The Evolution of the Southern California Uplift, 1955 Through 1976

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Landsat image showing cumulative uplift within the central part of the southern California uplift during the period 1959.0-74.5. Contour interval, 0.05 m, dashed where approximately located; hachures denote area of closed low.

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By ROBERT O. CASTLE, MICHAEL R. ELLIOT, JACK P. CHURCH, *and* SPENCER H. WOOD

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A description of the changing configuration of the southern California uplift from its inception to its partial collapse

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[Plates are in case]

THE EVOLUTION OF THE SOUTHERN CALIFORNIA UPLIFT, 1955 THROUGH 1976

By Robert O. Castle, Michael R. Elliot, Jack P. Church, and Spencer H. Wood

ABSTRACT

The southern California uplift culminated in 1974 as a 150-km-wide crustal swell that extended about 600 km eastward and east-southeastward from Point Arguello to the Colorado River and Salton Sea, respectively; it was characterized by remarkably uniform height changes between 1959 and 1974 of 0.30–0.35 m over at least half of its 60,000–70,000 km^2 area. At its zenith, the uplift included virtually the entire Transverse Ranges geologic province and parts of the Coast Ranges, San Joaquin Valley, Sierra Nevada, Basin and Range, Mojave Desert, Peninsular Ranges, and Salton Trough provinces. The alinement of the western part of the uplift closely paralleled the east-trending Transverse Ranges, whereas the southern flank of the eastern lobe roughly coincided with the west-northwest-trending San Andreas fault. The position and configuration of the uplift associate it with a singularly complex section of the boundary between the North American and Pacific plates that has certainly sustained major modification during the past 5 million years and probably during the past 1 million years.

Surface deformation can be categorized as tectonic or nontectonic. Nontectonic vertical displacements associated with the activities of man have overwhelmed natural compaction and areally significant soil expansion in the southern California area. Because tectonic displacements are implicitly defined as those that cannot be otherwise explained, those vertical movements that can be reasonably attributed to artificial processes have been subtracted from our reconstructed configurations of the uplift. Hence this reconstruction has necessarily included the assembly and evaluation of an enormous volume of data on oil-field operations, changes in ground-water levels, and measured subsidence (or rebound) associated with changes in the underground fluid regimen.

Measured changes in height at various stages in the evolution of the uplift have been based chiefly on first-order levelings carried out between 1953 and 1976. Exceptions to this generalization consist largely of the results of pre-1953 surveys through the western Transverse Ranges and the eastern Mojave Desert. Errors in measured height differences derive from blunders, systematic survey errors, random survey errors, improperly formulated orthometric corrections, and intrasurvey movement; the last of these has created the most serious problems encountered in our reconstruction of the basic data. A variety of independent tests indicate that survey error associated with the utilized levelings was generally small and fell largely within the predicted random-error range. Moreover, the redundancy and coherence displayed by the entire data set provide convincing evidence of survey accuracy and the virtual absence of height- and slope-dependent error in particular.

Our reconstructions of the changing configuration of the uplift derive chiefly from comparisons among sequentially developed observed elevations along the same route. Most of the observed elevations from which the vertical displacements were computed have been reconstructed with respect to bench mark Tidal 8, San Pedro, as invariant in height. Because the San Pedro tide station has been characterized by a history of modest relative uplift, vertical displacements referred to this station are biased slightly toward the appearance of subsidence. Where the observed elevations cannot be conveniently tied to Tidal 8, they have been referred to secondary control points whose history with respect to Tidal 8 can be independently established. Each of the lines of observed elevation changes provides, accordingly, a section athwart or along the axis of the uplift from which the changes in the configuration of the uplift can be roughly generalized. Because relatively few surveys were run in 1955, which we choose as a representative temporal datum, we have commonly incorporated the results of earlier or of somewhat later levelings as the equivalents of 1955 surveys. Although this procedure introduces a certain subjectivity, the probable equivalence between the results of these earlier or later surveys with those that would have been obtained had this leveling been carried out in 1955, usually can be independently tested. Wherever the calculated vertical displacements are based on comparisons between the results of levelings over different routes, the observed elevations have been orthometrically corrected to agree with those that would have been produced had each of these surveys been along the same route.

The growth of the southern California uplift consisted of two well-defined spasms of positive movement, the second of which was closely followed by partial collapse. Our reconstruction, although it clearly errs in detail, indicates that the uplift, together with marginal and apparently ephemeral tectonic subsidence, nucleated in the west-central Transverse Ranges near Ozena, sometime between the spring of 1959 and the spring of 1960. The uplift expanded rapidly eastward (and probably westward as well), and by the fall of 1961 much of the Transverse Ranges and the Mojave Desert at least as far east as Twentynine Palms had risen by as much as 0.25 m. Between 1962 and 1972 the area included by the initially developed (1959–61) uplift sustained additional but clearly decelerating uplift accompanied locally by oscillatory displacements. Between 1972/73 and 1974 a second crustal spasm extended the uplift eastward to the Colorado River and elevated much of the eastern Mojave Desert by values that equaled or exceeded those developed within the western lobe. Between 1974 and 1976, at least the central part of the uplift sustained partial collapse that nowhere amounted to less than 50 percent of the cumulative uplift since 1959. Whether this collapse affected the entire uplift is conjectural, but we now recognize well-defined evidence of major down-to-the-north tilting that must have occurred within the eastern part of the uplift at some time between 1974 and 1976.

Accumulating evidence indicates that nearly all the area included with the southern California uplift underwent similar uplift and partial collapse during the early part of the 20th century. Thus we infer that the recent uplift represents but a single event in an ongoing, more or less cyclic deformational process characterized by a period of about 50 years. Even though less than two full cycles are expressed in the geodetic record, the cumulative rate of uplift near the center of the recent uplift probably has averaged about 5 mm/yr, a value that is roughly consistent with the uplift rates that have been deduced for the late Quaternary emergent marine terraces along the south flank of the Transverse Ranges.

Although the evolution of the recent uplift is relatively well defined, its correlation with the regional seismicity is poorly defined. A comparison between the occurrence of southern California earthquakes of magnitude ≥4 during the period 1932 to 1976 with the 1974 configuration of the uplift demonstrates the existence of (1) relatively aseismic areas within the western lobe of the uplift (in the western Transverse Ranges), in the central part of the uplift (in the western Mojave Desert), and along an east-trending zone that extends into the eastern Mojave athwart the south flank of the uplift (north of the Salton Sea) and (2) localized concentrations of seismic activity along the flanks of the uplift. Moreover, 9 of the 10 largest earthquakes recorded within or around the area of the southern California uplift during the period 1932 to 1976 (the 1933 Long Beach, the 1941 Santa Barbara, the 1946 Walker Pass, the 1947 Manix, the 1948 Desert Hot Springs, and the four major 1952 Kern County shocks) occurred before the inception of the uplift in 1959 or 1960.

The area embraced by the southern California uplift has been identified with geodetically defined horizontal strain, part of which may have accumulated as a major north-south contractional event that roughly coincided with the first spasm of uplift. Nonetheless, continuing contractional strain associated with regionally developed partial collapse argues that the uplift cannot be fully explained simply as the vertical expression of continuing north-south compression. Consideration of the two well-defined historical episodes of uplift and partial collapse indicate that the southern California uplift may be the product of decoupling and viscous flow beneath the seismogenic zone, presumably driven by continuing motion between the irregularly margined plates south of the great bend of the San Andreas fault. Because the magnitude of the maximum uplift associated with each episode was approximately the same, there may be some threshold value above which collapse (viscous flow) may ensue; the absence of total collapse may be a function of precollapse strain hardening within the postulated subseismogenic viscoelastic layer.

INTRODUCTION

Examination of the vertical-control record after the 1971 San Fernando earthquake disclosed a sharply defined tilt developed between 1961 and 1964 along a survey traverse extending west-southwestward from Palmdale across what has since been identified as the south flank of the southern California uplift (Castle and others, 1974; Castle and others, 1976). The surprisingly large magnitude of this tilt (about 0.17 m over a distance of 30 km), together with its rapid growth, subsequently provoked a systematic examination of the vertical-control record along a number of level lines athwart the San Andreas fault in southern California. These studies, together with other investigations of continuing crustal deformation in the western Mojave Desert (fig. 1) (Church and others, 1974), culminated in the first published representation of the southern California uplift (Castle and others, 1976). However, this representation (fig. 2) was deliberately conservative, and both the lateral and vertical dimensions were based on what was explicitly defined as a preliminary examination of the geodetic record within an area between and adjacent to the San Andreas and Garlock faults and eastward from Maricopa to Barstow.

Because our initial reconstruction of the uplift was clearly skeletal, both with respect to the areal coverage and the volume of survey data that had been generated by various agencies operating in southern California, and because this earlier reconstruction incorporated several then-unverified assumptions, the resulting portrayal (fig. 2) was highly generalized. We have since attempted to assemble all the data that could be recovered through querying those southern California jurisdictions that are known to have carried out level surveys of at least third-order accuracy. We have, in addition, commissioned new leveling along several lines in order to better define the extent and history of the uplift. This report, accordingly, summarizes and synthesizes all the vertical-control data known to have been produced through 1976, thereby permitting a still-generalized but far more detailed description of the four-dimensional configuration of the southern California uplift than was heretofore possible.

The results of the relatively detailed study presented here indicate that the southern California uplift may have been at least twice as long and far more complex—both in its geometry and its evolution—than could have been deduced from our earlier reconstruction. Although the eastern third of the uplift is much more poorly defined than is that to the west, owing chiefly to the relatively few repeated surveys east of long 117° W., by 1973/74 it probably ranged eastward to Arizona and east-southeastward to the Salton Sea. Similarly, synthesis of data from west of Maricopa shows that at its zenith the uplift extended as far west as the western end of the Transverse Ranges. Hence by 1973/74 the total length of this feature probably exceeded 600 km—roughly the distance between San Francisco and Los Angeles. Moreover, in spite of continuing uncertainties, certain aspects of its configuration can now be defined relatively precisely. For example, the southern boundary of the uplift lay generally south of the coastline eastward as far as Ventura, where it projected inland and south of the Santa Susana fault system; east of the San Fernando Valley this boundary turned south-

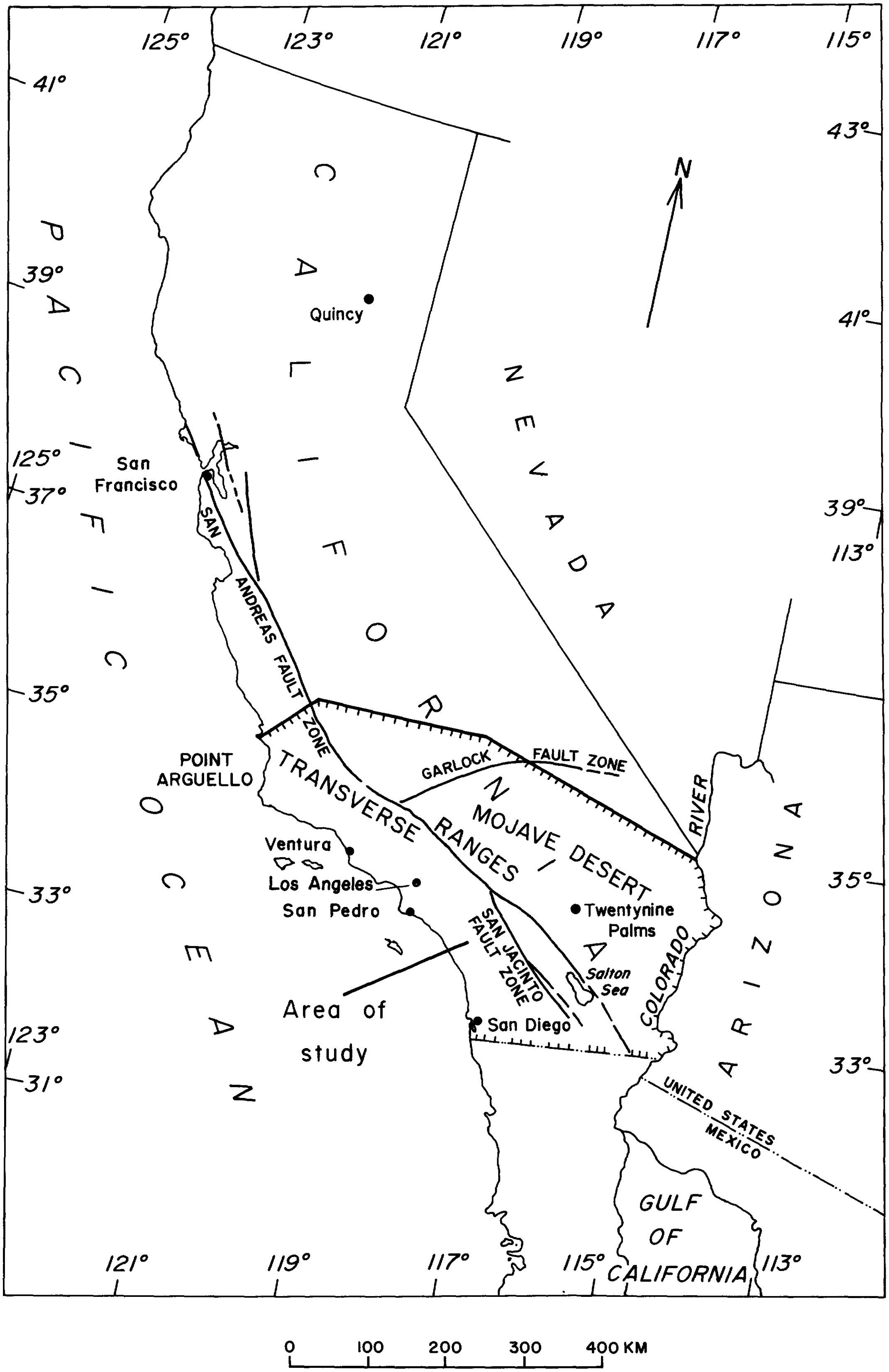

FIGURE 1.—Index map of California showing area of study that includes the southern California uplift.

eastward, and thence eastward along the frontal fault system of the Transverse Ranges and the south branch of the San Andreas fault system, respectively.

The evolution of the southern California uplift includes two well-defined spasms of uplift, the second of which was closely followed by partial collapse. The uplift apparently began in the west-central Transverse Ranges at some time between the spring of 1959 and the following spring; it spread rapidly eastward, and probably westward as well, such that by the fall of 1961 much of the Transverse Ranges and the Mojave Desert eastward as far as Twentynine Palms had been elevated by as much as 0.25 m. The second major spasm, probably confined largely to the period 1972/73–74, extended and amplified the uplift eastward to the Colorado River, elevating much of the eastern Mojave by values that equalled or exceeded those developed in the western lobe between 1959 and the fall of 1961. The distribution of the subsequent collapse, which could have begun as early as the end of 1974 but no later than 1976, remains poorly defined; it certainly encompassed the central part of the uplift and probably extended east-southeastward to the Salton Sea. Local oscillatory movement associated with the changing configuration of the uplift may prove to have been an integral part of its growth. Moreover, although our knowledge of its occurrence is very limited, apparently ephemeral downwarping along the leading edges of the propagating uplift has been recognized in enough places that it can now be regarded as a generally occurring aspect associated with the growth of the uplift.

ACKNOWLEDGMENTS

The synthesis presented here could not have been attempted without the generous assistance

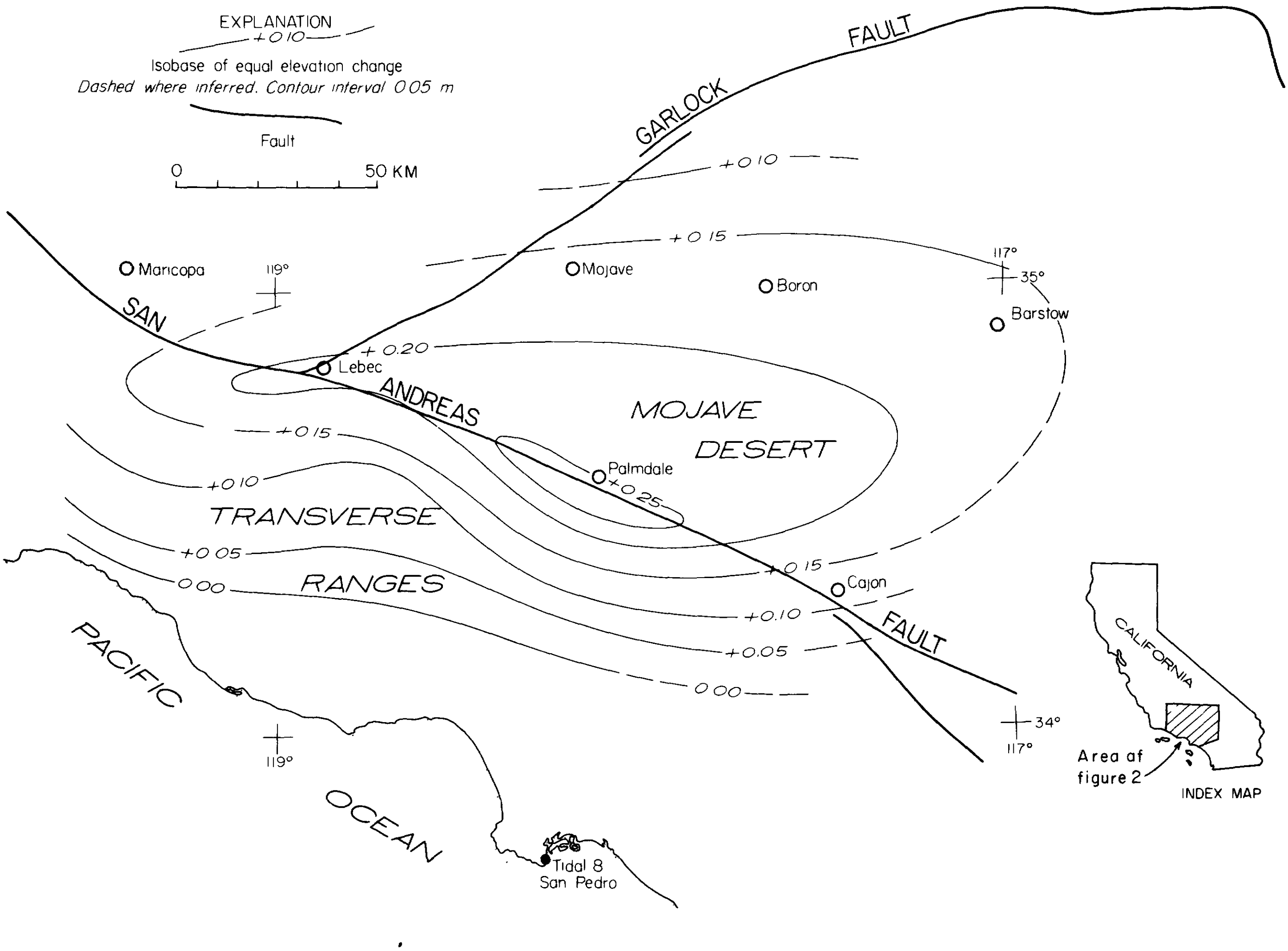

FIGURE 2.—An early representation of the southern California uplift based on a preliminary examination of the geodetic record by Castle and others (1976, p. 251).

and cooperation of many individuals and numerous public agencies operating in southern California. Nearly half of the utilized survey data derive from the field measurements of various southern California cities and counties. In particular, we thank the Los Angeles County Department of County Engineer, the County of Orange Office of County Surveyor and Road Commissioner, the County of Riverside Survey and Road Department, the County of San Bernardino Public Works Agency, the San Diego County Engineering Department, the Ventura County Department of Public Works, the City of Los Angeles Bureau of Engineering, the City of Riverside Bureau of Public Works, the California Department of Water Resources, the California Division of Mines and Geology, the California Department of Transportation, and the Metropolitan Water District of Southern California for the development and assistance in the acquisition of survey data utilized in this report. We are especially indebted to J. F. McMillan of the Los Angeles County Department of County Engineer and J. W. Raihle and R. E. Stone of the County of Riverside Survey and Road Department for the establishment within their respective jurisdictions of vertical control critical to the reconstruction described here.

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GEOLOGIC FRAMEWORK

The geology of the area embraced by the southern California uplift is characterized by a complexity that may be unparalleled in North America. Hence, while a detailed consideration of the geology of this area is clearly beyond the scope of this report, any interpretation of the movements described here requires at least a rudimentary knowledge of the major geologic features, especially of the major tectonic elements that fall within and adjacent to the area of the uplift. For simplicity and brevity, these features are summarized here chiefly in map form. Moreover, because it is certainly germane to the origins of the uplift, we also present a brief sketch of the recent tectonic history of this area. Because the uplift shows several associations with the naturally defined physiographic or tectonic provinces of southern California (pl. 1), our description of the geologic framework is organized by province.

The Coast Ranges province (pl. 1) is characterized by a generally northwest-trending structural and topographic grain. The rocks exposed at the surface in the southern Coast Ranges consist chiefly of clastic Mesozoic and Cenozoic sedimentary rocks that generally rest unconformably upon or are in fault contact with older highly deformed and mildly metamorphosed rocks commonly included with the Franciscan Complex (Jahns, 1954, p. 9). The deep crust and upper mantle beneath the central to southern Coast Ranges are apparently devoid of unusual features; Bateman and Eaton (1967, p. 1409–1413) show that the Mohorovičić discontinuity underlies this region at a "normal" depth of about 25 km, and that both crustal and upper-mantle P-wave velocities are characterized by more or less expectable values. The physiographically defined southern Coast Ranges province is transected along its northeastern edge by the San Andreas fault (pl. 2), which crudely defines the northeastern tectonic boundary of this province. The southern boundary, on the other hand, is obscurely and almost arbitrarily defined by the gradual change in topographic and structural trend from northwest to east-west.

The San Joaquin Valley (pl. 1) has served as a vast depositional basin throughout much of Late Cretaceous and Cenozoic time (Jahns, 1954, p. 9–13). The southern end of the valley contains an enormously thick terrestrial section; south of Bakersfield these deposits, which comprise nearly half the section from basement to surface, are as much as 4,000 m thick (de Laveaga, 1952, p. 102–103). The depth to basement, moreover, increases from 4,000–5,000 m northwest of Bakersfield to as much as 9,000 m at the southern end of the valley (de Laveaga, 1952, p. 102–103). Most of the 4,000-m terrestrial section in the southern part of the valley consists of the Kern River Formation, which ranges in age from latest Miocene to early Pleistocene(?) and is probably no more than 8–9 m.y. old (Bartow and Pittman, 1983, p. D12–D13). Owing to the enormous thickness of the Kern River Formation in the southernmost part of the valley, it is likely that the southern San Joaquin Valley has sustained periods of accelerating tectonic subsidence during latest Neogene and (or) Quaternary time, although it is uncertain whether accelerating downwarping has characterized the Holocene history of this area. The western, and in particular, the southern margins of the San Joaquin Valley province are associated with severe deformation. We know nothing of the deep-crustal and upper-mantle structure beneath the southern end of the valley; nevertheless, if this region is in isostatic equilibrium, the great thickness of low-density materials suggests an arching of the Mohorovičić discontinuity similar to that shown by Bateman and Eaton (1967, p. 1411) along the eastern edge of the valley north of Bakersfield. The physiographically defined eastern boundary (pl. 1) of the San Joaquin Valley province lies only slightly downslope from the contact between the underlying crystalline basement and the eastward- thinning, unconformably overlying Cenozoic sedimentary deposits (Smith, 1964). The southern boundary is essentially coincident with a well-defined zone of thrust faulting (Jennings, 1973), whereas the southwestern boundary, as we have already observed, virtually coincides with the San Andreas fault.

The Sierra Nevada province (pl. 1) is expressed as a "huge, asymmetric, westward-tilted block" that disappears to the west beneath the sedimentary rocks of the San Joaquin Valley (Jahns, 1954, p. 13). The province is underlain chiefly by Mesozoic plutonic rocks, "together with older metamorphic rocks that appear in most areas as inclusions, roof pendants, and screens in the igneous terrane" (Jahns, 1954, p. 13). The structural complexity of the Sierra Nevada block increases toward the south, particularly at the "triple point" with the San Joaquin Valley and Coast Ranges provinces (pl. 1). Much of this province, moreover, has been involved with major faulting during Pleistocene time, especially along its eastern and southeastern boundaries. The deep-crustal and upper-mantle structure of the Sierra Nevada province is relatively well known. Bateman and Eaton (1967, p. 1411–1413) show a low-velocity crustal root beneath the Sierra Nevada that depresses the Mohorovičić discontinuity to depths of as much as 50 km, an observation consistent with the seeming isostatic balance exhibited by this block (Oliver, 1960). The eastern boundary of the Sierra Nevada province virtually coincides with the generally high-angle Sierra Nevada fault zone (pl. 2), whereas the western boundary of this province is again defined by the zone where this giant, tilted block dips beneath the veneer of sedimentary deposits underlying the San Joaquin Valley. The southern or southeastern boundary of the Sierra Nevada province coincides almost precisely with the Garlock fault (pl. 2), against which it is sharply truncated.

The small part of the Basin and Range province (pl. 1) that impinges on this study "is characterized by north-trending ranges, intervening valleys and basins, and an interior drainage" (Jahns, 1954, p. 13). Many or most of the individual ranges included with this province are clearly distinguishable fault blocks that show conspicuous differences in geology from block to block. Expressions of both Mesozoic and Tertiary deformation are abundant throughout the Basin and Range province; it is, however, the "widespread Quaternary faulting and warping reflected by many elements of the present topography" (Jahns, 1954, p. 13) that is especially significant here. While the deep-crustal structure beneath the Basin and Range province probably is generally similar to that beneath most of southern California, several large-scale crustal features associated with this province may be especially germane to the contemporary deformation described in this report. Thus the Mohorovičić discontinuity lies at a depth of about 30 km beneath the Basin and Range province (Bateman and Eaton, 1967, p. 1141), a depth indicative of a crust slightly thickened over that identified with the Coast Ranges but of roughly the same thickness as that associated with the Transverse Ranges, the Mojave Desert, and the Peninsular Ranges provinces (Hadley and Kanamori, 1977a, p. 1474). Similarly, Braile and others (1974) recognize a low-velocity layer between 10 and 15 km deep which they interpret as a zone of low rigidity underlying the Basin and Range province; however, because their conclusion is based on seismic refraction studies carried out 500-600 km northeast of the area described here, we cannot conclude with certainty that this low-velocity layer pervades the entire province. The western boundary of the Basin and Range province is, of course, well defined by its coincidence with the Sierra Nevada fault zone, whereas the southern boundary is much less clearly defined. Eastward from the Sierra Nevada province to about the meridian of Baker, the southern boundary of the Basin and Range province closely coincides with the Garlock fault (pl. 2); still farther east, however, it tends to lose both its physiographic and tectonic identity and is almost arbitrarily defined.

The Transverse Ranges province (pl. 1), as its name implies, owes its definition to a generally east-west topographic grain that transects the prevailingly northwest trends that characterize most of southern California; it is perhaps the most significant of the several provinces described here, for it has been spatially identified with the southern California uplift from its inception to its partial collapse. Although the Transverse Ranges province is treated as a single feature owing to its unique and disruptive trend, it may consist of two fundamentally different structural units separated by the San Andreas fault where it cuts through Cajon Pass north of Colton (pl. 2). The east-west grain of the Transverse Ranges is displayed not only in the physiography, but by faults, fold axes, other internal structural features, and major chemical trends as well (Jahns, 1954, p. 17; Baird and others, 1974). Upper Mesozoic and Tertiary sedimentary and volcanic rocks characterize the western Transverse Ranges; eastward, the rocks of this province are generally older and of a more crystalline aspect. Physiographic evidence of intense Quaternary deformation is widespread throughout the Transverse Ranges. Locally, as in the Ventura basin, the combined stratigraphic and structural records provide compelling evidence of major and probably accelerating deformation and associated denudation and sedimentation during Quaternary time (see, for example, Yeats, 1977, p. 296). Because the Transverse Ranges straddle the San Andreas fault, whatever may be responsible for the existence of these ranges seemingly either is independent of massive displacement on the San Andreas or has persisted or regenerated in spite of continuing right-lateral movement along this fault system. Accumulating evidence suggests that the deep-crustal and upper-mantle structural configuration beneath the Transverse Ranges may be unique. Hadley and Kanamori (1977a) conclude from an analysis of seismic traveltime data that a high-velocity upper-mantle ridge underlies much of the Transverse Ranges and, like the Transverse Ranges themselves, projects across the San Andreas with little apparent offset. In order to explain the uninterrupted persistence of this postulated mantle ridge (and perhaps the Transverse Ranges as well) athwart the San Andreas, Hadley and Kanamori (1977a) suggest that the crustal and mantle-plate boundaries diverge north of the Salton Sea in such a way that the mantle-plate boundary projects northwestward toward and beyond the eastern end of the Transverse Ranges. There is no direct evidence of decoupling between crust and mantle of the sort implicit in the Hadley-Kanamori model; nevertheless, the gravity high over the San Gabriel Mountains is consistent with the absence of a root beneath this elevated structural block (Hanna and others, 1975) and hence with decoupling beneath the San Gabriel Mountains. While the extreme northwestern boundary with the Coast Ranges province and the extreme southeastern boundary with the Mojave Desert province are arbitrarily defined, the margins of the Transverse Ranges elsewhere generally coincide with well defined faults: the San Andreas, the Pinto Mountain, the south-flanking frontal fault system, and the steeply dipping reverse fault system along the north side of the San Bernardino Mountains (pl. 2).

The Mojave Desert province is generally defined as that great westward-pointing structural wedge of relatively monotonous physiographic aspect sandwiched between the Sierra Nevada and Basin and Range provinces on the north and the Transverse Ranges on the south (pl. 1). Of the several provinces described here, the Mojave Desert province is second only to the Transverse Ranges province in the clarity of its association with the southern California uplift. The Mojave Desert province is characterized by great geologic diversity. It consists largely of crystalline rocks ranging from Precambrian to Mesozoic in age together with complex assemblages of middle and upper Cenozoic rocks deposited in apparently separate basins (Jahns, 1954, p. 13–17). The entire province apparently "was subjected to widespread erosion from late Mesozoic to middle Tertiary time, and, unlike the regions to the north, south, and west, it contains no lower Tertiary sedimentary rocks"; the "younger fluvial and lacustrine sediments indicate a complex history of basin formation that began in middle Miocene time and continued to the present" (Jahns, 1954, p. 17). The west-central part of the Mojave Desert province, in particular, is transected by a series of northwest-trending right-lateral faults, many of which show evidence of Quaternary activity (pl. 2). Moreover, the northwest- to north-northwest-trending boundary that separates an area of Quaternary faulting on the west from one of little if any Quaternary faulting to the east coincides roughly with the boundary that separates a region of conspicuous seismicity on the west from a virtually aseismic terrain on the east (Hileman and others, 1973, p. 64–65). This boundary, in fact, effectively divides the Mojave Desert province into two subprovinces of markedly contrasting tectonic character. The northwest-trending faults identified with Quaternary activity form one of the most distinctive features of the western Mojave, and many of them project into the San Bernardino Mountains of the eastern Transverse Ranges as gouge and breccia zones; however, none of these faults offset significantly the northern steeply dipping reverse faults that separate the Mojave Desert from the Transverse Ranges (F. K. Miller, oral commun., 1977). Although the Mohorovičić discontinuity lies at a near-normal depth of about 30 km, other deep-crustal and upper-mantle features associated with the Mojave Desert province depart from the usual. Thus, the high-velocity mantle ridge under the Transverse Ranges apparently projects northeastward into the western Mojave (Hadley and Kanamori, 1977a). Moreover, Hadley and Kanamori (1977b) also suggest a velocity reversal at a depth of 15–20 km that could be interpreted as similar in its origins and rheologic significance to that recognized by Braile and others (1974) in the Basin and Range province. The boundaries of the western subprovince of the Mojave Desert province coincide neatly with a series of well-defined faults or fault systems. Moreover, even within the eastern subprovince, the southern boundary of the Mojave Desert is roughly defined by the San Andreas system (pl. 2), and only in the northeastern part of the province is there neither a clearly defined tectonic nor physiographic boundary.

The Continental Borderland province (pl. 1) is characterized by a northwest-trending ridge-basin configuration. It is "underlain chiefly if not entirely by Catalina Schist basement of Franciscan aspect" and has in this sense "both physiographic and geologic relevance" (Yerkes and Wentworth, 1965, p. 19). The Continental Borderland thus contrasts sharply with the adjacent Transverse Ranges and Peninsular Ranges provinces, both of which are devoid of basement rocks of this nature. Although Shepherd and Emery (1941) applied the term "Continental Borderland" to the entire offshore domain between the coastline and the continental slope, we have adopted the usage of Yerkes and Wentworth (a usage that includes only that part of the offshore tract lying generally south of the Channel Islands), simply because the Continental Borderland of Yerkes and Wentworth's definition can be viewed as a tectonic entity. We have no direct knowledge of either the deep crust or the upper mantle beneath the Continental Borderland province; we infer, in any case, that the high-velocity ridge of Hadley and Kanamori (1977a) projects at least a short distance seaward into the Continental Borderland and that the Mohorovičić discontinuity shallows somewhat toward the Patton escarpment. The Continental Borderland shares a common border on the north with the western Transverse Ranges, where it roughly coincides with the north-dipping Santa Monica thrust or reverse fault system of Barbat (1958, p. 38). The eastern boundary of the Continental Borderland province is defined by the Newport-Inglewood zone and its southeastern projection, which takes it seaward south of Newport and thence inland again along the Rose Canyon fault north of San Diego (Jennings, 1975).

The Peninsular Ranges province (pl. 1) is identified with a northwest-trending topographic grain truncated abruptly against the southern fault-bounded margin of the Transverse Ranges province. Jahns (1954, p. 19) has characterized the entire Peninsular Ranges province "as an uplifted and westward tilted plateau that has been broken into several large, elongate, subparallel blocks by major [northwest-trending] faults," many of which have been active during Quaternary or at least later Cenozoic time. The Peninsular Ranges province is underlain largely by crystalline rocks of Paleozoic and Mesozoic age that show a number of seeming affinities with the Sierra Nevada province. The western margin of the Peninsular Ranges consists of a coastal plain underlain chiefly by "clastic marine and nonmarine strata of Upper Cretaceous, Tertiary, and Quaternary age, as well as by scattered volcanic rocks of Tertiary and Quaternary age" (Jahns, 1954, p. 19); this coastal-plain section, moreover, thickens sharply toward the boundary with the adjacent Transverse Ranges province to the north. The nature of the upper mantle and the depth of the Mohorovičić discontinuity beneath the Peninsular Ranges probably are roughly comparable to that elsewhere in southern California. According to Hadley and Kanamori (1977a, p. 1474), however, a relatively high-velocity (6.7 km/s) layer at the base of the crust thickens southward across the Transverse Ranges and persists into the Peninsular Ranges without apparent thinning. Although both the northern and western margins of the Peninsular Ranges province coincide almost exactly with well-defined fault systems, the eastern boundary is less explicitly associated with major faults. It seems instead to step eastward to the north, where the northwest-trending faults through the eastern Peninsular Ranges province lose their surface expression beneath the thick sedimentary cover of the adjacent Salton Trough.

The Salton Trough province (pl. 1), as its name implies, is a broad crustal depression, the surface of which lies in part below sea level; it is virtually identical with the Colorado Desert province of Jahns (1954, p. 11). The wedge-shaped region included within this province trends generally northwest and expands almost uniformly southeastward from the confluence between the south and east boundaries of the Transverse Ranges province and Peninsular Ranges province, respectively. Overlying the basement complex beneath the Salton Trough is a sequence of chiefly nonmarine lacustrine and alluvial deposits that, together with various volcanic rocks, may be as much as 6 km thick (Biehler and others, 1964, p. 132); Muffler and White (1969, p. 170) have, in fact, described a 4.1-km stratigraphic section obtained from a well in the central part of the depression that seems to consist entirely of deltaic sediments of the Colorado River. The age of these deposits is conjectural, but they may be entirely Pliocene and younger (Sharp, 1972, p. 4–7). To the best of our knowledge, the presumably crystalline basement complex underlying the Salton Trough is unique within southern California. Specifically, seismic-refraction studies indicate that the velocity transition (at an average depth of about 5 km) between the sedimentary cover and the underlying basement is relatively smooth; it passes from less than 5 km/s through a zone about 1 km thick into basement velocities $\geqslant$5.65 km/s (Fuis and others, 1981). The basement in turn overlies what Fuis and others (1981) term the “subbasement,” the top of which is characterized by velocities of about 7.2 km/s. The relief on the top of the subbasement ranges through about 5 km within the study area alone; the high point, at a depth of about 10 km, occurs at or near the international border. A gravity model developed by Fuis and others (1981, fig. 11) suggests that the Mohorovičić discontinuity beneath the Imperial Valley occurs at an average depth of about 22–24 km, and that the subbasement is about as thick as the basement and sedimentary fill combined. Although the western margin of this province is irregularly outlined by the northwest-trending faults that transect the Peninsular Ranges and project southeastward into the Salton Trough, the eastern margin is relatively smooth and coincides approximately with the easternmost mapped strand of the San Andreas system (pl. 2).

The rocks associated with the southern California uplift range from Early Proterozoic (1,750 m.y., Silver, 1971) to Holocene in age; nevertheless, because we are concerned here chiefly with an analysis of the historical deformation, we may legitimately lump the numerous mapped units into several broadly defined groups, provided that these generalizations do not impede reasonable interpretations of the evolution of the uplift. Accordingly, we have simplified the complex geologic section exposed at the surface by combining all of these rocks into three categories (pl. 2): (1) undifferentiated crystalline rocks composed chiefly of Early Proterozoic to Cretaceous units; (2) generally well-indurated unmetamorphosed sedimentary and volcanic rocks composed chiefly of Upper Cretaceous and Tertiary units; and (3) unconsolidated to poorly consolidated sedimentary deposits composed almost entirely of Quaternary units. Although this simplification (pl. 2) obscures the full (and very involved) geologic history of southern California, it provides a reasonable basis both for assessing the very recent geologic history and for distinguishing between movements of clearly tectonic origin from those attributable to artificial or other natural processes. We have similarly simplified the structural configuration by showing only those faults known or suspected to have been active during Quaternary time (pl. 2). Many of these same faults, of course, were active during pre-Quaternary time, but it is doubtful that the literally hundreds of mapped faults that show no evidence of Quaternary activity are germane to our analysis of the historic deformation.

The tectonic history of southern California pertinent to this investigation can be said to have begun with the initiation of contractional strain athwart the present-day Transverse Ranges or, alternatively, with the inception of bending of the San Andreas fault north of Los Angeles. Precisely when either commenced is uncertain, but it is likely that the compressional stress system presently operating across the Transverse Ranges began no earlier than Pliocene time (Jahns, 1973). Moreover, whether this stress system was derivative from the bending of the San Andreas fault or vice-versa can only be inferred, but the two clearly are related. Powell (1981, p. 387) has suggested that as the regional stress system changed in orientation during the period 5–9 m.y. ago “the great keeled [Sierran and Peninsular Ranges] batholiths were rotated clockwise by right-lateral couples *** whereas the rootless Mojave Desert-Transverse Ranges block responded as an easily deformable 'soft' zone between the left-lateral couple of the rigid, rotating batholithic blocks." However, while it is this postulated rotation that led to the bending, the spatial confinement of the bend is believed to have been inherited from an earlier deformational event that imparted a unique structural aspect to what we now recognize as the Transverse Ranges-Mojave block. Thus, according to Powell (1981, p. 374–378), at some point during early Cenozoic time "the Mojave Desert-Transverse Ranges block was shallowly underthrust by a relatively young, hot segment of oceanic crust, whereas the Sierra Nevada and Peninsular Ranges were underthrust at steeper angles by older, cooler oceanic segments." It is this contrasting history between adjacent terranes that led to the creation of the "soft" zone that both permitted and localized the bending of the main strand of the San Andreas fault (if not the plate boundary itself). Acceptance of the basic scenario outlined by Powell invites several corollary conclusions of varying tectonic significance:

(1) The formation of the bend and its perhaps continuing accentuation during the period 5–9 m.y. ago or later, coupled with continuing right-lateral plate motion on the order of 60 mm/yr (Minster and Jordan, 1978, p. 5345), forced the generation of contractional strain across "crustal boundaries whose general east-west trends were established by earlier deformation" (Campbell and Yerkes, 1976, p. 555)—an observation that argues that the great bend in the San Andreas fault is more cause than effect.

(2) As both rotation of the batholithic blocks and right-lateral translation continued along the North American-Pacific plate boundary, it imposed a left-lateral couple across or within the intervening block that resulted in the relatively recent inception of left-lateral movement on the Garlock fault. Indeed, Carter (1980) has argued that strike-slip displacement on the Garlock fault, which sums to about 60 km, originated in Pliocene time—and probably late Pliocene time. If the displacement on the Garlock fault and the growth of the present-day Transverse Ranges are linked, which seems likely if not compelled, the evolution of the Transverse Ranges probably occurred within a small fraction of Cenozoic time—perhaps during the past 2–3 m.y.

(3) Comparison between the results of experimental modeling and the inferred recent tectonic evolution of southern California (Powell, 1981, p. 390) tend both to support Powell's reconstruction and suggest mechanical explanations for what is observed or reasonably inferred. Experimentally induced deformation generated within an overlying and partially decoupled layer in response to right-lateral motion between adjoining blocks of the underlying layer and attendant underthrusting of one beneath the other closely matched the geologically inferred pattern and sequence of deformation described by Powell (1981, p. 387–390). Powell's comparison suggests to us that horizontal or near-horizontal decoupling within the lithosphere has contributed significantly to the recent tectonic evolution of southern California.

(4) Even if the postulated opposing rotations between the rooted batholithic blocks have ceased, the clearly persisting right-lateral motion between the North American and Pacific plates has compelled continuing left-lateral displacement on the Garlock fault (or similarly oriented faults within the North American plate originating in the region of the great bend). Specifically, if we assume that the Pacific plate is fixed, that the relatively discrete rupture that defines the surface trace of the San Andreas extends to a depth of about 15 km (the base of the seismogenic zone), and that decoupling between upper and lower layers of the lithosphere occurs at this or some greater depth (but probably above the high-velocity mantle ridge of Hadley and Kanamori, 1977a—see below), owing to the constraint imposed on the motion of the upper layer by the present position of the San Andreas, parallel trajectories of upper and lower layers north of the great bend probably have diverged south of the bend (whatever its location) during much or most of Quaternary time. North of the bend, eastward displacement of the upper layer accompanying this divergence would tend to horizontally load the upper layer. This loading, in turn, could be accommodated through east-west extension of the North American plate north of the bend together with left-lateral displacement along a zone originating at the bend and trending at a high angle to the San Andreas fault (whether the Garlock, the White Wolf, or any similarly positioned fault), a mechanism seemingly compatible with (if not identical to) one first proposed by McKenzie (1972, p. 175).

There are several reasons for believing that the decoupling which plays an integral part in this model probably operates at some relatively modest depth within the crust (15–20 km) and, hence, that the lithosphere is a rheologically layered system: (1) The configuration of the high-velocity mantle ridge described by Hadley and Kanamori (1977a) is difficult to reconcile with significant right-lateral slip through the full thickness of the lithosphere eastward from the Newport-Inglewood zone to the eastern Mojave Desert; accordingly, although we recognize the limited resolution of the data that permitted definition of this feature, it seems unlikely that major right-lateral displacement through this part of the upper mantle could have occurred while leaving so little evidence. (2) Were the lithosphere not multilayered, the loading effects proposed here could certainly have occurred as a result of slip at the base of the lithosphere. However, the Quaternary contractional effects within and around the margins of the Transverse Ranges would be much more difficult to explain if the upper- and lower-plate boundaries coincided (that is, if there were no decoupling between these layers); the very occurrence of major thrusts and reverse faults along both the northern and southern boundaries of the Transverse Ranges argues for a form of decoupling that is reasonably extended to depth along progressively shallowing surfaces (see, for example, Thatcher, 1976, p. 693). (3) The studies of Lachenbruch and Sass (1973, p. 192) argue that the heat-flow distribution along the San Andreas is compatible with a model that "attributes the [thermal] anomaly to mechanical heat generation in a broad shear zone between the North American and Pacific plates." Acceptance of this internally consistent model requires that decoupling be generated at the base of the seismogenic zone (Lachenbruch and Sass, 1973, p. 204). (4) Hadley and Kanamori (1978) have described as nearly horizontal the preferred fault planes for two small shocks that occurred near the base of the seismogenic zone within and adjacent to the aftershock zone of the 1971 San Fernando earthquake, an observation that suggested to them that the Transverse Ranges may form an evolving decollement. The infrequency with which focal mechanisms of this sort have been detected probably is due to the relative infrequency of brittle failure at or near the base of the seismogenic zone. (5) Finally, observational evidence, coupled with various theoretical considerations outlined in the section on "The Origin of the Southern California Uplift," indicates that decoupling not only can occur but should be occurring at relatively shallow crustal depths.

We see no insurmountable arguments that refute the operation of plate-motion divergence as an explanation for the geologically recent left-lateral slip along the Garlock fault and the extensional strain effects recognized east of the San Andreas and north of the Garlock. However, this notion may carry within it the seeds of its own destruction. With continuing migration of the North American plate past the Pacific plate, pile-up between the lower layers is implied by the more sharply defined bends along the edges of the plate boundaries; it is this pile-up that may ultimately lead to a straightening of the entire system and a resultant narrowing of the shear zone that lies beneath the seismogenic zone south of the great bend.

HISTORICAL SURFACE DEFORMATION

Historical surface deformation within the area of the southern California uplift can be characterized as either tectonic or nontectonic. Nontectonic deformation is further divisible into artificially and naturally induced movement. Because the purpose of this report is the consideration of a certain category of tectonically derived surface movements, we have attempted to provide a basis for discriminating between tectonic movements and those of nontectonic origin. Our approach, which is both the most conservative and the only practical procedure open to us, has been to simply disregard those movements that are certainly or probably contaminated by a nontectonic signal, even though it requires that we discard a good deal of data that might have assisted in an assessment of the tectonic process.

NONTECTONIC DEFORMATION

Compaction, together with the much more subtly defined expansion of unconsolidated to incompletely consolidated basinal deposits produced through changes in the underground fluid-pressure regime, accounts for nearly all of the nontectonic surface deformation recognized in southern California. Surface movements of this derivation are, in fact, so significant in relation to all other types of nontectonic deformation that we may safely exclude from any further consideration the generally trivial and easily distinguished movements due to slope and free-face failures or to hydrocompaction. Because man-induced changes in the subsurface fluid-pressure regime have created the most dramatic examples of nontectonic deformation in southern California, this category of movement is examined first.

ARTIFICIALLY INDUCED DEFORMATION

Artificially induced surface deformation is clearly associated with both ground-water withdrawals and oil-field and gas-field operations throughout southern California (pls. 3 and 4). This type of deformation is most conspicuously expressed as differential subsidence (pl. 4), but it also includes elastic rebound, horizontal movement, faulting, and surficial fissuring (Church and others, 1974; Castle and Yerkes, 1976; Morton, 1977). However, even though all of these movements can be shown to be related, whether directly or indirectly, to fluid-pressure declines and resultant compaction at depth or to changes in ground-water levels, this discussion is restricted to a consideration of the vertical displacement field—that is, to differential subsidence and uplift.

The application of consolidation theory to the analysis of differential subsidence associated with changes in the fluid-pressure regime has been summarized by Poland and Davis (1969). It begins with the acceptance of Terzaghi's principle of effective stress, which states that within a porous, fluid-filled medium, $p = p' + u$, where p = total stress or pressure, p' = effective (grain-to-grain, intergranular, "solid") stress or pressure, and u = fluid (pore-water, reservoir, neutral, internal) stress or pressure. In a confined water system in which the compressibility of the fluid is disregarded, unit head decline (which may be equated with fluid-pressure reduction) will produce an equal increase in effective pressure; in an unconfined water system any reduction in liquid level will produce an increase in effective pressure through loss of buoyancy, and the total pressure will decrease slightly owing to loss of fluid mass (Poland and Davis, 1969, p. 193–196). Because the overburden is supported by both fluid and effective pressure, a decrease in fluid pressure to a point approaching zero will increase the effective pressure to a value approaching the lithostatic pressure, whereas an increase in fluid pressure to a point approaching the lithostatic pressure will decrease the effective pressure to a value approaching zero. Reservoir compaction thus becomes a function of both the magnitude of the increased effective stress (or applied load) and the compressibility of the materials, whereas any expansion of the reservoir skeleton is a function of the magnitude of the reduced effective stress and the elastic component of the compressibility.

Vertical Displacements Associated with Ground-Water Withdrawal and Recharge

Easily measured subsidence has accompanied artificially induced water-level declines in many of the ground-water basins of southern California (pls. 3 and 4). The subsiding areas are typically underlain by unconsolidated to semiconsolidated alluvial or lacustrine clastic deposits of chiefly Quaternary age. Water is generally extracted from semiconfined and confined sand or gravel aquifers of low to moderate compressibility that are commonly interbedded with relatively impermeable and highly compressible clay-rich aquitards. In the absence of recharge, continuing extraction reduces pressure head within the aquifers and sets up pressure gradients across aquifer-aquitard boundaries, ultimately leading to the dewatering of the aquitards and the compaction of both aquifers and aquitards. The magnitude of this compaction and of any resultant surface subsidence depends, of course, on the thickness of the affected system. Several local ground-water basins have shown little if any subsidence in spite of major head declines (>30 m). Most of those basins in which there has been relatively little subsidence are characterized by coalescing fan deposits that consist of relatively coarse clean gravel generally devoid of silt and clay beds. Examples include the Raymond basin northeast of Los Angeles (Lofgren, 1971a) and much of the San Fernando Valley (pls. 3 and 4).

Owing to limited preconsolidation produced through natural oscillations of the water table, there is generally some critical piezometric head decline at which compaction and resultant subsidence begin to accelerate in response to continuing exploitation. Although there are relatively few examples where there is good control on both head decline and changing elevation, significant subsidence in the semiarid southwestern United States typically begins following initial head declines of 15–20 m (Poland and Davis, 1969). During recharge, whether seasonal or long term, compaction commonly is almost completely arrested and slight elastic expansion and accompanying surface rebound may occur (Riley, 1969; Poland, 1969, p. 291).

Water levels in the several ground-water basins of southern California have been affected by various combinations of secular meteorological changes, changing land use, artificial recharge practices, and importation of water, as well as withdrawals. Regional drought, combined with increased land development and ground-water withdrawals, produced major water-level declines in southern California during the periods 1924–36 and 1945–64. In many of the coastal basins, unusually high precipitation during the winters of 1965/66 and 1968/69, coupled with increased use of imported water, led to recoveries in water levels that were apparently retained through at least 1974. However, water levels in the western Mojave Desert continued to decline through this period of general recovery (California Department of Water Resources, 1975a).

We have summarized in plates 3 and 4 a current appraisal of water-level declines and associated differential subsidence in southern California. Although this pair of illustrations is largely self-explanatory, several points merit amplification. While much of the Los Angeles basin has sustained significant differential subsidence due to ground-water withdrawals, a large fraction of this subsidence is indistinguishable from that attributable to natural compaction or even to tectonic downwarping, and it is locally masked by subsidence associated with oil-field and gas-field operations (pls. 3 and 4). For example, the so-called La Cienega subsidence bowl, which lies along the northern edge of the basin about 10–12 km west of Los Angeles (pl. 4), probably is attributable to a combination of causes including ground-water withdrawal, tectonic downwarping, and, perhaps, oil-field operations (Castle and Yerkes, 1976, p. 10–11). Similarly, southeastward from Los Angeles along the axis of the basin, most of the localized differential subsidence (pl. 4) clearly is associated with ground-water extraction (pl. 3). Nevertheless, from 1968 to 1974, during a period of rising water levels that apparently began in 1962/63, a broadly defined area centering about 10–15 km south of Los Angeles continued to subside at about 10 mm/yr. While this continuing subsidence could be the product of aquitard dewatering and compaction attributable to the persistence of a pore-pressure gradient between aquifer and aquitard long after fluid pressures within the various aquifers had begun to recover, it is just as likely to be related to natural causes.

The basinal complex extending westward from Colton to and beyond Ontario has undergone major water-level declines (pl. 3) that may have begun as early as 1904 (Mendenhall, 1908). Because the Quaternary stratigraphy and structural history of this area are so complex, most of the artificially induced subsidence is sharply localized; thus, unlike the situation in the Los Angeles basin, the occurrence of this subsidence has not generally constrained our reconstruction of the southern California uplift. Some fraction of this localized subsidence could be tectonic downwarping (analogous to that postulated to have occurred within the La Cienega subsidence bowl). However, because we usually are incapable of distinguishing between tectonic and artificially induced subsidence, we are forced to assume that all of the measured subsidence in this area is related to ground-water withdrawals.

The well-defined subsidence in the Bunker Hill ground-water basin, which lies between the San Jacinto and San Andreas faults east of Colton (pl. 4), seems to be closely tied to the Quaternary stratigraphy. That is, even though substantial water-level declines have been recognized on both sides of the San Jacinto fault (pl. 3), the subsidence is largely restricted to the east block. This seeming inconsistency may be easily explained, however, for the section northeast of the San Jacinto fault is unlike that to the southwest and consists of a sequence of clay and silt layers interbedded with sands and gravels (Eckis, 1934, p. 160), a sequence that virtually invites compaction and subsidence as a result of even modest head declines. Rising water levels in the Bunker Hill basin during the period 1968/69–75 apparently arrested the subsidence that had characterized this area during the preceding decades. This apparent cause-and-effect relation suggests accordingly, that the previously recognized subsidence east of the San Jacinto fault cannot be attributed to phenomena other than ground-water extraction.

Vertical Displacements Associated with Oil-Field and Gas-Field Operations

The most dramatic examples of artificially induced surface deformation recognized in southern California are those associated with oil-field and gas-field operations (Castle and Yerkes, 1976). Compaction and resultant subsidence attributable to the extraction of oil and gas (and the water that generally accompanies petroleum production) are mechanically analogous to that associated with the production of water from confined aquifer systems. Similarly, fluid injection and attendant increases in reservoir fluid pressure not only tend to retard further compaction and subsidence, but can actually induce limited elastic rebound. Allen and Mayuga (1969), for example, interpret most of the 0.34 m of rebound in the Wilmington oil field east of San Pedro (pl. 3) during the period 1965–69 as the product of elastic expansion accompanying massive water flooding of this field. While other mechanisms may figure in rebound around the margins of producing oil fields (see, for example, Castle and Yerkes, 1976, p. 73–75), broadly distributed rebound associated with injection is generally attributable to decreased effective stress accompanying repressurization.

Although fluid-pressure reductions and resultant increases in effective stress necessarily lead to a tendency toward compaction and surface subsidence, accumulating experience indicates that the occurrence of clearly measurable subsidence associated with oil-field and gas-field operations is generally restricted to a particular class of fields. Yerkes and Castle (1969, p. 56) show that subsidence is almost invariably identified with those fields characterized by production "from unconsolidated to poorly lithified and poorly sorted sands, generally Miocene or younger in age," where the "median depths of production range from about 360 to 3900 m and exceed 1800 m in only four cases."

Owing in part to the small scale of the map (pl. 4), we show only the better documented and most impressive examples of subsidence associated with petroleum production. However, nearly every oil field shown on plate 3 meets one or more of the subsidence-susceptibility criteria listed above. Because both spatial and temporal coincidence between oil-field operations and subsidence have been demonstrated repeatedly (Castle and Yerkes, 1976), differential height changes within or around these fields (pl. 3) should be attributed to processes other than oil-field operations only in the presence of overwhelming evidence to the contrary.

NATURALLY INDUCED DEFORMATION

Natural compaction probably is continuing, in some measure, throughout the sedimentary basins of southern California. It may be an especially important process in those areas characterized by rapid deposition of fine-grained materials during recent geologic time—such as the central Los Angeles basin, the southern San Joaquin Valley, and the Oxnard Plain. However, although natural compaction and resultant surface subsidence probably have continued during historical time within much of the area embraced by the southern California uplift, it is generally very difficult to distinguish surface deformation of this type from that due to ground-water extraction.

The Los Angeles basin, which contains about 1,400 m of Quaternary deposits alone and a combined upper Pliocene and Quaternary section over 3,500 m thick (Yerkes and others, 1965, pl. 4), is a case in point. Grant and Sheppard (1939) have outlined a trough of differential subsidence that increases progressively south-southeastward from Los Angeles along a zone that roughly coincides with the axis of the basin. Furthermore, comparison of 1968 and 1974 level surveys through the central part of the basin shows that subsidence during this period persisted at rates of about 10 mm/yr, whereas during the period 1962–76 ground-water levels in this same general area rose roughly 10 m. Hence, while there is a strong likelihood that the subsidence identified by Grant and Sheppard (1939) is due in part to natural compaction associated with rapid loading of the underlying section, we cannot be certain that it is not entirely man induced. That is, as suggested earlier, it is conceivable that the subsidence detected during the period 1968–74 is attributable to nothing more than the drainage of aquitards in response to earlier head declines in amounts significantly greater than the 1962–76 10-m water-level recovery. Similarly, while well-defined subsidence in the southern part of the Oxnard Plain (pl. 4) is reasonably attributed to natural compaction of Holocene lagoonal or marsh deposits (Castle and others, 1977, p. 220–225), the modest declines in ground-water levels recognized in this area (pl. 3) indicate that this subsidence is not necessarily due to natural phenomena.

TECTONIC DEFORMATION

Implicit in the preceding discussion is the notion that geodetically defined vertical-displacement fields of tectonic origin can be described in no more than an exclusionary sense—namely, as those vertical displacements that cannot be attributed, whether directly or indirectly, to natural compaction or to artificial processes. Accordingly, plates 3 and 4 provide a convenient guide for distinguishing between vertical movements of tectonic derivation and those of a probable or possible nontectonic origin. The value of these illustrations is enhanced, moreover, if they are used in conjunction with the physiographic map showing the natural provinces (pl. 1) and the generalized geologic map (pl. 2). Together, these two maps (pls. 1 and 2) provide a basis for assessing the form of those sedimentary basins that are especially susceptible to nontectonic deformation. Thus, in evaluating the changing configuration of the southern California uplift we have relied heavily on these data (pls. 1–4) in detecting (and discarding as irrelevant) those nontectonic vertical signals that appear in the profiles of height changes shown below.

VERTICAL-CONTROL DATA

The basic data used in the reconstructed height changes described in this report are drawn from repeated level surveys between two or more bench marks. While the determination of any change in height difference between marks is a basically simple procedure, it is commonly complicated by the fact that measured height differences are both path and time dependent. Moreover, because most of the survey data that we have assembled here have been developed for engineering or cartographic purposes (where crustal stability among a widely spaced array of bench marks usually has been assumed), the thrust of our effort has been directed toward reconstructing and interpreting the leveling data in such a way that the effects of any crustal movement during a given level survey can be assessed and considered in calculating height changes referred to a common datum (or reference bench mark).

Vertical-control surveys are divisible into several orders and classes of accuracy, each of which meets certain procedural and instrumental requirements (Federal Geodetic Control Committee, 1974). Although these requirements have been strengthened over the years, there have been no significant instrumental changes since 1916 (with the introduction of the invar rod) and relatively few procedural changes since 1925 (Rappleye, 1948a, p. 1–3, 7–9, 15–23; Federal Geodetic Control Committee, 1974, p. 9); hence the most recently established standards of the Federal Geodetic Control Committee provide a convenient basis for characterizing those requirements especially germane to the error estimates of the National Geodetic Survey. Moreover, although most all the height changes described in this report are based on comparisons between first-order level surveys (pl. 5), because we have used the results of lower-order surveys locally, the procedural specifications for each of the three orders of geodetic leveling are briefly summarized here.

All first-order leveling is, by definition, double run over sections of 1–2 km. Balanced sights are required, and the maximum sight lengths permitted since 1974 are 50 m for class I and 60 m for class II surveys (Federal Geodetic Control Committee, 1974, p. 9). Prior to 1961, maximum sight lengths of 150 m were authorized, but their use was permitted "only under the most favored conditions" (Rappleye, 1948a, p. 7). In 1961, sight lengths were reduced to a maximum of 75 m; in 1964 they were further reduced to 50 m for all first-order surveys utilizing instruments other than the Fischer level (formal class distinctions were not introduced until 1974) (E. I. Balazs, oral commun., 1979). The rejection limits (or maximum permissible closures) over individual double-run sections are 3 mm $\sqrt{K}$ for class I surveys and 4 mm $\sqrt{K}$ for class II surveys, where K is the distance in kilometers; the rejection limits for lines or loops are 4 mm $\sqrt{K}$ and 5 mm $\sqrt{K}$ for class I and class II surveys, respectively (Federal Geodetic Control. Committee, 1974, p. 9). The 3 mm $\sqrt{K}$ section-rejection limit, which is the singularly significant requirement for class I leveling, was not introduced until the 1950's; hence prior to the 1950's first-order leveling can be said to have consisted of a single class characterized by a section-rejection limit of 4 mm $\sqrt{K}$.

Second-order leveling may be either single or double run and is similarly divisible into two classes: class I leveling is in all cases double run, whereas class II work may be either single or double run (Federal Geodetic Control Committee, 1974, p. 9). Both class I and class II second-order surveys again require balanced sights, but the difference between forward and backward sights may be as much as 10 m. Maximum sight lengths currently range from 60 m for class I to 70 m for class II surveys (Federal Geodetic Control Committee, 1974, p. 9); they apparently have never exceeded 150 m (Rappleye, 1948a, p. 7), and because the U.S. Geological Survey (since 1928, at least) has permitted sight lengths no greater than 92 m for third-order leveling (Birdseye, 1928, p. 132), it is likely that the sight lengths used in second-order leveling rarely have exceeded 90 m. The rejection limits for both section closures and loop or line closures are given as 6 mm $\sqrt{K}$ for class I second-order surveys and 8 mm $\sqrt{K}$ for class II surveys (Federal Geodetic Control Committee, 1974, p. 9). Prior to 1974, and at least as far back as 1928, the rejection limit for all second-order leveling was 8.4 mm $\sqrt{K}$ (Birdseye, 1928, p. 130; Rappleye, 1948a, p. 2–3; U.S. Geological Survey, 1966, p. 2).

Third-order leveling is again divisible into single or double run, but because the procedural requirements are otherwise the same for both there is no formal "class" distinction for surveys of this order (Federal Geodetic Control Committee, 1974, p. 9). In practice, virtually no third-order leveling is double run unless a blunder or other major error is suspected. The maximum permissible sight length for modern third-order surveys is given as 90 m (Federal Geodetic Control Committee, 1974, p. 9). The older standards, moreover, were almost as stringent; since 1928 the Geological Survey has stipulated that maximum sight lengths not exceed 92 m except at river crossings or ravines (Birdseye, 1928, p. 132; U.S. Geological Survey, 1966, p. 20).

The loop- or line-rejection limit currently is given as 12 mm $\sqrt{K}$ (Federal Geodetic Control Committee, 1974, p. 9); this is the same maximum closure that has been in effect for third-order leveling since 1928 (Birdseye, 1928, p. 130; Rappleye, 1948a, p. 2–3).

ERRORS IN HEIGHT DETERMINATIONS

Errors in height differences, with the exception of usually easily detected blunders or "busts," are attributable to four major sources: (1) systematic survey error, (2) random survey error, (3) surface deformation (bench-mark motion) during the course of a specified level survey, and (4) an imprecisely formulated orthometric correction (see below). The magnitude of both the second and last of these error sources generally can be closely estimated; systematic error and errors inherent in crustal deformation during the leveling are much more difficult to assess, and there is no single technique that permits their clear discrimination.

SYSTEMATIC ERROR

Although the distinction between systematic and random error is poorly defined, the recognition or suspicion of various types of systematic error has dictated many of the procedural requirements stipulated for geodetic leveling. Systematic leveling errors are of two general types: those that can be assessed through loop closures and those that are independent of closure. Because many of the lines considered here do not close a loop and because the larger misclosures that we have identified are attributable chiefly to deformation that occurred during completion of the respective loops, misclosures are usually inadequate indices of systematic error—at least in southern California.

Systematic errors independent of closure are generally functions of topography and, hence, are either height or slope dependent. Thus, an undetected error in rod length can be expected to produce errors in measured elevation differences that are directly proportional to the error in rod length. For example, where the approximate elevation difference between marks is defined as Δe, an error of 0.03 mm in a 3-m rod would produce an error of $\Delta e \times 10^{-5}$—or about 24 mm in the maximum elevation difference (2,400 m) considered in this report. Similarly, "unequal refraction" (in which the refraction introduced in the foresight is unmatched by that in the backsight) may lead to significant gradient-dependent errors. Bomford (1971, p. 240–241) suggests that refraction errors may be as large as $\Delta e \times 2 \times 10^{-4}$— or about 480 mm for the maximum elevation difference considered here—although they generally must be much less than this "worst case" situation.

Because rod and refraction errors are height and slope dependent, they are most easily detected by searching for a correlation between topography and measured elevation discrepancies disclosed through repeated surveys. If the results of either survey are contaminated by significant rod error, the correlation between height and any seeming vertical displacement should be almost perfect. Although one could expect to see, for various geologic reasons, a rough correlation between height and apparent movement, the one-to-one correlations between height and apparent height changes associated with rod error are generally absent in the comparisons developed for this report. Hence, it seems unlikely that rod error has had any significant effect on the vertical signals described here. Refraction errors are less specifically correlated with terrain than are rod errors. That is, because refraction is a function of the atmospheric density along the line of sight, and thus is dependent on the vertical temperature gradient, short-term vagaries of climate superimposed on the normal diurnal and seasonal variations will tend to diffuse any correlation between slope and seeming height changes between surveys. Although the correlations are generally poor, several comparisons between height changes and topography within the area of the southern California uplift suggest that the apparent vertical displacements may be due in part to refraction error in one or the other of the comparative surveys. Nonetheless, because the associated misclosures are very small, these postulated refraction errors (if of any significant size) would have to have been almost precisely self-cancelling—a somewhat surprising conclusion in view of the path dependency of this error and that, in the general case, it should be expressed as a misclosure. It is conceivable, of course, that the atmospheric refraction error is so overwhelmingly slope dependent that it tends to cancel, regardless of weather, length of day, and so forth. The implicit corollary—namely, that refraction errors have contaminated successively measured height differences to about the same degree—carries with it the conclusion that refraction errors could not have contributed significantly to the calculated vertical displacement values. (Because "balanced slopes" are certainly the exception rather than the rule, the generally small misclosures produced during periods of tectonic quiescence (see below) suggest that refraction errors tend to randomize over distances of more than a few kilometers.) In any case, rigorous examination of the data assembled for this study has produced very little evidence that indicates that the vertical-control data have been seriously fouled by refraction error.

Systematic error may be the most elusive problem we face in utilizing the results of repeated level surveys as indices of historical crustal deformation. Further complicating this problem is that various types of unrecognized or unsubstantiated systematic error may have contaminated these measurements. For example, spirit leveling may be characterized by a directional bias, a possibility suggested by the existence of the so-called sea-slope problem (Fischer, 1977). However, even though recent investigations (Castle and Elliott, 1982) suggest that the discrepancy between geodetic and steric (oceanographic) leveling cannot be dismissed as the product of a postulated directionally dependent systematic error in geodetic leveling, we infer that the north-south component associated with each successive survey over the same route has been approximately equally, if at all, contaminated. It is sometimes possible to search for the existence and significance of systematic error even if the physical source of the error cannot be specified. Specifically, systematic error may appear in the cumulative divergence between the forward and backward runs of a double-run line. Granted that we have investigated the cumulative divergence in only a handful of surveys utilized in this report, only one of those that we did examine showed divergence of a significant magnitude and character that could be interpreted as the product of systematic error; nonetheless, even this divergence was but a small fraction of the vertical signal disclosed through a comparison of the results of this particular survey against those of an earlier leveling.

In the final analysis, the very strong likelihood that the large vertical signals described in this report have not been seriously distorted by systematic error rests heavily on circumstantial but very persuasive evidence, much of which is developed in detail in the body of the report. In the first place, replication of elevation determinations both before and after the large vertical displacements that are critical to our reconstruction, supports the argument that these determinations are free of measurably significant systematic error of whatever origin. Moreover, because the earlier set of concordant elevations is based on levelings that bracketed the procedural change that halved the maximum permissible sight length, it is especially unlikely that any subsequent displacements can be easily dismissed as refraction-induced (sight-length-dependent) artifacts. Similarly, Mark and others (1981, p. 2792–2794) show that successively developed elevation differences between Saugus and Palmdale (fig. 2) probably are no more than trivially contaminated by either rod or residual refraction error. In particular, the Saugus-to-Palmdale line is at once that part of the reach between San Pedro and Palmdale within which the south flank of the uplift is largely confined and which shows by far the clearest correlation between signal and terrain of any of those lines examined in this study. Yet levelings bypassing the Saugus-to-Palmdale line, over a variety of routes in which signal and topography are generally poorly correlated, have produced approximately the same pre- and post-uplift heights for marks in the Palmdale area as have those contemporary levelings propagated directly eastward from Saugus. Secondly, the generation of widely distributed large vertical signals (along five separate lines that occur within a zone more than 175 km in length) within a relatively tight time frame of only about 2 years argues that these signals are other than the products of survey error. In other words, interpretation of these broadly distributed signals as a time-constrained concatenation of errors would carry with it a probability approaching zero, for comparable signals (or errors) were undetected in this same general region during the decades before and after this 2-year interval. Thirdly, the detection of very subtly defined artificially induced movements (based on repeated levelings over lines where systematic error could be reasonably anticipated) that agree almost precisely with their predicted occurrence and configuration, testifies to the nearly error free nature of these measurements within and around the area of the southern California uplift (see, for example, Castle and others, 1974, p. 62, 65). Fourthly, the discovery of a similar uplift that apparently evolved during the early part of the 20th century suggests that the modern uplift represents but a single pulse in a continuing cyclic process (Castle and others, 1977) and supports by analogy the reality of both the southern California uplift and the validity of the measurements that permitted its identification. In other words, it would be very difficult to accept the contention that the remarkable correspondence in both the configuration and general history of these two episodes of uplift is simply the product of a cyclically distributed systematic error. Finally, accumulating geologic evidence (McCrory and Lajoie, 1977; Wehmiller and others, 1977a; Bull and others, 1979) indicates that the pattern of crustal deformation disclosed through the analysis of the historical geodetic record is consistent with the pattern of vertical displacements generated within the area of the southern California uplift during late Quaternary time. All in all, the preceding observations indicate that if the geodetically defined signals that permitted the identification and characterization of the southern California uplift are no more than measurement artifacts, chance coincidence has operated on a truly remarkable scale.

RANDOM ERROR

Random error developed during any double-run leveling may be assessed through statistical examination of the section closures, provided only that the sample population is sufficiently large. Double-run procedures are so specified that the expected random error in the measured elevation difference between any two bench marks a distance L apart is approximately normally distributed and hence proportional to $L^{1/2}$. While the results of single-run leveling are less amenable to statistical analysis, it is assumed that the random error in the measured elevation difference between any two marks is also normally distributed, if only because the procedures stipulated for both single- and double-run surveys are otherwise identical. This assumption is supported, moreover, by the experience of the Geological Survey in assessing the results of thousands of loop or line closures.

The higher the order and, in general, the more recent the leveling, the greater the accuracy. First-order leveling procedures currently are such that for class I and class II surveys the estimated standard error—which can be treated as the equivalent of σ, or the standard deviation over a unit distance—is 0.5 mm/km$^{1/2}$ and 0.7 mm/km$^{1/2}$, respectively (Federal Geodetic Control Committee, 1974, p. 3). However, the experience of the National Geodetic Survey with all first-order leveling indicates that σ was about 1.5 mm/km$^{1/2}$ and 1.0 mm/km$^{1/2}$ during the periods 1917–55 and 1956–74, respectively (Vaníček and others, 1980, p. 507). For simplicity, we have assumed in all of our calculations that σ has in no case dropped below 1.0 mm/km$^{1/2}$. Thus, one standard deviation in the measured elevation difference based on first-order leveling between two bench marks at opposite ends of a 600-km line—roughly the length of the longest line considered in this report—would be about 37 mm had the survey been carried out between 1917 and 1955, whereas it would be about 24 mm had it been carried out since 1955. Second-order leveling specifications today are such that σ is given as 1.0 mm/km$^{1/2}$ and 1.3 mm/km$^{1/2}$ for class I and class II surveys, respectively (Federal Geodetic Control Committee, 1974, p. 3). Again, however, the experience of the National Geodetic Survey with all second-order leveling indicates that σ was about 3.0 mm/km$^{1/2}$ and 2.0 mm/km$^{1/2}$ during the periods 1917–55 and 1956–74, respectively (Vaníček and others, 1980, p. 507–508). Moreover, we have again assumed for purposes of this report that σ has not dropped below 2.0 mm/km$^{1/2}$ for any second-order survey. Thus, one standard deviation in the measured elevation difference based on second-order leveling between two bench marks at opposite ends of a 150-km line—approximately the length of the longest second-order line examined in this report—would be about 37 mm had the leveling been carried out between 1917 and 1955, whereas it would be about 24 mm had it been carried out since 1955. Third-order leveling procedures currently are such that σ is given as 2.0 mm/km$^{1/2}$ (Federal Geodetic Control Committee, 1974, p. 3). The experience of the U.S. Geological Survey, based chiefly on the results of loop and line misclosures developed from third-order leveling indicates that before 1956 σ was close to 6 mm/km$^{1/2}$, whereas since that time it has been about 4 mm/km$^{1/2}$. The specifications for third-order leveling are such, however, that these estimates almost certainly err on the conservative side. Nonetheless, we have extended this conservatism by assuming for the purposes of this study, that σ has in no case dropped below 4 mm/km$^{1/2}$ for any third-order leveling. Thus, one standard deviation in the measured elevation difference based on third-order leveling between two bench marks at opposite ends of a 60-km line—nearly the length of the longest third-order line considered in this report—would be about 46 mm had the survey been run before 1956 and about 31 mm had it been carried out since 1955.

