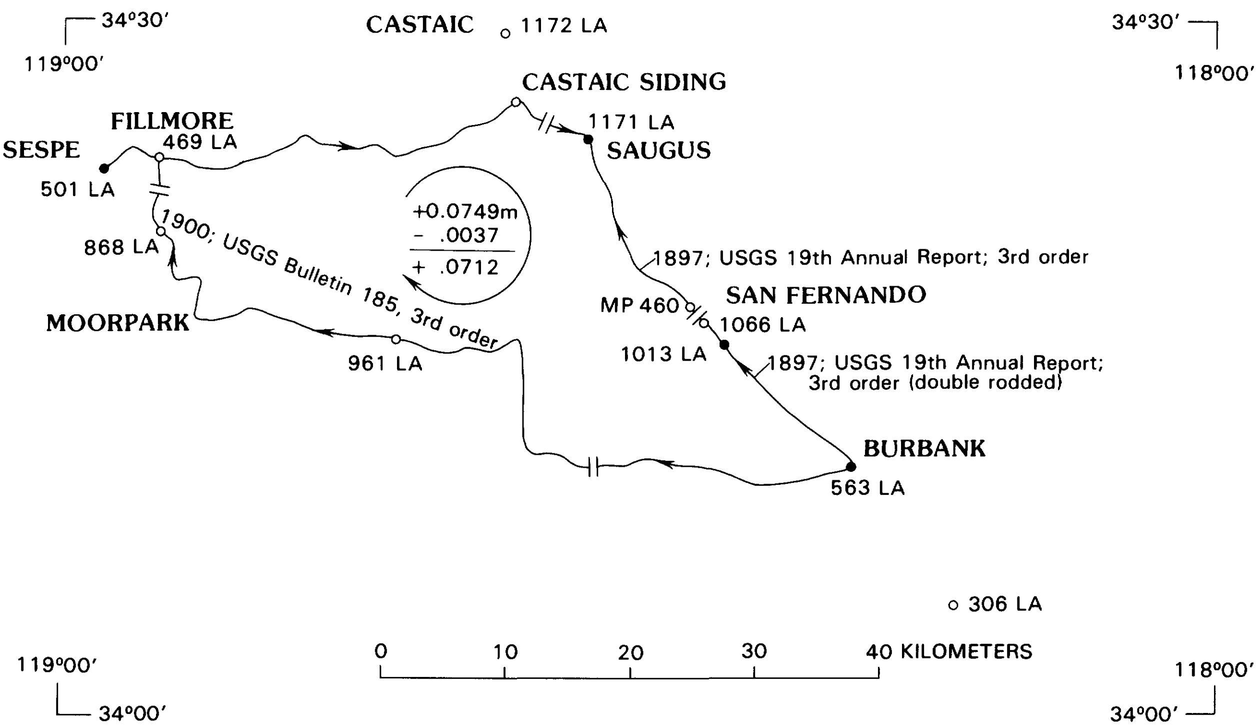

FIGURE 8.—Misclosure around the 1897/1900 circuit Burbank-Moorpark-Fillmore-Castaic Siding-Saugus-Burbank, where all known blunders have been removed. Relatively modest observed misclosure (given in USGS summary book 8304) is apparently the product of neatly compensating blunders, all of which are interpreted as 0.3048-m (even 1-ft) busts detected through comparisons between the results of the indicated levelings and subsequent levelings over the same or nearly coincident routes. Blunder between bench marks 563 LA and 961 LA is from a comparison of observed elevations given in NGS line 74203 against those given by the U.S. Geological Survey (1898, p. 382, 386–387) and the adjusted values of Wilson and others (1901, p. 174, 177); record discrepancy of 0.3118 m is based on successively developed measurements between bench marks 306 LA and 961 LA (see text for details). Blunder between bench mark 868 LA and Fillmore is from a comparison of adjusted elevations given in U.S. Coast and Geodetic Survey lines 140 Calif. (1954) and 142 Calif. (1948) against those given by Wilson and others (1901, p. 178); record discrepancy of 0.4602 m is based on successively developed measurements between bench mark 868 LA and the top of the north rail opposite Fillmore depot. Blunder between Castaic Siding and bench mark 1171 LA is from a comparison of observed elevations given in NGS line 82598 and USGS summary book B–3223 against adjusted values given by Wilson and others (1901, p. 180–181); record discrepancy of 0.3021 m is based on successively developed measurements between bench marks 1171 LA and 1172 LA (Castaic), whereas its localization is based on the occurrence of a comparable error in the loop to the north that has only the indicated segment in common (see text for details). Blunder between bench mark 1066 LA and Mile Post 460 is from a comparison of 1902 observed elevations (USGS summary book 9679) against those of the U.S. Geological Survey (1898, p. 391); record discrepancy of 0.3049 m is based on successively developed measurements between the two identified marks. Arrow indicates direction of running. See figure 5 for explanation of symbols and adopted conventions.

between the adjusted line (Wilson and others, 1901, p. 178) and the observed values along that part of the line extending westward into Ventura (USGS summary book 9189), we have simply diminished the adjusted elevation difference between 599 LA and 469 LA (Wilson and others, 1901, p. 178) by 0.6096 m (the equivalent of lifting the observed value of 469 LA obtained from the clockwise survey route through Oxnard by the same amount).

The results of one or the other of the two surveys that define the height changes along the Saugus-Ventura spur

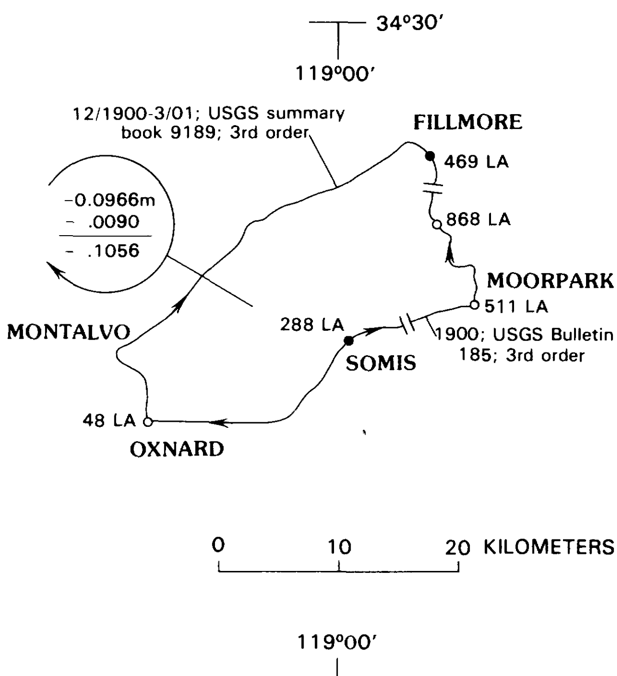

FIGURE 9.—Misclosure around 1900 circuit Moorpark-Somis-Oxnard-Montalvo-Fillmore-Moorpark, where known blunders are retained. This misclosure enlarges to +0.5040 m with removal of the two identified blunders, each of which is interpreted as a 0.3048-m (even 1-ft) bust. Blunder between bench mark 511 LA and Somis is from a comparison of observed elevations given in NGS line 74203 against those given in USGS summary book 9189 and the adjusted values of Wilson and others (1901, p. 180). Because intermediate marks were not recovered in 1920, record discrepancy of 0.2575 m is based on successively measured differences between bench marks 511 LA and 48 LA, whereas its localization is based on the apparent absence of any blunders clockwise around the circuit between Somis and bench mark 469 LA (see text for details). Blunder between bench mark 868 LA and Fillmore is from a comparison of the adjusted elevations given in U.S. Coast and Geodetic Survey lines 140 Calif. (1954) and 142 Calif. (1948) against those given by Wilson and others (1901, p. 178); record discrepancy of 0.4602 m is based on successively measured differences between bench mark 868 LA and the top of the north rail opposite Fillmore depot. Arrow indicates direction of running. See figure 5 for explanation of symbols and adopted conventions.

may include the effects of a significant height- or slope-dependent systematic error. Disregarding the spike at bench mark 599 LA, the profiled results of the 1935 leveling against that section of the 1900 datum based on the use of adjusted elevation differences defines a signal that is clearly uncorrelated with topography (pl. 5). However, within the section west of Fillmore for which the observed data still survive, a vague correlation exists between the terrain and the represented height changes (pl. 5). Regardless, because the height difference is so small and the slope is especially gentle between Ventura and Fillmore, it is unlikely (though certainly plausible) that any accumulated systematic error between these points exceeds several tens of millimeters. Furthermore, the localization of this postulated error within that section of the line associated with unadjusted elevation differences suggests that the observed correlation may result from nothing more than an accumulation of random error—or, equally likely, differential movement. With respect to Tidal 8, and again disregarding our use of adjusted data over a part of this line, the estimated random error in the discrepancy between the 1897/1900/02 and 1926/35 levelings at Ventura is given as approximately 85 mm.

The Saugus-Gorman spur (pls. 3, 5) consists of the results of only two levelings, which again provide us with no more than a measure of the residual postcollapse uplift along this line. The 1900 starting elevation at Saugus is based on the same reconstruction used in establishing the 1900 observed elevation for 1171 LA along the Saugus-Ventura spur. The 1926 starting elevation is taken directly from the 1926 value for bench mark J 52, Saugus.

The 1900 datum along the Saugus-Gorman spur is also composed of both adjusted values and unadjusted observed-elevation differences. However, the adjusted section forms but a small fraction of the datum (pl. 5). Moreover, as we have already indicated, the misclosures around two of the loops on which these adjusted values are based are relatively small; thus, the resulting adjustment corrections probably produced adjusted values that nearly match the observed-elevation differences. The 1900 datum is again corrected for the 0.3048-m blunder between 1171 LA and Castaic Siding (fig. 8). We have been unable to demonstrate the existence of any other blunder along this spur, but an additional blunder has been detected in the 1900 leveling extending eastward from Gorman (fig. 10). This added blunder cancels the 0.3048-m blunder between 1171 LA and Castaic Siding (fig. 10), such that the misclosure around this loop remains unchanged whether the blunders are retained or not. The recognition of this second blunder supports the occurrence of the first, and because a corresponding blunder is revealed in an analysis of the loop to the south (fig. 8), it virtually demands that this blunder was localized within the reach between Saugus and Castaic Siding. The record discrepancy between bench marks 3393 LA and 3039 LA (0.5203 m) produced by successive measurements between these two marks (fig. 10) suggests that this blunder should not be dismissed simply as the product of a 0.3048-m (even 1 ft) error in the 1900 leveling. However, the interval between these two levelings includes both uplift and partial collapse and probable differential movement between the two identified marks. Moreover, 3393 LA sits in the midst of the San Andreas gouge zone, an area especially subject to localized movement. Thus, we should expect to see a less than perfect 0.3048-m disparity in these successively measured elevation differences between bench marks 3393 LA and 3039 LA.

Although the 1900 datum could have been extended northward beyond bench mark 4230 LA (pls. 3, 5), there is a significant likelihood that the section between bench marks 4230 LA and 3174 LA (fig. 11) is associated with yet another 0.3048-m (even 1 ft) blunder. If we assume that the discrepancy in the successively measured elevation differences between these marks is, in fact, an expression of a 0.3048-m blunder, correction for the occurrence of this postulated blunder reduces the misclosure around this loop (fig. 11) to an acceptable +0.1095 m. Nevertheless, even if it could be clearly demonstrated that this value is based on blunder-free data, owing to the incorporation of the results of 1910 leveling between

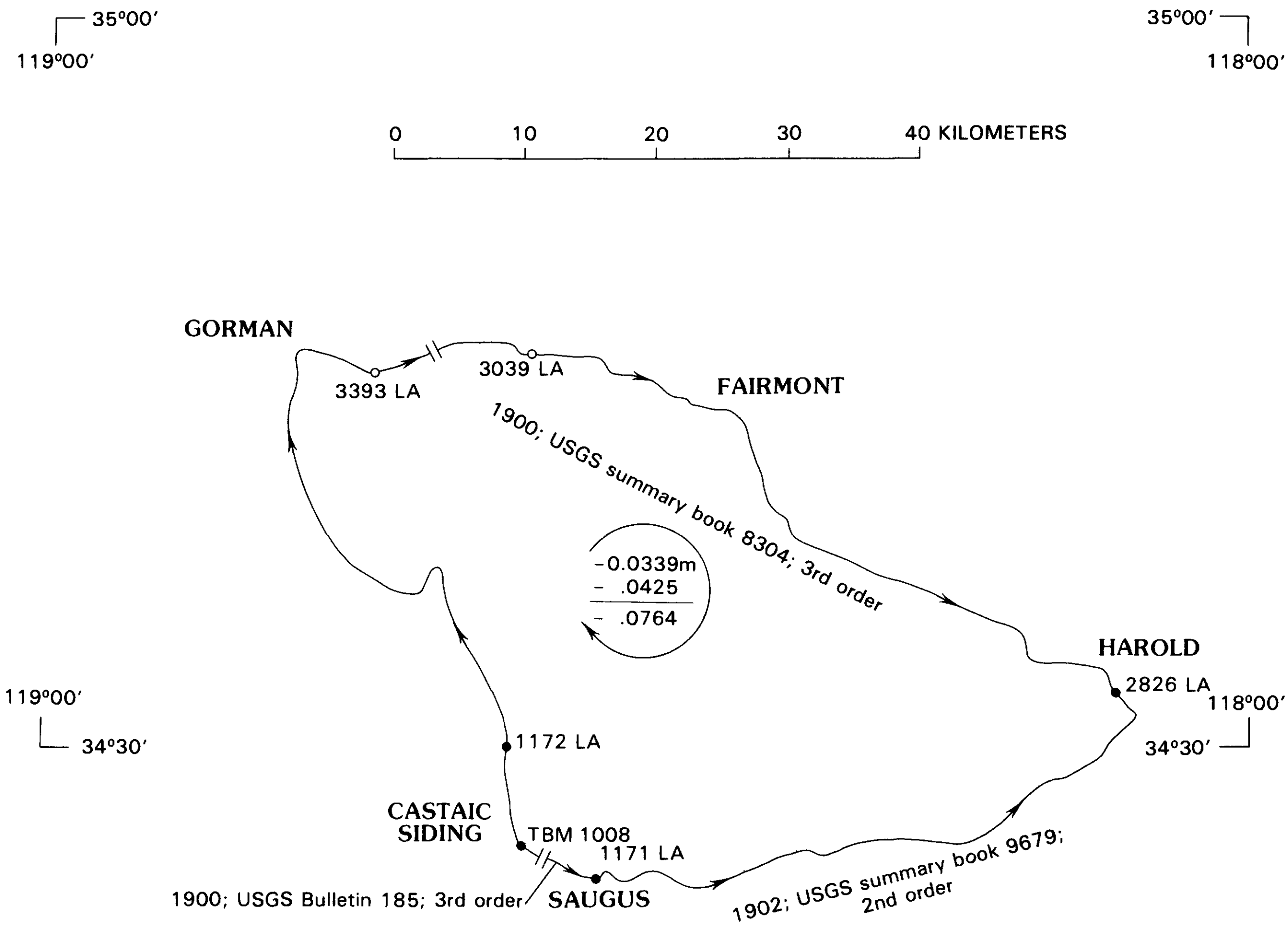

FIGURE 10.—Misclosure around the 1900/02 circuit Saugus-Gorman-Fairmont-Harold-Saugus, where all known blunders have been removed. Each identified blunder is interpreted as a 0.3048-m (even 1-ft) bust. Blunder between bench mark 1171 LA and Castaic Siding is from a comparison of 1926 observed elevations given in NGS line 82598 and 1929 observed elevations given in USGS summary book B–3223 against adjusted values given by Wilson and others (1901, p. 180–181); record discrepancy of 0.3021 m is based on successively developed measurements between bench marks 1171 LA and 1172 LA, whereas its localization is based on the occurrence of a comparable error in the loop to the south that has only the indicated segment in common (fig. 9). Blunder between bench marks 3393 LA and 3039 LA is from a comparison of 1926 observed elevations given in NGS line 82598 and 1929 observed elevations given in USGS summary books B–3213, B–3222, and B–3717 against those given in USGS summary book 8304; record discrepancy of 0.5203 m is based on successively developed measurements between these two marks. This misclosure would enlarge to +0.2418 m in the absence of the blunder between bench mark 1171 LA and Castaic Siding. Arrow indicates direction of running. See figure 5 for explanation of symbols and adopted conventions.

bench marks 864B and 2132 LA (fig. 11), this misclosure is opposite in sense to that which we would have anticipated. That is, the 1910 leveling followed the first major pulse of regional uplift, an event that could have been expected to increase the height difference between 864B and 2132 LA and thus lead to a clockwise negative misclosure around this loop rather than vice versa. Owing to these seemingly contradictory observations, prudence requires that the Saugus-Lebec spur be terminated at bench mark 4230 LA.

Although there is little likelihood that intrasurvey movement has affected the results of either of the levelings included with the Saugus-Gorman spur, systematic and random error has almost certainly contaminated both surveys to at least some degree. Nevertheless, signal and terrain along this line are certainly uncorrelated (pl. 5),

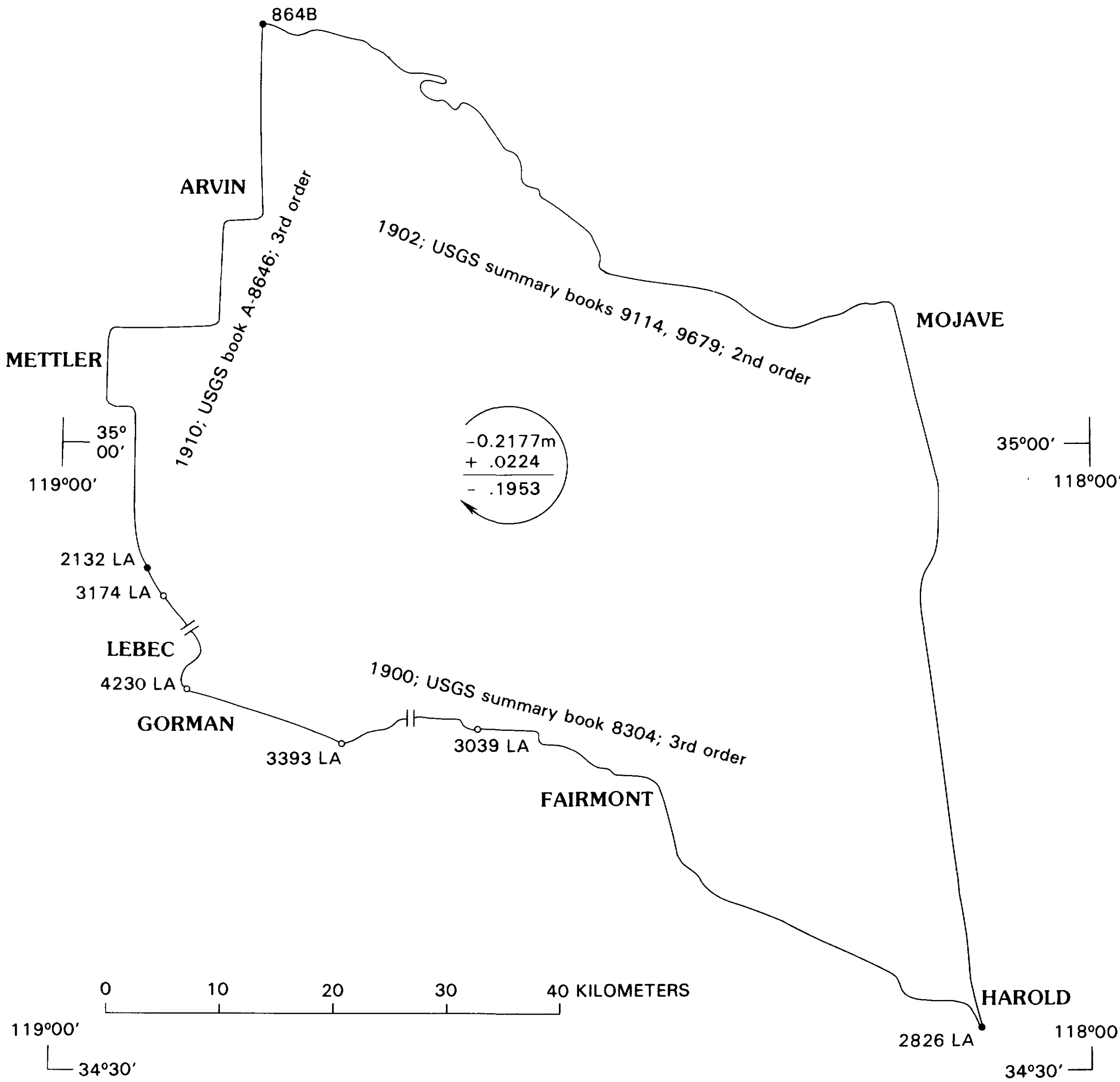

FIGURE 11.—Misclosure around 1900/02/10 circuit Gorman-Lebec-Arvin-Mojave-Harold-Gorman, corrected for the 0.3048-m blunder between bench marks 3393 LA and 3039 LA (see fig. 10). Suspected 0.3048-m (even 1-ft) blunder between bench marks 4230 LA and 3174 LA is from a comparison of the results of a 1926 leveling (NGS line 82598) against those obtained in the 1900 survey (USGS summary book 8304); record discrepancy of 0.3150 m is based on successively developed measurements between these two points. Correction of observed-elevation difference between bench marks 4230 LA and 3174 LA for the suspected blunder between these two marks reduces the misclosure to +0.1095 m. See figure 5 for explanation of symbols and adopted conventions.

such that it is very unlikely that either survey has been seriously affected by either height- or slope-dependent systematic error. With respect to Tidal 8, the estimated random error alone in the discrepancy between the 1897/1900/02 and 1926 levelings at Lebec is given as about 78 mm.

The Mojave-Olancha spur, which extends northward from Mojave along the east side of the Sierra Nevada, includes the results of three successive double-run surveys that contribute to the definition of the north margin of the uplift in both space and time. The starting elevation for the 1905 datum is based on the 1897/1902 elevation of bench mark 2732B, Mojave (pls. 3, 5), and the presumed stability of this mark during the 1902–05 junction interval. Specific evidence of the stability of 2732B during the period 1902–05 has not been discovered. Nevertheless, the 1905 leveling was completed during the first 3 months of 1905 (USGS summary book 6130), and comparisons with the results of the 1907 leveling indicate that nearly 90 percent of the 1902–14 uplift at Mojave occurred between 1905 and 1907, a consideration that severely restricts the magnitude of any 1902–05 uplift at junction mark 2732B—even though it provides no clue regarding its possible collapse during the 1902–05 junction interval. The 1907 leveling originated at bench mark 1013 LA, Pacoima (pl. 5), and because several lines of evidence indicate that this mark sustained major uplift by no later than 1907, a presumption of stability at 1013 LA during the period 1897/1902–07 is clearly unsupportable. An alternative approach to the establishment of a starting elevation for the 1907 leveling is through the northernmost comparative mark at Olancha. Specifically, because the reach between Freeman Junction and Olancha was characterized by the absence of any significant differential movement during the period 1905–07 (pl. 5), we can reasonably assume that bench mark 3649B, Olancha, remained invariant with respect to Tidal 8 during the brief interval between the 1905 and 1907 levelings. The results of the 1925/26 leveling into Freeman Junction and Olancha strongly support this assumption; the heights of the three marks that were hit in the 1905 leveling which can be tied to the results of the 1925/26 survey indicate that the section between Freeman Junction and Olancha remained virtually unchanged with respect to Tidal 8 during the full period 1897/1902/05–25/26 (pl. 5). The 1925 starting elevation at Mojave is based on the 1926 record elevation of 2732B (pl. 5) and an assumption of invariance with respect to Tidal 8 during the 1925–26 junction interval. Although this assumption is a seemingly reasonable one (as shown, for example, by the correspondence between the 1897/1902/05 and 1925/26 heights between Freeman Junction and Olancha), because it is very unlikely that the more easterly section of the uplift had begun to collapse until after 1924 (see subsection below entitled "The San Diego-Barstow Line"), the 1925 tie through the 1926 elevation of 2732B implies that the collapse of Mojave probably occurred largely within the period 1924–25—a remarkably constrained interval.

Because the second and third levelings leading into and along the Mojave-Olancha spur deviate in part from the 1897/1902/05 line that we have designated as the primary route (pl. 3), the differences in the orthometric corrections applicable to each of these levelings must be considered in calculating the height changes along (or beyond) this spur. The 1905 and 1907 survey routes between Mojave and Olancha virtually coincided, such that the differences in the orthometric corrections applicable to the results of the levelings along these two lines can be dismissed as negligible. However, the 1907 leveling between Saugus and Mojave lay well to the west of the primary 1897/1902 line (pl. 3). Accordingly, to bring the 1907 observed elevations along the Mojave-Olancha spur into orthometric compatibility with those that would have been obtained had this northward-propagated leveling between Saugus and Mojave followed the primary route, the 1907 starting elevation of bench mark 2732B, Mojave, has been reduced by 0.0019 m. Moreover, because the route of the 1925 leveling between Cantil and Freeman Junction lay to the east of the primary route (pl. 3), the 1925/26 observed elevations between Freeman Junction and Olancha have been brought into orthometric compatability with those that would have been generated had this leveling followed the primary route through a 0.0235-m reduction of the 1925/26 observed elevations over this reach. However, even though the 1925/26 observed elevations of both 3379B and 3649B are based on 1936 ties between these marks and the 1925/26 line (USGS summary book B–6965) and an assumption of invariance between these marks and their respective junction points along the 1925/26 line, because the 1925/26 line very nearly coincides with the primary route between Inyokern (or Freeman Junction) and Olancha, we have disregarded any orthometric corrections involved in these ties.