Calculation of the standard deviation of the measured elevation difference between the end points of a single line composed of several segments of differing survey class or order (or simply of differing σ) requires, in effect, that the standard deviation be calculated for each of these separately defined segments. Thus, 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 or classes of leveling, may be given as:

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

where σ_1, σ_2, etc., are the estimated standard deviations applicable to each successive segment of length L_1, L_2, etc. For example, one standard deviation in the measured elevation difference between the end points of a 1974 survey consisting of a 150-km segment of first-order leveling joined to a second 150-km segment of second-order leveling would be about

$$\sqrt{[1 \text{mm}^2/\text{km} \cdot 150 \text{ km} + 4.0 \text{ mm}^2/\text{km} \cdot 150 \text{ km}]} = 27 \text{ mm}.$$

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 as:

$$\sigma_{\delta \Delta E} = \sqrt{(\sigma^2_{\Delta E_1} + \sigma^2_{\Delta E_2})}, \quad (2)$$

where $\sigma_{\Delta E_1}$ and $\sigma_{\Delta E_2}$ are the calculated standard deviations for each of the separately determined differences. The more usual (and less general) situation dealt with here consists of comparisons based on successive levelings of the same order over the same route; in this case $\sigma_{\delta \Delta E}$ is given simply as $\sigma_d L^{\frac{1}{2}}$, where σ_d is one standard deviation in the discrepancy between two successively measured elevation differences over a unit distance. Thus, one standard deviation in the discrepancy between the measured elevation differences obtained through two post-1955 first-order surveys over a distance of 300 km (roughly the length of the level route between San Pedro and Bakersfield) would be about 1.4 mm/km$^{\frac{1}{2}}$ · (300 km)$^{\frac{1}{2}}$, or 24 mm.

Although we show one-standard-deviation error bars for the serially determined heights for various representative bench marks, we have not generally attempted to show the estimated random-error content in the calculated vertical displacements described here. That is, while the construction of one-standard-deviation error envelopes has certain merit, several arguments suggest that it is unnecessary (and perhaps undesirable): (1) The vertical signals recognized within the area of the southern California uplift generally dwarf the estimated random error. (2) Because both systematic errors and those associated with continuing crustal deformation may be difficult to assess, random error estimates may by themselves misrepresent the error content. (3) The addition of yet another item to an already complex graphical representation is unnecessary. (4) Finally, if the random error associated with a particular vertical displacement should be desired, it can be easily calculated from the information presented with the profiled height changes and the accompanying text.

ERRORS ASSOCIATED WITH CONTINUING CRUSTAL DEFORMATION

Although it is provisionally assumed that each vertical control line remained free of movement during the course of a specified continuous or discontinuous leveling, dogmatic acceptance of this assumption may obscure significant errors in the measured elevation differences between marks. Obviously, the shorter the survey interval, the more valid the assumption. Nevertheless, accumulating experience has shown that measurable aseismic deformation may occur within months or even weeks.

Perhaps the simplest illustration of how movement may lead to the generation of specious elevation determinations can be obtained from a consideration of the effects of movement at a junction bench mark during an interruption in the leveling, albeit very short. For example, if as shown in figure 3, junction bench mark B sustained unrecognized subsidence, 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 elevations between B and C Δe greater than those that actually obtained during the period Δt_3 and, furthermore, would produce an exaggerated elevation difference between A and C (ΔE) of Δe. Hence, while the set of measured elevation differences between A and

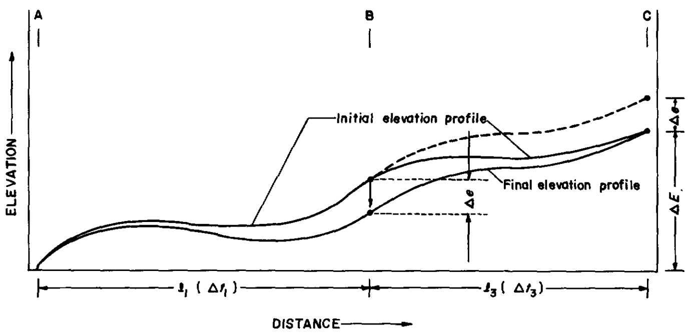


FIGURE 3.—Effect of subsidence Δe at junction bench mark B during the period Δt_2 on the observed elevations derived from discontinuous leveling along line ABC, where A and C have remained invariant. Dashed-line extension between B and C shows the calculated elevations based on leveling between A and B during the period Δt_1 and between B and C during the period Δt_3; actual elevations shown by solid lines.

B and that between B and C are appropriate to the periods Δt_1 and Δt_3, respectively, there exists no set of measured elevation differences appropriate to either interval over the full length of the line ($l_1 + l_3$). Similarly, 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 defining the end of one segment and the beginning of the next might be barely detectable, whether the leveling consisted of single-run segments or 1–2 km double-run loops, the cumulative effect of these otherwise trivial displacements (provided that the sense of movement remained the same throughout the indicated leveling) could lead to increasingly distorted elevation determinations toward the end of the line. In practice this "error," which is in no sense a function of measurement accuracy, is akin to systematic error. Because we have identified height distortions produced both by rapid elevation changes at junction bench marks and apparently continuous deformation accompanying continuous leveling, comparisons based on these surveys should have been seriously in error had we been unmindful of these possibilities.

Since crustal stability among a widely spaced array of bedrock bench marks generally has been assumed in the development of the survey data, we are left with showing either that there has been no movement at a junction bench mark (or at those marks that define the separate segments that together define a single continuous line) or, alternatively, showing both the sense and the magnitude of any movement that may have occurred during the indicated leveling. Regrettably, we have not always been able to address the second problem and have sometimes been forced to disregard otherwise useful data owing to demonstrable deformational contamination. We should add, however, that recognition that movement has occurred during the course of a given survey is not necessarily detrimental to our objectives, for it commonly provides a relatively precise basis for dating episodes of tectonic activity.

We have developed several tests for assessing crustal stability during the course of a given level survey. These tests are individually fallible, but when used together they provide a sound basis for determining whether measured elevations have been significantly distorted due to movement during the survey interval. Perhaps the least ambiguous index of the stability of a junction bench mark derives from the elevation history of the mark, as determined through repeated levelings between the junction mark and the mark selected as the basic control point (or reference point). If, for example, repeated surveys between the selected control point and the junction bench mark indicate that a constant elevation difference has persisted between these marks over some finite period, any leveling emanating from the junction mark during this period of apparent stability may be treated as if it had been produced through leveling emanating directly from the basic control point. A second objective procedure is based on misclosures defined by level circuits completed within the indicated interval. If an individual circuit consists of a series of temporally distinct legs, and if the misclosure is well below the stipulated rejection limit, it is especially likely that the junction bench marks have remained invariant in elevation with respect to each other and equally likely that the entire loop has remained free of tectonic deformation during the period required for the completion of the survey. This test is less than definitive, however, for we have identified several circuits where large tilts generated along opposite sides of the loop have so closely balanced each other that very small misclosures have been fortuitously preserved. On the other hand, misclosures well above the stipulated rejection limits are virtually certain indices of deformation somewhere along the level route during the survey interval. (Alternatively, of course, these misclosures may be due to a blunder or other major error, but these possibilities are generally easily assessed). Finally, the locations of the junction bench marks may provide at least subjective indications of their probable stability. For example, if a junction point lies along or adjacent to a recognized active tectonic element, such as a major fault, there is an a priori reason for questioning the usefulness of this mark as a starting point for any precise survey. A repeatedly surveyed junction bench mark at Colton (pl. 2) provides a case in point. This mark, which has served as a starting point for much of the precise leveling in southern California, is located adjacent to the San Jacinto fault, and those ties that we have been able to make between Colton and other southern California control points show that Colton has had an oscillatory history. Hence, we would be reluctant to accept any starting elevation for the Colton mark that had been established more than a few months before any subsequent leveling emanating from Colton. Similarly, if a junction bench mark is located within an area of demonstrable or probable extraction-induced subsidence (pls. 3 and 4), it is highly probable that this mark sustained measurable vertical displacement during the interval between the completion of the survey leading into the mark and the beginning of the survey leading away from it. In practice, however, this problem is less acute than might be anticipated, for network junction bench marks are generally established outside of areas of recognized subsidence (pl. 4), and leveling through these areas usually has been completed as rapidly as possible in order to minimize any distortion in the measured elevation differences. Moreover, given a reasonably detailed height history, we can estimate the subsidence that should have occurred during the junction interval. The most troublesome vertical-control problems associated with continuing subsidence can be traced to ignorance of its existence. It is largely for this reason that so much effort has been devoted to the preparation of a map showing areas of significant fluid extraction and concomitant changes in the subsurface fluid pressure regime (pl. 3).

In developing the reconstructions presented here, we have begun with the implicit assumption that all of the referenced surveys were completed during periods of tectonic quiescence. While this operating premise has proved tenable in most cases, we recognize that it is unsupportable in part. Hence, where we know or suspect that this assumption is invalid, we have included the basis for this conclusion in our discussion of the history of vertical movement along the line in question.

ERRORS ASSOCIATED WITH IMPRECISELY FORMULATED ORTHOMETRIC CORRECTIONS

Although nearly all the vertical displacements described in this report are based on changes in observed elevation differences developed from repeated levelings along the same (or nearly coincident) lines, those at certain critical bench marks are based on successive levelings over significantly different routes, a consideration that requires that a gravity-dependent (nonmeasurement related) geodetic correction, known as the "orthometric correction," be applied to these successively observed elevation differences before any comparisons are made. Because this correction, although gravity dependent, is insensitive to temporal variations in gravity, it can be disregarded if we confine our comparisons to the results of repeated levelings over the same line. The orthometric correction can be formulated in various ways depending on the height-precision requirements and the availability of suitably accurate gravity measurements. Because it can be shown that increasingly rigorous formulations of the orthometric correction can lead to significantly improved height determinations—on the order of decimeters (Vaníček and others, 1972; Nassar and Vaníček, 1975; Vaníček and others, 1980, p. 510–513)—it is imperative that we examine the extent to which discrepancies between rigorously calculated orthometric corrections and the more generally employed approximations impinge on studies of height changes in southern California. In order to explain both the nature of the orthometric correction and its significance to the problem at hand, we begin by considering several pertinent height concepts.

The orthometric height may be defined as the length of the plumb between a point, P, on the surface and the geoid and, hence, is usually other than a straight line (Heiskanen and Moritz, 1967, p. 50, 166); it is this height to which reference is made in most engineering and geologic studies.[1] In the general case, the orthometric height difference between two points, A and B, is unequal to the sum of the leveled height differences (leveling increments) between the points. That is,

$$\Delta n_{AB} = \sum_{A}^{B} \delta n = \int_{A}^{B} dn \neq H_B - H_A, \tag{3}$$

where Δn_{AB} = the sum of the leveling increments,
δn = a leveling increment between two closely spaced points, and
$H_B - H_A$ = the orthometric height difference between A and B (Heiskanen and Moritz, 1967, p. 161–162).

The basis of the inequality is the nonparallelism between successive level or potential surfaces; the magnitude of the inequality is a function of the path of integration (that is, the survey route). On the other hand, the potential difference between the same two points is given as

[1]Because the geoid is a time-dependent surface, changes in orthometric height cannot be equated directly with changes in length with respect to some invariant datum—such as the reference ellipsoid. Nevertheless, in dealing with features of significantly less than continental dimensions, perturbations of the geoid are generally very small in comparison with concomitant changes in orthometric height. In fact, worst-case calculations indicate that geoidal height changes rarely exceed more than 5 percent of the corresponding changes in orthometric height (Vaníček and others, 1980, p. 516–517). On the other hand, Whitcomb (1976) contends (on the basis of a postulated density change of -0.001 g/cm^3 through a disk-shaped volume of 66-km radius and 10-km thickness and an associated gravity change of -0.433 mGal) that a precursive orthometric height change of $+0.10$ m in the epicentral region of the San Fernando earthquake exceeded the calculated geometric or geocentrically referenced height change by 38 percent. However, observational experience indicates that a gravity change of the magnitude calculated by Whitcomb associated with an orthometric height change of only 0.10 m is unrealistically large. For example, Oliver and others (1975) show that a measured coseismic gravity change of -0.45 mGal (and, hence, nearly identical to that calculated by Whitcomb) in the epicentral region of the San Fernando shock was associated with a measured height change of about 2 m.

$$W_B - W_A = -\sum_A^B g\delta n = -\int_A^B g dn, \qquad (4)$$

where $W_B - W_A$ = the potential difference between A and B and
g = gravity at the leveling station or point of observation along the survey route (Heiskanen and Moritz, 1967, p. 161).

The potential difference, $W_B - W_A$, is independent of path and is "the result of leveling combined with gravity measurements," a true physical quantity. It is "basic to the whole theory of heights; even orthometric heights must be considered as quantities derived from potential differences" (Heiskanen and Moritz, 1967, p. 161–162).

Because orthometric height differences and potential differences can be developed through the measurement of gravity along the level route, an orthometric correction can be derived, whereby Δn_{AB} can be corrected to a true orthometric height difference even though

$$\sum_A^B \delta n \neq H_B - H_A \qquad (5)$$

(Heiskanen and Moritz, 1967, p. 162–169). The orthometric correction to be applied to Δn_{AB} is given by Heiskanen and Moritz (1967, p. 168–169) as:

$$OC_{AB} = \sum_A^B \left(\frac{g-\gamma_o}{\gamma_o}\right)\delta n + \left(\frac{\bar{g}_A-\gamma_o}{\gamma_o}\right)H_A - \left(\frac{\bar{g}_B-\gamma_o}{\gamma_o}\right)H_B, \qquad (6)$$

where OC_{AB} = the orthometric correction,
g = gravity at the leveling station or point of observation along the survey route,
$\bar{g}_A$ = mean value of gravity along the plumbline between A and the geoid (a value that can be calculated from the geopotential number, $C_A(\int_o^A gdn)$, at point A),
$\bar{g}_B$ = mean value of gravity along the plumbline between B and the geoid, and
γ_o = normal gravity at 45° latitude.

An exact determination of the orthometric correction clearly requires an explicit knowledge of gravity along the path of integration. However, because g commonly is unknown in detail along the survey route, it generally has been approximated (at least in the United States) in the following way:

$$g = g_{45}(1 - \alpha\cos 2\phi + \beta\cos^2 2\phi - kh), \qquad (7)$$

where g_{45} is the normal acceleration of gravity at sea level at latitude 45° (980.624 cm/s), α and β are dimensionless constants (0.002644 and 0.000007, respectively), k is a constant functionally dependent on the unit of height measurement, ϕ is the latitude, and h is the orthometric "elevation" (Rappeleye, 1948b, p. 157). Because the only variables in equation 7 are latitude, ϕ, and orthometric height, h, it follows that an approximation for the orthometric correction, dh, to be applied to the observed elevation difference between any two nearby points, may be formulated in terms of h and ϕ. That is,

$$dh = -2h\alpha \sin 2\phi\left[1 + \left(\alpha - \frac{2\beta}{\alpha}\right)\cos 2\phi\right]d\phi, \qquad (8)$$

where $d\phi$ is generally expressed in minutes of arc (Rappeleye, 1948b, p. 158–159). This correction can be further reduced to

$$dh = -C_o h d\phi, \qquad (9)$$

where C_o is the factor $2\alpha \sin 2\phi \left[1 + \left(\alpha - \frac{2\beta}{\alpha}\right)\cos 2\phi\right] \sin 1'$, h is the average elevation of the instrument between two nearby points, and $d\phi$ is the difference in latitude in minutes. C_o can be calculated for each minute of latitude; $d\phi$ is positive where the second point is north of the first (Rappeleye, 1948b, p. 159). Thus, the orthometric correction to be applied to Δn_{AB} finally can be approximated as

$$OC_{AB} = \sum_A^B dh. \qquad (10)$$

Because the orthometric correction (OC_{AB}) is very small with respect to the orthometric height, and because we are concerned here with changes in orthometric height (vertical displacements), changes in the orthometric correction associated with historic height changes may be dismissed as trivial. Nevertheless, because Δn_{AB} and, hence, the magnitude of the orthometric correction are path dependent, we need to consider any differences in the magnitude of this correction both as functions of path and as functions of their formulation. That is, if the "orthometric closure," which is simply the algebraic sum of the orthometric corrections between A and B and between B and A along two significantly different paths (or $OC_{\vec{AB}} + OC_{\vec{BA}}$, which, as a matter of convention, we consistently compute in a clockwise sense), is a large number with respect to the vertical signals reported here, the precision of its formulation may be critical to our reconstruction.

The results of repeated levelings around the same loops support the argument that the orthometric closures in southern California are generally small. For example, the observed misclosures around the Saugus-Lebec-Bakersfield-Mojave-Palmdale-Saugus circuit based on 1926 and 1953/55 surveys were +0.0257 m and +0.0244 m, respectively (fig. 4)[2]. Because these misclosures are nearly identical and fall well below the first-order rejection limit for this loop (about 0.07 m), neither should be dismissed as the product of compensating error. Were the precise orthometric closure around this loop (fig. 4) on the order of a decimeter, we would expect that at least one of these misclosures would approach this value. Because both of the measured misclosures are relatively small, the orthometric closure is itself probably very small. Moreover, since the addition of the orthometric correction based on normal gravity actually enlarges these misclosures (fig. 4), and because the measured misclosures are nearly identical, it is especially likely that a perfectly formulated orthometric correction around this loop is opposite in sign and probably departs from the value shown by no more than a centimeter or two. We have made similar comparisons around many of the loops shown in plate 5; with the exception of those cases in which one or the other of the surveys can be independently shown to have been contaminated by movement during the leveling, these comparisons all show similarly small, repeated misclosures. Hence, this subjective analysis argues that the orthometric closures in southern California are generally near or below the 1-σ random-error level (roughly 0.026 m for the first-order misclosures around the Saugus-Lebec-Bakersfield-Mojave-Palmdale-Saugus circuit; see fig. 4).

Alternatively, we can compare calculated orthometric closures based on observed gravity with those based on normal gravity. Computer-based numerical integrations around the circuits Los Angeles-Saugus-Mojave-Barstow-Colton-Los Angeles and Colton-Victorville-Lucerne Valley-Big Bear City-Colton (pl. 5) produce observed-gravity orthometric closures of +0.0282 m and +0.0376 m, respectively. These compare with normal-gravity orthometric closures around the same loops of +0.0142 m and +0.0276 m, respectively. The differences between these separately determined values are 0.0140 m and 0.0100 m, respectively, values which are well within the expected random error range for both loops.

[2]Dates separated by slashes refer to surveys performed during the stated years. The convention "1953/55" indicates that leveling done during 1953 and leveling done during 1955 are combined and treated as a single survey.

Because the observed-elevation data and observed-gravity data have not been generally available in the machine-readable form that permits computer calculation of the observed gravity orthometric correction, we have also produced a number of manually calculated numerical integrations based on an expression developed by Petr Vaníček (written commun., 1977). Vaníček's expression provides for a correction to be added to the approximate (normal-gravity) orthometric correction, given the existence of a suitable Bouguer gravity-anomaly map—in this case, the new gravity map of California (Oliver and others, 1980). Thus, according to this formula,

$$OGC_{ij} = -\frac{\bar{h}_{ij}}{G}(\delta\Delta g^{B}_{ij} - 0.1119\Delta h_{ij}), \qquad (11)$$

where OGC_{ij} = the correction (in meters) to be added to the normal-gravity orthometric correction applicable to the measured elevation difference (δn) between two nearby points, i and j,
$\bar{h}_{ij}$ = the mean height in m between i and j,
G = 10^6 mGal
$\delta\Delta g^{B}_{ij}$ = the difference in Bouguer gravity values between i and j,
0.1119 = a constant in mGal/m, and
Δh_{ij} = the height difference (in meters) between i and j.

Based on this expression (equation 11), we have calculated: (1) observed-gravity orthometric closures around five loops that range from less than 200 to nearly 1,000 km in length and (2) repeatedly determined observed-gravity orthometric heights at eight widely separated marks developed from successive levelings over significantly different routes. The orthometric closures based on observed gravity differ from those based on normal gravity by amounts ranging from a few millimeters to slightly less than 0.04 m. The magnitudes of the discrepancies between the two sets of closures seem to be independent of circuit length, but they may be crudely correlative with the occurrence of steep gravity gradients. Comparisons of the eight sets of successively determined observed-gravity orthometric heights with those based on normal gravity show, as might have been anticipated, that the two categories of heights differ significantly (by as much as 0.2 m). However, the differences between the measured height changes developed from orthometric heights corrected for observed gravity versus those corrected for normal gravity are generally trivial and range up to about 0.03 m.

The evidence developed in the preceding paragraphs indicates that, while orthometric heights based on observed gravity clearly are to be preferred over those based on normal gravity, use of the approximate (or normal-gravity) orthometric correction should result in no more than very slight errors in any of the comparisons described here. In fact, those bench marks that seem especially critical to our reconstruction, are just those marks at which we find the smallest discrepancies between orthometric heights based on observed gravity and those based on normal gravity. Accordingly, unless otherwise specified, the orthometric corrections and orthometric heights used or cited in subsequent parts of this report are based on normal rather than observed gravity.

THE RECONSTRUCTION

The basic data used in our reconstruction of the southern California uplift consist almost exclusively of corrected observed-elevation differences.

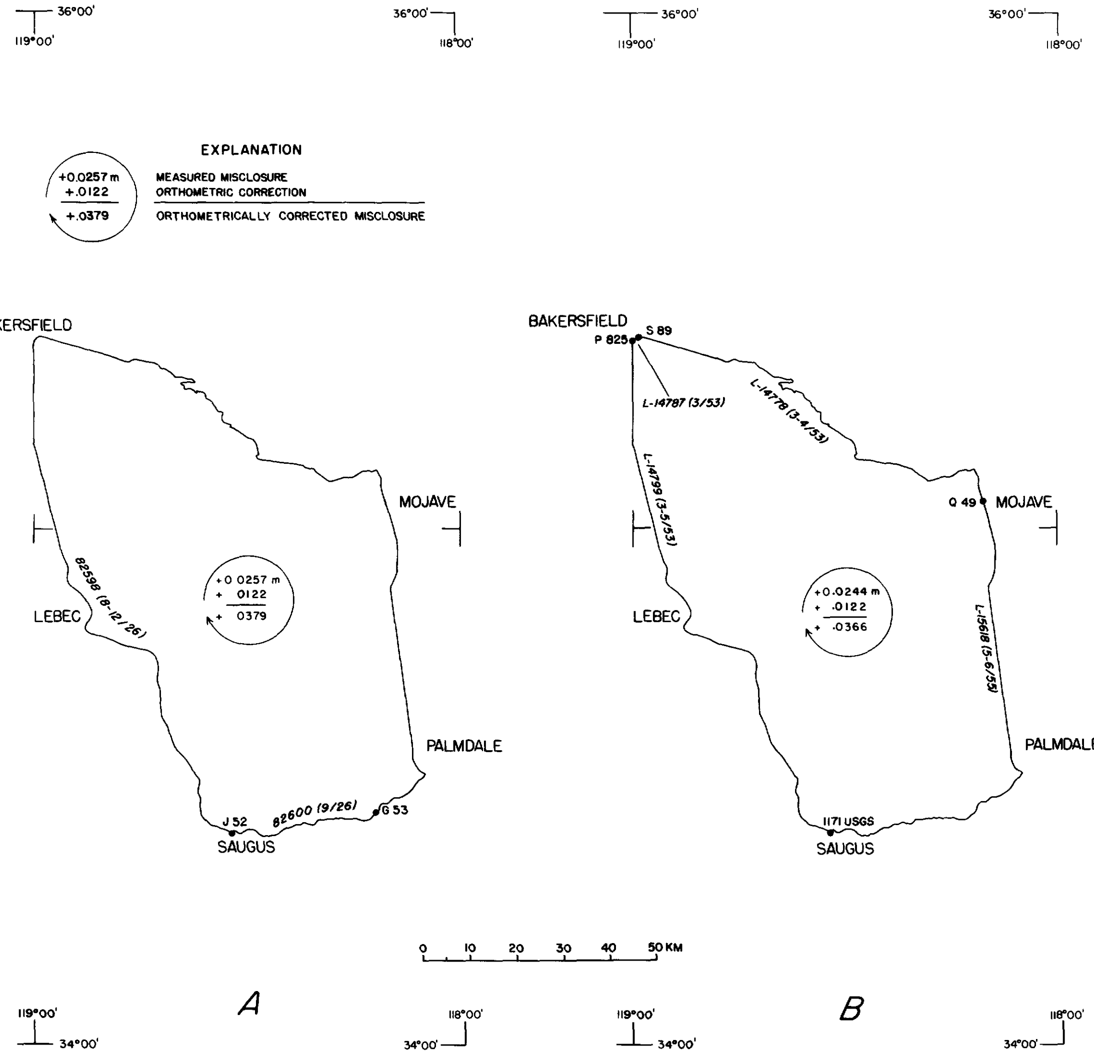


FIGURE 4.—Misclosures around the circuit Saugus-Lebec-Bakersfield-Mojave-Palmdale-Saugus based on levelings in 1926 (*A*) and 1953/55 (*B*). Data source for each survey segment indicated by National Geodetic Survey line number or by book or line number (if available) of originating agency; bench marks identify junction points at each end of the indicated segment or line; dates of leveling for each segment shown in parentheses. Measured misclosure is based on rod- and (commonly) instrument-corrected observed elevation differences derived, unless otherwise stipulated, from results of first-order leveling; orthometric correction based on normal gravity. Misclosures based on clockwise summations.

Corrections applied to the measured (field) elevation-differences consist of: (1) a temperature correction intended to account for any expansion or contraction of the rod with respect to the length of the rod at the calibration temperature, (2) a rod excess correction obtained through periodic calibrations and intended to compensate for differences between the nominal and actual lengths of the rod, and (3) relatively rarely (since it is generally tightly controlled through field procedures), an instrument correction (Rappleye, 1948b, p. 17–30). Although the observed data are not explicitly reiterated here as such, they are presented in a comparative format, chiefly as profiles of observed elevation changes (which can be equated with changes in orthometric height). These data could just as easily have been presented as tabulations of observed elevations and elevation changes; however, graphic representations provide a readily understood and much more useful way of showing how the uplift has evolved in different parts of the affected area. Each set of vertical-displacement profiles is accompanied by a terrain profile, a bar diagram specifying the interval during which each segment of leveling was completed, the order and rejection limit (if applicable) of the leveling, and the source of the data (by NGS line number if contained within their files).

The successive elevations used in calculating the vertical displacements described here have been reconstructed, insofar as possible, with respect to bench mark Tidal 8, San Pedro (pl. 5).The reconstruction process consists simply of correcting the observed elevations by some constant along a continuous line of leveling, whereby the starting elevation is brought into conformity with the ending elevation at the junction between two connecting segments of continuous leveling. Hence, for any specifically defined leveling, the reconstructed elevations are ideally equivalent to those that would have been produced had they been based on continuous leveling emanating directly out of Tidal 8. Where the routes of successive levelings locally diverge, the difference in measured elevation differences implicit in leveling over different paths is disregarded if the orthometric closure around the divergent legs is less than 1 mm. Since the reconstructed elevations may vary by a millimeter or two (depending on the choice of mark at the junctions between segments of continuous leveling) there is little point in introducing a correction of even lesser magnitude.

Bench mark Tidal 8 has been chosen as our primary reference point chiefly because it is virtually the only control point through which we may relate the observed elevations over the entire area of the southern California uplift. This bench mark is, in addition, adjacent to an automatic tide gauge (Berth 60) that has been in operation since 1924. Because continuous measurements at this gauge show that this site has been characterized by relatively negative sea-level changes with respect to most of the other primary tide stations in California (Hicks and Shofnos, 1965, p. 24–25; Hicks and Crosby, 1974, p. 4–5), height changes referred to Tidal 8 probably are biased against the detection of uplift. For example, comparison of the mean sea-level record obtained at Berth 60 with that obtained from San Diego (the nearest long-term, continuously operating station) shows that mean sea level at Berth 60 has been generally falling with respect to San Diego (fig. 5) or, alternatively, that Tidal 8 has been rising with respect to the San Diego tide station. A simple linear regression for the full period of comparison (1927–75) indicates that San Diego has been subsiding with respect to Tidal 8 at about 1.3 ± 0.1 mm/yr, a figure that is only slightly less than the long-period sea-level rise of about 1.5 ± 0.3 mm/yr established for the conterminous United States (Hicks and Crosby, 1975). The remarkably close correspondence between these two values suggests that the San Diego tide station has been rising at such a slow rate with respect to any arbitrarily defined invariant datum that it can be treated as if it were tectonically stable. This conclusion is, in fact, supported by uplift rates developed from dated marine terraces, which show that San Diego has been rising at about 0.2 mm/yr (with respect to present sea level) during late Quaternary time (Wehmiller and others, 1977b, table 13). Thus, we may safely infer that over any recent 15-year interval, “absolute” uplift of 18–27 mm could be completely masked were it based on successive surveys referenced to Tidal 8 as invariant.

We have chosen 1955 as our primary reference datum chiefly because it falls within a period (1953–58) that probably was characterized by tectonic quiescence over most of the area embraced by the southern California uplift. Nevertheless, even if we are incorrect in this assessment, we are obliged to choose some datum of about this vintage simply to ensure that we have described as completely as possible those vertical displacements that have been involved in the evolution of the uplift. Most of that part of southern California with which we are concerned was not covered by first- or second-order leveling during 1955 (pl. 5); hence, we have been forced to resort to several artifices in order to at least approximate the cumulative vertical displacements since 1955. In the absence of 1955 leveling along a primary vertical control line, we have generally adopted the most recent pre-1955 datum as an equivalent base; the validity of this procedure usually can be appraised through various independent tests. If we can show that the indicated survey route sustained (or probably sustained) significant movement during the interval between the earlier leveling and 1955, or if the most recent pre-1955 datum predates 1955 by more than a quarter of a century, we have rejected any assumed equivalence with a 1955 datum. Alternatively, we have from place to place adopted the earliest post-1955 datum as the equivalent of one that would have been produced in 1955, provided that the collective evidence supports this postulated equivalence. We have, however, been reluctant to accept post-1959 datums as 1955 equivalents simply because we are virtually certain that the deformation associated with the uplift began no later than 1960 and may have begun by the end of 1959. Finally, there are a number of cases where an equivalence between either a pre- or a post-1955 and a 1955 datum cannot be directly determined, and the acceptability of such an equivalence ultimately depends on the resulting coherence of our interpreted reconstruction over the entire area of the uplift.

The histories of vertical movement along each of a number of primary control lines are separately described in the following sections. Displacements recognized along relatively short lines or spurs, where the reconstructed elevations and height changes can be tied to Tidal 8 through the primary control line, are discussed together with the associated primary line. Special procedures, required assumptions, and problems involved in the generation of particular reconstructed elevations or height changes are also considered in the line discussions. Because each successive leveling along a given line generally has been accompanied by new monumentation, because there has almost inevitably been some destruction of marks between levelings, and because elevation changes between levelings would not otherwise be clearly evident, each set of profiles has been reconstructed with respect to a series of progressively later datums. Presentation of the data in this form tends to minimize any ambiguity yet preserves as much detail as possible.

THE VENTURA-AVILA BEACH LINE

GENERAL REMARKS

Calculated height changes between Ventura and Avila Beach (pl. 6) depend principally on the results of only two levelings. The earlier leveling consists of a combination of 1956 and 1960 surveys; the second was completed during the period 1970/71. Because significant vertical displacements probably occurred during junction intervals that accompanied both of these surveys, each of the resulting sets of observed elevation differences is almost certainly distorted. That is, a simple comparison of the survey data that disregards the likely occurrence of movement at Surf during the 1956–60 junction interval and that at Point Conception during

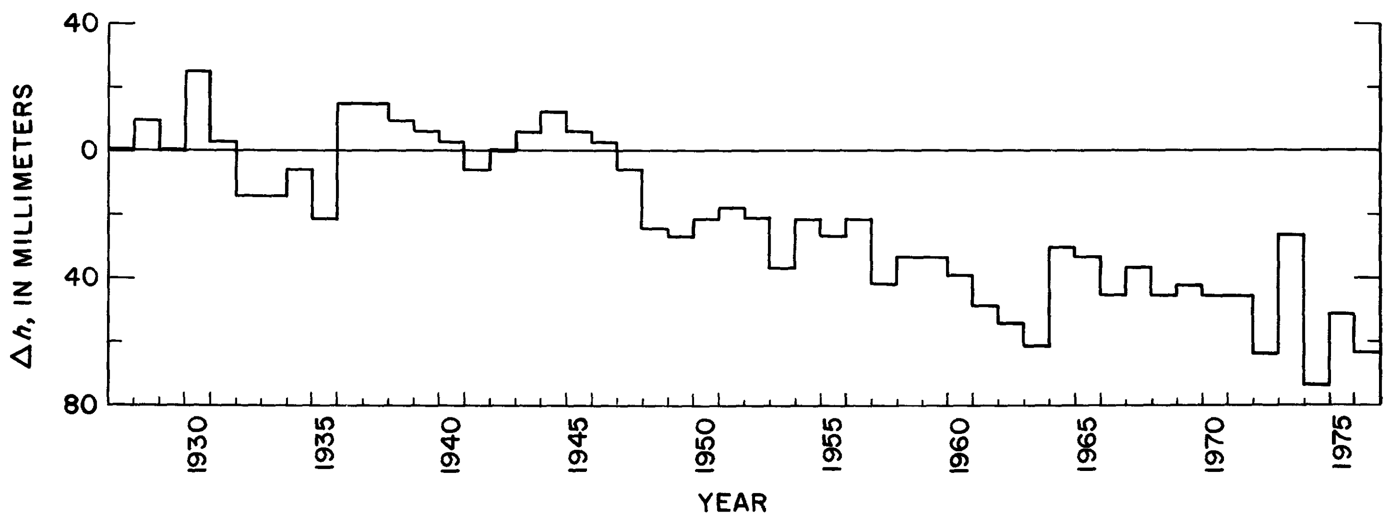


FIGURE 5.—Changes in mean sea level (Δh) at Berth 60, Los Angeles (San Pedro), with respect to Municipal Pier, San Diego. Based on unpublished data of the Tides and Currents Division of the National Ocean Survey (J. R. Hubbard, written commun., 1977).

the 1970–71 junctioning produces a seeming 0.23-m uplift of Avila Beach that is clearly inconsistent with the sea-level records and apparently an artifact of the reconstruction.

The probable occurrence of intrasurvey movement during the 1956/60 and 1970/71 levelings effectively limits useful comparisons to two parts of the main line: the section between Ventura and Gaviota and that between Surf and Avila Beach. Because the results both of repeated levelings and of discontinuous sea-level measurements indicate that the Santa Barbara tide station remained virtually invariant with respect to San Pedro during the interval 1920–60, 1939–48 surveys emanating from Santa Barbara can be treated as the equivalent of those propagated directly out of Tidal 8. Thus the results of the 1939/42/48 leveling tied to the reference tidal bench mark at Santa Barbara provide a reasonable preuplift datum for the sections between both Ventura and Gaviota and Gaviota and Los Olivos. Similarly, because the vertical displacement history of the Avila Beach tide station with respect to San Pedro can be assessed through differencing of the sea-level means, and because we are concerned here with height changes rather than with heights as such, the 1956 observed elevations provide an equally useful preuplift datum between Avila Beach and Surf.

A comparison of the results of the 1960 leveling against the preuplift datum shows that the uplift reached a maximum of about 0.07 m at Carpinteria and diminished westwardly to almost zero in the area of Gaviota. Two independent assessments indicate major tectonic subsidence at Surf during the interval 1956–60. Because the larger value is based on what we believe to be an unsupportable presumption of stability along the entire line during the 1970/71 leveling, subsidence at Surf of about 0.16 m, suggested by a 1960 misclosure on the 1956 height of Surf, is thought to be the more accurate estimate. By 1970, the uplift had increased to roughly 0.10 m within the reach between Carpinteria and Gaviota and the tectonic subsidence had diminished to about 0.08 m at Surf and to still lesser values northward to Avila Beach.

DETAILED RECONSTRUCTION

The Ventura-Avila Beach line consists of a primary control line between Ventura and Avila Beach, together with a single spur between Gaviota and Los Olivos incorporated in an alternative representation of the vertical movement history along this line (pl. 6). Starting elevations at Ventura are based on continuous first-order levelings between Tidal 8 and Ventura in 1960 and 1970/71. The 1960 starting elevation at Ventura derives from leveling between Tidal 8 and Ventura during the period March–May 1960 (NGS lines L-17850 and L-17847). Continuation of the "1960" datum northward from Surf to Avila Beach is based on 1956 leveling and an assumption of invariance between 1956 and 1960 at the junction bench marks at Surf. The 1970/71 starting elevation at Ventura is based on leveling between Tidal 8 and Ventura during the period October 1970–March 1971 (NGS line L-22292). The 1970 elevations between Pismo Beach and Avila Beach are based on the results of 1956 leveling, coupled with the assumption that the elevation differences remained invariant over this 10-km reach between 1956 and 1970.

The latest pre-1956 datum between Ventura and Avila Beach (or Pismo Beach) is based on 1920 leveling and is, as such, the only possible alternative to a combined 1956/60 datum as an approximation of a hypothetical 1955 primary datum. Even though its use violates our operating principle that this datum be no earlier than 1930, a 1920 datum is clearly preferable in the sense that it certainly predates any deformation associated with the initial development of the southern California uplift, whereas the 1956/60 datum probably does not. Nevertheless, the period 1920–56 includes the 1925 M = 6.3 Santa Barbara earthquake and the 1927 M = 7.5 Lompoc (or Point Arguello) earthquake, both of which occurred along or adjacent to this survey route (Richter, 1958, p. 534; Gawthrop, 1975, p. 8–9, 9–14). Morever, the relatively large misclosure around the 1920/27 circuit Gaviota-Surf-Pismo Beach-Buellton-Gaviota (fig. 6) suggests significant crustal deformation in this area during the period 1920–27. Accordingly, because we have no way of assessing the preseismic, coseismic, or even postseismic vertical movements that may have been associated with these shocks, we are especially reluctant to identify the 1920 elevations along this line with a hypothetical 1955 datum.

Comparison of the results of the 1970/71 surveys against a combined 1956/60 datum discloses modest uplift along the generally east-trending coastline between Ventura and Point Conception, together with sharply increasing uplift where the coast turns northwestward at Point Conception (pl. 6A). The 1960–70/71 uplift increased from virtually zero at Ventura to 0.05–0.06 m immediately east of Carpinteria and ranged generally between 0.05 m and 0.10 m westward from Carpinteria to about bench mark G 1050 near Point Conception. Northward from Point Conception, the apparent uplift increased to about 0.17 m at bench mark W 536 at Surf. Continuation of the comparison beyond Surf indicates that the 1956/60–70/71 uplift seemingly persisted (together with locally developed differential subsidence attributable to fluid extraction; see pl. 3), rising gradually toward the northern end of the line to a maximum of about 0.23 m.

An alternative reconstruction is suggested by several relatively large misclosures based on 1956 and 1960 levelings in the western Transverse Ranges (fig. 7). The 1956–60 misclosures, both of which are well above first-order limits, are consistent with crustal instability and are indicative of down-to-the-west tilting between Buellton-Los Olivos and Surf of 0.09–0.13 m during the period 1956–60. This probable instability, accordingly, precludes the use of the results of the 1960 surveys as

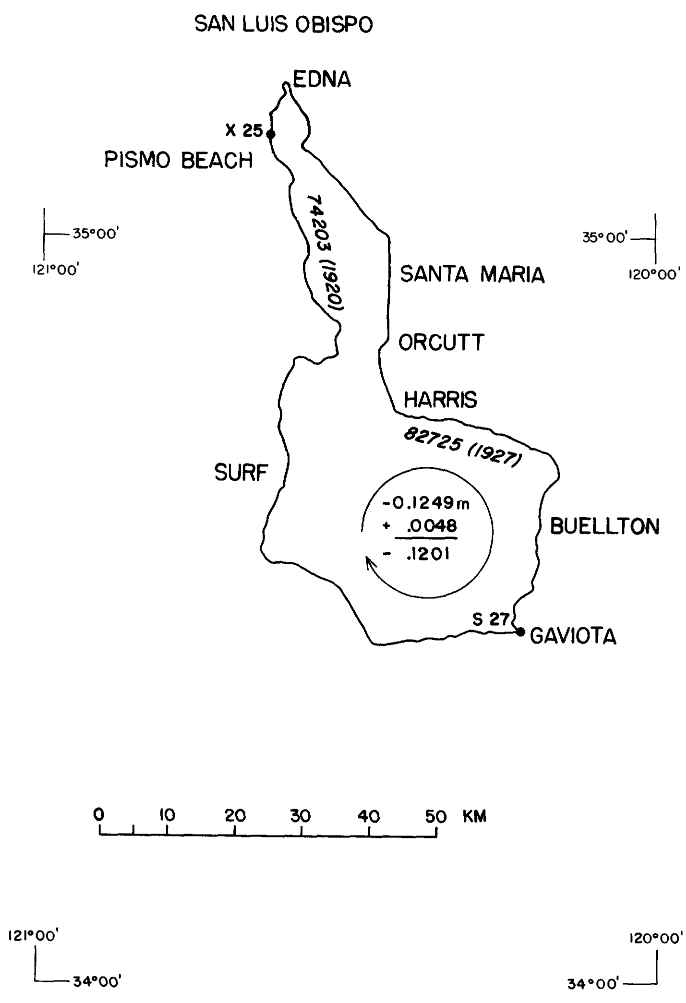


FIGURE 6.—Misclosure around the circuit Gaviota-Surf-Pismo Beach-Buellton-Gaviota based on 1920 and 1927 levelings. See figure 4 for adopted conventions and explanation of symbols.

a primary datum—that is, one that roughly matches the datum that would have been generated through 1955 leveling along this same route.

The development of an alternative primary datum derives from the recognition of relative stability at Santa Barbara during the period 1920–74 and sea-level measurements at the Avila Beach tide station as a basis for establishing elevations with respect to Tidal 8. Thus, the elevations of bench mark 0 28, Santa Barbara, with respect to Tidal 8, are:

1920—3.0915 m (the observed elevation at 0 28 has been reduced by 3 mm to account for the difference between the orthometric correction based on the 1920 interior route and that associated with the two subsequent levelings which followed nearly identical routes along the coast; it is assumed that bench mark I 33, San Pedro, remained invariant with respect to Tidal 8 during the period 1920–26)

1960—3.0911 m

1970/71—3.1278 m

(NGS lines 74203, 82583, L-17847, L-17850, L-21366, L-21537, L-21729, and L-22292). Because 0 28 remained virtually invariant with respect to Tidal 8 during the period 1920–60 (a conclusion supported by discontinuous sea-level measurements at Santa Barbara which show that Santa Barbara subsided less than 0.01 m with respect to Tidal 8 during the period 1933/34-74; J. R. Hubbard, National Ocean Survey, written commun., 1977), leveling emanating from 0 28 between 1920 and 1960 may be treated as if it had emanated directly from Tidal 8. Accordingly, the results of 1942 and 1948 levelings originating at 0 28 should closely approximate those that would have been obtained had these surveys originated at Tidal 8. Because the 1942 surveys extended eastward only as far as Carpinteria, we have used the results of 1939 leveling to develop a pre-1960 datum between Carpinteria and Ventura. Use of this 1939/42/48 datum as the approximate equivalent of a hypothetical 1955 datum is supported by a relatively small misclosure around the 505-km loop Santa Barbara-Santa Maria-San Luis Obispo-McKittrick-Maricopa-Ventura-Santa Barbara based on leveling carried out over the full interval 1934-57 (fig. 8). Morever, were it not for various differential displacements that almost certainly occurred at several junctions along this route, this misclosure (fig. 8) could have been even less. (For example, differential subsidence at I 30 during the period 1934–39 or at M 569 during the period 1939–42 would increase any positive clockwise misclosure.) Hence, we have provisionally accepted the combined results of the 1939, 1942, and 1948 levelings emanating from bench mark 0 28 as the approximate equivalent of a 1955 datum emanating from Tidal 8.

Although there are no data permitting the development of a pre-1960 datum between Gaviota and Surf (other than those obtained from the 1920 leveling), a 1956 datum between Avila Beach and Surf can be reconstructed through a combination of levelings between Tidal 8 and Avila Beach and sea-level measurements at both Avila Beach and San Pedro. Thus, the 1970/71 elevation of bench mark Tidal 11, Avila Beach, is determinable through the results of more or less continuous 1970/71 leveling between Tidal 8 and bench mark X 25 and 1956 leveling between X 25 and Tidal 11, where it is assumed that the elevation difference between X 25 and Tidal 11 remained unchanged between 1956 and 1970 (NGS lines L-15972 and L-22292). The 1956 elevation of Tidal 11 with respect to Tidal 8 is based on a comparison of annual sea-level means that show that the Avila Beach tide station subsided 21.4 mm between 1956 and 1970 (J. R. Hubbard, National Ocean Survey, written commun., 1977). The random error alone in the reconstructed 1956 elevations between Avila Beach and Surf probably is at least 50 percent greater than that based on leveling that proceeded directly out of Tidal 8. Morever, some uncertainty is occasioned by the probable noise level inherent in the differencing of sea-level measurements over the 300-km distance between San Pedro and Avila Beach. Nevertheless, both of these errors are probably in the centimeter range and the only necessary procedural assumptions are: (1) that the elevation difference between X 25 and Tidal 11 remained invariant during the period 1956–70/71, (2) that any changes in eustatic sea level have been expressed equally at both tide stations, and (3) that any changes in salinity, temperature, and other factors

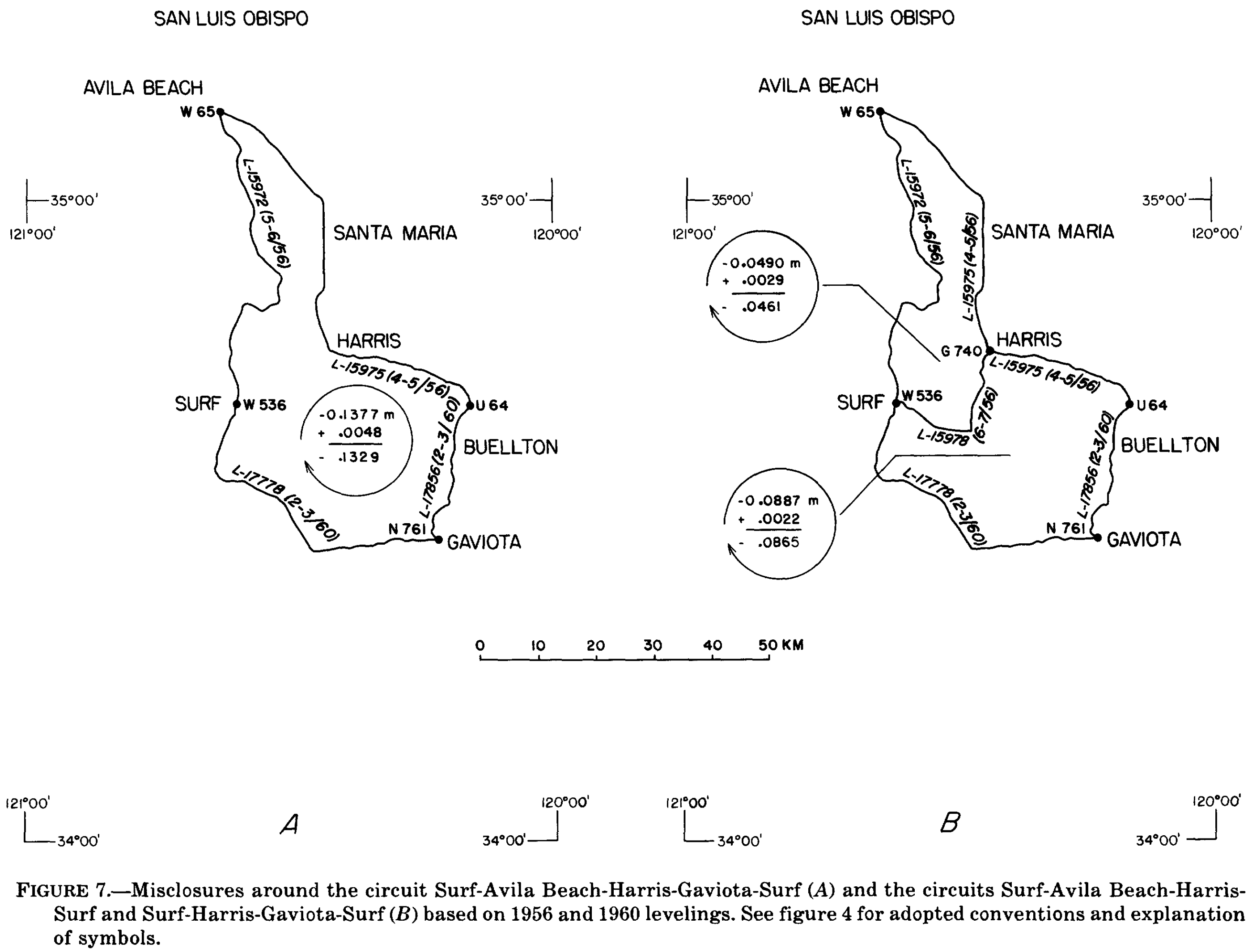


FIGURE 7.—Misclosures around the circuit Surf-Avila Beach-Harris-Gaviota-Surf (*A*) and the circuits Surf-Avila Beach-Harris-Surf and Surf-Harris-Gaviota-Surf (*B*) based on 1956 and 1960 levelings. See figure 4 for adopted conventions and explanation of symbols.

that affect the length of the water column can be disregarded over the 300-km distance between San Pedro and Avila Beach. Accordingly, the reconstructed 1956 datum should roughly approximate a 1956 (1955-equivalent) datum based on leveling emanating from Tidal 8.

The alternative representation of elevation changes between Ventura and Avila Beach (pl. 6B) provides further insight into the history of vertical movement in the western Transverse Ranges and contradicts, in part, the simple comparison between the results of the 1970/71 leveling against a 1956/60 datum (pl. 6A). Westward from Ventura, uplift during the period 1939/42/48–60 increased sharply from about −40 mm to roughly 70 mm at Carpinteria, declined to a nearly uniform figure of 40–50 mm between Carpinteria and Santa Barbara, and dropped still further between Santa Barbara and Gaviota to about 20 mm (pl. 6B). Cumulative vertical displacements during the period 1939/42/48–70/71 increased westward from about −40 mm at Ventura to well over 100 mm at Carpinteria, and held at or slightly below 100 mm between Carpinteria and Gaviota (pl. 6B).

The height changes between Surf and Avila Beach shown in the alternative reconstruction (pl. 6B) differ strikingly from those shown on profile A. Specifically, rather than uplift increasing northward from Surf during the period 1956–70, as shown in profile A, the alternative reconstruction

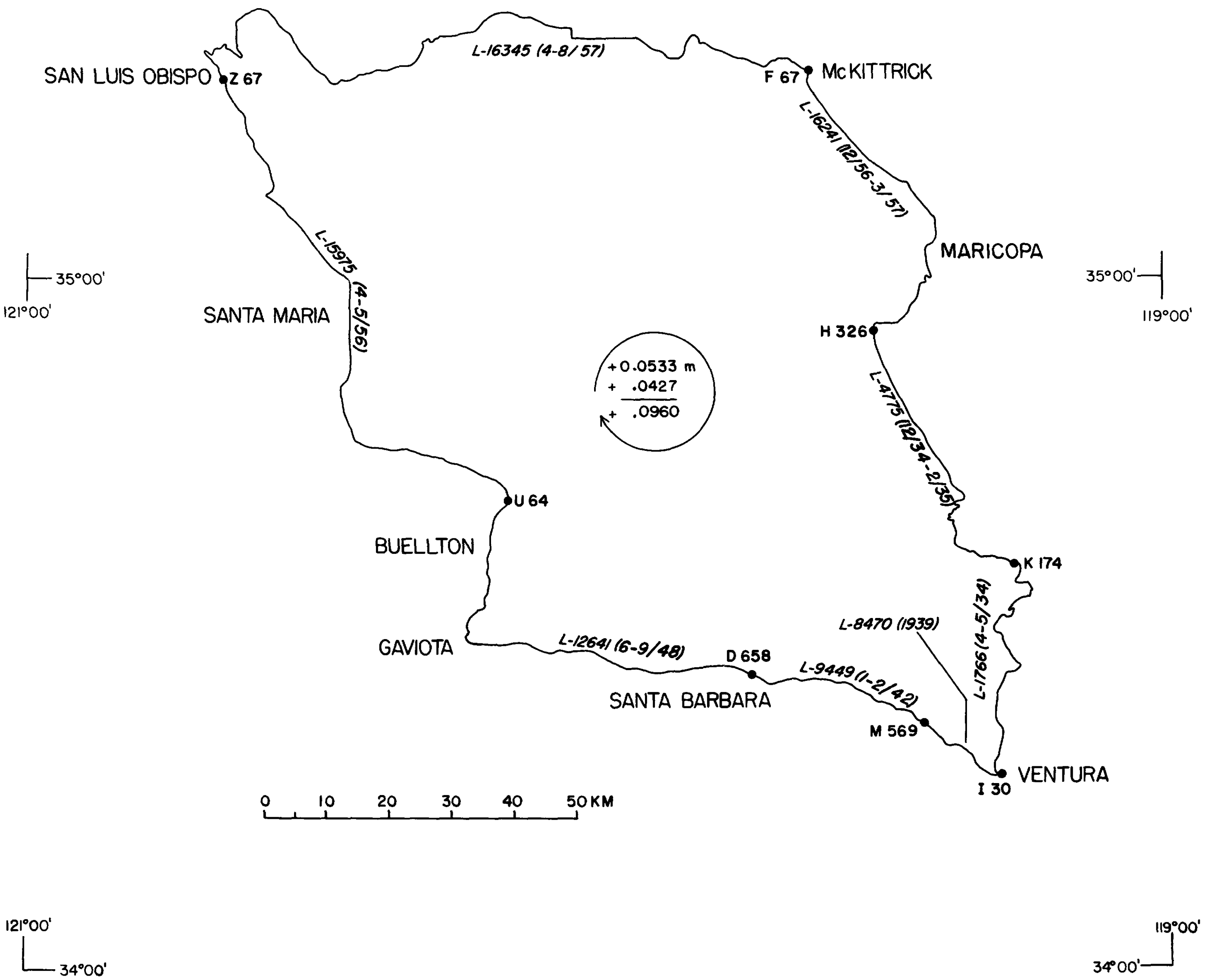


FIGURE 8.—Misclosure around the circuit Santa Barbara-Santa Maria-San Luis Obispo-McKittrick-Maricopa-Ventura-Santa Barbara based on 1948, 1956/57, 1934/35, 1939, and 1942 levelings. See figure 4 for adopted conventions and explanation of symbols.

indicates that this reach sustained tectonic subsidence that accumulated more or less uniformly southward from Avila Beach. Similarly, a comparison of 1960 elevations based on leveling originating at Tidal 8 against the reconstructed datum indicates that Surf sustained tectonic subsidence of about 0.25 m during the period 1956–60. Moreover, even though major uplift is inferred to have occurred at Surf between 1960 and 1970/71 (pl. 6A), it was apparently insufficient to restore Surf to its preuplift (1956) height. Hence, while the 1956-60 tectonic subsidence at Surf seems surprisingly large (pl. 6B), it is certainly not impossible.

Although we are convinced that the alternative reconstruction (pl. 6B) is a much more realistic and generally more consistent appraisal of height changes along the Ventura-Avila Beach line than that shown on profile A, the cumulative evidence suggests that certain aspects of this reconstruction (especially the 0.25-m 1956–60 subsidence at Surf) may be significantly in error. For example, if it is assumed that the western Transverse Ranges were characterized by crustal stability during the period 1934–57, unqualified acceptance of the alternative reconstruction coupled with the invariance of bench mark I 30 between 1939 and 1960 (see section on "The Ventura-Maricopa Line"), argues that the clockwise misclosure around the loop Surf-San Luis Obispo-McKittrick-Maricopa-Ventura-Gaviota-Surf based on 1960, 1956, 1957, 1956/57, and 1934/35 levelings should be about −0.25 m. Moreover, if allowance is made for the probable tectonic subsidence of 0.06 m at bench mark H 326 (fig. 8) during the 1952 Kern County earthquake (see section on "The Ventura-Maricopa Line"), this postulated misclosure would enlarge to about −0.3 m. In fact, however, the actual misclosure is only about −0.06 m (fig. 9). Several explanations may account, in whole or in part, for this seeming contradiction. (1) To the extent that it may indicate an error in the represented misclosure (fig. 9), an imprecisely formulated orthometric correction seems an especially plausible partial explanation for this apparent discrepancy. Not only might the orthometric closure be a good deal smaller than shown here, it might even be opposite in sign. Moreover, this possibility is consistent with the positive misclosure around the somewhat shorter loop that excludes the results of the 1960 leveling (fig. 8). That is, given the occurrence of 0.06 m of tectonic subsidence at H 326 during the 1952 earthquake, this misclosure (fig. 8) might otherwise have been even larger; algebraic reduction of the orthometric correction could reduce even the displacement-corrected misclosure to a value well within first-order limits (0.0899 m). Nevertheless, all of our experience in this area indicates that errors in the orthometric closure in excess of 0.05 m must be very rare. Hence, while rigorous calculation of the orthometric closure (based on observed gravity) could lead to a corrected misclosure involving the results of the 1960 leveling (fig. 9) of as much as −0.11 m, a value more in keeping with that predicted by the alternative reconstruction (pl. 6B), it could account for only a small fraction of the approximately 0.2-m discrepancy. (2) It is conceivable that the junction marks around that part of the loop north and east of Surf (fig. 9) sustained artificially induced differential displacements between connecting levelings. This possibility is challenged, however, by the relatively small misclosure that excludes the results of the 1960 leveling (fig. 8). (3) Finally, the indicated discrepancy may, in fact, be more apparent than real. Specifically, clockwise around the nearly congruent circuits shown in figures 8 and 9, the misclosures are based on the results of the same levelings between bench marks G 740 and I 30. Thus, if we assume that the actually measured elevation difference over the relatively short reach between N 761 and G 740 produced through 1948 leveling between N 761 and U 64 and 1956 leveling between U 64 and G 740 is the same as that that would have been obtained through 1948 leveling between N 761 and W 536 and 1956 leveling between W 536 and G 740, and if we disregard the trivial difference in the orthometric correction around these two loops (figs. 8 and 9), the misclosure around the exterior loop must have enlarged by −0.1651 m during the period 1956–60. This inferred change in the misclosure is much more consistent with the tectonic subsidence deduced from the alternative reconstruction (pl. 6B), and while it could have occurred for whatever reason, it is presumably attributable to tectonic activity within the reach between bench mark I 30 and W 536 during the period 1956–60.

The validity of the reconstructed 1956–60 height changes at Surf (pl. 6B) ultimately depends on the validity of the 1970/71 height difference between Tidal 8 and the Avila Beach tide station, a value that is currently suspect. Balazs and Douglas (1979) present fairly convincing evidence that the 1968/71 San Francisco-San Pedro height difference, based on leveling that includes the results of the 1970/71 survey between X 25 and Tidal 8, may be in error by 0.5 m or more. Thus there is a reasonable basis for assuming that a sizable fraction of this error occurred between Avila Beach and San

Pedro. And, in fact, recent investigations (Castle and Elliott, 1982, p. 7012–7021) have shown that a 0.2-m displacement could easily have occurred (and probably did occur) at Point Conception during a 3-month interruption in the 1970/71 "continuous" leveling. Accordingly, the indicated 1956–60 tectonic subsidence at Surf is almost certainly in error, whereas the 1956–70 displacements between Avila Beach and Surf are much less subject to question (pl. 6B). That is, while all of the possible explanations set forth in the preceding paragraph may have contributed in some measure to the discrepancy between the orthometrically corrected misclosure (fig. 9) and the represented 1956-60 height change at Surf (pl. 6B), the change in misclosures between 1956/57 and 1960 (figs. 8 and 9) probably closely approximates the actual 1956–60 tectonic subsidence at Surf. Hence the representation shown on plate 6B probably exaggerates the 1956–60 tectonic subsidence at Surf by about 0.1 m.

Height changes along the Gaviota-Los Olivos spur (pl. 6B) are based on comparisons between the results of 1948 (1955-equivalent) leveling emanating from 0 28, 1956 (1955-equivalent) leveling emanating from Avila Beach (NGS lines L-15972 and L-15975), and 1960 leveling emanating from Tidal 8. While the apparent subsidence of U 64 of 4.2 mm during the period 1948–60 contrasts sharply with the much greater (orthometrically corrected) subsidence of 113.4 mm between 1956 and 1960, both

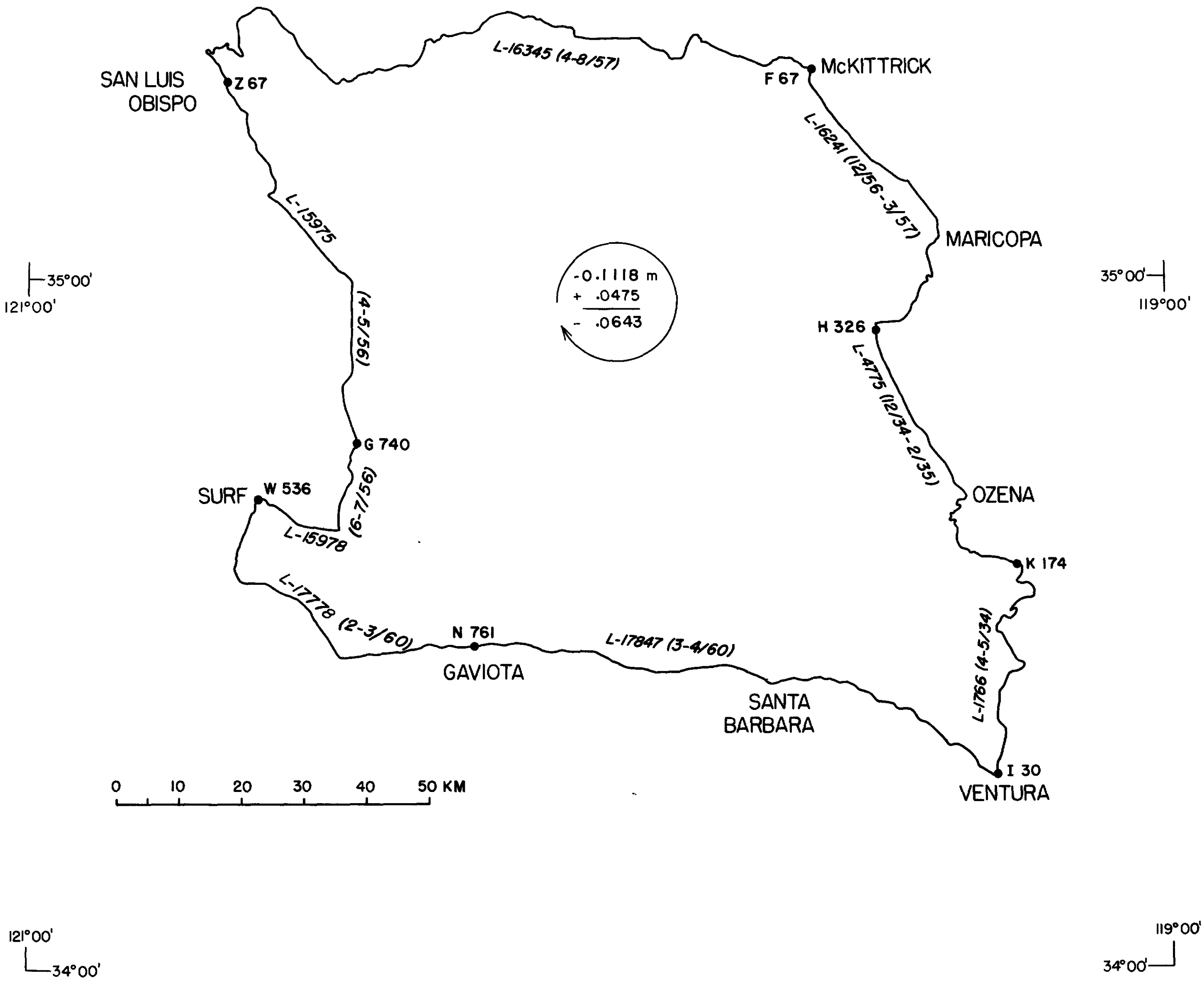


FIGURE 9.—Misclosure around the circuit Surf-San Luis Obispo-McKittrick-Maricopa-Ventura-Gaviota-Surf based on 1956/57, 1934/35, and 1960 levelings. See figure 4 for adopted conventions and explanation of symbols.

values indicate that the southern California uplift could not have extended significantly west of Los Olivos by 1960. Moreover, the relatively tight closure around the 505-km circuit that involves both the 1948 and the 1956 levelings (fig. 8) suggests that the discrepancy between the 1948–60 and the 1956–60 subsidence of U 64 cannot be attributed solely to uplift of U 64 between 1948 and 1956. Hence we again suspect that this discrepancy is a measure of the inaccuracy of the reconstructed 1956 elevations (based on a 1970/71 tie between Tidal 8 and Avila Beach and the 1956 leveling originating at Avila Beach). That is, the 1956–60 tectonic signal at Los Olivos probably was virtually zero.

THE VENTURA-MARICOPA LINE

GENERAL REMARKS

Assessments of the vertical displacements along the Ventura-Maricopa line (pl. 7) are complicated by the absence of an unambiguous preuplift datum and the probable occurrence of intrasurvey movement during one of the three surveys along the full length of this line. Although we have provisionally adopted a combined 1934/35 Ventura-Maricopa and 1942/43 Ozena-Frazier Park datum as the approximate equivalent of a hypothetical 1955 datum, it is virtually certain that the northern end of this line sustained at least modest coseismic deformation during the 1952 Kern County earthquake. Accordingly, in calculating post-1955 uplift along this line, use of the pre-1952 datum requires that we subtract out, wherever possible, any coseismic vertical displacements associated with this earthquake.

The near invariance of the southern end of the Ventura-Maricopa line during the 1952 earthquake, together with the results of 1953 leveling into the northern part of this area, provides a basis for a reasonably good characterization of the 1952 coseismic movements along much of this line. Specifically, immediately north of Ozena, the 1934/35 heights were as much as 0.10 m above the 1953 post-earthquake heights, whereas northward toward Maricopa this height difference diminished to about 0.06–0.07 m and, less certainly, to values approaching zero southward toward Wheeler Springs. Eastward from Ozena to Frazier Park, on the other hand, the coseismic subsidence inverted to uplift of about 0.06 m in the Lebec area. Thus, during the period 1953–59/60 aseismic uplift of about 0.21 m accumulated in the Ozena area and uplift of nearly this magnitude apparently persisted northward toward Maricopa, yet diminished southward to no more than 0.08–0.10 m in the Wheeler Springs area and eastward to roughly 0.18 m at Lebec. However, the exclusion of equivocally defined 1953–57 postseismic adjustment along the northern end of the line suggests that the 1955–59/60 uplift may have been somewhat less than these actually measured values. By 1968, the heights along most of the line had increased by 0.08–0.10 m over those that obtained in 1959/60, and the uplift reached a cumulative maximum at Ozena of about 0.31 m. Finally, comparisons of the results of 1974 surveys (limited to the southern half of the main line) against a 1968 datum indicate that a significant change in the displacement pattern, expressed as 0.05 m of tectonic subsidence over a 15-km reach between Ventura and Wheeler Springs, apparently occurred during this latest interval.

An alternative reconstruction of the data is suggested by the nearly certain stability of central Bakersfield during the period 1953–59 and a 0.29-m misclosure interpreted as the product of intrasurvey movement during the course of 1959–61 levelings through the west-central Transverse Ranges. Accordingly, because the 1953 heights of the Bakersfield marks are based on levelings tied directly to Tidal 8, the 1959 leveling emanating from Bakersfield may be treated as the equivalent of that propagated directly out of Tidal 8. Contrary to our expectation, this alternative reconstruction indicates that our basic presumption of stability at Ozena is invalid, and that Ozena actually rose 0.16 m between the 1959 and 1960 levelings into (or out of) Ozena. This same reconstruction also indicates that Lebec sustained tectonic subsidence of 0.11–0.14 m during the period 1959–60/61 and, hence, that a 1959–60/61 up-to-the-west tilt between Lebec and Ozena accounts for nearly the entire 1959–61 misclosure. Acceptance of this alternative reconstruction effectively divides the vertical displacement history along the Ventura-Maricopa line into two parts: one extending northward and eastward from Ozena to Maricopa and Lebec, respectively, and a second extending southward from Ozena to Ventura. The chronology of the uplift and partial collapse is much more clearly documented along the southern half of the line, whereas the magnitude of the uplift (through 1968) is less ambiguously described along the northern half. The ultimate effect of this preferred reconstruction is to reduce the calculated maximum aseismic uplift along the Ventura-Maricopa line from 0.31 m to about 0.28 m.

DETAILED RECONSTRUCTION

The Ventura-Maricopa line consists of a primary vertical-control line between Ventura and Maricopa, together with a single spur between Ozena and Frazier Park (pl. 7). Starting elevations at Ventura are based both directly on a series of virtually continuous first-order levelings between Tidal 8 and Ventura and indirectly on repeated first-order surveys between Tidal 8 and bench mark 0 28, Santa Barbara. The 1934 starting elevation at bench mark I 30, Ventura (pl. 7), is based on the results of a combination of surveys of various vintages. Because bench mark 0 28 remained nearly invariant with respect to Tidal 8 during the period 1920–60 (see section on "The Ventura-Avila Beach Line"), and because the observed elevation difference between bench marks 0 28 and D 29, Carpinteria (pl. 6), increased by less than 12 mm between 1920 and 1942 (NGS lines 74203 and L-9449), 1939 leveling emanating from D 29 may be treated as if it had originated at Tidal 8. Accordingly, combining the 1939 elevation difference between D 29 and I 30 (NGS line L-8470) with the 1920 elevation of D 29 (NGS lines 74203 and 82583—rather than with the more complexly determined 1942 elevation based on leveling emanating from 0 28, a determination that would increase the length of the Tidal 8-D 29 survey route by about 40 km—produces a 1939 observed elevation for I 30 of 5.2464 m. The reconstructed 1920 and 1960 orthometrically compatible observed elevations of I 30 are given as 5.3078 m and 5.2157 m, respectively (NGS lines 74203, 82583, L-17847, and L-17850); because the resulting 1939 interpolated elevation of I 30 is only about 0.01 m greater than the 1939 reconstructed elevation (5.2589 m versus 5.2464 m), it supports the validity of the reconstruction. Nonetheless, the 1934 starting elevation of bench mark I 30 finally depends on an assumed invariance of this mark between 1934 and 1939. The likelihood that I 30 in fact remained unchanged in height during this period is significantly enhanced by its relative stability during the full period 1939–73, and especially during the period 1939–60 (fig. 10). The 1960 starting elevation is based on leveling between Tidal 8 and Ventura completed during the period March–May 1960 (NGS lines L-17847 and L-17850). The 1968 starting elevation has been reconstructed from surveys carried out during the period February-September 1968 (NGS lines L-21366, L-21537, and L-21729). The 1974 starting elevation of the junction bench mark at Ventura is based on leveling completed during the period March–October 1973 (NGS lines L-23693, L-23697, L-23701, L-23709, and L-23891) and the presumed invariance of this mark during the period 1973–74. The 1953 orthometrically compatible starting elevation at Maricopa is based on the results of 1953/55 leveling propagated directly out of Tidal 8 (NGS lines L-14796, L-14799, and L-15577). The 1957 starting elevation at bench mark H 326 is based on an assumption of stability at this mark during the period 1953–57.

Several lines of evidence indicate that much or most of the Ventura-Maricopa line remained relatively free of regional deformation from 1934 through at least 1957 and, hence, that the reconstructed 1934/35 observed elevations roughly approximate those that would have been developed from the results of 1955 leveling originating at Tidal 8. Implicit in this judgment is the probable invariance of junction bench mark K 174 (fig. 8) during the interval between the 1934 and 1935 levelings; the 1934–35 stability of this mark seems especially likely since there is no evidence of physical disturbance (which would be revealed as a step in the profiled elevation changes), nor is there any indication that K 174 might have sustained any artificially induced or coseismic displacements during this period (pls. 3 and 4; Hileman and others, 1973, p. 16–17).