Although intrasurvey movement conceivably distorted the heights determined from successive levelings along the Mojave-Olancha spur, as measured with respect to Tidal 8, both the double running of all these surveys and comparisons between their results (pl. 5) virtually preclude the existence of blunders in any of the levelings along this spur. Similarly, because terrain and signal are devoid of correlation along this line (pl. 5), height- or slope-dependent errors in any of the Mojave-Olancha levelings can be dismissed as insignificant. In fact, were we to hypothesize that the apparent signal between Freeman Junction and Mojave is attributable to rod error in the 1905 leveling the error would have to have been about 2.5×10^{-3} (2,500 ppm), and of such a nature that it changed miraculously to virtually zero northward from

Freeman Junction. Moreover, to appeal to unequal refraction in the datum leveling in order to explain this signal would be equally (or even more) ridiculous because it would compel an enormous midwinter Δt value (equation 3) opposite in sign to that required to explain the observed signal (pl. 5). Because the 1897/1902/05 height of bench mark 3649B (pl. 5) has been held through 1907 in the reconstruction of the 1897/1902/05–07 height changes, the estimated random error in the discrepancy between the results of these two levelings increases southward from Olancha to a maximum at Mojave of 93 mm. Moreover, because the results of the 1907 survey can be backed into Pacoima, where allowance is made for the difference in the orthometric corrections applicable to the 1907 and 1897/1902 primary routes between Mojave and Saugus, the estimated random error in the discrepancy between the 1897/1902/05 and 1907 heights at Pacoima (pl. 5) is 96 mm. The estimated random error at Olancha, with respect to Tidal 8, in the discrepancy between the 1897/1902/05 and 1925/26 heights is given as 94 mm.

The regionally developed uplift along the San Pedro-Bakersfield line, including its several spurs (pls. 3, 5), is apparently matched by that along only one other line considered in this report (see subsection below entitled "The Colton-Mecca Line"). A comparison of the results of any of the subsequent levelings against the 1897/1902 datum indicates that uplift began to accumulate immediately north of San Pedro—though probably no farther south than bench mark 7 LA (pl. 5). Uplift increased steadily northward and culminated by 1914 within the reach between Lang and Palmdale at nearly 0.5 m. Northward from its near 0.5-m high, it diminished irregularly but gradually as far as Tehachapi and plummeted between Tehachapi and Caliente. However, northwestward into Bakersfield from Caliente, the 1897/1902–14 uplift actually increased slightly to the still-significant figure of nearly 0.3 m (pl. 5). Accepting the validity of our reconstruction, during the period 1897/1902/05–07 the uplift increased steadily southward from virtually zero north of Freeman Junction to about 0.35 m at Mojave. Moreover, between Pacoima and Saugus the uplift that had occurred by 1907 nearly equaled that developed during the full period 1897/1902–14, although the estimated random error in the 1897/1902/05–07 signal is such that it could have differed considerably from that shown here (pl. 5). Westward from the main line, and disregarding the spike at Moorpark (pl. 5), the uplift apparently held to values that nearly matched those in the central Los Angeles area. The spike that appears at bench mark 432 LA south of Burbank (pl. 5), though conceivably the result of bench-mark disturbance, is reasonably attributed to subsidence associated with ground-water withdrawals (pl. 2).

The chronology of uplift along the main line of the San Pedro-Bakersfield line obviously is imperfectly understood, but it is approximately characterized by the changes in orthometric height at representative bench marks at Vincent, Mojave, and Bakersfield (figs. 6, 12, 13). Evidence developed from repeated levelings along the Mojave-Olancha spur (coupled with a comparison of the results of the 1907 leveling against the 1897/1902 datum between Pacoima and Saugus) suggests that nearly all the uplift along the San Pedro-Bakersfield line occurred as a single, sharply defined aseismic pulse sometime between the spring of 1905 and 1907—and was, in this sense, very similar to its modern analog (Castle and others, 1984). The only other possibly significant information that focuses on the timing of the uplift is drawn from successively developed misclosures around the circuit Gorman-Lebec-Arvin-Mojave-Harold-Gorman (fig. 11). Because we believe that the +0.1095-m misclosure that allows for the probable 0.3048-m blunder between bench marks 4230 LA and 3174 LA is based on a more realistic analysis of the data than the indicated value, and because this misclosure includes the results of 1910 and, presumably, postuplift leveling (fig. 11), substitution of the 1914 observed elevation difference between bench marks 864B and 2826 LA could be expected to reduce this +0.1095-m misclosure to an even smaller value. In fact, substitution of the 1914 observed elevation difference enlarges the preferred misclosure to +0.2579 m (whereas it reduces the indicated misclosure [fig. 11] to only −0.0469 m). Because this substitution produces a misclosure that contradicts the expected change, it suggests both that the uplift may not have begun until after 1910 and, by implication, that the

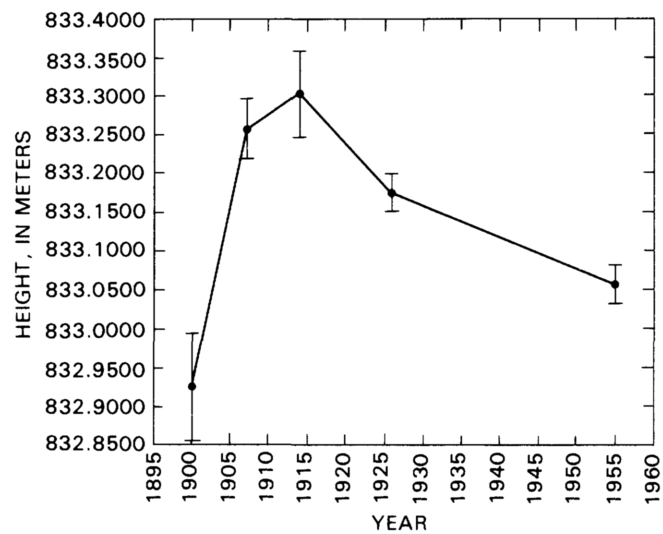

FIGURE 12.—Changes in orthometric height at bench mark 2732B, Mojave, with respect to bench mark Tidal 8, San Pedro. 1907 height is based on an assumption of stability at Olancha with respect to Tidal 8 during the period 1905–07. Orthometric corrections are based on observed gravity. Error bars show conventionally estimated random error only.

assumption of invariance of bench mark 3649B, Olancha, during the period 1897/1902/05–07 may be invalid. A more plausible and internally consistent explanation for this seeming paradox probably lies in either the occurrence or general absence of relative movement between bench marks 2132 LA and 864B during the course of the uplift. That is, it is likely that between 1902 and 1910 bench mark 864B sustained uplift of about the same (or even greater) magnitude as that at 2132 LA (a possibility suggested especially by the increasing 1897/1902–14 signal northwestward from Caliente; see pl. 5) and thus that the observed-elevation difference between these two marks remained unchanged or even decreased during this early and presumably chief episode of uplift.

Major collapse of the uplift along the San Pedro-Bakersfield line and several of its associated spurs obviously occurred sometime during the period 1914–26 (pl. 5). Because, as we have already indicated, measurements at least as far west as Barstow suggest that little, if any, tectonic subsidence could have occurred until after 1924, it is unlikely that any regionally developed collapse began before 1925. The pattern of the collapse, however, was

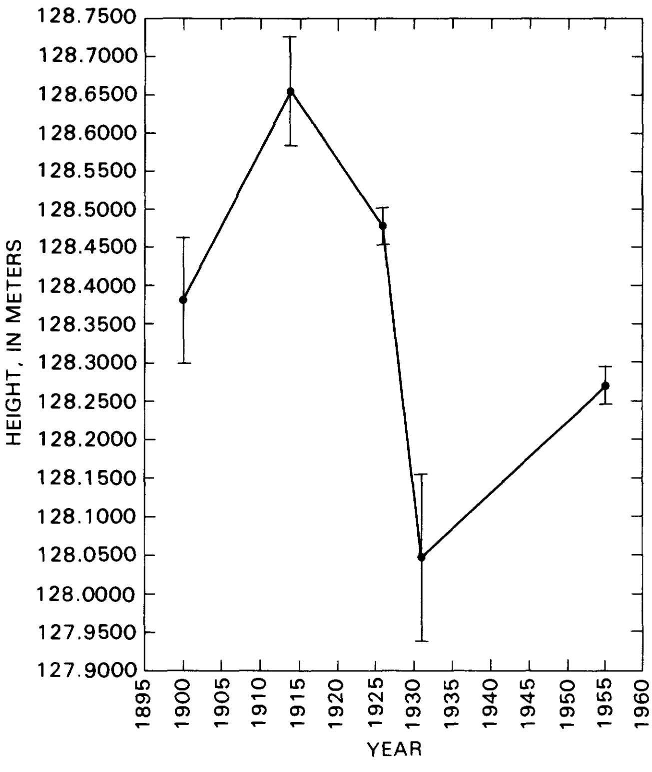

FIGURE 13.—Changes in orthometric height at bench mark 421B, Bakersfield, with respect to bench mark Tidal 8, San Pedro. 1931 height is based on the assumption that Chowchilla, about 250 km north-northwest of Bakersfield, sustained uplift of about 3 mm/yr with respect to Tidal 8 during the period 1902–30/31 (Castle and Elliott, 1982, p. 7002–7003, 7011). Orthometric corrections are based on observed gravity. Error bars show conventionally estimated random error only.

irregularly defined in both space and time. For example, although broadly defined collapse extended northward from San Fernando to Bakersfield and Freeman Junction, relatively little collapse occurred south of San Fernando. In fact, between 1914 and 1920, central Los Angeles sustained tectonic subsidence that clearly preceded major collapse, whereas this sequence was reversed between 1920 and 1926 (pl. 5). Similarly, the uplift that occurred at Ventura during the period 1897/1900/02–20 (pl. 4) was actually less than that during the period 1897/1900/02–26/35 (pl. 5), a period that presumably included the collapse. Because these height changes at Ventura were developed against the same datum, the only sources of survey error that could explain this anomaly would have to be in either or both the 1920 and 1926/35 levelings. The 1920 leveling has been independently assessed as exceptionally accurate; thus, it is more likely that the 1935 (second-order) leveling between Castaic Junction and Ventura was contaminated by measurably significant error. It is equally possible, however, that the junction mark at Saugus (J 52) subsided during the 1926–35 junction interval produced an apparent height change at Ventura which exceeded any real displacement. Regardless of whether this particular aberration is the product of actual movement at Ventura between 1920 and 1935 or simply a result of inaccuracies in the measurements or of the limitations of our reconstruction, the collapse of the uplift along the San Pedro-Bakersfield line must have been a highly complex deformational event.

THE LOS ANGELES-RIVERSIDE LINE

GENERAL REMARKS

The Los Angeles-Riverside line is a single, relatively short line that is simply a spur off the San Pedro-Bakersfield line. Nevertheless, because this line was characterized by major height changes within the period 1897–1935 and because the regionally developed deformation may have been contaminated by localized uplift toward the east end of the line, it is treated separately here.

Reconstruction of the height changes along the Los Angeles-Riverside line has proved relatively straightforward and is based exclusively on the results of blunder-free, double-rodded or double-run levelings, all but one of which met first-order standards. The 1897 datum, which was developed from the only leveling along this line that was neither first order nor double run, is almost certainly a good deal more accurate than suggested by its third-order (primary) classification. Valid discrimination between localized and regional uplift between Ontario and Riverside during the period 1897–1906, which summed to approximately 0.15 m, may be the chief difficulty encountered in assessing the height changes along this line. A secondary but significant problem derives from the relatively few marks that are common to both the datum and the several subsequent levelings along this line.

Cumulative 1897-1923/24 uplift along the Los Angeles-Riverside line reached nearly 0.4 m between Ontario and Riverside. Although this uplift seemingly increased by as much as 0.04–0.05 m between 1923/24 and 1931/32, at least a part of this apparent increase may be attributable to distortion of the 1931/32 observed-elevation differences associated with intrasurvey movement. Regardless, and even though some doubt attaches to the 1923/24–31/32 uplift, it is very likely that large sections of this line sustained collapse of 0.03–0.05 m during the period 1923/24–34.

DETAILED RECONSTRUCTION

The computed height changes along the Los Angeles-Riverside line are based on comparisons among the results of four successive levelings completed during the period 1897–1934 (pls. 3, 6*A*). All but one of the starting elevations have been developed from essentially continuous levelings extending northward from San Pedro into the central Los Angeles area through various junction marks and thence eastward toward Riverside (pls. 3, 5, 6*A*). The 1897 starting elevation is based on a tie with the observed elevation of bench mark 338 LA (S 32) obtained from 1897 leveling emanating from San Pedro (pl. 5). The 1923/24 starting elevation is taken from a tie with the 1926 observed elevation of bench mark 306 LA (V 32) with respect to bench mark Tidal 8 (NGS lines 82583 and 82656). Alternatively, we could have based the 1923/24 starting elevation on the 1920 observed elevation of V 32 (NGS line 74203; see subsection above entitled "The San Pedro-Bakersfield Line"). However, because the 1926 leveling into V 32 more nearly matched in time the November 1923 leveling (NGS line 82408) extending eastward along the Los Angeles-Riverside line, this alternative is less desirable on this basis alone. Moreover, elsewhere within the Los Angeles basin, comparisons between the results of the 1920 and 1923/24 levelings indicate that uplift of as much as 0.09 m occurred within the period 1920–23/24 (see subsection below entitled "The San Diego-Barstow Line"). Regardless, had we chosen to base the 1923/24 starting elevation on the 1920 elevation of V 32, it would have reduced the 1897–1923/24 signal along this line by no more than about 0.015 m. The 1931/32 starting elevation is based on a tie through 338 LA (S 32) obtained from an area leveling of the Los Angeles Basin that included a connection with Tidal 8 (NGS line L–386). Similarly, the 1934 starting elevation has been drawn from a tie with the observed elevation of S 32 developed from a general releveling of the Los Angeles Basin (NGS line L–991) following the 1933 Long Beach earthquake. Although the route of the several relevelings along the Los Angeles-Riverside line deviated somewhat from that of the 1897 survey (pl. 3), because the two routes approximately coincide, we have assumed that the differences in the orthometric corrections applicable to the levelings along both routes are negligible—differences that in any case do not even begin to compete with the estimated random error associated with any of these levelings.

The accuracy of the 1897 datum is supported by both the double rodding of the 1897 leveling and the inclusion of this leveling with that which produced relatively good closures on extrapolated mean sea-level values at San Pedro and San Diego (Castle and Elliott, 1982, p. 7005, 7014–7015). This accuracy is seemingly challenged, however, by the 0.1506-m uplift of bench mark 851 SB, Riverside (pls. 3, 6*A*), during the period 1897–1906 (see subsection below entitled "The San Diego-Barstow Line"). The apparent magnitude of the uplift and the fact that it diminished northward into Victorville (and, thus, in toward the area that ultimately sustained maximum uplift) to values of about 0.05 m suggest that this apparent signal is attributable largely to accumulated survey error between San Pedro and Riverside. Nevertheless, the 1902/06/26/27 misclosure around the circuit Colton-Mecca-Ogilby-El Centro-San Diego-Santa Ana-Colton (fig. 14) is consistent with 1902–6 uplift in the Colton area of about 0.15 m. This supporting evidence is qualified only by the size of the estimated random error associated with this misclosure (fig. 14) and the possibility that the misclosure is attributable to tectonic subsidence of bench mark 156 SB between 1902 and 1926/27. This possibility is unlikely, however, because a comparison of the results of a 1926/27 leveling against a combined 1902/05 datum extending eastward into southwestern Arizona indicates little, if any, movement in the junction area during the period 1902/05–26/27. Moreover, even though the estimated random error is nearly as large as the misclosure, this estimate is dominated by the probably excessively conservative value assigned to the random error associated with the third-order but double-rodded 1902 leveling between Colton and Ogilby. In addition, the 1902 sections were double run where the field differences failed to close on the results of an earlier (1898/1901) single-run leveling to within 12 mm/km$^{1/2}$ (USGS summary book 9488). Thus, the 1902 leveling between Colton and Ogilby probably closely matched second-order standards, a consideration that would reduce the estimated random error around this loop to 0.0804 m.

The misclosure defined by the 1897/1902/06 circuit Los Angeles-Saugus-Palmdale-Mojave-Barstow-Highgrove-Los Angeles (fig. 15), which includes the results of the

1897 leveling between Los Angeles and Riverside, is (at first glance) especially suggestive of survey error in the 1897 leveling as the source of the apparent 1897–1906 uplift of the Colton area. This conclusion is suggested by both the magnitude and sense of this misclosure, which is the inverse of that consistent with uplift of the Colton-Riverside area during the period 1897–1906. In fact, however, if we substitute the presumably more accurate and orthometrically compatible 1906 reconstructed observed-elevation difference between Tidal 8 and Highgrove based on leveling through San Diego (see subsection below entitled "The San Diego-Barstow Line") for the actually measured 1897 observed-elevation difference, this misclosure (fig. 15) would enlarge by an amount (0.1490 m) approximately equal to the 1897–1906 uplift of Riverside. Moreover, a comparison between this misclosure (fig. 15) and the indicated signals developed against the 1897 datum (pl. 6*A*) provides even more compelling evidence of the accuracy of the 1897 leveling. If we assume that the misclosure is attributable largely or entirely to survey error in the 1897 leveling, any correction for this assumed error designed to reduce the misclosure would decrease the observed-elevation difference between 338 LA and 945 SB and thus increase the 1897–1923/24, 1897–1931/32, and 1897–1933/34 uplift to even larger values than the already impressively large signals along the east end of this line (pl. 6*A*). Any correction that increased the 1897 observed-elevation difference would, of course, simply enlarge this misclosure (fig. 15). Thus, the cumulative evidence indicates that the reconstructed 1897–1906 0.15-m uplift of the Colton-Riverside area is, in fact, a close approximation of that which actually occurred. Because this reconstructed uplift agrees remarkably well with that predicted from the misclosure shown in figure 14, we infer that it occurred largely during the period 1902–06. This timing suggests, in turn, that any preseismic, coseismic, or postseismic uplift associated with either the Cajon Pass or San Jacinto earthquakes of 1899 (Coffman and von Hake, 1973, p. 161) must have been very small—at least in the Highgrove-Riverside area.

Comparisons of the results of the several successive levelings both with each other and against the terrain profile, coupled with the double running or double rodding of all these surveys, preclude the likelihood of either blunders or measurably significant height- or slope-dependent systematic errors in any of the indicated levelings along the Los Angeles-Riverside line (pl. 6*A*). Even though the 1897–1923/24 jump of 0.19 m between bench marks 300 and 987 (pl. 6*A*) seems remarkably large, we

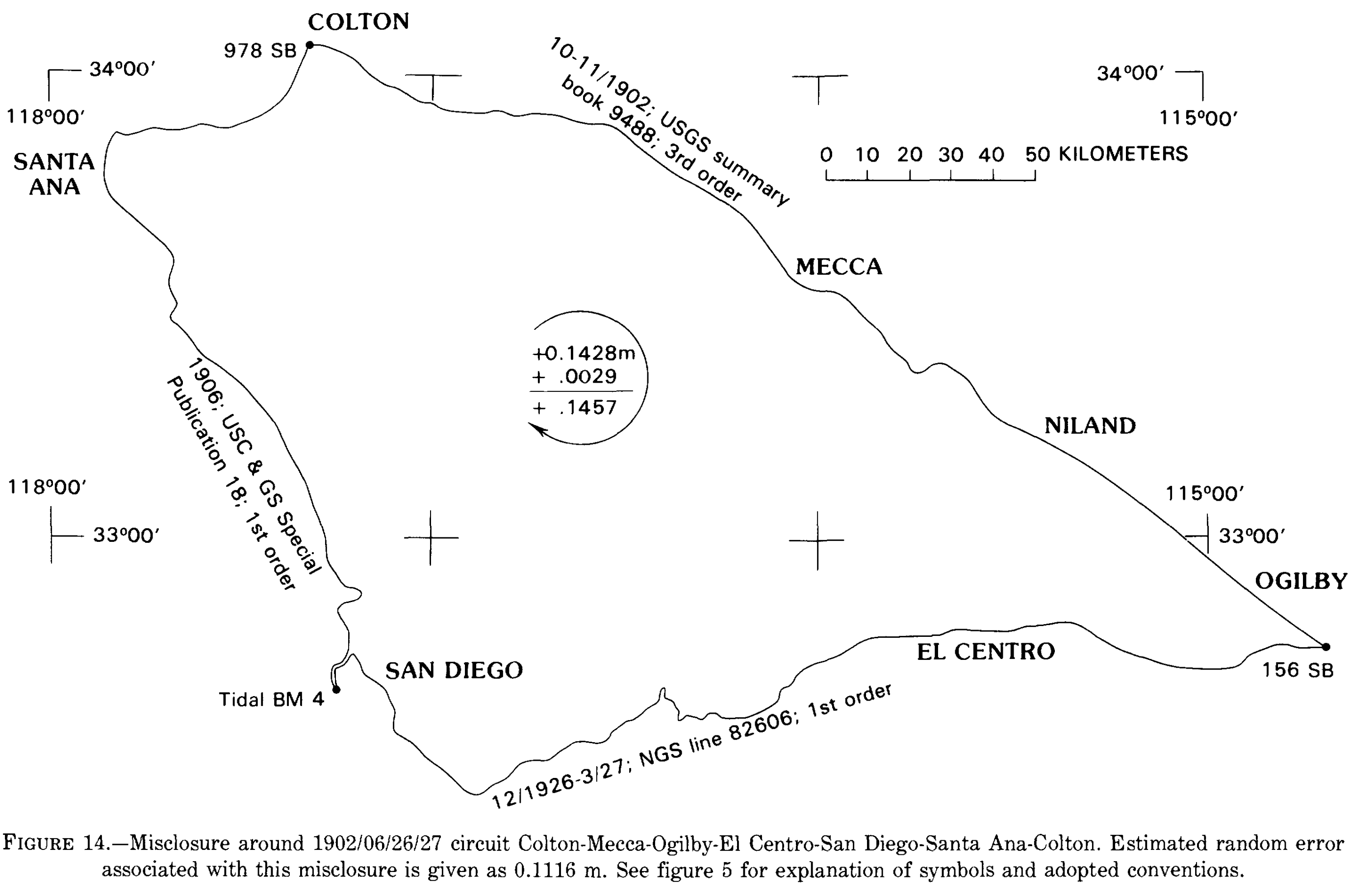

FIGURE 14.—Misclosure around 1902/06/26/27 circuit Colton-Mecca-Ogilby-El Centro-San Diego-Santa Ana-Colton. Estimated random error associated with this misclosure is given as 0.1116 m. See figure 5 for explanation of symbols and adopted conventions.

have already shown that this signal cannot be reasonably dismissed as the product of survey error in the 1897 datum. Moreover, because the height difference between Los Angeles and Riverside is only about 150 m and the maximum relief along the route of the 1897 leveling is only about 250 m (U.S. Geological Survey, 1898, p. 382–384, 393), height- or slope-dependent systematic errors in the 1897 survey probably were of no more than modest magnitude. With respect to Tidal 8, the estimated random error at Riverside in the discrepancy between the results of the 1897 survey and any of the subsequent levelings is about 72 mm, whereas that between the results of any other two levelings along this line is only about 21 mm.