Arguments suggestive of relative stability along the Ventura-Maricopa line during the period 1934–57 include: (1) Between 1934 and 1939, bench mark M 173 sustained differential uplift with respect to I 30 of no more than 15–16 mm (pl. 7). Moreover, because I 30 subsided at an average rate of about 2 mm/yr during the period 1920–60 (fig. 10), it is

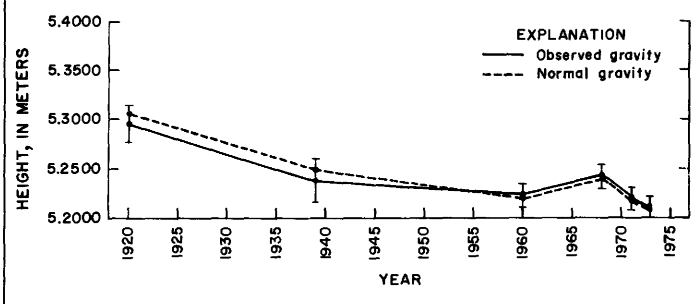


FIGURE 10.—Changes in orthometric height at bench mark I 30, Ventura. The 1939 height is based on 1920 leveling between bench mark I 33, San Pedro, and bench mark D 39, Carpinteria, and on assumptions of invariance between O 28, Santa Barbara, and bench mark Tidal 8 during the period 1920–60 and between 0 28 and D 39 during the period 1920–39. The 1973 height is based on an assumption of invariance between bench mark I 30 and adjacent bench mark P 1100 during the period 1968–73. See text for details. One-standard-deviation error bars show conventionally estimated random error only.

likely that even this modest tilt is attributable in part to compaction-induced subsidence beneath I 30. In any case, it is reasonably certain that the 20-km reach between I 30 and M 173 experienced little, if any, deformation (exclusive of the artificially induced differential subsidence centering on the Ventura oil field—see pls. 3 and 4 and Buchanan-Banks and others, 1975, p. 118, 123–124) during the period 1934–39. (2) The vertical displacement history of bench mark I 30 (fig. 10) indicates that at least the southern end of this line sustained little tectonic displacement between 1939 and 1960. (3) A comparison of the results of 1935 levelings against 1957 levelings between bench marks H 326 and Q 326 shows very little evidence of regional tilting along this 20-km segment at the northern end of the Ventura-Maricopa line during the whole interval 1935–57 (pl. 7). (4) The results of repeated levelings along the National Geodetic Survey monitor line athwart the San Andreas fault (fig. 11) indicate that this section of the Ventura-Maricopa line remained virtually free of regional deformation during the period 1935–59. Although reconstruction of these data with respect to bench mark N 326 indicates that measurable movement occurred between 1935 and 1938 (fig. 11*A*), this movement seems to have been confined largely to the area of the monitor line, for the more inclusive section between bench marks H 326 and Q 326 was devoid of significant tilting during the period 1935–57 (pl. 7). In any event, the relative stability of the monitor line during the interval 1938–59 is clearly evident, and such deformation as did occur between 1935 and 1959 was certainly much less than subsequent deformation recognized along this line (fig. 11). (5) The misclosure around the 505-km loop based on the results of first-order levelings during the 23-year interval 1934–57, which includes the results of the 1934/35 leveling between I 30 and H 326, is only 6 mm over first-order limits (fig. 8). Moreover, the indicated orthometric correction around this loop may be significantly in error (see section on "The Ventura-Avila Beach Line"); utilization of a correction based on observed gravity could diminish this misclosure to an even smaller value. Nonetheless, this relatively small misclosure (fig. 8) suggests that the western Transverse Ranges sustained no more than modest height changes during the period 1934–57.

The same set of arguments that supports the equivalence of the reconstructed 1934/35 elevations between Ventura and Maricopa with a hypothetical 1955 datum also supports the use of the 1942/43 reconstructed elevations between Ozena and Frazier Park as the approximate equivalents of those that would have been obtained had the leveling been carried out in 1955. The 1942/43 starting elevation at Ozena is necessarily based on the reconstructed 1934/35 observed elevation of junction bench mark 3450 (Tri-Co) (pl. 7) and the acceptance of the vertical stability of this mark during the interval 1934/35–42/43. The likelihood that the entire Ozena-Frazier Park spur, including 3450 (Tri-Co), remained free of significant vertical displacement during the interval 1934/35–42/43 is supported by the very small misclosure around the loop San Pedro-Ventura-Ozena-Lebec-San Pedro completed during the period 1920–42/43, which includes the results of both the 1934/35 surveys between Ventura and Ozena and the 1942/43 surveys between Ozena and Lebec (fig. 12). The sense of this small misclosure, moreover, is consistent with the similarly slight subsidence at Ventura (bench mark I 30) during the period 1920–39 (fig. 10). The likelihood that at least the eastern end of the Ozena-Frazier Park spur remained invariant during the period 1934/35–42/43 is reinforced by the elevation history of bench mark E 54, Lebec (pl. 7). Thus, the 1926 observed elevation (1097.5131 m) of bench mark E 54 based on first-order leveling originating at Tidal 8 (NGS lines 82466, 82583, and 82598) very nearly matches the reconstructed observed elevation (1097.4877 m) or the orthometrically compatible elevation (1097.4869 m) based on 1942/43 leveling via Ozena. Furthermore, had the 1934/35 starting elevation at I 30 been based on a 1934 interpolated elevation, rather than on a reconstructed 1939 elevation, the difference between the 1926 and 1942/43 elevations of E 54 would have been reduced by 16 mm. Thus, the very small misclosure incorporating the results of the 1934/35 and the 1942/43 surveys (fig. 12) and the excellent correspondence between the reconstructed 1926 and 1942/43 elevations of bench mark E 54 support both the likelihood of tectonic quiescence in the western Transverse Ranges between 1926 and 1942/43 and the validity of the reconstructed 1934/35 and 1942/43 elevations along the Ventura-Maricopa line. However, whether the inferred quiescence along the Ozena-Frazier Park spur persisted significantly beyond 1942/43 is much less certain.

In spite of the various indications of crustal stability cited in the preceding paragraphs, there is fairly compelling evidence of at least modest deformation along the Ventura-Maricopa line during the period 1934–55, particularly in the area between Wheeler Springs and the San Andreas fault and eastward from Ozena to Frazier Park (pl. 7):

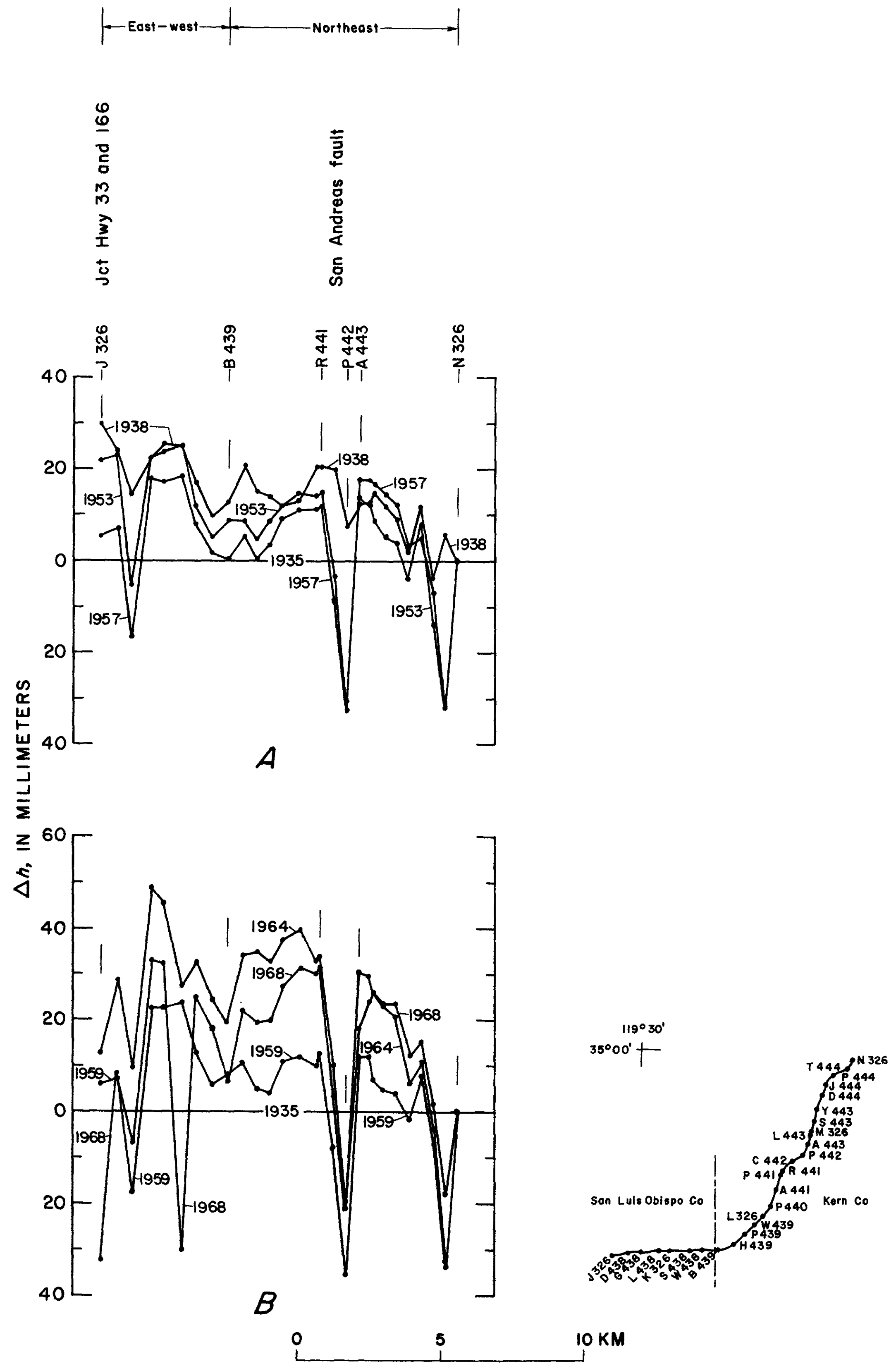


FIGURE 11.—Height changes (Δh) with respect to bench mark N 326 along National Geodetic Survey monitor line southwest of Maricopa (pl. 5). *A*, Comparisons against a 1935 datum of the results of repeated levelings carried out between 1938 and 1957. *B*, Comparisons against a 1935 datum of the results of repeated levelings carried out between 1959 and 1968.

(1) A comparison of the results of 1953 leveling against the 1934/35 datum indicates that measurably significant post-1934/35 tectonic subsidence occurred along the northern end of the line and apparently increased southward to Ozena (pl. 7). Moreover, the form of the profiled height changes between D 326 and Q 326 during the period 1934/35–53 is nearly congruent with that developed from a comparison of the results of the 1959 surveys against the 1934/35 datum, and, to a somewhat lesser extent, with that developed from a comparison of the results of the 1957 leveling against the 1934/35 datum (pl. 7). Hence, we infer that the elevation differences in this part of the Transverse Ranges remained virtually invariant during the period 1953–59 and that we may use measured differences obtained at any time during this interval as a basis for extending the 1953 elevations southward from D 326 to Ozena—whereby the height of junction bench mark 3450 (Tri-Co) dropped about 0.12 between 1934/35 and 1953. (2) The 1926 observed elevation (1097.5131 m) of bench mark E 54, Lebec (pl. 7), based on 1926 leveling between Tidal 8 and Lebec, lay 0.0650 m below its 1953 observed elevation (1097.5781 m), based on 1953 leveling over the same route (see section on "The Los Angeles-Mojave Line"). Accordingly, the 1953 elevations of the Lebec bench marks were significantly above their 1926 and, hence, their 1942/43 elevations (see above). Because the elevation difference between E 54 and 3450 (Tri-Co) increased by 0.1745 m during the interval 1942/43-59 (pl. 7), because the elevation differences through this part of the Transverse Ranges probably remained virtually unchanged

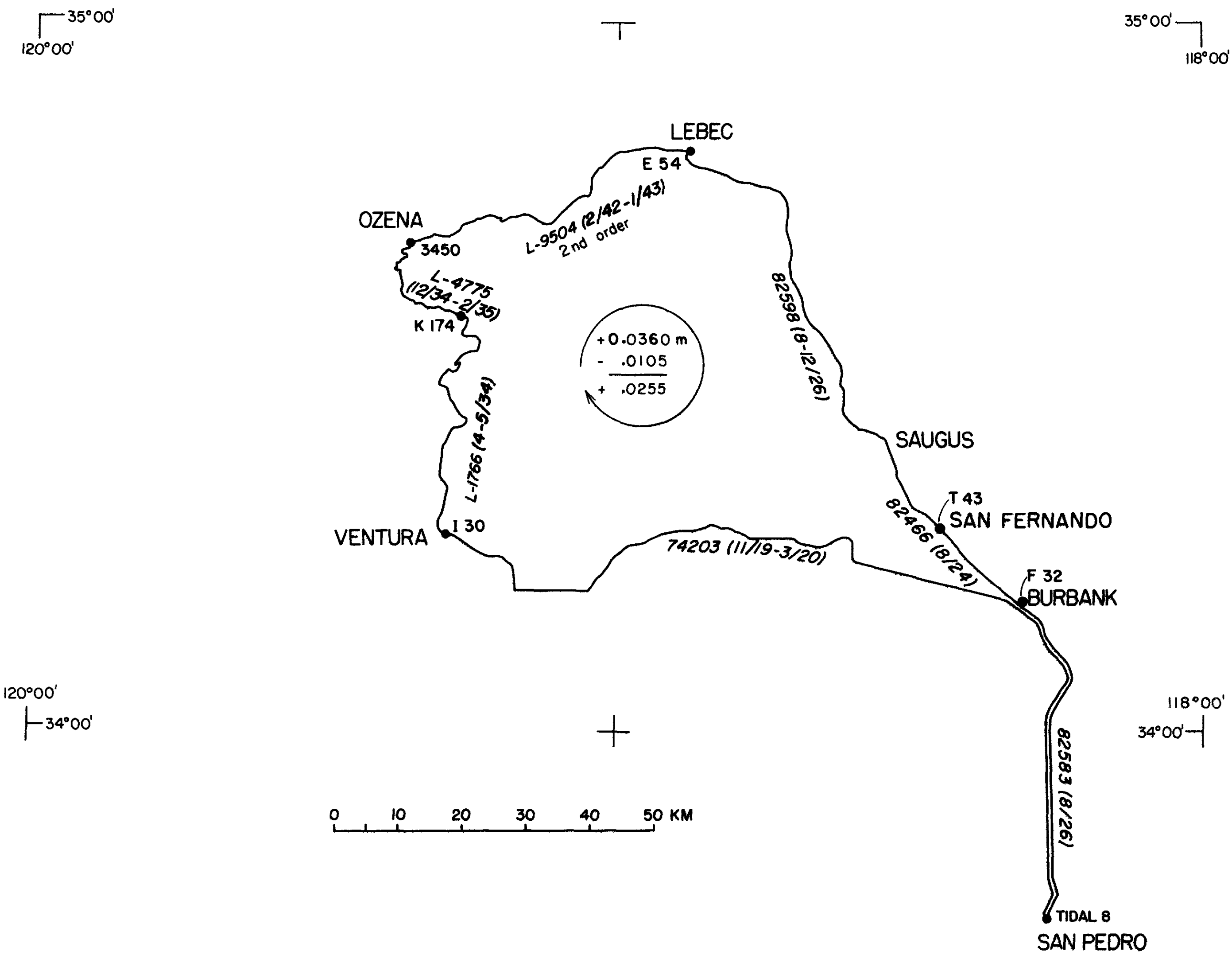


FIGURE 12.—Misclosure around the circuit San Pedro-Ventura-Ozena-Lebec-San Pedro based on 1920, 1934/35, 1942/43, and 1924/26 levelings. See figure 4 for adopted conventions and explanation of symbols.

during the period 1953-59, and because E 54 rose 0.0650 m with respect to Tidal 8 during the period 1942/43–53, we infer that during the period 1942/43–55 (or 1942/43–53) bench mark 3450 (Tri-Co) subsided 0.1095 m with respect to Tidal 8, a value that closely matches that deduced from a comparison of the results of 1953/59 leveling along the main line against the 1934/35 datum.

If the described differences between the 1934/35/42/43 datum and the elevations that obtained during the interval 1953–59 are accepted as accurate, then the configuration of a hypothetical 1955 datum along the Ventura-Maricopa line can be roughly characterized in terms of the 1934/35 datum. Thus, northward from Ventura (and disregarding the subsidence associated with production from the oil fields at either end of the line—pls. 3 and 4 and Buchanan-Banks and others, 1975, p. 118, 123–124), where the 1934/35 and 1955 heights virtually coincide (fig. 10), the 1955 surface dipped about 0.12 m below the 1934/35 datum at, or south of, Ozena. Northward from Ozena, this subsidence diminished to a minimum of about 0.06 m at bench mark 2749; it increased again still farther north to about 0.07 m in the area of bench mark Q 326 (pl. 7). Similarly, eastward from Ozena, the 1942/43–55 tectonic subsidence diminished to zero immediately east of Lockwood Airport, changing to uplift of about 0.07–0.08 m at Frazier Park and diminishing again to uplift of no more than 0.06–0.07 m near Lebec. The distribution of these displacements, in both space and time, indicates that they are almost certainly coseismic effects associated with the 1952 Kern County earthquake (Oakeshott, 1955).

Height changes along the Ventura-Maricopa line measured against a hypothesized 1955 datum can be calculated through algebraic differencing between: (1) the 1934/35–59/60 (and the 1942/43–59/60), the 1934/35–68 (and the 1942/43–68), and the 1934/35–74 height changes and (2) the 1934/35–55 (and the 1942/43–55) elevation changes described in the preceding paragraph. Comparisons with the 1959/60 elevations proceed from (1) an assumption of vertical invariance at the junction bench mark during the junction interval between the spring of 1959 and the spring of 1960 and (2) the likelihood that the measured elevation differences based on 1959 leveling between Ozena and Maricopa roughly match those that would have been obtained in 1960. It is assumed, in other words, that the results of the combined 1959 and 1960 level surveys are the same as those that would have been produced had the 1959 leveling been carried out entirely during the spring of 1960. Support for the likelihood that the measured elevation differences produced in 1959 closely approximate those that would have been generated in 1960 is provided by the near-congruency between the profiles of the 1934/35–59/60 (or the 1942/43–59/60) and the 1934/35–68 (or the 1942/43–68) height changes (pl. 7).

Northward along the Ventura-Maricopa line from bench mark I 30 (and again disregarding any differential subsidence associated with oil field operations), uplift between 1955 and 1959/60 increased from virtually zero at the southern end of the line (fig. 10) to perhaps 0.09 m or more as far south as Wheeler Springs (pl. 7) and to about 0.21 m [0.09 m − (− 0.12 m)] at Ozena. Northward from Ozena the 1955–59/60 uplift diminished to about 0.19 m [0.13 m − (− 0.06 m)] at bench mark 2749 and to about 0.15 m [0.08 m − (− 0.07 m)] at Q 326. Similarly, between 1955 and 1968, uplift increased steadily northward from about 0.02 m at I 30 (fig. 10), to a probable low value of 0.17 m at Wheeler Springs (pl. 7) and to about 0.31 m [0.19 m − (− 0.12 m)] at Ozena. Between Ozena and bench mark 2749, the 1955–68 uplift diminished slightly to about 0.28 m [0.22 m − (− 0.06 m)], whereas northward to Q 326 the 1968 height rose about 0.28 m [0.21 m − (− 0.07 m)] above the 1955 datum. Northward as far as bench mark Z 173, the cumulative uplift generated between 1955 and 1974 was generally less than that that occurred between 1955 and 1968, whereas northward from Z 173 the 1955–74 uplift closely matched that which developed between 1955 and 1968 (pl. 7). Comparisons against a 1959/60 datum (pl. 7) are again based on the assumption that the results of the combined 1959 and 1960 levelings are the equivalent of those that would have been produced had this leveling been carried out entirely during the spring of 1960. The 1959/60–68 uplift increased sharply to about 0.08 m at bench mark K 173, flattened between K 173 and P 1049, increased gradually northward from P 1049 to a maximum of about 0.12 m at Ozena and diminished to about 0.08 m at Q 326 (pl. 7). Cumulative uplift between 1959/60 and 1974 fell generally below that achieved by 1968 (pl. 7). The 1959/60–74 uplift converged with the 1959/60–68 uplift near bench mark P 1049, peaked at U 1049 and fell back to convergence through the rest of the comparison ending at Ozena. Our only comparison against a 1968 datum indicates that during the interval 1968–74 the Ventura-Maricopa line sustained tectonic subsidence of as much as 0.05 m that decreased steadily northward to P 1049 (pl. 7). In other words, this comparison discloses a clearly defined reversal in the movement pattern along the south flank of the uplift that must have developed no later than the spring of 1974 (pl. 7). Because the 1974 uplift above the 1968 datum peaked at about 0.02 m at bench mark U 1049 and fell off to a convergence with the 1968 datum at the northern end of the comparison, it is not unlikely that a continuation of the 1974 leveling would have revealed increasing tectonic subsidence north of Ozena.

The vertical displacement history along the Ozena-Frazier Park spur is in some ways more clearly defined than that along the main line. Between 1955 and 1959/60, uplift ranged between 0.21 m [0.09 m −(−0.12 m)] at Ozena, 0.19 m [0.16 m −(−0.03 m)] at Lockwood Airport, 0.20 m [0.27 m −0.07 m] at Frazier Park, and about 0.18 m [0.24 m −0.06 m] at Lebec. Between 1955 and 1968, the uplift at Ozena increased to about 0.30 m (see above), to about 0.26 m [0.23 m −(−0.03 m)] at Lockwood Airport, to about 0.29 m [0.36 m −0.07 m] at Frazier Park, and to about 0.25 m [0.31 m −0.06 m] at Lebec (pl. 7). Height changes measured against a 1959/60 datum indicate that the 1968 uplift reached a maximum of about 0.12 m at Ozena, held at this figure eastward to the crest of the range near bench mark M 595, and fell off gradually to about 0.06 m at Lebec (pl. 7).

Although the preceding interpretation of vertical displacements along the Ventura-Maricopa line is based on seemingly reasonable reconstructions with respect to Tidal 8, the existing data permit an alternative interpretation that is more consistent with the full geodetic record, but much more difficult to portray. Fundamental to this alternative interpretation are (1) convincing evidence of crustal instability between Ventura and the area west of Palmdale (pl. 5) during the period 1959–60 and (2) the probable invariance of bench mark F 55, Bakersfield, with respect to Tidal 8 during the period 1953–59.

Compelling evidence of crustal deformation in the west-central Transverse Ranges during the period 1959–61 is provided by a large misclosure involving leveling of this vintage (Vanicek and others, 1980, p. 519–520). Based on surveys extending over the period April 1959–May 1961, the orthometrically corrected misclosure around the loop San Pedro-Oxnard-Ventura-Ozena-Lebec-Sandberg-Palmdale-Saugus-San Pedro is given as 0.2773 m—or, alternatively, 0.2923 m (fig. 13). On the other hand, successive height determinations for bench mark I 30, Ventura, show that this mark remained essentially unchanged in height during the intervals 1934–60 and 1960–68 (fig. 10). Similarly, comparisons between the 1955 and 1961 elevations of bench mark D 430, Palmdale, show that that mark rose by only 0.0528 m during the period 1955–61 (see section on "The Los Angeles-Mojave Line"). Morever, the orthometrically corrected misclosure around the 1959 loop Lebec-Ozena-Maricopa-Greenfield-Lebec is only 0.0102 m (fig. 14), and that around the loop Castaic-Fairmont-Palmdale-Saugus-Castaic, based on leveling carried out between 1953 and the spring of 1961 (and including the results of second-order leveling between Castaic and Fairmont), is only 0.0442 m (fig. 15). Because these misclosures are well below limits, because both Ventura and Palmdale remained nearly invariant between 1955 and the spring of 1961, and because the likelihood of systematic error in the 1960 leveling between Ventura and Ozena seems especially remote owing to the absence of any significant correlation between terrain and signal (pl. 7), it is virtually certain that the 0.2773-m misclosure shown in figure 13 cannot be a measurement artifact and must be due largely to movement between Ventura and Fairmont some time after the spring of 1959. Moreover, if it is assumed only that the elevation difference between Boundary Monument 2 and X 53 (fig. 13) remained unchanged between the spring of 1960 and the following spring, this postulated crustal disturbance must have occurred during the period 1959–60.

The stability of bench mark F 55, Bakersfield, during the period 1953–59 is suggested by several lines of evidence, both direct and indirect. The 1953 elevation difference between F 55 and Boundary Monument 2, Lebec (pl. 7), is given as 1043.3013 m (NGS line L-14799); the 1956/57 elevation difference between these two marks (based on a fixed elevation difference between Boundary Monument 2 and adjacent Boundary Monument 1, a difference that held to within 0.6 mm between 1953 and 1961) is given as 1043.3216 m (NGS line L-16254); and, finally, the 1959 elevation difference between F 55 and Boundary Monument 2 is given as 1043.3078 m (NGS line L-17212). Thus, it seems unlikely that Bakersfield subsided during the period 1953–59, for Boundary Monument 2 would have had to subside by a corresponding amount in order to preserve the elevation difference between F 55 and Boundary Monument 2. Similarly, comparisons between the results of the 1953 and 1959 surveys show that the 6-km reach extending southward from Bakersfield toward the edge of the Arvin-Maricopa subsidence basin remained virtually free of tilting during this interval (NGS lines L-14799 and L-17212), suggesting, of course, that the included area sustained very little differential subsidence during the period 1953–59. Moreover, rigorous analysis of the susceptibility to compaction of the water-bearing and petroliferous deposits underlying central Bakersfield indicates that this area probably sustained very little compaction (and, hence, very little compaction-induced subsidence) during the period 1926–65 (Lofgren, 1975, p. D11–D15; Castle and others, 1983, p. 36–40). Finally, although we have only two comparisons between Tidal 8 and Bakersfield based on levelings carried out since 1953, these comparisons show that central Bakersfield rose about 0.08 m between 1953 and 1965 and an additional 0.03 m between 1965 and 1972/74 (see section on "The Los Angeles-Mojave Line"). Therefore, unless it is argued that F 55 oscillated during the interval 1953–65, all of the available evidence is consistent with the conclusion that F 55 could not have sustained significant compaction-induced subsidence during the period 1953–59. It is equally unlikely that F 55 rose during this period; the measured uplift at Bakersfield of about 0.08 m between 1953 and 1965 places a maximum limit on the amount of uplift that F 55 could have experienced between 1953 and 1959. It is highly doubtful that more than a small fraction of the 1953–65 uplift at Bakersfield had occurred by 1959. The measured elevation difference between F 55 and Boundary Monument 2, based on leveling between Bakersfield and Grapevine during November and December(?) of 1961 and between Grapevine and Lebec during

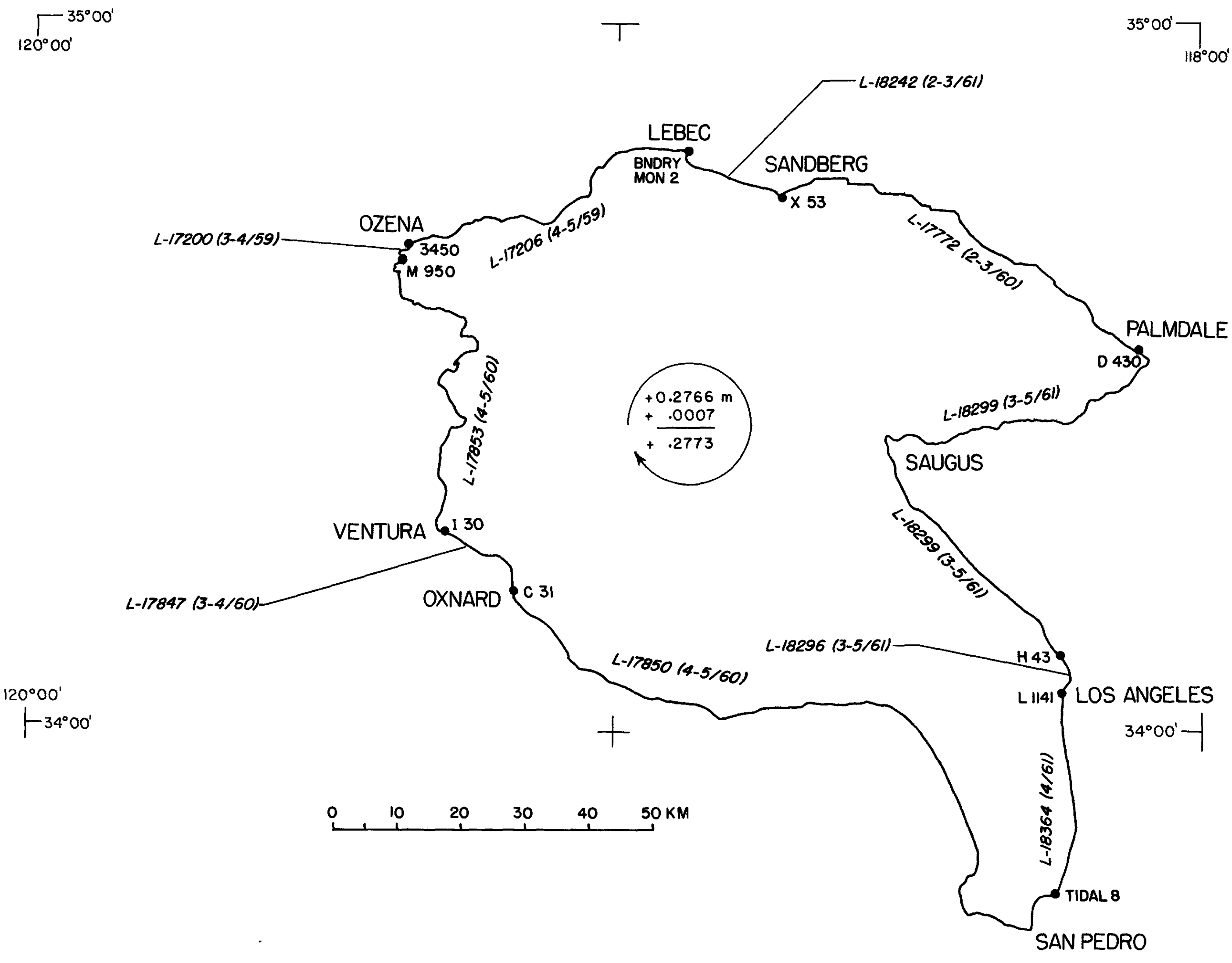


FIGURE 13.—Misclosure around the circuit San Pedro-Oxnard-Ventura-Ozena-Lebec-Sandberg-Palmdale-Saugus-Los Angeles-San Pedro based on leveling carried out during the period April 1959–May 1961. This misclosure enlarges to +0.2923 m where the orthometric correction is based on observed gravity. See figure 4 for adopted conventions and explanation of symbols.

February and March of 1961, increased to 1043.4146 m (NGS lines L-18242 and L-18529); this compares with the 1959 elevation difference between these two marks of 1043.3078 m. Because it is virtually certain that F 55 could not have subsided between 1953 and 1965, this 0.1068-m increase in the measured elevation difference must be an expression of the minimum uplift that could have occurred at Boundary Monument 2 between 1959 and 1961. That the elevation difference between these two marks remained essentially unchanged during the 6-year period 1953–59, yet increased by more than 0.1 m during the 2-year period (1959–61) identified with both the recognized crustal disturbance between Ventura and Fairmont and the onset of the southern California uplift (Castle and others, 1976, p. 252), is surely more than fortuitous. Accordingly, we conclude that during the period 1953–59, bench mark F 55 (1) did not subside, (2) probably sustained insignificant uplift, (3) could in no case have experienced more than 0.08 m of uplift, and (4) probably remained close to invariant with respect to Tidal 8.

Recognition of major aseismic deformation in the central Transverse Ranges between the spring of 1959 and the early months of 1960 indicates that the "1959/60" heights of the bench marks between Ozena and Lebec and Ozena and Maricopa, based on ties with 1960 leveling through Ventura, are almost certainly in error. In other words, the assumption that Ozena remained fixed in height during the period 1959–60 is invalid. Acceptance of the probable invariance of bench mark F 55 with respect to Tidal 8 during the period 1953–59 produces a 1959 observed elevation for Boundary Monument 2 (Lebec) of 1166.5452 m—that is, 0.1649 m less than the orthometrically compatible 1959/60 elevation based on 1960 leveling via Ventura. Thus, disregarding such systematic or random error as may have accumulated along the survey route during the 1959 leveling, the 1959 heights for all of the marks between Lebec and Maricopa should be reduced by 0.1649 m. Similarly, calculated height changes along the Lebec-Ozena-Maricopa line between 1934/35 and 1959 (or 1959/60) should be re-

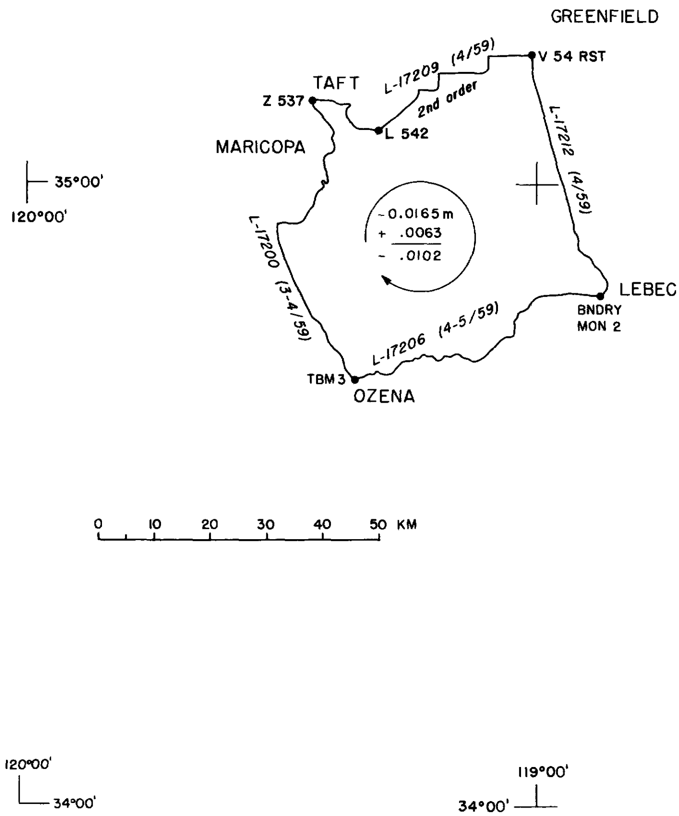


FIGURE 14.—Misclosure around the circuit Lebec-Ozena-Maricopa-Greenfield-Lebec based on leveling carried out during the spring of 1959. See figure 4 for adopted conventions and explanation of symbols.

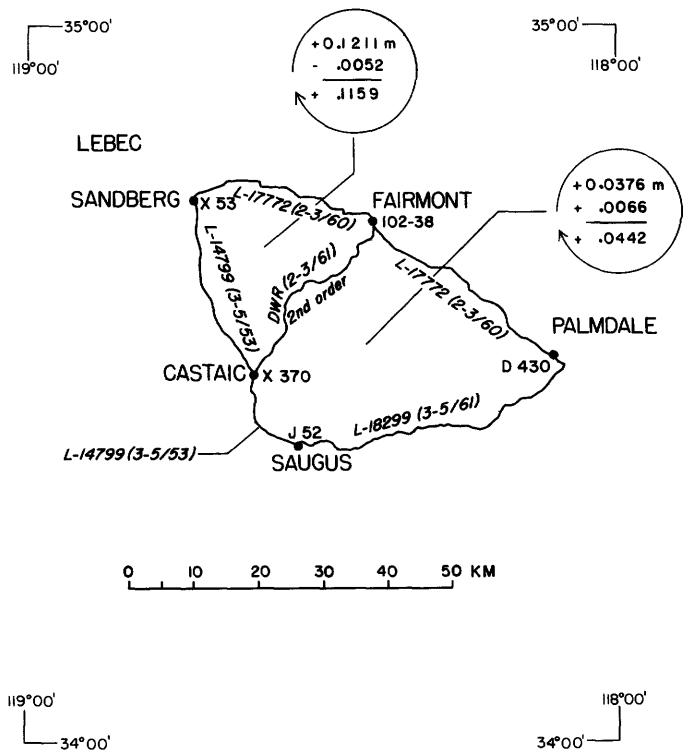


FIGURE 15.—Misclosures around the circuits Castaic-Fairmont-Palmdale-Saugus-Castaic and Castaic-Sandberg-Fairmont-Castaic based on levelings carried out during the period March 1953–May 1961. See figure 4 for adopted conventions and explanations of symbols.

duced by the same value, whereas those between 1959 (or 1959/60) and 1968 should be increased by the same amount. This alternative—and, in our judgment, much more defensible—interpretation of the vertical-movement record between Ozena and Maricopa and Ozena and Lebec is shown on plate 7 as the dashed-line representation.

Acceptance of the conclusion that bench mark F 55 remained stable during the period 1953–59 provides a basis for an alternative reconstruction of the 1953–57 height changes as well. Accordingly, the 1957 heights developed from this alternative reconstruction, again shown on plate 7 by the dashed-line representation, indicate that the 1957 heights for those bench marks northward from and including H 326, lay 0.0253 m above those based on a tie with the 1953 height of H 326 (NGS lines L-14796, L-14799, and L-16254). This alternative reconstruction also demonstrates (1) that the 1957 and 1959 heights were virtually identical and (2) the occurrence of postseismic adjustment since 1953. Allowance for continuing adjustment since 1953 indicates, in turn, that comparisons of the results of later levelings against a 1953 datum probably exaggerates the magnitude of the regionally developed uplift by 0.02–0.03 m.

The effect of this preferred interpretation is to divide the vertical-displacement history along the Ventura-Maricopa line into two clearly separable parts—one based on precise surveys between Ventura and Ozena and the second based on equally precise surveys between Ozena and Maricopa and somewhat less precise surveys between Ozena and Lebec. Providing only that we read "1960" for "1959/60," the profiled height changes between Ventura and Ozena (pl. 7) remain valid representations of the vertical movement history along this line during the indicated intervals. North and east of Ozena, however, the dashed-line representations are viewed as the more accurate portrayals of the vertical-movement history. Differential movements along the lines north and east of Ozena, whether measured against a 1959/60 or a 1959 datum, remain unchanged. For example, the 1942/43–59 differential uplift between R 595 and Boundary Monument 2 remains a conspicuous feature of this profile and is interpreted, as we have already indicated, as coseismic deformation associated with the 1952 Kern County earthquake. Similarly, the down-to-the-north tilt associated with the "1959/60"–68 uplift is no less real when measured against a 1959 datum.

The most conspicuous deficiency in our favored reconstruction of the vertical-movement history along the Ventura-Maricopa line lies in our almost complete ignorance of the significant height changes that must have occurred along this line between the spring of 1959 and the spring of 1960. The only place where the vertical displacements during the critical interval 1959–60 have actually been measured (except for the junction between the 1959 and "1960" leveling at Lebec—see below) is at the junction between the 1959 and 1960 surveys at Ozena, where we conclude that the displacement was +0.1649 m. Because the 1960 elevation of bench mark I 30, Ventura, very nearly matched the 1934 elevation (fig. 10), the 1959 and 1960 datums probably converged near or immediately north of I 30 (pl. 7). Thus, between the spring of 1959 and the following April the area between Ventura and Ozena must have sustained an up-to-the-north tilt of 0.16–0.17 m. Moreover, the configuration of the 1934/35–60 uplift (pl. 7) suggests that most of this tilt accumulated between I 30 and Wheeler Springs. Furthermore, between 1959 and 1968 there was very little differential movement north of Ozena (pl. 7), such that we assume that the configuration of the 1959–60 uplift was roughly similar to that developed between 1959 (or "1959/60") and 1968. Thus, between 1959 and 1960 uplift along this line probably increased by as much as 0.14 m between Ventura and Wheeler Springs, accumulated an additional 0.03–0.04 m between Wheeler Springs and the area immediately north of Ozena, and declined from a maximum value of 0.17–0.18 m north of Ozena to about 0.13–0.14 m at bench mark Q 326.

The pattern of vertical movements along the Ozena-Frazier Park spur during the period 1959–60 probably was dramatically different from that along the main line. That is, whereas Ozena rose 0.16–0.17 m between 1959 and 1960, Lebec may have subsided as much as 0.1432 m. This conclusion is based on a comparison between the 1953 and 1960 heights of Boundary Monument 2, where the 1960 elevation difference between bench marks X 53 and Boundary Monument 2 (fig. 13) is necessarily based on the results of either the 1953 or the 1961 levelings between these two marks (NGS lines L-14799, L-15577, L-17772, L-18242, L-18296, L-18299, and L-18364). Because the elevation difference between X 53 and Boundary Monument 2 increased by 0.0380 m between 1953 and the spring of 1961 (NGS lines L-14799 and L-18242), the 1959–60 tectonic subsidence of Boundary Monument 2 may have been somewhat less than 0.1432 m. Nevertheless, the apparent 1959–60 up-to-the-west tilt of 0.3081 m between Boundary Monument 2 and 3450

(Tri-Co) would be reduced to no less than 0.2701 m, even if it is assumed that all of the 0.0380-m increase in the elevation difference between X 53 and Boundary Monument 2 occurred between 1953 and the spring of 1960.

Had we based the misclosure shown in figure 13 and the "1960" height of Boundary Monument 2 on 1955 leveling between Tidal 8 and Palmdale (NGS lines L-15577 and L-15618), it would have increased both the misclosure and the subsidence of Boundary Monument 2 by 0.0528 m. Because there is some indication that the regional activity through the Transverse Ranges could not have propagated eastward as far as the junction bench mark at Palmdale (D 430) by the spring of 1960 (see section on "The Quail Lake-Hesperia Line"), this alternative characterization may be the more accurate. Nonetheless, it would impact on the reconstruction along the Ventura-Maricopa line only by increasing the magnitude of the 1959–60 tectonic subsidence at Lebec and the resulting up-to-the-west tilt between Lebec and Ozena by about 0.05 m.

Because either the 0.2701- or 0.3081-m 1959–60 tilt between Ozena and Lebec accounts for nearly the entire 1959/60/61 misclosure around the circuit San Pedro-Oxnard-Ventura-Ozena-Lebec-Sandberg-Palmdale-Saugus-Los Angeles-San Pedro (fig. 13), the alternative interpretation of the elevation history along the Ventura-Maricopa line is clearly preferred over the interpretation based on a simple tie at Ozena between the results of the 1959 and 1960 surveys. Moreover, this preferred interpretation is neatly supported by the vertical displacements that are otherwise inferred to have occurred north and east of Ozena during the period 1955–68 (see above). That is, because the 1955–68 height changes are independent of any assumption of stability at bench mark F 55 during the period 1953–59, it would be especially difficult to dismiss the results of the alternative reconstruction as artifacts attributable to some unrecognized aberration in the differential subsidence history between Bakersfield and Lebec.

We assume that the 1959 elevations incorporated in the alternative reconstruction (pl. 7) closely approximate those that obtained in 1955, chiefly because the elevation differences throughout this part of the Transverse Ranges seem to have held during the interval 1953–59. However, accumulating evidence suggests that tectonic subsidence has preceded or accompanied uplift around the margins of the evolving southern California uplift. Hence, it is not inconceivable that the 1959 heights lay below those of our hypothetical 1955 datum and that the 1934/35 elevations more closely match the 1955 elevations than do those based on 1959 leveling. Accordingly, the 1959–68 uplift northward and eastward from Ozena may have exceeded the cumulative uplift since 1955 by some undetermined, but probably small amount.

THE LOS ANGELES-MOJAVE LINE

GENERAL REMARKS

Calculated height changes along the Los Angeles-Mojave line (pls. 8A, 8B) are among the least ambiguously defined of any of those considered in this report. Moreover, survey data developed along this line and its several spurs provide the most illuminating and most tightly constrained history of vertical movements from anywhere within the area of the southern California uplift. This unusually complete history is due to the exceptionally large number of repeated surveys since the 1952 Kern County earthquake, including two that predate the earliest clearly defined uplift recorded in the Palmdale area. However, even this relatively straightforward reconstruction is complicated locally owing to our inability to fully assess such movements as may have preceded several significant levelings. For example, vertical displacements along the main line extending northward from Mojave to Cantil and along two short spurs extending westward from Castaic Junction and northward from Castaic are based on comparisons against datums that postdate the inception of the uplift and, hence, minimize the probable cumulative signals along these lines. Thus, the 1955–73 down-to-the-north tilt between Mojave and Cantil may have been as much as 0.15 m greater than that shown by a comparison against a March–May 1962 datum, the cumulative 1955–74 uplift westward from Castaic Junction must have been somewhat greater than the 1968/69–74 uplift, and the 1955–64 uplift northward from Castaic probably was at least 0.04–0.05 m greater than the 1961–64 uplift.

The primary datum along the main line and the two chief spurs is based on the results of 1955 and 1953 levelings, respectively. Because the closure of the 1953 leveling on the 1955 datum is at nearly the one-standard-deviation level, the equivalence between the results of the 1953 leveling and a hypothetical 1955 datum is thought to be generally sound. This judgment is qualified only to the extent that post-1953 slip along the White Wolf fault probably produced localized but generally modest height changes extending southward from the main trace of the fault. Because a number of the levelings on which we base the reconstruction of height changes along the Los Angeles-Mojave line did not originate at Tidal 8, we have once again based our reconstruction in part on generally demonstrable assumptions of stability at selected marks over limited intervals. For example, the height of bench mark L 1141, Los Angeles, is assumed to have remained invariant during the period 1964–65. Similarly, the results of 1956, 1959, and 1961 levelings over the Saugus-Grapevine spur are based on an assumption of stability at bench mark F 55, Bakersfield, during the interval 1953–61.

Comparisons against the 1955 datum indicate that much of the reach over the main line between San Fernando and Palmdale sustained nearly uniform uplift of about 0.05 m by the spring of 1961. However, the most dramatic of the signals revealed through comparisons of the results of successive levelings over this line is the 0.18-m uplift of Palmdale that occurred sometime between the spring of 1961 and 1964. Moreover, a variety of arguments indicates that this signal actually developed no later than the end of 1961 and probably during the interval June–September 1961. Specifically, comparisons between the results of a December 1961–March 1962 leveling over an adjacent route against a March–May 1961 datum along the primary route indicate that a 0.18-m up-to-the-east tilt developed between Saugus and Palmdale during the interval between these two closely spaced surveys—a tilt, in other words, that matched that which occurred between March–May 1961 and 1964. Similarly, the results of levelings extending southward from Bakersfield indicate that the Lebec area sustained cumulative episodic uplift in excess of 0.10 m between 1959 and the end of 1961 (and roughly 0.25 m between the beginning of 1960 and the end of 1961). The temporally constrained nature of this first major pulse of uplift is indicated as well by independent levelings over the San Gabriel Mountains between Azusa and Llano and between Colton and Hesperia over Cajon Pass. The results of these levelings, which were carried out during the periods October 1961–June 1962 and October–November 1961, respectively, and tied to east-west surveys carried out during the period February 1960–May 1961 (and, hence, prior to any indication of major uplift along the Los Angeles-Mojave line), produce a very small closure on Llano, a somewhat poorer closure on the 1961/62 Palmdale height, and a very poor closure on the results of the March–May 1961 survey between Saugus and Palmdale.

The first post-1961 leveling propagated over the full width of the uplift was completed in 1965. The results of this leveling show that Palmdale remained virtually invariant between 1962 and 1965, although modest uplift centering on Saugus apparently occurred during the interval 1964–65. Nonetheless, the 1965 leveling clearly demonstrates that the uplift diminished sharply north of Caliente and that Bakersfield sustained cumulative uplift of about 0.08 m during the period 1953–65. Moreover, the line between Saugus and Lebec, unlike that between Saugus and Palmdale, apparently sustained nearly uniform uplift of 0.05–0.06 m during the period 1964–65.

Disregarding the coseismic effects associated with the 1971 San Fernando earthquake, spasmodic uplift persisted through 1973/74 along both the main line and the line extending northwestward from Mojave to Bakersfield. However, by 1968/69 uplift had largely ceased between Saugus and Grapevine. Cumulative 1955–73 uplift along the Los Angeles-Mojave line achieved a maximum value of about 0.35 m south of Palmdale and northwest of Mojave, but nowhere along the line between Saugus and Grapevine did it exceed about 0.25 m.

Beginning no later than the middle of 1976, and probably as early as the end of 1974, significant collapse had begun over parts of the Los Angeles-Mojave line. The best evidence of pre-1976 collapse is found along the western end of the Castaic Junction-Montalvo spur. Interpretation of these data is complicated, however, by possible postseismic slip between 1971 and 1974 and by a 20-month junction interval during the course of the 1974 leveling westward from Castaic Junction. The 1973/74–76 collapse along the main line was expressed as a nearly uniform down-to-the-north tilt extending northward from San Pedro to at least Rosamond. The effect of this tilt was to diminish the maximum uplift south of Palmdale to a residual value of about 0.19 m and that at Rosamond to no more than 0.06 m.

DETAILED RECONSTRUCTION

The Los Angeles-Mojave line consists of a primary vertical-control line between Los Angeles and Cantil (pl. 8A), plus major spurs extending northward from Saugus to Grapevine and westward from Mojave to Bakersfield and two minor spurs off the Saugus-Grapevine spur (pl. 8B). The primary datum along the main line is based on 1955 leveling between Tidal 8 and Mojave; the primary datum along both major spurs derives from 1953 leveling following the 1952 Kern County earthquake.

Relatively few assumptions of vertical stability over extended periods are required of the reconstruction shown on plates 8A and 8B. Nonetheless, even along these lines of well-defined vertical-displacement history we have been forced to make several assumptions that tend to qualify the representation shown here (pls. 8A and 8B). For example, in extending the 1961 leveling northward from Mojave to Cantil (pl. 8A) we have assumed that the elevation differences over this reach remained constant during the interval March 1961–May 1962. In fact, because we suspect, but are unable to directly demonstrate, that the height of Mojave increased during this interval, it is not unlikely that a down-to-the-north tilt developed between Mojave and Cantil during this same period. Hence, if we assume that Cantil remained fixed during the period March 1961–May 1962, comparisons against the 1961/62 datum between Mojave and Cantil almost certainly underestimate the down-to-the-north tilt generated since the spring of 1961.

The 1955 and later starting elevations at Los Angeles have been developed from generally continuous first-order levelings between Tidal 8 and central Los Angeles. Most of the surveys between Tidal 8 and Los Angeles were completed within a month or two; the longest completion interval (1968) extended over a six-month period. The 1955 starting elevation at Los Angeles is based on continuous leveling between Tidal 8 and Los Angeles during the period March–May 1955 (NGS line L-15577). The 1961 starting elevation is based on continuous leveling between Tidal 8 and central Los Angeles carried out during the month of April 1961 (NGS line L-18364). The 1964 starting elevation is based on leveling between Tidal 8 and Los Angeles completed during a period of less than 3 months between March 1964 and June 1964 (NGS line L-19752). The 1965 starting elevation at Los Angeles is based on the 1964 elevation of bench mark L 1141 and an assumption of stability at this mark between the spring of 1964 and the following winter; this assumption is supported by the relative invariance of nearby bench mark S 32 (about 2 km south of L 1141) during the period 1926–64 (fig. 16). The 1968 starting elevation at Los Angeles was developed from discontinuous leveling between Tidal 8 and S 32 during the period August 1968–January 1969 (NGS lines L-21729 and L-21731). Although the 1968 leveling interval extended over a 6-month period, the relatively small misclosure around the 1968–69 loop San Pedro-Oxnard-Ventura-Ozena-Lebec-Sandberg-Saugus-Los Angeles-San Pedro (fig. 17) suggests that S 32 remained nearly invariant during the 1968 leveling. The 1971 starting elevation at Los Angeles is based on leveling between Tidal 8 and Los Angeles completed in less than 6 months during the interval February–July 1971 (NGS line L-22429). The 1974 starting elevation at Los Angeles is based on discontinuous leveling between Tidal 8 and bench mark S 32 during the period January–March 1974 (NGS lines L-23611 and L-23644). Finally, the 1976 starting elevation is based on continuous leveling between Tidal 8 and Los Angeles carried out during the period August-September 1976 (NGS line L-24116).

The observed elevations along the main line of the Los Angeles-Mojave line are based chiefly on levelings completed within periods of a few months. The 1955 elevations along the main line are the products of levelings completed during a 4-month interval (pl. 8A), such that they should provide a relatively unambiguous datum against which we can compare the results of any subsequent surveys. Because the several parts of the 1961 surveys between Los Angeles and Mojave were completed well within a 3-month period (pl. 8A), the 1961 levelings can be treated as a continuous, virtually instantaneously propagated survey—although the 1-year interruption in the continuation northward of this leveling (pl. 8A) may have led to a major distortion of the actual "1961" surface between Mojave and Cantil. Both the 1964 and the 1965 observed elevations are based on levelings produced over such a short interval (pl. 8A) that they too can be viewed provisionally as the results of instantaneously propagated surveys. Although analyses

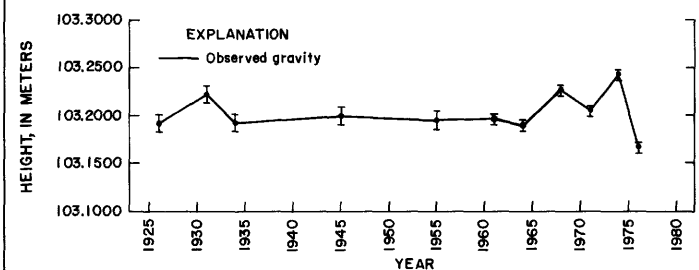


FIGURE 16.—Changes in orthometric height at bench mark S 32 (or its reset equivalent, S 32 Reset 1936), Los Angeles. Because S 32 was not recovered in 1964, the 1964 height has been based on an assumption of invariance between S 32 and bench mark L 1141 (about 2 km north of S 32) during the period 1961–64. One-standard-deviation error bars show conventionally estimated random error only.

of the "1968" network indicate that little significant movement occurred during the course of these surveys, because the 1968 elevations between Los Angeles and Rosamond are based on levelings that extended over a 6-month period (pl. 8A), there is some reason for suspecting that the reconstructed 1968 elevations are contaminated by movement-induced error. The 1969 observed elevations along the main line (as well as the Saugus-Grapevine spur) have been tied to the 1968 elevation of bench mark Loft A, and they are compared here against the 1968 datum only (pl. 8A). Although the 1969 elevations cannot be tied directly to Tidal 8, because Loft A remained virtually invariant with respect to bench marks along the northwestern end of the line near Lebec (Castle and others, 1974, p. 65; Castle and others, 1975, p. 134), and because this mark also remained unchanged with respect to Tidal 8 during the full period 1964–68, the reconstructed 1969 elevations are reasonably viewed as if they had been measured with respect to Tidal 8. The 1971 leveling was completed within a 6-month interval (pl. 8A). Nevertheless, because the 1971 surveys were carried out during the period immediately following the 1971 San Fernando earthquake, the 1971 elevations within and northward from the epicentral region may be distorted as a result of postseismic intrasurvey movement. The reconstructed 1974 observed elevations between Los Angeles and Mojave are based on sur-

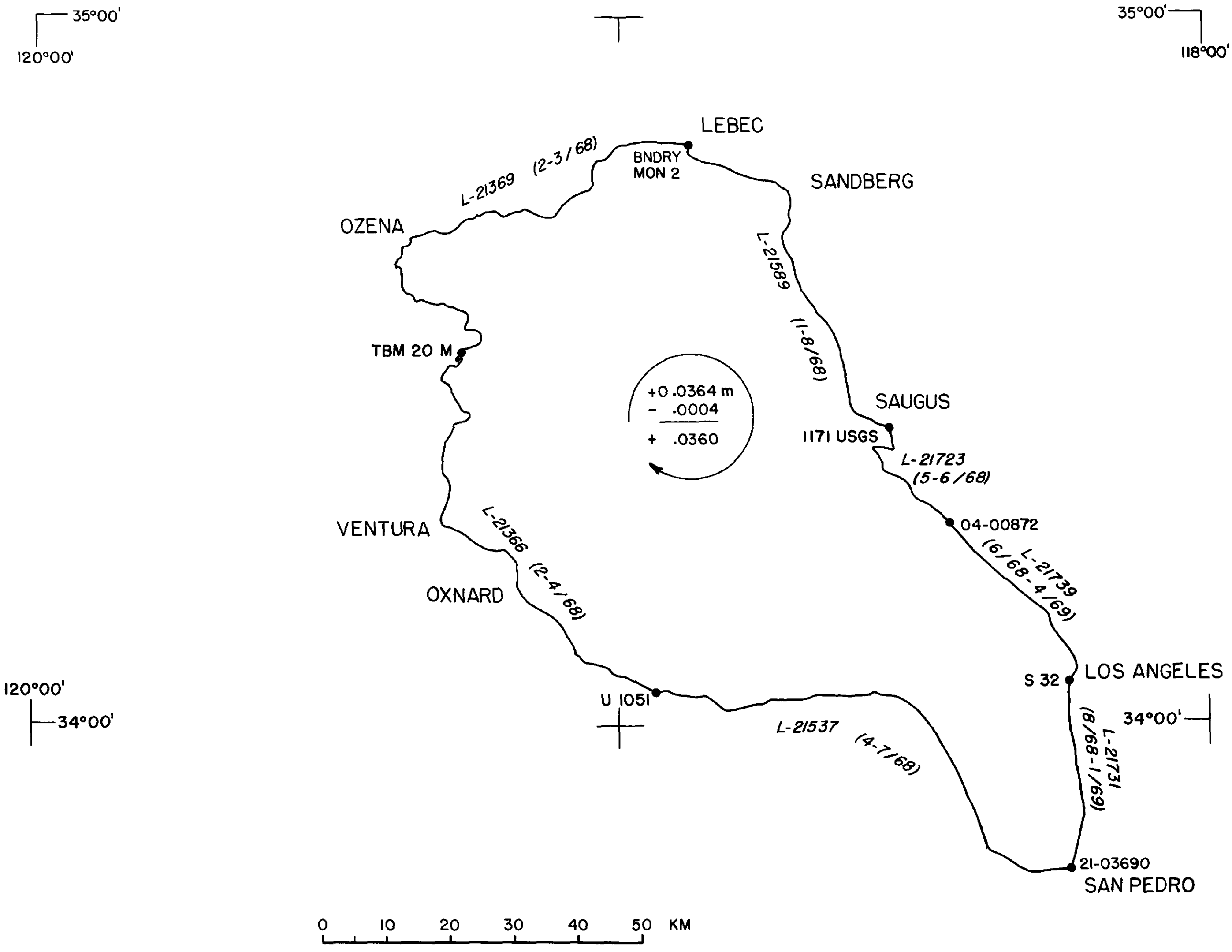


FIGURE 17.—Misclosure around the circuit San Pedro-Oxnard-Ventura-Ozena-Lebec-Sandberg-Saugus-Los Angeles-San Pedro based on leveling carried out during the period January 1968–April 1969. See figure 4 for adopted conventions and explanation of symbols.

veys that extended over the period November 1972–February 1974 (pl. 8A), such that in this case as well there is a reasonable likelihood that these elevations are contaminated by movement-related error. This likelihood is enhanced, moreover, by the 1972/74 misclosures around the circuits San Pedro-Los Angeles-Saugus-Palmdale-San Bernardino-San Pedro (fig. 18) and Saugus-Castaic-Sandberg-Lancaster-Palmdale-Saugus (fig. 19). Both of these misclosures are consistent with subsidence of about 0.06 m at bench mark 201-33A during the interval between the completion of the 1972/73 leveling into this mark and the subsequent levelings extending eastward and northward from Palmdale. However, in spite of the consistency between these two misclosures (figs. 18 and 19) and the postulated subsidence of 201-33A, the misclosures in themselves are less-than-definitive evidence of the subsidence of this mark between the winter of 1972/73 and the following winter. Specifically, the join at bench mark R 449 between leveling extending southeastward from Palmdale and that extending northeastward from San Pedro was delayed by nearly a year (fig. 18). Thus either tectonic or compaction-induced subsidence of this junction mark, which is located about 4 km southwest of the San Jacinto fault (see pls. 2 and 3), could also have produced a misclosure of the sense and magnitude

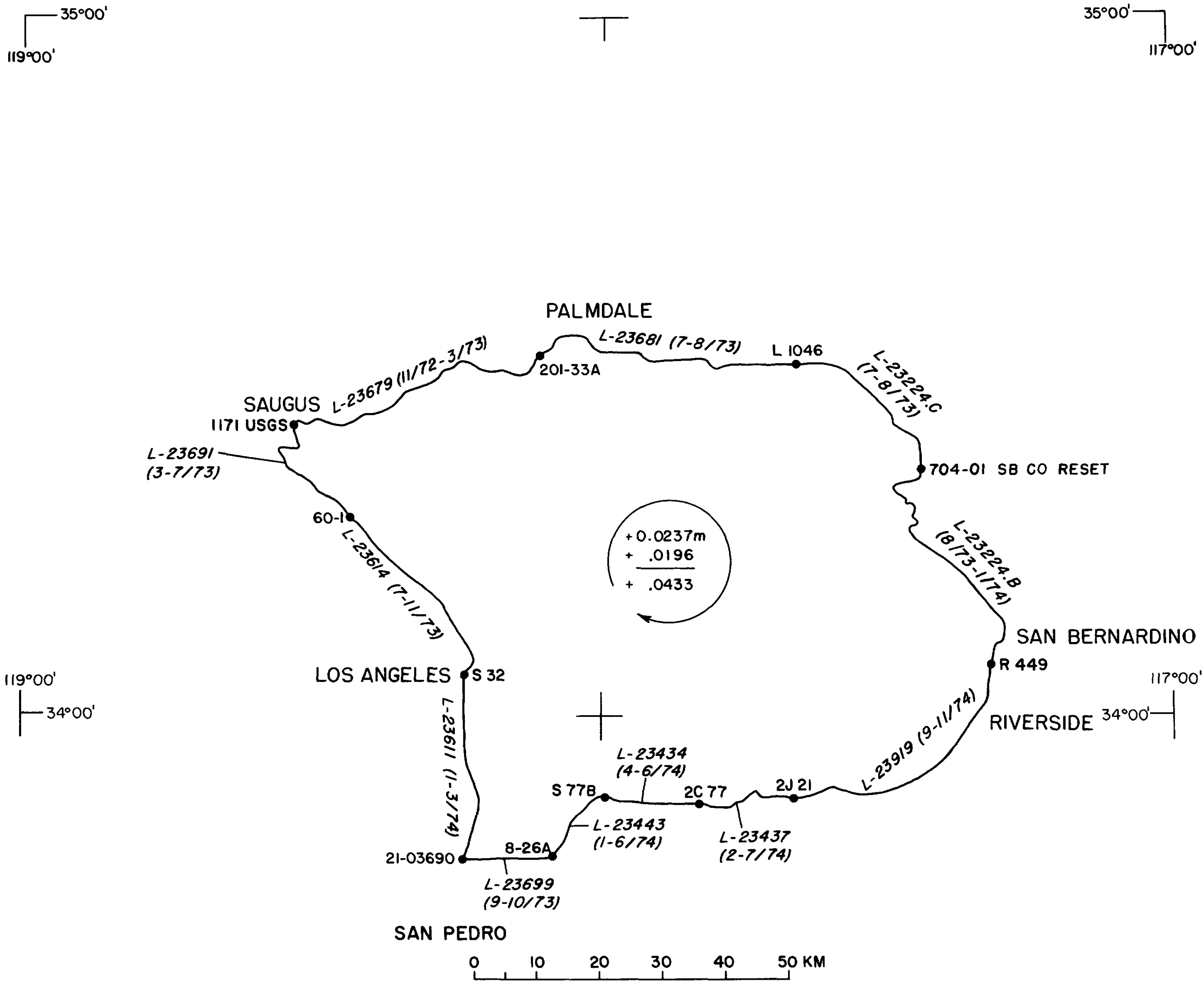


FIGURE 18.—Misclosure around the circuit San Pedro-Los Angeles-Saugus-Palmdale-San Bernardino-San Pedro based on leveling carried out during the period November 1972–November 1974. This misclosure enlarges to +0.0591 m where the orthometric correction is based on observed gravity. See figure 4 for adopted conventions and explanation of symbols.

shown here (fig. 18). It is perhaps equally likely that the collapse of the southern California uplift in the San Bernardino-Riverside area had begun by the end of 1974 (see below), whereby the height difference between San Pedro and R 449 was significantly diminished sometime during 1974. Similarly, the misclosure around the loop Saugus-Castaic-Sandberg-Lancaster-Palmdale-Saugus (fig. 19) is based on leveling that junctioned at a mark (M 487) which falls within the Antelope Valley subsidence bowl (pls. 3 and 4). Because subsidence of this mark during the period between the completion of the leveling between M 487 and Palmdale and the beginning of the leveling leading westward out of M 487 to Sandberg could lead to a misclosure of the observed sense, the significance of this misclosure (fig. 19) with respect to the vertical displacement history of 201-33A is again compromised. Accordingly, because the 1974 observed elevation of 201-33A based on leveling propagated directly eastward from Saugus should (other things being equal) be less contaminated by measurement error

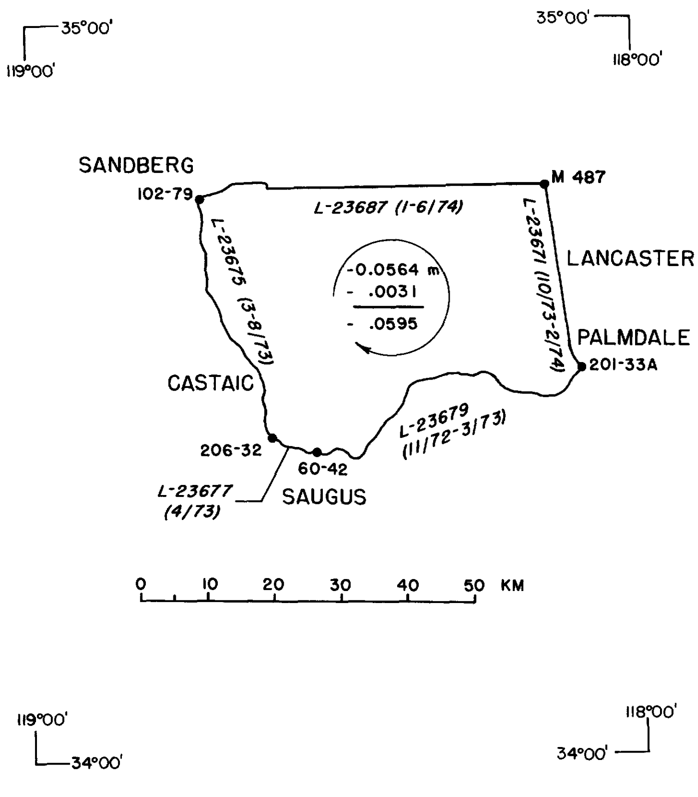


FIGURE 19.—Misclosure around the circuit Saugus-Castaic-Sandberg-Lancaster-Palmdale-Saugus based on leveling carried out during the period November 1972–June 1974. This misclosure enlarges to −0.0660 m where the orthometric correction is based on observed gravity. See figure 4 for adopted conventions and explanation of symbols.

than those elevations involving the more circuitous paths into this mark, and because these misclosures (figs. 18 and 19) are otherwise explainable, the 1972/73 observed elevation difference between Saugus and Palmdale is provisionally accepted as the equivalent of that that would have been obtained had this leveling been carried out during the winter of 1973/74. However, because we have no clearly defined basis for choosing between the alternative 1974 height differences between Saugus and Palmdale, and because there is at least an inferred basis for believing that Palmdale had begun to subside by the beginning of 1974, the 1974 observed elevations extending northward from Palmdale to Mojave could easily have been about 0.05 m less than those used in the development of the comparisons shown on plate 8A. The 1972/73 (second-order) leveling between Rosamond and Cantil was completed during the same general period as the 1974 leveling between Saugus and Palmdale (pl. 8A). Accordingly, because comparisons between the results of the 1971 and 1974 surveys between Palmdale and Rosamond indicate that this reach maintained its vertical integrity during the period 1971–74 (pl. 8A), the 1974 elevation of Rosamond (based on the 1974 leveling) probably closely matched the 1972/73 elevation that would have been obtained had the leveling between Tidal 8 and Rosamond been carried out at any time during the period November 1972–May 1973. Accordingly, in reconstructing the 1972/73 observed elevations between Rosamond and Cantil we have tied the results of the 1972/73 surveys to the 1974 elevation of bench mark 2407 USGS (pl. 8A). Although the 1976 leveling along the main line was completed within a relatively short period (June–December 1976), because it was carried out immediately following (or during) a period of dramatic tectonic subsidence, the reconstructed 1976 elevations may be contaminated by errors associated with intrasurvey movement. Because the 1976 surveys departed from the main line between Los Angeles and San Fernando, we have accepted the 1974–76 observed elevation change (with respect to Tidal 8) at bench mark 60-1 (about 5 km north of San Fernando) developed by the Los Angeles County Department of County Engineer as a basis for a special reconstruction of the 1974 observed elevations north of 60-1—thereby avoiding the computation of orthometrically compatible heights for this mark. That is, we have added 0.0067 m to all of the 1974 observed elevations north of and including 60-1 in order to preserve the 1974–76 height change of −0.1071 m at 60-1 reported by the Department of County Engineer (Los Angeles County Department of County Engineer, written commun., 1977).

Observed elevations along the Saugus-Grapevine spur have been reconstructed largely from the results of virtually continuous levelings between Los Angeles and Grapevine. The 1953 elevations, which we have tied to the 1955 elevation of bench mark J 52, Saugus, form the chief exception to this generalization. The assumption of equivalence between the reconstructed 1953 elevations along this spur and those that would have been generated had this leveling been carried out in 1955 is strongly supported by the 1953–55 0.0366-m misclosure around the circuit Saugus-Lebec-Bakersfield-Mojave-Palmdale-Saugus (fig. 4). Moreover, the near invariance of bench mark J 52 during the period 1953–55 is clearly supported by the apparent stability of this mark over the inclusive interval 1926–64 (fig. 20). The 1956 and 1959 elevations between bench marks N 54 and Boundary Monument 2 (pl. 8B) are based on the probable invariance (with respect to Tidal 8) of bench mark F 55, Bakersfield, during the period 1953–59 (see section on "The Ventura-Maricopa Line"). The 1961 observed elevations between bench marks N 54 and X 53 are similarly based on an assumption of invariance at F 55 during the period 1953–61. However, because Bakersfield rose about 0.08 m at some time between 1953 and 1965 (pl. 8B), the reconstructed 1961 elevations (and hence the 1953–61 uplift) between N 54 and X 53 probably err on the low side. Although the 1961 leveling between bench marks H 537 and X 53 preceded the 1961 leveling between F 55 and H 537 by about 8 months (pl. 8B), we have assumed that the elevation differences over this short reach remained unchanged between the spring and late fall of 1961. Moreover, even though comparisons of the elevation differences between H 537 and Boundary Monument 2 based on 1959 and early 1961 levelings show an up-to-the-south tilt of about 0.01 m (pl. 8B), if tilting persisted through November of 1961, the March–November 1961 uplift of the marks south of bench mark H 537 would be even greater than indicated by our reconstruction. Because the reconstructed 1964 elevations along the Saugus-Grapevine spur are based on levelings between Los Angeles and Grapevine completed within a 4-month period (pls. 8A and 8B), they may be reasonably viewed as the products of instantaneously propagated surveys. Although the 1965 elevations are based on rapidly propagated leveling between Los Angeles and Lebec, the starting elevation at Los Angeles is again based on the apparently valid presumption of stability at bench mark L 1141 between the spring of 1964 and the following winter. The 1968 and 1971 surveys between Saugus and Grapevine extended over periods of as much as 7 months (pl. 8B). Nevertheless, the generally good correspondence between the 1968 and 1971 elevation differences north of the epicentral region of the 1971 earthquake indicates that both sets of reconstructed observed elevations probably are free of significant error associated with intrasurvey movement. Because the 1973 surveys between Saugus and Lebec were completed within a 6-month period, and because the height of the junction bench mark at Saugus remained virtually unchanged during the period 1971–74 (fig. 20), it is unlikely that any measurable movement occurred along this spur during the 1973 leveling.

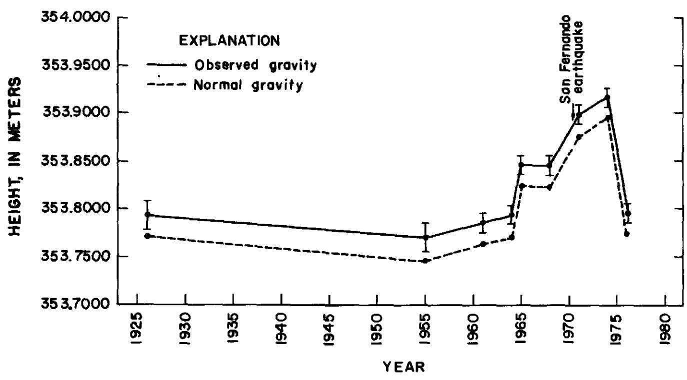


FIGURE 20.—Changes in orthometric height at bench mark J 52, Saugus. One-standard-deviation error bars show conventionally estimated random error only.

The observed elevations along the several subspurs of the Saugus-Grapevine spur generally have been reconstructed through direct ties with temporally compatible and rapidly propagated surveys emanating from Tidal 8. The most conspicuous exception is based on a tie between the 1953 elevation of bench mark X 370, Castaic, with the results of the February–March 1961 leveling along the Castaic-Fairmont subspur. Nonetheless, the stability of the junction bench mark and the probable vertical integrity of this line between 1953 and the spring of 1961 are suggested by the 0.0442-m misclosure around the 1953–(spring) 61 loop Saugus-Castaic-Fairmont-Palmdale-Saugus (fig. 15). The other conspicuous exception derives from the tie between the 1973 elevation of bench mark RV 55 west of Castaic Junction with the results of 1975 leveling extending westward along the Castaic Junction-Santa Paula subspur. The 1974 elevations westward to the county line are based on March

1973 leveling; the 1974 elevations between the county line and Montalvo are based on surveys carried out during the winter of 1974/75 (pl. 8B). Whether or not movement occurred at the junction bench mark during the 2-year period between these surveys has not been determined, but the +0.0690-m clockwise misclosure around the 1973/74/75 loop Castaic Junction-San Fernando-Topanga Canyon-Ventura-Castaic Junction (fig. 21) suggests a down-to-the-west tilt between the county line and Ventura sometime between 1973 and the beginning of 1975. Because the heights diminished by progressively larger values southward from Ozena along the Ventura-Maricopa line during the period 1968–74 (pl. 7), we interpret the 1973/74/75 misclosure (fig. 21) as an expression of downwarping at Ventura (or Montalvo) rather than uplift at the county line.

None of the reconstructed elevations used in calculating the height changes along the Mojave-Bakersfield spur are based on continuous leveling between Tidal 8 and Bakersfield. The probable equivalence between the results of the 1953 leveling and those that would have been produced had this leveling been carried out entirely in 1955 is again based on the small misclosure around the 1953/55 loop Saugus-Lebec-Bakersfield-Mojave-Palmdale-Saugus (fig. 4). The 1956 and 1959 elevations along the Mojave-Bakersfield spur are based on the presumed invariance of Bakersfield with respect to Tidal 8 during the period 1953–59 (see section on "The Ventura-Maricopa Line"). The 1961/62 elevations along this line are similarly based on an assumption of equivalence between the 1953 and 1961 heights for the starting bench mark in central Bakersfield. However, this assumption is especially questionable, for there is a reasonable likelihood that the southern California uplift had propagated northward as far as Bakersfield by the end of 1961; thus the represented 1953–61/62 uplift (pl. 8B) probably is a minimal value. The 1965 elevations along the Mojave-Bakersfield spur are based on surveys between bench mark L 1141 (Los Angeles) and Bakersfield completed within a 6-month interval (pls. 8A, B); however, the starting elevation at L 1141, as we have already indicated, is based on the presumed sta-

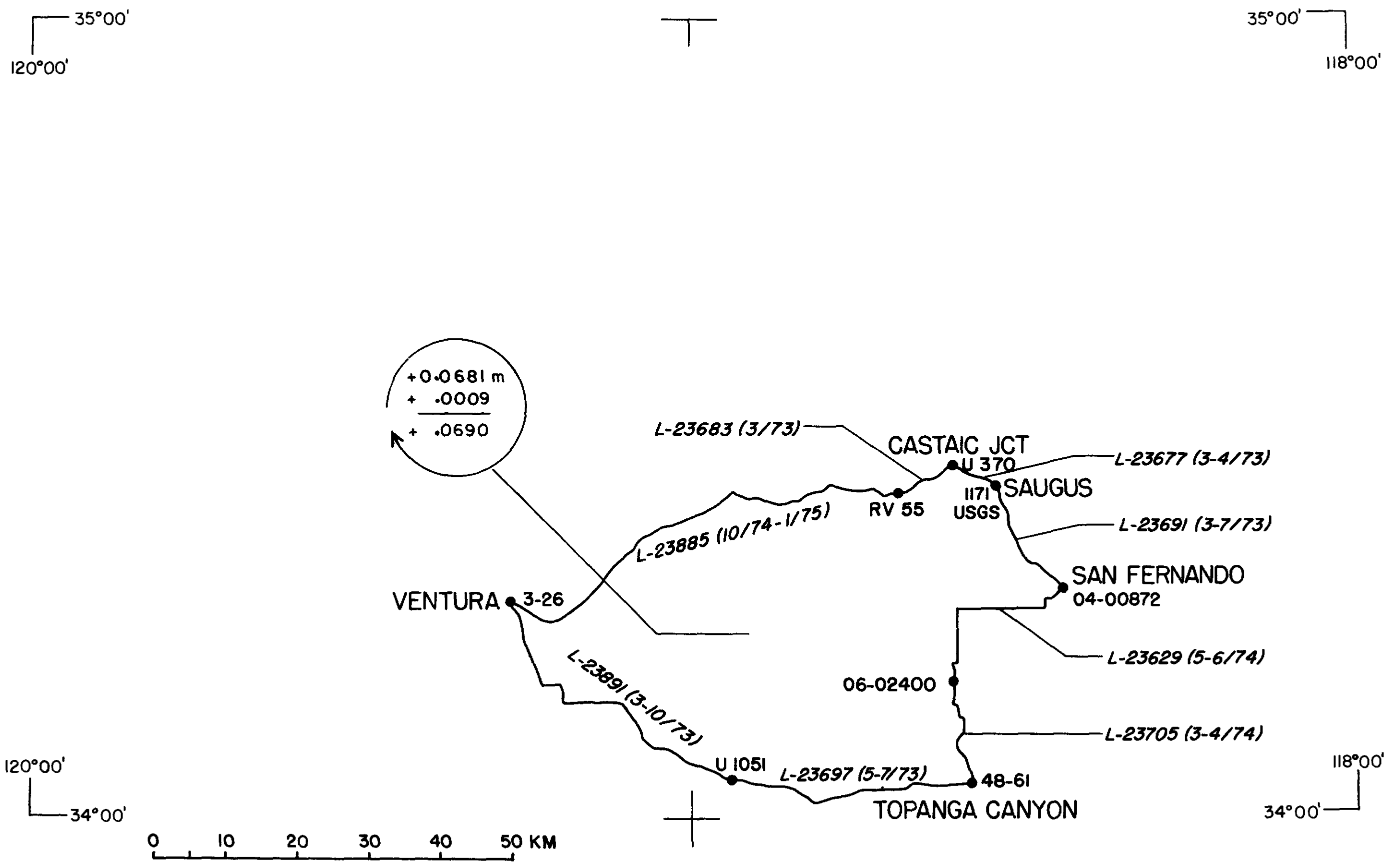


FIGURE 21.—Misclosure around the circuit Castaic Junction-San Fernando-Topanga Canyon-Ventura-Castaic Junction based on leveling carried out during the period March 1973–January 1975. See figure 4 for adopted conventions and explanation of symbols.

bility of this mark during the period 1964–65. The 1972/74 elevations along the Mojave-Bakersfield line are based on an assumption of stability at bench mark A 367, Caliente, during the period 1972–74 (pl. 8B). Although this assumption is supported by the 0.0231-m misclosure around the 1972/73/74 loop Saugus-Lebec-Grapevine-Bakersfield-Caliente-Mojave-Rosamond-Palmdale-Saugus (fig. 22), this small misclosure may be fortuitous. This likelihood is suggested in particular by a +0.0587-m observed (orthometrically uncorrected) misclosure around a smaller loop that roughly bisects the indicated loop (fig. 22) with a 1974 connection between Lebec and Rosamond, yet includes the results of the same surveys around the northern half of the circuit (E. I. Balazs, written commun., 1977).

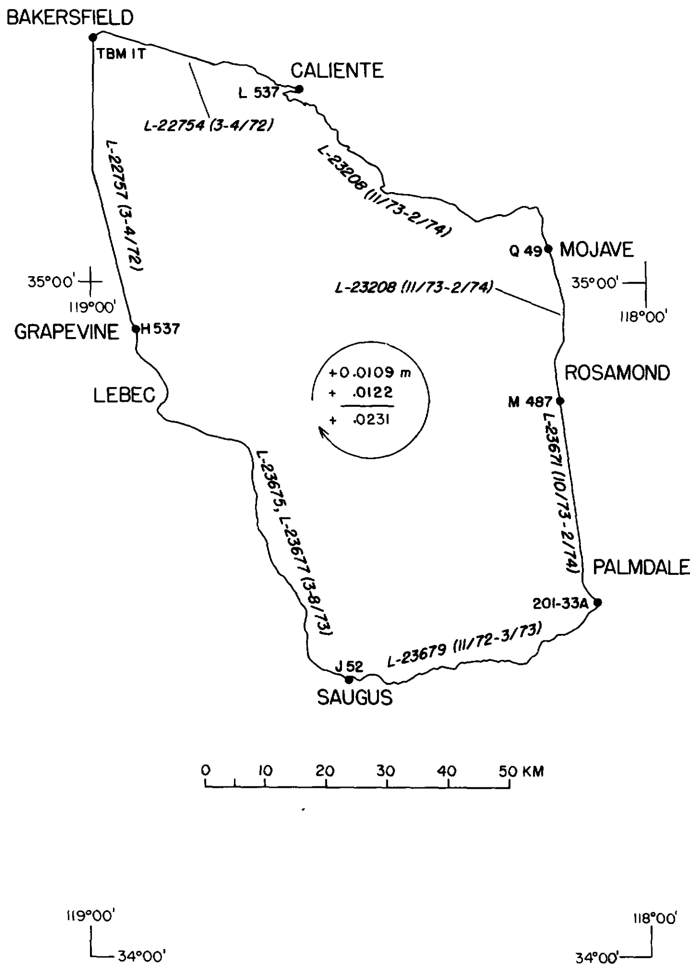


FIGURE 22.—Misclosure around the circuit Saugus-Lebec-Grapevine-Bakersfield-Caliente-Mojave-Rosamond-Palmdale-Saugus based on leveling carried out during the period March 1972–February 1974. See figure 4 for adopted conventions and explanation of symbols.

Comparisons of the results of 1961 leveling against the 1955 datum along the main line suggest relatively modest displacements during the interval 1955–61 (pl. 8A). Other than the differential subsidence associated with ground-water extraction (see pls. 3 and 4), nearly the entire reach between Los Angeles and San Fernando remained free of significant height changes during this period. Northward from San Fernando to bench mark Q 898, however, uplift increased to a measured maximum of 55 mm, but still farther northward it diminished to about 20 mm at bench mark J 52, Saugus. Because the 1955–61 differential uplift between San Fernando and Saugus was localized within the relatively narrow band identified with the San Fernando-Santa Susana fault system, it may be a function of equally localized contractional strain athwart this fault system (Castle and others, 1974, p. 63–64). Northeastward from Saugus the 1955–61 uplift increased sharply to a maximum of about 0.07 m at bench mark H 486 (pl. 8A) and persisted at about this level over the 35-km reach between H 486 and the San Andreas fault. Parenthetically, because there seems to be no systematic correlation with topography, it is particularly unlikely that the 1955–61 uplift between Saugus and the San Andreas fault can be attributed to elevation- or slope-dependent systematic leveling error. Whether the differential uplift between San Fernando and Saugus is temporally or mechanically associated with the more broadly defined uplift between Saugus and the San Andreas fault remains conjectural. Nevertheless, during the interval 1926–55 the reach between San Fernando and the San Andreas fault remained virtually free of significant differential uplift (NGS lines 82598, 82600, and L-15168). Hence, it is not unlikely that the differential uplift developed between San Fernando and Saugus during the period 1955–61 is linked to that northeast of Saugus and that the modest differential subsidence at Saugus is simply a detail imposed on the broader pattern of uplift. We are uncertain just when within the period 1955–61 the regionally developed uplift between San Fernando and the San Andreas fault began. Nonetheless, because its broad expanse is unlike that which might be expected to develop athwart the trace of an active fault, we interpret the 1955–61 uplift between San Fernando and Palmdale as an incipient pulse in the evolution of the southern California uplift. The history of vertical movement between Ventura and Maricopa suggests that this uplift probably began sometime after the spring of 1959 (see section on "The Ventura-Maricopa Line"), a suggestion consistent with the vertical displacement history of bench mark 3219 USGS, Vincent (pl. 5 and fig. 23).

Height changes between Palmdale and Rosamond during the period 1955–61 were dominated by differential subsidence centering on Lancaster (pl. 8A). This subsidence is almost entirely attributable to the effects of ground-water extraction (pls. 3 and 4) that have simply overwhelmed whatever tectonic movement may have persisted north of Palmdale. Because the Rosamond-Mojave area sustained little if any change in height between 1955 and 1961 (pl. 8A), it is reasonably certain that the trivial uplift which extended northward as far as Palmdale probably diminished to nothing well south of Rosamond.

Height changes generated between Los Angeles and Saugus during the interval 1961–64 differed only in detail from those that occurred during the period 1955–61, whereas east-northeastward from Saugus the vertical-displacement pattern changed dramatically during the 1961–64 interval (pl. 8A). The uplift centering on bench mark Q 898, for example, continued to grow at about the rate that had characterized its development between 1955 and 1961. Moreover, the subsidence developed in the Burbank area apparently continued unabated between 1961 and 1964. Northeastward from Saugus, however, the 1961–64 uplift increased almost uniformly to a maximum of about 0.18 m at bench mark 3219 USGS, a value that persisted northward

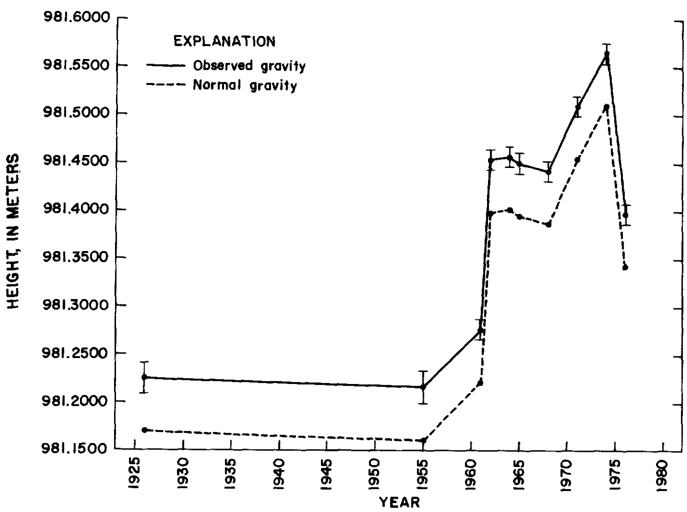


FIGURE 23.—Changes in orthometric height at bench mark 3219 USGS, Vincent. The 1962 height is based on an assumption of invariance at bench mark X 898, Saugus, during the period March 1961–March 1962. One-standard-deviation error bars show conventionally estimated random error only.

to the end of the 1964 leveling at Palmdale. Whether the 1961–64 uplift extended northward beyond Palmdale is uncertain. However, because the control point from which the 1965 leveling emanated probably shifted very little between 1964 and 1965 (fig. 16), because comparisons between the 1964 and 1965 surveys show that the heights between the San Andreas fault and Palmdale remained essentially invariant during the period 1964–65, and because the results of the 1965 leveling northward from Palmdale show that Mojave sustained 0.18–0.19 m of uplift between 1961 and 1965 (pl. 8A), it is virtually certain that major uplift developed during the period 1961–64 persisted at least as far north as Mojave. In fact, the only significant change along the Los Angeles-Mojave line during the interval 1964–65 consisted of differential uplift of as much as 55 mm within the reach between Burbank and the San Andreas fault (pl. 8A). It remains conjectural, however, whether this differential uplift should be viewed as a southward expansion of the southern California uplift or as an expression of a some local effect, such as creep at depth along a northward-dipping fault of the San Fernando-Santa Susana system (Castle and others, 1974, p. 63, 66).

Although the uplift or tilting between Saugus and Palmdale disclosed through a comparison of the results of the 1961 survey with those of the 1964 (or 1965) survey (pl. 8A) suggests remarkably rapid aseismic deformation, at least two lines of evidence indicate that this uplift actually occurred within a period of no more than 7 and probably less than 5 months. The chief and least equivocal evidence of very rapid tilting between Saugus and Palmdale is based on a comparison between the results of December 1961–March 1962 leveling of the Los Angeles County Department of County Engineer against the 1961 datum between bench marks X 898 and D 430 (pl. 8A). The 1961/62 leveling, which followed a course both subparallel with and somewhat north of the 1961 survey route, was tied to 1961 control points at both ends of the 1961/62 survey as well as to several additional sets of bench marks along the line of the 1961 leveling (pl. 5). A comparison between the results of these two levelings shows that the 1961–61/62 tilt between Saugus and the San Andreas fault is virtually identical to that which developed between 1961 and 1964 (pl. 8A). Moreover, because the various surveyed segments that form the 1962 ties with the results of the March–May 1961 leveling were almost randomly distributed over an 8-month period, yet produced elevation differences between X 898 and D

430 that almost precisely matched the 1964 elevation differences between these marks (pl. 8A), and because Saugus remained virtually unchanged in height between the spring of 1961 and 1964 (fig. 20), it is nearly certain that the 1961–64 uplift between Saugus and the San Andreas fault had ceased by the end of 1961 (figs. 23 and 24). That is, had tilting continued during or beyond the 1961/62 leveling, the 1961/62 elevation difference between bench marks X 898 and D 430 would have been much less (or at least significantly different) than that which was measured in 1964.

A second, although indirect line of evidence that indicates that the 1961–64 uplift between Saugus and the San Andreas fault developed very early within the period 1961–64 is based on a large misclosure around the 1961 loop Los Angeles-Burbank-Saugus-Palmdale-Mojave-Boron-Barstow-Oro Grande-Hesperia-Colton-Azusa-Los Angeles (fig. 25). All of the leveling involved in this circuit, other than the leg between Colton and Barstow, was carried out during the spring of 1961; the Colton-Barstow section was surveyed in October and November of 1961. The indicated misclosure (fig. 25) is consistent with up-to-the-north or down-to-the-south tilting of 0.1522 m over the reach between Barstow and Colton during the interval between the spring and fall of 1961—specifically between

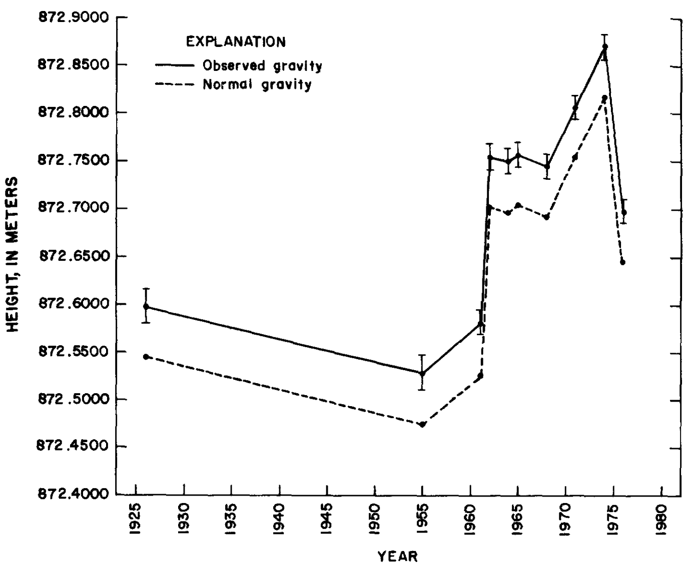


FIGURE 24.—Changes in orthometric height at bench mark D 430, Palmdale. The 1962 height is based on an assumption of invariance at bench mark X 898, Saugus, during the period March 1961–March 1962 (see pl. 8B and fig. 20). One-standard-deviation error bars show conventionally estimated random error only.

May and October. Because the results of a 1960 connection between Hesperia and Palmdale produced a loop that roughly bisected the loop shown in figure 25 yet generated a trivial misclosure around the northern half of the larger loop (fig. 26), the postulated 1961 tilt between Colton and Barstow must have been localized between Colton and Hesperia. Moreover, it is especially unlikely that the misclosure shown in figure 25 can be attributed to a down-to-the-south tilt. Had Colton subsided 0.15 m during the middle months of 1961, the implied invariance in the elevation difference between Azusa and Colton during the period March–November 1961, indicated by the small misclosure around the circuit Azusa-Big Pines-Llano-Hesperia-Cajon Junction-Colton-Riverside-Azusa (fig. 27), would have compelled roughly comparable subsidence at Azusa. Yet, as shown by combined 1961, 1962, 1960, and 1961/62 levelings via Saugus and Palmdale, Azusa rose (by about 0.05 m) rather than subsided between the spring of 1961 and the following fall—or certainly no later than the middle of 1962 (see section on "The Los Angeles-San Bernardino Line"). Moreover, based on the 1961/62 leveling over the San Gabriel Mountains (coupled with an assumption of invariance between bench marks D 430, Palmdale, and 3409, Llano, during the period February 1960–June 1962), the change in the observed elevation of bench mark D 430 (based on orthometrically compatible measurements over different routes) with respect to Tidal 8 during the period May 1961–June 1962 was +0.1477 m (+0.1706 m less the 0.0229-m difference between the orthometric corrections). Obviously, this uplift closely matches that deduced from a comparison of the results of the 1961/62 leveling of the Los Angeles County Department of County Engineer against the 1961 datum between Saugus and the San Andreas fault (figs. 23 and 24), and it is fully consistent with the 1960/61/62 misclosure around the loop Azusa-Los Angeles-Burbank-Saugus-Llano-Big Pines-Azusa (fig. 28). Several conclusions emerge from this four-dimensional analysis: (1) The 1961 tilt between Colton and Barstow indicated by the −0.1522-m misclosure (fig. 25) represents uplift at Barstow (with respect to Tidal 8) rather than subsidence at Colton. (2) If it is assumed only that the roughly contemporaneous tilts between Saugus and Palmdale, Azusa and Llano (or Palmdale), and Colton and Hesperia either evolved simultaneously or propagated from west to east, then the 1961–64 uplift of Palmdale must have developed between the end of May and the beginning of October 1961—and probably within less than a four-month period between June and September.

Whether the 1961 uplift that occurred between Saugus and the San Andreas fault persisted as far north as Rosamond or Mojave cannot be verified. A comparison of the results of a 1962 first-order survey against a 1925 datum based on first-order leveling that extended northward from Mojave shows no significant tilting between bench marks Q 49 and E 49 (pl. 8A), whereas a 1925–62 down-to-the-north tilt of about 0.075 m is disclosed by a continuation of this comparison northward from E 49 to bench mark C 49 (NGS lines 82536 and L-18658). Contrary to an earlier statement of Castle and others (1976, p. 252), Mojave was associated with about 0.12 m of tectonic downwarping during the interval 1926–55 (fig. 29), downwarping reasonably interpreted as either a coseismic effect associated with the 1952 Kern County earthquake or continuing post-1926 collapse of an early-20th-century uplift (Vaníček and others, 1979); thus, it is not unlikely that a 1925–62 down-to-the-north tilt between Q 49 and E 49, roughly coincident with the more recently developed (late 1961) northern margin of the southern California uplift, may have been obscured by a roughly comparable down-to-the-south tilt that developed between 1926 and 1952. Accordingly, 1961 uplift of as much as 0.12 m or more may have occurred as far north as Q 49, diminishing to no more than 0.05 m at bench mark E 49. Alternatively, the 1961 uplift could have closed off south of Mojave or Rosamond. This seems unlikely, however, since uplift of about 0.15 m had apparently propagated northeastward to Barstow by the fall of 1961 (see preceding paragraphs), such that late-1961 uplift of about 0.15 m probably extended northward as far as Mojave. Acceptance of this interpretation, of course, challenges the validity of incorporating the results of the 1962 leveling north of Mojave with the 1961 (preuplift) datum (pl. 8A). In other words, comparisons of the results of later surveys against the "1961" datum north of Mojave probably underestimate by as much as 0.15 m any down-to-the-north tilting developed over this reach since the spring of 1961.

Beginning in 1968, the primary vertical-control surveys between the northern San Fernando Valley and Palmdale commonly followed routes that

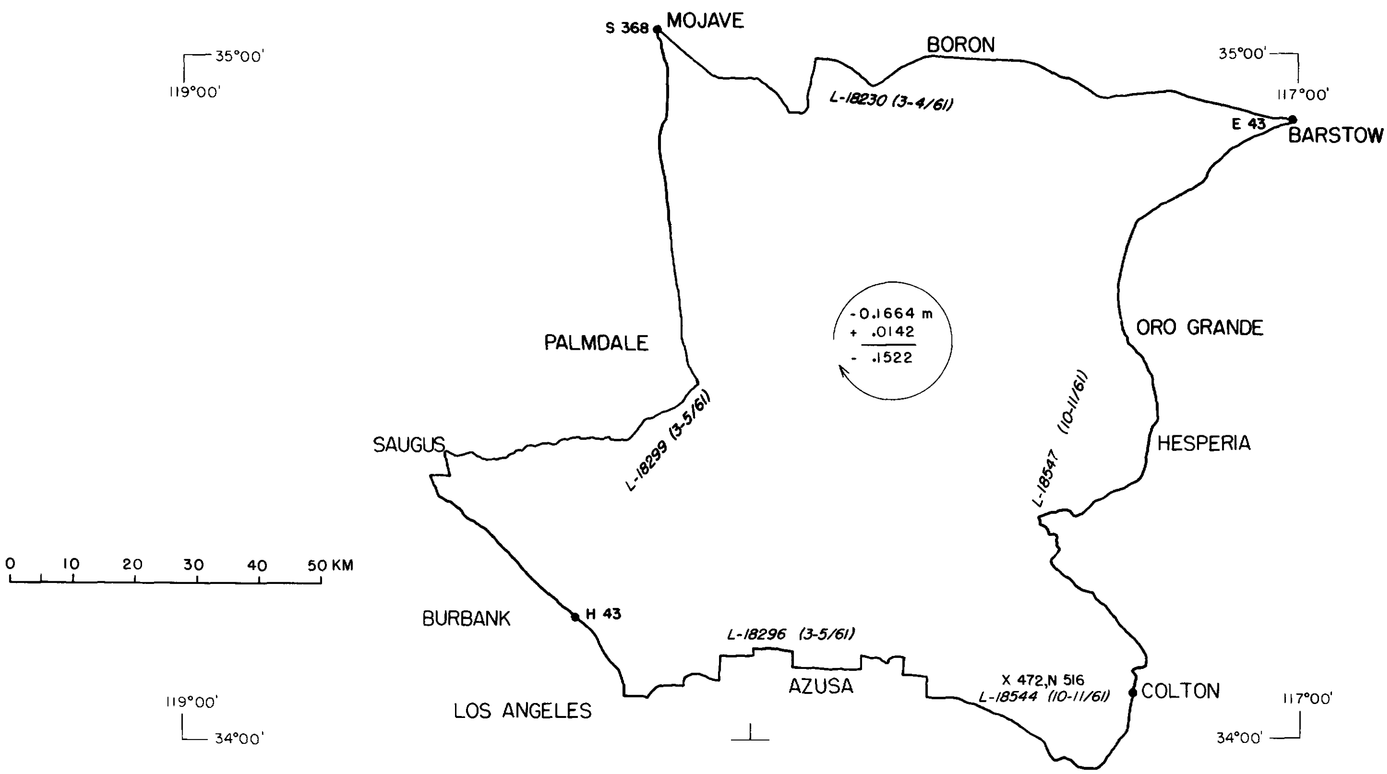


FIGURE 25.—Misclosure around the circuit Los Angeles-Burbank-Saugus-Palmdale-Mojave-Boron-Barstow-Oro Grande-Hesperia-Colton-Azusa-Los Angeles based on leveling carried out during the period March–November 1961. This misclosure diminishes to −0.1382 m where the orthometric correction is based on observed gravity. See figure 4 for adopted conventions and explanation of symbols.

differed somewhat from the pre-1968 line (pl. 5). Hence, height changes along this part of the Los Angeles-Mojave line, and specifically between bench mark 1239 USGS and bench mark Sloot, are less completely described than they would have been had the survey route along the main line remained the same. Nonetheless, the only seemingly significant change along the main line during the period 1965–68 consisted of a modest northward expansion or increase in the uplift between Palmdale and Rosamond (pl. 8A). Uplift of about 0.07 m centering on the Saugus area was subsequently recorded, however, during the period 1968–69 (pl. 8A). Because this relatively localized uplift is clearly associated with the epicentral region of the subsequent 1971 San Fernando earthquake, it can be thought of—much as can the 1964–65 uplift—either as a local aseismic fault-slip phenomenon or as a relative detail in the growth of the southern California uplift.

Height changes along the main line during the period 1968–71 are based on comparisons over generally different routes between bench marks M 53 and Sloot (pl. 8A). Nevertheless, because the reach between Saugus and the San Andreas fault remained virtually invariant between 1965 and 1968 (pl. 8A), elevation changes during the period 1965–71 based on a comparison between the 1965 and 1971 reconstructed elevations along the southern route (pl. 5) should nearly match those that would have been developed through a comparison of the 1971 elevations against a hypothetical 1968 datum along the same route. The especially large vertical displacements disclosed through a comparison of the results of the 1971 (postearthquake) surveys against the 1965 (or 1968) datum consist of major uplift north of the San Fernando fault and corresponding, although markedly diminished tectonic downwarping between the San Fernando fault and Burbank. Virtually all of the 1965–71 or 1968–71 uplift between bench marks R 43 and E 53 and nearly all of the contemporary downwarping between R 43 and 08-25525 are most reasonably interpreted as coseismic movements accompanying the 1971 San Fernando earthquake (Castle and others, 1975). However, because at least 0.07 m of the uplift in the Saugus area probably occurred during the preearthquake period beginning in 1968, this

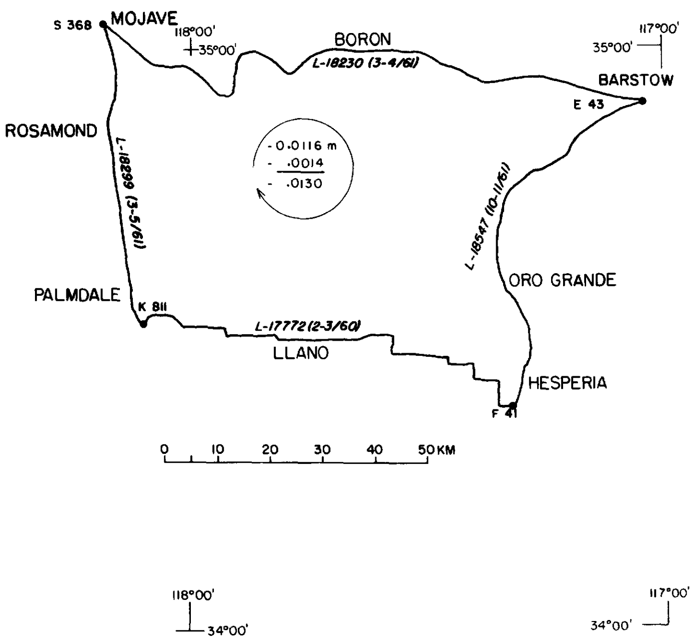


FIGURE 26.—Misclosure around the circuit Palmdale-Rosamond-Mojave-Boron-Barstow-Oro Grande-Hesperia-Llano-Palmdale based on leveling carried out during the period February 1960–November 1961. See figure 4 for adopted conventions and explanation of symbols.

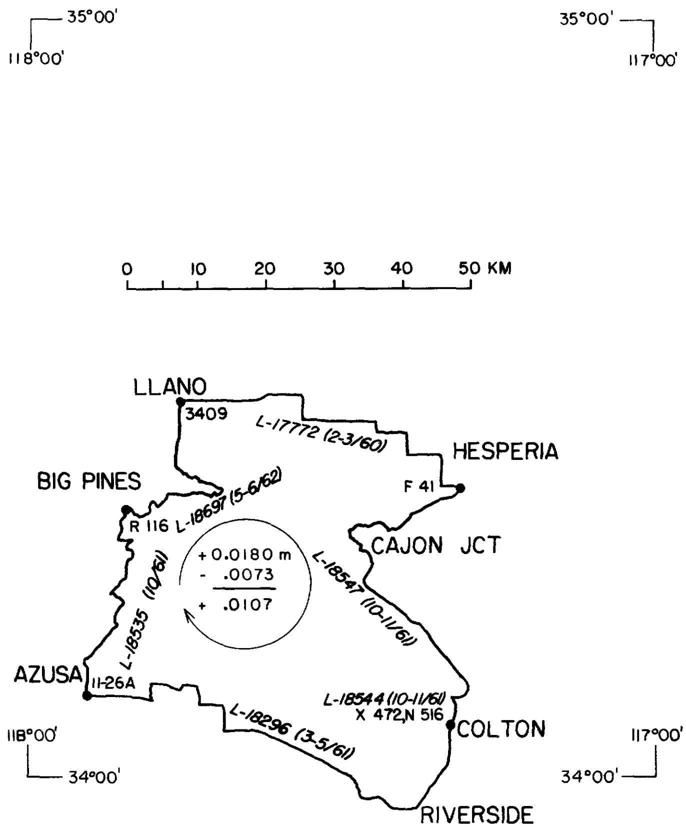


FIGURE 27.—Misclosure around the circuit Azusa-Big Pines-Llano-Hesperia-Cajon Junction-Colton-Riverside-Azusa based on leveling carried out during the period February 1960–June 1962. See figure 4 for adopted conventions and explanation of symbols.

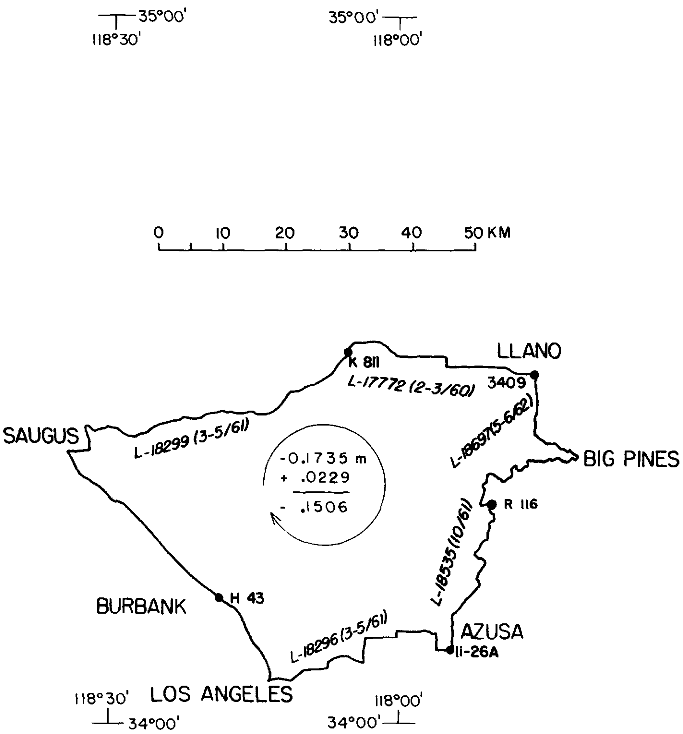


FIGURE 28.—Misclosure around the circuit Azusa-Los Angeles-Burbank-Saugus-Llano-Big Pines-Azusa based on leveling during the period February 1960–June 1962. This misclosure enlarges to −0.1579 m where the orthometric correction is based on observed gravity. See figure 4 for adopted conventions and explanation of symbols.

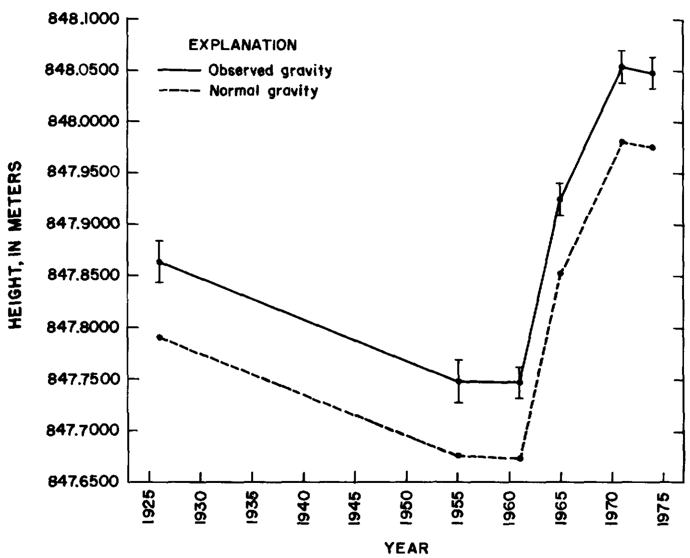


FIGURE 29.—Changes in orthometric height at bench mark Q 49, Mojave. One-standard-deviation error bars show conventionally estimated random error only.

preseismic uplift should be subtracted from the 1968–71 displacements in generating the true coseismic displacement field.

Several sets of significant height changes emerge from comparisons of the results of the 1972/73 and 1974 surveys against 1971 and earlier datums along the main line. The most obvious of these is the continued uplift of the Palmdale-Rosamond (or Mojave) block by as much as 0.08 m during the period 1971–74. Regrettably, the 1971 and 1974 level surveys followed different routes between bench marks 1239 USGS and Sloot (pls. 8A, B), such that we can only infer that the uplift between Saugus and the San Andreas fault increased almost uniformly. Although less obvious, the nearly 0.04 m of uplift at Los Angeles (fig. 16) that accompanied the 1971–74 uplift of the Mojave block represents the most conspicuous positive displacement in this area since the one that occurred between 1964 and 1968. Because the Los Angeles area subsided by a roughly equal amount during the period 1968–71, the 1971–74 uplift simply returned S 32 to its 1968 height. A second striking change revealed through a comparison of post-1971 surveys against an earlier datum is the surprisingly steep tilt between Mojave and Cantil that developed during the interval "1961"–72/73 (pl. 8A). Moreover, as we have already indicated, this down-to-the-north tilt is almost certainly a minimum value with respect to an unambiguously defined preuplift datum. Nonetheless, the dramatically diminished uplift between Mojave and Cantil is especially significant, for it provides one of the very few cases where the northern margin of the southern California uplift can be defined fairly clearly.

The results of the 1976 levelings are the first of the post-1955 data sets clearly indicative of regionally developed reversals in the generally positive displacement field that had characterized the southern California uplift since 1960. Comparisons of the results of the 1976 surveys against the 1955 (preuplift) datum (pl. 8A) suggest modest tectonic downwarping centering north of Los Angeles (see also section on "The Los Angeles-San Bernardino Line"), recovery to null values near San Fernando (discounting the coseismic effects associated with the 1971 earthquake), and uplift that increased gradually northeastward to a maximum of about 0.18–0.19 m (or roughly half the maximum cumulative 1955–74 value) near the San Andreas fault. Northward from the San Andreas fault to Rosamond, the uplift dimished gradually to only about 0.06 m (or about one-fifth the maximum uplift developed between 1955 and 1974). If the results of the 1976 surveys are compared, instead, against the 1974 surface that defined the maximum uplift along the main line (pl. 8A), the displacement pattern that emerges is relatively unusual among those developed within or around the southern California uplift. Specifically, between Tidal 8 and Rosamond the 1974–76 vertical displacements (disregarding the differential subsidence centering in the Lancaster area) are expressed as a remarkably uniform, gradually increasing down-to-the-north tilt that apparently bottoms out at Rosamond at about −0.25 m (pl. 8A). Because such rapid and extensive tectonic subsidence is so unusual in this area, there is some likelihood that the reconstructed 1976 observed elevations between Tidal 8 and Rosamond have been contaminated by intrasurvey movement. Regardless, tectonic tilting of this same sense and of approximately the same chronology has been independently confirmed by subsequent studies of the Los Angeles County Department of County Engineer (J. F. McMillan, written commun., 1977). A comparison of the results of early 1977 leveling against a 1973 datum extending northward along the coastline from San Pedro shows that the Santa Monica tide station dropped about 0.04 m with respect to Tidal 8 during nearly the same period in which S 32 subsided roughly 0.08 m (fig. 16; pl. 8A).

Vertical displacements along the Saugus-Grapevine spur since 1953 (or 1955) are relatively unambiguously defined (pl. 8B) and need no more than minimal explanation. The sharply localized elevation changes developed against the 1968 and older datums southeastward from bench mark U 370 are interpreted as chiefly coseismic effects associated with the 1971 San Fernando earthquake (Castle and others, 1974, p. 64–65; Castle and others, 1975). Similarly, the very limited differential uplift that occurred northward from Lebec between 1953 and 1956 (or 1959) is viewed as a local phenomenon that probably did not extend significantly south of the San Andreas fault. The reality of the apparent reversal of the vertical displacements in the area of Lebec between 1956 and 1959 remains in doubt. This seeming reversal (in the form of a down-to-the-south tilt) could conceivably derive from some combination of measurement error and actual uplift of bench mark F 55, Bakersfield, with respect to Tidal 8. Alternatively, and much more likely, the several stages of vertical movement shown through comparison of the results of the 1953, 1956, and 1959 surveys are an expression of postseismic slip on the White Wolf fault following the 1952 Kern County earthquake (R. S. Stein, oral commun., 1977).

We are uncertain both as to exactly when and exactly where the post-1953 regional uplift began along the Saugus-Grapevine spur. Several lines of evidence indicate that this uplift could not have begun until after the spring of 1960, yet was well established by no later than the fall of 1961. The orthometrically corrected misclosure around the 1953–61 loop Castaic-Fairmont-Palmdale-Saugus-Castaic, including the results of second-order leveling between Castaic and Fairmont, is given as 0.0442 m (fig. 15). This misclosure (fig. 15) suggests relative stability between Saugus and Castaic through at least the early spring of 1961, associated with (if anything) a slight down-to-the-northwest tilting between these two communities. Similarly, the 1960 heights of bench marks Boundary Monument 2 and X 53 were apparently depressed well below their 1953 heights (pl. 8B; figs. 15 and 30). However, by the fall of 1961, uplift of more than 0.1 m had occurred at least as far east-southeast as bench mark X 53. Moreover, while this uplift represents a minimum value based on the assumption that the subsequently recognized uplift of central Bakersfield had not yet begun (that is, that F 55 remained invariant between 1953 and the fall of 1961), the fact that the 1961 heights are virtual overlays of the 1964 heights between X 53

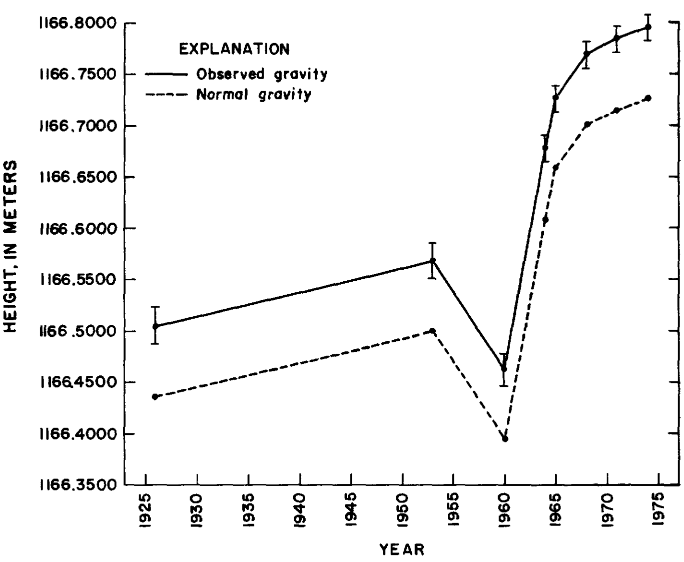


FIGURE 30.—Changes in orthometric height at bench mark Boundary Monument 2, Lebec. The 1960 height is based on an assumption of invariance between Boundary Monument 2 and X 53 (pl. 8B) during the period 1960–61 (see section on "The Ventura-Maricopa Line"). One-standard-deviation error bars show conventionally estimated random error only.

and Lebec (pl. 8B) argues that the represented 1953–61 uplift closely matched that which would have been deduced had the 1961 leveling emanated from Tidal 8. However, whether the 1961 elevations matched the 1964 elevations between X 53 and Saugus remains undetermined and probably undeterminable. The sharp down-to-the-north tilt that occurred between bench marks E 54 and N 54 during the period 1961–64 (pl. 8B) is conceivably an effect of extraction-induced compaction or associated marginal drag around the periphery of the Arvin-Maricopa subsidence basin (Lofgren, 1975, p. D14). However, because most of the marks that define this tilt lie well within the foothills of the Tehachapi Mountains, we suspect that this downwarping is chiefly tectonic.

Post-1964 uplift along the Saugus-Grapevine spur continued at an apparently decelerating rate through 1965 and had nearly ceased by 1968 (pl. 8B). That is, the profiles developed from the results of levelings since 1968 indicate that the reach extending northward from Saugus to at least bench mark H 537 remained virtually free of further uplift during the period 1968–73. This stability contrasts significantly with that section of the main line between Saugus and Palmdale, where the heights continued to increase after 1968.

The represented uplift along the Castaic-Fairmont subspur is almost certainly minimal. That is, we have assumed an equivalence between the 1961 elevation differences along this line and those that would have resulted from 1955 (or 1953) leveling over this route. This assumption is supported chiefly by the relatively small closure around the loop Castaic-Fairmont-Palmdale-Saugus-Castaic (fig. 15). However, because modest uplift at Palmdale is known to have occurred between 1955 and the spring of 1961 (pl. 8A; fig. 24), it seems likely that similar uplift in fact occurred between Castaic and Fairmont. Comparable up-to-the-northeast tilts between Saugus and Palmdale and between Castaic and Fairmont between 1955 and 1961 would have had no effect on the closure (fig. 15), since the height differences would have increased equally along each of these two legs of the circuit. In addition, the 1964 misclosures involving the leg Castaic-Fairmont (fig. 31) suggest that the 1964 Castaic-Fairmont observed-elevation difference may include an error of roughly −0.03 m. Accordingly, the 1955–64 uplift at Fairmont probably was at least 40-50 mm greater than shown here (pl. 8B).

Vertical movements along the Castaic Junction-Montalvo subspur have been measured against both the 1968/69 and the 1971 datums. Height changes between 1968 and 1971 along the east end of this spur, and westward as far as RV 47 or even RV 43, probably are attributable chiefly to coseismic slip associated with the 1971 San Fernando earthquake. Westward from RV 43, however, we can only assume that the 1968/69–71 downwarping of over 0.06 m was an essentially aseismic phenomenon. Moreover, while this apparent subsidence is conceivably attributable to ground-water withdrawals, Buchanan-Banks and others (1975, p. 115, 119) show that there was virtually no differential subsidence (with respect to Ventura) at the western end of this line between 1960 and 1971.

Differential movements along the western half of the Castaic Junction-Montalvo subspur between 1971 and 1974 may be especially significant. That is, while modest uplift may have developed between 1971 and 1974 westward from Castaic Junction, conspicuous downwarping apparently occurred during this same general period within the reach between Fillmore and Montalvo. Moreover, while this down-to-the-west tilt is clearly defined by the profiles of elevation changes measured against both the 1968/69 and 1971 datums, it is especially likely that it was produced during the period March 1973–January 1975 (pl. 8B). The clockwise misclosure around the "1974" loop Castaic

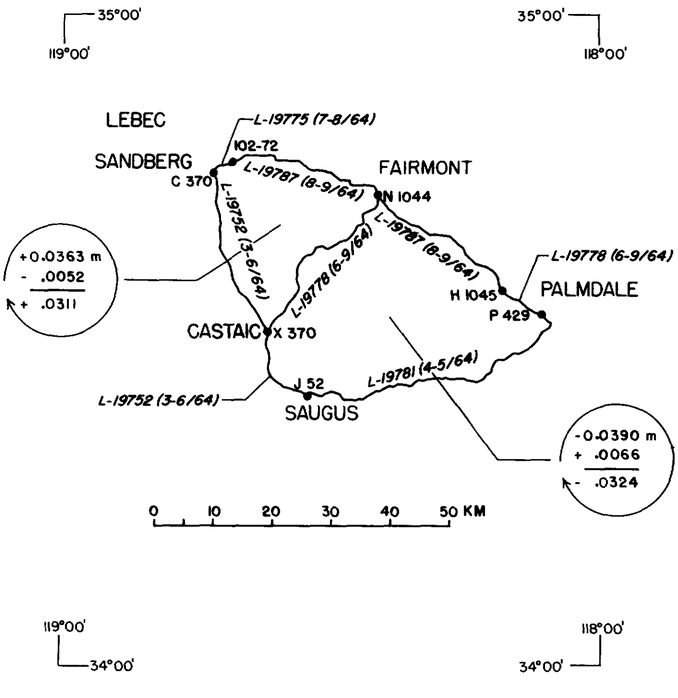


FIGURE 31.—Misclosures around the circuits Castaic-Sandberg-Fairmont-Castaic-and Castaic-Fairmont-Palmdale-Saugus-Castaic based on 1964 levelings. See figure 4 for adopted conventions and explanation of symbols.

Junction-San Fernando-Topanga Canyon-Ventura-Castaic Junction is about +0.07 m (fig. 21). This misclosure is consistent with a major down-to-the-west tilt between bench marks RV 55 and 3-26 developed during the completion of this loop (fig. 21). Moreover, the apparently tectonic downwarping of more than 0.08 m at Montalvo during the period 1968/69–74/75 is about twice that recognized north of Ventura (pl. 7) during approximately the same interval. This difference may derive from the fact that the 1974 leveling between Montalvo and the Los Angeles-Ventura county line was carried out several months after the completion of the 1974 leveling extending northward from Ventura; hence, downwarping in the Ventura-Montalvo area may have accelerated toward the end of 1974.

Vertical movements between Mojave and Bakersfield since 1953 are explicitly described by the profiles of height changes along the Mojave-Bakersfield spur (pl. 8B) and require little explanation or interpretation. Because the differential subsidence centering on Edison and Tehachapi is almost certainly an expression of artificially induced compaction (see pls. 3 and 4), it may be disregarded in assessing any tectonic deformation in this area. Moreover, the uplift that occurred eastward from Bank AZ during the periods 1953–56, 1953–59, and 1953–61/62 probably can be attributed to postseismic slip on the White Wolf fault (or one of its main branches) and, hence, is similar in origin to the uplift recognized in the Lebec area during the same general period. Although it is conceivable that the relatively trivial uplift developed during the period 1959–61/62 between bench marks Bank AZ and W 55 is an expression of regional uplift in this area, it is questionable whether the southern California uplift had propagated this far north as early as the beginning of 1962. The roughly 50 mm of differential uplift, measured with respect to either Mojave or Caliente and disclosed through a comparison of the results of the 1965 survey against the 1953 (1955-equivalent) datum, is reasonably interpreted as an expression of aseismic slip on the White Wolf fault. Because there were no Mojave-Caliente surveys between 1953 and 1965, the inception of this differential uplift cannot be precisely dated; however, we assume that it may have evolved largely by the spring of 1961. Because indications of similar movement are absent from the profile developed against the 1965 datum, and because the uplift extends smoothly across the White Wolf fault without any evident discontinuity, we infer that the regional uplift developed since 1953, and specifically since 1965, cannot be attributed to slip on the White Wolf fault.

THE LOS ANGELES-SAN BERNARDINO LINE

GENERAL REMARKS

The reconstructed height changes along the Los Angeles-San Bernardino line (pl. 9) are based on the results of six nearly continuous levelings. However, owing to variations in route, particularly over the reach between Los Angeles and Azusa, the comparisons between successive surveys commonly are lacking in detail. Moreover, the 1976 survey, the latest of the levelings along this line, extends only a short distance northeastward, from Los Angeles to La Cañada.

The selection of a suitable datum is the chief problem we face in calculating the recent height changes along this line. Although we have provisionally adopted the results of 1934 leveling as the approximate equivalent of a 1955 datum, because the 1961 leveling along the main line was completed during the spring of 1961, and hence prior to the inferred propagation of major uplift through this area, the results of the 1961 leveling may provide an equally good equivalent, especially since the differences between the 1934 and 1961 surveys are generally trivial west of Claremont. Nonetheless, because the 1961 heights along the main line lie generally below the 1934 datum, there is a reasonable likelihood that modest tectonic subsidence occurred along this line sometime between 1934 and 1961.

While the choice of a suitable datum along the main line obviously has complicated the reconstruction, we are effectively denied a preuplift datum over the San Gabriel Mountains between Azusa and Llano. The earliest first-order survey was carried out in 1934 and ended at Falling Springs; the first leveling that traversed the entire range was completed during the interval October 1961–June 1962—that is, subsequent to the first major pulse of uplift to encompass this area. This point is easily demonstrated through a comparison between the 1960/61 (or 1955/60) height for Llano based on leveling via Saugus and Palmdale versus that based on 1961/62 leveling over the San Gabriel Mountains, which shows that Llano rose about 0.20 m during the period 1960/61–61/62.

Between the spring of 1961 and the following fall (and certainly no later than 1968/69), heights along the main line increased by 0.04–0.06 m, at least as far east as Claremont. Moreover, although the heights in the Azusa area remained nearly constant between 1968/69 and 1971, uplift at Azusa increased by as much as 0.04 m between 1971 and 1974. On the other hand, between 1974 and 1976, and possibly no later than the end of 1974, the western end of the main line collapsed by as much as 0.14 m.

Cumulative post-1955 height changes between Azusa and Llano cannot be deduced through direct comparisons owing to the absence of a preuplift datum extending over the full width of the San Gabriel Mountains. Nevertheless, between 1934 and the fall of 1961 the reach between Azusa and Falling Springs sustained at least 0.06 m of northward-accumulating tectonic subsidence. Accordingly, the 1934 (or 1955)–61/62 uplift over the San Gabriel Mountains must have been localized between Falling Springs and Llano and must have been expressed as an up-to-the-north tilt of about 0.25 m. Because the uplift over the San Gabriels apparently increased by no more than 0.07–0.08 m between 1961/62 and 1971, and because the tectonic subsidence of Falling Springs apparently recovered by 1971, the gradient between Falling Springs and Llano must have been preserved through at least 1971.

DETAILED RECONSTRUCTION

The Los Angeles-San Bernardino line consists of a primary vertical control line between Los Angeles and San Bernardino (via Glendale and La Cañada) and two spurs, the Los Angeles-Monrovia line and the Azusa-Llano line (pl. 9). The 1934 starting elevation at Los Angeles is based on leveling between Tidal 8 and S 32 carried out during the period January–April(?) 1934 (NGS line L-991). The 1976 starting elevation derives from leveling between Tidal 8 and S 32 carried out during the interval August–September 1976 (NGS line L-24116). Starting elevations at Los Angeles in all other cases are the same as those used in developing the observed elevations along the Los Angeles-Mojave line (see section on "The Los Angeles-Mojave Line").

Observed elevations along the Azusa-Llano spur were developed from four separate levelings, only two of which extended over the full length of this line. Only one of these two surveys (1971), moreover, consisted of essentially uninterrupted leveling between Tidal 8 and Llano. Starting elevations at Azusa are based on the junction elevations at bench marks Q 35 (1934) or 11-26A developed from levelings along the main line.

The development of a primary datum for the Los Angeles-San Bernardino line has been complicated by the occurrence of regional tilting along the Azusa-Llano spur during the period 1961–62 and the absence of a post-1934 yet pre-1961 leveling along this line. Because the 1961 surveys between Tidal 8 and Azusa were completed during the period March–May 1961 (NGS lines L-18296 and L-18364) and, hence, probably before significant uplift in this area (see section on "The Los Angeles-Mojave Line"), the results of these surveys should provide a reasonably suitable primary (1955-equivalent) datum. However, the 1961/62 leveling along the Azusa-Llano spur over the San Gabriel Mountains was not completed until June 1962, well after the first major episode of uplift propagated eastward into this area (see section on "The Los Angeles-Mojave Line"). Thus the only possible alternative to a 1961/62 datum is the development of a primary datum based on the results of 1934 levelings along both the main line and the Los Angeles-Monrovia and the Azusa-Llano spurs. We assume that the 1955 heights lay somewhere between the 1934 and 1961 heights. And since the height changes were relatively small along both the main line and the Los Angeles-Monrovia spur during the interval 1934–61, we have adopted the results of the 1934 leveling as a primary (1955-equivalent) datum. Nonetheless, equating 1934 observed elevations with 1955 observed elevations invites several reservations. For example, we are virtually certain that compaction-induced subsidence occurred over much of this line between 1934 and 1955 (pls. 3 and 4) and that the 1956 (1955-equivalent) heights in the San Bernardino-Colton area probably were about 0.20 m below the 1961 heights as well, perhaps, as those that obtained in 1934 (see section on "The Orange-Barstow Line").

Although height changes along both the main line and the Los Angeles-Monrovia spur have been generally small since 1934, they have included a single dramatic reversal. Eastward from bench mark T 96 (on the Los Angeles-Monrovia spur) to Azusa, the 30–40 mm of differential subsidence that seems to have characterized the vertical movements between 1934 and 1961 (pl. 9) probably is attributable chiefly to ground-water withdrawals and resulting compaction of the surficial deposits that underlie most of this area (pls. 2 and 3). This explanation is even more likely within the reach between Azusa and Claremont, where the differential subsidence has been even greater (pls. 2, 3, and 9). Thus, in reconstructing the history of vertical movement associated with tectonic activity along this line, much of the movement that occurred between 1934 and 1961 should be subtracted. The effect of this subtraction would be to increase any uplift with respect to a 1934 (1955-equivalent) datum by as much as the differential subsidence that occurred between 1934 and 1961.

Height changes along the main line between 1961 and 1968/69 were remarkably uniform (pl. 9). That is, the whole area between bench marks S 32 and 11-47 rose roughly 40–50 mm. The only exceptions to this generalization are the differential subsidence at the western end of this line (almost certainly associated with ground-water withdrawals) and sharply defined uplift midway between Azusa and Claremont (pl. 9). The differential uplift of about 0.05 m between bench marks 11-47 and 11-52 is an anomaly that cannot be clearly associated with any geologic feature. Nevertheless, it lies within 1 km of the Sierra Madre fault zone on the north and occurs within or adjacent to the structural knot defined by the intersection of the Sierra Madre, Walnut Creek, and San Dimas Canyon fault zones (Rogers, 1967). Between 1968/69 and 1971 the Los Angeles-San Bernardino line remained relatively free of vertical displacements (pl. 9). That is, while S 32 apparently subsided during this interval, the area between Monrovia and Azusa remained almost invariant. The period 1968/69–74 (and, hence, by inference, the period 1971–74) was a time of regional uplift that extended from La Cañada to San Bernardino (pl. 9). If allowance is made for the compaction-induced differential subsidence that probably occurred during this interval (see pls. 3 and 9), it is clear that the magnitude of this regional uplift apparently ranged within very narrow limits of 50–60 mm. The surprisingly large up-to-the-east tilt defined by the 1968/69–74 comparison at the east end of the main line is adjacent to the San Jacinto fault (pl. 9) and may, as such, be reasonably interpreted as an expression of slip on this fault. It is conceivable that this differential uplift is due to aquifer recharge in the Bunker Hill ground-water basin (pl. 3), but the magnitude of this uplift is much greater than that generally associated with this phenomenon.

The observed elevation changes developed from a comparison between the results of the 1974 and 1976 surveys between Tidal 8 and La Cañada (pl. 9) form one of the most clearly defined reversals recognized in this study. The 1974–76 0.14-m downwarp at La Cañada is so large that there can be little doubt of its authenticity and virtually no chance that it can be other than tectonic in origin. Moreover, although over half of this subsidence accumulated south of Los Angeles, the down-to-the-north tilt steepened sharply toward La Canada (pl. 9). Northward from Tidal 8 to Los Angeles (S 32), bench mark heights generally declined between 1974 and 1976 (NGS lines L-23611, L-23644, and L-24116), and we suspect that much of this subsidence is tectonic. Nevertheless, because large sections of the Los Angeles basin have been identified with compaction-induced subsidence (pls. 3 and 4) that is generally indistinguishable from tectonic downwarping, there seems little point in showing profiled elevation changes south of Los Angeles.

A comparative elevation study based on three successive levelings in the La Cañada area suggests that most of the 1974–76 downwarping may have occurred between October 1973 and November 1974 (J. F. McMillan, Los Angeles County Department of County Engineer, written commun., 1976). Thus, between October 1973 and November 1974, a measurable up-to-the-west tilt of about 6 mm developed over a 2-km section of the Los Angeles-San Bernardino line in the La Cañada area (fig. 32*A*). This tilt is roughly equal to four standard deviations in the expected discrepancy between two separate measurements of the height difference between the end points of this section. Releveling of this same section in September 1976 showed that the elevation difference between the end points remained virtually invariant during the period November 1974–September 1976 (fig. 32*B*); thus there is a reasonable suspicion that the tectonic activity associated with the subsidence of La Cañada had largely ceased by the end of 1974.

Height changes accompanying the evolution of the southern California uplift along the Azusa-Llano spur have been based on both a presumed equivalence between the 1934 heights and a hypothetical 1955 datum and an assumption of stability at bench mark Q 35 during the period March–October 1961. However, because the 1961/62 survey (pl. 9) was not even begun until after the southern California uplift propagated into this area (see section on "The Los Angeles-Mojave Line"), the stability of Azusa through 1961 is in doubt. A comparison between the March–May 1961 observed elevation of Q 35 with the orthometrically compatible elevation of Q 35 based on March–May 1961 leveling between Tidal 8 and Saugus, 1961/62 leveling between Saugus and Palmdale (see section on "The Los Angeles-Mojave Line"), 1960 leveling eastward from Palmdale to Llano (see section on "The Quail Lake-Hesperia Line"), and 1961/62 leveling over the San Gabriel Mountains (pl. 9) indicates that Q 35 sustained uplift of 0.0548 m between the spring of 1961 and the following year. Accordingly, there is a good chance that the solid-line representations shown on plate 9 exaggerate by 54.8± mm both the 1934–61/62 downwarping and the 1961/62–71 uplift along the Azusa-Llano spur. Thus an alternative and seemingly more objective reconstruction of the 1934–61/62 and 1961/62–71 vertical movements along the Azusa-Llano spur is based on the probable uplift of Azusa between the spring of 1961 and the following year; this alternative reconstruction is indicated by the dashed-line representation (pl. 9).

Interpretation of the profiles of height changes along the Azusa-Llano spur is complicated by the near certainty that the 1961/62 leveling postdated the first surge of uplift in this area. While it seems likely that the dashed-line representation more closely approximates the actual height changes between Azusa and Falling Springs during the period 1934–61/62 than does that shown by the solid line (pl. 9), both suggest significant down-to-the-north

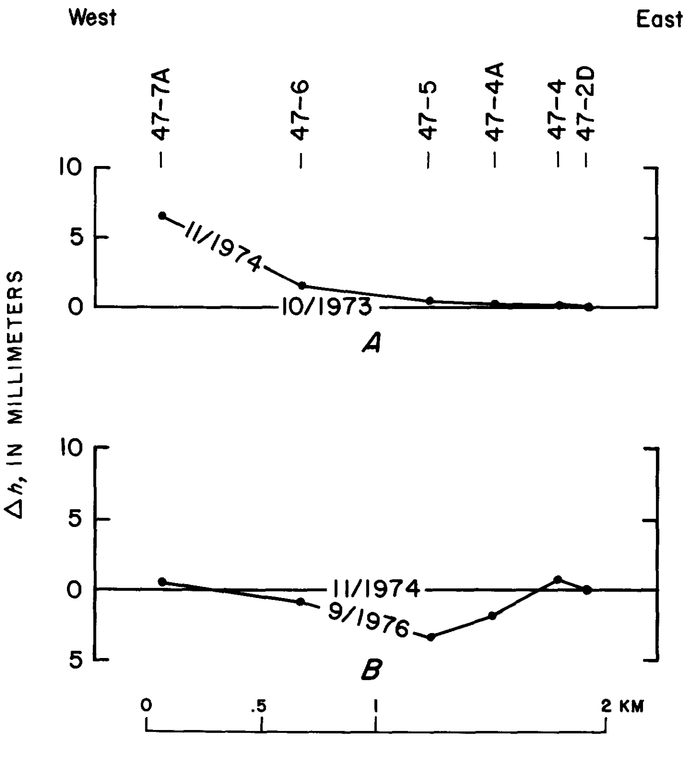


FIGURE 32.—Profiles showing height changes (Δ*h*) with respect to bench mark 47-2D along 2-km segment of the primary vertical control line through La Cañada (pl. 9). Based on repeated first-order levelings of the Los Angeles County Department of County Engineer (J. F. McMillan, written commun., 1976) and the National Geodetic Survey. *A*, Height changes between October 1973 and November 1974. *B*, Height changes between November 1974 and September 1976.

tilting that could easily have been associated with uplift farther to the north. The orthometrically compatible observed elevation of bench mark 3409, Llano, based on 1960 leveling tied to the results of a March–May 1961 survey between Tidal 8 and Palmdale is given as 1,038.8610 + 0.0229 m (see section on "The Quail Lake-Hesperia Line"); the 1961/62 (postuplift) elevation of this same mark based on the results of leveling tied to the October 1961 elevation of Q 35 is given as 1,039.0864 m. Thus the uplift at Llano between the spring of 1960 and 1961/62 apparently was at least 0.2025 m. Because Falling Springs sustained tectonic subsidence of about 0.05 m that could have occurred during this same period, up-to-the-north tilting of as much as 0.25 m during the period March 1961–1961/62 may have been localized between Falling Springs and Llano. Moreover, even if this determination were to be based on an assumption of stability at Q 35 between the spring of 1961 and the following year, this 0.25-m gradient would remain unchanged, since the 1961/62 heights of both Falling Springs and Llano would each be diminished by the same amount. The 1971 elevation of bench mark 3409 is given as 1,039.1587 m, such that between 1960 and 1971, 3409 apparently sustained uplift of 0.2748 m, only 0.0723 m of which was generated after 1961/62. Moreover, because the differential uplift that occurred between Azusa and Falling Springs during the period 1961/62–71 consisted chiefly of the recovery of the down-to-the-north tilt developed during the preceding (1934–61/62) period (pl. 9), the cumulative uplift between those localities probably was no more than 0.04–0.05 m, whereby the steep gradient of uplift between Falling Springs and Llano must have been preserved through 1971. Finally, because the misclosure around the 1970/71 loop Azusa-Los Angeles-Burbank-Saugus-Palmdale-Llano-Big Pines-Azusa is relatively tight (fig. 33), it seems unlikely that this interpretation can be categorically dismissed as the product of survey error in the 1970/71 leveling.

THE ORANGE-BARSTOW LINE

GENERAL REMARKS

Among the several sets of observed elevations extending over all or parts of the Orange-Barstow line (pl. 10), only two (the 1968 and the 1974) were developed from essentially continuous levelings propagated directly out of Tidal 8. Accordingly, the absence of a well-defined preuplift datum tied directly to Tidal 8 forms the fundamental problem associated with the reconstruction of height changes along this line. Because about two-thirds of this line—including virtually all of that which falls within the confines of the uplift—was leveled in 1956, reconstructions with respect to the results of this leveling should, in theory, produce reasonably good characterizations of the cumulative stages of uplift through 1974. However, use of the results of the 1956 leveling as a reference datum requires that we choose between one of two options that produce dramatically different results. The first of these options is based on an assumption of stability at Colton during the period 1955–61; the second is based on 1956 leveling emanating from a control point whose height determined with respect to Tidal 8 can be shown to have remained invariant during a period that includes 1956. Both alternatives are presented here, but the second is clearly preferable in spite of several limitations.

If it is assumed that Colton remained invariant between 1956 and the fall of 1961, cumulative uplift over Cajon Pass prior to 1974 amounted to a maximum of about 0.05 m. However, the small misclosure around the 1960/61/62 circuit Azusa-Big Pines-Llano-Hesperia-Cajon Junction-Riverside-Azusa is consistent with major (0.15–0.20-m) mid-1961 up-to-the-north tilts over both the San Gabriel Mountains and

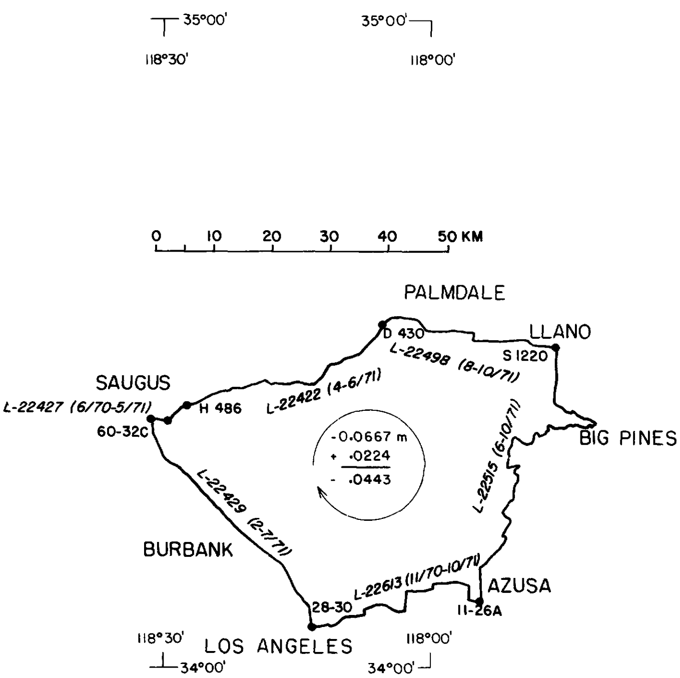


FIGURE 33.—Misclosure around the circuit Azusa-Los Angeles-Burbank-Saugus-Palmdale-Llano-Big Pines-Azusa based on leveling carried out during the period November 1970–October 1971. This misclosure enlarges to −0.0511 m where the orthometric correction is based on observed gravity. See figure 4 for adopted conventions and explanation of symbols.

Cajon Pass. Moreover, the vertical-displacement history of Hesperia indicates that it sustained uplift of 0.13–0.19 m between 1960 and the fall of 1961, an observation that is clearly inconsistent with the seeming 1956–61 tectonic subsidence of Hesperia based on a presumption of stability at Colton during the period 1956–61. Accordingly, our preferred reconstruction of the 1956 datum is based on a tie to a March–April 1961 height for bench mark E 43, Barstow, a reconstruction supported by the near invariance of this mark between 1926/27 and March–April 1961.

The alternative and preferred reconstruction of the 1956 datum provides what we believe to be an accurate basis for assessing the cumulative uplift between Colton and Barstow since 1956. However, because the uplift between Colton and Barstow during the period 1956–October 1961 was relatively uniform, it indicates that the 1956 height of Colton must have been about 0.22 m below that which obtained during the fall of 1961. Since several lines of evidence indicate that an up-to-the-north tilt of nearly this magnitude occurred between Colton and Hesperia sometime between the spring and fall of 1961, the cumulative 1956–October 1961 uplift between Colton and Hesperia must have consisted of two successive tilts of opposite sense.

Major uplift along the Orange-Barstow line between 1956 and 1974 was localized in the Cajon Pass area, where it reached a maximum of 0.36 m. However, we have no way of knowing what fraction of the 1956–74 uplift south of Hesperia predates the broader regional deformation that we associate with the southern California uplift. Because the cumulative 1956–74 value based on 1974 leveling that ends well south of Hesperia is only 0.32 m, there is a reasonable likelihood that the post-1959 uplift over Cajon Pass never exceeded 0.30 m. On the other hand, the remarkably uniform 1956–68 regional uplift between Hesperia and Barstow is unambiguously defined and was about 0.25 m. Moreover, while nearly all of this uplift had occurred by the fall of 1961, northward from Colton the 1968 heights increased over their 1961 values by as much as 0.08 m. Similar generalizations apply to height changes that occurred along the line over the San Bernardino Mountains between Colton and Lucerne Valley. The cumulative 1956–October 1961 uplift between Colton and Big Bear City roughly matched the uplift that occurred between Colton and Hesperia during the same interval. However, the 1956–75 cumulative uplift at Big Bear City of only 0.25 m (and conceivably less) seems surprisingly small and may be an artifact of our reconstruction, which is based on an assumption of stability at the junction bench mark at Summit during the period 1974–75.

DETAILED RECONSTRUCTION

The Orange-Barstow line consists of a primary vertical control line extending northward from Orange to Barstow, together with a single spur, the Colton-Lucerne Valley line (pl. 10). Because this line passes through an area of at least local instability attributable to both continuing tectonic activity and compaction-induced subsidence centering on Colton and San Bernardino (pls. 3 and 4), reconstructions of elevations based on level surveys emanating from the Colton-San Bernardino area are of doubtful validity. Moreover, of the four levelings used here, only one (1968) extends over the full length of the line and only two (1968 and 1974) are based on level surveys that are (or can be treated as) the product of nearly continuous surveys between Tidal 8 and the northern ends of the respective surveys.

Because the 1956 leveling emanated from Colton, the starting elevations for both the 1956 and 1961 surveys are based on 1961 leveling that originated at Tidal 8 and was completed during the period March-May 1961 (NGS lines L-18296 and L-18364). Moreover, because the 1961 surveys followed a path through Los Angeles, as opposed to the primary route through Orange and Riverside (pl. 5), the 1956 and 1961 starting elevations have been orthometrically corrected by +0.0062 m (in order to bring them into conformity with those that would have been obtained had the 1961 surveys followed the primary route). The 1968 starting elevation at Orange derives from leveling carried out during the interval April 1968–June 1969 (NGS lines L-21537, L-21596, L-21729, L-21807, and L-21868). The 1974 starting elevation is based on the results of surveys between Tidal 8 and Orange completed during the period September 1973–June 1974 (NGS lines L-23434, L-23437, L-23644, L-23443, and L-23699).

Reconstructed observed elevations along the Colton-Lucerne Valley line are based on three level surveys carried out during 1956, 1961, and 1975. Only one of these surveys (1961) extended over the full length of the level line. The 1956 leveling ended at Big Bear City; the 1975 leveling followed a different route between Colton and Big Bear City, such that comparisons with the results of the 1975 surveys are limited to the reach between Big Bear City and Lucerne Valley (pl. 10). The 1956 and 1961 starting elevations for the Colton-Lucerne Valley line are the same as those used for the main line; the 1975 starting elevation is based on a tie with a 1974 elevation at Summit and a presumption of stability at bench mark N 709 during the period 1974–75.

Because the section between Colton and Barstow was leveled in 1956, the development of a primary datum (1955-equivalent) for the major part of the Orange-Barstow line is a seemingly straightforward procedure. Nevertheless, this development is based on an assumption of stability at Colton during the period 1956–61, an assumption of dubious merit owing to the deformational history of this area during the first half of this century. Moreover, any interpretation of height changes developed through comparisons with the results of subsequent surveys carries with it the questionable implication that any movements that might be revealed by these comparisons occurred at the same time—whatever the time frame defined by these surveys. Thus, the comparisons shown on plate 10 suggest trivial height changes between Colton and Hesperia (other than the differential subsidence centering on the Bunker Hill ground-water basin east of the San Jacinto fault) and relatively modest tectonic subsidence between Hesperia and Barstow during the period between 1956 and the fall of 1961. This interpretation is susceptible to challenge on at least two counts: (1) minimum uplift at Hesperia (E 41) between the spring of 1960 and the fall of 1961 is given as 0.13 m (see section on "The Quail Lake-Hesperia Line") and (2) the 0.15-m up-to-the-north tilt developed between Colton and Barstow between the spring and fall of 1961 (see section on "The Los Angeles-Mojave Line"). That is, either the 1956 heights along the line between Colton and Barstow closely approached and locally exceeded those that prevailed during the fall of 1961 (whereby major tectonic subsidence would have to have occurred at Hesperia between 1956 and the spring of 1960) or the 1956 height of D 39 (Colton) was substantially below its March–May 1961 height.