The height changes along the Los Angeles-Riverside line (pl. 6*A*) are surprisingly large, even if we allow for much larger measurement errors than are probably contained in any of these levelings. The large accumulation of uplift between San Gabriel and Ontario coincides with the approach of this line toward the front of the high Transverse Ranges and, thus, toward a part of the margin of the modern uplift characterized by especially steep gradients (Castle and others, 1984). In other words, the steep front of each major uplift probably has advanced or receded through some limited zone during successive deformational cycles. Although the east end of the line apparently continued to increase in height beyond 1923/24 to nearly 0.45 m (pl. 6*A*), because the 1931/32 leveling was

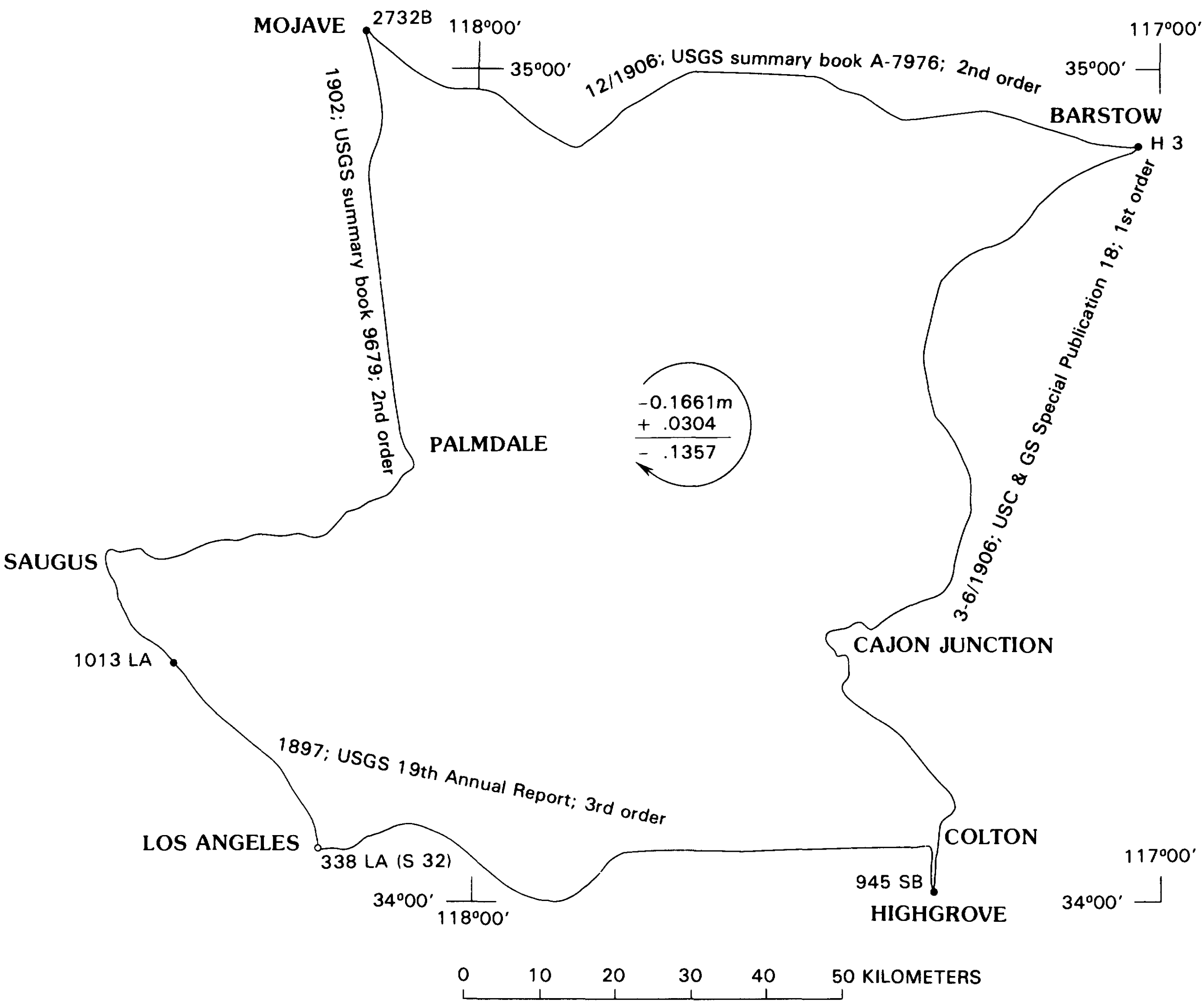

FIGURE 15.—Misclosure around 1897/1902/06 circuit Los Angeles-Saugus-Palmdale-Mojave-Barstow-Highgrove-Los Angeles. Estimated random error associated with this misclosure is given as 0.0951 m. See figure 5 for explanation of symbols and adopted conventions.

carried out over a relatively extended period, the reconstructed 1931/32 observed-elevation differences may have been distorted as a result of intrasurvey movement (particularly that attributable to compaction-induced subsidence at several junction marks in the Los Angeles Basin). Thus, the 1897–1931/32 uplift over the reach between Ontario and Riverside is conceivably exaggerated by 40–50 mm.

The vertical-displacement history along this line emphasizes again the complexity of the collapse of the early-20th-century uplift. If we accept the representation shown on plate 6*A*, the relatively modest collapse along this line did not even begin until after 1931/32—thus, almost 5 years after major collapse within the western Mojave block.

THE MOJAVE-BARSTOW LINE

GENERAL REMARKS

The Mojave-Barstow line, like the Los Angeles-Riverside line, is simply a spur off the San Pedro-Bakersfield line. Nevertheless, the Mojave-Barstow line is considered separately here, largely because the deformational history disclosed through an analysis of the height changes along this line indicates that it has been characterized by complex episodic displacements.

Height changes along the Mojave-Barstow line have been based on the results of but two levelings extending over a distance of only about 120 km. However, these two levelings were carried out at such times that the results of these surveys both complicate and heighten our general perception of the evolution of the early-20th-century uplift. The accumulated evidence indicates that the late 1906 leveling which defines the datum probably postdates major uplift at Mojave. Moreover, the 1927/28 leveling, which is the only pre-1961 survey along the full length of this line, clearly followed major collapse that could have begun no later than 1925. Accordingly, these two surveys do not in themselves provide any direct evidence of the magnitude of the uplift or its subsequent collapse along the full length of the line. Nevertheless, the results of these two levelings provide compelling evidence of the almost-surgelike growth that accompanied the evolution of the early-20th-century uplift.

Reconstruction of the height changes along the Mojave-Barstow line is based on two conceptually different approaches to development of the late 1906 datum and, thus, to characterization of the height changes along this line. We have begun by assuming that the height of bench mark 2732B, Mojave, remained unchanged during the period 1897/1902–06, an assumption that permits the use of the 1897/1902 observed elevation of this mark as a 1906 starting elevation for this line. Comparison of the 1927/28 observed elevations against the resulting 1906 datum indicates that the residual uplift between Mojave and Barstow ranged within narrow limits around 0.25 m. Alternatively, the late 1906 starting elevation at 2732B can be computed from the results of reconstructed leveling through San Diego and thence northward into Mojave via Barstow. This procedure, which produces late 1906–27/28 height changes along this line that fall generally within the range −0.05 to 0.00 m, suggests an end-to-end 1897/1902–06 up-to-the-west tilt between Barstow and Mojave (or San Diego and Mojave) of about 0.3 m. Because we have no basis for assuming that Barstow remained invariant during this postulated tilt, coincidental uplift of Barstow of less than 0.1 m would have produced a late 1906 height for Mojave that nearly matched its 1914 height. Because Barstow sustained uplift of about 0.28 m between spring 1906 and 1923/24, a post-1906 up-to-the-east tilt of about the same magnitude probably occurred between Mojave and Barstow, and so the residual (postcollapse) uplift of Barstow probably was somewhat less than 0.1 m.

DETAILED RECONSTRUCTION

Height changes along the Mojave-Barstow line have been developed from comparisons between the results of two successive levelings completed during the period 1906–27/28 (pls. 3, 6*B*). Although the starting elevation at Mojave for the 1927/28 leveling is based on the 1926 value for bench mark 2732B (see subsection above entitled "The San Pedro-Bakersfield Line") and an assumption of invariance during the period 1926–27/28, because both the 1926 and 1927/28 levelings followed major collapse of the uplift at Mojave, this particular assumption probably is reasonably sound. Establishing a starting elevation for the 1906 leveling, however, is much more difficult and clearly limits the value of the resulting comparisons along this line. The most straightforward approach, and the one that we have adopted in our basic reconstruction (pl. 6*B*), is simply to accept the 1897/1902 observed elevation of 2732B (pl. 5) as the equivalent of that which would have been obtained in 1906. If we accept the validity of the two provisional starting elevations for 2732B used in our initial reconstruction, the 1897/1902/06–26/27/28 residual uplift between Barstow and Mojave was fairly uniform and averaged around 0.25 m (pl. 6*B*). However, even though this signal held within a relatively narrow range, it is, nonetheless, surprisingly noisy. Whether this noise is attributable either to real mark-to-mark differential movement or to an unusually high random-error content in either or both of these levelings is unknown. There is, however, a reasonable likelihood that the 1906 survey was accompanied by deformation that aliased the mark-to-mark height differences and, possibly, the accumulated difference between Mojave and Barstow. Although the residual (postcollapse) uplift at Barstow implicit in this reconstruction was about 0.26 m (pl. 6*B*), the 1906–23/24 uplift of Barstow was only about 0.28 m (see next subsection). Accordingly, if Barstow was identified with 0.26 m of residual uplift, it suggests that Barstow sustained virtually no tectonic subsidence during the post-1924 collapse of the western Mojave block or that the 1897/1902–23/24 cumulative uplift at Barstow was a good deal greater than 0.28 m, or, finally, that this "straightforward" reconstruction (pl. 6*B*) is, in fact, invalid.

An alternative approach to establishment of a 1906 starting elevation for 2732B produces a vertical-displacement pattern along the Mojave-Barstow line that is much more consistent with the full spectrum of the available data. Specifically, because the late 1906 leveling between Mojave and Barstow was completed during a period perilously close to the 1907 leveling that postdated the massive uplift of Mojave with respect to Olancha—if not with respect to Tidal 8 (see subsection above entitled "The San Pedro-Bakersfield Line")—we have calculated a 1906 starting elevation for 2732B that does not depend on the presumed invariance of this mark during the period 1897/1902–06. The strategy adopted here is based on the computation of an orthometrically compatible elevation for 2732B obtained through the construction of a 1906 observed elevation for a representative mark adjacent to the San Diego tide station, coupled with the results of a 1906 first-order survey between San Diego and Barstow and the 1906 leveling between Barstow and Mojave (fig. 16). We could have manufactured the 1906 elevation difference between San Pedro and San Diego from the results of either an 1897/98 third-order survey or some combination of the 1906 leveling and one of several later levelings between San Pedro and Santa Ana. However, the resulting elevation differences would have been clouded with uncertainties associated with either the accuracy of the lower-order leveling or height changes at Santa Ana during the junction interval between the 1906 and any later leveling leading into San Pedro. The earliest more or less continuous first-order leveling between San Pedro and San Diego was completed during the period 1931–33 (fig. 16). If we accept the relatively high accuracy of this leveling and the near-certainty that the end-to-end observed-elevation difference was uncontaminated by significant height- or slope-dependent systematic error, the conversion of the 1931/32/33 observed elevation of Tidal BM 4 into a 1906 equivalent requires only that we closely approximate any height change at Tidal BM 4 with respect to Tidal 8 during the 26-year period 1906–31/32/33. An accurate assessment of this height change can be obtained through a comparison of (1) the rise in sea level at San Diego against that at San Pedro during the indicated period and (2) the interpretation of any discrepancy as differential movement between Tidal 8 and Tidal BM 4 (fig. 16). Coupling of the estimated height change at Tidal BM 4 with the appropriately corrected 1931/32/33 observed elevation of this mark (3.6126 m) produces a 1906 observed elevation for Tidal BM 4 of 3.6901 m. Summing clockwise the 1897/1902 observed-elevation difference between Tidal 8 and 2732B, the reconstructed 1906 observed-elevation difference between 2732B and Tidal 8, and the orthometric correction around the circuit San Pedro-Los Angeles-Mojave-Barstow-Santa Ana-San Diego-Santa Ana-San Pedro produces a misclosure of −0.2917 m (fig. 16). Disregarding for the moment any errors in the estimated height change at Tidal BM 4 during the period 1906–31/32/33 and the possible displacement of Barstow between spring 1906 and the following winter, this misclosure argues convincingly that the 1906 height of 2732B was about 0.3 m above its 1897/1902 height and thus that our primary reconstruction is unsupportable. Acceptance of this misclosure as a basis for the 1906 starting elevation lifts the 1906 datum shown on plate 6*B* by 0.2917 m and reduces the 1906–26/27/28 signal by an equal amount. The resulting alternative 1906–26/27/28 height changes along the Mojave-Barstow line are represented by the dashed-line reconstruction (pl. 6*B*).

It is unlikely that either of the levelings used in developing the represented height changes along the Mojave-Barstow line (pl. 6*B*) was seriously flawed by survey error. Because both the 1906 and 1927/28 levelings were double run and because the profiled height changes shown here (pl. 6*B*) are characterized by neither stepped changes in the signal nor any discernible correlation with the terrain, the likelihood that either leveling was contaminated by blunders or significant height- or slope-dependent systematic error is very small. Indeed, the accuracy of the 1906 leveling is independently supported by the correspondence between the results of this survey and the combined 1907 first- and third-order surveys around the circuit Mojave-Freeman Junction-Johannesburg-Barstow-Mojave (fig. 17). On the basis of our alternative reconstruction, and with respect to Tidal 8, the estimated random error in the represented height change at Barstow is given as about 68 mm.

The large misclosure on the 1897/1902 height of bench mark 2732B, Mojave (fig. 16), indicates that (1) the regional uplift that occurred within the western Mojave block apparently began before the end of 1906 and (2) a very large fraction of this uplift probably occurred sometime between spring 1905 and fall 1906. Substitution of the 1914 observed-elevation difference between Tidal 8 and 2732B reduces this misclosure to +0.0932 m (fig. 16), where the estimated random error around this reconstructed 1906/14 circuit is about 84 mm, and thus supports the assertion that most of the uplift at Mojave

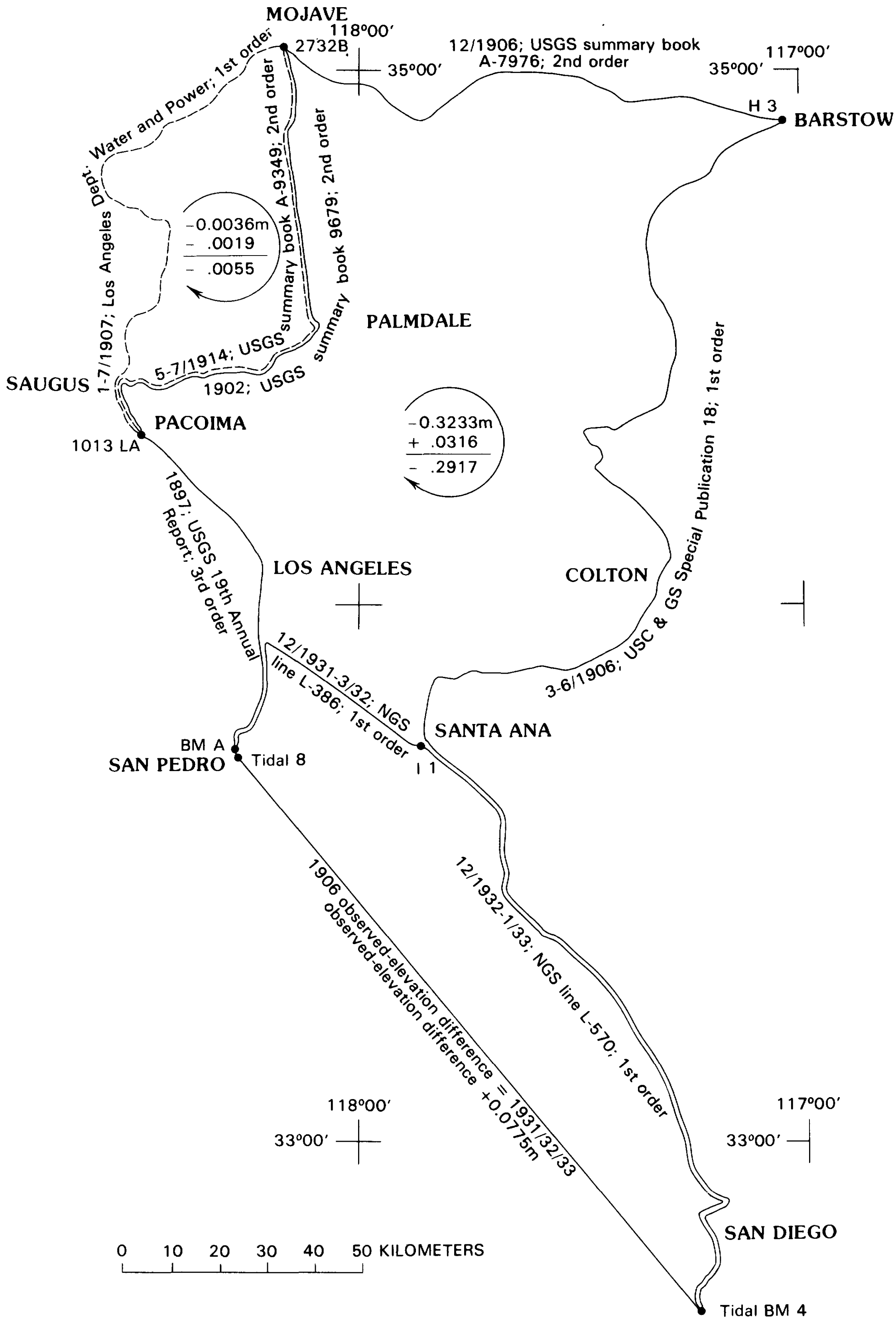
MOJAVE
118°00′
2732B
35°00′
12/1906; USGS summary book A-7976; 2nd order
117°00′
35°00′
H 3
BARSTOW
1-7/1907; Los Angeles Dept. Water and Power; 1st order
summary book A-9349; 2nd order
summary book 9679; 2nd order
−0.0036m
− .0019
− .0055
PALMDALE
5-7/1914; USGS
1902; USGS
SAUGUS
PACOIMA
1013 LA
−0.3233m
+ .0316
− .2917
3-6/1906; USC & GS Special Publication 18; 1st order
1897; USGS 19th Annual Report; 3rd order
LOS ANGELES
COLTON
12/1931-3/32; NGS line L-386; 1st order
SANTA ANA
BM A
SAN PEDRO
Tidal 8
I 1
1906 observed-elevation difference = 1931/32/33 observed-elevation difference +0.0775m
12/1932-1/33; NGS line L-570; 1st order
118°00′
33°00′
117°00′
33°00′
SAN DIEGO
Tidal BM 4
0 10 20 30 40 50 KILOMETERS

FIGURE 16.—Misclosures around 1897/1902/06/06(equivalent) circuit San Pedro-Los Angeles-Pacoima-Mojave-Barstow-Santa Ana-San Diego-Santa Ana-San Pedro (solid line) and 1907/14 circuit Pacoima-Saugus-Mojave-Palmdale-Saugus-Pacoima (dashed line). 1897 elevation difference between bench marks BMA and Tidal 8 is based on a comparison against an 1897 tidal datum (see introductory remarks in section entitled "The Reconstruction"). 1931/32/33 elevation difference between bench marks Tidal BM 4 and Tidal 8 is corrected for compaction-induced subsidence of 0.01 m during an approximately 1-yr junction interval at Santa Ana (Castle and Elliott, 1982, p. 7005); its conversion to a 1906 equivalent is based on the computed 1906–32 subsidence of bench mark Tidal BM 4 with respect to Tidal 8, developed from linear regressions through the 19-yr sea-level means for San Pedro and the pre-1934, 19-yr sea-level means for San Diego (figs. 3, 4), a procedure that yields an average subsidence rate for bench mark Tidal BM 4 (or the San Diego tide station) with respect to Tidal 8 of 2.98 mm/yr. Eastern (solid line) misclosure is reduced to +0.0932 m where the 1897/1902 observed-elevation difference between bench marks Tidal 8 and 2732B is replaced by the 1914 difference between these two marks (USGS summary book A–9349; see introductory remarks in section entitled "The Reconstruction"). See figure 5 for explanation of symbols and adopted conventions.

occurred no later than the end of 1906. Coupling of the misclosures given in figures 16 and 17 reduces the discrepancy between the 1906 and 1914 levelings into 2732B still further to only +0.0354 m and thereby reinforces the likelihood that most of the uplift at Mojave occurred no later than the end of 1906. Finally, because substitution of the results of the 1907 leveling between Pacoima and Mojave for the orthometrically compatible 1914 equivalent reduces this misclosure by only 0.0055 m (fig. 16), virtually all of the 1897/1902–14 uplift at Mojave could easily have occurred as early as 1907.

The alternative (dashed line) and clearly preferred reconstruction of the 1906–27/28 height changes shown on plate 6*B* indicates that bench mark 2732B subsided 0.0478 m during this period and, indeed, that virtually the entire line subsided by about 0.00–0.05 m during this period. Barstow probably sustained little, if any, uplift with respect to Tidal 8 before 1906; yet it rose by 0.28 m between 1905 and 1923/24 (see next subsection), implying that the residual uplift at Barstow was nil or even

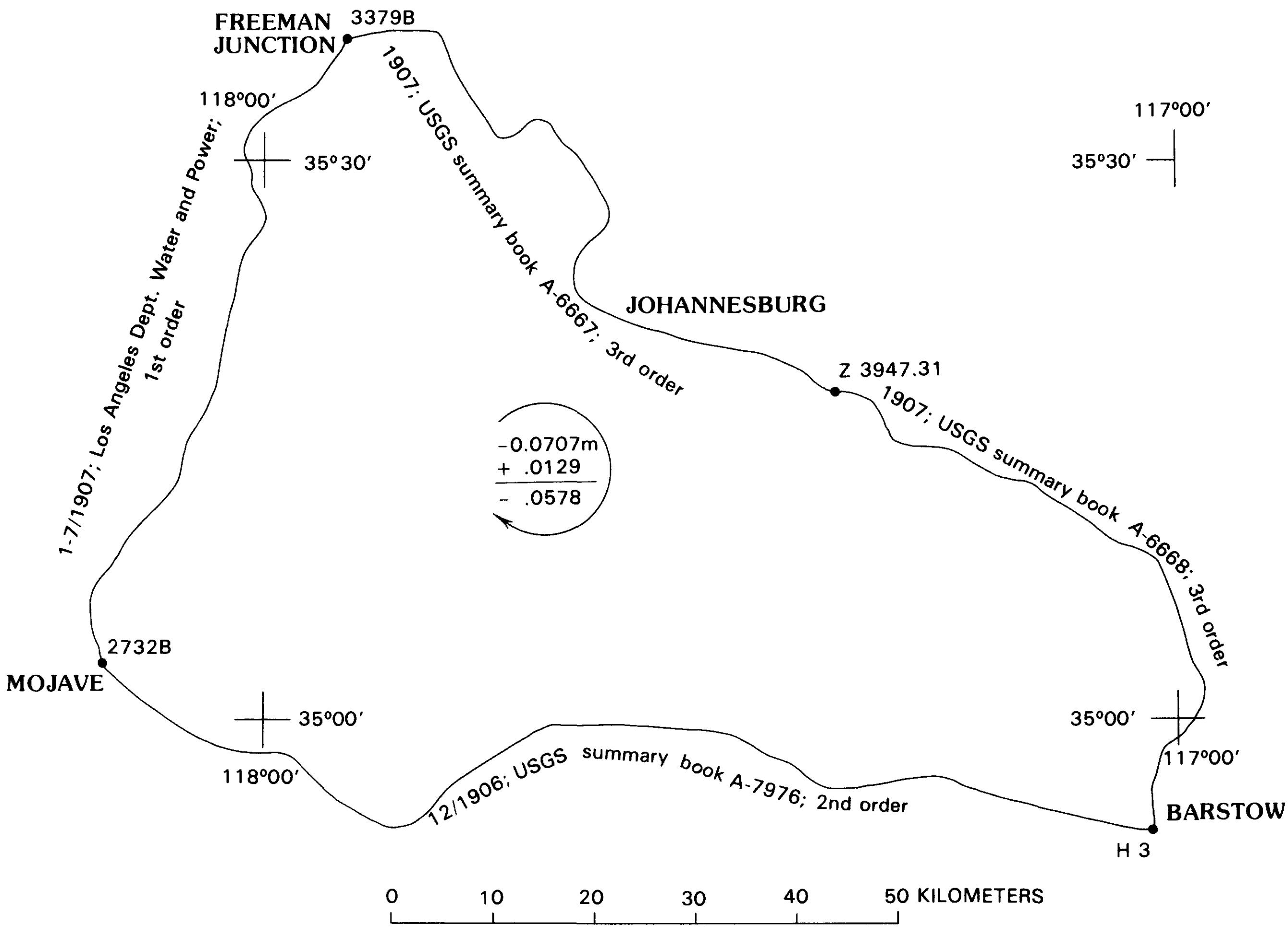

FIGURE 17.—Misclosure around 1906/07 circuit Mojave-Freeman Junction-Johannesburg-Barstow-Mojave. See figure 5 for explanation of symbols and adopted conventions.

negative. The magnitude of the collapse at Barstow can be shown alternatively by the 1923/24/26/27/28 misclosure around the circuit Los Angeles-Saugus-Mojave-Barstow-Riverside-Los Angeles (fig. 18). Although interpretation of this −0.3140-m misclosure as an expression of tectonic subsidence at Barstow during the period 1923/24–26/27/28 is based on an assumption of invariance at Los Angeles during the full measurement period, central Los Angeles probably sustained very little vertical displacement between 1914 and 1964 (pl. 5; Castle and others, 1984). Moreover, if this circuit (fig. 18) were extended into and out of Tidal 8 through the results of the 1920 and 1926 levelings, respectively, the misclosure would have been reduced by only about 0.02 m. However, for consistency, the reconstructed 1906–23/24 uplift at Barstow would have to have been diminished by an equal amount, such that this alternative approach would have had no effect on the computed cumulative subsidence at Barstow during the period 1923/24–26/27/28.