An alternative reconstruction of the 1956 datum may be developed by means of 1956 leveling emanating from Barstow (rather than Colton), where it is assumed that Barstow remained invariant between 1956 and the spring of 1961—an assumption for which there exists some support. Thus, as shown in figure 34, the height of bench mark E 43, Barstow, held within 0.05 m during the period 1927–April 1961. Moreover, because the 1939 height of E 43 is based on a combination of 1939 first- and second-order leveling and less precise 1936 third-order leveling, even this relatively narrow 0.05-m range probably is exaggerated. Accordingly, if it is accepted that this history demonstrates crustal stability at Barstow during the period 1927–April 1961, the 1956 height of D 39 (Colton) may be established by means of the 1956 measured elevation difference between E 43 and D 39 and the orthometrically compatible April 1961 observed elevation of E 43 (fig. 35). Although the 1956 height of Colton could just as easily have been based on the "1956" or even the "1939" height of E 43, it is more reasonably developed from either the 1927 or April 1961 heights for this mark. The 1927 and the April 1961 heights of E 43 fall within 2 cm of each other (fig. 34), and both are based on nearly continuous first-order leveling between San Pedro and Barstow, whereas the intermediate heights are based in part on lower-order leveling and an assumption of local stability over periods of up to 13 years. The first of our reconstructions, moreover, does not allow for the likelihood that D 39 sustained several centimeters of uplift between the spring and fall of 1961. That is, if bench mark 11-26A, Azusa, rose about 0.04 m between March–May 1961 and 1961/62 (see section on "The Los Angeles-San Bernardino Line"), the trivial misclosure around the loop Azusa-Big Pines-Llano-Hesperia-Cajon Junction-Colton-Riverside-Azusa (fig. 27) suggests that Colton rose by about the same amount during the interval between March–May 1961 and October–November 1961. Thus, the 1956–61 uplift developed along the Colton-Barstow section of the Orange-Barstow line represented by the solid line (pl. 10) is almost certainly an expression of minimum uplift during this period.

The alternative dashed-line reconstructions shown on plate 10 represent cumulative movement since 1956; they do not necessarily imply uniformity in the rate of movement, nor do they purport to characterize the distribution in time of the vertical displacements within the various sections of this line. That is, several independent arguments indicate that the 1956–61 vertical displacements increased differentially with time northward along the survey line. The probable minimum uplift of E 41, Hesperia, based on 1960 leveling through Palmdale and October–November 1961 leveling via Col-

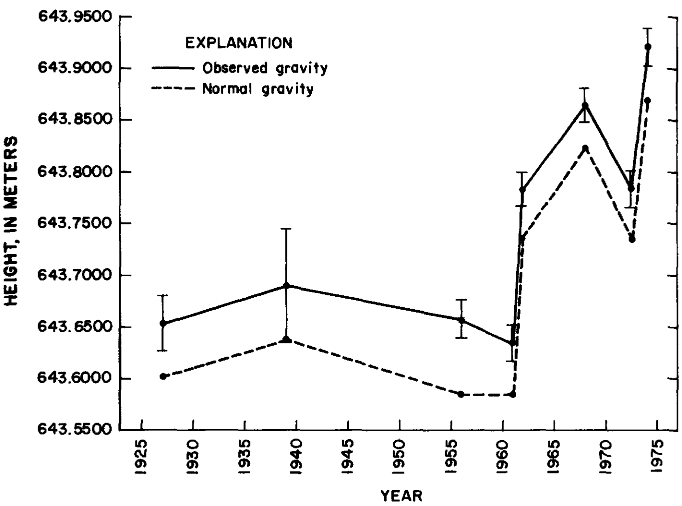


FIGURE 34.—Changes in orthometric height at bench mark E 43, Barstow. The 1939 height is based on (1) an assumption of stability at bench mark D 57, Palmdale, during the period 1926–35, (2) 1935 leveling between bench marks D 57 and E 57, Palmdale (NGS line L-3680), (3) an assumption of stability at E 57 during the period 1935–39, (4) 1939 second-order leveling between E 57 and the Llano area, (5) 1936 U.S. Geological Survey third-order leveling between the Llano area and Kramer Junction, and (6) 1939 first-order leveling between Kramer Junction and E 43 (NGS line L-8531). The 1956 height is based on (1) the 1955 height of D 430 (fig. 24), (2) 1960 leveling between D 430 and E 41, Hesperia, (3) an assumption of invariance between D 430 and E 41 during the period 1955–60, and (4) 1956 leveling between E 41 and E 43. One-standard-deviation error bars show conventionally estimated random error only.

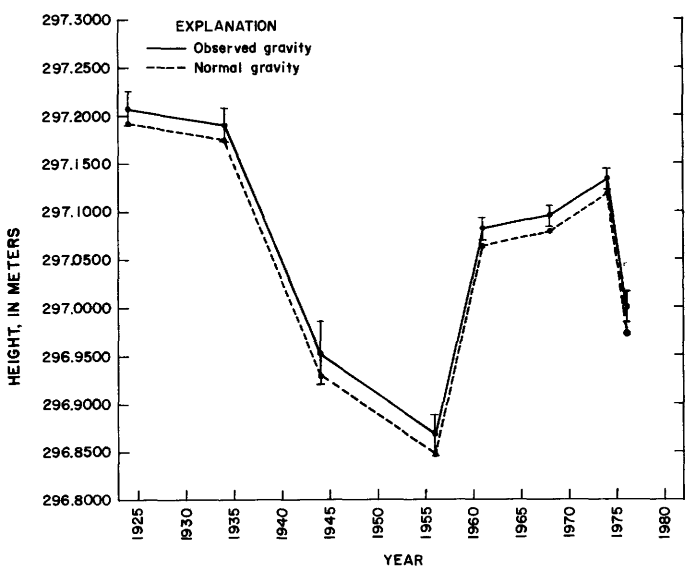


FIGURE 35.—Changes in orthometric height at bench mark D 39, Colton. The 1944 height is based on an assumption of invariance at bench mark R 41, Victorville, between 1939 and 1944 (fig. 54) and 1944 leveling between R 41 and D 39. The 1956 height is based on an assumption of invariance at bench mark E 43, Barstow, between 1956 and the spring of 1961 (fig. 34) and 1956 leveling between E 43 and D 39. One-standard-deviation error bars show conventionally estimated random error only.

ton, is given as 0.13 m (see fig. 39). In fact, however, the uplift of E 41 during this period may have been as great as 0.19 m (see section on "The Quail Lake-Hesperia Line"), a figure that agrees almost perfectly with the alternative 1956–61 uplift of E 41 shown on plate 10. This implies, of course, that the height of E 41 remained virtually unchanged between 1956 and the spring of 1960 and, hence, that such uplift as occurred at Hesperia between 1956 and 1961 must have occurred largely between the spring of 1960 and October–November 1961. Moreover, the misclosure defined by 1961 leveling around the loop Los Angeles-Burbank-Saugus-Palmdale-Mojave-Boron-Barstow-Oro Grande-Hesperia-Colton-Azusa-Los Angeles (fig. 25) indicates a 0.15-m up-to-the-north tilt between Colton and Barstow that must have occurred between the spring and fall of 1961 (see section on "The Los Angeles-Mojave Line"). Because the misclosure around the loop Palmdale-Rosamond-Mojave-Boron-Barstow-Oro Grande-Hesperia-Llano-Palmdale based on 1960/61 leveling is virtually zero (fig. 26), we infer, as we have already indicated, that the up-to-the-north tilt between Colton and Barstow accumulated entirely between Colton and Hesperia. In fact, that the northern loop (fig. 26) closes as well as it does may be largely fortuitous; that is, the 1955–61 down-to-the-north tilt between Palmdale and Mojave of about 0.05 m (pl. 8A) almost precisely matches the 1956–61 down-to-the-north tilt between Hesperia and Barstow (pl. 10), which suggests that the axis of the uplift closely coincides with a line between Palmdale and Hesperia. If, as the bulk of the evidence suggests, the 0.15-m up-to-the-north tilt between Colton and Barstow (or the 0.20-m tilt between Colton and Hesperia) developed between the spring and fall of 1961, the 1956–61 uplift of the reach between Hesperia and Barstow must have occurred during the same small fraction of the 1956–61 observation period.

An obvious corollary clearly follows from the preceding analysis: the 1956–61 uplift between Colton and Hesperia must have developed largely before the spring of 1961—and hence in advance of the regional uplift to the north and west. A crude approximation of the pre-1961 uplift may be obtained through subtracting a uniform tilt between Colton and Hesperia, developed between the spring and fall of 1961, from the cumulative 1956–61 uplift between Colton and Hesperia. The resulting difference represents the uplift developed between 1956 and the spring of 1961 (fig. 36). The most vulnerable feature of this reconstruction is that whereas the 1956–61 up-to-the-south tilt probably accumulated entirely within the area between Colton and Hesperia, it could have developed over a much narrower band between Colton and some point well south of Hesperia.

Height changes since 1961 are less ambiguously defined than those that occurred between 1956 and 1961. Nevertheless, because the October–November 1961 height of bench mark D 39, Colton, was tied to a March–May 1961 height that may have been about 0.04 m below its fall height, subsequent uplift measured against the 1961 datum may be exaggerated by the same amount. That is, the height of D 39 may have remained virtually invariant between October–Nobember 1961 and 1968/69 such that the actual uplift between 1961 and 1968/69 may have been confined largely to the area north of Victorville (pl. 10). We have no evidence of similar movements at junction points during either the 1968/69 or 1973/74 levelings. Hence, the profiled height changes developed against the 1968/69 datum probably provide a fairly accurate representation of vertical displacements during the 1968/69–73/74 interval.

Reconstruction of height changes along the Colton-Lucerne Valley spur involves many of the same problems encountered in the reconstruction of height changes along the main line. Use of the results of the 1956 leveling as a primary (1955-equiv-

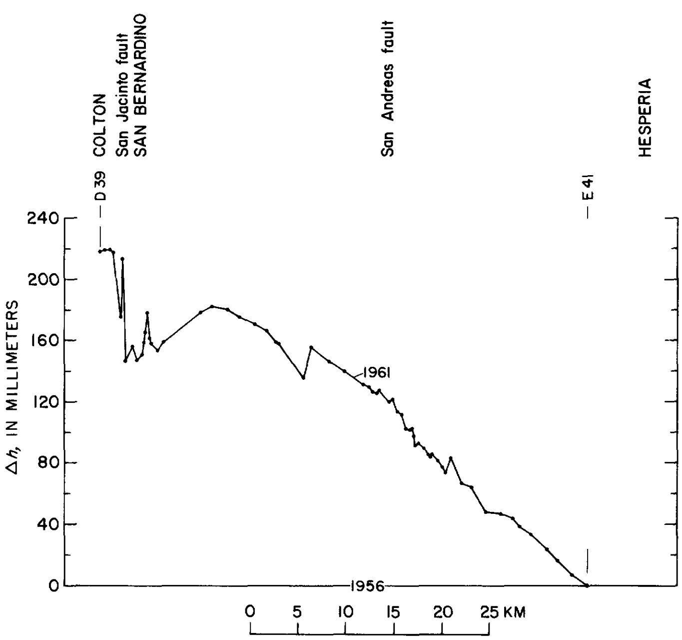


FIGURE 36.—Postulated form of cumulative uplift (Δh) developed between Colton and Hesperia between 1956 and the spring of 1961. See text for details.

alent) datum is again a reasonable basis for assessing height changes since 1955. Hence, we again begin with the presumption that the 1956 height of D 39, Colton, remained unchanged between 1956 and the spring of 1961. Acceptance of this premise suggests that height changes across the San Bernardino Mountains between 1956 and October–November 1961 (postuplift) were trivial. Not only does this comparison suggest little, if any, uplift along this line, but also, rather curiously, that the upper plate of the Santa Ana Canyon fault subsided with respect to the footwall of this north-dipping reverse fault (F. K. Miller, oral commun., 1976). In fact, the only significant movement disclosed by this comparison is the differential subsidence of up to 0.08 m that developed within the Bunker Hill groundwater basin east of the San Jacinto fault.

An alternative reconstruction of height changes measured against a 1956 datum along the Colton-Lucerne Valley spur may be developed in a manner similar to that used in the alternative reconstruction of height changes since 1956 along the main line. Thus, we again infer that the 1956 height of D 39 was 0.2179 m below its March–May 1961 height (fig. 35). The effect of this datum drop, as shown by the dashed-line representation (pl. 10), is to increase the 1956–61 uplift at Big Bear City from −0.03 m to 0.19 m. Moreover, the likelihood that up-to-the-north tilting occurred between Colton and Lucerne Valley between the spring and fall of 1961 is virtually compelled by the tolerably small misclosure around the loop Colton-Victorville-Lucerne Valley-Colton (fig. 37), the persistently invariant observed elevation difference between Victorville and Lucerne Valley (see section on "The Lucerne Valley Line"), and the demonstrated up-to-the-north tilt between Colton and Hesperia during the same period. However, while we have been able to isolate the up-to-the-north tilt developed along the main line, there is no clear basis for confining the tilt along this spur to a particular reach between Colton and some point well south of Lucerne Valley. Nevertheless, because comparisons between the results of the 1974 leveling with earlier datums indicate that most of the up-to-the-north tilting along the main line developed between Colton and the San Andreas fault, it is very likely that the up-to-the-north tilting between Colton and Lucerne Valley was similarly confined. Moreover, because (as we concluded earlier) the October–November 1961 height of D 39 may have been about 0.04 m higher than its March–May 1961 height, the maximum 1956–61 uplift at Big Bear City may have been as much as 0.23 m. Finally, if the cumulative uplift between the San Andreas and Big Bear City developed between the spring and fall of 1961, the uplift of Colton or up-to-the south tilt between Colton and the San Andreas must have occurred before the spring of 1961.

Height changes between Big Bear City and Lucerne Valley developed against a 1961 datum suggest little additional cumulative uplift (pl. 10). Moreover, if it is assumed that the 1961 heights were in fact about 0.04 m higher than those developed from the March-May 1961 observed elevation of D 39, even this very small increment of uplift must have been correspondingly diminished.

THE QUAIL LAKE-HESPERIA LINE

GENERAL REMARKS

Because the Quail Lake-Hesperia line (pl. 11) consists, in effect, of two major spurs off the Los Angeles-Mojave line, the height changes along this line are relatively clearly expressed. Moreover, because this line is subparallel to the axis of the

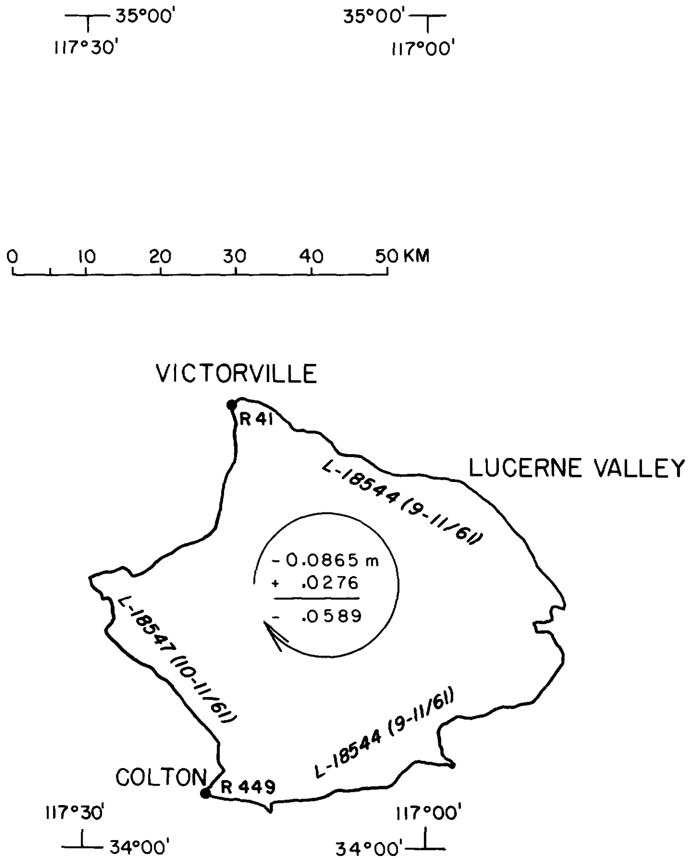


FIGURE 37.—Misclosure around the circuit Colton-Victorville-Lucerne Valley-Colton based on leveling carried out during the period September-November 1961. See figure 4 for adopted conventions and explanation of symbols.

uplift, the vertical displacements along the Quail Lake-Hesperia line tend to mimic those that developed at the intersections with the Los Angeles-Mojave and Orange-Barstow lines. Nonetheless, and in spite of the rough correspondence between the signals developed along these three lines, a remarkable amount of relatively short-wavelength crustal mobility is indicated by comparisons among the exceptionally large number of repeated surveys over all or parts of the Quail Lake-Hesperia line. Because three of these surveys were leveled to only second-order standards, we remain suspicious of several of the more dramatic signals based on comparisons with the results of this lower-order work, particularly the 0.25-m down-to-the-west tilt developed between 1968 and 1969. However, we have been unable to discover any basis in the data for challenging the accuracy of any of these levelings. Hence the results of these frequently repeated levelings along this line suggest that large, rapidly developed differential signals have occurred both along and athwart the axis of the southern California uplift.

The chief problem in reconstructing height changes along the Quail Lake-Hesperia line again relates to the generation of an appropriate preuplift datum—which we are compelled to base on the results of 1960 leveling. We have provisionally tied the results of the 1960 leveling to the March–May 1961 leveling extending into Palmdale from Tidal 8 simply because these two surveys were relatively closely spaced in time. However, because the March–May 1961 leveling probably postdates the initial uplift of the Palmdale area, and because there is an excellent chance that the uplift had not propagated into this area by the beginning of 1960, a good case can be made for linking the results of the 1960 surveys to those of the 1955 leveling along the Los Angeles-Mojave line. The effect of this alternative reconstruction would be to increase the uplift referred to the 1960 datum by about 0.05 m.

DETAILED RECONSTRUCTION

The Quail Lake-Hesperia line consists of a single primary vertical control line established in 1960. Subsequent levelings along this line commonly diverged slightly from the main route; nevertheless, because in all but one area these alternative routes coincided almost precisely with the main line, the orthometric corrections theoretically required to accommodate for these path differences have been disregarded (pl. 11). Ties between the Quail Lake-Hesperia surveys and Tidal 8 have in all cases been made through bench mark D 430 south of Palmdale (pls. 8A and 11). Because of the many levelings between Tidal 8 and D 430 and because the height history of D 430 is relatively well known (fig. 24), it has usually been possible to tie the Quail Lake-Hesperia levelings to Tidal 8 without resorting to assumptions of stability at D 430 over extended periods.

Utilization of the results of the 1960 surveys as a primary (1955-equivalent) datum is less than wholly satisfactory. Nevertheless, because a suitable pre-1960 datum between Quail Lake and Hesperia is unavailable, we have used the 1960 results for this purpose in spite of two significant problems: (1) The 1960 observed elevation of D 430 is based on March–May 1961 leveling between this mark and Tidal 8, rather than 1960 leveling between these two points (pl. 8A). Thus, because D 430 sustained about 0.05 m of uplift between 1955 and March–May 1961 (fig. 24) and because there is a good chance that most of this uplift occurred between the spring of 1960 and the following spring (see section on "The Los Angeles-Mojave Line"), uplift referred to a "true" 1960 datum between Quail Lake and Hesperia could have been (and probably was) as much as 0.05 m greater than that shown on plate 11. (2) Tectonic downwarping in the Lebec area of about 0.14 m between 1953 and 1960 (based on an assumption of stability at D 430 during the period 1960–61), and probably between 1959 and 1960 (see fig. 30 and section on "The Ventura-Maricopa Line"), suggests that the cumulative uplift along the western end of this line since 1960 (pl. 11) was a good deal greater than that since 1955. For example, the 1953–64 uplift at bench mark X 53 based on levelings between Saugus and X 53 was about 0.07 m (pl. 8B), whereas the 1960–64 uplift of the same mark is shown here (pl. 11) as 0.21 m (a figure that would rise to more than 0.25 m if allowance were made for the probable uplift of D 430 between 1960 and the spring of 1961). The comparative misclosures shown in figure 15 suggest, in any case, that the anomalous post-1960 uplift (anomalous, that is, with respect to that measured against a hypothetical 1955 datum) probably diminished from more than 0.14 m near Quail Lake to virtually zero near Fairmont.

Owing to the well-controlled history of vertical movement at D 430 (fig. 24), relatively little ambiguity attaches to the representation of height changes along the Quail Lake-Hesperia line—other than those changes measured against a 1960 datum. Both the 1964 and 1965 observed elevations along the Quail Lake-Hesperia line derive from virtually continuous leveling between Tidal 8 and L 1141, respectively (see section on "The Los Angeles-Mojave Line"). The results of both the 1968 and 1969 levelings have been tied to the 1968 elevation of D 430; hence, because D 430 sustained several centimeters of uplift between 1968 and 1971 (fig. 24) the actual uplift since 1969 may have been somewhat less than that shown on plate 11. The results of both the 1971 and 1971/72 surveys have been tied directly to the 1971 elevation of D 430. Because the 1971 elevation of D 430 was based on surveys between D 430 and Tidal 8 that postdated the 1971 San Fernando earthquake, the 1971 and 1971/72 elevations along the Quail Lake-Hesperia line may have been contaminated by postseismic movement in the epicentral area, through which the 1971 surveys passed. The results of the 1974 leveling are tied to a "1974" elevation of D 430 obtained from surveys between Saugus and Palmdale during the winter of 1972/73. However, because D 430 may have subsided about 0.05 m between 1972/73 and 1974 (see section on "The Los Angeles-Mojave Line"), the reconstructed 1974 observed elevations along the Quail Lake-Hesperia line may be about 0.05 m greater than those that actually obtained in 1974. The 1976 elevations are based on a tie with D 430 developed through 1976 leveling between Tidal 8 and D 430 completed shortly after the 1976 surveys along the Quail Lake-Hesperia line (see section on "The Los Angeles-Mojave Line").

Most of the leveling along the Quail Lake-Hesperia line meets first-order standards. The 1971/72 surveys, however, consist of a mixture of first- and second-order levelings, and the 1969 and 1971 surveys, although at one time identified by the California Department of Water Resources as "first-order, single run" (D. J. Davis, oral commun., 1976) should, in fact, be classified as second order. Thus, according to a 1971 letter from M. C. Hendrickson of the California Department of Water Resources to the Los Angeles County Department of County Engineer (California Department of Water Resources, written commun., 1976), both the 1969 and 1971 surveys probably met no better than second-order standards. The "specifications for the 1969 project called for second-order leveling. A Zeiss Ni2 level with a parallel plane attachment and Wild 10 MM rods were used." Similarly, the 1971 leveling employed a "Zeiss Ni1 level with parallel plane attachment and Breithaupt 5 mm rods ***. Since the 1969 leveling was done in only one direction, reruns were made only on those sections that closed in excess of 8.4 mm x square root of distance in Km." These remarks suggest to us that both the 1969 and 1971 surveys should be treated as second-order, class II levelings. Where random error dominates, one standard deviation in the discrepancy between the measured elevation differences between any two bench marks based on two successive second-order, class II levelings is given as 1.84 (mm) x $km^{1/2}$ (Federal Geodetic Control Committee, 1974, p. 3). Accordingly, over the maximum distance from D 430 (about 80 km), the estimated random error at the 95-percent confidence level should be no greater than 33 mm for any measured change in observed elevation between either 1969 or 1971 and any other period of observation. Moreover, because this route is characterized by very little relief (pl. 11), it is unlikely that any of the Quail Lake-Hesperia surveys were significantly contaminated by height-dependent systematic error. Similarly, since there are no sharply defined breaks in the profiles of height changes developed from the results of either the 1969 or 1971 surveys with respect to any earlier datum, there is little likelihood of a bust in either survey. Accordingly, the results of the single-run second-order leveling along the Quail Lake-Hesperia line probably are nearly as accurate (with respect to the observed crustal signals) as those derived from first-order leveling along this same route.

Although the profiled height changes shown here (pl. 11) are virtually self-explanatory, the crustal mobility implicit in these profiles is somewhat disturbing. The oscillatory displacements that seem to characterize so much of the Quail Lake-Hesperia line are shown especially well, moreover, in the elevation histories of bench marks 3409 USGS, Llano (fig. 38), and E 41, Hesperia (fig. 39).

Uplift measured against the 1960 datum, as we have already indicated, probably is minimal between Fairmont and Hesperia and may have been as much as 0.05 m greater than that shown here (pl. 11). Westward from Fairmont, on the other hand, the cumulative uplift since 1960 was almost certainly greater than had it been measured against a 1955 datum. Height changes since 1964 and 1965 are shown with respect to an offset datum at D 430. That is, because D 430 apparently rose by roughly 7 mm between 1964 and 1965, the 1965 datum has been shifted upward by the same amount. The alternative, of course, would have been to split the profile at D 430 and show the combined profiles as separate representations.

Height changes developed against 1968 and later datums are in many respects the most intriguing of any of those shown along the Quail Lake-Hesperia line. The down-to-the-west (or up-to-the-east) tilt generated between 1968 and 1969 is based on a comparison with what is perhaps the least reliable data included with this report. Moreover, the nearly perfect recovery by 1971 of this down-to-the-west tilt reinforces the suspicion that the 1969 data may be significantly in error. Nevertheless, the magnitude of the tilt between E 41 and K 1044 is sufficiently large that it is difficult to simply dismiss it as the product of measurement error. Similarly, the development of differential subsidence of about 0.15 m in the Quail Lake area between 1968 and 1969 (pl. 11) coincides in time with the remarkable episode of uplift within what was to become the epicentral area of the 1971 San Fernando earthquake (Castle and others, 1974, p. 65); this coincidence lends credibility to both a mechanical connection between these phenomena and the validity of the Quail Lake subsidence.

The remarkably steep 1971–71/72 up-to-the-east tilt of about 0.06 m between bench marks 377.3C and 395.1C, along the eastern end of the Quail Lake-Hesperia line, seems to have set the stage for the westward propagation of comparable uplift between 1971/72 and 1974. Moreover, the 1971/72–74 episode apparently defined the culmination of uplift that probably began in this area as early as 1960, for sometime between 1973/74 and 1976 the entire line between Quail Lake and Hesperia collapsed by as much as nearly 0.2 m.

THE MOJAVE-COTTONWOOD PASS LINE

GENERAL REMARKS

Because the Mojave-Cottonwood Pass line (pl. 12) is simply a very long spur attached to the Los Angeles-Mojave line, the several sets of reconstructed observed elevations along the main line (with one singularly significant exception) are based on ties to the results of temporally equivalent observed elevations at Mojave. Accordingly, the starting elevations at Mojave are neither more nor less accurate than the contemporaneous elevations at

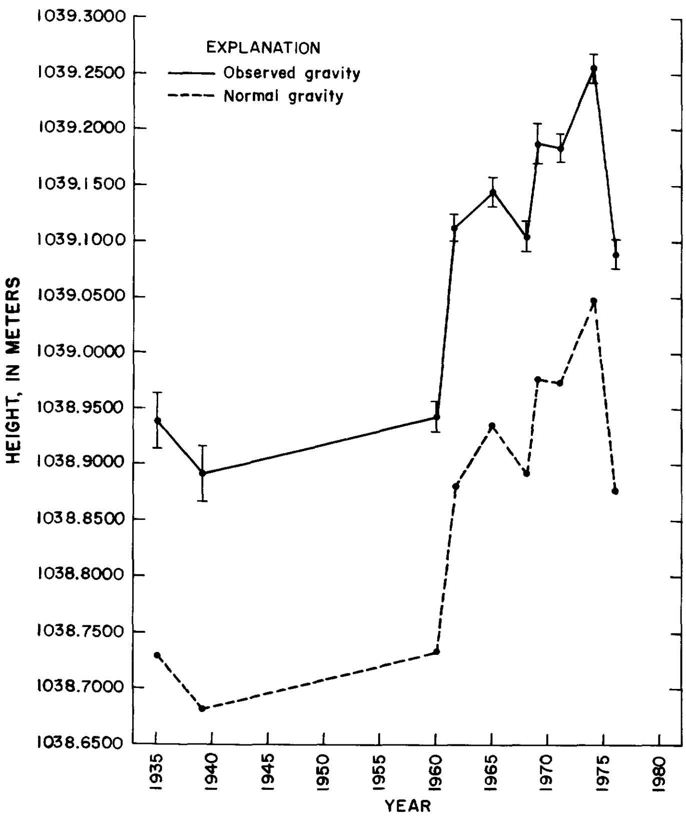


FIGURE 38.—Changes in orthometric height at bench mark 3409 USGS, Llano. The 1961 height is based on an assumption of stability at bench mark Q 35, Azusa, between the spring of 1961 and the following year (see section on "The Los Angeles-San Bernardino Line"). One-standard-deviation error bars show conventionally estimated random error only.

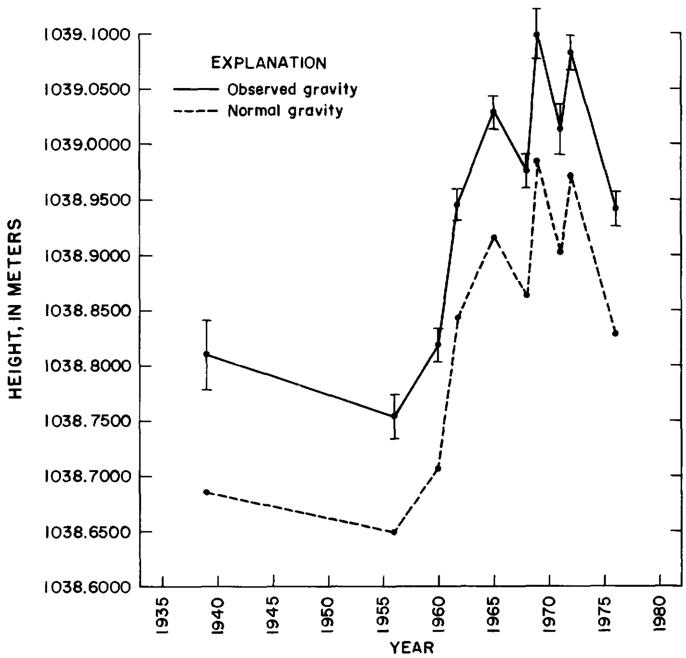


FIGURE 39.—Changes in orthometric height at bench mark E 41, Hesperia. The 1939 height is based on the 1939 height of R 41, Victorville (fig. 54), 1944 leveling between R 41 and E 41 (NGS line L-11045), and an assumption of relative stability between R 41 and E 41 during the period 1939–44. The 1956 height is based on the 1955 height of D 430, Palmdale (fig. 24), 1960 leveling between D 430 and E 41, and on an assumption of relative stability between D 430 and E 41 during the period 1955–60. The 1960 height is based on the (spring) 1961 height of D 430 (fig. 24) and 1960 leveling between D 430 and E 41. One-standard-deviation error bars show conventionally estimated random error only.

Mojave developed from successive relevelings along the Los Angeles-Mojave line. On the other hand, the height changes along the spur extending northward from Bryman to Barstow are based in part on orthometrically compatible observed elevations derived from levelings along the Orange-Barstow line.

The preuplift datum between Mojave and Daggett is based on March–May 1961 leveling. Because the March–May 1961 heights between Rosamond and Mojave are almost identical to the 1955 heights along this section of the Los Angeles-Mojave line, we have used the results of early-1961 leveling as the equivalent of a hypothetical 1955 datum—we have assumed, in other words, that the 1961 heights northward and eastward from Rosamond to Daggett remained invariant between 1955 and the beginning of 1961. However, the generation or extension of a preuplift datum east of Daggett depends on the results of 1944 leveling between Daggett and Cottonwood Pass. That is, it is necessarily assumed in the reconstruction of the reference datum that the elevation differences based on 1944 leveling eastward from Daggett are the same as those that would have been obtained had this leveling been carried out no later than March–April 1961 (or in 1955). We have attempted to test this assumption in three ways: (1) by examining a series of postulated 1944–61 regional tilts between Daggett and Amboy that requires, as actually observed, that the elevation difference between Daggett and Amboy be preserved during the period 1944–74, (2) by comparing the results of pre-1961 or post-1944 levelings against those generated during or before this period, and, finally, (3) by examining a series of misclosures involving the results of the 1944 leveling between Daggett and Cottonwood Pass together with post-1930 and pre-1961 levelings through the region traversed by the 1944 survey. The collective results of these tests indicate that the line between Daggett and Cottonwood Pass probably sustained little, if any, regional tilting between 1931 and the beginning of 1961.

Cumulative uplift along the Mojave-Cottonwood Pass line nearly matches the maximum uplift (about 0.45 m) detected anywhere within the southern California uplift. However, the most intriguing feature disclosed through comparisons among the results of the repeated surveys along this line is the irregular or almost wavelike eastward propagation of the uplift. Specifically, the results of the 1972/73 surveys suggest that the area eastward from Boron and northward from Bryman collapsed by as much as 0.1 m between 1968 and 1972/73, yet had recovered by an even greater amount by the following winter. Moreover, the nearly 0.3 m of uplift that had accumulated at Barstow following this recovery apparently persisted at least as far east as Amboy and actually increased southward to Cottonwood Pass, where the comparison ends.

DETAILED RECONSTRUCTION

The Mojave-Cottonwood Pass line consists of a primary vertical-control line between Mojave and Cottonwood Pass, together with a single spur between Barstow and Bryman (pl. 12). The starting elevations at Mojave are taken directly from the results of repeated surveys along the Los Angeles-Mojave line (see section on "The Los Angeles-Mojave Line"). The starting elevations at Barstow, on the other hand, are based in part on orthometrically compatible elevations derived from leveling along the Orange-Barstow line (see section on "The Orange-Barstow Line" and fig. 34).

The chief, and actually the only, problem encountered in the reconstruction of observed elevation changes along the Mojave-Cottonwood Pass line derives from the development of a suitable primary (1955-equivalent) datum. Because the height of Mojave changed almost imperceptibly during the interval 1955–61 (pl. 8A; fig. 29), and because Barstow declined by less than 0.02 m during the period 1927–April 1961 (fig. 34), it is especially likely that the results of the March–April 1961 leveling between Mojave and Daggett (immediately east of Barstow) very closely matched the values that would have been generated had this leveling been carried out in 1955. Hence, a 1955-equivalent datum between Mojave and Daggett probably is closely approximated by the results of the March–April 1961 surveys between these points.

While the establishment of a primary (1955-equivalent) datum between Mojave and Daggett is a relatively simple procedure, the generation of a similar datum between Daggett and Cottonwood Pass is much more difficult and much less convincingly corroborated. The latest preuplift first-order leveling between Daggett and Cottonwood Pass was carried out in 1944. Thus, even though the actual 1944 heights (with respect to Tidal 8) of marks along this route are of no direct relevance, we are forced to begin with the assumption that the elevation differences generated through 1944 leveling eastward from Daggett are the same as those that would have been produced had these levels been run in the spring of 1961. We must, in other words, proceed with the assumption that the area included by the 1944 leveling remained free of regional tilting during the 17-year period between 1944 and the spring of 1961. Corroboration or refutation of this assumption depends, accordingly, on evidence of (or against) regional tilting within this area during the period 1944–April 1961.

Permissive evidence of relative stability between Daggett and Amboy during the period 1944–61 is implicit in the 1944/61–74 profile of elevation changes, which shows that this reach retained its vertical integrity through the period 1944–74 (pl. 12). Specifically, the summation of the results of the 1944 and 1974 surveys between Daggett and Amboy produces a misclosure of less than 1 cm (pl. 12). Although this apparent integrity could have been preserved through compensating tilts that preceded and followed the 1961 leveling between Mojave and Daggett (see, for example, sections on "The Ventura-Avila Beach Line" and "The Quail Lake-Hesperia Line"), it is unlikely that such neatly compensating tilts actually occurred here. Nevertheless, combinations of pre- and post-uplift compensating tilts that could have produced the obviously tight 1944–74 closure around the Daggett-Amboy loop are certainly possible and easily illustrated. Thus, we have postulated four paired tilts (fig. 40) where it has been assumed that the tilt axes shifted in position; identical results are obtained if it is assumed that the axes of rotation remained fixed in space.

The effects of a postulated 1944–61 down-to-the-west tilt between Daggett and Amboy associated with a comparable 1961–74 down-to-the-east reversal are illustrated in figure 40*A*. If it is assumed that the 1944–61 tilt is expressed as uniform tectonic downwarping of *Z* displacement beginning at some point, A, east of Daggett, the vertical integrity between A (or Daggett) and Amboy could have been maintained by a balanced 1961–74 down-to-the-east tilt, represented by the dashed line in figure 40*A*. Because Daggett rose about 0.30 m with respect to Tidal 8 between March–May 1961 and 1974 (pl. 12), Amboy would have to have risen by 0.30-*Z* m during this same interval in order to preserve the 1944 elevation difference between Daggett and Amboy. The cumulative 1961–74 uplift between A and Amboy associated with this sequence of movements is represented by the shaded area in figure 40*A*. However, the 1961–74 uplift at both Mojave and Daggett was very close to 0.30 m (pl. 12); thus it is very unlikely that the vertical integrity between these two points could have been preserved if *Z* were other than a very small number. Moreover, given this reconstruction, the likelihood that *Z* was, in fact, a very small number is supported by the near invariance of bench mark E 43, Barstow (about 10 km west of Daggett), between 1927 and March–May 1961 (fig. 34). Expression of this postulated 1944–61 down-to-the-west tilt as uplift at Amboy permits an alternative conclusion. Thus, if Amboy rose by some amount, *Z*, between 1944 and 1961, compensation could occur during the period 1961–74 through rotation about an axis at Amboy that produced *Z* displacement at A, where *Z* in this case represents some fraction of the approximately 0.30 m of uplift that occurred at both Daggett and Mojave during the period 1961–74. According to this scenario, then, a significant tilt could have occurred between Daggett and Amboy during the 1944–61 interval and would, in the absence of any additional information, remain unrecognized. The cumulative 1961–74 uplift between A and Amboy would thus be represented by the eastwardly diminishing values shown by the shaded area (fig. 40*A*), yet still preserve the 1944 elevation differences between these two localities.

Balanced regional tilting acting to preserve the 1944 elevation difference between Daggett and Amboy could also have begun with a 1944–61 down-to-the-east tilt east of Daggett (fig. 40*B*). If it is assumed that this down-to-the-east tilt was generated about an axis through Amboy and expressed as upwarp of *Z* displacement beginning at A, compensation would require that Amboy sustain positive displacement, *Z*, with respect to A during the period 1961–74. Moreover, because Daggett sustained uplift of about 0.30 m between 1961 and 1974, preservation of the 1944 elevation difference between Daggett and Amboy would require that the 1961–74 uplift had increased steadily eastward from A, as shown by the shaded area (fig. 40*B*, 1), to a maximum of 0.30 + *Z* m at Amboy. This sequence of tilts demands that Amboy should have sustained even greater uplift between 1961 and 1974 than shown on plate 12, a conclusion that begins to challenge credibility. Moreover, because Barstow remained roughly invariant between 1927 and March–May 1961, the likelihood that *Z* could have been more than a few centimeters is very low. If the postulated 1944–61 down-to-the-east tilt between Daggett and Amboy developed through vertical displacement, *Z*, at Amboy, compensation would have required a comparable down-to-the-west tilt during the period 1961–74, as shown by the dashed line (fig. 40*B*, 2). Again, moreover, because Daggett rose about 0.30 m between 1961 and 1974, cumulative 1961–74 uplift would have to have increased eastwardly from Daggett, as shown by the shaded area (fig. 40*B*, 2), to a maximum value of 0.30 + *Z* m at Amboy.

Of the four preceding combinations of tilt that might have preserved the 1944 elevation difference between Daggett and Amboy, only one (expressed schematically in fig. 40*A*, 2) is inconsistent with 1961–74 uplift between Daggett and Amboy of a magnitude at least as great as that shown on plate 12. Although this combination of regional tilts is certainly possible, it suggests an extremely unlikely sequence of movements. Moreover, depending on the magnitude of *Z*, this suggested tilt sequence simply displaces in time some fractional value of the uplift at Amboy to the period 1944–61.

A second general approach used in searching for evidence of regional tilting along or adjacent to the line of the 1944 levels depends on the results of level surveys that can be compared with either the 1944 or March–April 1961 datum (pl. 12). We have, regrettably, discovered only one set of post-1944 surveys that both predates the uplift and can be compared directly with the 1944 datum. Thus, a comparison of the results of 1959 third-order levels against the 1944 datum shows that the maximum deviation from the mean (with one conspicuous exception) over a 15-km reach near Ludlow (roughly midway between Daggett and Amboy) was less than 1 cm (fig. 41). Moreover, the maximum movement of one end of the line with respect to the other during the same period was about 13 mm (fig. 41). The apparent uplift of bench mark K 4 (fig. 41), which is clearly at variance with the preceding generalizations, is almost certainly the product of survey error in the 1959 leveling, for it disappears in comparisons between the results of the 1944 and 1974 levelings. Because the discrepancy between the measured elevation differences between the end points of this line based on a comparison between the results of first- and third-order surveys is characterized by a one-standard-deviation figure of about 33 mm, the apparent elevation changes (fig. 41) lie well within the noise level. Hence, it is unlikely that significant regional tilting occurred along this 15-km line during the period 1944–59.

Comparisons among 1927, 1939, and March–April 1961 first-order levels between Kramer Junction and Barstow (fig. 42) support the conclusion that the central Mojave Desert remained virtually free of regional tilting during the period 1944–61. Thus, between Kramer Junction and Barstow there was

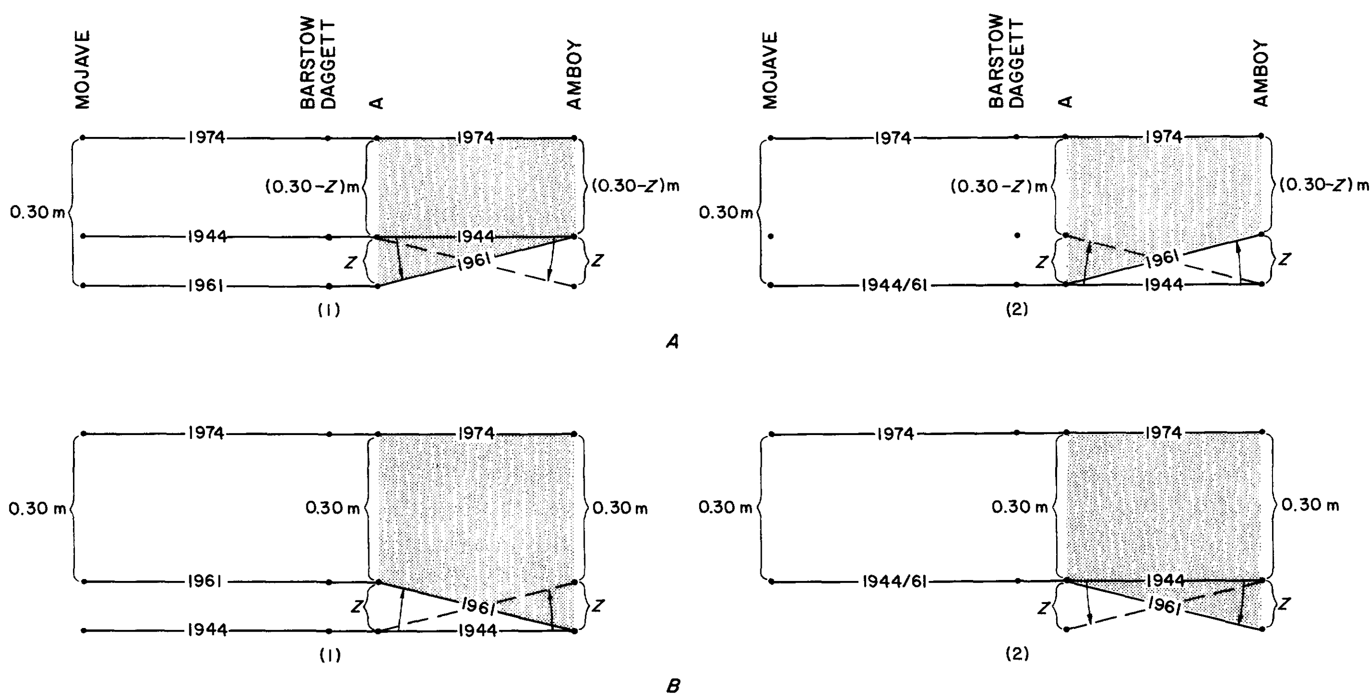


FIGURE 40.—Postulated 1944–61 tilts over unspecified reach between Daggett and Amboy coupled with 1961–74 tilts required to preserve the elevation difference between these locales during the period 1944–74. Shaded area indicates cumulative 1961–74 uplift between arbitrary point A and Amboy. *Z* indicates displacement of uniform tectonic downwarping. *A*, 1944–61 down-to-the-west tilt associated with 1961–74 down-to-the-east reversal (dashed line). *B*, 1944–61 down-to-the-east tilt associated with 1961–74 down-to-the-west reversal (dashed line).

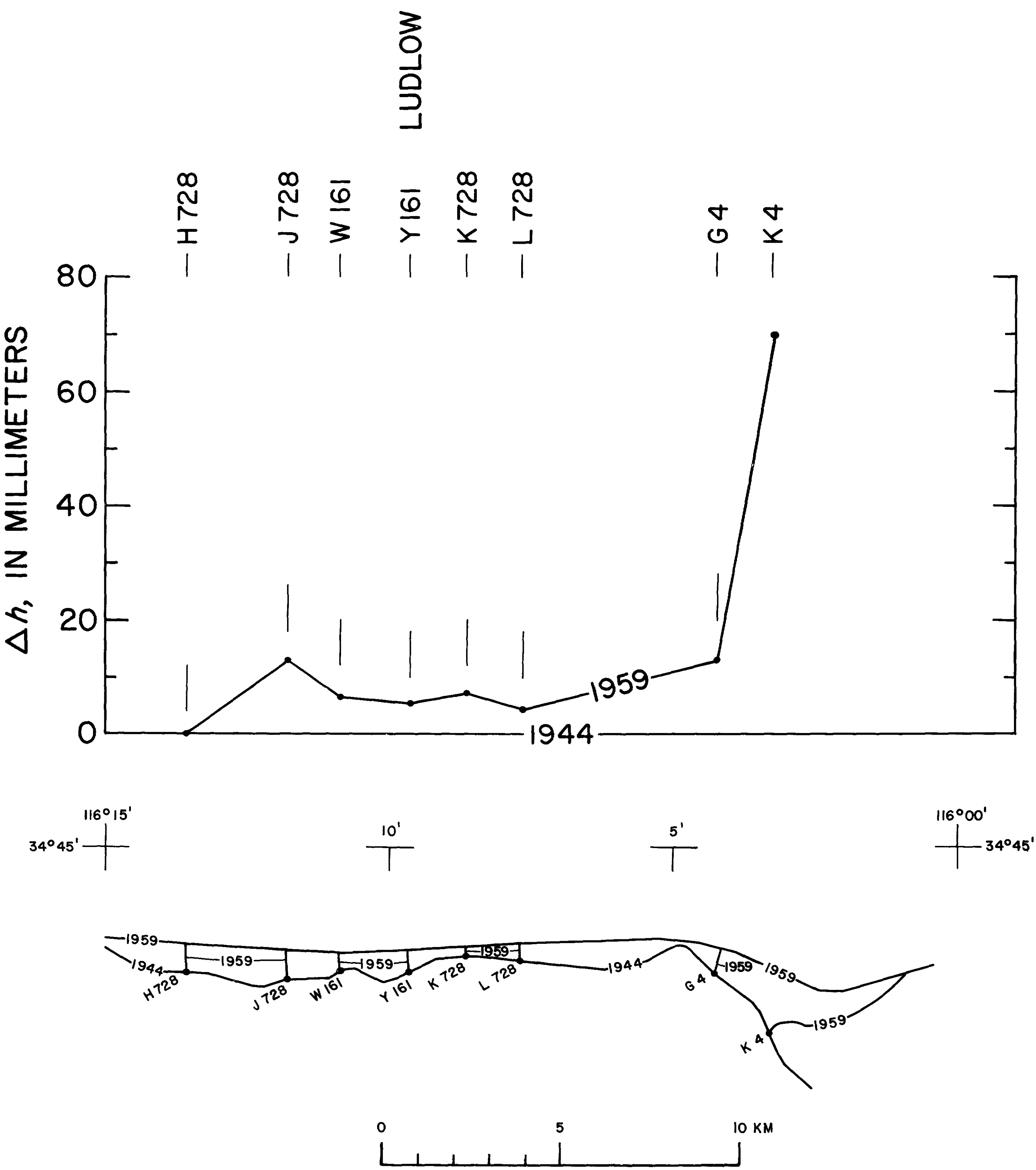


FIGURE 41.—Height changes (Δ*h*) over a 15-km reach near Ludlow. Based on a comparison between the results of 1959 third-order leveling against the 1944 datum (pl. 12), where bench mark H 728 is assumed to have remained invariant. 1959 observed-elevation differences courtesy of California Department of Transportation.

very little differential movement during the periods 1927–39, 1939–61, and 1927–61. Moreover, if the differential subsidence developed within the Hinkley Valley ground-water basin (see pls. 3 and 4) is subtracted from these profiles (fig. 42), the reach between bench marks E 43 and 2368 remained virtually invariant during the period 1939–61. West of bench mark 2368, especially during the period 1927–39, the elevation differences tended to diverge. Nevertheless, even though the elevation difference between Barstow and Kramer Junction increased about 0.04 m during the period 1939–61 (fig. 42), and though this figure is equivalent to about four standard deviations in the predicted discrepancy between two successive measured elevation differences between E 43 and Q 68, it still suggests a very small tilt over this 50-km distance (<1 μrad). Moreover, because Kramer Junction lies along the eastern edge of an area of continuing tectonic activity, a part of which may have been involved with the 1952 Kern County earthquake, we would be surprised to see a complete absence of differential movement along the western end of this line. Hence, the relatively limited differential movement between Barstow and Kramer Junction during the periods 1927–39, 1939–61, and especially 1927–61 (the last two of which include the 1944 leveling epoch) suggests that the area extending some indeterminate distance eastward from Barstow remained similarly free of regional tilting during the period 1939–61.

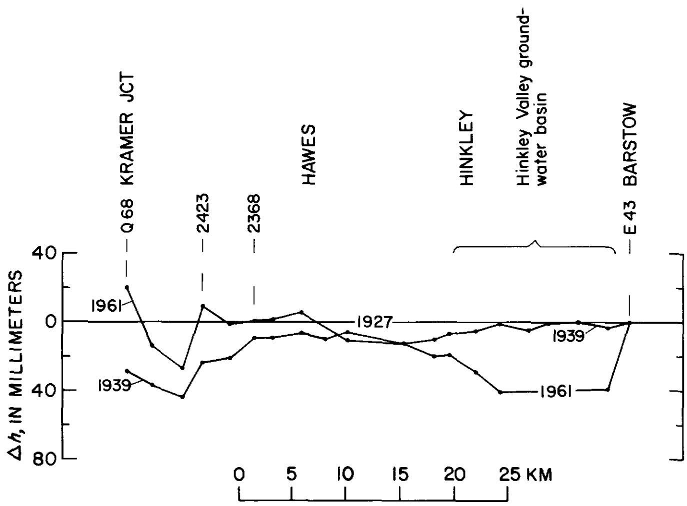


FIGURE 42.—Height changes (Δh) between Kramer Junction and Barstow with respect to bench mark E 43, Barstow. Based on the results of first-order levelings by the National Geodetic Survey (NGS lines L-1, L-8531, and L-18230).

A third technique used in assessing the regional stability along the line of the 1944 leveling between Daggett and Cottonwood Pass depends on an examination of misclosures developed from the results of leveling of varying vintage within and including the period 1944–61. Although, as we noted earlier, small misclosures are less than infallible indices of tectonic stability during the period of leveling around a single circuit, examination of an entire network tends to strengthen (or refute) conclusions based on closures. Two classes of misclosure have been used in this assessment: those derived exclusively from first-order surveys and those derived from a mix of the results of first- and third-order levelings. This assessment suggests that little, if any, regional tilting occurred within the area of the 1944 leveling during the period 1931–61.

All but one short section of the largest of the loops shown here are based exclusively on first-order levelings completed between 1931 and March–April 1961 (fig. 43)—that is, prior to the propagation of the southern California uplift into the central or eastern Mojave. The one exception to this generalization consists of a 35-km survey segment between Victorville and Lucerne Valley that was completed during the fall of 1961, well after the uplift had extended into this area. Nevertheless, because the elevation difference between the ends of this segment remained virtually invariant between 1935 and October–November 1961, and because at least three-quarters of this line (defined by the extent of surveys common to both 1953 and 1961) retained its vertical integrity between 1953 and October–November 1961 (see section on "The Lucerne Valley Line"), substitution of this short segment of postuplift leveling for nonexistent 1944–60 first-order work should have a negligible effect on any resulting misclosures.

The largest single loop considered here is based on leveling extending over the full period 1931–61; it is characterized by an observed misclosure of +0.0466 m and an orthometrically corrected misclosure of −0.0110 m around a 633-km circuit (fig. 43). The smaller (403-km) loop, Barstow-Daggett-Amboy-Twentynine Palms-Yucca Valley-Lucerne Valley-Victorville-Barstow, is identified with an observed misclosure of only −0.0175 m and an orthometrically corrected misclosure of −0.0482 m. Misclosures around both of these loops are well within first-order limits. Moreover, although the smaller loop shows a larger misclosure, we suspect that the measured (observed) misclosures are nearly as reliable as indices of both stability and measurement precision as are the "corrected" (and, in the case of the smaller loop, larger) closures, which may be artifacts due to imprecisely formulated orthometric corrections.

The first-order closures defined by the 1944 and 1931–44 levelings (fig. 44) provide some indication of the pre-1961 stability of the central and eastern parts of the area traversed by the 1944 surveys. The misclosure around the 384-km loop Amboy-Cadiz-Freda Junction-Cottonwood Pass-Twentynine Palms-Amboy (fig. 44) suggests relative stability during the period 1931–44 and for some indeterminate period beyond 1944. On the other hand, the 331-km loop defined solely by the 1944 leveling (fig. 44) shows a misclosure strongly indicative of either measurement error or crustal movement during the 4-month 1944 survey period. Because the closures around the larger first-order loops that include all but the Lucerne Valley-Newberry Springs segment are well within first-order limits (fig. 43), it is virtually certain that any crustal deformation that might account for the large 1944 misclosure must have occurred along this line between January and April of 1944. However, profiles of height changes that compare the results of various later surveys against a 1944 datum show no evidence of localized deformation at either end of the Newberry Springs-Lucerne Valley line (see pl. 12 and section on "The Lucerne Valley Line"). Moreover, the occurrence of aseismic tilting of this magnitude within this particular 4-month period seems most unlikely.

Alternatively, the misclosure around the 1944 circuit may be due to measurement error. First-order leveling procedures are so specified that busts are extremely uncommon; nevertheless, they do occur, and a good deal of evidence indicates that the large misclosure around the 1944 loop (fig. 44) is due to a simple measurement error between Lucerne Valley and Newberry Springs: (1) The elevation differences between two adjacent bench marks, 1607 and 1604, common to both the 1944 leveling and a 1935 third-order survey (CWA line G-36) differ by 0.0822 m. Substitution of the 1935

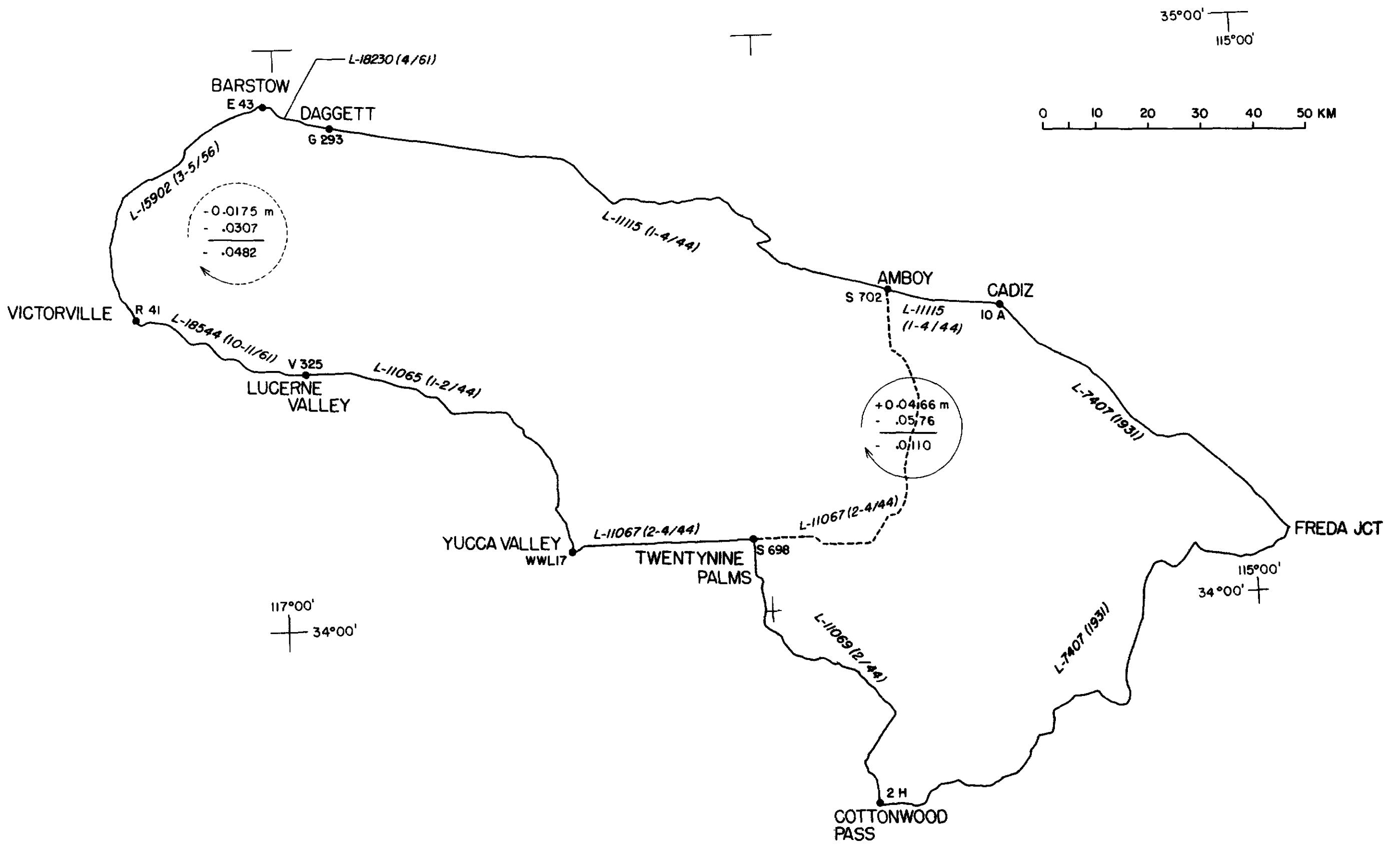


FIGURE 43.—Misclosures around the circuits Barstow-Daggett-Amboy-Cadiz-Freda Junction-Cottonwood Pass-Twentynine Palms-Lucerne Valley-Victorville-Barstow and Barstow-Daggett-Amboy-Twentynine Palms-Yucca Valley-Lucerne Valley-Victorville-Barstow (dashed line); based on levelings carried out during the periods 1931–November 1961 and January 1944–November 1961, respectively. See figure 4 for adopted conventions and explanation of symbols.

elevation difference between these two marks, which are located toward the northern end of the line, would reduce the 1944 observed misclosure from −0.1194 m (fig. 44) to −0.0372 m, well within first-order limits. (2) Examination of the 1944 field books that include the survey data connecting bench marks 1607 and 1604 shows a 0.091-m discrepancy between TBM 16V and BM 1607. The original "back-of-the-rod" reading is given as 1.18 ft; this reading was later changed to 0.88 ft. If the original value were correct, the elevation difference over this section would be reduced by 0.091 m and the observed misclosure would drop to −0.0284 m. (3) The relatively large misclosures defined by the two small adjacent loops that include the 1944 Lucerne Valley-Newberry Springs segment are almost perfectly balanced (fig. 45). The balanced nature of these misclosures is consistent with a measurement error of about 0.12 m in the 1944 leveling between Lucerne Valley and Newberry Springs. Although the balanced aspect of this misclosure is conceivably attributable to a January–April 1944 down-to-the-north tilt, this postulated tilting is clearly ad hoc, in the sense that the tilt vector would have to have virtually coincided with the survey route in order to preserve the balanced misclosures. The preceding evidence, accordingly, convincingly demonstrates that the 1944 misclosure around the loop Newberry Springs-Amboy-Twentynine Palms-Yucca Valley-Lucerne Valley-Newberry Springs (fig. 44) is almost entirely attributable to an error of about 0.09 m in the Lucerne

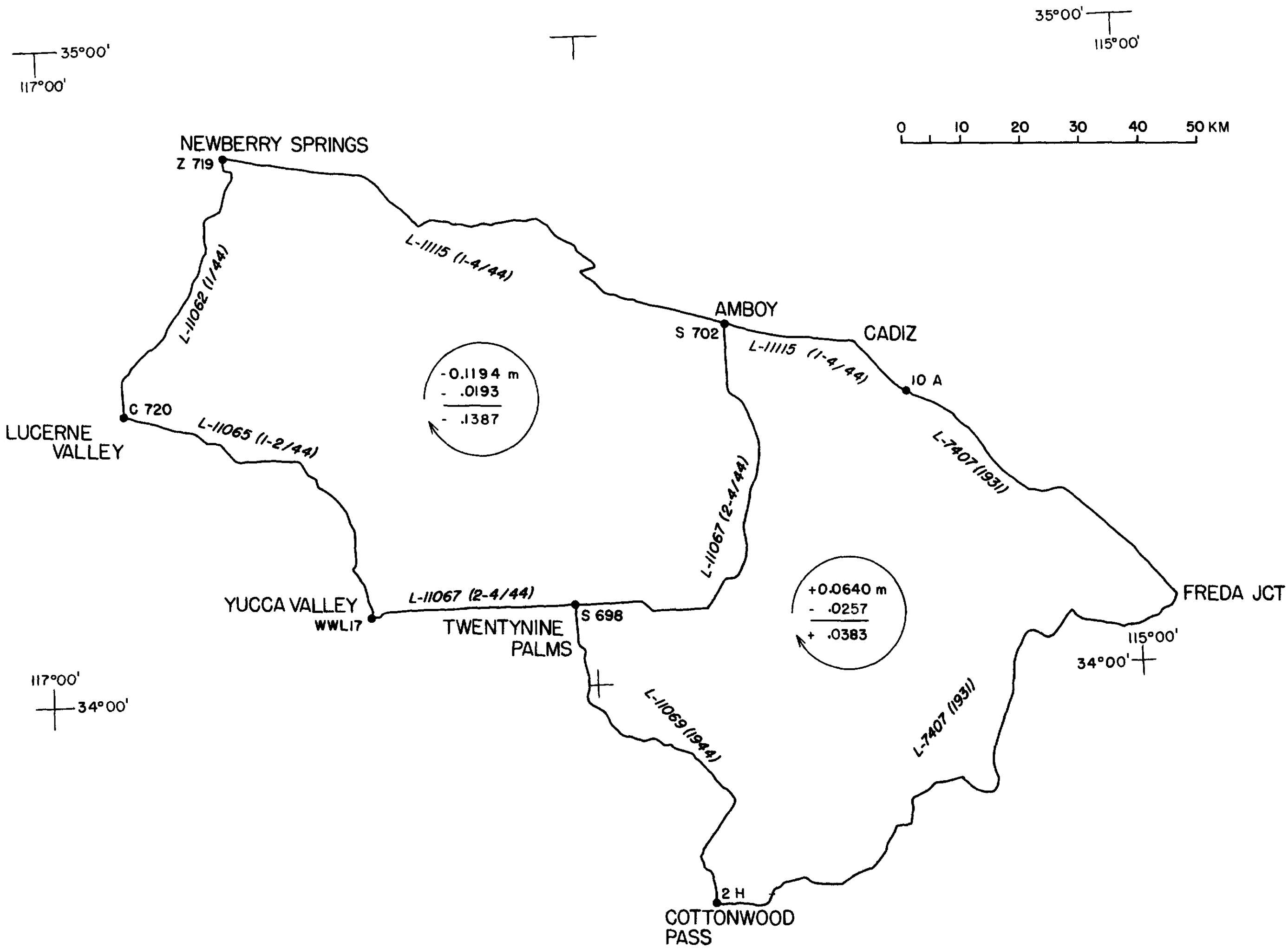


FIGURE 44.—Misclosures around the circuits Newberry Springs-Amboy-Twentynine Palms-Yucca Valley-Lucerne Valley-Newberry Springs and Amboy-Cadiz-Freda Junction-Cottonwood Pass-Twentynine Palms-Amboy; based on levelings carried out during the periods January-April 1944 and 1931–April 1944, respectively. See figure 4 for adopted conventions and explanation of symbols.

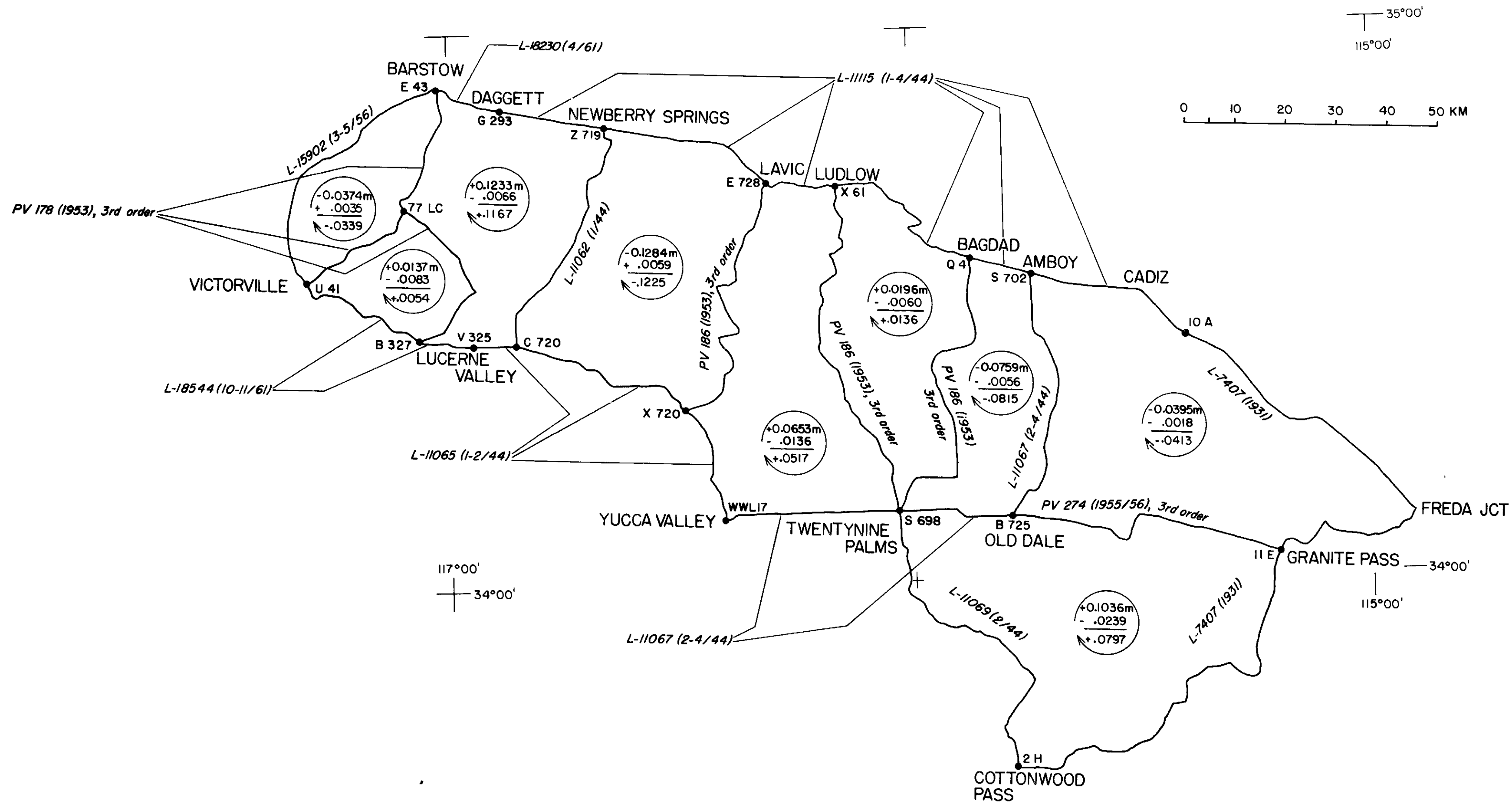


Figure 45.—Misclosures around various circuits within the larger circuit Barstow-Amboy-Freda Junction-Cottonwood Pass-Yucca Valley-Victorville-Barstow developed from various combinations of the results of first-and third-order levelings. Based on surveys carried out during the period 1931–November 1961. See figure 4 for adopted conventions and explanation of symbols.

Valley-Newberry Springs segment. Correction for this error would reduce the misclosure around this loop to about 0.03 m. Accepting this correction, all of the closures defined by the results of first-order leveling extending from 1931 through the beginning of 1961 are well below first-order limits (figs. 43 and 44) and are clearly consistent with crustal stability within the area of the 1944 leveling during the period 1944–61.

A series of small loops, developed from the results of 1931, 1944, 1956, and 1961 first-order levelings and 1953 and 1955/56 third-order surveys (fig. 45), supports the preceding generalization. Although third-order leveling provides a much less sensitive vehicle for the detection of crustal deformation than does leveling of a higher order, the results of these surveys (all of which were completed well after the 1944 leveling, yet somewhat before 1961) define a relatively tight network over the area of the 1944 first-order leveling. Specifically, all but one or two of these loops (fig. 45) are identified with both balanced and very small corrected misclosures. While the loops that include the first-order 1944 survey between Lucerne Valley and Newberry Springs are relatively large, correction for the virtually certain 0.09-m error in this line would reduce these misclosures to about +0.03 m and −0.03 m, respectively. The relatively large misclosure (−0.0815 m) defined by the Bagdad-Amboy-Old Dale-Twentynine Palms-Bagdad loop is almost certainly due to cumulative measurement error in the third-order line; this particular line includes the largest end-to-end elevation difference of any third-order line considered here and is, as such, the most subject to systematic error. The exceptionally small closure around the adjacent loop probably is the result of balanced errors in the third-order surveys that define this loop. The misclosures around the easternmost of the loops, which include the results of 1931 leveling, are relatively well balanced, particularly if allowance is made for the size of each of these circuits. Moreover, if it is assumed that the closure error in the first-order circuit that includes these loops (fig. 44) is evenly split between the two, subtraction of this error would increase the northern misclosure by 0.02 m and decrease the southern misclosure by 0.02 m. The resulting "corrected" misclosures would thus become nearly perfectly balanced and would indicate a measurement error of only about 0.06 m in line PV 274 (or a 1931/44–55/56 down-to-the-east tilt of this same magnitude). In short, it is clear that the misclosures developed from this network of combined first- and third-order surveys suggest, both by their generally small magnitudes and balanced nature, that this area remained free of significant (regionally defined) tilting from 1931 or 1944 through at least 1953 and probably through 1955/56.

We have considered three lines of evidence, no one of which is necessarily compelling, in order to assess the crustal stability during the period 1944–61 of the area traversed by the 1944 leveling. Taken together, however, this evidence provides an excellent basis for concluding that there was very little regional deformation during this period and that we may treat the results of the 1944 levelings as the equivalent of those that would have been produced had these levelings been carried out during the early spring of 1961.

Although height changes along the Mojave-Cottonwood Pass line since 1961 (1955-equivalent) are largely self-explanatory, they are sufficiently dramatic that several comments seem in order. Probably the most startling feature revealed by these profiles of elevation changes (pl. 12) is the extent of the large cumulative uplift that apparently occurred between the spring of 1961 and 1974. From our preliminary studies of this phenomenon (Castle and others, 1976), we fully expected that the uplift would close off somewhat east of Barstow and certainly west of Amboy. It appears instead, however, that the uplift between Mojave and Amboy rarely fell below about 0.28 m, and that it actually increased toward the east-southeast (pl. 12).

The growth of the uplift along the Mojave-Cottonwood Pass line was both irregular and, at least in part, oscillatory. A comparison of the results of the 1974 surveys against a 1972/73 datum shows that there was a modest deflation between Mojave and Kramer Junction during the interval 1972/73–74, whereas east of Boron clearly defined up-to-the-east tilting was associated with about 0.12 m of uplift at Barstow (pl. 12). The axis around which this tilting occurred is very nearly coincident with bench mark 2509, which in turn is centered on a zone of differential uplift that developed between 1961 and 1972/73. Earlier studies (Church and others, 1974) show that this uplift coincided with a more broadly defined band that sustained about 0.5 m of differential uplift during the preceding (1939–61) survey epoch. Hence, we infer a genetic connection between this seemingly persistent feature and the tilt axis between Boron and Barstow. This evolutionary complexity is equally evident in the history of movement along the Barstow-Bryman spur (pl. 12). Between 1956 (1955-equivalent—see section on "The Orange-Barstow Line") and the fall of 1961 the entire reach between Bryman and

Barstow rose about 0.15 m; it continued to rise during the succeeding period, 1961-68, by 0.06 m and 0.08 m at Bryman and Barstow, respectively. During the period 1968–73, on the other hand, a conspicuous reversal occurred which resulted in tectonic subsidence of about 0.08 m at Barstow, as contrasted with virtual stability at Bryman. Because it was consistent with a pattern of movement based on geodetic control emanating from Tidal 8, we initially interpreted the 1968–73 down-to-the-north tilt as an up-to-the-south tilt coupled with invariance at Barstow during the period 1961–72/73 (Castle and others, 1976, p. 252). While this earlier judgment is now recognized as clearly incorrect, it had little effect on the published reconstruction, which purports to show the minimum cumulative uplift developed between 1959 and 1974 and depended heavily on other evidence.