Two unknowns affect our interpretation of the height changes along the Mojave-Barstow line. Because there is no direct evidence of any uplift at Barstow before spring 1906, we have interpreted the misclosure shown in figure 16 as the product of a 0.3-m up-to-the-west tilt somewhere between Barstow and Mojave—an interpretation, of course, that requires a nearly comparable up-to-the-east tilt between Mojave and Barstow sometime before 1923/24. In fact, however, we have no direct way of assessing the magnitude or even the sense of any vertical displacement at Barstow that may have coincided with

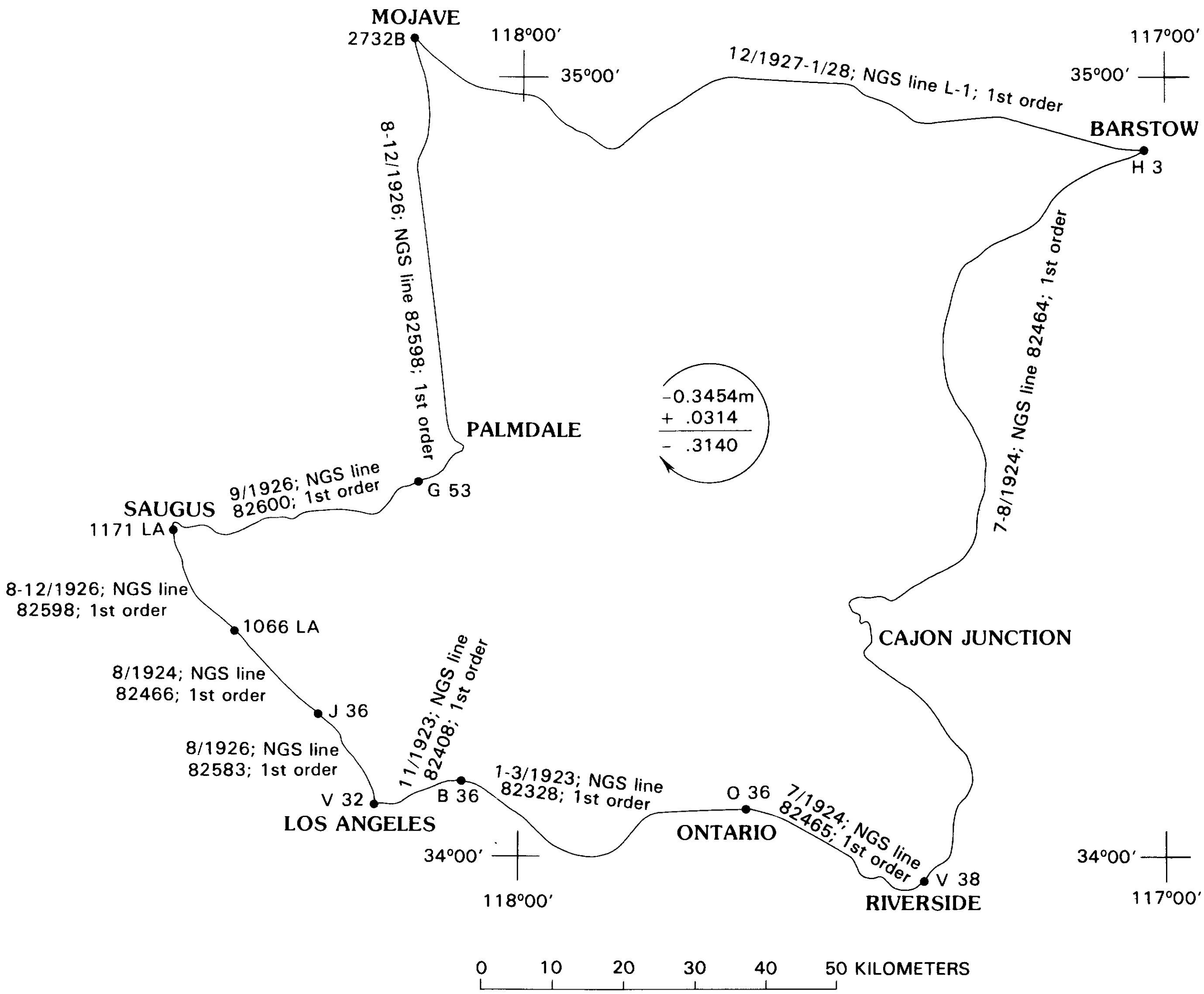

FIGURE 18.—Misclosure around 1923/24/26/27/28 circuit Los Angeles-Saugus-Mojave-Barstow-Riverside-Los Angeles. See figure 5 for explanation of symbols and adopted conventions.

this pre-1907 up-to-the-west tilt. For example, if this tilt were accompanied by no more than about 0.1 m of measurable uplift at Barstow, it would have led to a virtually perfect (corrected) closure on the 1914 height of bench mark 2732B. Alternatively, Barstow could have subsided during this tilt episode. If we could be sure that this postulated subsidence, however limited, had actually occurred, it would further constrain any attempts to explain the origin of the uplift. Regardless, if Barstow subsided during the second half of 1906, it would have had to recover by an equal amount well before 1923/24, such that this postulated subsidence would have had no effect on the cumulative 1906–23/24 uplift. The second factor that could invalidate the interpretation presented here relates to the stability of Mojave during the period between the completion of the 1926 leveling into Mojave and its extension eastward to Barstow during winter 1927/28. There is a natural, almost intuitive suspicion that Mojave continued to subside during this junction interval. This continued subsidence would require, in turn, that the region traversed by the Mojave-Barstow line subsided by an even greater amount than shown on plate 6*B* (or that the misclosure shown in fig. 18 minimizes the actual subsidence of Barstow with respect to Los Angeles). Although a possible uplift of Mojave during the 1926–27/28 junction interval is admittedly counterintuitive, oscillatory displacements accompanying the collapse of regionally developed uplift in southern California have by now been well documented (Jachens and others, 1983). Any uplift at Mojave during the 1926–27/28 junction interval obviously would increase the residual uplift along the entire line by an equal amount—and, accordingly, to values above those shown by the dashed-line representation (pl. 6*B*).

THE SAN DIEGO-BARSTOW LINE

GENERAL REMARKS

The San Diego-Barstow line is the longest and one of the two most revealing of any line considered in this report. However, among the five surveys used in the calculation of height changes along this line, only one extends over the full distance between San Diego and Barstow, even though all five levelings include all or most of the south flank of the early-20th-century uplift. All but the earliest of these levelings met first-order standards, a consideration that contributes to a less equivocal presentation and minimizes the likelihood of major measurement error in any of the described signals.

Although the earliest end-to-end leveling along the San Diego-Barstow line was not produced until spring 1906, the results of an older set of levelings completed during the period 1897–99 form a partial datum extending northward from San Onofre to Victorville—about two-thirds of the full distance between San Diego and Barstow. Because a relatively large signal is disclosed through a comparison of the results of the 1906 survey against the 1897/98/99 datum, we have computed height changes based on subsequent levelings against both the full (1906) and partial (1897/98/99) datums. The later levelings along the San Diego-Barstow line were completed in 1924, 1932/33, and 1933/34. Taken together, the results of these five surveys embrace what we believe to be the full cycle of uplift and partial collapse associated with the early-20th-century uplift, an especially serendipitous circumstance considering the limited geodetic control that had been established in the United States through the end of this period.

Reconstruction of the height changes along the San Diego-Barstow line is a generally straightforward procedure requiring few assumptions of stability at the several junction marks along or connecting with this line. Although our analysis of the results of the several levelings along the San Diego-Barstow line suggests little intrasurvey deformation, the composite 1897/98/99 leveling may be an exception. Because the resulting datum has been spliced together from several survey segments identified with junction intervals of as much as 2 years, and because several critical parts of this line traverse an active fault system, there is some likelihood that the results of this composite survey may have been aliased by intrasurvey movement. Regardless, there is no indication in the profiled height changes against the 1897/98/99 datum of significant differential tilting or other evidence of especially pronounced deformation at the junctions between the individual segments that form the datum. Because the results of the 1906 leveling cannot be tied directly to Tidal 8, we have again computed a starting elevation at San Diego through the use of a later (1931/32/33) first-order leveling between the San Pedro (Tidal 8) and San Diego tide stations and the differenced sea-level changes at these two stations during the period 1906–31/32/33. Although the 1923/24 starting elevation is based on a direct tie through Riverside with the 1923/24 leveling off the Los Angeles-Riverside line, this elevation depends, as we have already indicated, on a demonstrably reasonable presumption of stability at bench mark V 32, Los Angeles, during the period 1923/24–26.

Height changes along the San Diego-Barstow line reached their maximum near Riverside, where the 1897/98/99–1924 uplift sums to approximately 0.40 m. Northward from Cajon Junction into Victorville this signal drops to less than 0.40 m, although this apparent change may be an expression of a height-dependent systematic (rod) error in the 1897/98/99 leveling. Comparisons against the full 1906 datum show that the 1906–24 uplift began to accumulate well south of Santa Ana, where the comparisons begin, and continued to increase northward to a near-maximum of 0.25 m in the Riverside-San Bernardino area. The magnitude of the uplift increased at a very modest rate northward from San Bernardino into Barstow, where it culminated at about 0.28 m. Although the evidence is equivocal, owing to possible intrasurvey movement, uplift along the San Diego-Barstow line may have continued beyond 1924. By 1934, however, the south flank of the uplift between Colton and San Juan Capistrano had collapsed by values that ranged through 0.05–0.10 m. Northward from Colton, the uplift apparently sustained much more dramatic collapse; that at Barstow probably matched or even exceeded the 1906–24 uplift of 0.28 m.

DETAILED RECONSTRUCTION

The primary survey route to which we have referred the height changes along the San Diego-Barstow line extends out of San Pedro through Florence and Santa Ana, southward into San Diego, and thence northward via Santa Ana, Riverside, and Victorville into Barstow (pl. 3). Because only two of the five surveys used in our analysis of height changes along the San Pedro-Barstow line coincide with this route, the observed elevations based on the other three levelings have been orthometrically corrected to bring them into agreement with those that would have been obtained had all five surveys followed the designated primary route.

The starting elevations for the partial (1897/98/99) and full (1906) datums have been developed from both direct and indirect ties with the results of contemporary or later levelings. The 1897/98/99 starting elevation is based on the 1897 observed elevation of bench mark 851 SB, Riverside, coupled with a trivial orthometric correction of +0.0012 m to bring it into conformity with that which would have been obtained from the results of leveling along the primary route (see subsection above entitled "The Los Angeles-Riverside Line"). The 1906 starting elevation is ultimately based on the 1931/32/33 observed elevation for bench mark Tidal BM 4, San Diego (see below). Tidal BM 4, in turn, is located adjacent to the primary San Diego tide station (at the Quarantine Station on Point Loma) that operated during the period 1906–27. The 1906 observed elevation of Tidal BM 4 with respect to Tidal 8 is obtained from simple differencing of the linear regressions through the computed 19-year sea-level means for the San Pedro tide station and the pre-1934 19-year means for the San Diego tide station (figs. 3, 4), respectively, where the differenced value is interpreted as an expression of differential movement between Tidal BM 4 and Tidal 8. Adoption of this procedure indicates that Tidal BM 4 subsided at a rate of 2.98 ± 0.11 mm/yr with respect to Tidal 8 during the period 1906–33 and thus that the 1906 elevation of Tidal BM 4 was approximately 0.0775 m above its 1931/32/33 elevation.

The starting elevations for the later surveys along the San Diego-Barstow line are based on direct ties with Tidal 8, either through the results of levelings along the Los Angeles-Riverside line or leveling directly into San Diego. The 1924 starting elevation is based on the 1923/24 observed elevation of bench mark V 38, Riverside, obtained from a combination of 1923, 1924, and 1926 levelings emanating from Tidal 8 (NGS lines 82328, 82408, 82465, 82583, 82656), coupled with the same +0.0012-m orthometric correction applied to the 1897 observed elevation of bench mark 851 SB (see subsection above entitled "The Los Angeles-Riverside Line"). Several alternatives exist for the development of a starting elevation for an appropriate bench mark included with the 1924 leveling along the San Diego-Barstow line, but these alternatives are believed to be less satisfactory than the one that we have selected here. One of these alternatives, based on the use of the 1920 observed elevation of bench mark V 32, Los Angeles, has already been rejected in favor of the 1926 connection through Los Angeles (see subsection above entitled "The Los Angeles-Riverside Line"). A second alternative is based on the 1920 observed elevation of bench mark I1, Santa Ana. However, although there is little doubt that the Los Angeles Basin had sustained major uplift by 1920, the misclosure around the 1919/20/23/24 circuit Santa Ana-Florence-Los Angeles-Ontario-Riverside-Santa Ana (fig. 19) suggests that I1 rose nearly 0.1 m with respect to Los Angeles between 1920 and 1923/24. The 1932/33 starting elevation for Tidal BM 4 is based on direct leveling into this mark that was completed during the period 1931–33 (NGS lines L–386, L–570). The resulting observed elevation of Tidal BM 4 has been corrected here to accommodate approximately 0.01 m of compaction-induced subsidence at Santa Ana during the 1-year junction interval between the Santa Ana-to-Tidal 8 leveling and the San Diego-to-Santa Ana survey carried out during the following winter (Castle and Elliott, 1982, p. 7005). Moreover, this same subsidence-corrected observed elevation for Tidal BM 4 has been used in developing the 1906 starting elevation for this mark. The 1933/34 starting elevation is based on the 1933/34 observed elevation of bench mark 851 SB developed from leveling via Los Angeles and Riverside (NGS line L–991), coupled with the same +0.0012-m orthometric correction applied to the 1923/24 value for bench mark V 38.

Survey error associated with the several levelings used in the reconstruction of height changes along the San Diego-Barstow line (pls. 3, 7) probably was minimal for leveling of this vintage. Blunders could be most reasonably expected in the results of the single-rodded third-order 1897/98/99 levelings that form the partial datum between San Onofre and Victorville (pl. 7). Nevertheless, comparisons against the results of the 1906 leveling show no apparent mark-to-mark height changes that could be reasonably identified as blunders in this early datum. The likelihood of systematic height- or slope-dependent error again is much greater in the 1897/98/99 leveling than in any of the later surveys. However, in comparing the results of the 1906 (or 1924) levelings against the 1897/98/99 datum between San Bernardino and Victorville, where the relief becomes most significant, there is no evident correlation between the indicated signals developed against the 1897/98/99 datum and the relief over this section of the line (pl. 7). There is a somewhat greater likelihood that the 1897/98/99 leveling may have been contaminated by a slope-dependent error. This possibility is suggested in particular by the correspondence between the change in the sense of the 1897/98/99 –1906 tilt and the slope reversal at the summit of Cajon Pass (pl. 7). Regardless, even here the tilt between the datum and the results of the 1906 leveling northward from the summit is so modest that this postulated slope-dependent error could have summed to no more than a few centimeters. Comparisons among the results of height changes based on any combination of the post-1897/98/99 levelings show that the resulting signals are clearly uncorrelated with terrain (pl. 7). To suggest that more than trivial fractions of the signals measured against the 1906 datum (pl. 7) are attributable to either height- or slope-dependent error is totally unsupportable. Because the results of the post-1906 levelings generally agree closely, we would be forced to appeal to error in the 1906 leveling in attempting to explain the indicated signals as the products of systematic error. However, because terrain and signal are clearly uncorrelated, significant rod error is extremely unlikely. Moreover, to attribute the apparent 1906–32/33 uplift of those marks immediately south of Corona to rod error would require an unassessed rod error of 1.9×10^{-3} (1,900 ppm) in the 1906 leveling. Significant contamination of the datum leveling by refraction error is equally implausible, if only because the sense of the signal north of Cajon Summit is inconsistent with its attribution to residual refraction error in the 1906 leveling. Alternatively, we can compute those values for Δt (given in equation 3) required to explain the 1906–32/33 uplift of the Corona marks as the product of atmospheric refraction. Reverting again to the extreme assumption that the average sight length associated with the 1906 leveling matched the maximum permissible value of 150 m and that that associated with the 1932/33 leveling was zero,

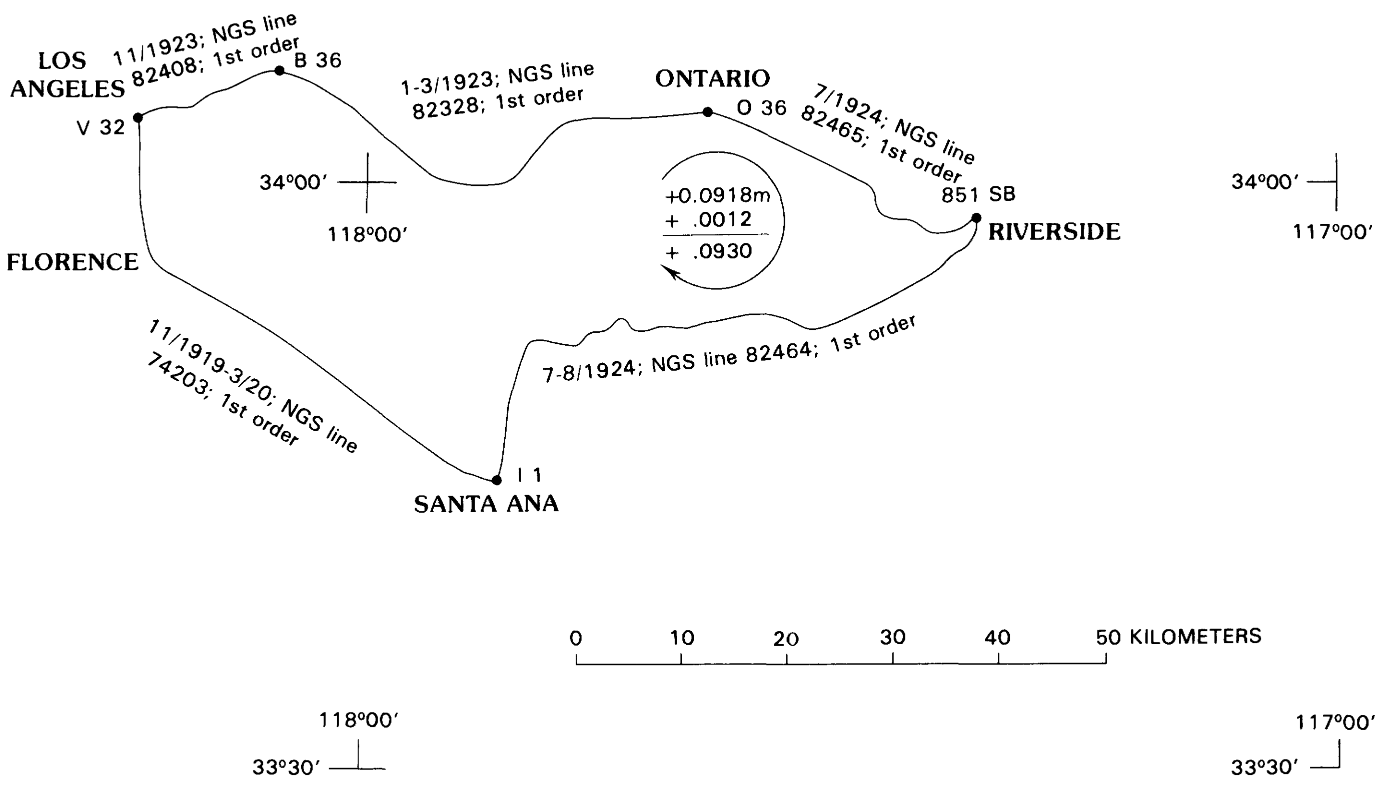

FIGURE 19.—Misclosure around 1919/20/23/24 circuit Santa Ana-Florence-Los Angeles-Ontario-Riverside-Santa Ana. See figure 5 for explanation of symbols and adopted conventions.

equation 3 predicts a value for Δt of $-1.9°C$. Obviously, had we chosen more realistic figures for the average sight lengths, this still relatively large estimate for Δt would further enlarge to even more unbelievable values.

Various combinations of estimated random error with respect to Tidal 8 can be computed for the discrepancies between successive levelings along the San Diego-Barstow line. For example, the maximum estimated random error is associated with the discrepancy between the 1897/98/99 and 1906 heights for Victorville and is given as approximately 97 mm. However, the estimated random error in the discrepancy between the 1906 and 1924 heights for Barstow, based on the longest comparative levelings along this line, is approximately 51 mm. The errors in the end-point discrepancies are scaled down still farther in considering comparisons among the results of still later surveys. That at Santa Ana, for example, based on the results of the 1924 and 1933/34 leveling, is approximately 31 mm. Of course, none of these error estimates allows for the error inherent in our computation of the 1906 starting elevation for Tidal BM 4, San Diego, developed from comparative sea-level measurements. Nonetheless, it is very unlikely that this error exceeds 0.02–0.04 m (Castle and Elliott, 1982, p. 6993).

Height changes along the San Diego-Barstow line reached a maximum in the Riverside-San Bernardino area, where the 1897/98/99–1924 uplift approached 0.40 m (pl. 7). Measured against the full datum, the 1906–24 uplift increased gradually northward from the Riverside-San Bernardino area to slightly less than 0.30 m south of Barstow (pl. 7). North of Santa Ana, the uplift based on a comparison between any earlier datum and the results of the 1932/33 leveling is slightly underestimated. Specifically, owing to compaction-induced subsidence at Santa Ana, the elevation differences between Santa Ana and points to the north probably increased by as much as 0.01 m during the three-quarter-year junction interval between the 1932/33 San Diego-to-Santa Ana survey and the 1932 (earlier) survey extending northward from Santa Ana. Accordingly, the 1932/33–33/34 subsidence at Riverside shown here should be somewhat less than the comparable 1931/32–33/34 subsidence based on leveling along the Los Angeles-Riverside line (see subsection above entitled "The Los Angeles-Riverside Line"). This discrepancy, of course, could be expected to have been even larger if allowance is made for both normal survey error and any intrasurvey deformation in the 1931/32 leveling leading directly into Riverside through Los Angeles.

Although the inception of regional uplift along the San Diego-Barstow line is imperfectly understood, it almost certainly began after 1902, yet no later than the end of February 1906. The misclosure around the 1902/06/26/27 circuit Colton-Mecca-Ogilby-El Centro-San Diego-Santa Ana-Colton (fig. 14) provides what we believe to be the clearest evidence that uplift probably commenced sometime after 1902 (see subsection above entitled "The Los Angeles-Riverside Line"). The likelihood that it could have begun no later than the early months of 1906 is based on the detailed history of the 1906 leveling and the localization of the 1897/98/99–1906 signal. The 1906 leveling was begun in San Diego on March 5, 1906, reached Santa Ana by the middle of April, and closed on Barstow on June 7 (Bowie and Avers, 1914, p. 31; E.I. Balazs, oral commun., 1983). Because the southern peak of the double-lobed uplift along the San Diego-Barstow line (pl. 7) is defined by leveling that was begun only 6 weeks earlier, it is unlikely that this uplift occurred after the leveling began. This view is supported as well by the misclosure shown in figure 14, which is of a sense and magnitude consistent with about 0.15 m of uplift at Colton in advance of the 1906 survey.

Direct evidence of collapse along the San Diego-Barstow line is limited to the section between El Toro and San Bernardino. Maximum collapse apparently occurred between 1924 and 1932/33 (pl. 7). Although the 1924–32/33 subsidence centering on Santa Ana is largely attributable to ground-water extraction, as much as 0.06–0.07 m of what we interpret as tectonic collapse accumulated southward from the Riverside-San Bernardino area to about the position of the Whittier-Elsinore fault (pl. 7). Northward from San Bernardino, the postuplift collapse apparently increased dramatically and is believed to have reached a maximum of 0.30 m or more at Barstow (fig. 18).

THE SAN DIEGO-ARLINGTON LINE

GENERAL REMARKS

Height changes along the San Diego-Arlington line, which nearly parallels the San Diego-Barstow line northward as far as Arlington, are based on a comparison between the results of only two surveys. Although the accuracy of both these surveys, each of which is actually a composite of several surveys, is well below that of comparable surveys that define the height changes along the San Diego-Barstow line, the resulting signal generally agrees with that produced from temporally equivalent levelings along the San Diego-Barstow line. Nevertheless, the 1897/98–1927/35 uplift at Arlington is much less than that obtained from a comparison between the 1897/98/99 and 1933/34 surveys along the San Diego-Barstow line. Because this discrepancy probably depends largely on inaccuracies in one or the other of the two 19th-century third-order datums, we have attempted to independently assess the relative accuracy of the two contributing surveys. Our assessment suggests that the 1897/98 survey between San Diego and Arlington is contaminated by error of suspected but unknown origin that tended to increase the 1897/98 observed-elevation differences to values above those that would have been produced through instantly propagated, perfect leveling. Accordingly, the 1897/98–1927/35 uplift disclosed by our reconstruction is believed to be less than the actual uplift along this line.

Because neither of the comparative surveys is tied directly to Tidal 8, the 1897/98 and 1927/35 starting elevations at Tidal BM 4, San Diego (with respect to Tidal 8), have again been reconstructed from differenced sea-level changes at the San Pedro and San Diego tide stations, coupled with a later first-order tie between these stations. Moreover, even though the first few kilometers of the 1927/35 line northward from Tidal BM 4 were actually surveyed in 1932, we have treated the resulting elevation differences as the equivalent of those that would have been obtained in 1927. Assuming that our reconstruction is valid, uplift with respect to Tidal 8 accumulated more or less steadily northward from Escondido to a maximum of about 0.23 m immediately south of Arlington. As we have already indicated, however, this value probably underestimates the 1897/98–1927/35 uplift, possibly by as much as 0.1 m or more.

DETAILED RECONSTRUCTION

The primary route to which we have referred height changes along the San Diego-Arlington line is defined by leveling propagated out of Tidal 8 through Florence and southward to San Diego, and thence northward via Temecula into Arlington (pl. 3). Both starting elevations at Tidal BM 4, San Diego, are ultimately based on 1931/32/33 first-order leveling between Tidal 8 and Tidal BM 4 that coincided with the designated primary route (NGS lines L–386, L–570). If the 1931/32/33 observed-elevation difference between Tidal 8 and Tidal BM 4 is again corrected for the approximately 0.01 m of subsidence that occurred during the 1931/32–32/33 junction interval at Santa Ana, we obtain a "1932" elevation for Tidal BM 4 of 3.6126 m. The differenced linear regressions through the 19-year sea-level means for the San Pedro and San Diego tide stations indicates that Tidal BM 4 has been subsiding with respect to Tidal 8 at a rate of about 2.98 ± 0.11 mm/yr (see subsection above entitled "The San Diego-Barstow Line"). Accordingly, the 1898 elevation of Tidal BM 4 with respect to Tidal 8 was 3.7139 m, whereas the 1927 elevation was 3.6275 m; these values provide the starting elevations with respect to Tidal 8 for the 1897/98 and 1927/35 surveys along the San Diego-Arlington line (pls. 3, 8). Because the 1927 first-order leveling into Temecula (pl. 8) follows the 1897/98 survey route only in part, we have used the results of a 1935 second-order survey, junctioning at bench mark U 63 (NGS lines 82706, L–5581), to increase the density of common marks along this line. This reconstruction, in effect, treats the 1935 leveling as a short spur extending southward into Escondido off the 1927 first-order line and obviously is based on an assumption of invariance at U 63 during the period 1927–35.

Survey error is thought to be a significantly greater problem here than along any other line considered in this report—except, of course, for the Ventura-Cuyama spur and the several spurs extending westward off the San Pedro-Bakersfield line (see subsections above entitled "The Oxnard-Guadalupe Line" and "The San Pedro-Bakersfield Line"). However, the most suggestive evidence of survey error in one or the other (or both) of the levelings that define the height changes along this line is indirect: The 1897/98–1927/35 uplift at bench mark 861 SB (pl. 8) is about 0.13 m less than the 1897/98/99–1933/34 uplift of this mark shown on the San Diego-Barstow line (pl. 7). Several lines of evidence indicate that the chief source of this discrepancy lies in one or the other of the late-19th-century surveys and is more apt to be found in the 1897/98 leveling along the San Diego-Arlington line than the 1897/98/99 leveling along the San Diego-Barstow line. Disregarding any height changes at Tidal BM 4 with respect to Tidal 8 during the period 1898–1906, the misclosure around the 1898/1906 circuit Arlington-Temecula-San Diego-Santa Ana-Arlington (fig. 20) suggests 1898–1906 uplift at bench mark 861 SB of about 0.04 m. Although the sense of this misclosure is consistent with uplift at 861 SB based on a direct comparison between the results of the 1897/98/99 and 1906 levelings along the San Diego-Barstow line, the magnitude of the implied signal is about 0.09 m less than that shown on plate 7. Accordingly, this comparison virtually compels that a major source of the discrepancy in the cumulative uplift of 861 SB lies largely or entirely in the late-19th-century leveling. If the larger error were in the 1897/98/99 survey leading into and along the San Diego-Barstow line, it is unlikely that it could be assigned to that part of the leveling extending eastward into Colton (or Riverside) from San Pedro (see subsection above entitled "The Los Angeles-Riverside Line"). Thus, this postulated error would have to have been localized between bench marks 978 SB, Colton (or 851 SB, Riverside), and 861 SB. Because the height difference between these marks is small and because there is no evidence of blundered leveling between Colton and Riverside or Arlington (pl. 7), an error of about -0.1 m in the 1897/98/99 height of bench mark 861 SB would be difficult to accommodate. Therefore, if the indicated discrepancy remains unexplained by any significant error in the 1897/98/99 leveling into 861 SB from San Pedro, we infer that the 1897/98 leveling between San Diego and Arlington probably contains a measurably significant error attributable to one or more of several possible sources. Moreover, although the 1927/35 comparative survey was carried out during a period of probably continuing collapse within at least a part of the early-20th-century uplift, it is possible but unlikely that intrasurvey deformation during the period 1927–35 can account for any significant fraction of the discrepancy in the uplift of bench mark 861 SB disclosed by repeated surveys along the San Diego-Barstow and San Diego-Arlington lines, respectively (pls. 7, 8). Specifically, the misclosure around the 1927/31/32/33/35 circuit Arlington-Temecula-San Diego-Santa Ana-Arlington (fig. 21) indicates (although it certainly does not compel) both that any deformation along the San Diego-Arlington line during the period 1927–35 probably was minor and that the accuracy of the leveling around the entire loop was of an acceptable standard. Nevertheless, the sense of this misclosure (fig. 21) indicates that the measured elevation difference may have been several centimeters less than the actual 1927/35 elevation difference between bench marks 42 SD and 861 SB and thus may have accounted for a modest fraction of the 0.13-m discrepancy at 861 SB.

Evidence suggestive of either a blunder or significant intrasurvey movement during the course of the 1897/98 leveling that defines the datum along the San Diego-Arlington line is of questionable significance. Southward from Arlington to Temecula, the relatively smooth profile showing the changes in height during the period 1897/98–1927/35 (pl. 8) virtually precludes the existence of a blunder. The abrupt change in height that occurred at Escondido (pl. 8) could be interpreted as evidence of a blunder. However, the relatively tight closure around the 1898/1906 circuit Arlington-Temecula-San Diego-Santa Ana-Arlington (fig. 20) suggests, instead, that this knick point is much more reasonably attributed to bench-mark disturbance between surveys. Height-dependent systematic error in the 1897/98 leveling is a much more likely source of error than blundered measurements or intrasurvey deformation, especially over that part of the line between Temecula and Arlington (pl. 8). The signal over this reach is at least suggestive of rod error that would tend to enhance the 1898 observed-elevation difference between Temecula and Arlington. Regardless, however, and as suggestive as this signal may be of a height-dependent error in the datum leveling, too few

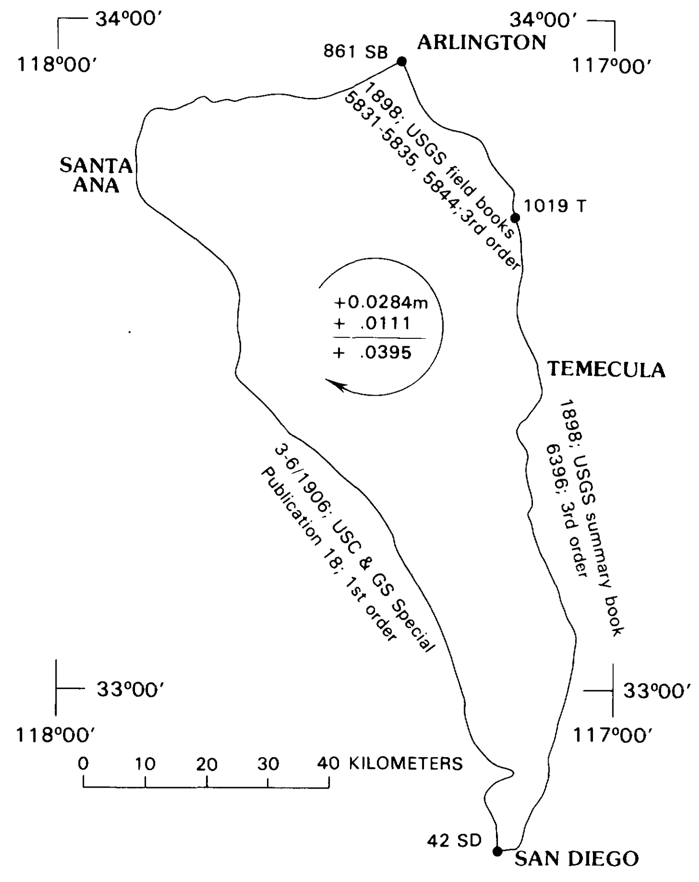

FIGURE 20.—Misclosure around 1898/1906 circuit Arlington-Temecula-San Diego-Santa Ana-Arlington. See figure 5 for explanation of symbols and adopted conventions.

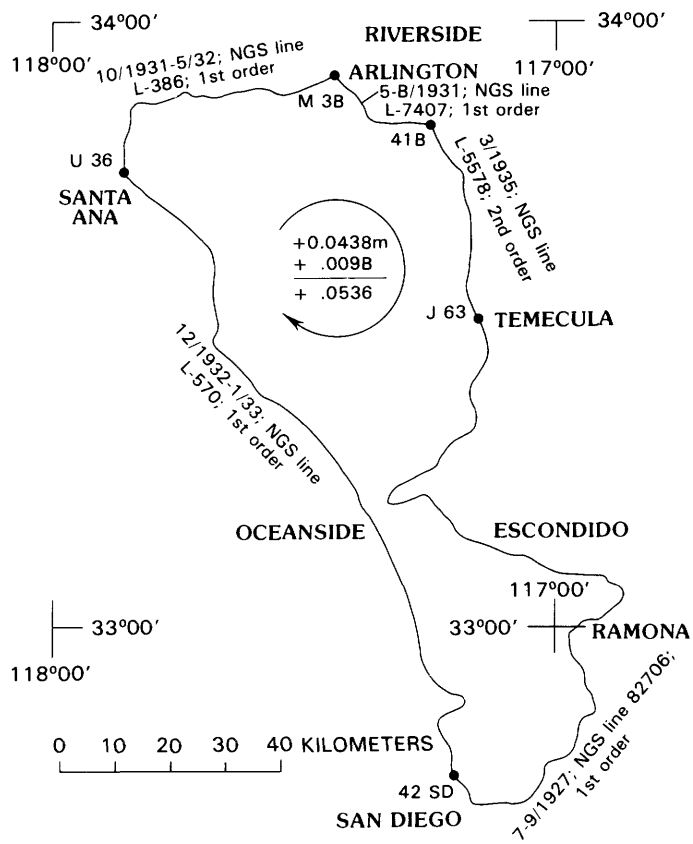

FIGURE 21.—Misclosure around 1927/31/32/33/35 circuit Arlington-Temecula-San Diego-Santa Ana-Arlington. Estimated random error associated with this misclosure is given as 0.0380 m. See figure 5 for explanation of symbols and adopted conventions.

comparative marks exist on which to base any firm conclusions. Finally, the estimated random error with respect to Tidal 8 in the 1897/98–1927/35 uplift at 861 SB, Arlington, is given as about 106 mm, a value that is dominated by the estimated error in the 1897/98 leveling between San Diego and Arlington. Accordingly, if we allow for a modest height-dependent systematic error within at least the single-rodded section of the 1897/98 leveling between San Diego and Arlington (pl. 8), coupled with possibly 0.05–0.10 m of random error of the same sense, the diminished 1897/98–1927/35 signal at bench mark 861 SB is reasonably explained. In fact, because the 1898 San Pedro-San Diego down-to-the-south sea slope based on the 1897/98 leveling between Arlington and San Diego is about 0.12–0.14 m greater than that produced by subsequent first-order levelings (Castle and Elliott, 1982, p. 7005, 7014–7015), it is especially likely that the 1897/98 observed-elevation difference between Tidal BM 4 and 861 SB is identified with an error of +0.1 m or more and thus that the 1897/98–1927/35 signal is underestimated by an equal amount.

The height changes disclosed by a comparison between the two surveys (or composite surveys) along the San Diego-Arlington line probably provide a mimimum estimate of the uplift that accumulated northward along this line during the period 1897/98–1927/35 (pl. 8). Specifically, if we allow for the probably cumulatively positive error northward in the 1897/98 datum, the 1897/98–1927/35 signal would enlarge to about +0.3 m toward the north end of the line. In the final analysis, the chief value of the comparison produced by the repeated surveys along this line is that it corroborates the occurrence of major, aseismic uplift within this section of the Peninsular Ranges (see section on "The San Diego-Barstow Line").

THE COLTON-MECCA LINE

GENERAL REMARKS

The Colton-Mecca line may be thought of as an extension of the Los Angeles-Riverside line, even though the actual comparisons begin about 10 km north of Riverside. The feature that clearly distinguishes this line is the magnitude of the uplift disclosed by repeated surveys during the period 1902–28, uplift that had by 1928 exceeded 0.6 m near White Water. However, because we lack intermediate surveys leading into or along this line, this surge of uplift can be isolated only as having occurred sometime within the period 1902–28. In other words, we have no direct way of knowing when within the period 1902–28 the uplift actually occurred and, especially significantly, whether it preceded, accompanied, or followed the 1924–26 partial collapse elsewhere within the area of the early-20th-century uplift. This element of uncertainty leaves us with at least two reasonable interpretations of the growth of the uplift along its southeastward extension.

We recognize three major problems associated with the reconstruction of height changes along the Colton-Mecca line. (1) The starting height can be reasonably based on the results of either the 1897 leveling through Los Angeles or the 1906 leveling through San Diego into Colton, an option that produces a discrepancy of about 0.15 m in the resulting signal southeastward from Colton. (2) The 1902 datum is based on the results of third-order, even though double-rodded, leveling, and so the accuracy of the datum is questionable. (3) The 1928 leveling that defines the signal is identified with a large (0.3 m) misclosure suggestive of measurement error. We see no way whereby we can categorically demostrate that one or the other of the two possible starting heights at Colton is the more valid. However, the existing evidence indicates that (1) the 1897 elevation of the starting mark was relatively accurately determined and (2) the uplift of Colton that apparently developed sometime between 1897 and 1906 actually occurred after 1902—thus, after the propagation of the 1902 leveling eastward from Colton. Secondly, although the 1902 leveling was run to only third-order (primary) standards, it was double rodded over its entire length and is unlikely to have been contaminated by blunders. Moreover, the results of the 1902 leveling closely agree with those based on an earlier (1898/1901) third-order leveling, except for a single section north of Palm Springs. Because these separate levelings were carried out by three different crews using different instrumentation, it is extremely unlikely that the 1902 (or 1898/1901) leveling was distorted by a large height-dependent systematic error over that part of the line common to both levelings (virtually the entire line between Colton and Mecca). Moreover, because signal and terrain are completely uncorrelated over this line, it is unlikely that either height- or slope-dependent systematic error affected the 1902 leveling to any significant degree. Finally, even though the 1928 leveling was associated with a large misclosure, this misclosure is based on the results of 1926/27/28/31/32/33/34 Invar-rodded leveling, all of which met first-order standards. Thus, to dismiss cavalierly this above-limits misclosure as the product of measurement error simply begs the question. Independent evidence corroborates the accuracy of all but the 1928 leveling that extends northward from El Centro to Colton, such that the source of the 1926/27/28/31/32/33/34 misclosure must in some way be associated with the 1928 leveling. Because the 1928 leveling was carried out by a single survey crew and because this leveling southeastward from Colton to the crest of the 1902–28 uplift is corroborated by 1931 and 1934 levelings, this large misclosure is best explained by intrasurvey deformation during the course of the 1928 leveling extending at least as far north as Indio.

DETAILED RECONSTRUCTION

The primary route that defines the Colton-Mecca line (pls. 3, 9) is, in effect, a continuation of the Los Angeles-Riverside line, where we have again disregarded the modest difference in the orthometric corrections applicable to leveling over the 1897 path and the near-coincident route followed by later surveys into Riverside (pl. 3). The 1902 starting elevation at Colton is based on the 1897 observed elevation of bench mark 978 SB with respect to Tidal 8 (see subsection above entitled "The Los Angeles-Riverside Line"). The 1928 starting elevation is based on the 1923/24 observed elevation of 978 SB derived from the results of the 1923/24 leveling into Riverside through Los Angeles, and thence northward along the San Diego-Barstow line (pls. 6*A*, 7). Virtual stability at 978 SB during the period 1924–28 is strongly supported by the agreement between the results of the 1924, 1932/33, and 1934 levelings into bench marks 851 SB and 978 SB, respectively (pl. 7). The 1931 starting elevation is based on the 1931 observed elevation of bench mark M 71, Banning (NGS line L–7407), which, in turn, is derived from a tie with the 1931/32 elevation of bench mark M 38, Riverside (NGS line L–386). To bring the starting elevation of M 71 into orthometric compatibility with that which would have been produced had the 1931/32 leveling followed the primary route into Banning, the 1931 observed elevation for this mark has been increased by 0.0032 m. The 1934 starting elevation of 978 SB is based on a continuation of the 1934 leveling along the Los Angeles-Riverside line, coupled with a 1934 connection northward from Riverside into Colton (pls. 6*A*, 7).

The 1902 starting elevation at Colton might have been based alternatively on the 1906 elevation of bench mark 978 SB obtained from the 1906 leveling emanating from San Diego (see subsection above entitled "The San Diego-Barstow Line"). However, use of this alternative reconstruction, as opposed to a simple tie with the 1897 observed elevation of 978 SB, produces a 0.15-m discrepancy in the 1902 starting elevation at Colton (pl. 7), such that a choice must be made between these two alternatives. In fact, the excellent agreement between the 1902/06/26/27 misclosure around the circuit Colton-Mecca-Ogilby-El Centro-San Diego-Santa Ana-Colton (fig. 14) and the 1897–1906 uplift at Colton (pl. 7) strongly supports the conclusion that the 1897–1906 uplift was largely confined to the period 1902–06. It is certainly conceivable, of course, that this uplift may have consisted in part of coseismic displacement associated with either the July 22, 1899, San Bernardino or the December 25, 1899, San Jacinto earthquakes (Coffman and von Hake, 1973, p. 161). However, the breadth of the 1897/98/99–1906 signal (pl. 7) is inconsistent with its attribution to an exclusively coseismic source. Finally, even though the 1897 elevation of bench mark 978 SB is based on third-order leveling, this leveling was double rodded over the entire length of the survey between San Pedro and Colton (pls. 5, 6*A*). Moreover, if we assume that the resulting 1897 observed elevation of 978 SB was underestimated (and thus that the 1897–1906 signal was overestimated), correction for this postulated error would again compel an enlargement of the already measurably significant misclosure around the 1897/1902/06 circuit Los Angeles-Saugus-Palmdale-Mojave-Barstow-Highgrove-Los Angeles (fig. 15).

Inaccurate observed-elevation differences attributable to conventional survey error are probably of modest magnitude in all the levelings used in development of the reconstructed heights along the Colton-Mecca line. However, we now believe that intrasurvey deformation almost certainly distorted the resulting observed-elevation differences associated with the 1928 leveling at least as far north as Indio.

Because all the later surveys along the Colton-Mecca line were based on Invar-rodded leveling that met first-order standards, the accuracy of the 1902 third-order leveling that defines the datum (pl. 9) is clearly the most suspect. Nevertheless, because this line was double rodded over its full length (USGS summary book 9488), it is unlikely that it was contaminated by survey blunders. In addition, the results of the 1902 leveling generally agree well with those based on an earlier, composite (1898/1901) third-order survey that it repeated over all but a single section between Colton and Mecca (fig. 22). This agreement is enhanced, moreover, if allowance is made for the likelihood that the modest 1898–1902 uplift at the west end of the line is, in fact, a coseismic signal associated with either of the 1899 earthquakes with which it was more or less spatially coincident (Coffman and von Hake, 1973, p. 161). Because different field units and, thus, probably different instrumentation were employed in each of the surveys involved in the comparison shown in figure 22 (USGS summary books 5816, 8305, 9488), it is unlikely that rod error was a source of significant height-dependent systematic error in the 1902 survey. The absence of a slope-dependent systematic error in the 1902 leveling is less easily demonstrated through a comparison with the earlier survey, if only because the stipulated field procedures are believed to have remained unchanged during the period 1898–1902. However, disregarding compensating error, the accumulation of significant residual refraction error in the 1902 survey would require that it was nearly matched in the earlier survey, even though the meteorologic conditions that generally prevail in the northern Salton Trough during the fall differ significantly from those that characterize late winter or early spring.

Utilization of the 1898/1901 survey for comparative purposes (fig. 22) introduces a complexity that cannot be ignored, because this comparison suggests a possible blunder in either the 1898 or 1901 levelings through which bench marks 1130 and 685 T can be connected. (A blunder in the 1902 leveling between these marks is virtually precluded by the double rodding of this survey and the misclosure shown in figure 14.) Specifically, the 1898 and 1901 surveys junctioned through a common mark, 455, in Palm Springs, about 18 km south of bench mark 685 T, Garnet (pl. 9), and thus provide the basis for a comparison of the results of the 1902 leveling against an uninterrupted 1898/1901 datum. This somewhat involved comparison suggests, in turn, that the entire reach between Garnet and Mecca sustained relatively uniform uplift of about 0.1 m during the period 1898/1901–02 (USGS summary books 5816, 8305, and 9488). We recognize three possible explanations for this seeming signal: (1) actual block movement between Garnet and Mecca; (2) a blunder in either the 1898 or 1901 surveys between 1130 and 455 or between 455 and 685 T, respectively; or (3) disturbance of the junction mark, 455, sometime between 1898 and 1901. Although we cannot categorically rule out the possibility, to appeal to tectonic movement to explain the apparent 1898/1901–02 uplift would require fortuitous truncation of this movement at the north end of the common leveling at Garnet. Moreover, because the 1898 leveling was double rodded directly into 455 (USGS summary book 5816), it is especially unlikely that the single section between 1130 and 455 was the only one along the entire line that was associated with a blunder. Similarly, the misclosure around the 1901 circuit Palm Springs-Garnet-Indio-Palm Desert-Palm Springs (fig. 23) tends to eliminate the likelihood of a blunder in the 1901 leveling. Finally, the junction mark,

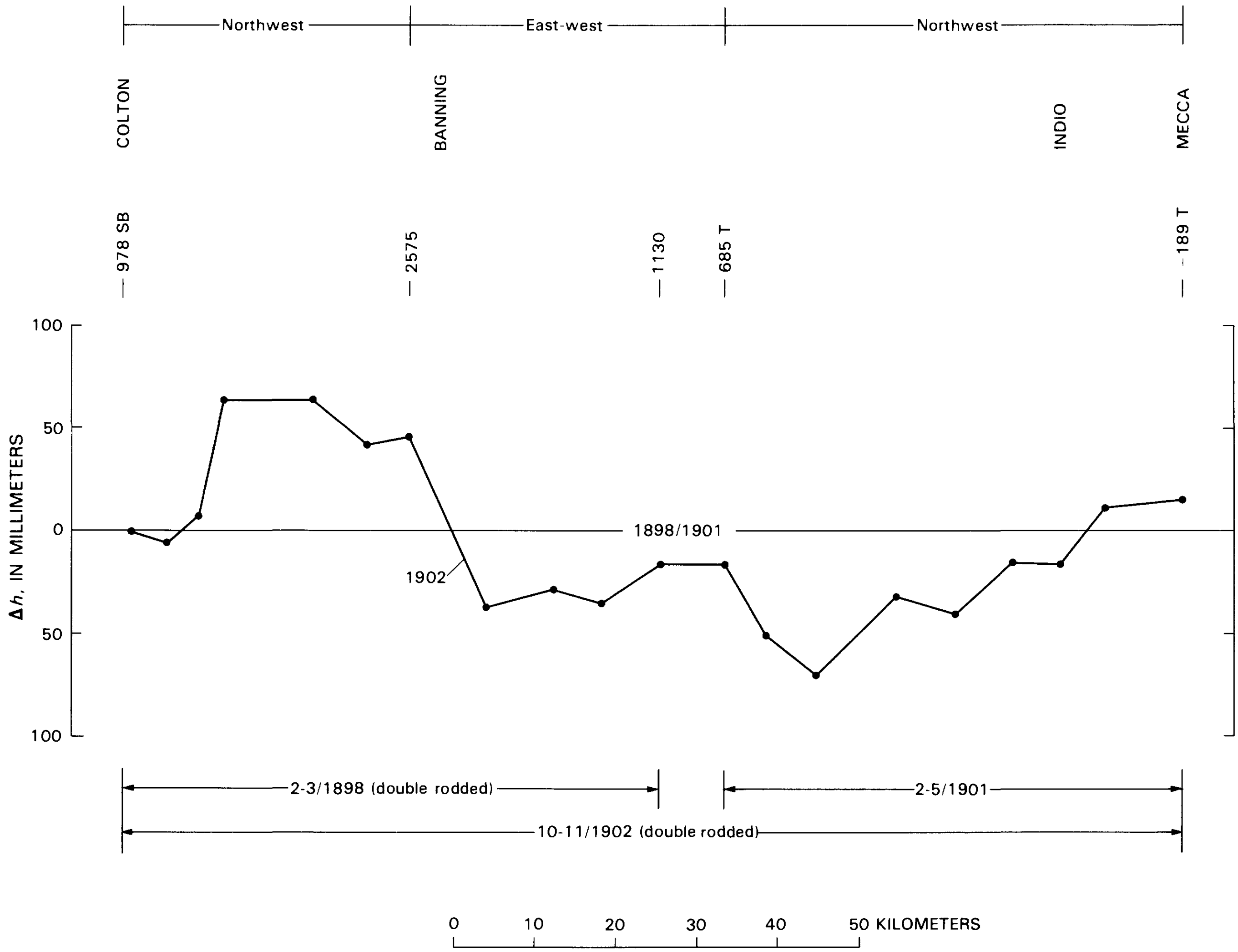

FIGURE 22.—Height changes with respect to bench mark 978 SB, based on a comparison of the results of 1902 third-order leveling against a combined 1898/1901 third-order datum along the Colton-Mecca line. Because bench marks 1130 and 685 T were not tied directly during either the 1898 or 1901 levelings, we assume here that the 1902 observed-elevation difference between these marks is the same as that which would have been obtained in either 1898 or 1901. Data from U.S. Geological Survey summary books 5816, 8305, and 9488 (see text for details).

which is described as a "Brass plate stamped 455 in the south wall of the Concrete Hotel building at Palm Springs, Calif." (USGS summary book 5816), could certainly have sustained modest collapse during the December 1899 earthquake (Coffman and von Hake, 1973, p. 161). Accordingly, the most likely explanation for the seeming 1898/1901–02 0.1-m uplift between Garnet and Indio lies in the probable differential subsidence of bench mark 455 sometime during the period 1898-1901.

Alternatively, the accuracy of the 1902 leveling between Colton and Mecca can be independently assessed through incorporation of the results of this leveling in the establishment of a "1902" height for bench mark 0 10, Hassayampa, Ariz., with respect to bench mark M 57, San Diego (fig. 1). All of the evidence available to us indicates that bench mark 0 10, located adjacent to an outcrop of crystalline basement, lies within a tectonically stable part of southwestern Arizona. Bench mark M 57 (pl. 3) is one of several tidal marks tied to the primary tide station located at the Municipal Pier in San Diego. Because both oceanographic and geologic evidence shows that this tide station has remained virtually invariant with respect to the reference ellipsoid or some explicitly defined geoid (Castle and Vaníček, 1980, p. 291–292), successive heights referred to M 57 should be relatively unbiased toward indications of either uplift or subsidence.