Although the 1961–74 cumulative uplift eastward from Barstow was relatively uniform over most of the Mojave-Cottonwood Pass line, several significant exceptions challenge this generalization. The inflection centering on bench mark S 3 near Newberry Springs (pl. 12) marks the western end of a 0.05 m tilt between S 3 and V 727 (about 6 μrad). Moreover, because this differential movement lay athwart the active right-lateral Pisgah fault, it is reasonably interpreted as an expression of strain accumulation along this fault. South of bench mark K 725, cumulative uplift increased well above the 0.28–0.30 m that prevailed north and west of this point to a maximum value of over 0.40 m at Twentynine Palms. Between Twentynine Palms and the end of the line, the magnitude of the uplift ranged within narrow limits and dropped off by only about 0.05 m between bench marks N 724 and 2H (MWD). This very small decrease implies a very steep gradient in the 1961–74 isobases of equal height change between Cottonwood Pass and Mecca (see section on "The Colton-Mecca Line"). Finally, although there is a vaguely defined association between the differential uplift developed between K 725 and 2H (MWD) and the relatively elevated Pinto and Hexie Mountains, the correlation between uplift and terrain is certainly very poor (pl. 12). Hence, it is unlikely that the differential uplift south of K 725 is unreal and attributable simply to systematic survey error.

The pattern that emerges from even this fragmentary reconstruction of height changes along the Mojave-Cottonwood Pass line suggests an almost wavelike west-to-east propagation of uplift during the period 1961–74. That is, between the spring and fall of 1961, an initially large uplift pervaded this area at least as far east and north as Barstow. This was followed by additional although lesser uplift between 1961 and 1968 which increased south to north and perhaps west to east as well. Similarly, sometime after 1968, but before 1972/73, collapse occurred within the quadrant defined by Barstow at the center and Boron and Bryman along its western and southern margins, respectively. Between 1972/73 and 1974, further uplift overcame and in fact exceeded this localized subsidence eastward from Boron to and beyond Barstow and was accompanied by modest downwarping in the area between Boron and Mojave. Because this second major surge of uplift occurred between 1972/73 and the following winter, we infer that the eastwardly increasing increment of uplift, produced sometime after 1968 but before 1974 (compare pl. 12 and sections on "The Lucerne Valley Line" and "The Colton-Mecca Line"), probably developed during this same interval (1972/73–74).

THE COLTON-MECCA LINE

GENERAL REMARKS

Because the Colton-Mecca line (pl. 13) forms a spur off the Orange-Barstow line, many of the problems associated with the assessment of height changes along the Orange-Barstow line apply to this line as well. In addition, reconstructed height changes along the Colton-Mecca line are complicated by the fact that the successively developed heights are based on only two virtually continuous levelings (the 1931 and 1968) emanating directly from Tidal 8, and one of these (the 1931) probably is seriously contaminated by intrasurvey movement. Moreover, while the results of 1956 leveling can be reconstructed as a reasonable equivalent of a hypothetical 1955 datum at the extreme western end of the line, the fragmentary development of the 1956 data, together with the otherwise indirect ties with Tidal 8, precludes use of the 1956 surveys as a generally appropriate preuplift datum.

Since the 1956 data cannot be used for this purpose, the results of the 1931 leveling provide the only potentially suitable alternative preuplift datum. However, three independent lines of evidence indicate that the 1931 leveling was error ridden, owing chiefly, in our judgment, to intrasurvey deformation. Arguments suggestive of major errors in the 1931 leveling include unusually large (above limits) misclosures against the primary 1931 leveling developed from nearly temporally equivalent levelings, a large discrepancy between the 1931 and 1944/61 reconstructed heights for the junction bench mark at Cottonwood Pass, and measurably significant subsidence of a primary junction bench mark south of Riverside sometime between the summer of 1931 and the following winter. Thus, because the 1931 leveling produced, at the very least, ambiguous heights, we are left without a suitable preuplift datum over nearly all of the main line.

A similar problem attaches to the use of the latest of the postuplift levelings—that is, the results of the 1974/76 survey. Nearly all of the most recent leveling between Colton and Mecca and White Water and Twentynine Palms was carried out in 1976, and the results of these surveys have been provisionally tied to the 1974 height of the junction bench mark at Colton. However, a good deal of collectively compelling evidence indicates that the Colton-Mecca line sustained major tectonic collapse sometime between 1974 and 1976. Thus, even though there are several ways whereby we can estimate the cumulative vertical displacements along this line during the interval 1968–76, height changes that occurred between 1968 (or 1956) and 1974 can be developed along only a few segments (based in part on the use of the 1976 misclosure on the results of the 1974 leveling between Twentynine Palms and Mecca) and at the junction points between the 1974 and 1976 leveling at Mecca and Twentynine Palms.

In spite of the disjointed and limited reconstruction of accurate heights along the Colton-Mecca line, several significant sets of height changes emerge from even these partial comparisons. Specifically, comparisons of the results of subsequent levelings against a 1956 datum indicate that the area extending from Mecca northwestward to Indio and southward toward Truckhaven experienced modest but well-defined tectonic subsidence between 1956 and 1968. This subsidence was apparently overcome by 1974, during the 1968–74 0.13–0.18-m uplift of Mecca. Similarly, through a combination of the results of the 1974 and 1976 surveys, we can also show that virtually the entire line between White Water and Twentynine Palms probably sustained uplift of no less than several tenths of a meter during the interval 1968–74. Finally, the results of the 1976 leveling, together with the recognition of about 0.13 m of subsidence at Colton during the period 1974–76, indicate that by 1976 the main line between Colton and Mecca had collapsed well below the 1968 datum, and that much of the line probably collapsed below a hypothetical preuplift datum as well.

DETAILED RECONSTRUCTION

The Colton-Mecca line consists of a primary vertical-control line between Colton and Mecca, together with a spur between White Water and Twentynine Palms, a second very short spur extending northeastward from Indio, and a third short spur between Mecca and Truckhaven (pl. 13). The starting elevations are taken, insofar as possible, directly from the temporally equivalent junction bench mark elevations along the Orange-Barstow line. The 1931 starting elevation is based on nearly continuous leveling between Tidal 8 and bench mark M 71, Banning, completed during the period July(?) 1931–March 1932 (NGS lines L-386 and L-7407). The 1931 observed elevation of M 71 has been orthometrically corrected to agree with the observed elevation which would have been obtained had this leveling followed the primary route through Riverside and Colton eastward to Banning. The 1956 starting elevations are based on local datums—an assumption of stability, in other words, at bench marks D 39, P 517, S 70, and H 516 during the periods 1956–61, 1956–76, 1931–68, and 1956–68/69, respectively. The 1969/73 White Water-Twentynine Palms datum depends on an assumption of relative stability along this line during the period 1969–73 (see section on "The Lucerne Valley Line"), together with a starting elevation based on the 1968 elevation of bench mark 603-68; the 1976 starting elevation of 603-68 is based on 1975/76 leveling extending eastward from Colton (pl. 13). Owing to uncertainties in both the 1931 and 1956 heights toward the eastern end of the Colton-Mecca line, all height changes along the Indio spur are referred to bench mark S 70 (pl. 13).

Although we have profiled observed elevation changes here against a 1931 datum (pl. 13), chiefly because this datum was developed from the most recent preuplift surveys between Tidal 8 and Indio completed within a reasonably short period (March 1931–March 1932; NGS lines L-386 and L-7407), the results of the 1931 surveys regrettably cannot be equated with those that would have been developed in 1955 (or the spring of 1961). Moreover, not only have we been unable to establish a satisfactory preuplift (1955-equivalent) datum along this particularly critical line, observed elevations developed from the 1931 surveys probably form a generally invalid datum, a judgment that has nothing to do with the quality of the measurements. Rather, comparisons between the results of disconnected pre- and post-1931 surveys show that the region traversed by the Colton-Mecca line was characterized by significant crustal mobility during the period 1928–56. Moreover, it seems likely that nearly all of the differential movement implied by comparisons with the 1931 datum is tectonic, for none shows any evident association with known areas of fluid extraction (compare pls. 4 and 13). Hence, while the most obvious conclusion that could be drawn from the results shown on plate 13 is that the cumulative movement during the periods 1931–68 and 1931–74/76 was conspicuously negative, this conclusion is suspect and contrasts significantly with conclusions developed from the results of post-1931 levelings.

Several lines of evidence indicate that the results of the 1931 surveys cannot be viewed as a reliable basis for the development of "true" or instantaneously established elevations with respect to Tidal 8. Specifically, we conclude that the junction bench mark at White Water rose about 0.15 m and by as much as 0.16 m during the periods 1961–68 and 1968–74, respectively, and that the height of Mecca increased by as much as 0.18 m during the period 1968–74 (see below and section on "The Lucerne Valley Line"), a conclusion that suggests that the 1931 heights along the Colton-Mecca line must have been almost unbelievably high. Similarly, simple comparisons between 1928 and 1931 observed elevations (with respect to Tidal 8) indicate that the Banning area sustained about 0.07 m of uplift during the period 1928–31. Because this area was elevated about 0.4 m during the period 1902–28, and probably largely during the period 1902–14 (Wood and Elliott, 1979, p. 254–256), it seems unlikely (but certainly not impossible) that continuing major uplift could have persisted into the period 1928–31.

A further indication that the 1931 heights (as reconstructed here) are of questionable validity emerges from a comparison between the 1931 and 1974 observed elevations at Cottonwood Pass. The 1931 elevation of 2H (MWD) based on leveling via Riverside, Banning, and Indio, is given as 526.7318 m, whereas the 1974 elevation based on leveling via Palmdale, Mojave, and Twentynine Palms is given as 526.7638 m, for a difference of only 0.0320 m. Application of orthometric corrections based on normal gravity would increase these figures to 526.7386 m and 526.7843 m, respectively, and thus increase the 1931–74 difference slightly to 0.0457 m. Use of orthometric corrections based on observed gravity would further modify this difference by no more than a few millimeters, for the observed gravity orthometric closure around nearly identical paths (fig. 46) differs from that based on normal gravity by only 7 mm. Accordingly, because a comparison between the 1944/61 and 1974 heights of 2H (MWD) based on leveling over the same route indicates that this mark rose about 0.35 m (see section on "The Mojave-Cottonwood Pass Line"), it suggests either that the 0.35-m figure is based on an improper reconstruction or that the 1931 observed elevation is invalid. In fact, abundant evidence indicates uplift of 2H (MWD) of 0.30–0.35 m (and certainly no less than 0.25 m) (see sections on "The Los-Angeles-Mojave Line" and "The Mojave-Cottonwood Pass Lines"). Moreover, to contend that there was virtually no uplift of this mark during the period 1961–74 directly contradicts the results of the 1931–76 comparison between Cottonwood Pass and the Arizona border, which shows that differential uplift of 2H (MWD) with respect to Parker Dam could have been no less than and probably a good deal more than 0.27 m during the period 1931–74 (see section on "The Cottonwood Pass-Parker Dam Line").

Although various indirect arguments indicate that reconstruction of the results of the 1931 surveys has almost certainly produced an invalid (exaggerated) observed elevation for bench mark 2H (MWD), an explanation of the source of this invalid determination is of more than academic importance to this study. That is, if the discrepancy between the 1931 and the 1944/61 elevations of 2H (MWD) cannot be explained, it casts great doubt on the 1972/73–74 eastward propagation of the southern California uplift implied by the comparison shown on plate 12.

Several lines of evidence indicate that the discrepancy between the 1931 and 1944/61 observed elevations of 2H (MWD) is attributable chiefly to the occurrence of crustal deformation during the 1931/32 leveling eastward from Tidal 8: (1) The observed misclosure around a narrowly defined loop between Cabazon and Indio, derived from first-order leveling carried out during the spring of 1931, is given as −0.0684 m (fig. 47). Orthometric corrections based on normal gravity reduce this closure to 0.0669 m. However, because this circuit lies astride the San Andreas fault, an orthometric correction based on observed gravity has also been calculated; this recalculated value (−0.0148 m) enlarges the misclosure to −0.0832 m. Hence, the corrected misclosure implies a down-to-the-west tilt of more than 0.08 m between 1D (MWD) and 1442 USGS during the interval bracketed by the levelings of March 26–May 15, 1931, and May 31–June 12, 1931 (fig. 47), a remarkably large tilt developed over a remarkably short period. (2) Several rela-

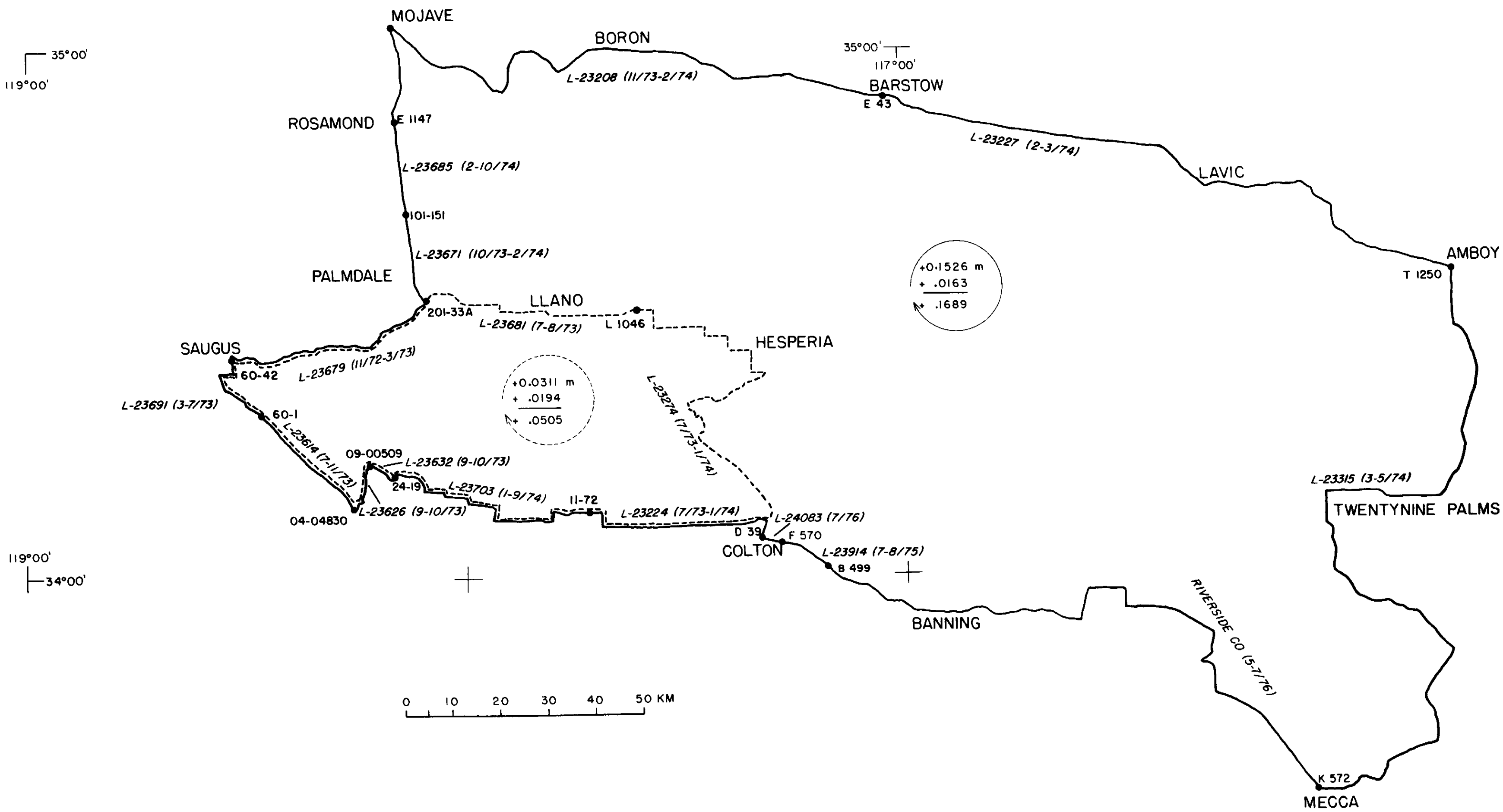


FIGURE 46.—Misclosures around the circuits Colton-Saugus-Palmdale-Rosemead-Mojave-Boron-Barstow-Lavic-Amboy-Twentynine Palms-Mecca-Banning-Colton and Colton-Saugus-Palmdale-Llano-Hesperia-Colton (dashed line); based on levelings carried out during the period November 1972–July 1976. See figure 4 for adopted conventions and explanation of symbols.

tively small circuits between White Water and Cajon Pass that either involve or closely bracket the 1931 leveling produce misclosures ranging from 0.0847 m (NGS lines L-11 and L-991) to 0.1594 m (NGS lines 82464 and L-5334; USGS line B 6637). Disregarding measurement errors, orthometric corrections, and any differential movement between Riverside and Colton during the period 1928–34, the smallest of these misclosures (based exclusively on first-order leveling) is consistent with down-to-the-west tilting of more than 0.08 m between the 1928 and the 1931 surveys—probably carried out entirely during the summer of 1931 (W. Edwards, Metropolitan Water District of Southern California, oral commun., 1977). (3) The observed elevation of bench mark M 38 of 242.3681 m, used here as a starting elevation for the 1931 leveling eastward to Indio, is based on leveling between Tidal 8 and M 38 via Orange carried out largely during the period February–March 1932. The observed elevation of M 38, based on leveling between Tidal 8 and M 38 via Los Angeles and Ontario, carried out largely during the period August–December 1931, is given as 242.4266 m. Hence, while we have again made no attempt to incorporate any orthometric correction in this comparison, the

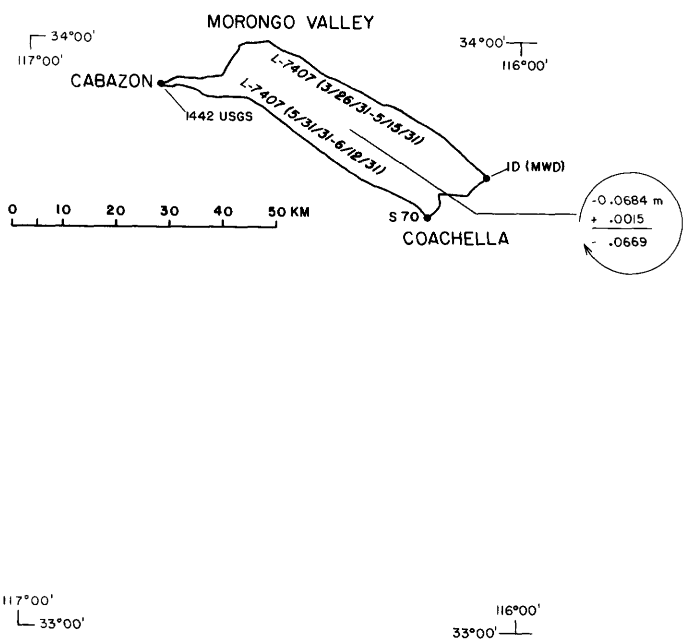


FIGURE 47.—Misclosure around the circuit Cabazon-Morongo Valley-bench mark 1D (MWD)-Coachella-Cabazon based on leveling carried out during the period March 26, 1931–June 12, 1931. This misclosure enlarges to −0.0832 m where the orthometric correction is based on observed gravity. See figure 4 for adopted conventions and explanation of symbols.

0.0579-m difference between these two "1931" elevations argues that M 38 probably subsided about 0.05 m sometime between the summer of 1931 and the following winter. The preceding evidence strongly suggests, accordingly, that crustal collapse, probably proceeding from east to west, occurred during the course of the 1931 leveling. For example, simply substituting the alternative elevation differences disclosed by the two described misclosures involving the 1931 leveling diminishes the 1931 observed elevation of 2H (MWD) to 526.5787 m and, hence, increases the 1931–74 uplift of this mark to 0.1851 m (0.1988 m, if orthometric corrections based on normal gravity are added to the observed elevations). Regardless of the validity of this particular reconstruction of the 1931 observed elevation of 2H (MWD), it now seems certain that crustal deformation during the 1931 leveling virtually guaranteed the generation of an invalid height for this mark; whether the resulting height could be expected to have been higher or lower than the "true" height is a function of the distribution of the 1931 leveling in both space and time relative to the concomitantly evolving deformation.

The likelihood that the actual 1931 height of 2H (MWD) is closely approximated by the orthometrically corrected results of the 1961/44 leveling into this mark via Los Angeles, Mojave, Barstow, and Amboy (see sections on "The Los Angeles-Mojave Line" and "The Mojave-Cottonwood Pass Line")—and, hence, that 2H (MWD) in fact rose about 0.35 m between the beginning of 1961 and 1974—is convincingly supported by the results of 1926/27/31 levelings into this mark through southwestern Arizona. The 1931 height developed from leveling via Los Angeles, Mojave, Barstow, and Amboy is again based on an assumption of invariance between Daggett and Cottonwood Pass during the period between 1931 and March–April 1961 (see section on "The Mojave-Cottonwood Pass Line"). The 1931 height developed from leveling through southwestern Arizona is based on one correction and one assumption. Because the 1926/27 leveling emanated eastward from San Diego, the tie between Tidal 8 and San Diego is based on a combination of 1931/32 and 1932/33 levelings that have been corrected for about 0.01 m of compaction-induced subsidence during the 1931/32–1932/33 junction interval at Santa Ana (Castle and Elliott, 1982, p. 7005, 7014–7015). Similarly, the establishment of a 1931 height for 2H (MWD) based on the 1926/27 leveling through southwestern Arizona has required that we assume that the height difference between the starting mark (M 57), adjacent to the San Diego

Municipal Pier tide station, and bench mark 22 Q, about 20 km east of Parker Dam (see section on "The Cottonwood Pass-Parker Dam Line"), remained invariant during the period 1926/27–31. This assumption is strongly supported by the near certain tectonic stability of the Municipal Pier tide station during historical time (Castle and Vaníček, 1980, p. 292; K. R. Lajoie, oral commun., 1983) and the geologically inferred stability at the site of bench mark 22 Q along the Bill Williams River in southwestern Arizona (Suneson and Lucchitta, 1983, p. 1006–1008). Based on the stated assumptions and correction, the 1931 observed elevation of 2H (MWD) obtained from the 1961/44 leveling via Los Angeles, Mojave, Barstow, and Amboy is 526.4073 m (NGS lines L-11067, L-11069, L-11115, L-18230, L-18296, L-18299, and L-18364), whereas that obtained from the 1926/27/31/32/33 leveling via southeastern California and southwestern Arizona is 526.4620 m (NGS lines 82606, 82625, 82632, L-386, L-570, and L-7407). Orthometric corrections based on normal gravity produce 1931 heights for this mark of 526.3512 m and 526.3966 m, respectively. Where the orthometric corrections are based on observed gravity, the separately determined 1931 heights for 2H (MWD) are given as 526.4707 m and 526.4877 m, respectively. While this exercise provides no assurance that the area between Daggett and Cottonwood Pass remained free of deformation during the period between 1931 and the beginning of 1961, it does demonstrate that 2H (MWD) remained virtually fixed in height between 1931 and at least as late as 1944 and that the uplift at Cottonwood Pass during the period 1931–1974 is much more accurately described through use of the results of the 1961/44 leveling via Los Angeles, Mojave, Barstow, and Amboy than it is by those obtained from the 1931/32 leveling via Riverside and Banning.

Height changes profiled against a 1956 datum involve an assumption of invariance at bench marks D 39, P 517, S 70, and H 516 during the periods 1956–61, 1956–76, 1931–68, and 1956–68/69, respectively (see above). Although this assumption is clearly invalid in terms of the stability of these marks with respect to Tidal 8, it provides a basis for showing differential movement significant to the evolution of the southern California uplift. An alternative reconstruction of elevation changes along the short segment eastward from D 39 (shown by the dashed-line representation, p. 13) is drawn from a reconstruction of the 1956 height of D 39 based on 1956 surveys between Colton and Barstow. Because the stability of Colton during the period 1956–61 is doubtful, whereas Barstow is believed to have remained relatively stable between 1926/27 and the spring of 1961, the alternative reconstruction is preferred (see section on "The Orange-Barstow Line").

Although the 1968 leveling was completed during a period of relative quiescence, the 1974/76 surveys extended over a 3-year period (1973–76) during which considerable deformation occurred, such that a comparison of the results of the 1974/76 surveys against a 1968 datum probably differs significantly from that which would have been obtained had the later leveling been run entirely in 1974. That is, while the 1968–74/76 comparison may approximate the cumulative movement with respect to Tidal 8 between 1968 and 1976, this cumulative representation cannot be used as a basis for estimating the maximum uplift developed along this line since 1968. Similarly, while comparisons of the results of the 1976 leveling against the combined 1969/73 datum along the White Water-Twentynine Palms spur suggest no more than about 0.12 m of uplift at Yucca Valley, 0.08 m at Twentynine Palms, and virtually zero uplift at White Water, these values are almost certainly less than the uplift developed at these points between 1968/69 and 1974.

Probably the most direct way of showing the extent to which the 1974 heights along the Colton-Mecca line had changed by 1976 is through the examination of the 1968–74 height changes at several junctions along this line that can be determined independently of those shown on plate 13. (1) The 1968 observed elevation of bench mark H 516, Mecca, is given as −54.9160 m; the 1974 elevation of H 516, based on leveling via Mojave, Barstow, and Amboy, is given as −54.7450 m. Application of orthometric corrections based on normal gravity increases these values to −54.9100 m and −54.7217 m, respectively. Owing to the length (~ 1,000 km) and breadth of the circuit defined by the 1974–68 leveling, orthometric corrections based on observed gravity have also been calculated; these corrections further increase the 1968 and 1974 heights to −54.8990 m and −54.7190 m, respectively. Accordingly, the 1968–74 uplift at H 516 probably was very close to 0.1800 m (or 0.1300 m— see section on "The Los Angeles-Mojave Line"). Because a comparison between the 1968 and 1974/76 observed elevations of H 516 (−54.9160 m and −54.8977 m, respectively) indicates that this mark rose by only 0.0183 m during the period 1968–74/76 (pl. 13), H 516 apparently subsided by about 0.16 m (or 0.11 m— see above) during the interval 1974–76, provided, of course, that the starting elevation of D 39 remained unchanged during this same period. A down-to-the-east tilt developed between Colton and Mecca during the period 1974–76 is suggested by the +0.1689 m clockwise misclosure around the 896-km Colton-Saugus-Mojave-Amboy-Mecca-Colton loop defined by the "1974"–76 surveys (fig. 46) and, hence, tends to corroborate the 1974–76 subsidence of Mecca deduced from a direct comparison with the 1968–74 uplift. The smaller misclosure (0.1184 m) around the 1974–76 loop that bypasses the 1972/73 Saugus-Palmdale leg (fig. 46) suggests that the 1974–76 differential movement between Colton and Mecca may have been somewhat less than 0.17 m. (2) The 1968–74 uplift of the junction bench mark (603-70) at White Water may be estimated by assuming either that the elevation difference between White Water and Mecca remained invariant between 1968 and 1976, or that the elevation difference between White Water and Twentynine Palms remained invariant between 1974 and 1976. Acceptance of the first of these assumptions indicates that White Water (specifically, bench mark 603-70) rose by 0.1800 m during the period 1968–74—that is, by an amount equal to that sustained at H 516 during the same interval—as contrasted with cumulative uplift at White Water between 1968 and 1974/76 of only 0.0136 m (pl. 13). The second or alternative assumption is supported by the misclosure around the circuit White Water-Yucca Valley-Twentynine Palms-Mecca-White Water defined by the 1974/76 leveling (fig. 48). Thus, the misclosure based on observed elevation measurements around this circuit is only 0.0558 m, and although this figure is enlarged to 0.0768 m through the inclusion of the orthometric closure based on normal gravity, a manually computed correction based on observed gravity changes the clockwise orthometric closure from +0.0210 m to −0.0186 m and, hence, reduces the misclosure to only 0.0372 m. Even though this misclosure rigorously describes no more than the relative deformation between Twentynine Palms and Mecca, it suggests that the area included by this loop sustained very little differential movement during the period 1974/76. Proceeding with the postulated assumption of invariance between White Water and Twentynine Palms, the 1974 observed elevation of bench mark Z 1250, Twentynine Palms, based on leveling via Mojave, Barstow, and Amboy is given as 591.2618 m, whereas the 1974/76 observed elevation of this mark based on leveling via Colton, White Water, and Yucca Valley is given as 591.1604 m. Corresponding, orthometrically corrected heights based on normal and observed gravity, respectively, are 591.2498 m and 591.2920 m (1974) and 591.1529 m and 591.1455 m (1974/76). Use of the orthometrically corrected figures based on observed gravity indicates that Z 1250 collapsed 0.1465 m between 1974 and 1976. Hence, the 1974 heights of Z 1250 and, by extension, of 603-70 were at least 0.1465 m greater than those produced by the 1976 leveling eastward from Colton (see below). These calculations argue that the 1968–74 uplift of bench mark 603-70 was equal to the sum of 0.0136 m (the cumulative uplift between 1968 and 1974/76) and 0.1465 m, or 0.1601 m. Because these alternative assumptions produce estimates of the uplift at 603-70 that agree very closely (0.1800 m versus 0.1601 m), we conclude that White Water probably rose at least 0.16–0.18 m during the period 1968–74. The corollary of this conclusion is that bench mark 603-70 probably subsided 0.14–0.16 m between 1974 and 1976—provided, of course, that D 39 remained invariant during the period 1974–76.

The preceding estimates of uplift at White Water between 1968 and 1974 and tectonic subsidence at

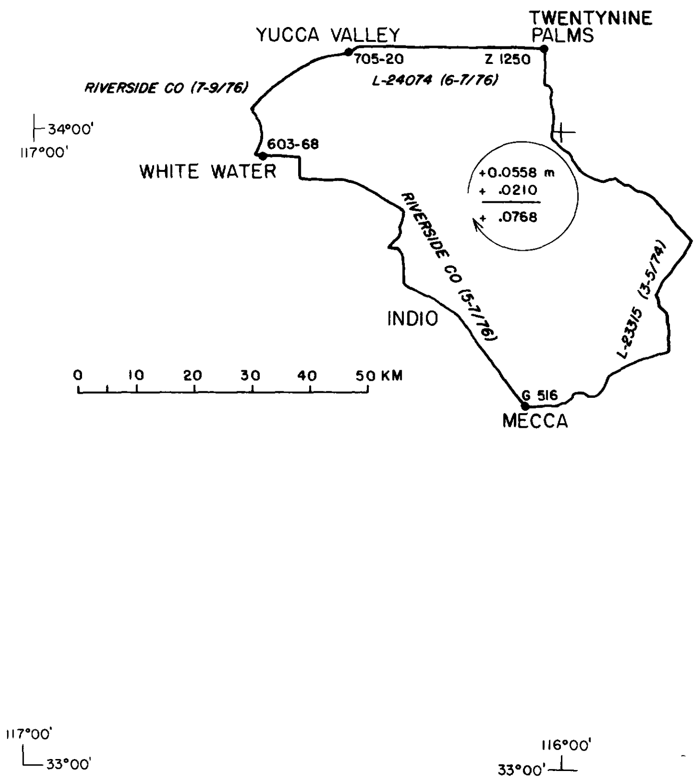


FIGURE 48.—Misclosure around the circuit White Water-Yucca Valley-Twentynine Palms-Mecca-White Water based on leveling carried out during the period March 1974–September 1976. This misclosure is reduced to +0.0372 m where the orthometric correction is based on observed gravity. See figure 4 for adopted conventions and explanation of symbols.

White Water, Twentynine Palms, and Mecca during the period 1974–76 (as well as of cumulative movement along the entire line between Colton and Mecca between 1968 and 1974/76) have been based on the previously stipulated but unverified assumption of invariance at bench mark D 39 during the interval 1974–76. While evidence of cumulative uplift of D 39 during the period 1974–76 is, at best, equivocal, there is excellent evidence that D 39 actually subsided by as much as 0.13 m during the full interval 1974–76/77. The clockwise misclosure based on observed elevation measurements around the circuit San Pedro-La Cañada-Palmdale-Llano-Hesperia-Colton (1976/77)-San Pedro (1973/74) is given as −0.1624 m (fig. 49). Orthometric corrections based on normal and observed gravity reduce this misclosure to −0.1428 m and −0.1270 m, respectively. However, even though we are reasonably certain that D 39 subsided about 0.13 m between 1974 and 1976/77, we are uncertain when this collapse occurred with respect to the completion of the 1976 leveling eastward to Mecca. The evidence now before us indicates that tectonic subsidence of the Los Angeles-La Cañada area may have occurred as early as the fall of 1974 and almost certainly no later than July 1976 (see section on "The Los Angeles-San Bernardino Line"). Similarly, massive subsidence of both Mecca and Twentynine Palms (with respect to D 39), together with demonstrable collapse of much of the eastern Mojave that apparently occurred between 1974 and the summer of 1976 (see above and section on "The Cottonwood

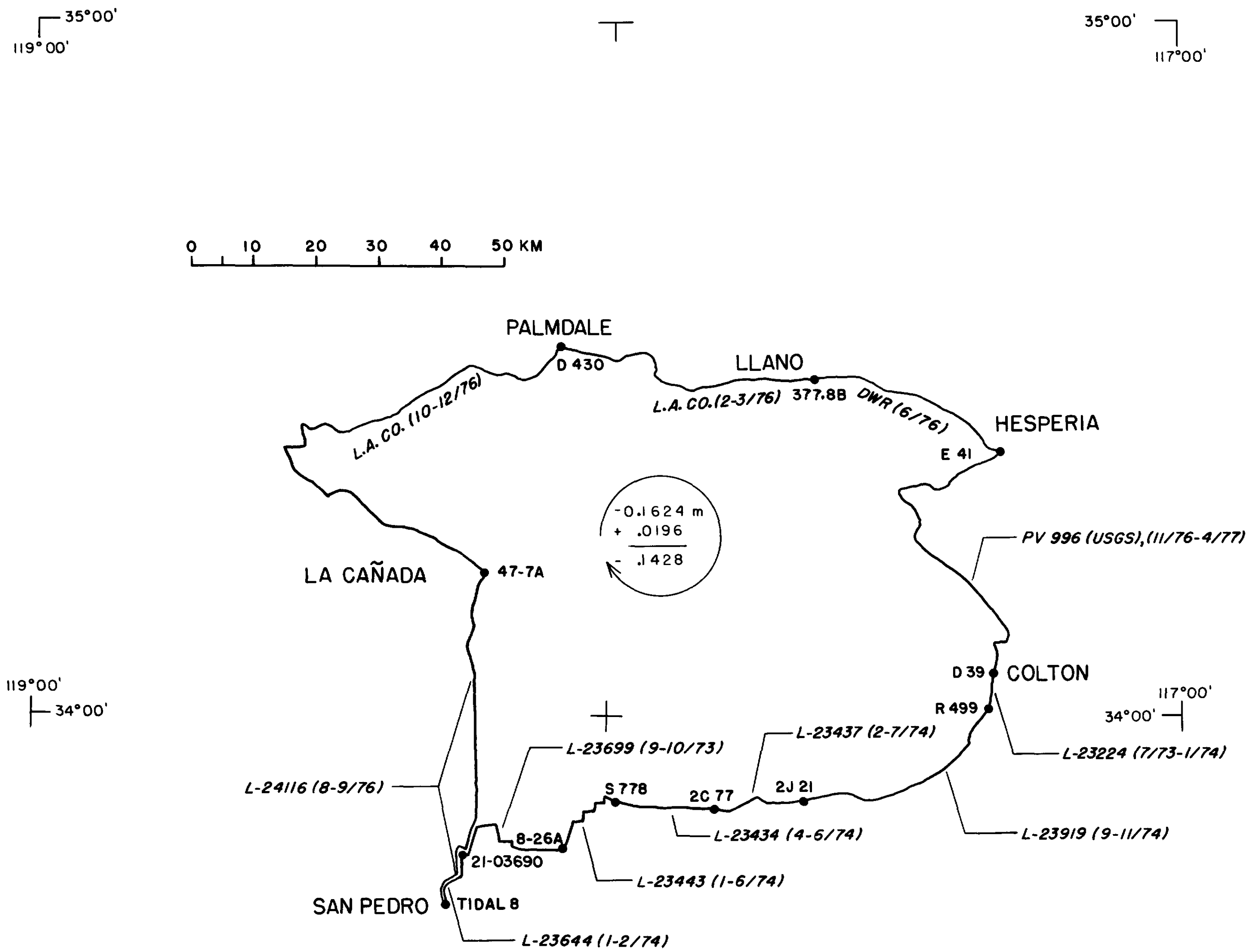


FIGURE 49.—Misclosure around the circuit San Pedro-La Cañada-Palmdale-Llano-Hesperia-Colton-San Pedro based on leveling carried out during the period July 1973–April 1977. This misclosure is reduced to −0.1270 m where the orthometric correction is based on observed gravity. See figure 4 for adopted conventions and explanation of symbols.

Pass-Parker Dam Line"), suggests that the crustal disturbance that produced the subsidence of D 39 had largely run its course by the spring of 1976. Finally, R. C. Jachens (written commun., 1977) has shown through precise gravity ties between Riverside and Glendale (adjacent to La Cañada) that gravity changes at Glendale with respect to Riverside were +18 ± 4 μGal during the period June 1976–May 1977 (two gravity meters) and +6 ± 6 μGal during the period October 1976–May 1977 (three gravity meters). These observations, accordingly, are at least consistent with the probable cessation of massive subsidence by September of 1976.

The implications of as much as 0.13 m of tectonic subsidence at Colton between 1974 and the spring of 1976 are, at the very least, disturbing. Specifically, if the 1974–76 subsidence of D 39 is disregarded, the already impressive determinations of tectonic collapse at White Water, Mecca, Twentynine Palms, Amboy, Cottonwood Pass, and Frink, based on an assumption of invariance at D 39 during the same interval (see above and sections on "The Cottonwood Pass-Parker Dam Line" and "The Cottonwood Pass-Frink Line"), may be underestimated by as much as 0.13 m. Moreover, because we have discovered no evidence to suggest that any significant fraction of the subsidence of D 39 occurred after the completion of the 1976 leveling eastward to Mecca, whereas there is both direct and indirect evidence of the collapse of Colton between 1974 and the summer of 1976, the profiles of height changes based on comparisons of the results of the 1976 surveys against the 1968 and 1969/73 datums (pl. 13) probably should be dropped by 0.1270 m. In other words, the 1968–76 cumulative vertical displacements between Colton and Mecca and between White Water and Twentynine Palms may have been uniformly negative.

The preceding discussion demonstrates, at the very least, that the profiled height changes along the Colton-Mecca line (pl. 13) are the most equivocal of any considered to this point and could, in the absence of any other information, seriously mislead us. Thus, the height changes measured against a 1931 datum are certainly suspect, at least to the extent that this datum could hardly be selected as a 1955-equivalent. Similarly, while the relative movements over the full period 1968–76, with respect to virtually any control point along this line, can be assessed and accepted, there is no direct evidence indicating that this period actually harbored a dramatic aseismic vertical oscillation. Nevertheless, and in spite of the ambiguity inherent in the results of all but the 1968 leveling, these reconstructions provide additional insight into the history of vertical movement along the south flank of the southern California uplift.

Although the profiled height changes along the Colton-Mecca line (pl. 13) are ambiguous and even misleading, they provide a basis for several useful generalizations, particularly when coupled with additional information. For example, although the 1931 datum is clearly suspect, it is very unlikely that the true 1931 heights fell below the 1976 heights between Banning and Indio; hence, if the 1931 heights even approached those that obtained in 1955, it is equally unlikely that post-1955 uplift persisted along the main line through 1976. Similarly, height changes since 1956 along the western end of the main line probably are closely approximated by the dashed-line representations (pl. 13). Again, however, the post-1956 uplift is incompletely described by the cumulative movements profiled here (see section on "The Orange-Barstow Line"). Moreover, while we have plotted the 1956–68 and 1956–76 height changes along the eastern end of the line with respect to local datums (pl. 13), estimates of height changes with respect to Tidal 8 during the period 1956–68 (or 1956–76) can be determined through a knowledge of the height history of any bench mark included in these several surveys. Thus, if it is accepted that H 516, Mecca, rose 0.0023 m with respect to Tidal 8 during the interval 1955/56–68 (fig. 50), in order to show the 1956–68 displacements with respect to Tidal 8, the 1956–68 profiled height changes along the main line should be datum-shifted by −0.0887 m, those along the Indio spur by −0.0557 m, and those along the Mecca-Truckhaven spur by +0.0023 m. In other words, bench marks S 70, P 517, and 1C (MWD) are interpreted as having subsided 0.0557 m, 0.0887 m, and 0.1177 m, respectively, between 1956 and 1968. Moreover, this tectonic subsidence apparently increased southward from Mecca as well. That is, again accepting the 0.0023 m of uplift at H 516 with respect to Tidal 8 during the interval 1955/56–68 (fig. 50), representative bench marks C 517 and G 577 sustained height changes of −0.0466 m and −0.0835 m, respectively, during this same interval. Perhaps significantly, the form of the differential subsidence developed north of Mecca between 1956 and 1968 apparently persisted through 1976, regardless of whether Mecca remained invariant between 1968 and 1976 (fig. 50*A*) or actually subsided about 0.13 m (fig. 50*B*). Finally, even though comparisons against the 1968 datum permit the determination of no more than cumulative height changes and, therefore, obscure such intraperiod movements as may have occurred between 1968 and 1976, localized differential movements can be determined with considerable confidence. For example, the narrow zone of differential uplift centering on bench mark H 525 is very well defined and is certainly real; because this uplift cannot be reasonably attributed to elastic rebound accompanying recharge of the Bunker Hill ground-water basin (pl. 4), it is likely that it is an expression of strain accumulation on the Banning fault near its junction with the San Jacinto fault (pl. 2).

THE COTTONWOOD PASS-PARKER DAM LINE

GENERAL REMARKS

The Cottonwood Pass-Parker Dam line (pl. 14) is in effect a continuation of the Mojave-Cottonwood Pass line. It has not been treated as such, however, because the described signal is based on the results of only two levelings, the latest of which (the 1976) was produced subsequent to the 1974–76 tectonic collapse that pervaded the Colton-Mecca line and apparently extended into the Cottonwood Pass area as well. Accordingly, the up-to-the-west tilt based on the results of the 1976 leveling between Parker Dam and Cottonwood Pass is almost certainly a minimum expression of the 1955–74 uplift along this line. The results of the 1976 leveling between Cottonwood Pass and Parker Dam probably differ significantly from the observed elevation differences that would have been obtained had this survey been completed in 1974; however, it is much less likely that the 1931 elevation differences along this line are significantly different from those that would have been obtained in 1955. This conclusion is supported explicitly by the very small misclosure involving both 1931 and 1944 leveling around the circuit Cottonwood Pass-Amboy-Freda Junction-Cottonwood Pass, by the previously developed evidence of regional stability within the area extending east-southeastward from Daggett to Cottonwood Pass between 1944 and the early spring of 1961, and by the excellent correspondence between the 1926/27/31/32/33 and 1944/61 heights for the Cottonwood Pass junction mark developed from levelings through southwestern Arizona and the western Mojave Desert, respectively.

The results of a variety of measurements indicate that the entire region traversed by the Cottonwood Pass-Parker Dam line, including the area extending westward from Freda Junction to Amboy, sustained major tectonic deformation during the period 1974–76. Moreover, virtually all of the evidence at our disposal indicates that the Cottonwood Pass junction mark subsided as much as several decimeters with respect to Tidal 8 during the period 1974–76. The implications of this tectonic subsidence are several fold. For example, if it is accepted that Parker Dam remained essentially invariant with respect to Tidal 8 during the period 1931–76, an assumption for which there exists at least permissive support, the 1931–74 uplift of Cottonwood Pass could easily have been about 0.44 m and perhaps as much as 0.57 m; these values clearly exceed the 1944/61–74 0.36-m uplift developed from comparisons along the Mojave-Cottonwood Pass line. The occurrence of a large up-to-the-west tilt (0.44–0.57 m) between Parker Dam and Cottonwood Pass could be equally well explained by a combination of uplift at Cottonwood Pass coupled with

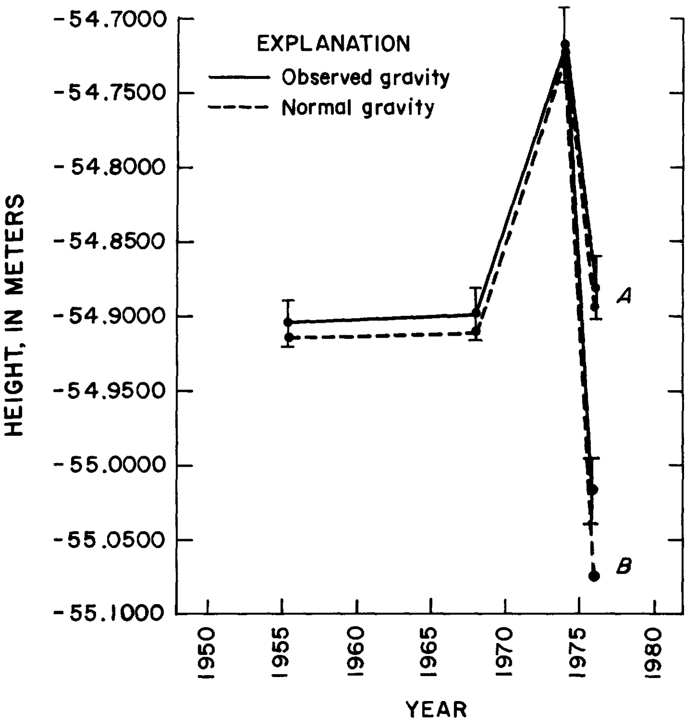


FIGURE 50.—Changes in orthometric height at bench mark H 516, Mecca. The 1955/56 height is based on repeated surveys which show that H 516 rose 0.0480 m with respect to La Jolla during the period 1955/56–68/70 (NGS lines L-15546, L-15872, L-15875, L-21529, L-21532, L21883, L-22379, and L-21770), and changes in annual sea-level means which show that La Jolla subsided 0.0457 m with respect to Tidal 8, San Pedro, during the period 1955/56–68/70 (J. R. Hubbard, National Ocean Survey, written commun., 1976). *A*, Calculated heights based on an assumption of stability at bench mark D 39, Colton, during the period 1974–76. *B*, Calculated heights based on the acceptance of 0.1270 m of subsidence at bench mark D 39, Colton, during the period 1974–76 (see text for details). One-standard-deviation error bars show conventionally estimated random error only.

tectonic subsidence toward the Arizona border. Because tectonic subsidence has been recognized elsewhere around the margins of the uplift, this less conservative interpretation is a real, although much less likely, possibility.

DETAILED RECONSTRUCTION

The Cottonwood Pass-Parker Dam line consists of a primary vertical-control line between Cottonwood Pass and Parker Dam, together with a single spur between Freda Junction and Amboy (pl. 14). Height changes along the main line are based on a single comparison between a 1931 (1955-equivalent) datum and the results of 1976 leveling between Cottonwood Pass and the east side of the Colorado River; height changes along the Freda Junction-Amboy spur are limited to a comparison of the results of 1976 leveling against a combined 1931/44 datum (pl. 14). The 1931 starting elevation at bench mark 2H (MWD) is based on a tie with the 1944/61 elevation of this mark derived from leveling via Mojave and Amboy (see section on "The Mojave-Cottonwood Pass Line"). The 1976 starting elevation of 2H (MWD) is based on the 1974 elevation of this mark, less 0.0230 m of tectonic subsidence with respect to H 516, Mecca, during the period 1974–76, together with an assumption of stability at H 516 during this same interval (see sections on "The Mojave-Cottonwood Pass Line" and "The Cottonwood Pass-Frink Line").

The implied equivalence between the reconstructed 1931 (or 1931/44) observed elevations and those that would have been produced had this leveling, together with a tie to Tidal 8, been carried out in 1955, is based on several considerations: (1) The very small misclosure around the 384-km circuit Cottonwood Pass-Amboy-Freda Junction-Cottonwood Pass, based on 1944 leveling between Cottonwood Pass and Cadiz and 1931 leveling southeastward to Freda Junction and southwestward to Cottonwood Pass (fig. 44), suggests that this region remained free of crustal deformation during the period 1931–44. (2) Analyses of the stability of the area traversed by the 1944 leveling southeastward from Daggett to Cottonwood Pass indicate that this area was characterized by little if any regional tilting between 1944 and the spring of 1961 (see section on "The Mojave-Cottonwood Pass Line"). (3) The excellent correspondence between the 1926/27/31/32/33 and the 1944/61 heights for 2H (MWD) obtained from levelings through southwestern Arizona and the western Mojave Desert, respectively (see section on "The Colton-Mecca Line"), indicates that the Cottonwood Pass area remained tectonically invariant between 1931 and at least 1944 (and probably between 1931 and 1961). Accordingly, the 1931 observed elevations along the Cottonwood Pass-Parker Dam line derived through a tie with the 1944/61 observed elevation of 2H (MWD) may be treated provisionally as the approximate equivalents of those that would have been produced through a continuation of the 1955 leveling eastward from bench mark Q 49, Mojave (see section on "The Los Angeles-Mojave Line").

A subjective, yet compelling argument in support of a rough equivalence between the reconstructed 1931 observed elevations and a hypothetical 1955 datum is based on the results of the 1976 leveling along the Cottonwood Pass-Parker Dam line. The 1976 leveling was commissioned specifically to test the conclusion that the southern California uplift extended eastward to and beyond Cottonwood Pass. If the uplift projected well into the eastern Mojave Desert, a comparison eastward from Cottonwood Pass of the results of postuplift (1976) leveling against the most recent preuplift (1931) datum should disclose a major down-to-the-east tilt—provided, of course, that the uplift closed off largely within the area traversed by the 1976 leveling. Hence, given our initial assumption of stability at H 516, Mecca, during the period 1974–76, we could reasonably expect a down-to-the-east 1931 (1955-equivalent)–1976 tilt between Cottonwood Pass and the Colorado River of as much as 0.33 m. Because the actually measured tilt over this reach was about 0.27 m (pl. 14), it strongly supports both the extension of the uplift into the eastern Mojave and a rough equivalence between the reconstructed 1931 elevations and a hypothetical 1955 datum along this line.

An alternative explanation for the prominent 1931–76 down-to-the-east tilt between Cottonwood Pass and Parker Dam (pl. 14) is based on the supposition that the 1931 bench mark heights were depressed by progressively increasing amounts westward from the Colorado River, and that these diminished heights recovered after the 1931 surveys but well before 1955 (or at least prior to any major uplift east of Barstow). According to this argument, even had there been no deformation between 1955 and 1976, a comparison between the results of the 1931 and 1976 levelings might still reveal a down-to-the-east (or up-to-the-west) 1931–76 tilt very much like that shown on plate 14. However, a good deal of evidence (see below) indicates that the 1931–76 tilt (pl. 14) is even less than that

that would have been measured had the 1976 leveling been carried out in 1974; hence, the postulated 1931–55 recovery would have to have been much greater than the already exceptionally large tilt that was actually measured (pl. 14). Moreover, because the misclosure around the 1931–44 Cottonwood Pass-Amboy-Freda Junction-Cottonwood Pass circuit is well within first-order limits (fig. 44) and because virtually all of the available evidence indicates that the entire central and eastern Mojave Desert remained free of significant regional deformation between 1944 and the spring of 1961 (see section on "The Mojave-Cottonwood Pass Line"), there is very little likelihood that any post-1931 recovery could have occurred before mid-1961.

A variety of measurements indicate that the area traversed by the Cottonwood Pass-Parker Dam line sustained major aseismic deformation during the period 1974–76. The least equivocal evidence of post-1974 deformation derives from misclosures involving the results of both 1974 and 1976 surveys. Thus, the 1974/76 misclosure around the loop Cottonwood Pass-Twentynine Palms-Amboy-Freda Junction-Cottonwood Pass (fig. 51) is consistent with a down-to-the-north tilt of 0.1338 m. Although this orthometrically corrected misclosure might be reduced through calculation of an observed-gravity correction, the 1931/44 observed misclosure around the same circuit (fig. 44) was only about one-third the 1974/76 misclosure developed from even more precise surveys; thus it is very unlikely that a significant fraction of this misclosure could be removed through recalculation of an orthometric correction based on observed gravity. Similarly, the orthometrically corrected misclosure around the loop Mecca-White Water-Yucca Valley-Twentynine Palms-Amboy-Freda Junction-Mecca (fig. 52) indicates a down-to-the-north tilt between Twentynine Palms and Amboy of 0.2360 m, a figure that cannot be lightly dismissed as survey error or the product of an improperly formulated orthometric correction. The difference between these two misclosures (figs. 51 and 52) suggests a 1974–76 down-to-the-south 0.1022-m tilt between Twentynine Palms and Cottonwood Pass. However, because the clockwise orthometric closure around the Mecca-White Water-Twentynine Palms-Mecca circuit based on observed gravity is −0.0186 m rather than +0.0210 m (see section on "The Colton-Mecca Line"), this down-to-the-south tilt may be no more than about 0.06 m. Nonetheless, these misclosures by themselves disclose 1974–76 arching about an axis through the Twentynine Palms area associated with relative collapse of both Amboy and Cottonwood Pass.

Alternatively, determinations of aseismic deformation within the area of the Cottonwood Pass-Parker Dam line during the period 1974–76 can be derived from calculated height changes based on 1976 leveling through Mecca. Thus, if it is assumed that bench mark H 516, Mecca, remained invariant with respect to Tidal 8 during the period 1974–76, because bench mark Amboy sustained 0.2889 m of uplift between 1944/61 and 1974 (pl. 12), yet only 0.1734 m of uplift during the period 1931/44/61–76 (pl. 14), Amboy apparently subsided 0.1155 m and bench mark Z 1250, Twentynine Palms, apparently rose 0.1205 m between 1974 and 1976 (fig. 52). If, on the other hand, it is assumed that bench mark D 39, Colton, remained invariant during the period 1974–76, then we must infer that H 516 subsided about 0.1617 m with respect to Tidal 8 (fig. 50), and, hence, that 2H (MWD) subsided 0.1847 m (rather than the 0.0230 m on which we have based the re-

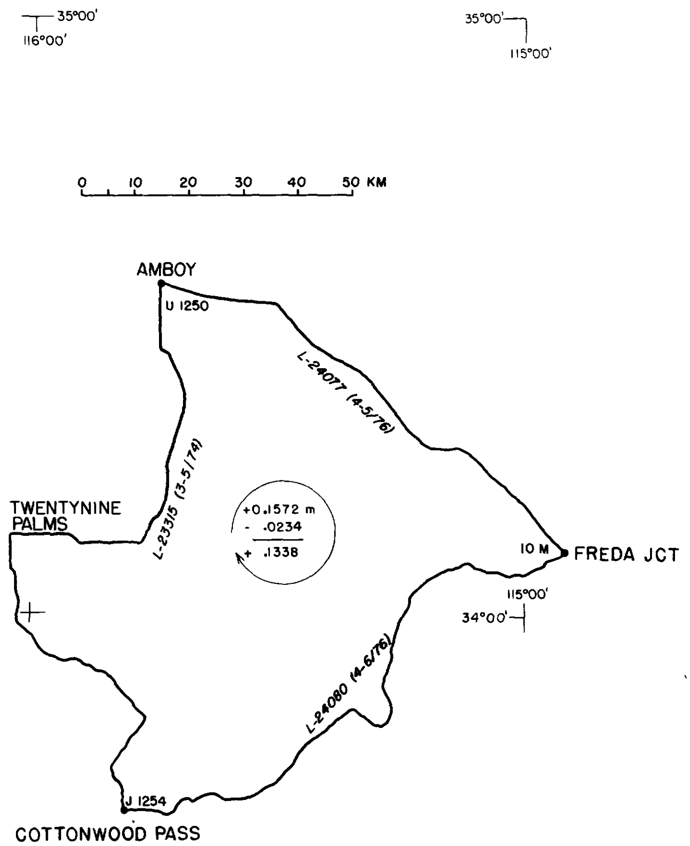


FIGURE 51.—Misclosure around the circuit Cottonwood Pass-Twentynine Palms-Amboy-Freda Junction-Cottonwood Pass based on leveling carried out during the period March 1974–June 1976. See figure 4 for adopted conventions and explanation of symbols.

construction shown on pl. 14). Moreover, a 0.1617-m collapse of H 516 implies that Amboy subsided 0.2772 m, virtually cancelling its earlier uplift, and that Z 1250, rather than sustaining additional uplift, actually subsided 0.0412 m during the period 1974–76. Finally, if, as now seems especially likely, D 39 subsided 0.1270 m with respect to Tidal 8 during the period 1974–76 (see section on "The Colton-Mecca Line"), H 516 subsided 0.2887 m (fig. 50), 2H (MWD) subsided 0.3117 m, Amboy subsided 0.4042 m, and Z 1250 subsided 0.1681 m between 1974 and 1976.

The preceding conclusions carry implications that clearly affect any estimates of the magnitude and gradient of the 1931/44/61–74 uplift along the Cottonwood Pass-Parker Dam line. Regrettably, a unique determination of the 1931/44/61–74 uplift along this line is unobtainable, and the truth probably lies somewhere between two postulated extremes. (1) As one possible option, it may be assumed that the uplift never propagated eastward beyond Parker Dam, and that bench mark 22 Q (pl. 14) has remained invariant since 1931. Independent support for this assumption derives from the form of the profile of height changes shown on plate 14. Because the down-to-the-east tilt defined by this profile (pl. 14) projects eastward to bench mark 22 C, yet flattens between 22 C and 22 Q, and because this break in the slope of the tilt is not simply a function of the changing azimuth of the profile (pl. 14), this 20-km segment may owe its virtually undeformed aspect to the likelihood that it remained

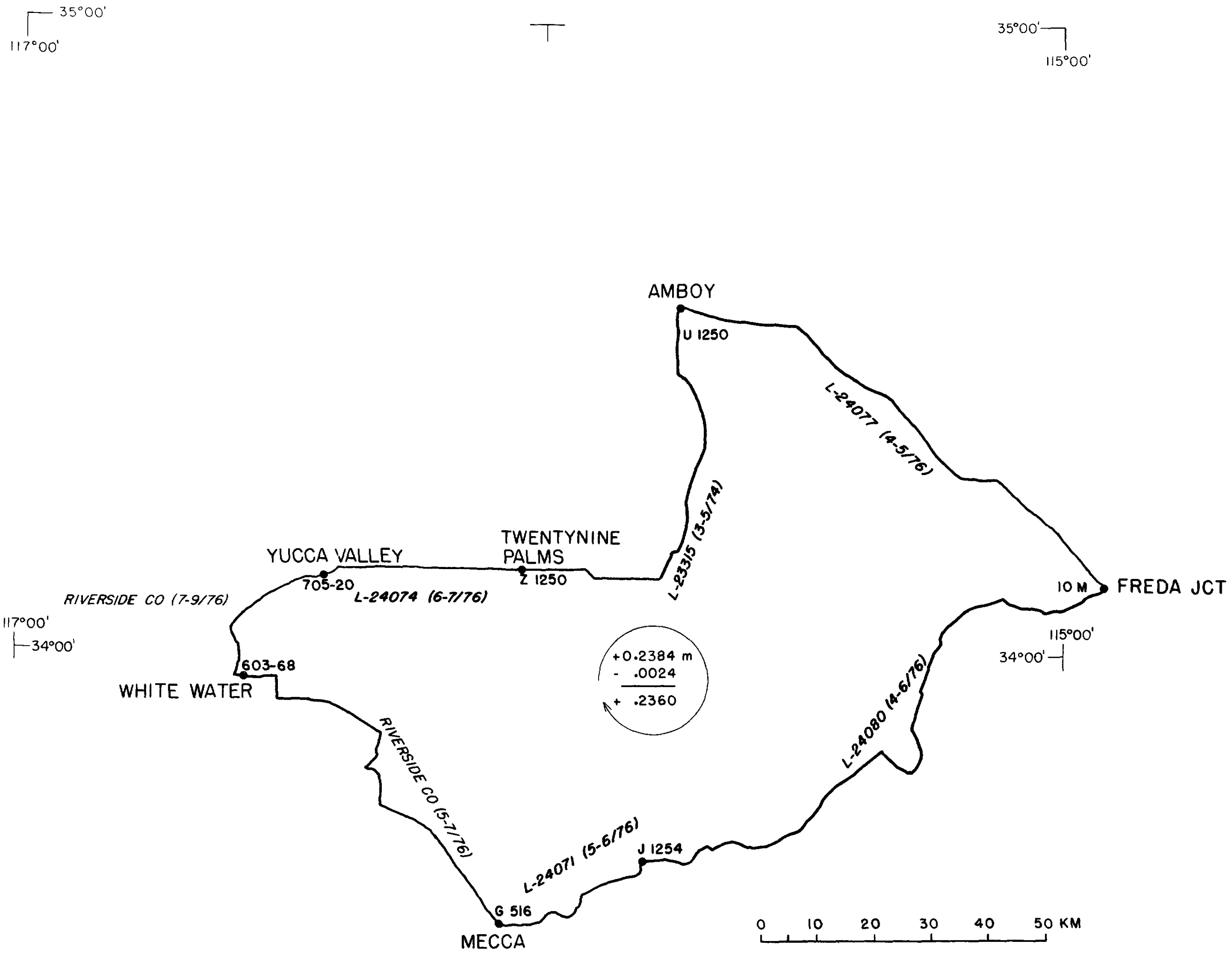


FIGURE 52.—Misclosure around the circuit Mecca-White Water-Yucca Valley-Twentynine Palms-Amboy-Freda Junction-Mecca based on leveling carried out during the period March 1974–September 1976. See figure 4 for adopted conventions and explanation of symbols.

uninvolved with the development of the southern California uplift. Thus, if one accepts the premise that 22 Q has remained invariant (or, more likely, subsided slightly) with respect to Tidal 8, because the 1974–76 collapse of 2H (MWD) probably was at least 0.1847 m and perhaps as much as 0.3117 m, yet retained a 1931–76 0.2586-m uplift with respect to 22 Q, the 1931–74 uplift of 2H (MWD) was at least 0.4433 m and could have been as much as 0.5703 m. This conclusion obviously implies that the previously calculated 1961–74 (or 1944/61–74) 0.3565-m uplift of 2H (MWD) (see section on "The Mojave-Cottonwood Pass Line") probably errs on the low side. (2) Alternatively, even though 2H (MWD) probably subsided 0.1847-0.3117 m during the period 1974–76, a large up-to-the-west tilt could have been preserved through a correspondingly large 1931–76 downwarping along the eastern reaches of the Cottonwood Pass-Parker Dam line. This possibility, although consistent with recognized tectonic subsidence developed elsewhere around the leading edge of the uplift, is much more difficult to accept. Nevertheless, if the 1944/61–74 uplift of 2H (MWD) was no less than 0.3565 m, and if the uplift of this mark was followed by a 1974–76 collapse of 0.1847-0.3651 m, the measured tilt between 2H (MWD) and 22 C (pl. 14) could have resulted from some combination of residual (and conceivably negative) uplift at 2H (MWD) and tectonic subsidence of 22 Q of 0.0868-0.2672 m. Because the 1974–76 tectonic subsidence of bench mark H 516, Mecca, probably was much nearer 0.2887 m than 0.1617 m (see section on "The Colton-Mecca Line"), and because 22 Q probably has subsided by no more than 0.0868 m since 1931, the 1931–74 uplift of 2H (MWD) must have been at least 0.3565 m and may have been as great as 0.5369 m. In the absence of any uplift at 2H (MWD) during the interval 1931–74, the measured tilt between 2H (MWD) and 22 Q could have been preserved only through the collapse of 22 Q by an amount equal to 0.2586 m+0.3117 m$-X$, where X=the difference between the maximum probable 1974–76 collapse of 0.3117 m and the true or actual collapse of 2H (MWD). Accordingly, had there been no uplift at 2H (MWD), because the 1974–76 tectonic subsidence of this mark may have approached 0.3117 m, the 0.2586-m tilt between 2H (MWD) and 22 Q could have resulted only through something slightly less than 0.5703 m of tectonic subsidence at 22 Q, an extremely unlikely possibility in this otherwise tectonically quiescent area. Hence, we are again driven to the conclusion that the post-1931 uplift of 2H (MWD) must have at least equalled and probably exceeded 0.3565 m.

Although the data developed from repeated surveys along the Cottonwood Pass-Parker Dam line confirm the occurrence of continuing crustal deformation in the eastern Mojave Desert, the magnitude and chronology of this deformation remain ambiguously defined. That is, while major tilting during the full interval 1931–76 is clearly documented along this line (pl. 14), owing chiefly to reversals in the vertical-movement pattern associated with deformation persisting into the period 1974–76, a clear determination of the uplift developed between 1961 and 1974 may be unobtainable. Moreover, while virtually all of the evidence recovered to date strongly supports uplift of 2H (MWD) during the interval 1931–74 of at least 0.31–0.36 m, we have no direct evidence that constrains the uplift of this mark within this period. Thus, we can only infer from the histories of vertical movement along the Mojave-Cottonwood Pass line (see section on "The Mojave-Cottonwood Pass Line") and at bench mark H 516, Mecca (fig. 50), that this uplift probably occurred largely within the period 1968–74. Similarly, although it is very likely that a down-to-the-east tilt of about 0.1 m developed between bench marks Amboy and 10 M (pl. 14) sometime during the period 1961–74, the 1974–76 collapse led to a reversal of this postulated tilt, such that a comparison of the results of the 1976 leveling against a 1931/44 datum shows a 0.03 m down-to-the-west tilt between these two marks (pl. 14).

THE LUCERNE VALLEY LINE

GENERAL REMARKS

The Lucerne Valley line (pl. 15A) is one of three considered in this report in which the height changes have been referred to a local datum, chiefly because the vertical-displacement histories along these lines are poorly controlled with respect to Tidal 8. Nevertheless, four successive heights have been established for the Lucerne Valley control point to which we have referred the height changes along this line; hence a limited set of height changes along the Lucerne Valley line can be at least roughly estimated for several periods through 1969/73. Moreover, because the vertical integrity between Lucerne Valley and Victorville has been closely preserved through the period 1935–69 (and especially through the period 1953–69), and because the height changes at Victorville are relatively well controlled, we infer that the vertical-displacement history of Lucerne Valley has closely mimicked that of Victorville. Accordingly, the chronology of the height changes along the Lucerne

Valley line is much more accurately established than would otherwise be possible.

The preuplift datum is based, in effect, on a combination of the results of 1935 leveling extending westward from Lucerne Valley and 1944 leveling extending eastward from the Lucerne Valley control point. Because our analysis of height changes along the Mojave-Cottonwood Pass line suggests little if any long-wavelength deformation through this region between 1944 and the spring of 1961, the equivalence between a 1944 datum and a hypothetical 1955 datum is reasonably presumed. Moreover, even though a similar equivalence between the results of the 1935 leveling is less certain, any resultant errors in height changes along this line would be at the several-centimeter or even millimeter level.

The vertical displacements along the entire line with respect to Tidal 8 during the period 1955–69/73 may be calculated by summing algebraically the differential movements with respect to the Lucerne Valley control point to those of the control point with respect to Tidal 8. Although this procedure permits the development of several alternative reconstructions, the bulk of the evidence indicates that nearly all of the uplift between 1955 and 1969/73 occurred largely, but less than entirely, between the spring and fall of 1961. The cumulative uplift during the full interval 1955–69/73 diminished gradually from about 0.20 m at Victorville to 0.18 m at Lucerne Valley, 0.14 m near White Water, and about 0.10 m at Twentynine Palms.

DETAILED RECONSTRUCTION

The Lucerne Valley line consists of a primary-control line between Victorville and White Water, together with a single spur between Yucca Valley and Twentynine Palms. Although the observed elevation changes are referred to a local datum, because the vertical displacements along this line can be determined with respect to bench mark V 325, Lucerne Valley (pl. 15A), and because the history of this mark with respect to Tidal 8 can be independently assessed for three selected periods since 1935 (fig. 53), several sets of height changes along the Lucerne Valley line may be calculated through 1969 and 1969/73.

The history of vertical movement at bench mark V 325 (fig. 53) is based on only four separately determined orthometric heights, two of which depend on assumptions of stability over extended periods. However, because V 325 and R 41, Victorville (fig. 54), retained their vertical integrity with respect to each other over the full interval 1935–69 (pl 15A), we are virtually certain that the vertical displacement history of V 325 has closely mimicked that of R 41; hence, the represented history of V 325 (fig. 53) probably is about as accurate as that of R 41 (fig. 54). Moreover, because the movements at these two marks have so closely matched each other, the inflection point shown at 1953 in figure 53 probably would shift 7 years to the right were a 1960 tie available between R 41 and V 325.

Because our analysis of crustal stability within the area traversed by much of the Lucerne Valley line suggests little, if any, regional deformation between 1944 and the spring of 1961 (see section on "The Mojave-Cottonwood Pass Line"), a suggestion supported by the general absence of vertical crustal movements in the Lucerne Valley area during the period 1935–53 (fig. 53), we may view any height changes based on comparisons with the results of the 1944 (or even the 1935) surveys as the approximate equivalents of those that would have been produced had this earlier leveling been carried out in the spring of 1961 (or 1955). Moreover, we may reasonably infer that the late-1961 ob-

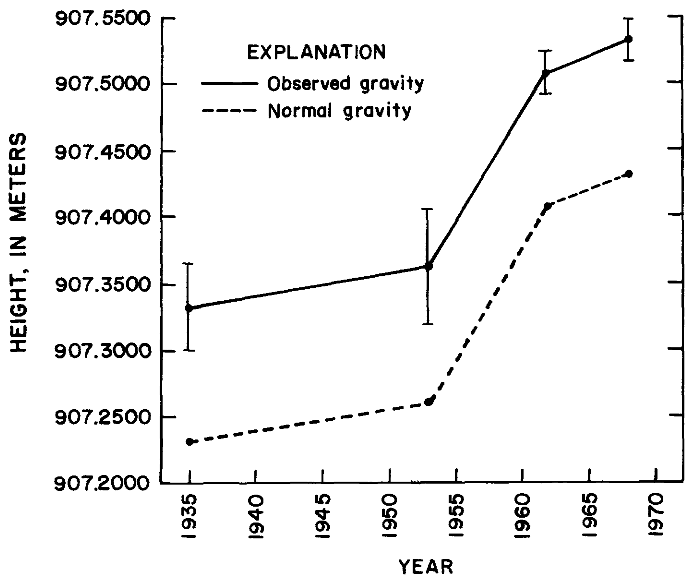


FIGURE 53.—Changes in orthometric height at bench mark V 325, Lucerne Valley. The 1935 height is based on the 1935 height of R 41, Victorville (fig. 54), and 1935 leveling between R 41 and V 325. The 1953 height is based on the 1956 height of R 41, Victorville (fig. 54), an assumption of stability at R 41 during the interval 1953–56, 1953 third-order leveling between R 41 and B 327, 1961 leveling between B 327 and V 325, and an assumption of relative stability between B 327 and V 325 during the period 1953–61 (pl. 15A). One-standard-deviation error bars show conventionally estimated random error only.

served elevations referred to bench mark V 325 lay somewhere between those measured in 1944 or 1935 (early-1961 equivalents) and those measured in 1969 (pl. 15A) —provided only that the differential movements generated between the spring and fall of 1961 did not exceed those produced between the spring of 1961 and 1969. Even though this provision cannot be demonstrated categorically, and even though the late-1961 elevations generally closely matched the 1969 elevations between Victorville and Lucerne Valley, the measured 1961 elevations consistently fell closer to the older datum than did the 1969 elevations (pl. 15A). Hence, in estimating the spring 1961-fall 1961 height changes, we may take zero differential movement between 1944 (early-1961 equivalent) and the fall of 1961 as one extreme. As an alternative extreme, we may assume that the spring 1961-fall 1961 elevation changes matched the elevation differences developed through a comparison of the results of the 1969 surveys against a 1944 datum (pl. 15A). The difference between these two postulated extremes reaches a maximum of about 0.08 m (at bench mark WWL 15), and it generally averages less than 0.06 m. Hence, simply meaning the 1944–69 differential movements between Lucerne Valley and White Water should, in theory, provide a fairly good approximation of the relative height changes generated with respect to V 325 between the spring and fall of 1961. Similarly, differential movements along the Yucca Valley-Twentynine Palms spur between the spring and fall of 1961 can be developed through meaning the differential movements deduced from a comparison of the results of the 1973 leveling against a 1944 datum (pl. 15A). The only assumption required in order to make this comparison is that the heights eastward from and including bench mark W 721 remained invariant between 1969 and the beginning of 1973. Nonetheless, because the signal generated at R 41 between the spring and fall of 1961 very nearly matches the signal generated between the beginning of 1961 and 1969 (fig. 54), and because the 1961 observed elevation differences westward from V 325 so closely match the 1969 differences (pl. 15A), the 1969 observed elevation differences may much more closely match the late 1961 differences along the entire line than do the means between the 1944 and 1969 values.

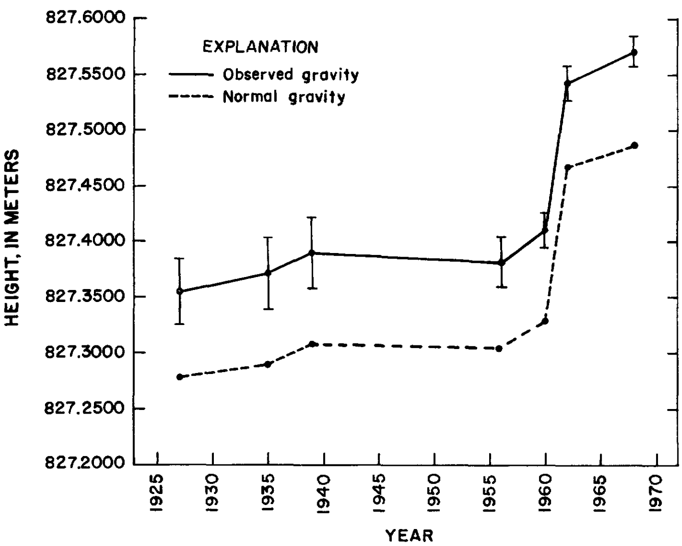


FIGURE 54.—Changes in orthometric height at bench mark R 41, Victorville. The 1927 height is based on the 1927 height of E 43, Barstow (fig. 34), 1924 leveling between E 43 and R 41 (NGS line 82464), and an assumption of relative stability between these two marks during the interval 1924–27. The 1935 height is based on the 1935 height of bench mark E 57, Palmdale, determined through 1935 leveling between bench marks E 57 and D 57 (NGS line L-3680), together with an assumption of stability at D 57 during the interval 1926–35 and 1935 second-order leveling between E 57 and R 41 (NGS line L-5334). The 1939 height is based on the 1935 elevation of E 57, an assumption of stability at E 57 during the period 1935–39, and 1939 second-order leveling between E 57 and R 41 (NGS line L-8498). The 1956 height is based on the 1955 height of bench mark E 41, Hesperia (fig. 39), and 1956 leveling between E 41 and R 41. The 1960 height is based on the 1960 elevation of E 41, Hesperia (fig. 39), 1961 leveling between E 41 and R 41, and an assumption of stability between these two marks during the interval 1960–61. One-standard-deviation error bars show conventionally estimated random error only.

Because the uplift of bench mark V 325 (with respect to Tidal 8) between the spring and fall of 1961, as well as that between 1955 and the fall of 1961, can be estimated with considerable confidence, the uplift developed at various other marks along the Lucerne Valley line during the interval spring 1961–fall 1961 can be obtained simply by summing algebraically the vertical displacement at V 325 and the differential movements measured with respect to V 325. The 1960 height of R 41, Victorville (fig. 54), is based on a tie with the spring 1961 height of D 430, Palmdale; thus, because D 430 sustained uplift of about 0.05 m between 1955 and the spring of 1961 (fig. 24), most of which may have occurred between the spring of 1960 and the following spring (see section on "The Los Angeles-Mojave Line"), the reconstructed 1960 heights of both R 41 and E 41, Hesperia (figs. 54 and 39), may be about 0.05 m too high. Accordingly, the spring 1961–fall 1961 vertical displacements at V 325 and R 41 probably are more closely approximated by their 1953–61 and 1956–61 uplifts, respectively, than they are by the represented 1960–61 uplift of

R 41 (fig. 54). Accepting this likelihood, uplift at these two marks between the spring of 1961 and the fall of 1961 apparently diminished from about 0.17 m at R 41 to approximately 0.15 m at V 325 (figs. 54 and 53). Eastward from V 325 to C 720, and disregarding the probably compaction-induced subsidence between these two marks (pls. 3 and 15A), the uplift held at about 0.15 m, whereas eastward from C 720 to bench mark Z 720 it diminished smoothly to about 0.12 m (fig. 53, pl. 15A). The spring 1961–fall 1961 uplift along the Lucerne Valley line reached its lowest value, of about 0.11 m, at bench mark WWL 15. Southward from WWL 15, it rose steadily from 0.11 m to 0.12-0.13 m at W 721 and held at roughly this value to the end of the comparison at 1800 USGS (pl. 15A).

The spring 1961–fall 1961 uplift along the Yucca Valley-Twentynine Palms spur may be derived through a procedure identical to that used along the main line. Thus, eastward from W 721 the uplift decreased sharply from 0.12–0.13 m to about 0.11 m at WWL 20 and decreased gently eastward from this mark to roughly 0.10 m at M 724, Twentynine Palms (fig. 53, pl. 15A).

The spring 1961 (1955-equivalent)–69 uplift along the Lucerne Valley line may be estimated somewhat more directly, and certainly more accurately, than that developed between the spring and fall of 1961. Specifically, the spring 1961–69 uplift was approximately 0.20 m at R 41 (fig. 54) and fell off eastwardly to about 0.18 m at V 325 (fig. 53). By means of a procedure analogous to the one described in the preceding paragraph, it can be determined that the spring 1961–69 uplift was about 0.18 m at C 720, 0.11 m at Z 720, 0.10 m at WWL 15, 0.13 m at W 721, and 0.14 m at 1800 USGS. Although the spring 1961–69 comparison ends at bench mark 1800 USGS, the uniformity of the vertical displacements between Yucca Valley and 1800 USGS (pl. 15A) implies that uplift of 0.13-0.14 m persisted an additional 6 km southward to the junction bench mark, 603-70 (see section on “The Colton-Mecca Line”). Eastward along the Yucca Valley-Twentynine Palms spur, the spring 1961–69 uplift can be estimated only if it is assumed that the elevation differences remained invariant between 1969 and the beginning of 1973, when the leveling was actually carried out (pl. 15A). While we have no direct evidence to support this assumption, we have determined that the second great deformational surge that accompanied the evolution of the southern California uplift probably propagated eastward from Boron following the winter of 1972/73 (see section on “The Mojave-Cottonwood Pass Line”). This suggests that as far east as Yucca Valley there was little post-1961 differential movement until after the beginning of 1973. Accordingly, we infer that the spring 1961–69 uplift along the Yucca Valley-Twentynine Palms spur diminished from about 0.13 m at W 721 to 0.11 m at WWL 20 and fell off gently east of WWL 20 to 0.09–0.11 m at M 724, Twentynine Palms (fig. 53, pl. 15A).

The preceding estimates of uplift along the Lucerne Valley line indicate that virtually all of the vertical displacements generated along this line over the full interval spring 1961–69 actually occurred between the spring and fall of 1961. Thus, while modest increments of uplift may have been recorded at Victorville and Lucerne Valley between the fall of 1961 and 1968 (or 1969) (figs. 54 and 53), the fall 1961–69 uplift apparently diminished eastward to very small or even negative values at Yucca Valley and Twentynine Palms.

THE COTTONWOOD PASS-FRINK LINE

GENERAL REMARKS

Height changes along the Cottonwood Pass-Frink line (pl. 15B) are referred to a local control point at Cottonwood Pass and are based on the results of only two levelings, one produced in 1974 and the second in 1976. The 1976 leveling was commissioned solely and explicitly to assess the extent of any 1974–76 differential movement over what was believed to be an exceptionally steep gradient athwart the south flank of the southern California uplift.

DETAILED RECONSTRUCTION

The Cottonwood Pass-Frink line consists of a short primary vertical-control line for which we have developed a single comparison, provisionally referred to bench mark D 723 as invariant in height (pl. 15B).

Reference of the 1974–76 vertical movements along the Cottonwood Pass-Frink line to a local datum derives chiefly from our persisting uncertainty regarding the 1974–76 vertical displacement at Mecca. Nevertheless, our best analysis of the vertical-displacement history of H 516 (which can be considered as having been fixed with respect to G 516 during the period 1974–76) indicates that between 1974 and 1976 H 516 dropped 0.1617 m or, much more likely, 0.2887 m (see section on “The Colton-Mecca Line”). Accordingly, the apparent 1974–76 0.0240-m uplift of G 516 with respect to D 723 (pl. 15B) may equate with as much as 0.29 m of tectonic subsidence with respect to Tidal 8. Hence, the absence of major 1974–76 differential movement along this line could signal the occurrence of 0.3 m of tectonic subsidence over an area of hundreds and perhaps thousands of square kilometers centering on the northern Salton Sea. Moreover, these same data also argue that the 1974–76 cumulative subsidence over this large area could easily have exceeded the cumulative uplift generated between 1955 and 1974.

THE OCOTILLO-OGILBY LINE

GENERAL REMARKS

Height changes along the Ocotillo-Ogilby line (pl. 15C) have been reconstructed with respect to a local control point at the western end of the line. Because the described changes are based on the results of only two levelings, both of which were carried out in the early 1970's, the extent to which the results of the earlier leveling approximate a preuplift datum obviously is in doubt.

Although a fairly compelling argument suggests that the designated control point probably remained virtually invariant with respect to Tidal 8 during the interval 1971–74, the vertical-displacement history of this same mark prior to 1971 is unknown. Nevertheless, because the observed elevation differences between the Ocotillo control point and a host of marks westward from Ogilby remained virtually invariant during the period 1941–71/72, a reasonable argument can be made for the stability of the selected control point with respect to Tidal 8 since at least 1942. Moreover, the results of repeated horizontal measurements, together with differenced lake-level measurements from the Salton Sea, indicate that deformation within the Salton Trough during the interval 1941–67 had largely ceased by 1954. Accordingly, we contend that the results of the 1971/72 leveling referred to the Ocotillo control point may be treated as the approximate equivalents of a hypothetical (1955) preuplift datum referred to Tidal 8.

Although very modest height changes occurred along the line between Ocotillo and Ogilby during the period 1971/72–74, major tectonic subsidence of as much as 0.14 m accumulated northward from El Centro to Frink. Although this inferred subsidence is an expression of nothing more than relative deformation, the alternative interpretation—namely, uniform uplift across the full width of the Imperial Valley and westward into the Peninsular Ranges—seems much more unlikely.

DETAILED RECONSTRUCTION

The Ocotillo-Ogilby line consists of a primary vertical-control line between Ocotillo and Ogilby, together with a single spur extending northward from El Centro to Frink (pl. 15C). Vertical movements along this line are limited to a single comparison referred to a local datum, bench mark Y 58, Ocotillo, as invariant in height. Because the results of the 1971/72 leveling cannot be tied to Tidal 8, either directly or indirectly, through the tide stations in San Diego or La Jolla, use of a local datum is unavoidable.

Although the observed elevation changes along the Ocotillo-Ogilby line cannot be referred directly to Tidal 8, it is likely that Y 58 probably sustained very little differential movement with respect to Tidal 8 during the comparison period 1971/72–74. Thus, because the likelihood of movement at any particular bench mark is inversely proportional to the period of observation, the brevity of the interval between these two sets of measurements (pl. 15C) is in itself an indication of the probable stability of Y 58. However, the most convincing evidence of the 1971/72–74 stability of Y 58 with respect to Tidal 8 is shown by the virtual invariance of Y 58 with respect to a host of bench marks in the Ogilby area during this same interval. That is, had either Y 58 or Ogilby, which lie at opposite ends of a 135-km line athwart the Salton Trough, experienced significant differential movement with respect to Tidal 8, it is very unlikely that the other mark or group of marks would have experienced vertical displacements of almost precisely the same magnitude. Moreover, except for the very shallow downwarp developed eastward from Ocotillo to about bench mark H 60 (pl. 15C), nearly all of the marks along the main line retained their vertical integrity with respect to each other. Especially significant is the extraordinary stability that obtained within the 40-km segment that defines the eastern end of the line (pl. 15C), a stability that testifies to the tectonically undisturbed nature of this part of the Salton Trough. The only alternative to the 1971/72–74 invariance of Y 58 and the Ogilby marks with respect to Tidal 8 is uniform uplift or subsidence of these marks. Because this alternative seems much more implausible in this tectonic setting than does the absence of significant differential movement with respect to Tidal 8, we infer that the 1971/72–74 height changes along the Ocotillo-Ogilby line measured with respect to Y 58 closely approximate height changes with respect to Tidal 8 during this same interval.

Although it is indeed probable that bench mark Y 58 remained invariant with respect to Tidal 8 during the period 1971/72–74, this does not in itself contribute to an assessment of the vertical-displacement history along the Ocotillo-Ogilby line with respect to a preuplift datum. Comparisons of the results of the 1971/72 levelings along the main line against those developed from 1941 surveys (NGS lines L-9176, L-9179, and L-22603) indicate that Y 58 remained virtually unchanged with respect to a suite of bench marks extending at least 30 km westward from Ogilby and, hence, probably with respect to Tidal 8 as well during the interval 1941–71/72. The chief activity along the main line during the period 1941–71/72 consisted of differential warping of up to 0.08 m extending both east and west from the trace of the Imperial fault, together with sharply localized displacements athwart both the Imperial fault and an inferred fault about 15 km west of El Centro. Similar 1941–71/72 comparisons along the El Centro-Frink spur document about 0.07 m of uplift with respect to Y 58 within the area extending about 30 km southward from Frink, associated with localized differential displacements across or adjacent to the Imperial, Brawley, and Calipatria faults (NGS lines L-9173 and L-22606). Although there is no direct way of showing precisely when these displacements occurred within the interval 1941–71/72, indirect yet persuasive evidence indicates that nearly all had occurred by 1954. Specifically, Thatcher (1979) has shown that the Imperial Valley horizontal network was characterized by large right-lateral shear-strain rates during the period 1941–54, whereas this pattern virtually disappeared during the period 1954–67. Moreover, although studies of differenced lake-level measurements indicate that the southwestern edge of the Salton Sea sustained significant 1967–71 down-to-the-south tilting with respect to a control point about 12 km south of Mecca, the vertical displacements that accompanied this tilting probably were very small—perhaps 0.03–0.04 m of tectonic subsidence with respect to the selected control point (Wilson and Wood, 1980, p. 183–184). Because it is very unlikely that the area traversed by the Ocotillo-Ogilby line experienced significant deformation during the interval 1954–67, and because such displacements as may have occurred during the period 1967–71/72 were almost certainly small, it is likely that the 1971/72 datum closely approximates one that would have been obtained had the leveling been propagated southeastward from Tidal 8 in 1955—an interpretation that minimizes any 1955–74 tectonic subsidence along this line.

Height changes along the Ocotillo-Ogilby line consist of almost inconsequential subsidence extending eastward from Ocotillo to beyond Holtville, coupled with conspicuous tectonic subsidence increasing northward from about 0.02 m at El Centro to nearly 0.14 m at Frink (pl. 15C). While interpretation of the subsidence centering on Frink as downwarping with respect to Tidal 8 remains conjectural, the complete absence of such downwarping would compel a virtually uniform 0.14-m uplift over the full expanse of the southern Imperial Valley, an interpretation that seems especially unlikely. If the depicted tectonic subsidence between El Centro and Frink (pl. 15C) is, in fact, a valid representation of the 1971/72–74 vertical displacement field with respect to Tidal 8, we are once again confronted with evidence of tectonic downwarping developed along the leading edge of the eastwardly and southeastwardly propagating uplift. Moreover, the probable existence of this downwarping (with respect to Tidal 8) also implies a 0.5-m 1968–74 (or, more likely, a 1972/73–74) down-to-the-south tilt between Cottonwood Pass and Frink.

SELECTED STAGES IN THE EVOLUTION OF THE SOUTHERN CALIFORNIA UPLIFT

The objectively developed vertical-displacement histories described in the preceding sections provide a basis for an interpretive characterization of the changing configuration of the southern California uplift during the inclusive period 1955–1976. This characterization is shown here as a series of maps of the vertical-displacement field through a sequence of unequal time frames. Each time frame is a function of both the distribution of the data (in both space and time) and the occurrence of several distinct episodes of sharply accelerating vertical movement. Even though it is impossible to show how the configuration of the uplift was changing over its full extent during each of the indicated periods, it is possible to show how at least parts of the uplift were changing during these periods. Hence most of the successively developed representations shown here are limited in the area of their coverage.

The depiction of the uplift at various stages in its development obviously is in part the product of inference. While we are confident of the general accuracy of this characterization, it is certain that it errs in detail. Specifically, owing to the wide variation in the distribution of the usable data, the displacement history must be extrapolated in both space and (in a certain sense) time. Moreover, we have arbitrarily removed any signals conceivably attributable to changes in the underground fluid regime (see pls. 3 and 4), and we have smoothed or discarded both coseismic displacements (such as those associated with the 1971 San Fernando earthquake) and short-wavelength features (of whatever origin) of less than a few kilometers.

THE 1955–59.0 EPOCH

There is no compelling evidence of any major aseismic height changes within or adjacent to the uplift that must have occurred during the period 1955–59. Nonetheless, it is not unlikely that the 1956–61 uplift centering on Colton (see sections on "The Orange-Barstow Line" and "The Colton-Mecca Line" and fig. 36) occurred entirely within this interval. And because the 1956–61 uplift is, in any case, apparently localized in space, we show it here (fig. 55) as: (1) the only significant tectonic signal developed during the period 1955–59.0 and (2) as having evolved entirely within this period. The measured control on the areal extent of the 1955–59.0 vertical displacement field is limited to the line between Colton and Barstow. Hence its inferred extent in all other directions is based on the assumption that it is indeed a locally developed feature.

THE 1959.0–60.5 EPOCH

Clearly recognized deformation within the area of the southern California uplift during the period 1959.0–60.5 is limited to the western Transverse Ranges (see sections on "The Ventura-Avila Beach Line" and "The Ventura-Maricopa Line"). Moreover, while the occurrence of a major pulse of uplift (marking the inception of the southern California uplift) has been unambiguously established for this interval, its distribution and magnitude beyond the area of Ozena, together with the peripheral collapse that apparently accompanied this initial pulse, is poorly defined. Accordingly, our characterization of the 1959.0–60.5 vertical-displacement field (fig. 56) is highly smoothed—perhaps unrealistically so.

The most conjectural feature associated with the 1959.0–60.5 representation (fig. 56) is the magnitude of the tectonic subsidence that occurred at Surf. Assuming that the reported displacement at Surf between 1956 and 1960 occurred entirely during the period 1959.0–60.5, an assumption clearly consistent with the chronology of the uplift (see section on "The Ventura-Maricopa Line"), Surf may have sustained subsidence of roughly 0.25 m during this brief period (pl. 6B). However, the validity of this value depends directly on the validity of the 1956 reconstructed elevation for the Avila Beach Tide station, which depends in turn on the accuracy of the 1970/71 observed elevation difference between Pismo Beach and San Pedro (see section on "The Ventura-Avila Beach Line"). Accordingly, because the 1970/71 leveling produced a large down-to-the-south sea slope reported by Balaz and Douglas (1979, p. 6199), and because examination of the field abstracts indicates that the 1970/71 leveling (NGS line L-22292) was marked by several significant interruptions within a tectonically active area (notably at Point Conception), there is an excellent chance that the 1970/71 observed elevation difference between Pismo Beach and San Pedro was aliased by intrasurvey movement (Castle and Elliott, 1982). Nonetheless, major tectonic subsidence at Surf during the period 1956–60 is independently implied by the probable 0.16–0.17-m misclosure of 1960 leveling on 1956 leveling into Surf (see section on "The Ventura-Avila Beach Line"), a value that we take to be a reasonable estimate of the probable tectonic subsidence of this junction during the period 1959.0–60.5.

The eastward divergence of the −0.05-m and −0.10-m contours south of Lebec (fig. 56) is inferred from the probably localized nature of the tectonic subsidence. Directly supportive of the sharp turn to the north of the −0.10-m contour southeast of Lebec is the localization of the large misclosure involving early 1960 leveling around the subcircuit Sandberg-Fairmont-Castaic-Sandberg (fig. 15). The alternative interpretation—namely, that these negative contours curve westward toward and south of Ventura—is even less plausible, for it conflicts with the observation that the northern Oxnard Plain remained substantially free of tectonic subsidence during the period 1939–60 (Buchanan-Banks and others, 1975).

THE 1959.0–61.4 EPOCH

By 1961.4 the southern California uplift had expanded eastward to and beyond Palmdale (fig. 57). The postulated eastward extension of the +0.05-m contour as far as Hesperia extends both the measurement system and the reconstruction to their respective limits. However, the probability that the reported signals at both Hesperia and Victorville (figs. 39 and 54) err in a positive sense is no more

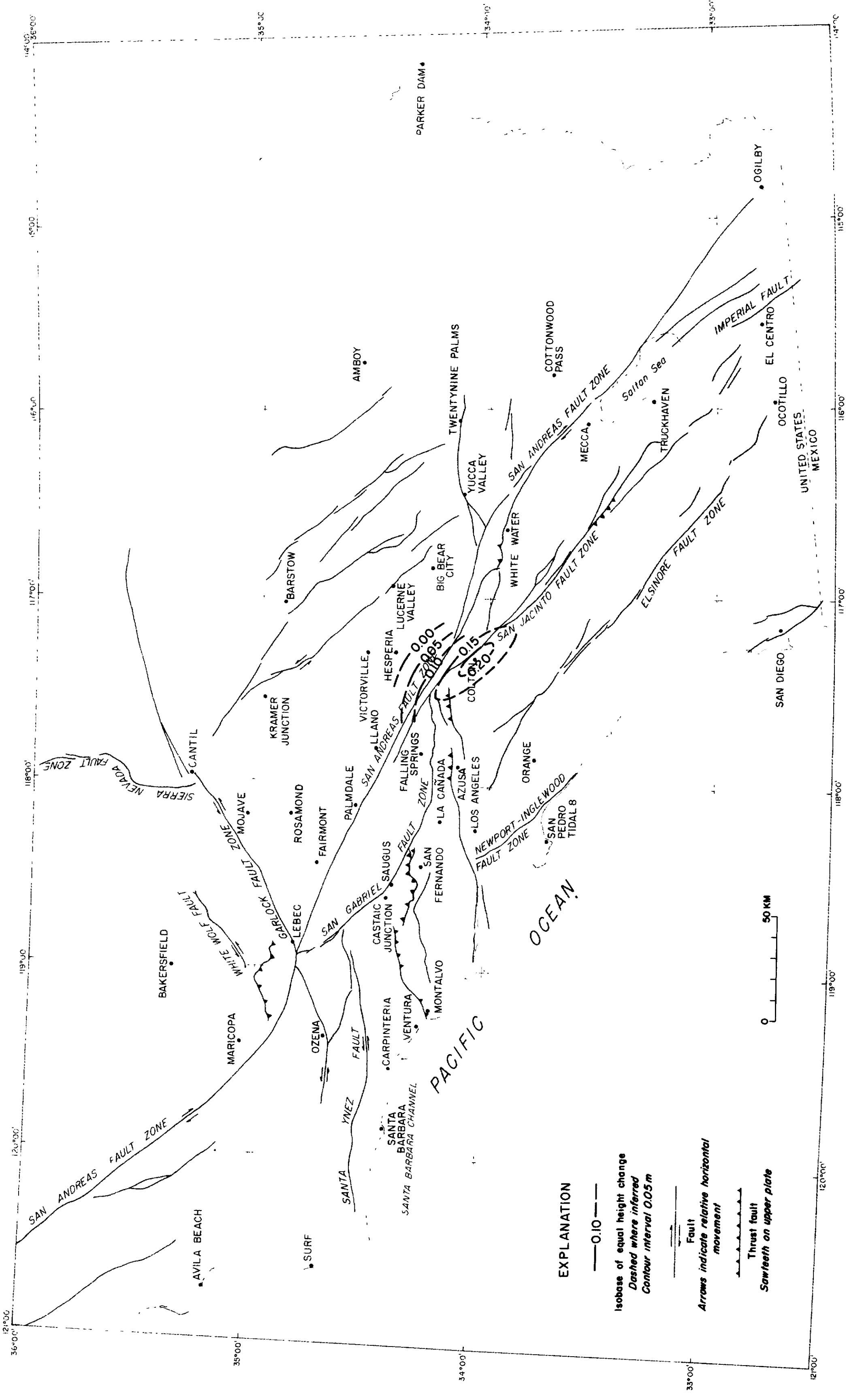


FIGURE 55.—Height changes with respect to bench mark Tidal 8 within the area of the southern California uplift, 1955–59.0. See text for details.

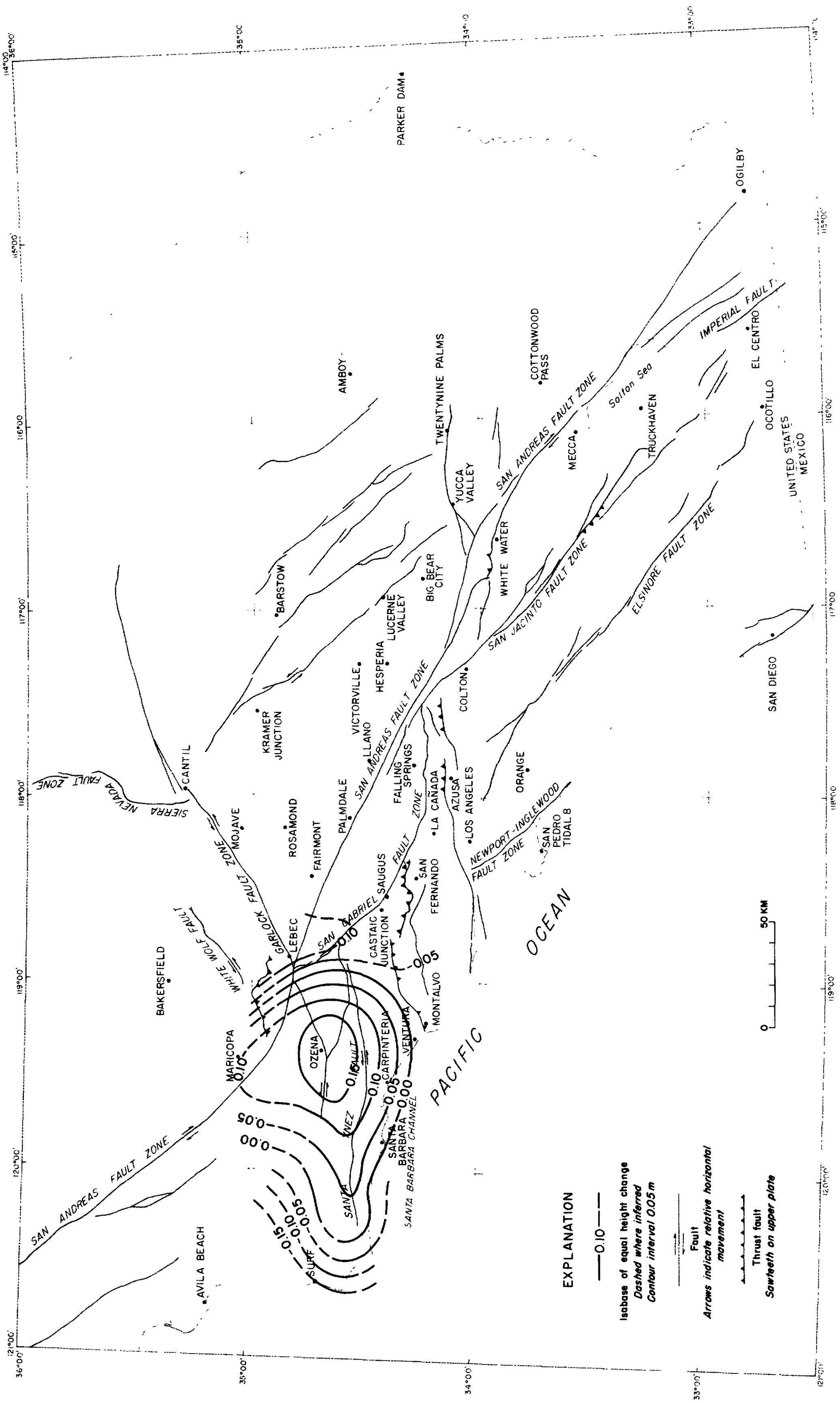


FIGURE 56.—Height changes with respect to bench mark Tidal 8 within the area of the southern California uplift, 1959.0–60.5. See text for details.

likely than the reverse; hence the ridgelike form of the uplift between Palmdale and Hesperia (fig. 57) probably is real.

While the magnitude of the 1959.0–61.4 uplift in the area north of Los Angeles is clearly implied by the pattern of height changes developed along the main line between Los Angeles and Mojave during the period 1955–61.4 (pl. 8A), we cannot be certain that this eastward extension had not occurred as early as 1960.5, or even before. We infer, however, that the 1955–61.4 eastward propagation of the uplift probably accompanied the recovery of the tectonic subsidence centering on Lebec (fig. 56), which apparently occurred no later than the fall of 1961 and certainly subsequent to 1960.5 (see sections on "The Ventura-Maricopa Line" and "The Los Angeles-Mojave Line"). Nevertheless, our characterization of the cumulative vertical displacements developed in the Lebec area through 1961.5 (fig. 57) is a compromise representation. The chronology of the 1961 surveys into this area (see section on "The Los Angeles-Mojave Line") is such that the recovery of the subsidence at Lebec may have occurred entirely after the middle of 1961, in which case the 1959–61.4 contours in the general area of Lebec should approximate those shown in figure 56. Alternatively, the uplift that occurred by 1961.4 may have matched that which must have occurred no later than 1962.0, in which case the contours in the Lebec area (fig. 57) should be displaced northeastward several tens of kilometers. Because we see no objective basis for choosing between these two alternatives, we have effectively split the difference. Our prejudices are such, however, that we clearly favor the second alternative over the first.

The cumulative 1959.0–61.4 vertical-displacement field within the area extending westward from Ozena to Surf (fig. 57) probably changed very little from that which had developed through 1960.5. Because the tectonic subsidence at Lebec is believed to have recovered completely by the fall of 1961, it is assumed that modest uplift during the period 1960.5-61.5 probably took place west of Ozena as well. The maximum value for this uplift is taken to be that which had occurred at Surf by 1970. Because Surf probably subsided about 0.16–0.17 m during the period 1959–60.5 (see above), and because the cumulative subsidence at Surf during the period 1956–70 is given as 0.08 m (pl. 6B), we infer that about half the recovery between 1960.5 and 1970, or roughly 0.05 m, had occurred by the middle of 1961.

THE 1959.0–62.0 EPOCH

The first of the two major episodes of aseismic uplift identified with the evolution of the southern California uplift occurred between the middle and end of 1961. Because the geodetic measurements developed over the area of the uplift during this short interval obviously are very limited, the vertical displacements that occurred during the full period 1959.0–62.0 (fig. 58) have been inferred largely from measurements that both preceded and followed the period 1961.4–62.0.

Controls on the magnitude and distribution of this massive pulse of uplift derive chiefly from the results of repeated levelings through the central part of the uplift (see sections on "The Los Angeles-Mojave Line," "The Los Angeles-San Bernardino Line," "The Orange-Barstow Line," and "The Lucerne Valley Line"). Thus we can only assume that the shape of the uplift west of Lebec changed very little, if at all, between 1961.4 and 1962.0 (compare figs. 57 and 58). Because the 1959/60 surveys along the Ventura-Maricopa line were not repeated until 1968 (pl. 7), we cannot be certain that any post-1960 displacements along this line occurred before 1968, although it is very likely that at least a part of the 1960–68 uplift had occurred by 1965 (see below). Nonetheless, because Lebec apparently sustained more than 0.1 m of uplift during the period 1961.4–62.0 (or more than 0.2 m during the period 1960.5–62.0), even if no additional uplift had occurred along the Ventura-Maricopa line, it is likely that the contours northwest of Ozena had begun to migrate northwestward by 1962.0—or, alternatively, that they had done so during the preceding epoch.

The 1962.0 configuration of the uplift along both its northern flank and its eastward projection remains somewhat conjectural. A comparison of the 1961 height of Barstow against its 1956 height suggests that Barstow rose about 0.13 m by the fall of 1961, whereas a similar comparison indicates that Barstow rose about 0.15 m between the spring and fall of 1961 (fig. 34). Although these values are nearly identical, the additional constraints placed on the 1962.0 configuration by height changes recorded at Victorville and Lucerne Valley (see section on "The Lucerne Valley Line") suggest that the smaller figure may be the more accurate. This smaller value is also supported by the 0.1382-m misclosure around the 1961 circuit Los Angeles-Saugus-Palmdale-Mojave-Barstow-Colton-Los Angeles (fig. 25) developed from the application of a machine-integrated orthometric correction based on observed gravity. The 1961.4–62.0 uplift of Mo-

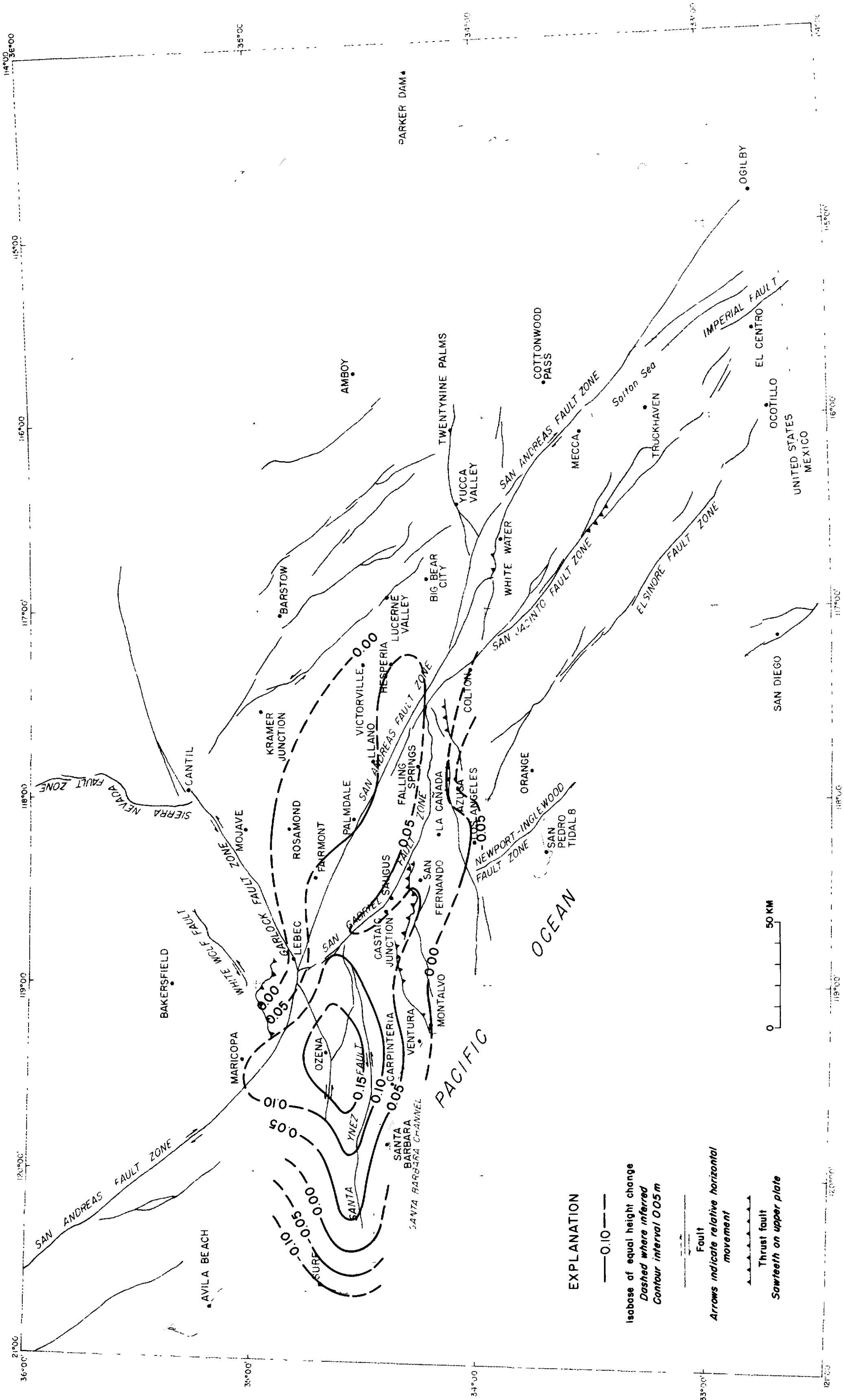


FIGURE 57.—Height changes with respect to bench mark Tidal 8 within the area of the southern California uplift, 1959.0–61.4. See text for details.

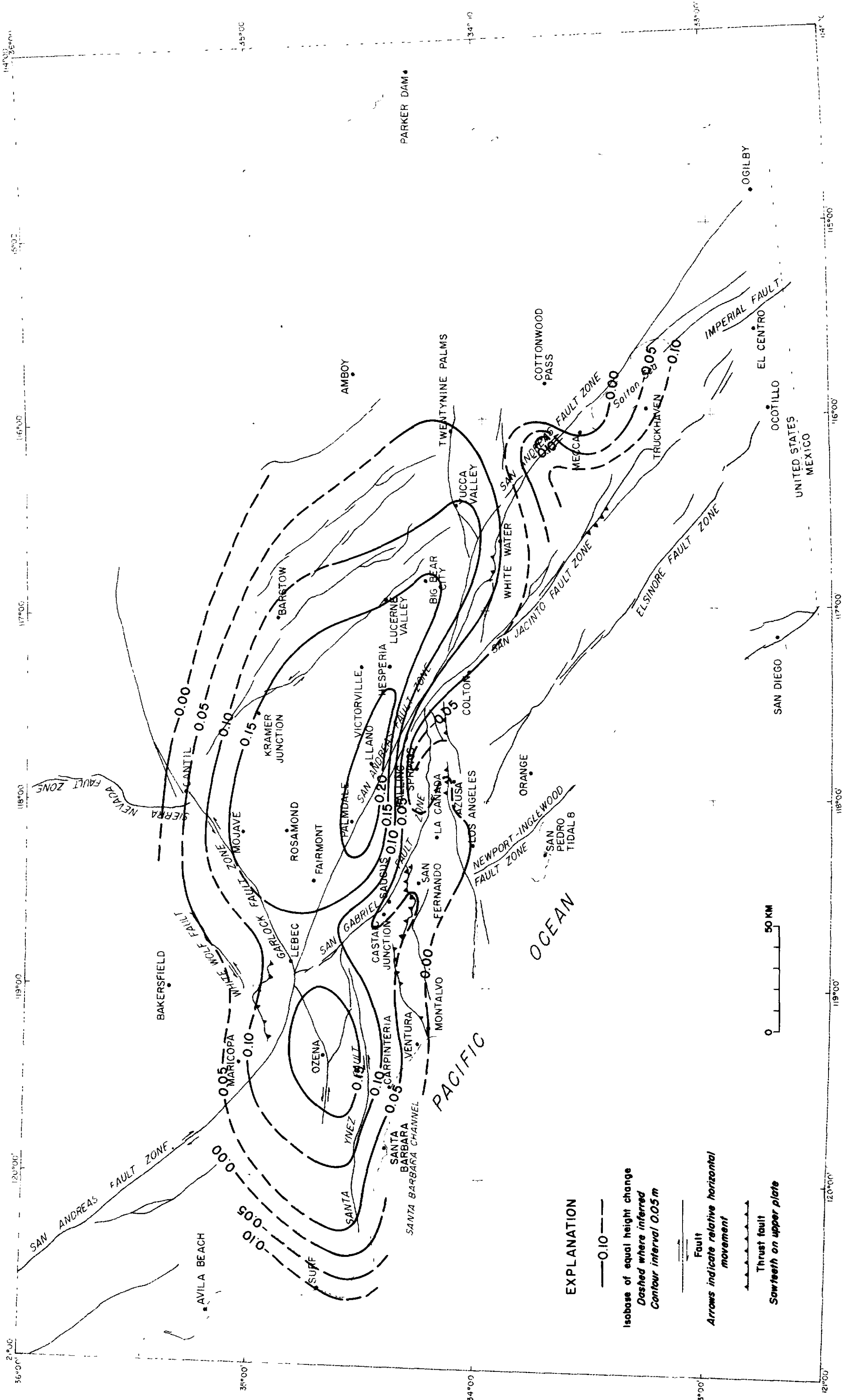


FIGURE 58.—Height changes with respect to bench mark Tidal 8 within the area of the southern California uplift, 1959.0–62.0. See text for details.

jave can be estimated in two ways. If it is assumed that the measured uplift of Mojave during the interval 1955–65.5 (or 1961.4–65.5) matched that which had occurred by 1962.0, Mojave probably sustained roughly 0.19 m of uplift during the period 1959–62.0. Alternatively, if it is assumed that the marks in the Cantil area remained invariant in height between 1959.0 and 1962.0, the 1959.0–62.0 uplift at Mojave probably was about 0.15 m (see section on "The Los Angeles-Mojave Line"). While neither of these assumptions is supported directly, because they are independent of each other and because the elevation difference between Palmdale and Mojave remained nearly invariant during the precollapse phase of the uplift, both estimates probably constitute farily good approximations of the 1959.0–62.0 uplift at Mojave. The estimated 1959.0–62.0 uplift extending eastward from Lucerne Valley is based on the assumption that the 1959.0–62.0 down-to-the-east tilt with respect to bench mark V 325 was about the same as the tilt that developed during the interval 1944–69/73 (see section on "The Lucerne Valley Line"). While the assumption of a lesser tilt is seemingly more conservative (see section on "The Lucerne Valley Line"), its acceptance implies that the +0.10-m and +0.05-m contours extended even farther eastward—certainly a possibility, but one for which we have no direct evidence whatsoever. Alternatively, the 1959.0–62.0 tilt may have been even greater than that shown on plate 15A. The acceptance of this assumption, however, would force us to box in the contours toward the west, producing a pattern of uplift characterized by an especially unrealistic cast. Similarly, the represented uplift south of Lucerne Valley is based on the assumption that the 1956–59.0 recovery centering on Colton (see above) could have extended no farther northeastward than Big Bear City.

The 1959.0–62.0 vertical-displacement field along the south flank of the uplift north of Azusa (fig. 58) represents a conservative interpretation of the data (see section on "The Los Angeles-San Bernardino Line"). Both the reentrant and the very steep gradient to the north are implied (if not compelled) by the uplift of Llano and the apparent down-to-the-north tilt developed between Azusa and Falling Springs sometime between 1934 and the fall of 1961. However, because we have no direct control between Falling Springs and Llano, the gradient could have been even steeper than the one shown here (fig. 58).

The most conjectural element of the representation shown in figure 58 is the tectonic subsidence in the northern Salton Trough. Although the evidence strongly supports the occurrence of subsidence of this form and magnitude sometime during the interval 1956–68 (see section on "The Colton-Mecca Line"), the precise timing remains in doubt. However, because the large positive pulses generally seem to have been accompanied by downwarping along the flanks of the uplift, there is every likelihood that this subsidence was associated with the uplift that propagated eastward during the interval 1961.4–62.0. This interpretation is loosely supported, moreover, by the results of differenced lake-level measurements, which suggest that the western edge of the Salton Sea sustained a down-to-the-southeast tilt episode that began no later than about 1961 (Wilson and Wood, 1980, p. 183–184).

THE 1959.0–65.5 EPOCH

Although the areal extent of the height changes that are known to have occurred after 1962.0 but well before 1965.5 was insignificant, those changes that had occurred by 1965.5 (see sections on "The Los Angeles-Mojave Line" and "The Quail Lake-Hesperia Line") substantially modified the configuration of the uplift over the one that prevailed at the end of 1961 (compare figs. 58 and 59). Again, however, even though large changes are known to have occurred over much of the uplift, our interpretation of height changes over the full area of the uplift is largely inferred.

Increased uplift in the westernmost Transverse Ranges proceeds from the assumption that changes along the Ventura-Maricopa line roughly matched those that occurred along the Saugus-Grapevine spur (see section on "The Los Angeles-Mojave Line" and "The Ventura-Maricopa Line"). Thus we have provisionally assigned about one-half of the 1960–68 uplift along the Ventura-Maricopa line to the period 1962.0–65.5. Moreover, because very little uplift occurred between 1962.0 and 1964 (see section on "The Los Angeles-Mojave Line"), we infer that nearly all of the 1962.0–65.5 uplift occurred after the middle of 1964.

Eastward from Palmdale, the 1965.5 configuration is based on the results of repeated surveys over the Quail Lake-Hesperia line and the Azusa-Llano spur. Because the 1960 leveling along the Quail Lake-Hesperia line corresponded much more closely in time to the 1961 leveling than to the next preceding leveling into Palmdale, the 1960 observed elevations were tied to the 1961 observed elevation of bench mark D 430 (see section on "The Quail Lake-Hesperia Line"). However, because the

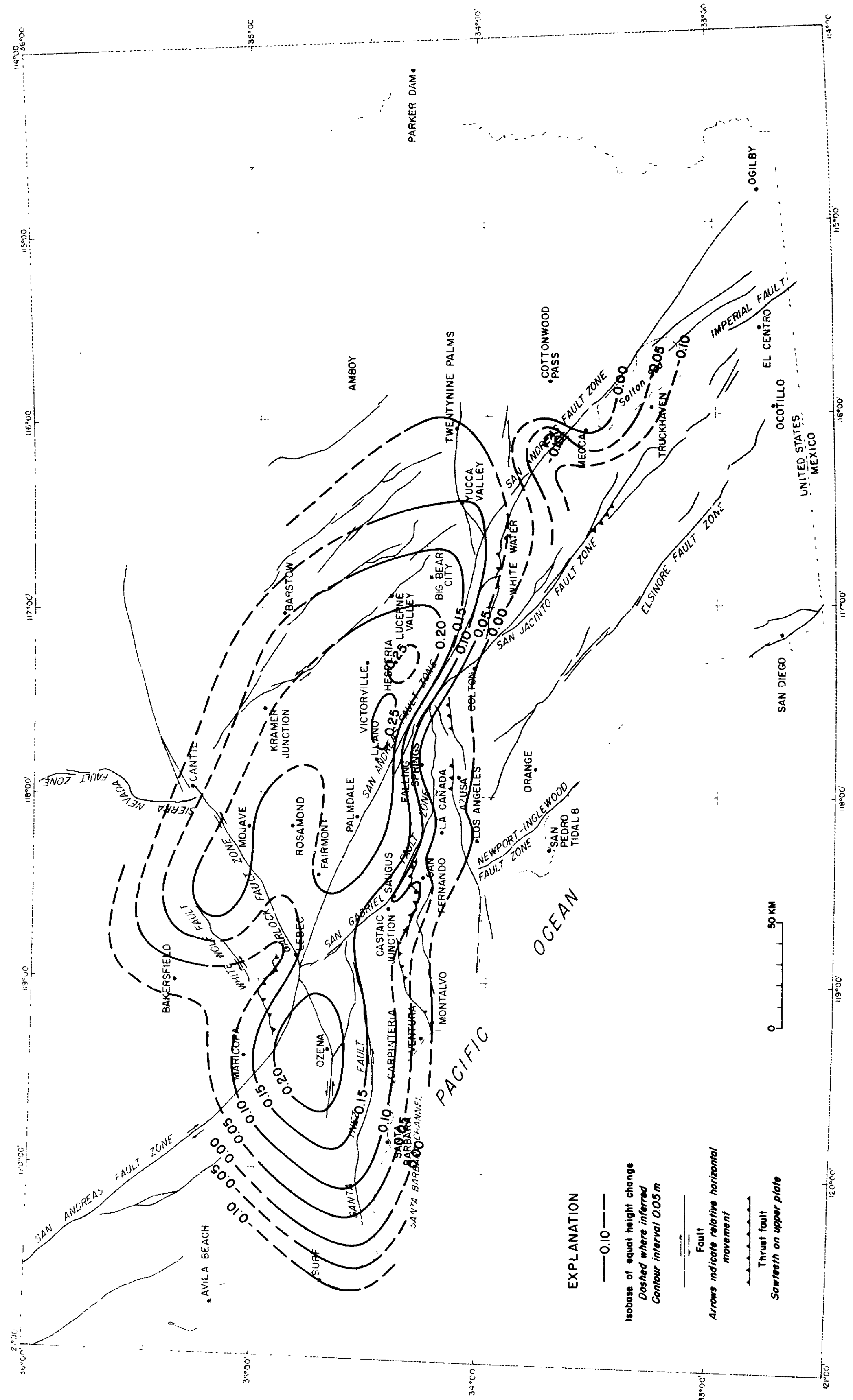


FIGURE 59.—Height changes with respect to bench mark Tidal 8 within the area of the southern California uplift, 1959.0–65.5. See text for details.

uplift almost certainly had not extended eastward beyond Lebec by 1960.5 (see section on "The 1959–60.5 Epoch"), the 1960 height of D 430 probably closely matched its 1955 height, a consideration that would put it about 0.05 m below the figure actually used (pl. 8A). Hence we have arbitrarily added 0.05 m to all of the vertical displacements along the Quail Lake-Hesperia line referred to the 1960 datum (pl. 11).

The inferred disappearance of the reentrant north of Azusa stems from the assumption that the height changes which had certainly occurred by 1971 actually occurred as early as 1965.5. Although there is no direct support for this interpretation, because the contours to the west were displaced southward during the interval 1964–65.5, we have assumed that the change in the configuration of the uplift along the south flank of the San Gabriel Mountains coincided with this increased bulging.

THE 1959.0–69.0 EPOCH

Changes in the configuration of the uplift between 1965.5 and 1969.0 are based on the results of the so-called "1968" leveling. In fact, however, parts of the "1968" leveling were completed in 1969 and one small section (between Yucca Valley and Twentynine Palms) tied to the 1968 results was not surveyed until the beginning of 1973 (see section on "The Lucerne Valley Line"). Nonetheless, the "1968" network closures were generally good, and it is doubtful that the local inclusion of post-1968 results has substantially altered the reconstruction of the height changes that occurred within the area of the uplift during the period 1959.0–69.0 (fig. 60).

The 1969.0 configuration of the uplift in the western Transverse Ranges (fig. 60) is based on the results of both 1968 leveling along the Ventura-Maricopa line and 1970 leveling extending westward from Ventura (see sections on "The Ventura-Avila Beach Line" and "The Ventura-Maricopa Line"). Whether the uplift that had occurred west of Ventura by 1970 in fact occurred by the end of 1968 remains moot. The 1970 leveling is, in any case, the latest precollapse survey along this line, and we have simply assumed that the results of this survey closely matched those that would have been produced had this work been carried out a year or so earlier. Accordingly, we infer that the configuration of the uplift west of Ventura shown here (fig. 60) prevailed through at least the initiation of the collapse—which could have begun locally by the middle of 1974.

In addition to changes along the Ventura-Avila Beach line and the Ventura-Maricopa line, the chief changes in the form of the uplift during the interval 1965.5–69.0 occurred in the western Mojave. Specifically, the virtual disappearance of the large, rather muted, eastward-projecting reentrant (figs. 59 and 60) and the appearance of a small tectonic depression southeast of Lebec (fig. 60) are deduced directly from the results of the 1968 leveling (see section on "The Los Angeles-Mojave Line"). These modifications, moreover, were accompanied by the growth of a shallow trough projecting westward through Lucerne Valley nearly to Palmdale (fig. 59), the partial collapse of the 0.25-m ridge immediately north of the San Andreas fault (figs. 59 and 60), and the probable elevation of the Barstow area by nearly 0.1 m (see sections on "The Quail Lake-Hesperia Line" and "The Orange-Barstow Line").

THE 1959.0–70.0 EPOCH

Our knowledge of height changes that occurred between 1969.0 and 1970.0 is limited to the south-central part of the uplift and is based largely on the results of 1969 relevelings along the Quail Lake-Hesperia line and the Saugus-Vincent and Saugus-Sandberg sections of the Los Angeles-Mojave line. The 1959.0–70.0 reconstruction (fig. 61) is based on the assumption that the junction bench marks south of Palmdale (D 430 and Loft A) remained invariant with respect to Tidal 8 during the period 1969.0–70.0. However, because levelings carried out after the 1971 San Fernando earthquake show that these marks rose about 0.06 m between 1968 and 1971, the 1969 heights of these marks may have been somewhat greater than those used in the reconstruction of the 1969 heights. The effects of this postulated increase in the 1969 heights of the junction bench marks would be to: (1) diminish the indicated extent and magnitude of the tectonic subsidence between Lebec and Palmdale (fig. 61), (2) increase the indicated magnitude of the uplift between Llano and Hesperia (fig. 61), and (3) increase the indicated 1968-69 uplift centering on Saugus (see section on "The Los Angeles-Mojave Line").

The portrayal of the uplift northeast of Barstow (fig. 61) is the same as that shown in figure 60. This configuration (fig. 61), however, must be inferred, for Barstow is known to have collapsed roughly 0.1 m between 1968 and 1972 (fig. 34); hence, if this

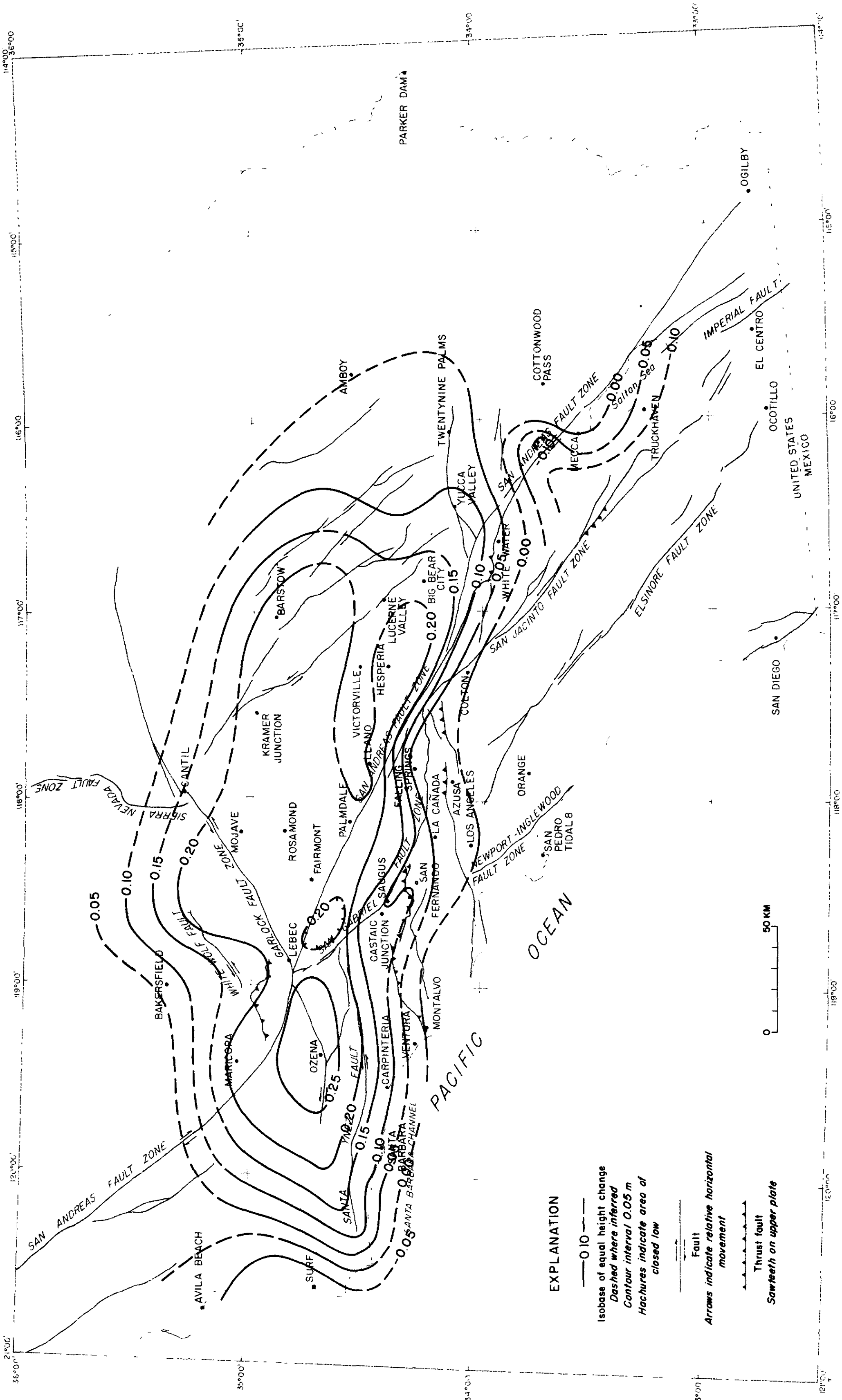


FIGURE 60.—Height changes with respect to bench mark Tidal 8 within the area of the southern California uplift, 1959.0–69.0. See text for details.

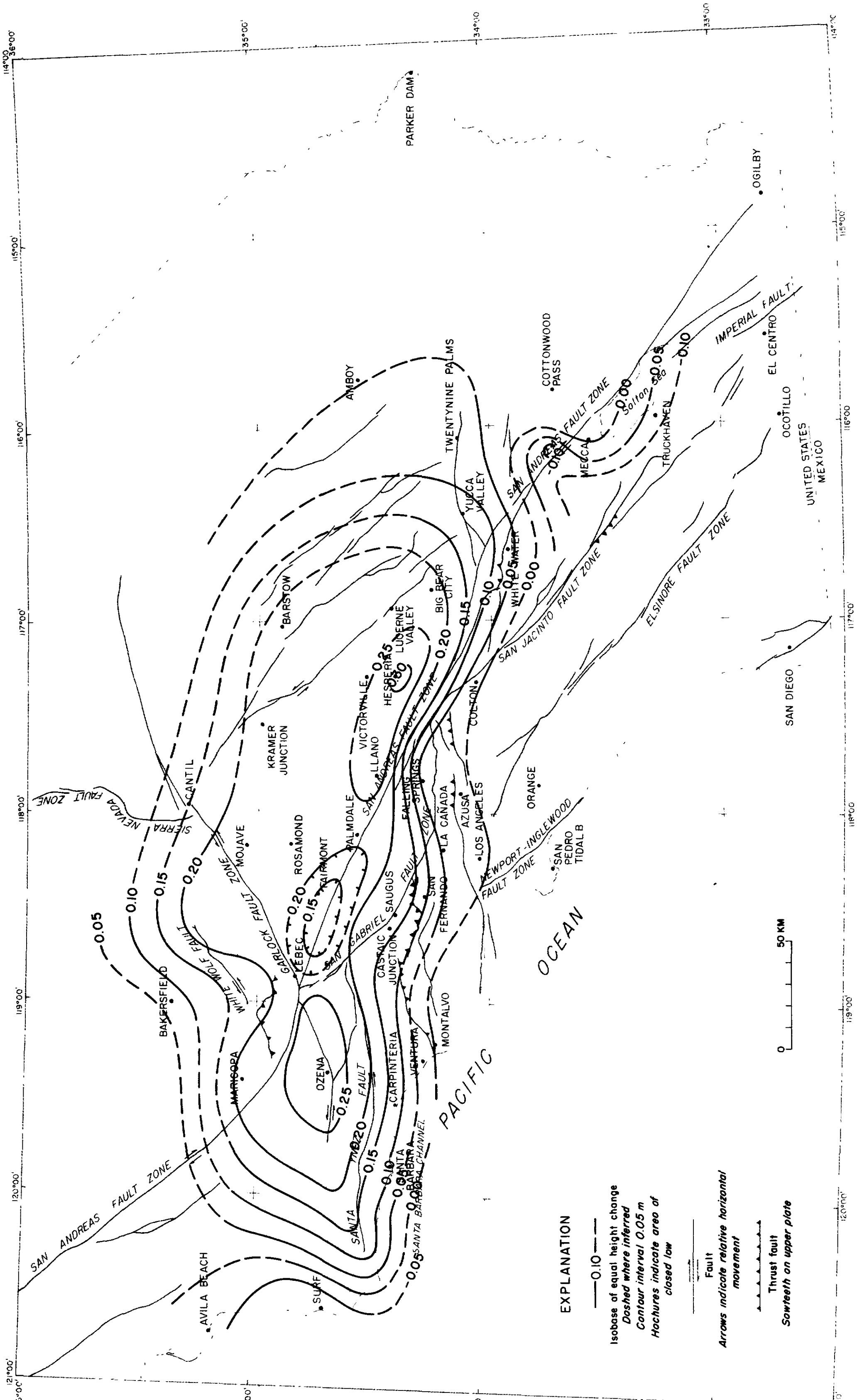


FIGURE 61.—Height changes with respect to bench mark Tidal 8 within the area of the southern California uplift, 1959.0–70.0. See text for details.

collapse occurred as early as 1970.0, the contours north and northeast of Barstow should be pulled sharply to the south.

THE 1959.0–71.5 EPOCH

The 1970.0–71.5 height changes within the area of the uplift were dominated by the vertical displacements that accompanied the 1971 San Fernando earthquake. Because our purpose here is to show the specifically aseismic changes that have occurred within the area of the southern California uplift, we have attempted to remove the specifically coseismic changes through the simple expedient of projecting the peripheral contours smoothly through the clearly defined epicentral region. This is, of course, a less than fully satisfactory procedure for, among other disadvantages, it obscures those preseismic changes that probably occurred after 1960, but in advance of the earthquake (Castle and others, 1975, p. 137–138). Hence our representation of the 1959.0–71.5 configuration of the uplift (fig. 62) differs very little—with one especially conspicuous exception—from that which obtained at the end of 1969 (fig. 61).

In addition to the clearly coseismic changes associated with the 1971 earthquake, significant 1970.0–71.5 vertical displacements also occurred along both the Los Angeles-Mojave line (including its several spurs) and the Quail Lake-Hesperia line. The changes in the configuration of the south flank of the uplift between Montalvo and Castaic Junction (compare figs. 61 and 62) are based on comparisons between the results of 1971 leveling against a 1968/69 datum (pl. 8B). However, because the 1971 surveys were propagated through the epicentral region during a period of probable postseismic adjustment, the results of these surveys may have been distorted by intrasurvey movement. In particular, the 1970.0–71.5 steepening of the south flank of the uplift and the apparent development of tectonic subsidence extending eastward through Montalvo are clearly suspect. In fact, our belief that tectonic subsidence had not occurred in the Montalvo area by the beginning of 1971 is supported by the near invariance of the 1968 and 1971 observed elevation differences extending southward from Ventura into the northern Oxnard Plain (Buchanan-Banks and others, 1975, p. 115, 119). Northward along the Los Angeles-Mojave line, the 1971.5 heights at the crest of the grade near Vincent increased by roughly 0.05 m over those that prevailed during the next preceding leveling, whereas still farther to the north, at Rosamond, the 1969.0–71.5 height changes diminished to virtually zero (pl. 8A).

Westward along the San Andreas fault from Palmdale, the broad tectonic depression that had developed between Lebec and Palmdale by 1970.0 largely disappeared by 1971.5 (compare figs. 61 and 62). This disappearance was accompanied, moreover, by the evolution of a narrow band of uplift extending westward from Palmdale to beyond Fairmont and the partial collapse of the previously developed high centering on Hesperia (compare figs. 61 and 62). Whether these neatly compensating vertical displacements represent a truly balanced redistribution of mass within the lower crustal or subcrustal layers is obviously conjectural, but the spatial and temporal relations are most suggestive.

THE 1959.0–73.0 EPOCH

The results of repeated levelings over the Quail Lake-Hesperia and the Mojave-Cottonwood Pass lines (pls. 11 and 12) indicate that a major deformational event occurred along the north flank of the uplift sometime after the 1971 San Fernando earthquake, but before the end of 1972. Because this deformation preceded the massive surge of positive movement that had propagated eastward by no later than the beginning of 1974 (see below), we have assumed that (with one exception) those displacements disclosed by the 1973/74 surveys did not occur until at least 1973.0. Accordingly, in the absence of any evidence to the contrary, we have assumed that the configuration of the uplift at the end of 1972 matched its 1971.5 configuration (fig. 62). Specifically, even though measurable and presumably significant changes occurred along the southern edge of the uplift between 1971 and 1974, it is assumed here that none of these changes occurred before the end of 1972 along or south of a boundary defined by straight-line connections between Ventura, San Fernando, Azusa, and Colton. This operational premise is explicitly violated, however, by the procedure that we have adopted in developing the 1972/73 starting elevation at Rosamond. That is, the results of the 1972/73 levelings extending north and east from Rosamond are tied to the 1973/74 elevation of bench mark 2407 USGS, which in turn is based on the 1974 elevation of the junction bench mark at Los Angeles, a mark that rose 0.04 m between 1971 and 1974 (see section on “The Los Angeles-Mojave Line”). Although we believe that the approach used in the reconstruction of the 1972/73 observed elevations along the Los Angeles-Mojave and Mojave-Cottonwood Pass

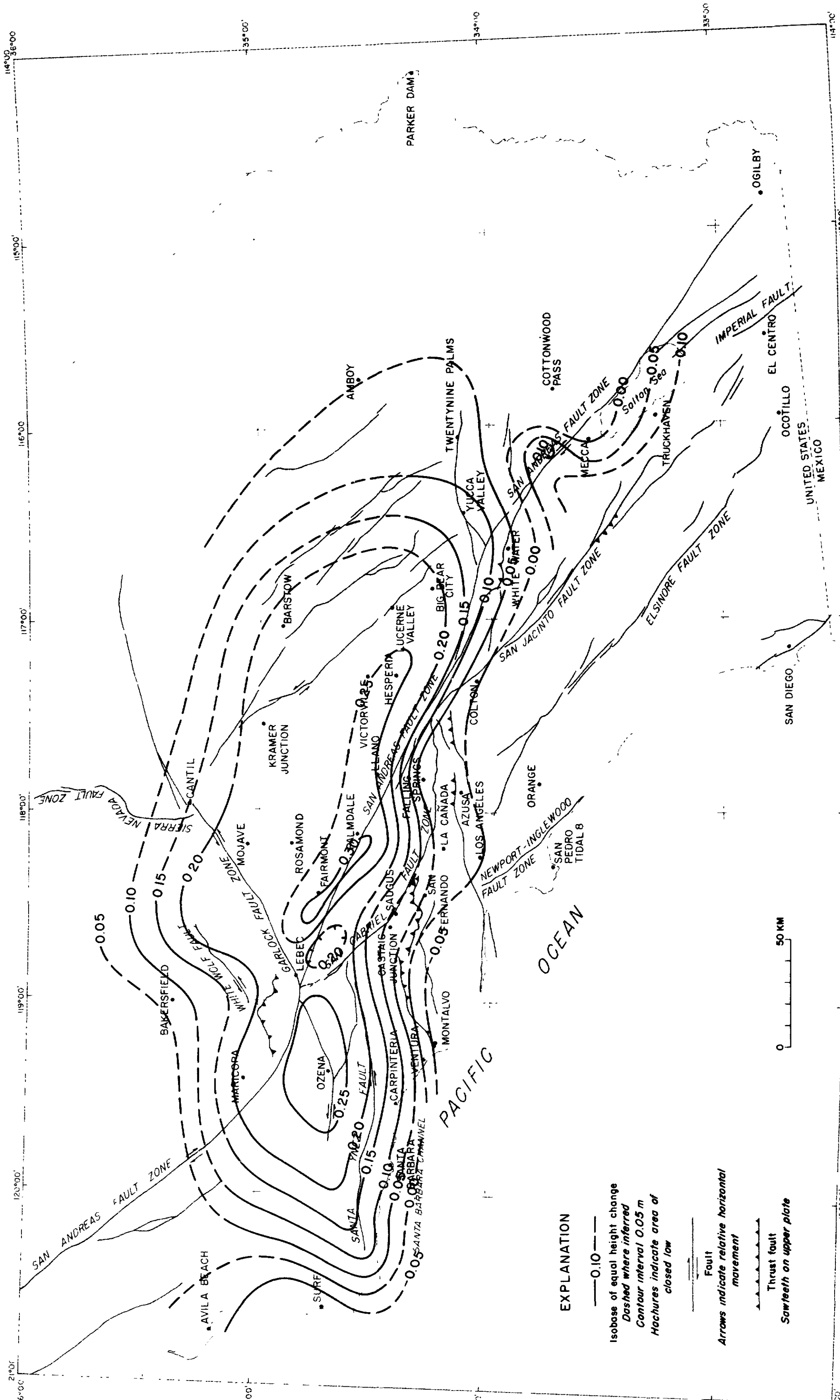


FIGURE 62.—Height changes with respect to bench mark Tidal 8 within the area of the southern California uplift, 1959.0–71.5. See text for details.

lines is generally sound (see section on "The Los Angeles-Mojave Line"), there is a reasonable likelihood that the 1959.0–73.0 height changes along the north flank of the uplift (fig. 63) are in error by as much as +0.04 m. On the other hand, however, the 1971/72 observed elevations that identify the 1971.5–73.0 event along the Quail Lake-Hesperia line have been tied to the 1971 elevation of D 430 south of Palmdale. While this approach is seemingly inconsistent and certainly subject to challenge, it is less capricious than it might seem to be. Specifically, D 430 rose 0.02 m less than 2407 USGS during the period 1971–74 (pl. 8A), such that the choice of a tie at D 430 is less critical than the choice at 2407. Similarly, the acceptance of our reconstruction (fig. 63) implies 1959.0–73.0 height changes of +0.24 m and +0.32 m at D 42, Bryman, and E 41, Hesperia, respectively. Because the results of the 1971/72 leveling along the Quail Lake-Hesperia line suggest a 1959–73.0 axial high of +0.33 m about 10 km south of Victorville, the extrapolated displacement closure between Bryman and Hesperia is surprisingly good. We infer that the Rosamond-Mojave-Edwards area probably achieved its maximum precollapse height by 1973.0 (pls. 8A and 12), even where allowance is made for the possibility that the 1973.0 heights may be exaggerated by as much as +0.04 m; hence it is assumed that the 1972/74 elevation differences along the Mojave-Bakersfield spur approximate those that would have been obtained had these surveys been completed by the beginning of 1973. Similarly, even though the 1972/73 levelings northward to Cantil and eastward to Barstow and Bryman extended several months into 1973 (pls. 8A and 12), we have assumed that the results of these surveys are the same as those that would have been produced had they been completed by the end of 1972.

Constraints on the timing of the postulated 1971.5–73.0 deformation along the north flank of the uplift are best developed along the Quail Lake-Hesperia line. Comparisons of the results of the 1971/72 levelings against both early-1971 and 1969 datums (pl. 11) show that the height differences eastward from Quail Lake to at least Pearblossom and probably to about 15 km east of Llano remained virtually unchanged during the interval 1971–71/72. Between Pearblossom (or bench mark 377.30) and Hesperia, on the other hand, differential uplift of about 0.09 m occurred during the same interval. Hence there is a strong likelihood that the changing configuration along the north flank of the uplift (compare figs. 62 and 63) was well under way by the beginning of 1972.

The most striking features shown by the 1959.0–73.0 representation (fig. 63) are the increased uplift extending northward to and beyond Mojave and eastward to Kramer Junction and the probably simultaneous collapse of Barstow. Whether this collapse extended significantly east or north of Barstow is unknown, but the possibility certainly cannot be precluded. Moreover, because the 1973.0 starting elevation at Rosamond may be off by as much as +0.04 m, this subsidence could have been even greater than shown here (fig. 63).

THE 1959.0–74.5 EPOCH

The southern California uplift culminated no later than 1974.5, and it was apparently during the period 1973.0–74.5 that the uplift sustained its second major episode of spasmodic growth. Although the uplift clearly peaked during the interval 1973.0–74.5, it is unlikely that maximum uplift of the eastern and western halves coincided or even overlapped in time. Moreover, because the timing of the change in configuration of the uplift within the period 1973.0–74.5 is equivocal, we have prepared two interpretations of the 1959.0–74.5 configuration (fig. 64). Both interpretations are based on the acceptance of: (1) the virtually certain pre-1974.5 partial collapse along the south flank of the uplift in the western Transverse Ranges and (2) an assumed invariance between 1968 (or 1970) and 1974.5 of the heights in the area north and west of Ozena and Carpinteria, respectively. These interpretations differ in that the first (fig. 64*A*) is based on the assumption that the south-central sections of the uplift remained at their maximum precollapse heights through at least the beginning of 1974, whereas the second (fig. 64*B*) presupposes that the southern edge of the most elevated part of the uplift subsided 0.05 m below its 1973.0 maximum prior to the development of the 1973/74 tie between the junction marks at Palmdale and Rosamond (see section on "The Los Angeles-Mojave Line"). Even though we believe that the second is the more technically defensible interpretation, we see no objective basis for choosing between these two alternatives. On the other hand, even though endless variations on any of the interpretations presented in this series could be reasonably entertained, the two interpretations shown here (fig. 64) represent the chief viable options for the period 1959–74.5.

The most conjectural aspects of the 1959.0–74.5 reconstruction (fig. 64) involve the displacements extending west-southwestward from Twentynine

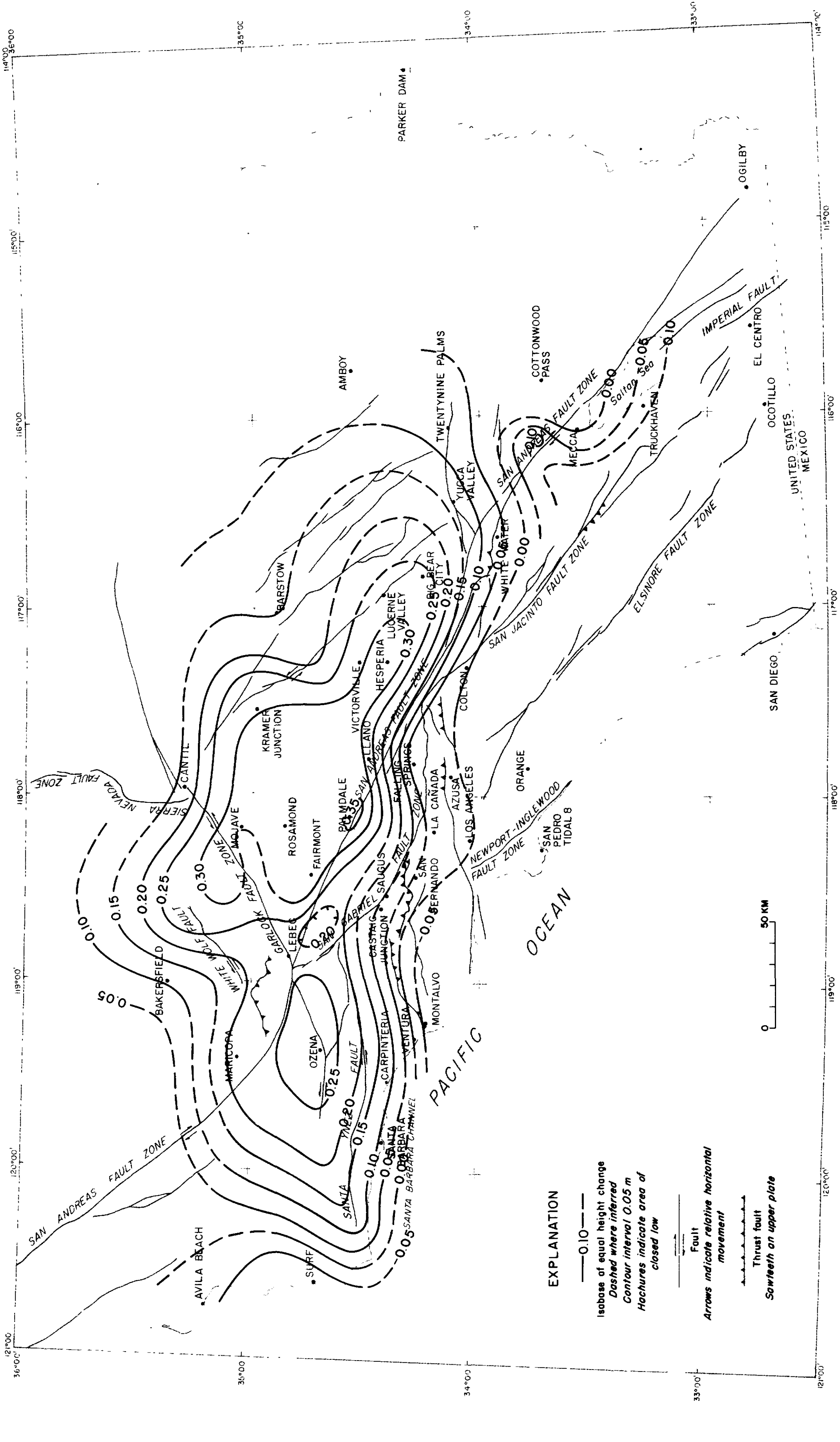


FIGURE 63.—Height changes with respect to bench mark Tidal 8 within the area of the southern California uplift, 1959.0–73.0. See text for details.