The successively determined heights for bench mark 0 10 (table 2) have been derived from various combinations of temporally disconnected surveys. The 1902 height is based in part on 1931/32/33 leveling between M 57 and Tidal 8, corrected both for the approximately 0.01 m of subsidence that occurred at Santa Ana during a 1931/32–32/33 junction interval (Castle and Elliott, 1982, p. 7005)

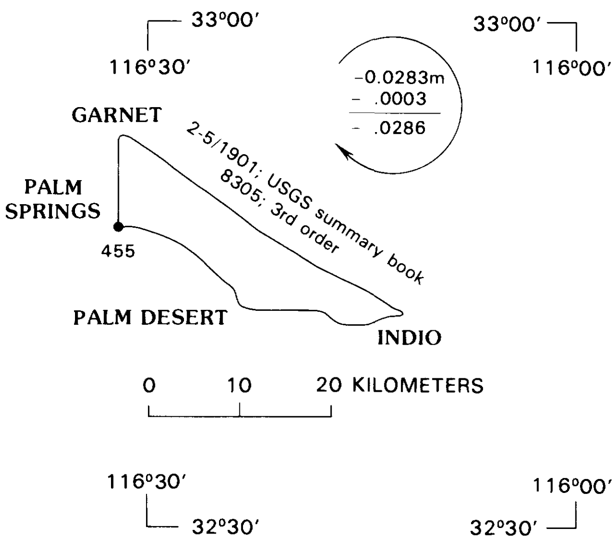

FIGURE 23.—Misclosure around 1901 circuit Palm Springs-Garnet-Indio-Palm Desert-Palm Springs. See figure 5 for explanation of symbols and adopted conventions.

and for the uplift of Tidal 8 with respect to M 57 of approximately 1.56 mm/year (pl. 3; figs. 3, 4) between 1897 and the 1931/32/33 leveling. Had we not made this second correction, the 1902 height of O 10 would have been 0.0546 m higher. The 1897 height difference between Tidal 8 and the 1897 starting mark, BMA, is based on the reconstructed height difference between BMA and Tidal 8 developed earlier in this report (see section above entitled "The Reconstruction"). Accordingly, joining of the 1897 height difference between bench marks M 57 and BMA with the results of the 1897 leveling between BMA and Colton, the 1902 leveling between Colton and Yuma, the 1905 first-order leveling between Yuma and Gila Bend, and the 1927 first-order leveling between Gila Bend and Hassayampa produces the "1902" height for bench mark O 10 listed in table 2. The other heights listed in table 2 are based exclusively on the results of first-order leveling and are much less complexly derived than the 1902 height. However, the 1976/78/81 height makes use of a 40-km segment of 1931 leveling east of the Colorado River. Moreover, the 1978/81 height is suspect because it is based on leveling that involved a 3-year junction interval at El Centro which bracketed the 1979 Imperial Valley earthquake. In any case, the generally good agreement among the heights listed in table 2 supports the conclusion that the height of bench mark O 10 has remained virtually unchanged through the past 80 years and thus that the 1897 and 1902 levelings that contributed to the earliest listed value (table 2) probably were highly accurate.

Comparisons between signal and terrain along the Colton-Mecca line (pl. 9) show that the two are completely uncorrelated. This conclusion, together with the near-conformity between the 1902 datum and the results of earlier leveling over this line (fig. 18), indicates that none of these surveys was contaminated by measurably significant height- or slope-dependent error. For example, were we to attempt to explain the 1902–28 signal between bench marks 2575 and 539 T (pl. 9) as the product of an unassessed rod error, an error of 7.2×10^{-4} (720 ppm) would be required in either the 1928 or the datum leveling (together with some sort of rationale as to why this error apparently reversed in sign at the crest of the grade). To appeal to refraction error to explain the same signal is even more challenging, because this error should cancel over opposing slopes; yet the signal accumulated at a remarkably uniform rate throughout this reach (pl. 9). Moreover, if we assume that this postulated error is in the datum leveling, the error is opposite to that predicted by the operation of unequal refraction. However, the above-limits misclosure around the 1926/27/28/31/32/33/34 circuit Colton-Banning-Mecca-Niland-El Centro-San Diego-Santa Ana-Colton (fig. 24) demonstrates a gross inaccuracy in the end-to-end observed-elevation difference

TABLE 2.—*Successively determined heights for bench mark O 10, Hassayampa, Ariz., with respect to bench mark M 57, San Diego*

[Orthometric corrections to height are based on observed gravity]

Date	Survey route	Height (m)	Date sources
1902	Via Los Angeles, Colton, Mecca, Yuma, and Gila Bend.	274.4060	U.S. Geological Survey (1898, p. 381-384); U.S. Geological Survey summary book 9488; NGS lines 63082, 82625, L-386, and L-570; Castle and Elliott (1982, p. 7005, 7014-7015).
1926/27	Via El Centro, Yuma, and Gila Bend.	274.4282	NGS lines 82606 and 82632.
1976/78/81	Via El Centro, Freda Junction, and Parker Dam.	274.4541	NGS lines L-7407, L-24068, L-24077, L-24085, L-24301, L-24555, L-24562, and L-24684.
1978/81	Via El Centro, Yuma, and Gila Bend	274.4214	NGS lines L-24301, L-24555, and L-24562.

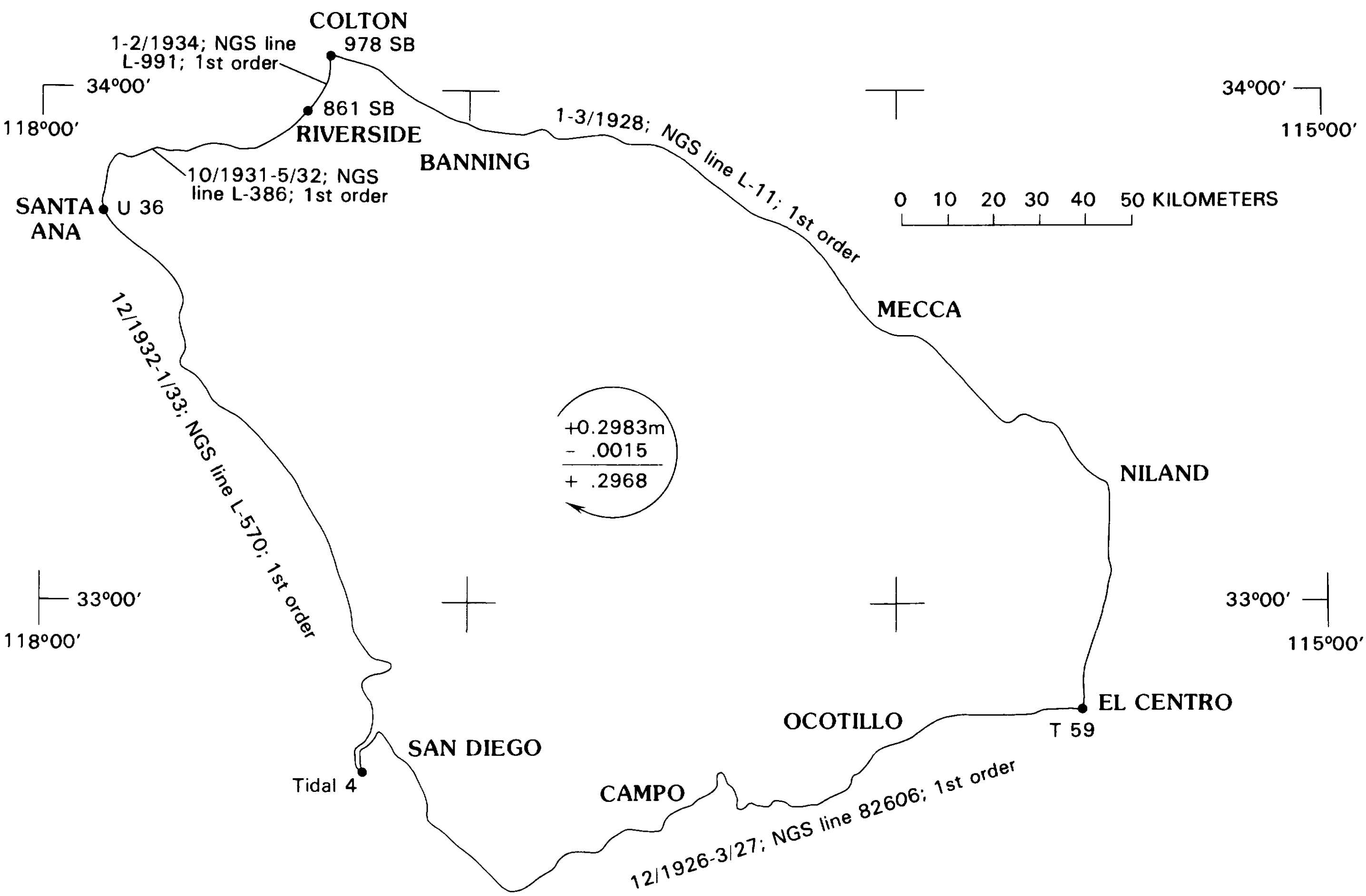

FIGURE 24.—Misclosure around 1926/27/28/31/32/33/34 circuit Colton-Banning-Mecca-Niland-El Centro-San Diego-Santa Ana-Colton. See figure 5 for explanation of symbols and adopted conventions.

in at least one of the legs included with this loop. Because the accuracy of the 1931/32/34 leg between San Diego and Colton is independently corroborated (pl. 7; fig. 21), this error must have occurred in either the 1926/27 leg between El Centro and San Diego or the 1928 leveling between Colton and El Centro—or both. Inasmuch as the results of a 1931 first-order leveling eastward from Ocotillo (fig. 24) through El Centro are virtually identical to those drawn from the 1926/27 leveling (NGS lines 82606 and L–222), and because the 1926/27 heights obtained for Campo (fig. 24), which lies at about 700 m, fall within about one standard deviation of those developed from 1956 leveling between San Diego and Campo (Gilmore and Castle, 1983, p. 477), we are virtually certain that this large misclosure (fig. 24) is somehow attributable to a failure in the 1928 leveling between Colton and El Centro. This interpretation is independently supported by substitution of the results of the 1931 leveling between bench marks M 71 and S 70 for the 1928 results over this same reach (pl. 9), an operation that reduces this misclosure (fig. 24) to +0.1633 m. The entire circuit shown in figure 24 was developed from Invar-rodded first-order leveling based on instrumentation of the same design and identical field procedures. Accordingly, to argue that the 1928 leveling was singularly error prone is unsupportable. Therefore, we are finally left with the compelling inference that the 1928 observed-elevation difference between El Centro and Colton was distorted as a result of intrasurvey deformation, even though this survey was completed in less than 3 months. Because the signal between Colton and Indio is corroborated by subsequent leveling, this distortion is inferred to have been localized largely within the reach between El Centro and Indio. However, although intrasurvey deformation during the 1928 leveling is believed to be the most likely explanation for the 0.2968-m misclosure shown in figure 24, it would be futile to speculate on the distribution of this deformation in both space and time because the possible combinations are virtually limitless. Finally, although both height- and slope-dependent systematic error seems to have been minimal in this leveling, the estimated random error with respect to Tidal 8 in the discrepancy between the results of the 1902 and 1928 leveling at Mecca is given as about 103 mm, whereas that based on the 1928 and 1931 leveling into Indio is about 35 mm.

The height changes along the Colton-Mecca line (pl. 9) are by far the largest described in this report. Nevertheless, we have no reason to believe that they are any less valid than those based on comparable repeated levelings along other lines considered here. In fact, because the accuracy of the 1902 leveling is independently corroborated both by earlier levelings and a remarkably tight closure on a demonstrably stable mark in southwestern Arizona, and because the 1931 leveling suggests an even greater tilt between the crest of the uplift and Indio than does that based on the 1928 survey, the height changes along the Colton-Mecca line may be among the best controlled of those reported in our investigation of the early-20th-century uplift. However, the chronology of the uplift along this line—as shown, for example, by the successively determined heights for a representative mark near White Water (fig. 25)—is relatively poorly understood. That is, although it seems extremely unlikely when considered in context, this uplift (fig. 25) could have begun as early as 1902 and proceeded at a more or less uniform rate through 1931.

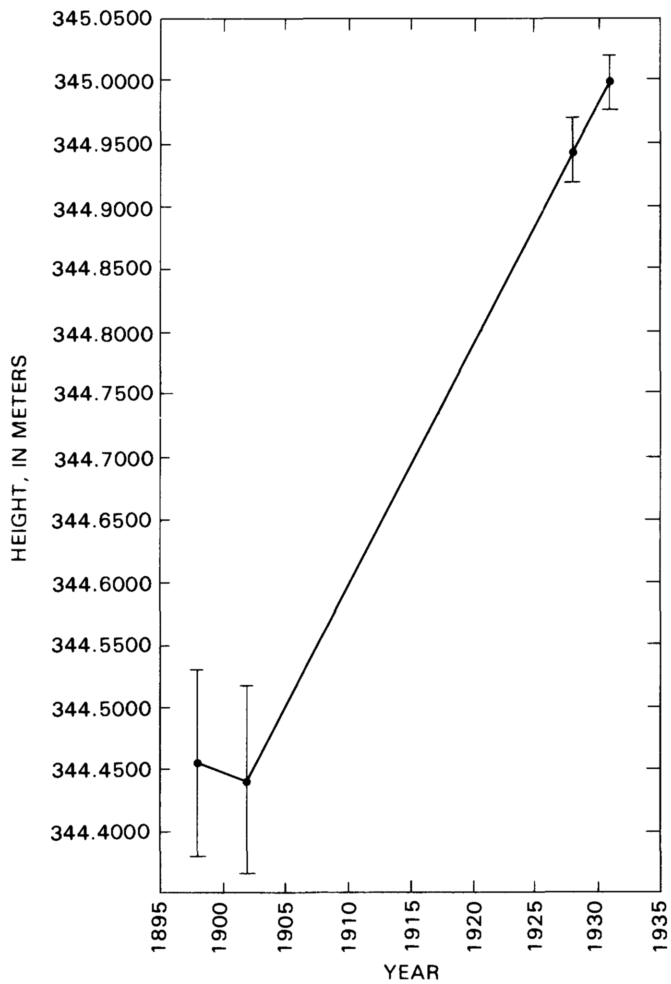

FIGURE 25.—Changes in orthometric height at bench mark 1130, White Water, with respect to bench mark Tidal 8, San Pedro. 1902 height is based on an assumption of invariance at bench mark 978 SB, Colton, during the period 1897–1902. Orthometric corrections are based on observed gravity. Error bars show conventionally estimated random error only.

SELECTED STAGES IN THE GROWTH OF THE EARLY-20TH-CENTURY UPLIFT

The vertical displacements along the several lines described in the preceding sections provide a basis for a generalized characterization of the evolution of the early-20th-century uplift from its inception to its partial collapse. Even though the data are both less accurate and much more skeletal in their distribution, the gross configuration of the cumulative uplift described here probably is nearly as accurate as that developed for the modern uplift.

THE 1902-06.2 EPOCH

The only aseismic displacements of any certainty that occurred within the period 1902–06.2 were confined largely to the reach between San Onofre and Cajon Summit (see subsection above entitled "The San Diego-Barstow Line" and pl. 7). Nevertheless, fairly convincing evidence indicates that a much broader area was involved with this initial uplift. Accordingly, we have developed two alternative interpretations of the uplift that apparently occurred within this period (fig. 26). Our conviction that the 1897/98/99–1906.2 uplift was restricted to the post-1902 period, whichever interpretation is favored, is dictated by the misclosure shown in figure 14, coupled with independent evidence of the accuracy of the leveling that produced this closure (see subsections above entitled "The Los Angeles-Riverside Line" and "The Colton-Mecca Line"). Similarly, the near-certainty that the pre-1907 uplift along the San Diego-Barstow line occurred no later than 1902.2 is based on the chronology of the 1906 leveling and the localization of the 1897/98/99–1906 uplift (see subsection above entitled "The San Diego-Barstow Line").

The first of the two alternative representations of height changes during the period 1902–06.2 (fig. 26*A*) is based on the assumption that the uplift did not extend appreciably beyond the area for which there is direct evidence of its existence—specifically, along the San Diego-Barstow line (pl. 7). If we accept this premise, the configuration of the uplift orthogonal to the San Diego-Barstow line must be inferred or left undetermined. Because the 1902–06.2 pulse closed off northward across Cajon Summit (pl. 7), whereas the chief burst of uplift extending northward from Los Angeles clearly involved the western Mojave block (see below), we have assumed in this first reconstruction (fig. 26*A*) that the initial pulse diminished steadily westward toward the Los Angeles-San Pedro area. Eastward from the San Diego-Barstow line we have no direct evidence of any postdatum (1902) displacements before 1927. Nevertheless, because the 1897/98/99–1906.2 and 1897/98/99–1932/33 displacements tend to converge south of San Juan Capistrano (pl. 7), we infer that about half of the 1897/98–1927/35 uplift along the San Diego-Arlington line (pl. 8) probably occurred during the period 1902–06.2. Still farther to the east, however, there is not even a suggestion of any vertical displacement by 1906.2. Accordingly, the contours have been left open eastward beyond the San Diego-Arlington line (fig. 26*A*). The 1897/98/99–1906.2 differential subsidence immediately north of the San Jacinto fault (pl. 7) may be attributable to ground-water withdrawals within this area of recognized compaction-induced subsidence. It is equally likely, however, that this subsidence was associated with slip on either the San Jacinto or San Andreas faults. In either case, we have disregarded it in contouring the regional height changes that occurred within the period 1902–06.2. Finally, if the uplift shown in figure 26*A* clearly preceded the major spasm of uplift that must have occurred by 1907.0, we are left with the interpretation of the 1902–06.2 pulse centering on the Santa Ana-Colton area as the nucleation point for the full uplift.

The alternative representation of uplift during the period 1902–06.2 (fig. 26*B*) is based on two considerations. (1) All the available evidence indicates that the uplift that defines the western lobe of the early-20th-century uplift probably culminated by the end of 1906. That is, even though at least one of the levelings that characterizes the magnitude of the pre-1907 uplift was not completed until 1920, had all these surveys been run at the beginning of 1907 the resulting displacement field would be about the same as that shown here. (2) A single but fairly persuasive line of evidence indicates that the pre-1907 uplift probably had occurred largely or entirely by 1906.2.

We take the 1897/1902/05–07 vertical displacements developed along the San Pedro-Bakersfield line (pl. 5) as representative of the cumulative uplift that had occurred by 1907 within what we now recognize as the area of the early-20th-century uplift. This minimal uplift, in turn, is based on the assumed invariance of Olancha during the period 1905–07 (see subsection above entitled "The San Pedro-Bakersfield Line"). Because the results of the 1907 leveling can be compared against the datum over only a part of the San Pedro-Bakersfield line (pl. 5), we have prorated the 1897/1902–14 displacements to bring them into conformity with the 1897/1902–07 displacements where the 1907 and 1914 surveys involve common marks. Owing to the nearly perfect closure of the 1907 leveling on the 1914 survey between Pacoima and Mojave (fig. 16), we have assumed that the 1907 height differences over the main line between Pacoima and Mojave matched those obtained from the 1914 leveling. Southward from Pacoima toward San Pedro, the hypothetical 1907 heights are assumed to converge more or less linearly with those

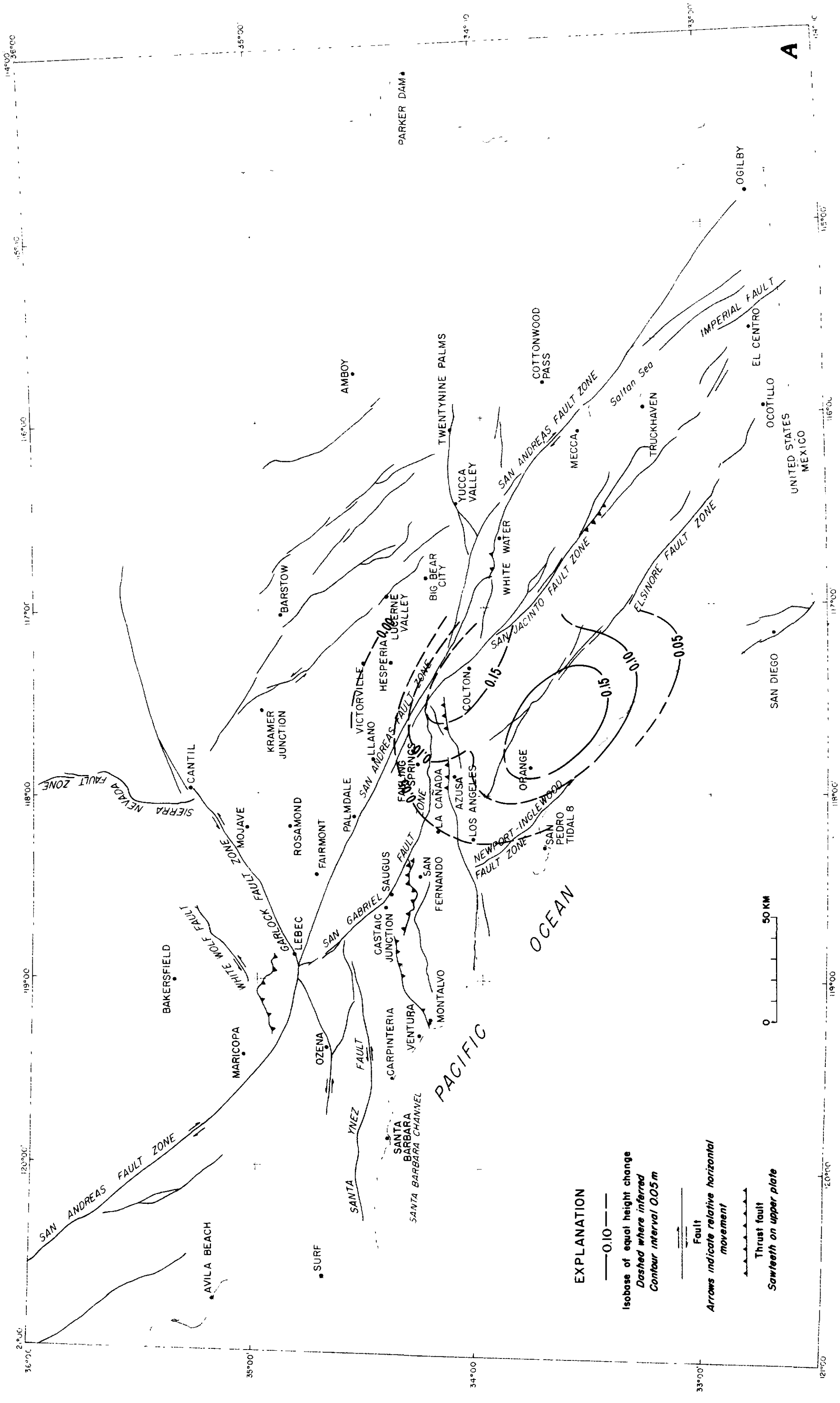

FIGURE 26.—Height changes with respect to bench mark Tidal 8 within area of the early-20th-century uplift, 1902–06.2. *A*, Interpretation based on the possibility that the uplift did not extend north of Hesperia. *B*, Interpretation based on the likelihood that the first major pulse of uplift had occurred by 1906.2 (see text for details).

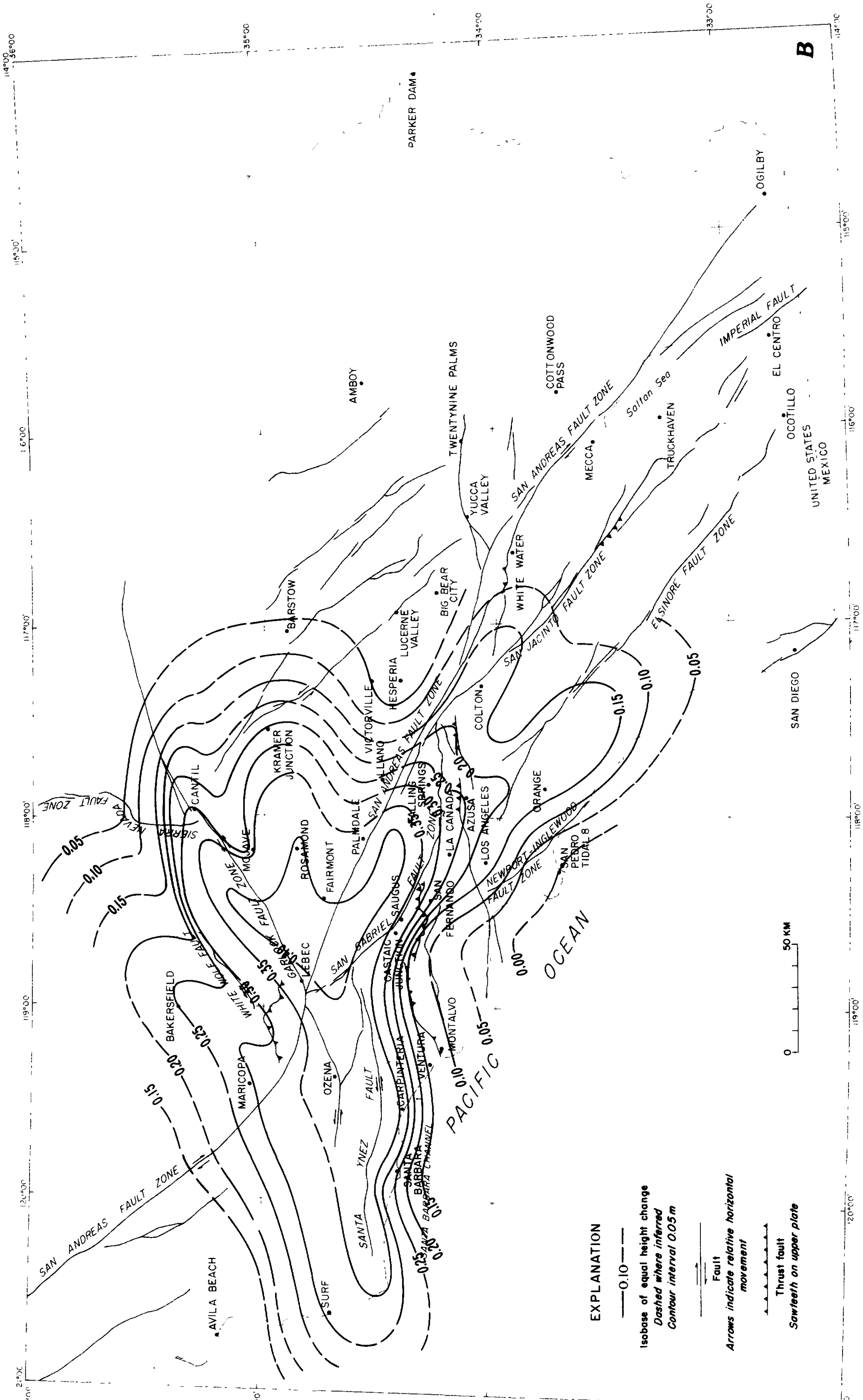

FIGURE 26.—Continued

developed from the 1914 survey. Similarly, northward from Mojave, the two heights are assumed to converge toward Bakersfield to about half the discrepancy at Mojave. This clearly subjective procedure probably errs on the conservative side because the misclosure shown in figure 16 indicates that we could just as reasonably have assumed that the uplift disclosed by the 1914 survey was all over by the end of 1906.

Both westward and eastward from the main line between San Pedro and Bakersfield (pl. 5), our characterization of the pre-1907 uplift is much less certain. The position of the 0.15-m contour west-northwestward from Los Angeles (fig. 26*B*) is constrained by the 1897/1900–20 uplift at Santa Susana and the likelihood that the apparent uplift at Moorpark probably is attributable to bench-mark disturbance (pl. 5). Similarly, because the alternative reconstruction along the Ventura-Cuyama spur indicates that Cuyama sustained cumulative uplift of at least 0.30 m during the period 1900/01–34/35 (pl. 4), the 0.30-m contour probably lies south of the Cuyama mark. This is a likely and certainly conservative interpretation, even allowing for the poor quality of the 1900/01 leveling along this line, simply because this cumulative figure is based on postcollapse leveling. Our provisional characterization of the pre-1907 uplift (fig. 26*B*), moreover, is based on the postulated pre-1907 uplift of Barstow of 0.05–0.10 m. This interpretation depends on the +0.0932-m misclosure around the easterly circuit shown in figure 16, produced through substitution of the results of the 1914 leveling for the 1897/1902 survey between San Pedro and Mojave or the +0.0354-m misclosure where, in addition, the 12/1906 leveling between Mojave and Barstow is replaced by the results of the 1907 leveling via Freeman Junction (fig. 17). That is, these +0.0932-m or +0.0354-m misclosures would be reduced to virtually zero if the 1902–07.0 tilt between Barstow and Mojave had been accompanied by 0.05–0.10 m of uplift at Barstow.

Our basic characterization of the pre-1907 uplift through the western Transverse Ranges (fig. 26*B*) is based on the results of the 1920 leveling between Oxnard and Guadalupe (pl. 4), where we have assumed that the signal developed during the period 1901/03/04–20 accumulated entirely within the period 1902–07.0. Although we have no independent evidence that supports this deformational chronology, the magnitude of the uplift that had occurred by 1907 along the San Pedro-Bakersfield line (pl. 5) indicates that it is very unlikely that the western Transverse Ranges remained free of major uplift during the period 1902–07.0. Accordingly, because we are unable to clearly identify that fraction of the 1901/03/04–20 uplift along the Oxnard-Guadalupe line that had occurred by 1907.0, we have arbitrarily assumed that the entire uplift occurred sometime before 1907.

Although abundant evidence argues convincingly that the first of the two major episodes of uplift that define the early-20th-century uplift occurred sometime before 1907 (pl. 5; figs. 16, 17), we are much less confident of how much in advance of 1907 this episode actually occurred, even though it was almost certainly bracketed within the period 1905.2–07.0 (see subsection above entitled "The San Pedro-Bakersfield Line"). That is, although we have already shown that the signal defined by the 1906 leveling between San Diego and Barstow almost certainly occurred no later than 1906.2, this evidence does not in itself demonstrate that the uplift north and west of the San Diego-Barstow line occurred this early. Because it is very unlikely that any significant vertical displacement occurred along the San Diego-Barstow line between the initiation of the 1906 survey at San Diego and its completion into Barstow, a determination of the stability of Barstow between June 7, 1906, and the beginning of 1907 could further constrain the period during which this first large spasm of uplift actually occurred.

The clearest evidence that Barstow in fact remained invariant in height between June and December of 1906 can be obtained from the results of a combination of 1906/07 and 1909 first-order levelings propagated eastward from Barstow into a tectonically stable section of southwestern Arizona. The 1906/07 leveling was begun in Barstow on December 13, 1906, and extended eastward to Goffs, Calif., where it junctioned with 1909 leveling between Goffs and Albuquerque, N.Mex. (Bowie and Avers, 1914, p. 35, 41). The results of these surveys can be used to generate a "1906" height for a representative mark along the Bill Williams River, Ariz., for which we have obtained four successive and independently established heights (fig. 27*A*). These four heights define a trend that closely matches the negative sea-level trend at San Diego with respect to San Pedro (fig. 27*B*). In other words, because the San Diego tide station can be shown to have remained virtually invariant during recent geologic time (Castle and Vaníček, 1980, p. 291–292), the close match between these two trends reinforces the conclusion that bench mark 22Q has, indeed, remained invariant with respect to some fixed datum (such as the reference ellipsoid or a geoid of stipulated date). Since the 1906 height falls almost precisely on trend (fig. 27*A*), the starting height at Barstow probably remained unchanged during the period 1906.2–07.0. Moreover, if allowance is made for the fact that the leveling between Goffs and 22Q extended over several decades (Gilmore and Elliott, 1985), the mean date of the "1906" leveling into bench mark 22Q would fall somewhere between 1910 and 1915, which would put the "1906" height even closer to its predicted position. That is, if Barstow had risen 0.05–0.10 m between March and December 1906, the height difference between Barstow and 22Q would have been increased by a corresponding value, and the 1906 heights would have plotted someplace in the range 186.5000–186.5500 m—rather than 186.6173 m. Thus, the measured 1906 height for bench mark 22Q supports the conclusion that the first major pulse of uplift in the evolution of the early-20th-century uplift had occurred by 1906.2. The only alternative explanation for what is actually observed at 22Q (fig. 27*A*) is that Barstow lay outside the area affected by this major event in the history of the uplift—an explanation that strikes us as unrealistically contrived.

THE 1902–07.0 EPOCH

If the representation shown in figure 26*A* actually occurred as a discrete event that preceded the first major pulse of uplift, the uplift that occurred during the expanded period 1902–07.0 probably differed only in detail from that shown in figure 26*B*. That is, we are virtually certain that the first major event involved in the growth of the early-20th-century uplift must have occurred by the end of 1906 and thus that the rationale on which we have based the cumulative uplift through 1907.0 (fig. 28) must be nearly identical to that used in the alternative reconstruction of the uplift through 1906.2 (fig. 26*B*).

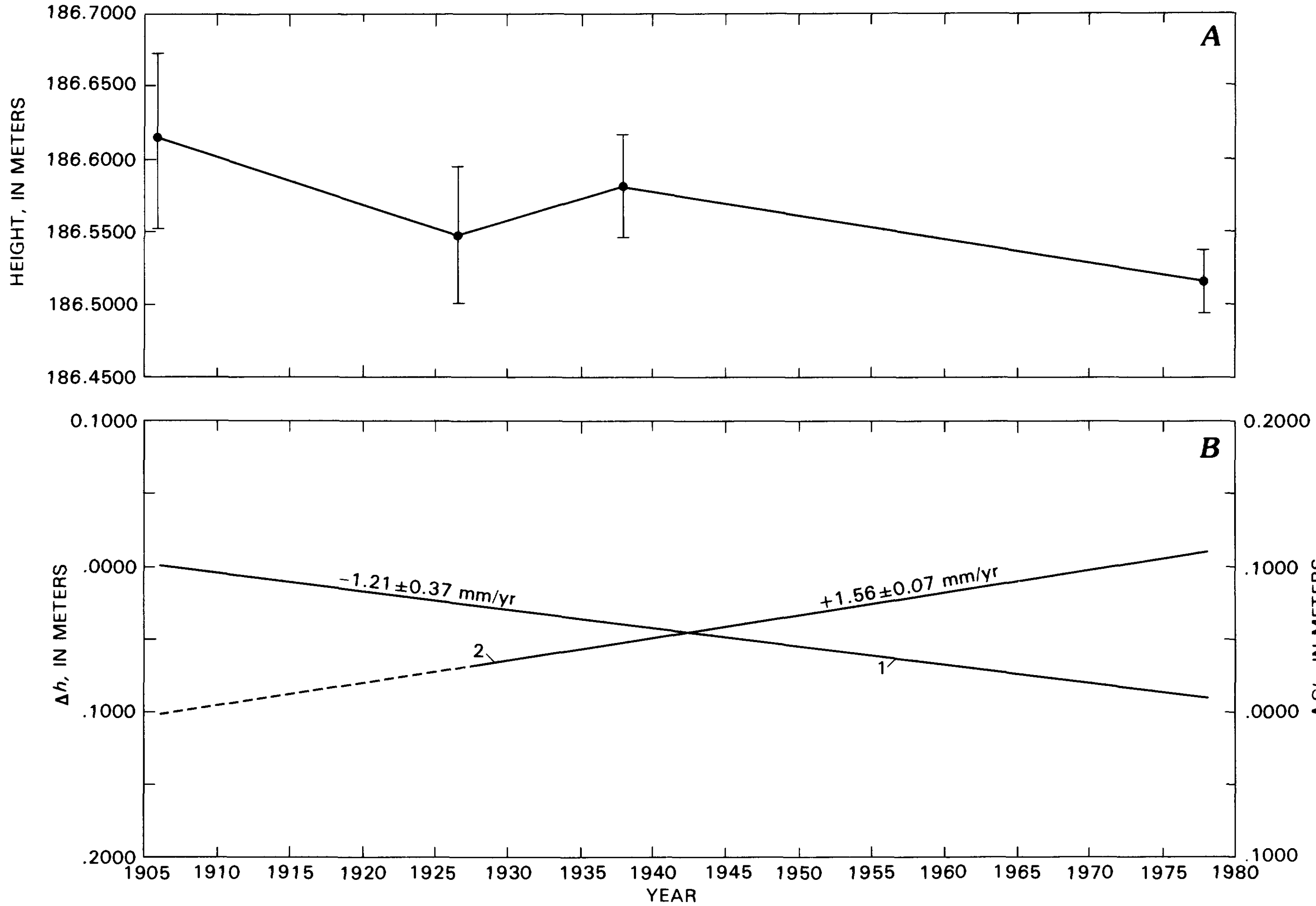

FIGURE 27.—Comparison between height changes for a representative bench mark (22Q) within a tectonically stable area and sea-level changes at San Diego, both with respect to the San Pedro tide station. *A*, Changes in orthometric height at bench mark 22Q, Bill Williams River, Ariz., with respect to bench mark Tidal 8, San Pedro. Error bars show conventionally estimated random error only. *B*, (1) Weighted, least-squares linear regression through points in figure 27*A*, showing average change in height (Δh) at bench mark 22Q with respect to Tidal 8, San Pedro, during the period 1906–78. (2) Sea-level trend (ΔSL) at the Municipal Pier tide station, San Diego, with respect to San Pedro during the period 1906–78; dashed line shows extrapolation backward in time before occupation of the Municipal Pier tide station. Data from Gilmore and Elliott (1985) and figures 3 and 4.

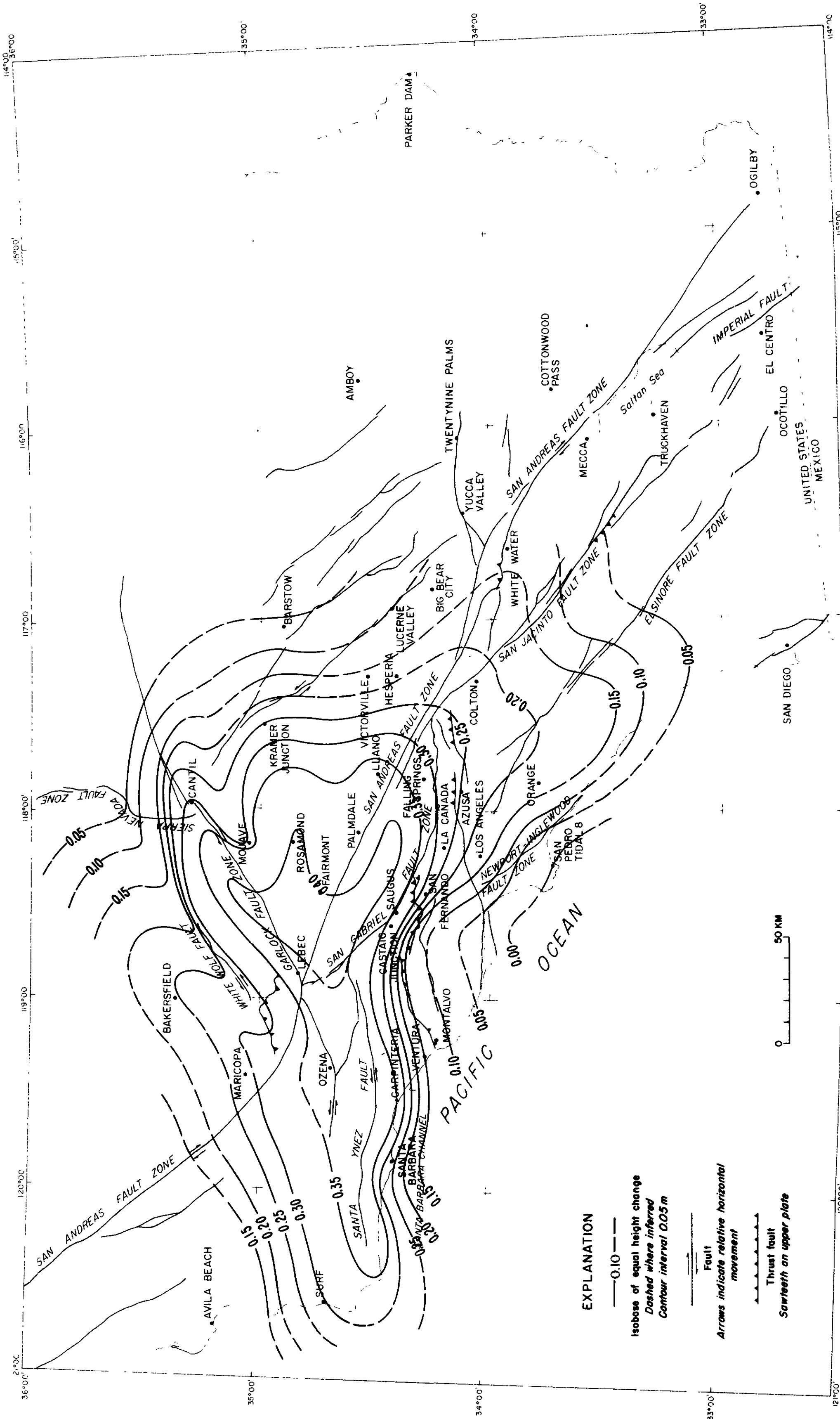

FIGURE 28.—Height changes with respect to bench mark Tidal 8 within area of the early-20th-century uplift, 1902–07.0.

If the first major pulse of uplift did not occur by 1906.2 but was, instead, delayed until 1907.0, the difference between the uplift that occurred during the period 1902–07.0 and that which we show in our alternative representation of uplift during the period 1902–06.2 (fig. 26*B*) clearly was minimal. The chief difference—in fact, the only place where we see any basis for significant modification—is along the southeast flank of the uplift. The extreme south flank of the 1902–07.0 uplift between San Diego and Santa Ana (fig. 28) is assumed to match that which obtained in 1906.2. However, owing to the major surge of deformation that is postulated here to have occurred after 1906.2, we have eliminated the trough between the lobes in the 1902–06.2 uplift (fig. 26*A*) and infer a more or less uniformly diminishing uplift between Victorville and Barstow.

THE 1902–24.0 EPOCH

Cumulative uplift through 1924.0 may have either closely approximated that which had developed by as early as 1907.0 (fig. 28) or propagated significantly eastward. Because we have no objective basis for choosing between these two possibilities, both are shown here (fig. 29).

The cumulative uplift through the period 1902–24.0 shown in the first of these two interpretations (fig. 29*A*) differs only in detail from that which is believed to have occurred by 1907.0 eastward from the area between Ventura and Maricopa, whereas the two interpretations are identical west of the line between these two communities. The only significant differences between figures 28 and 29*A* derive from the results of the 1914 leveling along the full length of the San Pedro-Bakersfield line, a comparison between the results of the 1897 and 1923/24 levelings along the Los Angeles-Riverside line, and the results of various surveys along the San Diego-Barstow line and the San Diego-Arlington line (pls. 5, 6*A*, 7, 8).

The 1902–24.0 uplift along the San Pedro-Bakersfield line is based on a comparison of the results of the 1914 leveling against the 1897/1902 datum, coupled with an assumption of invariance between 1914 and 1924. The effect of this procedure is to increase the amplitude of the maximum signal along this line by only about 0.05 m over that which had developed by 1907.0 (figs. 28, 29*A*). Because there were no post-1907 precollapse surveys along the Mojave-Olancha spur (pl. 5), we have simply increased the 1905–07.0 signal uniformly southward from the 0.05-m contour (fig. 28) to bring it into conformity with the 1897/1902–14 uplift at Mojave. The magnitude of the 1897–1923/24 uplift increased sharply eastward from Los Angeles to Ontario and Riverside to nearly 0.4 m (pl. 6*A*), an observation that tightly constrains the position of the 0.35-m contour (fig. 29*A*). We cannot be sure, of course, that this signal (pl. 6*A*) had not developed entirely by 1907.0, and can only state that it could have occurred no later than 1923/24. The 1902–24.0 signal along the San Diego-Barstow line (pl. 7) is based on a direct comparison against the 1897/98/99 datum over the reach between Corona and Victorville, where the spike at Victorville is interpreted as the product of a disturbed mark. Northward from Victorville, the magnitude of the 1902–24.0 uplift is based on a direct comparison against the 1906 datum (pl. 7), chiefly because the 1897/98/99 and 1906 heights tend to converge near Victorville. Because the 1897/98/99–1924, 1897/98/99–1932/33, and 1897/98/99–1933/34 signals converge southward toward Corona (pl. 7), we assume that the 1932/33 heights nearly matched those that would have been produced through a continuation of the 1924 leveling southward into San Diego—even though the comparison against the 1906 datum (pl. 7) suggests that the 1924 heights may have been somewhat greater. The chief contribution of the reconstructed height changes along the San Diego-Arlington line (pl. 8) to the characterization of the 1902–24.0 uplift shown here (fig. 29*A*) is in the confirmation of the 1906–32/33 height changes along the San Diego-Barstow line (pl. 7). Because the observed elevations that define the San Diego-Arlington datum probably exaggerate the actual 1897/98 elevation differences (see subsection above entitled "The San Diego-Arlington Line"), the reconstructed uplift along this line probably represents a lower limit. Moreover, the 1927/35 comparative leveling may have postdated the collapse of the uplift in this area.

The alternative interpretation of the 1902–24.0 uplift (fig. 29*B*) is compelled by our ignorance of the chronology of uplift along the Colton-Mecca line (pl. 9). Although there are mechanical reasons for favoring the preceding interpretation (fig. 29*A*)—which assumes that major uplift along the Colton-Mecca line postdated the partial collapse of the western lobe—we lack even a clue as to when within the period 1902–28 this uplift actually occurred (pl. 9). Although it seems very unlikely, we cannot even be certain that this uplift had not occurred as early as the middle of 1906. Because the 1931 and 1934 levelings approximately corroborated the 1928 results (pl. 9), the only significant chronologic generalization that can be made is that uplift along the Colton-Mecca line apparently persisted beyond 1928. If we accept the likelihood that the 1902–28 signal along the Colton-Mecca line had, in fact, occurred by 1924.0, the chief consequence of this interpretation is to force a reentrant of the 0.25-m contour along the north flank of the uplift and the creation of a major saddle between the eastern and western lobes (fig. 29*B*).

THE 1902–28.0 EPOCH

The height changes that occurred within the area of the early-20th-century uplift between 1924.0 and 1928.0 are deduced largely from the results of the 1925/26 leveling

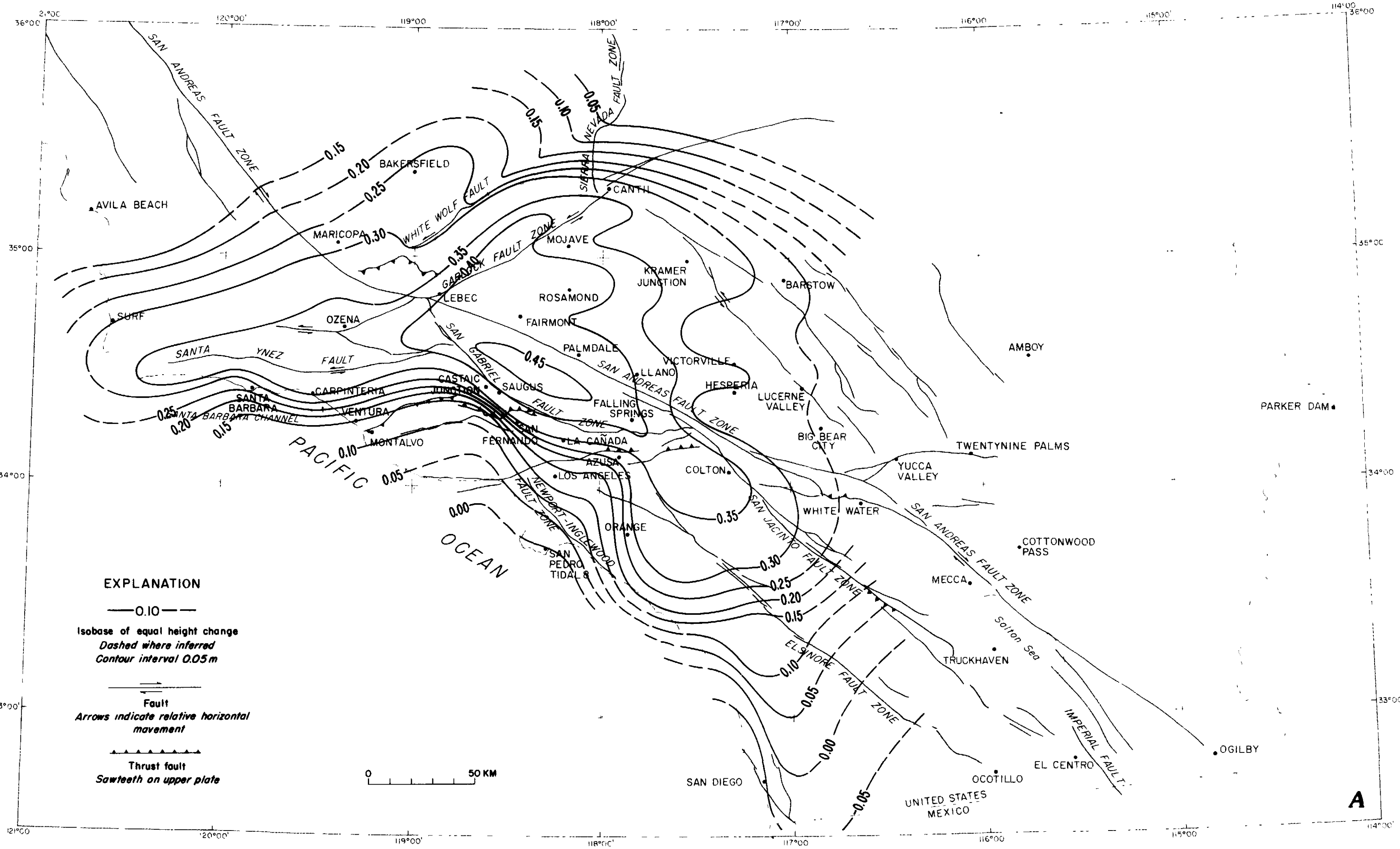

FIGURE 29.—Height changes with respect to bench mark Tidal 8 within area of the early-20th-century uplift, 1902–24.0. *A*, Interpretation based on a presumption of relatively modest height changes since 1907.0 (fig. 28). *B*, Interpretation based on the possibility that the uplift had propagated significantly eastward by 1924.0 (see text for details).