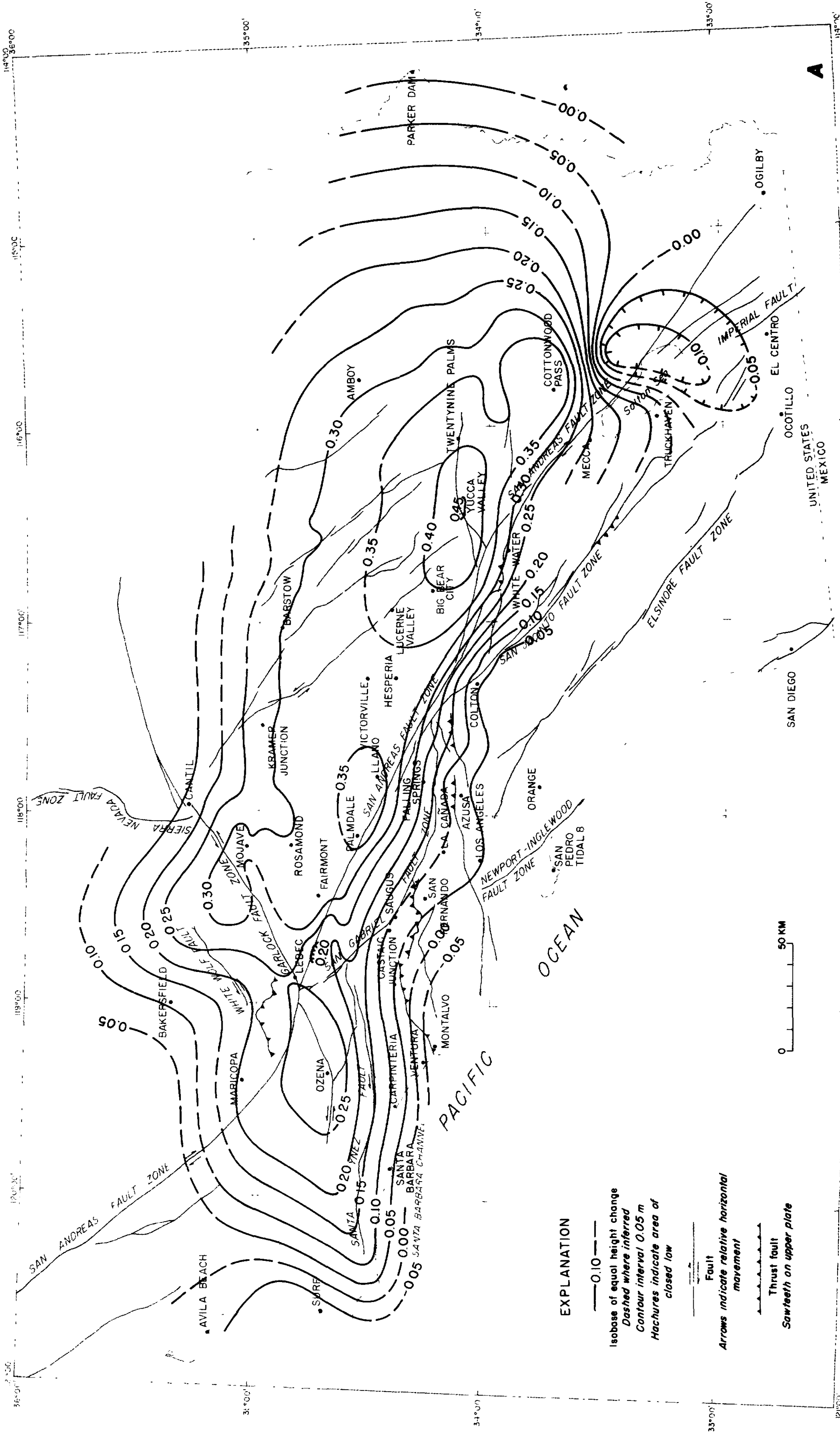


FIGURE 64.—Two interpretations of height changes with respect to bench mark Tidal 8 within the area of the southern California uplift, 1959.0–74.5. *A*, Based on an assumption of invariance at Palmdale during the period 1973.0–74.5. *B*, Based on the likelihood that Palmdale subsided 0.05 m during the period 1973.0–74.5. See text for details.

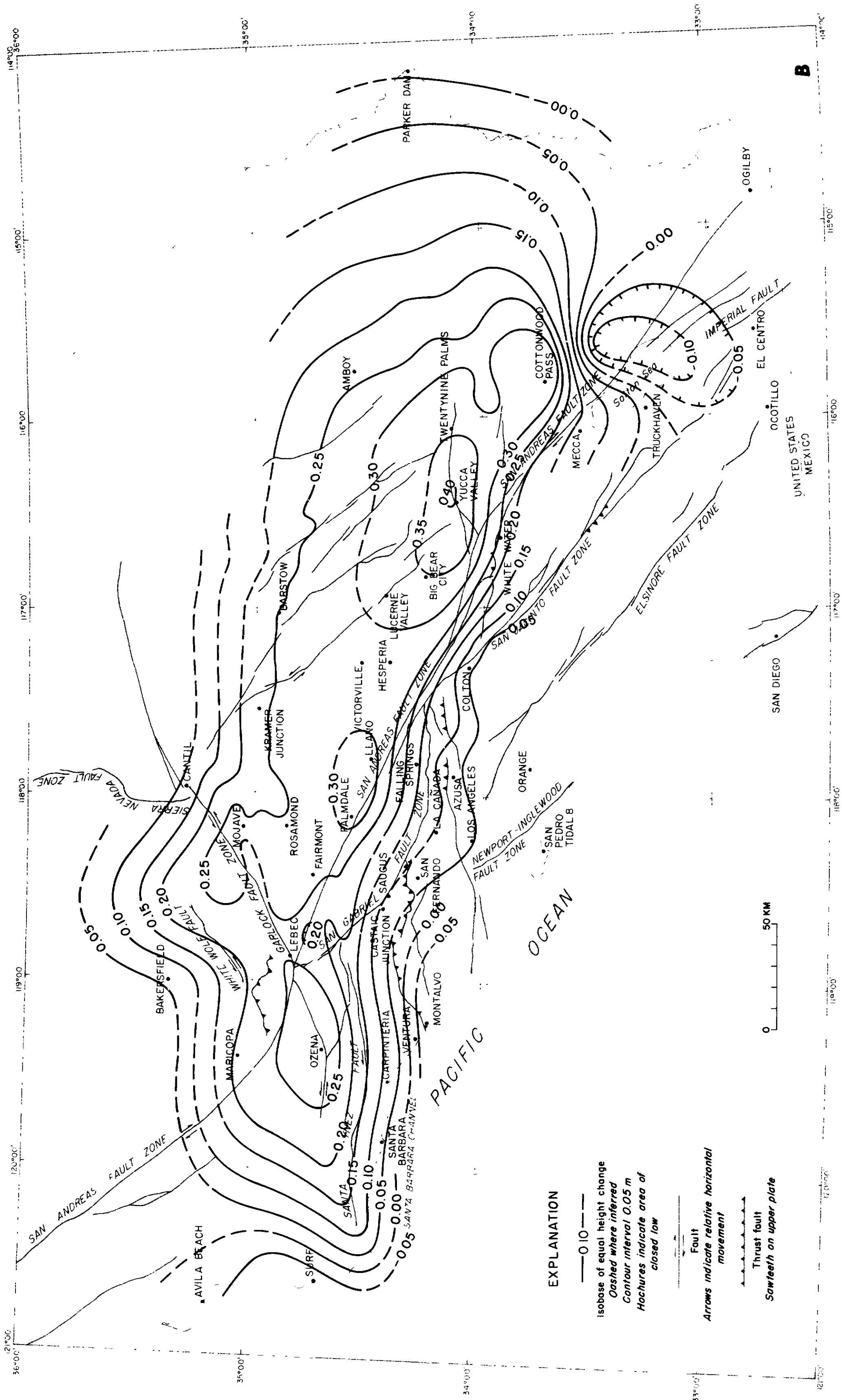


FIGURE 64.—Continued

Palms and eastward from Cottonwood Pass. This conjecture derives from the necessary use of the results of 1976 levelings along the Twentynine Palms-White Water and Cottonwood Pass-Parker Dam routes, levelings that postdate the inception of the collapse within the eastern reaches of the uplift.

Both reconstructions (fig. 64) accept the equivalence between the 1944/61 datum and one that would have been obtained had the leveling along the entire line between Mojave and Cottonwood Pass been carried out not only simultaneously but during 1955 (or 1959; see section on "The Mojave-Cottonwood Pass Line"). Because the comparative mark at Twentynine Palms (N 724) appears as a spike on the Mojave-Cottonwood Pass profile, the 1959.0–74.5 displacement of this junction is assumed to have been approximately 0.02 m less than that shown on plate 12. Accordingly, the 1959.0–74.5 displacements extending westward to Yucca Valley and White Water are based on a +0.39-m (or a +0.34-m) displacement at Twentynine Palms, coupled with the cumulative 1944–76 displacements measured with respect to Twentynine Palms (see sections on "The Lucerne Valley Line" and "The Colton-Mecca Line"). It is assumed as well, of course, that our interpretation of the equivalence of the 1974.5 and 1976 height differences between Twentynine Palms and White Water is indeed valid (see section on "The Colton-Mecca Line").

Because the 1959.0–74.5 down-to-the-east tilt between Parker Dam and Cottonwood Pass may have been nearly 0.6 m, the represented gradient extending eastward to the Arizona border (fig. 64) may be unrealistically conservative. However, owing to the probable occurrence of unassessed movement at various critical junctions during the course of the 1974/75/76 levelings leading into (or out of) Cottonwood Pass, we have based our reconstruction on the first of several possible options and have assumed that Parker Dam remained invariant with respect to Tidal 8 during the interval 1931–74.5 (see section on "The Cottonwood Pass-Parker Dam Line"). Thus we have distributed the 1959.0–74.5 vertical-displacement gradient along this line almost uniformly, diminishing from a maximum of +0.36 (or +0.31) m at Cottonwood Pass to zero at Parker Dam (fig. 64). While this is clearly a less than wholly satisfactory characterization, because bench mark 2H (MWD) (Cottonwood Pass) had almost certainly sustained significant collapse by the time the 1976 leveling was underway (such that the measured tilt was less than that that would have been revealed had the leveling been carried out in 1974), and because the actually measured tilt between Cottonwood Pass and Parker Dam was relatively smooth (pl. 14), the attenuation of the uplift eastward from Cottonwood Pass probably is closely approximated by that shown in figure 64.

The configuration of the tectonic subsidence in the Salton Trough (fig. 64) is constrained by the results of the 1974 leveling between Mecca and Truckhaven and the inferred equivalence between the 1971/72 datum and a hypothetical 1955 datum along the Ocotillo-Ogilby line (see sections on "The Colton-Mecca Line" and "The Ocotillo-Ogilby Line"). Because Mecca apparently rose about 0.18 (or 0.13) m during the period 1968–74, and because the height differences between Mecca and Truckhaven remained virtually unchanged during this interval, the entire spur must have undergone uplift of about 0.18 m (or 0.13 m) between 1956 and 1974.5 (see section on "The Colton-Mecca Line"). The magnitude of the represented subsidence centering on the Salton Sea (fig. 64) is based on the probable stability of bench mark Y 58 (Ocotillo) with respect to Tidal 8 during the period 1971/72–74 (and, less certainly, 1941–74 as well), coupled with the inferred equivalence between the 1971/72 datum and the datum that would have been developed had the surveys been carried out in 1955 (see section on "The Ocotillo-Ogilby Line"). If the 1971/72 heights were significantly below the 1955 heights along the Ocotillo-Ogilby line, it would tend to reduce the 1959.0–74.5 subsidence, but probably not by enough to eliminate the −0.10-m contour. Similarly, if the 1971/72 heights were well above the 1955 datum, the represented 1959.0–74.5 subsidence would be increased to the point that it probably would catch a −0.15-m contour (see pl. 15C).

THE 1959–77.0 EPOCH

The partial collapse of the southern California uplift is clearly revealed by the results of the 1976 (and, locally, 1977) levelings. However, because the distribution of the 1976 data are very limited, we have attempted to describe the residual uplift in only two areas (fig. 65). Moreover, because those 1976 data that do exist indicate that the collapse proceeded very rapidly, such that the "1976" height differences between bench marks, and especially between successive junction points, are much more apt to have been aliased by intrasurvey movement than those based on earlier levelings. Accordingly, the 1959.0–77.0 reconstruction (fig. 65) is perhaps the most questionable of any of those shown here.

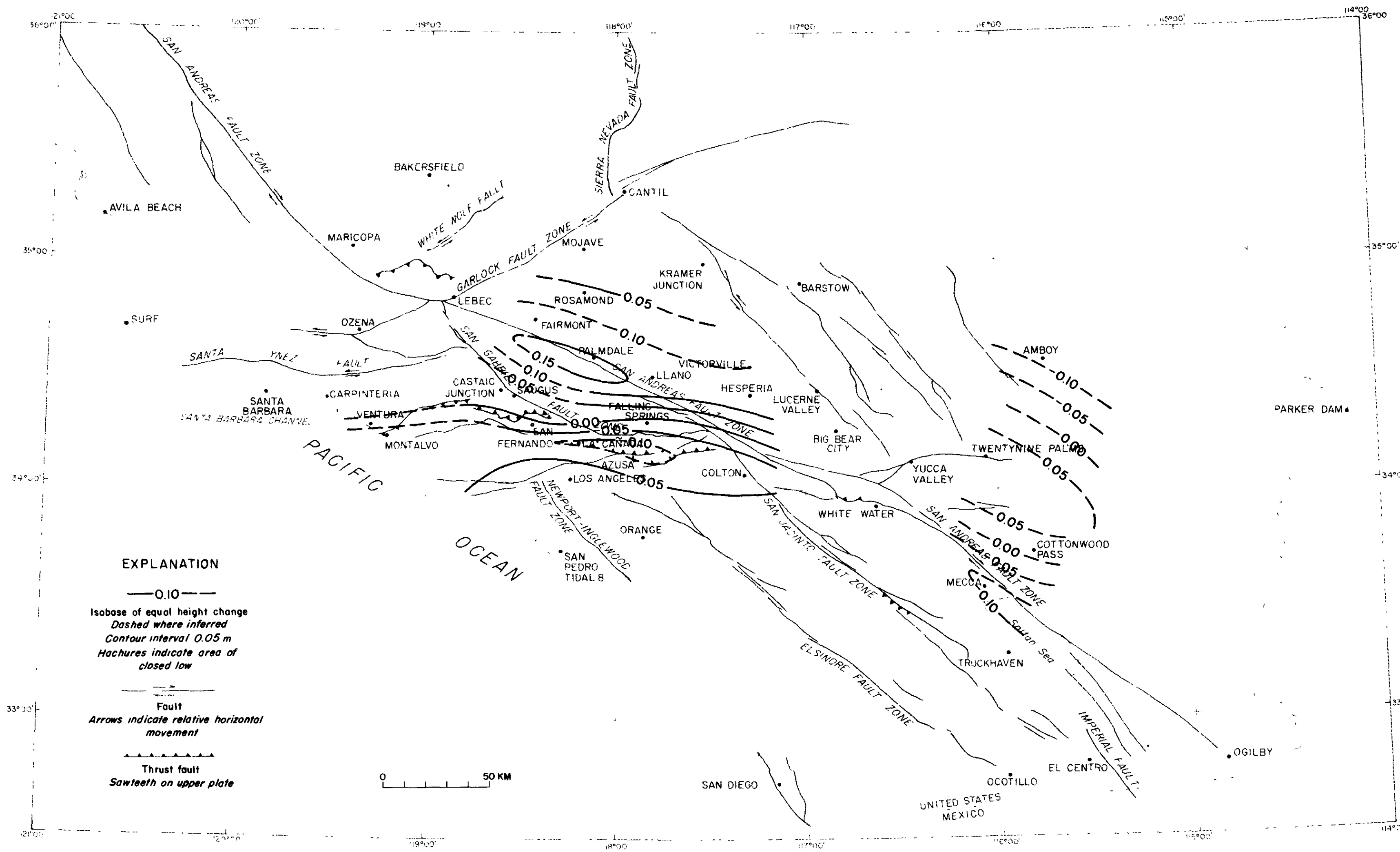


FIGURE 65.—Height changes with respect to bench mark Tidal 8 within the area of the southern California uplift, 1959.0–77.0. See text for details.

The 1977.0 configuration of the uplift is relatively unequivocally defined through its central girth by the results of 1976 levelings in this area (see sections on "The Los Angeles-Mojave Line, The Los Angeles-San Bernardino Line" and "The Quail Lake-Hesperia Line"). However, the demonstrably tectonic subsidence along the south flank of the uplift (fig. 65) is based on no more than skeletal information from both east and west of the Los Angeles-Mojave line and from the westernmost part of the Los Angeles-San Bernardino line. Specifically, the results of December 1976–April 1977 levelings by the Bureau of Engineering of the City of Los Angeles and the Los Angeles County Department of County Engineer indicate that by 1977 the coastal route between San Pedro and Santa Monica (directly west of Los Angeles) had sustained significant tectonic subsidence with respect to earlier datums. Comparisons against 1960 and 1968 datums show that this subsidence accumulated more or less linearly northward, whereby Santa Monica subsided about 0.03 m and 0.05 m during the intervals 1960–77 and 1968–77, respectively (NGS lines L-17850 and L-21537; J. F. McMillan, Los Angeles County Department of County Engineer, written commun., 1977). Similarly, comparisons of the results of March–May 1977 surveys against a 1968 datum between La Cañada and Azusa by the Los Angeles County Engineer show that tectonic subsidence referred to a control point in La Cañada increased smoothly eastward to a maximum of only about 0.02 m at Azusa (J. F. McMillan, Los Angeles County Department of County Engineer, written commun., 1977). Accordingly, because the line between La Cañada and Azusa probably sustained nearly uniform uplift between the spring of 1961 and 1968, and because the La Cañada reference mark (47-11) apparently subsided about 0.07 m between the spring of 1961 and 1976 (see section on "The Los Angeles-San Bernardino Line"), we infer that tectonic subsidence measured with respect to a hypothetical 1955 (or 1959) datum increased gradually eastward to a maximum of about 0.09 m at Azusa. Finally, the "1976" height of bench mark D 39, Colton, is based on the results of 1977 leveling through Cajon Pass tied to 1976 surveys propagated eastward from Palmdale to Hesperia (see section on "The Colton-Mecca Line"). Thus there is a reasonable likelihood that the "1976" heights of both D 39 and those bench marks extending northward to Hesperia may have been contaminated by intrasurvey movement.

The characterization of the residual (post-1974) uplift through its eastern reaches (fig. 65) has been developed from what we believe to be an extreme interpretation of the 1974–76 collapse in this area. That is, the represented reconstruction is based on a very conservative estimate of the 1959–74.5 uplift at Cottonwood Pass (fig. 64*B*) and the likelihood that the alternative (lower) of the two 1976 heights for bench mark H 516, Mecca (fig. 50), is the more accurate choice. However, even if these prove to be inaccurate judgments that lead to exaggerated estimates of the 1974–76 collapse, the form of the eastern part of the residual uplift would remain unchanged. If, for example, the 1959.0–74.5 uplift at Cottonwood Pass was 0.05 m greater than that used in this reconstruction (fig. 65), it would simply add 0.05 m to the value of each contour.

OTHER EXAMPLES OF ASEISMIC UPLIFT

Although aseismic uplift identified with active orogenic belts has been recognized before, both here and elsewhere, we know of no example (with one conspicuous exception) that matches the southern California uplift in areal extent, magnitude, and its spasmodic growth. Gilluly (1949, p. 562–565), for example, in one of the earliest references to this phenomenon, described uplift of up to 0.20 m based on 1906 and 1944 levelings across Cajon Pass. Additional examples from southern California include the aseismic uplift that preceded the 1971 San Fernando earthquake (Castle and others, 1974; Castle and others, 1975), uplift apparently precursive to the Point Mugu earthquake of 1973 (Castle and others, 1977), and uplift deduced from differenced sea-level measurements in the Los Angeles harbor area (Leypoldt, 1938; Nason, 1976; Wyss, 1977b, p. 1092) that preceded the 1933 Long Beach earthquake. Elsewhere, the most commonly cited example of aseismic uplift is that which reportedly occurred in advance of the 1964 Niigata earthquake (Tsubokawa and Dambara, 1968). Thatcher and Matsuda (1981), moreover, have described apparently continuing extensive uplift in the Tokai district southwest of Tokyo. This zone of uplift is about 40–50 km wide, projects northward about 250 km through the Akaishi Mountains, and has been characterized by positive height changes of more than 0.20 m during the period ~1900–70. Additionally, and although it might be viewed as other than strictly orogenic, Reilinger and Oliver (1976) have described uplift in the Socorro district of New Mexico that is inferred to be associated with deep-seated magmatic activity. Similarly, aseismic doming over a roughly elliptically shaped area perhaps 100 km across, also interpreted as the product of magmatic intrusion at depth, has been reported from the Yellowstone area, Wyoming (Reilinger and others, 1977).

Although several of the examples cited in the preceding paragraph are in some respects comparable to the southern California uplift, the differences clearly outweigh the similarities. The Tokai uplift, for example, is certainly a major feature by any measure, yet there is no evidence that its aseismic growth has proceeded spasmodically or episodically (Thatcher and Matsuda, 1981). On the other hand, the uplift in the Los Angeles harbor area was identified with accelerated and unusually rapid growth and subsequent collapse (Leypoldt, 1938), but it probably extended over an area of no more than several hundred square kilometers. Thus, as contrasted with any of these examples, the southern California uplift emerges as a unique tectonic event.

The remarkably similar uplift that apparently occurred within this same general area during the early part of the 20th century (Castle and others, 1976; Castle and others, 1977; Castle, 1978; Vaníček and others, 1979; Wood and Elliott, 1979; Yerkes and others, 1980) is clearly an exception to the preceding generalization. Although our investigation of this earlier event is incomplete, we have assembled sufficient information on its history and distribution to enable us to draw a number of comparisons between this early uplift and its recent counterpart.

Comparisons between the results of 1897/1902 and 1914 levelings along the Los Angeles-Mojave line indicate that the area northward from San Pedro sustained increasing uplift during this interval that culminated south of the San Andreas fault at about +0.5 m (fig. 66*A*). Moreover, uplift of about this same magnitude apparently propagated across the full width of the western Mojave, diminishing to about 0.27 m at Bakersfield (fig. 66*A*). Preliminary comparisons based on the 1897/1902 levelings and a combination of 1914, 1924, 1926, and 1928 surveys between San Pedro and Mecca indicate that comparable uplift (of up to 0.5 m or more) must have extended eastward as well, to at least White Water (Wood and Elliott, 1979, p. 254–256). Similarly, comparisons based on somewhat more fragmentary data argue that this early uplift persisted westward along the southern margin of the western Transverse Ranges and thence northward to beyond Point Arguello (Yerkes and others, 1980). Accordingly, even though we have discovered no data from the area east of Barstow and north of the Salton trough that bear on this problem, and even though the data that we have assembled are relatively skeletal, this earlier uplift certainly rivaled or even surpassed the more recent uplift in both magnitude and areal extent. Not surprisingly, the evolutionary chronology is much less well defined for this early-20th-century event than it is for the later uplift. Nonetheless, comparisons between the results of 1897 and 1902 levelings indicate that uplift could not have begun before 1902. Furthermore, our analysis of misclosures associated with a part of the early level network supports the conclusion that significant uplift did not begin before 1905, yet was almost certainly well underway by 1907.

The accuracy of the measurements that define the early-20th-century southern California uplift was well below the accuracy of the measurements that have been incorporated in the reconstruction of the recent uplift. For example, the estimated random errors identified with the 1897/1902 and 1914 height determinations for a representative mark located well within the uplift are about three times the magnitude of those computed for the results of later levelings (fig. 67). Nevertheless, both circuit closures and the results of repeated levelings obtained prior to the inception of the uplift indicate that the accuracy of even the least accurate (primary) geodetic leveling of this vintage was a good deal higher than suggested by these error bars (fig. 67). Moreover, permissive support for the accuracy and certainly the validity of these earlier measurements is implied by the gross similarity in both distribution and magnitude between the early-20th-century and later southern California uplifts. Furthermore, the reported signals are so large in comparison with any likely error that it would be difficult to dismiss these displacements as artifacts of the measurement system.

We must acknowledge, however, that our initial identification of the early-20th-century uplift (Castle and others, 1976, p. 252–253) was developed from uncorrected or improperly corrected field values which are now known to be substantially in error. Specifically, our earlier report was based on 1897 leveling between San Fernando and the San Andreas fault that, contrary to our original statement (Castle and others, 1976, p. 252), was single rodded over this particular reach; subsequent reconstruction of the field observations revealed two major blunders (one of which could be corrected) that led to significant errors in the 1897 datum extending northward from San Fernando (or, more precisely,

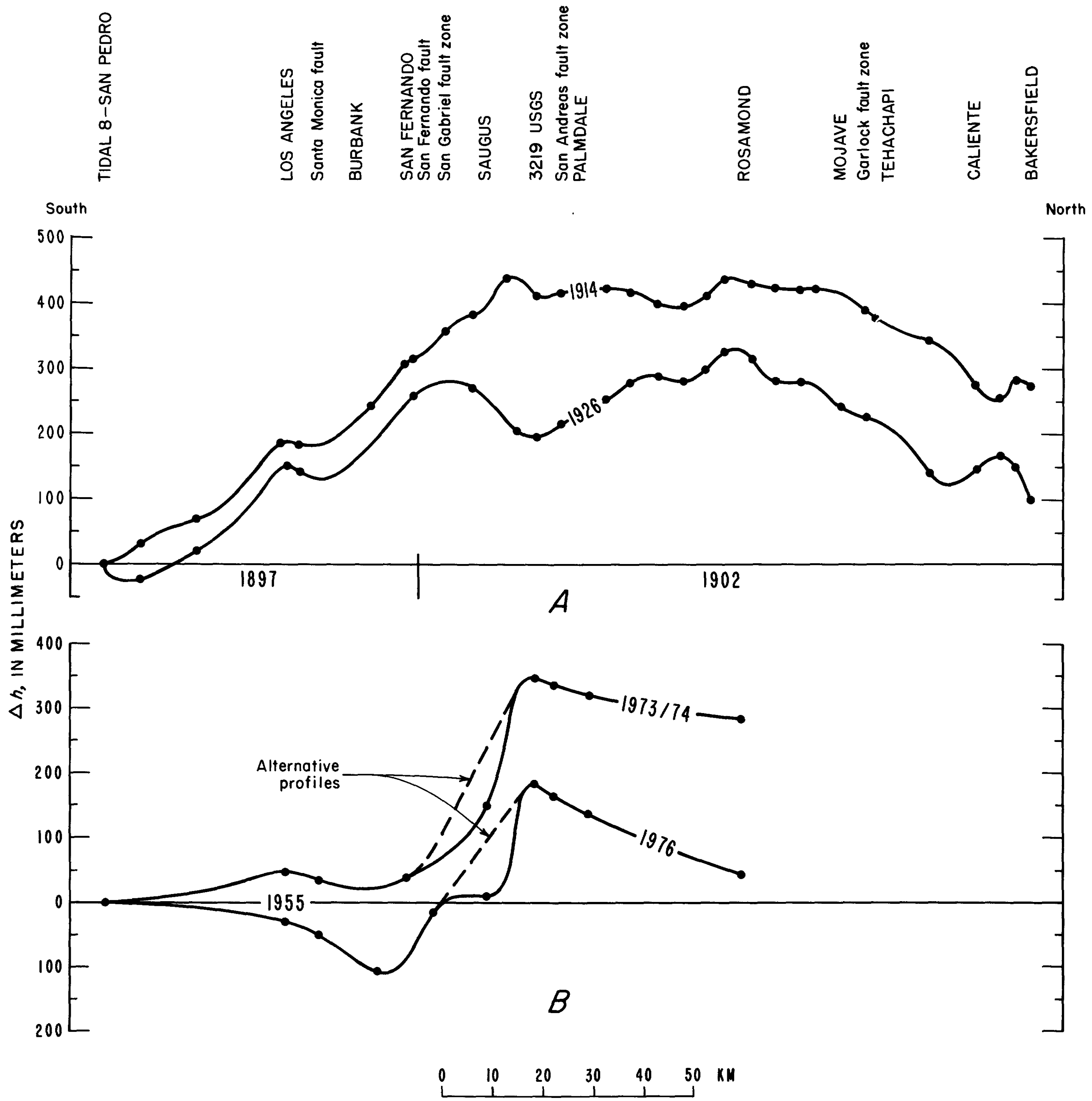


FIGURE 66.—Projections into north-south section through San Pedro showing height changes (Δh) with respect to bench mark Tidal 8 along parts of the Los Angeles-Mojave and Los Angeles-San Bernardino lines. Marks that appear as spikes or fall within areas of recognized compaction-induced subsidence have been discarded in these comparisons. *A*, Height changes identified with early-20th-century uplift measured against an 1897/1902 datum. *B*, Height changes identified with modern uplift measured against a 1955 datum. Estimated coseismic displacements associated with the 1971 San Fernando earthquake have been subtracted from these comparisons; data through region of recognized coseismic displacements were not used in the construction of the alternative profiles (dashed lines).

the adjacent community of Pacoima). Similarly, the results of the 1914 double-run leveling were found to be contaminated by unusually large errors of as much as 0.15 m that had been produced through improperly computed rod corrections. The datum has since been corrected through the substitution of the results of 1902 double-rodded (precise) leveling between the San Andreas fault and San Fernando that junctioned with 1897 double-rodded surveys extending southward to San Pedro. The 1914 measurements have also since been corrected through the application of recomputed rod corrections based on the original field calibrations of the wooden rods incorporated in the 1914 survey and a subsequent U.S. Bureau of Standards recalibration of one of the two standardized steel tapes used in the field calibrations. Accordingly, our earlier characterization (Castle and others, 1976, p. 252–253) should be disregarded and should be replaced by the revised interpretation shown in figure 66*A*.

The early southern California uplift roughly mimicked the recent uplift in a number of ways. That is, not only did this uplift extend over the same general area, but its growth was both generally aseismic and apparently characterized by rapidly accelerating vertical displacements of about the same magnitude as those identified with the later uplift. Moreover, the partial collapse of

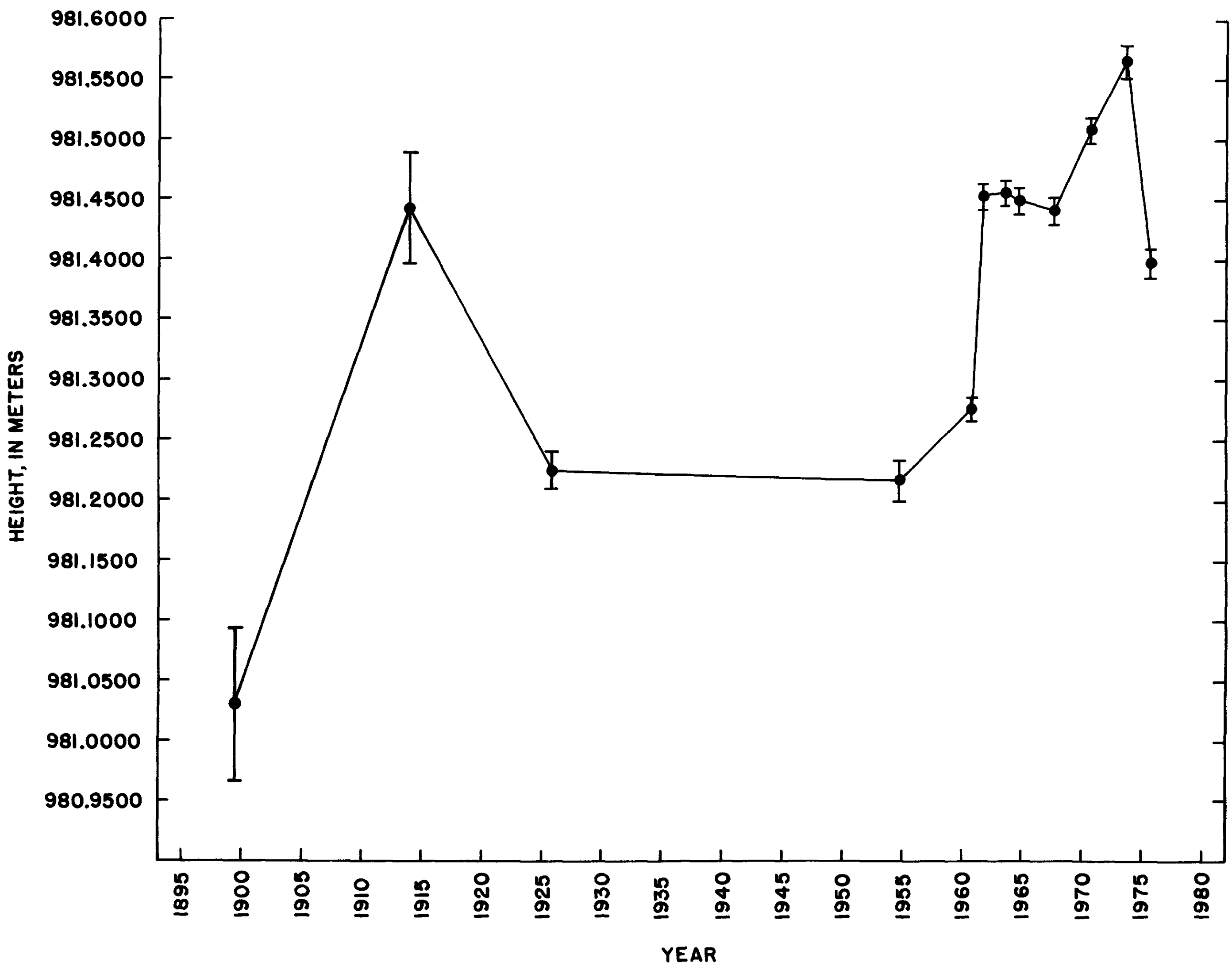


FIGURE 67.—Changes in orthometric height at bench mark 3219 USGS, Vincent, with respect to bench mark Tidal 8, San Pedro, since 1897/1902. The 1897/1902 height is based on double-rodded third-and second-order levelings of the U.S. Geological Survey. The 1914 height is based on second-order (double-run) leveling of the U.S. Geological Survey. All other heights are based on the results of first-order levelings of various agencies. One-standard-deviation error bars show conventionally estimated random error only. Orthometric corrections based on observed gravity.

about the same magnitude as those identified with the later uplift. Moreover, the partial collapse of the early uplift is similar in chronology, if not in form, to that which followed the 1974 culmination of the recent uplift (figs. 66 and 67). In fact, it is not unlikely that the uplift across Cajon Pass described by Gilluly (1949, p. 562–565) is characteristic of the general form of the south flank of the residual early uplift—that is, the uplift that persisted following the partial collapse that must have begun no later than 1926 (figs. 66*A* and 67).

Granting the similarities between the earlier and later uplifts, there remain several notable differences that can be loosely described as second-order variations. The most significant of these differences is the much more pervasive involvement of the Peninsular Ranges in the earlier uplift (fig. 66; Wood and Elliott, 1979). Indeed, the significant propagation of this earlier uplift into the Peninsular Ranges south of Los Angeles (fig. 66*A*) suggests that these vertical displacements may be as much the product of collapse of the northern edge of the Peninsular Ranges as uplift of the Transverse Ranges. While this interpretation would neither remove nor diminish the measured tilt along the south flank of the early-20th-century uplift, it implies that the represented displacement field (fig. 66*A*) distorts the vertical-movement history with respect to a tectonically invariant control point. However, several short-term occupations of the San Pedro tide station during the second half of the 19th century (Wood and Elliott, 1979, p. 258) argue that this has not occurred to any significant degree. Specifically, the results of these measurements indicate that the sea-level trend at this tide station remained virtually unchanged through the growth and partial collapse of the early uplift. The earlier uplift apparently differed as well in its mode of collapse. That is, as can be deduced from direct inspection of the profiled height changes, the collapse of the modern uplift was expressed as a remarkably uniform down-to-the-north tilt that extended at least as far north as Rosamond (fig. 66*B*). The earlier uplift, on the other hand, was characterized by a much more irregular pattern of collapse, and its southern margin was virtually devoid of tectonic subsidence (fig. 66*A*). Moreover, while there is some indication that the deflation of the recent uplift may have begun in the western Transverse Ranges and spread rapidly eastward, the earlier uplift apparently sustained major collapse in the western Transverse Ranges and the western Mojave block well in advance of any collapse in its eastern reaches. Specifically, if we assume that the reported 0.6-m uplift of the northern Salton trough was at its maximum in 1928 (Wood and Elliott, 1979, p. 255)—and it is difficult for us to reject this assumption—major collapse of the western lobe (fig. 66*A*) must have begun at least 2 years before any significant subsidence had occurred in the eastern part of the uplift. There is, in addition, at least permissive evidence that the collapse of the eastern uplift probably persisted at least into 1931 (see Wood and Elliott, 1979, p. 254 and section on "The Colton-Mecca Line"). Finally, conspicuous downwarping along the south flank of the uplift, such as occurred between 1955 and 1976 (figs. 65 and 66*B*), almost certainly did not accompany the collapse of the earlier uplift. It is, in fact, this distinction that most clearly differentiates these two episodes of uplift and partial collapse. The occurrence of an earlier episode of uplift within the same general area as that occupied by the recent southern California uplift suggests that the recent uplift represents but a single event in a continuing and more or less cyclic tectonic process. Although the historic record embraces less than two full cycles, if we assume the later cycle to be representative, it suggests a period of about 50 years. Use of this value indicates that the cumulative uplift rate in the Palmdale area during the past century has been about 5 mm/yr (fig. 67), a figure that is certainly in acceptable agreement with the uplift rates deduced from studies of emergent marine terraces along the south flank of the western Transverse Ranges (Wehmiller and others, 1977; Wehmiller and others, 1979), and hence along the south flank of the uplift. In the larger geologic context, moreover, the areas of maximum cumulative uplift and maximum cumulative collapse are generally consistent with their geologic locale. For example, based on repeated geodetic measurements, the high desert and western Transverse Ranges and at least parts of the San Bernardino Mountains have been identified as areas of relatively high cumulative uplift rates (figs. 65 and 67) that roughly coincide with areas of geologically determined high uplift rates during Holocene or late Quaternary time (Wehmiller and others, 1977; Bull and others, 1979; Wehmiller and others, 1979; Herd, 1980, p. 15–16). Similarly, the geodetically determined maximum cumulative collapse (or negative uplift) rates are at perhaps their greatest in the central Salton trough (fig. 50; Wood and Elliott, 1979, p. 255), which is precisely the environment in which one would expect continuing cumulative tectonic subsidence.

SEISMICITY ASSOCIATED WITH THE SOUTHERN CALIFORNIA UPLIFT

The rapidly accelerating vertical displacements identified with the evolution of the southern California uplift (figs. 55–65) invite an almost intuitively obvious comparison with the instrumentally recorded earthquakes in this same general area. Accordingly, we have compared the distribution of earthquakes of magnitude 4 and greater during the period 1932–76, inclusively, with our preferred interpretation of the cumulative uplift developed during the period 1959–74.5 (pl. 16). Shocks of less than magnitude 4 have been excluded chiefly because they probably contributed very little to the elastic strain release in this area. Moreover, while we recognize that much more rigorous comparisons could (and probably should) be made between the changing pattern of seismicity and the evolving uplift, our purpose here is simply to draw attention to several of the evident relations between the uplift and the spatially associated earthquakes that occurred during the interval 1932–76.

Perhaps the most valid generalization that can be made in this connection is that the uplift and the seismicity of this area are surprisingly poorly correlated. The generally uncorrelated nature of these two phenomena would be even more striking were we to exclude from consideration those earthquakes that preceded the uplift. Specifically, virtually all of the earthquake activity along the Newport-Inglewood zone (pl. 16) can be attributed to the 1933 Long Beach earthquake and associated aftershocks (Hileman and others, 1973, p. 11, 15–20). Similarly, a large part of the seismicity south of Santa Barbara, north of Cantil, east of Barstow, and in the area centering on White Water is clearly identified with the 1941 Santa Barbara, the 1946 Walker Pass, the 1947 Manix, and the 1948 Desert Hot Springs earthquakes, respectively (Hileman and others, 1973, p. 11, 34–39). Finally, and perhaps most importantly, nearly all of the shocks developed along the northwest flank of the uplift can be related to the 1952 Kern County earthquake (Hileman and others, 1973, p. 34–41). In short, although a significant part of the 1932–76 seismicity occurred after 1959, more than half of the seismic energy produced during this period probably preceded the inception of the uplift.

Apart from the pre-1960 earthquake activity, the seismicity associated with both the growth and partial collapse of the uplift is localized largely within (1) the Santa Barbara Channel westward from Ventura, (2) the Saugus-San Fernando area, (3) the San Bernardino Mountains area, and (4) various areas along the trend of the San Jacinto fault (pl. 16). Perhaps even more apparent, however, is the occurrence of several large, generally aseismic areas within and around the uplift. Specifically, the western lobe of the uplift (exclusive of the Saugus-San Fernando area) remained virtually free of earthquakes during the period 1960–76. In addition, and even if the pre-1960 earthquakes are taken into consideration, the area projecting eastward across the southeast flank of the uplift into the eastern Mojave has been almost totally free of seismic activity.

The apparent spatial independence between the uplift and the temporally associated seismicity could be interpreted as indicating that the two are genetically dissociated. It could be argued with equal conviction, moreover, that the identified "seismic gaps," particularly around the flanks of the uplift, represent zones of significant elastic-strain accumulation indicative of impending and conceivably major earthquake activity. However, at least one and perhaps both of these generalizations probably are wide of the mark. That is, there is no evidence to conclude other than that both the seismicity and the apparently aseismic deformation are equally valid expressions of the orogenic process. Simply because we are unable to show that one is somehow directly derivative from the other does not preclude an ultimately demonstrable relation between the two. Similarly, there is as yet no clearly defined basis for assuming that the aseismic areas within and around the uplift should be targeted as sites for major seismic activity in the near term—although we should add that this is certainly a reasonable possibility. Nonetheless, and even though we recognize at least one major difference between the two historically defined episodes of uplift that may bear on this problem, what little we know of the early-20th-century uplift argues by analogy that we need not necessarily expect to see these seismic gaps filled by large earthquakes.

THE ORIGIN OF THE SOUTHERN CALIFORNIA UPLIFT

The southern California uplift is, at best, an imperfectly understood phenomenon. Nevertheless, various scholarly speculations dealing with the origin of this feature appeared almost immediately after its recognition (Thatcher, 1976; Hadley and Kanamori, 1977b, p. 1474–1477; Kosloff, 1977; Wyss, 1977a; Castle, 1978, p. 7; Savage and Prescott, 1977;

Rundle and Thatcher, 1980). However, several of these hypotheses were generated in advance of significant constraints that have since been placed on any theory of the origin of the uplift; thus the range of reasonable explanations has been correspondingly narrowed and, in a certain sense, further complicated. Specifically, any model that attempts to explain the origin of the uplift must consider the episodic or spasmodic growth of the uplift and its subsequent collapse, the apparently cyclic nature of this phenomenon, the surprisingly short period identified with each cycle, and the generally aseismic nature of the uplift and subsequent collapse. Moreover, any viable explanation of the uplift must also accommodate its apparent involvement with the Transverse Ranges (or, alternatively, with the double bend of the San Andreas fault) and both the measured and inferred contractional strain athwart the uplift. Although we have seriously considered all of those explanations for the origin of this feature of which we are aware, we obviously favor some over others; hence this discussion focuses on what we perceive to be the most soundly based suggestions and criticisms formulated to date.

Shortly after the recognition of the southern California uplift, but prior to the identification of its partial collapse, Thatcher (1976) concluded from an analysis of repeated triangulation surveys that the impulsive inception of the uplift was accompanied by horizontal strain rates roughly four times greater than those normally associated with the San Andreas system. Thus, according to Thatcher (1976, p. 691–692), anomalous shear straining during the periods 1952–63 and 1959–67 probably destructively interfered with the normal pattern in such a way that the compressive stress axes were rotated into azimuths roughly perpendicular to the axis of the uplift. This anomalous pattern suggested to Thatcher (1976, p. 693) that the uplift could be explained as the product of aseismic slip along a virtually horizontal megathrust diving beneath the Transverse Ranges or, alternatively, decoupling between the asthenosphere and a relatively thin lithosphere. Savage and Prescott (1979) subsequently challenged this model, chiefly because (1) geodimeter lines that roughly parallel the maximum compressive axes identified by Thatcher (1976, p. 693) seemed to lengthen during the critical period 1956–63 and (2) they could detect no evidence of anomalous horizontal straining accompanying the partial collapse of the uplift during the period 1974–77. Rundle and Thatcher (1980) have since proposed a modified megathrust model that is seemingly consistent with Thatcher's (1976) earlier analysis and may overcome several of the earlier objections. The Rundle-Thatcher model presupposes a layered system extending into the asthenosphere, in which each layer is characterized by significantly different time constants. Thus, according to Rundle and Thatcher, relatively rapid slip along a shallowly dipping megathrust within the lithosphere would be accompanied by correspondingly rapid elastic uplift along the leading edge of the upper plate. The viscoelastic asthenospheric response to this rapid slip would tend to produce relatively slow uplift overlying the slip zone that would persist until such time as equilibrium was restored. Collapse rapid enough to overcome the asthenospheric recovery could occur within a porelastic layer characterized by relatively short time constants and extending to a depth of perhaps no more than 5 km. The deformation of the porelastic layer is attributed in turn to fluid diffusion, although other mechanisms might be postulated. Unfortunately, the complexities of the Rundle-Thatcher model preclude a simple synopsis; hence we have attempted here to outline only its more basic aspects in order to demonstrate its general consistency with Thatcher's (1976) earlier hypothesis.

While the post-1973/74 partial collapse persists as perhaps the most enigmatic feature associated with the evolution of the uplift, the seemingly divergent positions of Thatcher (1976) and Savage and Prescott (1979) may be less irreconcilable than the data suggest. Specifically, the occurrence of an unusual horizontal strain event superimposed on the secular strain pattern could explain the association between the inception of the uplift and the anomalous shear straining identified by Thatcher (1976), yet at the same time show at least partial consistency with the data reported by Savage and Prescott (1979). For example, lines 43, 59, and 61 (fig. 68) are characterized by apparent strain histories that Savage and Prescott (1979, p. 172–173) largely dismiss as the products of measurement error, but which we contend are consistent with discontinuous migration of slip (in both space and time), both athwart the axis of the uplift and along a horizontal or subhorizontal surface underlying the uplift. Owing to the relatively short length of these lines (with respect to the width of the uplift) and the discontinuous nature of the postulated slip events, we see no reason why such events should necessarily be expressed at the surface as shortening—even though we would expect that a contractional trend should be evident along the av-

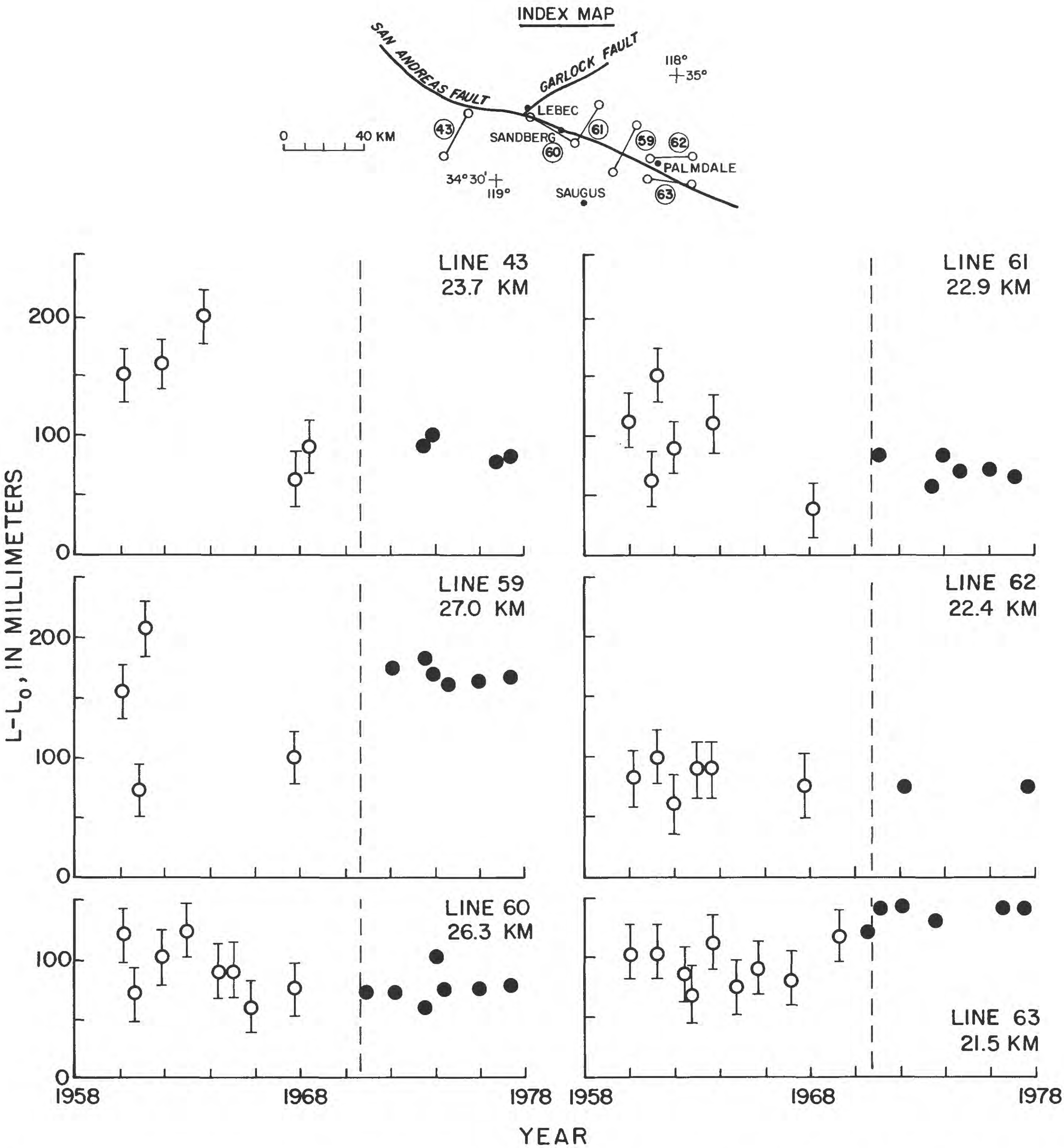


FIGURE 68.—Measured length (L) less a constant nominal length (L_0) as a function of time for each of six geodimeter lines in the west-central Transverse Ranges. Corrections have been applied for suspected systematic errors introduced as a result of earlier survey procedures. Error bars show one-standard-deviation figures for plotted points; for solid circles the radius of the plotted point is about one standard deviation. The vertical line in 1971 represents the time of occurrence of the San Fernando earthquake. After Savage and Prescott (1979, figs. 3 and 5).

erage line during the full interval 1959–74. Nonetheless, the seemingly oscillatory strain (contraction alternating with extension) shown by lines 59 and 61 between the beginning of 1960 and the early spring of 1961 (fig. 68) is especially intriguing (the intermediate measurement is missing along line 43). This period is included within the interval defined by the collapse of the Lebec area (sometime after the spring of 1959 but no later than the beginning of 1960) and its subsequent recovery (no later than the end of 1961) (see sections on "The Ventura-Maricopa Line" and "The Los Angeles-Mojave Line"). The significance of this observation is not that we can associate the tectonic collapse (or later recovery) with either extensional or contractional strain along either of these lines, but rather that reversals are disclosed in both the vertical and horizontal regimes during the same general period in the same general area—and that these reversals are reasonably interpreted as expressions of inchworm-like migration of slip along an essentially horizontal surface underlying the identified area. Similarly, repeated measurements along line 43 (roughly coincident with the northern end of the Ventura-Maricopa line) and line 61 (extending north-northeast off the Saugus-Grapevine spur of the Los Angeles-Mojave line) indicate that both lines experienced contractional strain sometime between 1963 and 1968 (fig. 68), a period during which a well-defined pulse of uplift occurred along the Saugus-Grapevine spur (see section on "The Los Angeles-Mojave Line"). Measurements along line 59 (extending north-northeast off the Saugus-Palmdale segment of the Los Angeles-Mojave line) indicate that comparable contractional strain occurred along this line sometime between the spring of 1961 and 1968, and conceivably as early as the middle of 1961 (fig. 68). Because the vertical-displacement histories of the marks in the Palmdale area indicate that the pre-1971 uplift occurred largely between the spring and fall of 1961 (figs. 23 and 24), it is likely (although obviously not demonstrable) that the uplift and the indicated contractional strain along line 59 occurred simultaneously. Significantly, moreover, the 100-mm 1961–68 (or March–October 1961) shortening along line 59 (Savage and Prescott, 1979, p. 172–173) is consistent with that predicted by the megathrust model. On the other hand, there is relatively little indication of strain along those lines (60, 62, and 63) that roughly parallel the axis of the uplift. This is especially true of line 62 (fig. 68), which shows little if any strain above noise level and—unlike line 63—is not apt to have been influenced by deformation preceding or accompanying the San Fernando earthquake (Savage and Prescott, 1979, p. 173–174). Finally, provided only that the collapse of the uplift (whether in response to fluid flow within a postulated porelastic layer or to some other phenomenon) does not demand a major relaxation of the contractional strain athwart the uplift, reinstitution of a secular pattern is hardly inconsistent with partial collapse; that is, anomalous straining, of whatever nature, need not necessarily accompany the collapse. Accordingly, aseismic slip along a horizontal or subhorizontal surface at depth, as suggested by the triangulation data (Thatcher, 1976), remains a plausible explanation for the uplift, if not for its subsequent collapse.

Our position, we suspect, is clearly revealed in the preceding remarks: the existing data strongly support the argument that the southern California uplift was produced through slip (or decoupling) along a virtually horizontal surface, much as first suggested by Thatcher (1976). Our preferred explanation (it would be presumptuous to identify it as a model) proceeds from one that was first proposed and subsequently reiterated in very similar form by Lachenbruch and Sass (1973; 1981) to explain the heat-flow distribution across the San Andreas fault. We assume the existence of a brittle seismogenic layer overlying a viscoelastic or ductile layer extending to the base of the lithosphere (fig. 69*A*); we further assume that these two layers are partially decoupled through a thin low-viscosity layer that extends over at least the width of the subseismogenic shear zone that marks the boundary between the North American and Pacific plates. The postulated existence of the low-viscosity layer obviously is speculative, but its occurrence is at least consistent with the modest velocity reversal at 15 to 20 km suggested by Hadley and Kanamori (1977a). The configuration of the San Andreas fault implied by this representation (fig. 69*A*) departs significantly from the conventional characterization of this fault, which assumes that it extends to the base of the lithosphere as a more or less discrete surface. That is, if one accepts the Lachenbruch-Sass model, a section through the San Andreas has the form of an inverted "T" whose stem represents the vertical (or transcurrent) part of the fault, bottoming at the base of the seismogenic layer, and whose cross represents the horizontal (or decoupled) part of the fault. Implicit in this characterization is the likelihood that the horizontal part of this structure tends to dominate the San Andreas fault, especially in the locked section.

The Lachenbruch-Sass model—at least in its unmodified form—assumes that simple shear is continuous across the entire subseismogenic plate boundary. It also assumes that right-lateral shear straining associated with this continuous movement is symmetrically distributed with respect to the medial line that traverses the length of the boundary zone, falling off to zero at either edge of the boundary zone. Because the velocity of any point within the subseismogenic shear zone is, by definition, unimpeded, whereas that for a corresponding point within the overlying brittle zone is constrained (Lachenbruch and Sass, 1973, p. 198, fig. 4Cb), a horizontal shearing traction, τ_h (fig. 69*A*), is necessarily imposed on the base of the brittle layer (or, alternatively, on the base of some arbitrarily designated section within the low-viscosity layer).

Adoption of this characterization of the San Andreas fault (fig. 69*A*) carries with it implications significant to the origin of the southern California uplift. Specifically, "the seismogenic layer could offer appreciable resistance to plate motion even though stress on the main fault were negligible; [thus] the principal resisting surface would be the horizontal base of the seismogenic layer" (Lachenbruch and Sass, 1980, p. 6219). Hence, provided that τ_h rises to values large enough to overcome the shearing resistance along the horizontal fault, the brittle or seismogenic layer may simply ride out over the subseismogenic zone (fig. 69*B*). Moreover, because of the geometric and strength conditions that govern movement on the San Andreas fault where it traverses the Transverse Ranges, slip along the horizontal fault need not necessarily be accompanied by movement along the vertical or main fault. That is, since continuing contractional strain across the San Andreas fault between the two chief bends in the system is enhanced with respect to that both north and south of this reach, increasing normal stress across the vertical fault will increase the frictional resistance to movement throughout and immediately beyond this section of the fault, whereas the shear stress along the main fault, $\bar{T}$, probably remains at a minimum with respect to that elsewhere within the seismogenic layer (Lachenbruch and Sass, 1973, p. 198, fig. 4Cc). Hence the interaction between these stresses effectively bonds the main fault over short periods. However, those factors that probably led to this welded-like condition in no way preclude movement along the main fault (it would be absurd to argue otherwise since it is known to have sustained large displacements during historical time); that is, provided that the horizontal shearing traction across the horizontal fault rises to some critical value, slip may occur along both parts of the fault.

The variation in τ_h as a function of both position and time is controlled by a variety of factors. Perhaps the most obvious of these is the velocity distribution across the subseismogenic layer, which is ultimately dependent on interplate motion. That is, the velocity must increase gradually from zero at the edge of the boundary zone to a value along the opposite edge that matches the velocity of the plate motion itself. Similarly, the shearing resistance must vary widely across the width of the boundary zone, but it may be controlled chiefly by the rheologic properties that characterize the postulated low-viscosity layer. Accordingly, if the relative velocities for points within the subseismogenic zone fall off toward the edges of the plate boundary, whereas the shearing resistance increases toward the edges, failure conditions along the horizontal fault will, in general, tend to develop toward the central part of the boundary zone. Failure (where $\tau_h \geqslant$ the shearing resistance) may be achieved much more readily and, hence, much more frequently than one might intuitively infer. For example, if the shortening (90 ± 20 mm/yr) between Quincy, Calif., and San Diego (fig. 1) reported by Smith and others (1979) and Smith (1980) is even approximately correct, relative motion of 110 mm/yr between the North American and Pacific plates is certainly a reasonable expectation. Thus, for corresponding points on opposite sides of the low-viscosity layer midway across the plate boundary, differential movement over a period of 50 years could easily rise to about 1.35 m (or roughly half the displacement of a point within the subseismogenic zone with respect to some point beyond the plate boundary). Differential movement of this magnitude could easily increase τ_h to values large enough to produce failure within the decoupled zone. Accordingly, if the southern California uplift is, in fact, attributable to slip along the horizontal San Andreas fault, cyclic repetition of uplift at about 50-year intervals may be much more expectable than would have otherwise seemed possible.

Given the occurrence of slip along the horizontally decoupled zone (fig. 69*B*), the displacement may be braked through the restoration of equilibrium between τ_h and the horizontal shearing resistance (that is, through a reduction of τ_h), the strength of the brittle seismogenic layer (which would tend to inhibit breakthrough at the bends along the vertical fault), and, conceivably, the intersection between the northward-dipping frontal

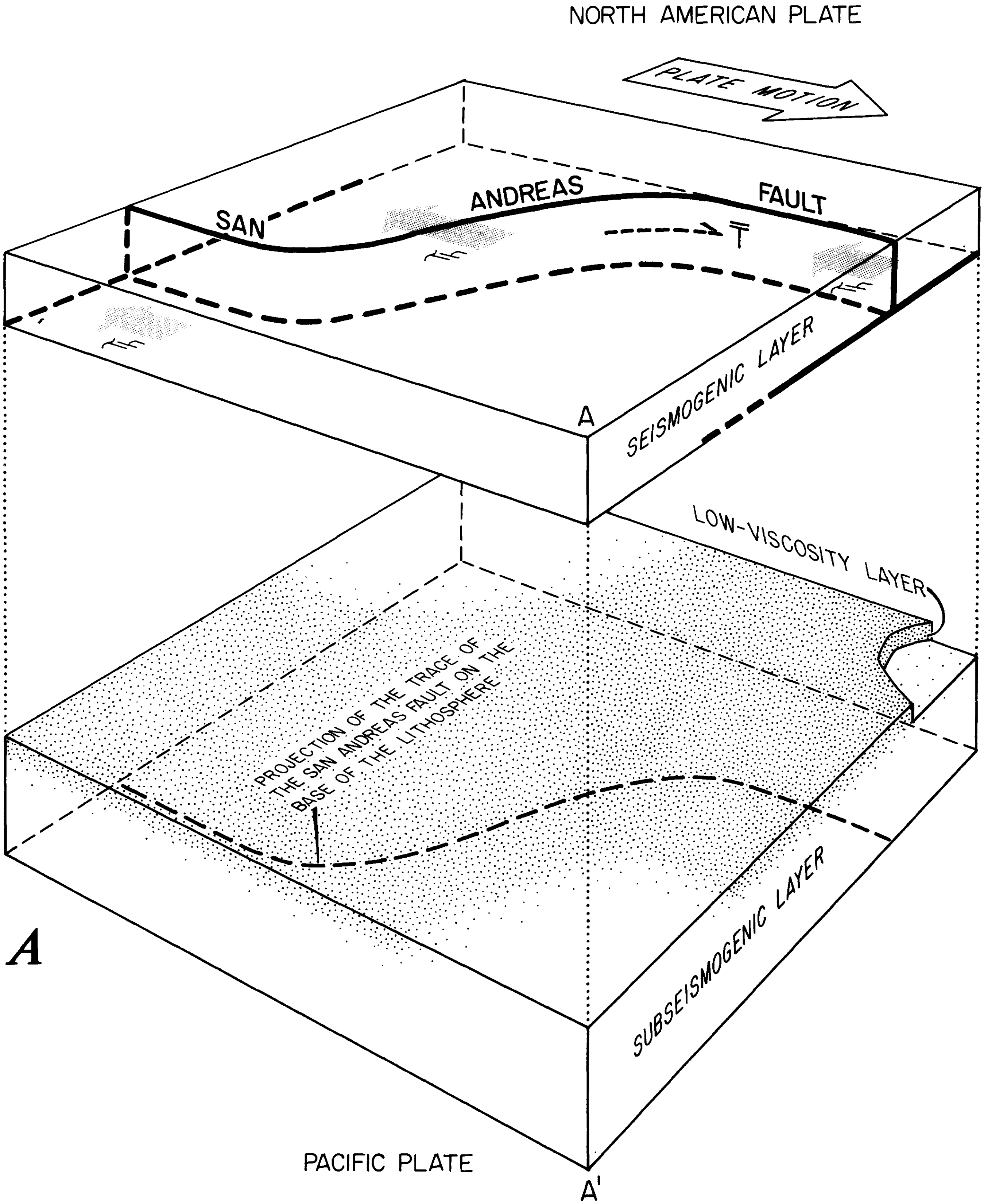
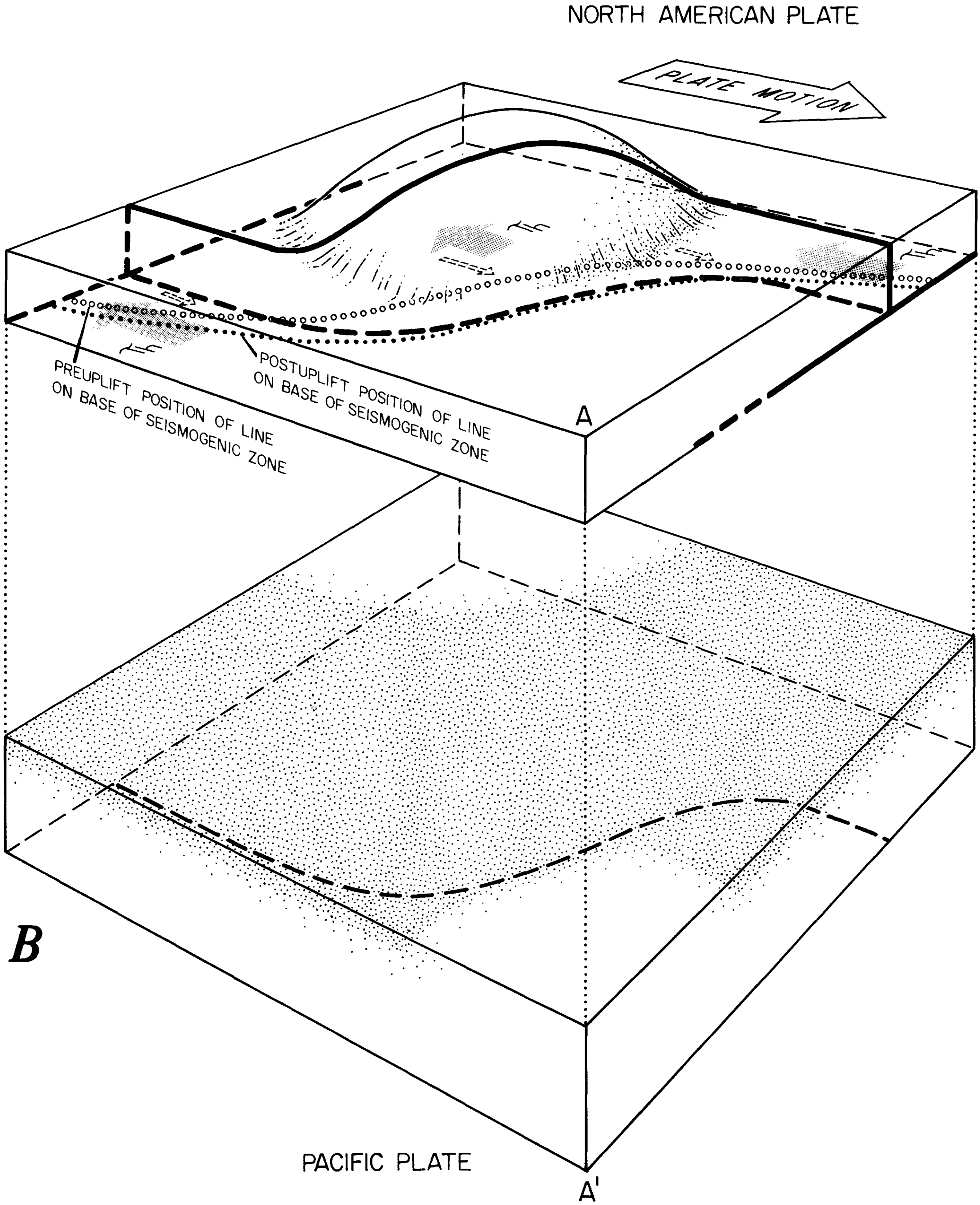


FIGURE 69.—Schematic representation of layered lithosphere astride the plate boundary in southern California. *A*, Preuplift. *B*, Postuplift. All movement is with respect to A-A', whose position and configuration are fixed. The shear stress along the east side of the vertical part of the San Andreas fault is indicated by $\bar{T}$; that along the seismogenic layer on the



B

subseismogenic layer of the horizontal part of the San Andreas is indicated by τ_h. The uplift is assumed to be the product of slip along the decoupling surface (or layer) between the seismogenic and subseismogenic layers. Relative displacements of upper layer indicated by dimensionless arrows. See text for details.

fault system and the decoupled zone—or through some combination of all of these. Because the maximum uplift associated with this postulated decoupling seems to have been about the same for each of the two historic uplift cycles, there may be some threshold load above which collapse may occur through flow within the low-viscosity layer (Castle, 1978). Moreover, the prevention of complete collapse could result from strain hardening set up within the low-viscosity layer during the uplift period. We hasten to add, however, that we see no reason why a general collapse should necessarily preclude further slip through the decoupled zone and, hence, the occurrence of localized uplift during or immediately following this general collapse.

The explanation we present here may be unrealistically idealized, and we probably would be well advised to simply dismiss the evolutionary complexities of the uplift as the products of unassessed variations and perturbations within the decoupled zone. However, several of the more evident second-order features may be significant to our understanding of the overall process. For example, Thatcher (1976, p. 693) observed that the southern California uplift nucleated immediately west of the southwestern end of the 1952 Kern County aftershock zone. If the slip event that produced the 1952 earthquake is viewed as underthrusting of the wedge defined by the White Wolf fault and the base of the seismogenic zone, it would tend to increase the gradient in τ_h westward from the rupture zone and load the horizontal fault in the area north of Ventura. Thus, there is some basis for arguing that the uplift should have nucleated in this area. Similarly, the early-20th-century uplift propagated well into the Peninsular Ranges province, whereas the southern boundary of the recent uplift is closely coincident with the active front of the Transverse Ranges. Thus, it seems to us that there is a significant likelihood that the recent uplift may have terminated on the south through slip along the frontal fault system and, hence, further loaded this potentially active series of faults.

CONCLUSION

We have attempted in this report to outline the evolution of the southern California uplift as clearly as the data permit, recognizing that our reconstruction almost certainly errs in detail. That is, we must contend not only with the possibility that some of the measurements may be systematically contaminated owing to the occasional use of a bad rod or local runs of unequal-refraction error, but also with the much more difficult problem associated with intrasurvey movement. Nonetheless, and in spite of persisting uncertainties surrounding the changing configuration of the uplift, the coherence of the reconstruction argues convincingly that the general pattern of vertical displacements described here is indeed real and not simply an artifact of the measurement system. This conviction is strengthened, moreover, by the 1978 general releveling of southern California which shows that nearly the entire uplift sustained a general collapse (Burford and Gilmore, 1984) remarkably similar to the collapse that followed its early-20th-century counterpart. To suggest that the measurements that defined the recent uplift and its partial collapse were characterized by cyclically distributed distortion of the same form and the same order as were those that defined the earlier episode, asks too much of coincidence. Moreover, the consistency of the pattern of uplift with the late Quaternary tectonic history of southern California strongly supports the existence of this feature, although obviously not its spasmodic growth and subsequent collapse.

The presumably cyclic phenomenon that produced the southern California uplift may be unique to this area and directly related to the very recent and certainly complex, if not convoluted, development of the San Andreas system in southern California. Regardless, those whose efforts are directed toward an improved perception of not only the recent tectonic history of southern California, but the orogenic process in general, can hardly ignore the significance of the episodic and spasmodic deformation that seems to have characterized the evolution of this feature.

Finally, how the uplift may be related to the evolving seismicity of southern California is no better understood than is the origin of the uplift itself. Specifically, the question that ultimately will be addressed and hopefully answered is whether this regionally developed uplift (as contrasted, for example, with the localized uplift that preceded the 1971 San Fernando earthquake) is directly or indirectly precursive to a large-magnitude earthquake. We are aware of no firm evidence indicating a one-to-one relation between the growth of the uplift and the temporally associated seismicity. Nonetheless, if our preferred explanation for the origin of the uplift retains any technically redeeming merit, the mere existence of the uplift suggests that the occurrence of a large-magnitude earthquake is especially enhanced in the region of either of the two major bends in the San Andreas fault or in the central section of the frontal fault system. For example, the horizontal slip that is postulated to have produced the uplift would tend to decrease the basal tractional stress through the central part of the uplift, yet could at the same time have armed the frontal fault system along its southern margin. Similarly, if we shift our reference to some point along the San Andreas (rather than to one outboard or west of the boundary zone and well within the Pacific plate—fig. 69), horizontal slip along the decoupled surface would tend to increase τ_h in the area west of the San Andreas and north of Ventura (or, and perhaps less likely, east of the San Andreas north of the Salton Trough). In either case, significant indications of the imminence of a large-magnitude shock in southern California may prove quite different than our earlier experience might have suggested. For example, if we accept both the Lachenbruch-Sass model and the reality of the uplift, the increasing frequency in either of the bend areas or along the frontal fault system of small relatively deep-focus (~12–15 km) earthquakes characterized by horizontal or shallow thrust solutions could be interpreted as foreshock activity precursive to a major seismic slip event in the higher crust. Similarly, a sudden acceleration in the contractional strain rate astride the frontal fault system, particularly were it associated with migrating tilt reversals of the sort that preceded the San Fernando earthquake (Castle and others, 1974, p. 64–65; Thatcher, 1976, p. 693–695), would suggest updip propagation of slip conceivably precursive to major seismic activity along one or more of the faults that make up this system.

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