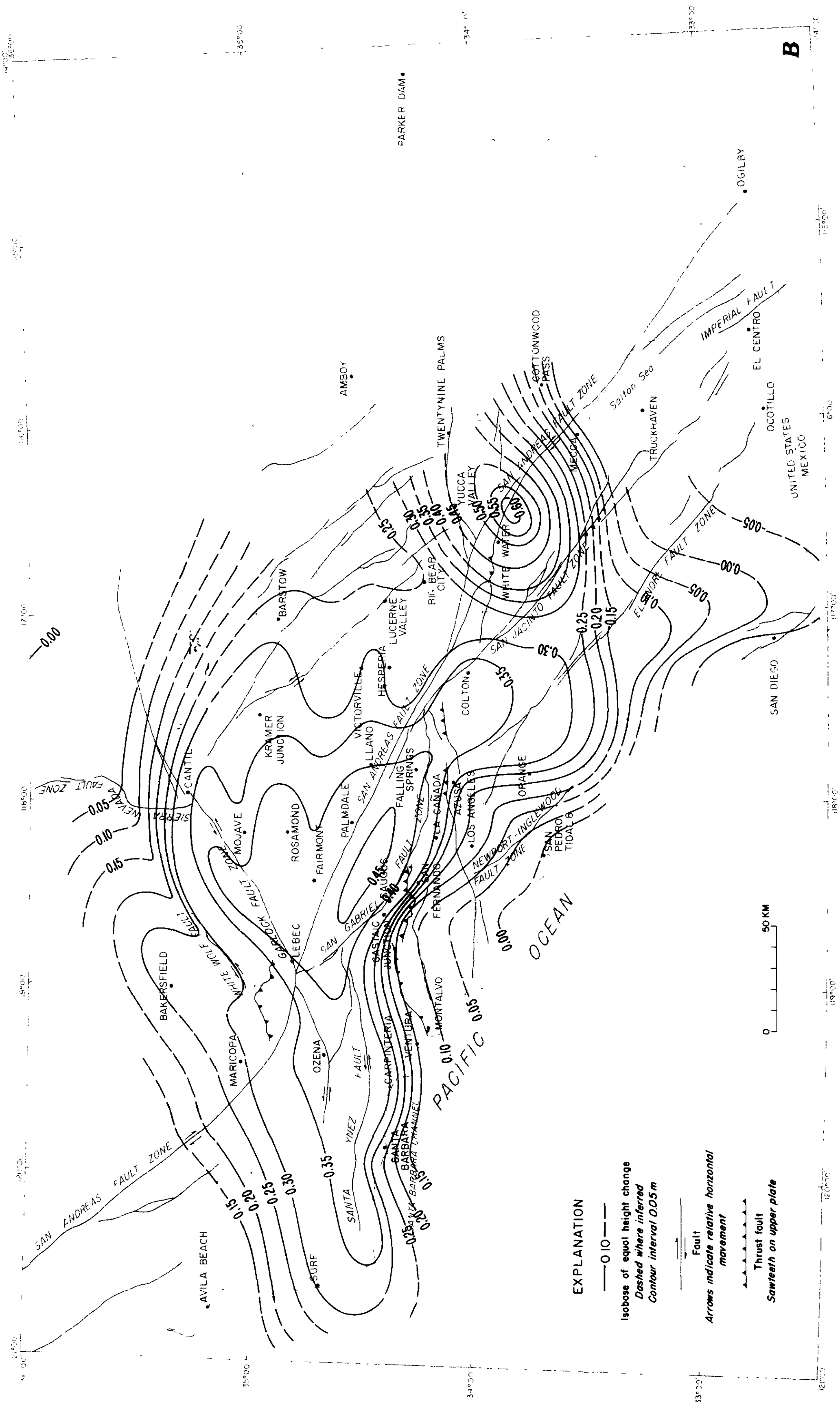

Figure 29.—Continued

along the San Pedro-Bakersfield line (pl. 5) and the alternative reconstruction of the 1906–27/28 height changes along the Mojave-Barstow line (pl. 6*B*). Discounting the possibility or even the probability that the 1902–28 signal along the Colton-Mecca line developed within the period 1924.0–28.0, the pervasive, partial collapse of the uplift northward from San Fernando (compare figs. 29 and 30) constitutes the most striking and certainly the most clearly defined change during this period. This collapse, which must have occurred over much of the central part of the uplift, does not seem to be associated with any known structure, and the rate at which it developed matched that associated with the first major spasm of uplift.

Elsewhere, changes in the configuration of the early-20th-century uplift during the period 1924.0–28.0 are based largely on sketchy, indirect, and commonly equivocal evidence. A misclosure around a first-order circuit involving Gaviota and Edna (approx 10 km east of Avila Beach) indicates that Gaviota subsided about 0.12 m with respect to Edna during the period 1920–27 (NGS lines 74203, 82725). If we assume that Edna remained invariant with respect to Tidal 8 during the period 1920–27, we can simply prorate this collapse eastward toward Ventura. Similarly, we can further assume that the coastal reach northward toward Surf sustained subsidence comparable to that which occurred at Gaviota. Although these several assumptions are obviously suspect, Edna lies well north of the area of recognized activity associated with the early-20th-century uplift, and it is unlikely that the western Transverse Ranges could have totally escaped the major collapse that occurred within the more central part of the uplift (pl. 5). Furthermore, the alternative reconstruction of height changes along the Ventura-Cuyama spur (pl. 4) is certainly suggestive of major tectonic subsidence by no later than 1934/35. Accordingly, if the residual uplift defined by the 1934–35 leveling is the same as that which would have been produced by 1928 leveling, it is likely that the 1902–28.0 residual uplift west of the San Pedro-Bakersfield line approximately matched that shown in figure 30.

Rapid collapse along the line between Mojave and Barstow is most clearly shown by the misclosure around the 1923/24/26/27/28 circuit Los Angeles-Saugus-Mojave-Barstow-Riverside-Los Angeles (fig. 18), which indicates that Barstow subsided 0.3140 m with respect to Los Angeles between 1923/24 and the end of 1927. However, because central Los Angeles may have risen slightly with respect to Tidal 8 between 1920 and 1926 (pl. 5), the subsidence of Barstow during the period 1923/24–27 probably was somewhat less than 0.3140 m. Moreover, because the 1906–27/28 signal between Mojave and Barstow was relatively uniform (pl. 6*B*), we have assumed that the collapse increased more or less uniformly eastward from Mojave (fig. 30). Eastward from Los Angeles, the uplift apparently increased between 1923/24 and 1931/32 to a maximum of about 0.44 m at Ontario and Riverside (pl. 6*A*). We assume here that this modest increase had occurred by 1928.0, although we have discovered no corroborative evidence that supports this assumption. Southward toward San Diego from Orange, the residual uplift is presumed to have remained the same as that which obtained in 1924 (fig. 29)—which is based, in turn, on 1932/33 and 1927/35 levelings along the San Diego-Barstow and San Diego-Arlington lines (pls. 7, 8).

THE 1902–34.0 EPOCH

The chief change in the early-20th-century uplift that is believed to have occurred between 1928.0 and 1934.0 was localized in the area centering on Bakersfield (compare figs. 30 and 31). However, the control on the height changes that occurred in this area between 1926 and 1934.0 (and which are assumed to have occurred no earlier than 1928.0) extends only as far southward as Bakersfield, and we are forced to infer that the difference between the 1902–28.0 (fig. 30) and 1902–34.0 (fig. 31) configurations diminishes to insignificance about halfway between Bakersfield and Mojave.

Evidence that the area extending north-northwestward from Bakersfield sustained major collapse between 1926 and 1931 is drawn from a comparison between the results of 1902 and 1931 levelings between Bakersfield and Chowchilla, about 250 km north-northwest of Bakersfield (Castle and Elliott, 1982, p. 7002–7003, 7011). Because this evidence of surprisingly large tectonic subsidence is based on an assumption of invariance at Chowchilla (whether with respect to Tidal 8 or any other control point) through the period 1902–31, it clearly errs in detail. In fact, Chowchilla probably sustained uplift with respect to Tidal 8 of 1–3 mm/yr during this period (Castle and Elliott, 1982, p. 7003). Acceptance of the larger value (3 mm/yr) limits the 1926–31 tectonic subsidence of Bakersfield with respect to Tidal 8 to less than 0.35 m, a value that we have adopted in the reconstruction shown here (fig. 31).

Elsewhere within the area of the early-20th-century uplift, any height changes between 1928.0 and 1934.0 probably were relatively modest. Because the uplift over the area extending southward into the Peninsular Ranges and eastward from Los Angeles to Riverside is based on the results of the 1932/33 and 1933/34 levelings, respectively (pls. 6*A*, 7), the indicated signals probably form a fairly accurate characterization of the residual uplift in those areas through 1933. The eastern lobe of the uplift along the Colton-Mecca line (pl. 9) apparently steepened somewhat along the south flank and spread out along its crest sometime between 1928 and 1931. However, the 1931 control ends well north of Mecca, and we have made

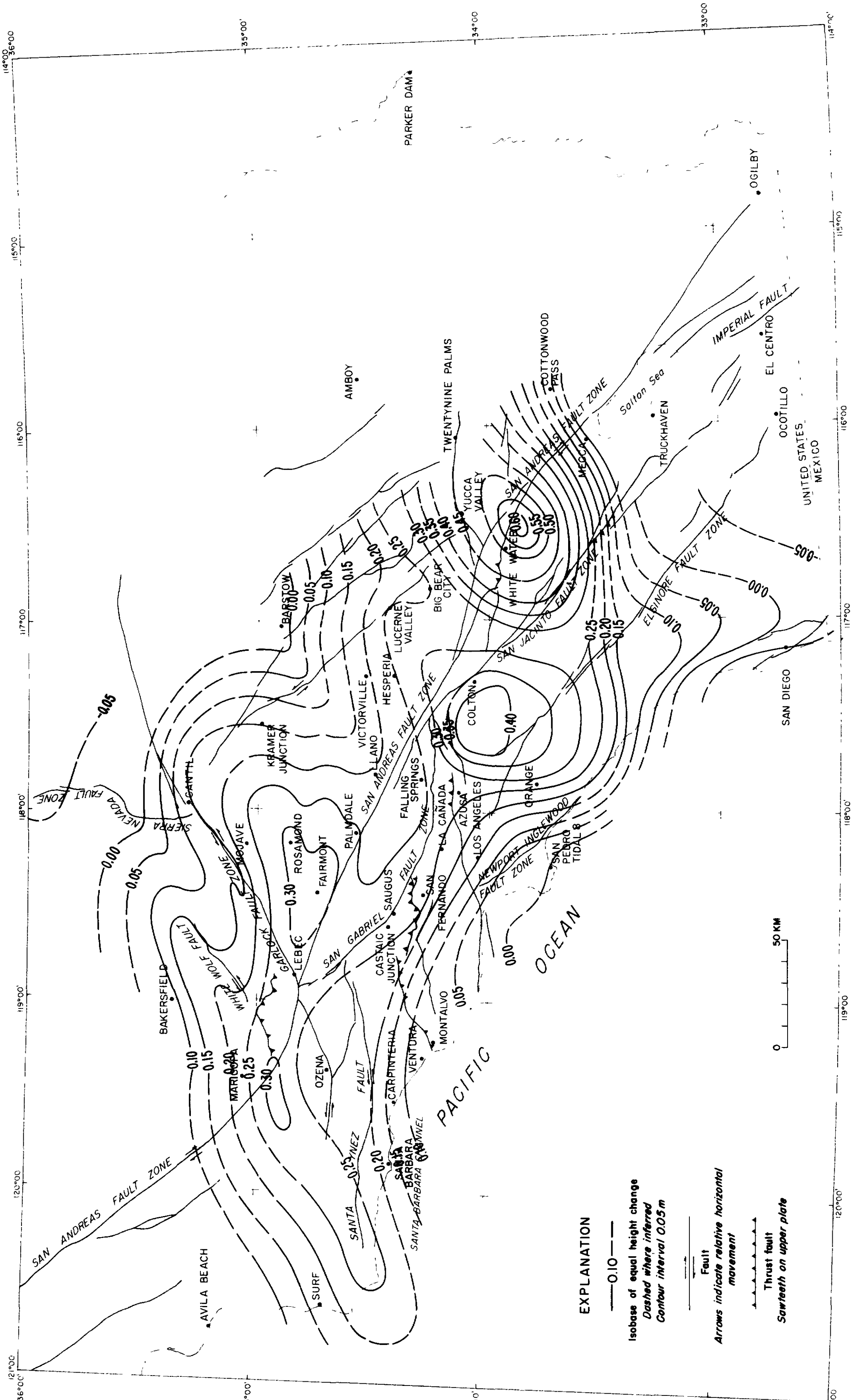

FIGURE 30.—Height changes with respect to bench mark Tidal 8 within area of the early-20th-century uplift, 1902–28.0.

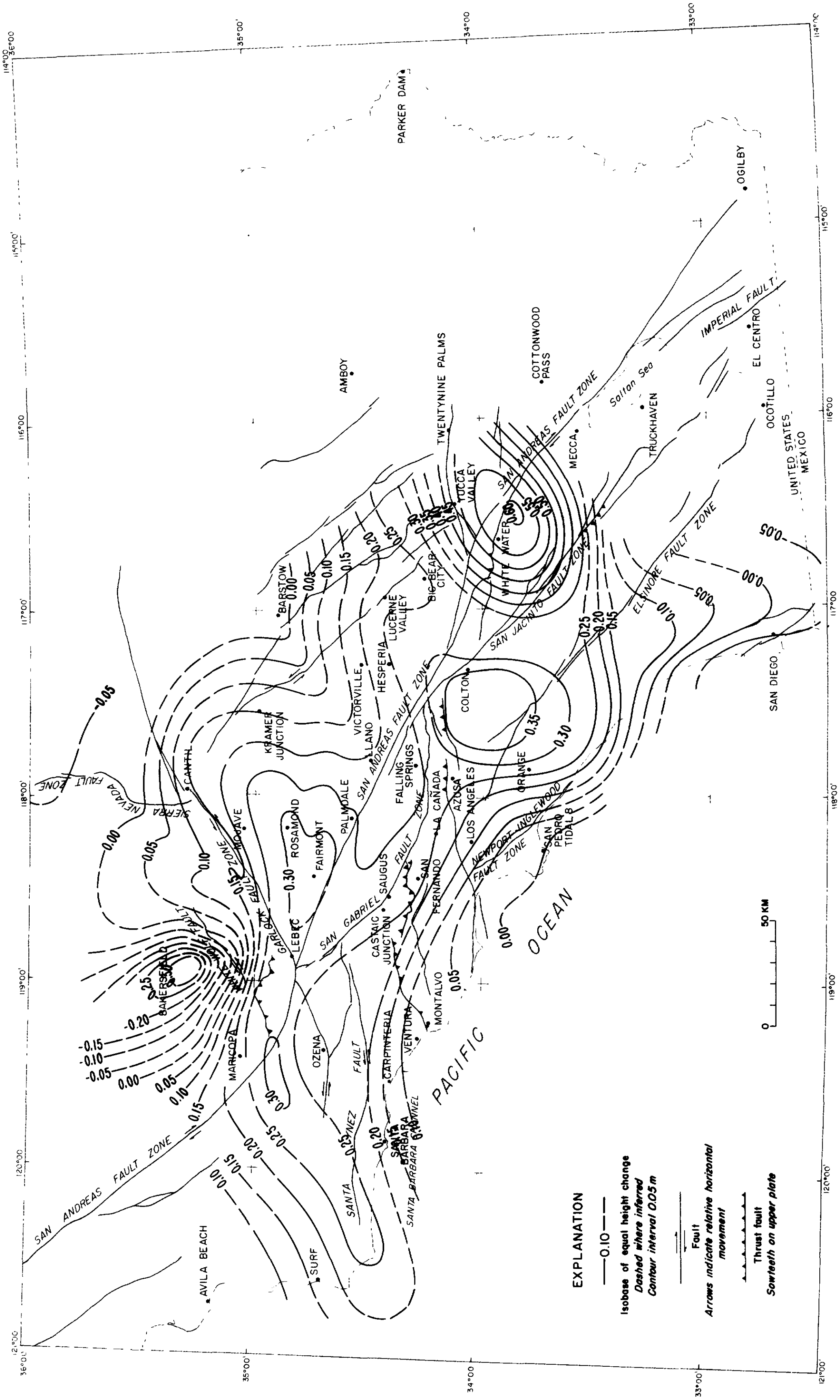

FIGURE 31.—Height changes with respect to bench mark Tidal 8 within area of the early-20th-century uplift, 1902–34.0.

TABLE 3.—*Earthquakes of magnitude 5 or greater that occurred within southern California and adjacent parts of northern Mexico during the period 1902.0–36.0 within the latitude range 32.000–36.000° N.*

[Modified from Real and others (1978). See plate 10 for locations of epicenters]

Location		Date	Magnitude
Latitude (° N.)	Longitude (° W.)		
32.000	114.750	12/31/1934	7.1
32.000	115.000	11/21/1915	7.1
32.083	116.667	11/25/1934	5.0
32.250	115.500	12/30/1934	6.5
32.500	115.500	04/19/1906	6.0
32.500	115.500	05/01/1918	5.0
32.500	115.500	09/08/1921	5.0
32.500	115.500	11/05/1923	5.0
32.500	115.500	11/07/1923	5.5
32.500	115.500	01/01/1927	5.7
32.500	115.500	01/01/1927	5.5
32.800	115.300	05/28/1917	5.5
32.800	115.500	06/23/1915	6.2
32.800	115.500	06/23/1915	6.2
32.900	115.217	10/11/1935	5.0
32.900	115.700	10/02/1928	5.0
33.000	115.500	02/26/1930	5.0
33.167	115.500	12/20/1935	5.0
33.200	116.700	01/01/1920	5.0
33.500	116.500	09/30/1916	5.0
33.575	117.983	03/11/1933	5.2
33.617	117.967	03/11/1933	6.3
33.617	118.017	03/14/1933	5.1
33.683	118.050	03/11/1933	5.5
33.700	117.400	04/11/1910	5.0
33.700	117.400	05/13/1910	5.0
33.700	117.400	05/15/1910	6.0
33.700	118.067	03/11/1933	5.1
33.700	118.067	03/11/1933	5.1
33.750	117.000	04/21/1918	6.8
33.750	117.000	06/06/1918	5.0
33.750	118.083	03/11/1933	5.1
33.750	118.083	03/11/1933	5.1
33.750	118.038	03/11/1933	5.0
33.750	118.038	03/11/1933	5.0
33.750	118.083	03/13/1933	5.3
33.783	118.133	10/02/1933	5.4
33.850	118.267	03/11/1933	5.0
33.950	118.632	08/31/1930	5.2
34.000	116.000	04/03/1926	5.5
34.000	116.000	09/05/1928	5.0
34.000	117.250	07/23/1923	6.2
34.000	118.500	08/04/1927	5.0
34.000	119.500	02/18/1926	5.0
34.100	116.800	10/24/1935	5.1
34.180	116.920	01/16/1930	5.2
34.180	116.920	01/16/1930	5.1
34.200	117.100	09/20/1907	6.0
34.200	119.800	06/29/1925	6.2
34.500	119.500	06/29/1926	5.5
34.500	119.500	08/05/1930	5.0
34.700	119.000	10/23/1916	5.5
34.700	120.300	07/31/1902	5.5
34.700	120.300	01/12/1915	5.5
34.830	116.520	09/26/1929	5.1
34.900	118.900	10/23/1916	6.0
34.900	120.700	11/04/1927	7.5
35.000	119.000	02/16/1919	5.0
35.300	118.800	12/23/1905	5.0
35.500	118.700	01/06/1905	5.0
35.600	118.800	06/30/1926	5.0
35.750	120.250	03/10/1922	6.5
35.750	120.330	08/18/1922	5.0
35.800	120.330	06/05/1934	5.0
35.800	120.330	06/08/1934	6.0
35.800	120.330	06/08/1934	5.0
35.930	120.480	12/24/1934	5.0
36.000	117.000	11/04/1908	6.5
36.000	117.000	11/10/1916	5.5

no attempt to show the configuration of the 1902–34.0 uplift southeastward beyond the end of the 1931 survey (fig. 31). Finally, because we have no basis for assessing any height changes within the Transverse Ranges during the period 1928–34.0, other than those in the immediate area of Bakersfield, the residual uplift shown here (fig. 31) is otherwise the same as that shown in figure 30.

SEISMICITY ASSOCIATED WITH THE EARLY-20TH-CENTURY UPLIFT

Owing to the relatively rapid growth and subsequent collapse of the early-20th-century uplift, we have compared its evolution with the contemporary seismicity to assess their association in both space and time. The instrumental control on the earthquakes that occurred during this period was obviously limited, such that their locations and magnitudes are relatively inaccurate. Accordingly, our examination of the data is correspondingly constrained, and we have arbitrarily restricted this comparison to shocks of magnitude 5.0 and greater (pl. 10; table 3).

Surprisingly, there seems to be a much clearer association between the growth and subsequent collapse of the early-20th-century uplift and the contemporary seismicity than could be detected in comparing the evolution of the modern uplift against the seismicity that accompanied its growth (Castle and others, 1984). Specifically, several relatively large shocks either immediately preceded or closely accompanied the major pulse of uplift, which apparently occurred sometime between early spring 1905 and the following winter. The 1906 magnitude 6.0 earthquake south of El Centro (lat 32.500° N., long 115.500° W.), the 1907 magnitude 6.0 shock north of Colton (lat 34.200° N., long 117.100° W.), and the 1908 magnitude 6.5 earthquake north-northeast of Avila Beach (lat 36.000° N., long 117.000° W.) were among the largest shocks recognized within or around the area of the southern California uplift through the entire period 1902.0–36.0 (pl. 10; table 3). All of these earthquakes, however, were closely associated in time with the first major spasm of uplift. Similarly, several large shocks occurred within the period that we identify with the culmination of the uplift; these events include the 1910 magnitude 6.0 earthquake along the Elsinore fault zone (lat 33.700° N., long 117.400° W.), the almost precisely coincident 1915 magnitude 6.2 earthquakes near El Centro (lat 32.800° N., long 115.500° W.), the 1916 magnitude 6.0 earthquake near Lebec (lat 34.900° N., long 118.900° W.), and the 1918 magnitude 6.8 earthquake along the San Jacinto fault (lat 33.750° N., long 117.000° W.) (pl. 10; table 3). Moreover, two fairly large shocks were recorded in this area during the period that just preceded or accompanied the collapse of the western lobe of the uplift—the 1922 magnitude 6.5 earthquake north-northeast of Avila Beach (lat 35.750° N., long 120.250° W.) and the 1923 magnitude 6.2 shock near Colton (lat 34.000° N., long 117.250° W.).

Several relatively large earthquakes closely followed the collapse (or at least the inception of the collapse) of the west half of the early-20th-century uplift. These events include the 1925 magnitude 6.2 Santa Barbara earthquake (lat 34.200° N., long 119.800° W.), the 1927 magnitude 7.5 Point Arguello earthquake (lat 34.900° N., long 120.700° W.), the 1933 magnitude 6.3 Long Beach earthquake (lat 33.617° N., long 117.967° W.), the 1934 magnitude 6.5 and 7.1 shocks south of El Centro (lat 32.250° N., long 115.500° W., and lat 32.000° N., long 114.750° W., respectively), and the 1934 magnitude 6.0 earthquake along the San Andreas north-northeast of Avila Beach (lat 35.800° N., long 120.330° W.). Although none of these shocks can be associated with a particular phase of the collapse, they represent a collectively large fraction of the total seismic energy released within this area during the period 1902.0–36.0 (table 3).

The most intriguing association between the evolution of the early-20th-century uplift and contemporary earthquake activity is with an earthquake that occurred well north of the study area—the April 18, 1906, San Francisco earthquake on the San Andreas fault. This magnitude 8.2 shock (Real and others, 1978) closely followed the large spasm of uplift that is believed to have occurred between March 1905 and the following February. Coincidentally, moreover, the 1906 magnitude 6.0 shock about 35 km south of El Centro (see above) followed the great San Francisco earthquake by only about 10 hours (Real and others, 1978). The close temporal association between the San Francisco earthquake and the first major episode of uplift over much of the area of the early-20th-century uplift may be nothing more than the product of chance. However, these two events may be mechanically related in some as yet poorly understood way.

CONCLUSION

The existence of an early-20th-century uplift that compares closely with its modern counterpart in terms of distribution, magnitude, and history indicates that a vast area centering on the Transverse Ranges of southern California has sustained more or less cyclic deformation through at least a fraction of late Quaternary time. Our characterization of the changing configuration of the early uplift obviously is much more poorly controlled than that developed for the modern uplift over the same area. Moreover, the accuracy of the leveling that defines the early-20th-century uplift is certainly below that used in the reconstruction of the later uplift (Castle and others, 1984). Surprisingly, however (and with several explicitly noted exceptions), analysis of a series of misclosures and other evidence indicate that the accuracy of these earlier surveys was remarkably high. In any case, the likelihood that the early-20th-century-uplift and its subsequent collapse may be artifacts of the measurement system is no greater than the likelihood that its modern analog can be similarly regarded. Were we to suggest that this earlier uplift was unreal and, in fact, the product of slope- or height-dependent error, it would require that the baseline measurements were characterized by uniformly negative errors (associated, for example, with uniformly long rods) and that the surveys that defined the uplift were identified with uniformly positive errors (associated, for example, with uniformly short rods). In fact, the mix of rods, surveys of differing standards of accuracy, and a modest amount of redundancy combine to indicate that the surveys which permitted detection of the signals described in this report probably met generally high standards of accuracy.

The origin of this continuing and apparently cyclic uplift remains conjectural. We persist in believing, however, that it is somehow related to the recent and clearly complex evolution of the plate boundary projecting into and through southern California (Castle and others, 1984). Correlations with seismicity suggest that the growth of the uplift may have either triggered or been triggered by one or more moderate or major earthquakes, such as the 1906 San Francisco shock. Should this be so, it would suggest the occurrence of a tectonic event of varying expression extending over a plate-boundary distance well exceeding 1,000 km. Though difficult to accept, notions of this sort have now begun to achieve a degree of respectability that would have been unheard of only a few years ago.

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