Recent Surface Movements In the Baldwin Hills, Los Angeles County, California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 882

RECENT SURFACE MOVEMENTS
IN THE BALDWIN HILLS,
LOS ANGELES COUNTY,
CALIFORNIA

Oblique aerial view south-southeastward across the Baldwin Hills. (A) trace of the Inglewood fault; (B) Stocker Street–La Brea Avenue–Overhill Drive intersection; (C) highest point in the Baldwin Hills; (D) surface projection of structural high east of the Inglewood fault on surface 50 feet above Vickers-Machado zone of the Inglewood oil field (the Inglewood fault dips westward here); (E) surface projection of structural high west of the Inglewood fault on surface 50 feet above Vickers-Machado zone of the Inglewood oil field; (F) approximate location of bench mark Hollywood E–11; (G) approximate center of subsidence in the Baldwin Hills area as shown by Los Angeles Department of Water and Power leveling surveys conducted since 1950; (H) Baldwin Hills Reservoir. Photograph by Spence Air Photos, November 1952.

Recent Surface Movements In the Baldwin Hills, Los Angeles County, California

By ROBERT O. CASTLE *and* ROBERT F. YERKES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 882

A study of surface deformation associated with oil-field operations

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RECENT SURFACE MOVEMENTS IN THE BALDWIN HILLS, LOS ANGELES COUNTY, CALIFORNIA

By Robert O. Castle and Robert F. Yerkes

ABSTRACT

The Baldwin Hills comprise one of several isolated groups of hills extending along the Newport-Inglewood zone of folds and faults, a northwest-trending structural lineament identified with a series of highly productive oil fields. Surface deformation in the Baldwin Hills has been closely monitored since 1939. This deformation, which includes differential subsidence, horizontal displacements, and surface rupturing, is attributed virtually entirely to the exploitation of the spatially associated Inglewood oil field, located in the northern part of the hills.

The hills are underlain by gently to moderately arched and conspicuously faulted Cenozoic sedimentary and volcanic rocks that overlie crystalline basement at a depth of more than 10,000 feet. They are transected diagonally by the Inglewood fault, a major feature of the Newport-Inglewood zone. Evidence of recent and apparently continuing deformation is seen in the seismicity and elevation changes that characterize both the hills and their environs.

A well-defined, northwest-trending subsidence bowl enbracing the northwest part of the Baldwin Hills has been revealed through repeated levelings. Selected level lines have been reconstructed with respect to a common, relatively stable control point located at the edge of the subsidence bowl, in order to assess the subsidence since 1910 and 1911 at two points near the center of the bowl. Bench mark PBM 67 is estimated to have subsided 4.324 feet between June 1910 and February 1963; bench mark PBM 68 (the only one within the subsidence bowl that was leveled prior to 1926 and has been repeatedly leveled since) subsided 3.846 feet between November 1911 and June 1962. PBM 122, which has remained very close to the center of subsidence since at least 1950, is calculated to have subsided 5.67 feet between 1911 and 1963.

Horizontal displacements (with respect to an external base line) of six triangulation points within the subsidence bowl have been measured for various periods between 1934 and 1963. Displacements have been generally toward the center of subsidence and almost precisely perpendicular to the immediately adjacent isobases of equal elevation change. Maximum movement has been recorded at triangulation point Baldwin Aux, which was displaced 2.21 feet between 1934 and 1961; horizontal displacements of three other points ranged from 0.95 foot to 1.85 feet between 1936 and 1961. Displacements of 0.10–0.29 foot were recorded at all six monuments during the period 1961–63. Remeasurement of earlier survey traverses has shown that the peripheral part of the subsidence bowl is identified with radially oriented extensional horizontal strain and that the central part is associated with contractional or compressional horizontal strain.

"Earth cracks" and surficial fault displacements were recognized in the Baldwin Hills at least as early as 1957. The cracks are relatively straight, generally continuous fractures confined almost exclusively to the structural block east of the Inglewood fault; they are concentrated in two areas centering on (1) the Baldwin Hills Reservoir and (2) the Stocker Street–LaBrea Avenue–Overhill Drive intersection. The cracks trend north to north-northeast, are nearly everywhere parallel to or coincident with minor faults and joints, and are generally orthogonal to radii emanating from the center of subsidence. Differential movement along the cracks has been almost entirely dip slip along steep to nearly vertical surfaces, and generally down toward the center of subsidence. Cumulative displacements have been as much as 6 or 7 inches. Rates of displacement have varied widely, and the movement has generally occurred as creep or small discrete jumps. A probable exception is the several inches of differential movement that is believed to have occurred along a crack through the floor of the Baldwin Hills Reservoir on or about December 14, 1963.

Possible explanations for the contemporary surface movements include: (1) exploitation of the Inglewood oil field, (2) changes in the ground-water regimen, (3) compaction of sedimentary materials in response to surface loading, (4) tectonic activity, or (5) some combination of these.

The following considerations indicate that the differential subsidence is attributable largely or entirely to oil-field exploitation: (1) the coincidence among the centers of the oil field, the producing structure, and the subsidence bowl, (2) the general correspondence between the pattern of subsidence and the outlines of the oil field, (3) the approximate coincidence between the onset of production and the onset of subsidence, (4) the generally linear relations between various measures of subsidence and liquid production from both the field as a whole and the exceptionally prolific Vickers zone in particular, (5) the coincidence between the sharp deceleration of subsidence in the east block of the field and the beginning of full-scale waterflooding there, (6) the many other examples of spatial and temporal associations between oil-field production and subsidence, (7) the many similarities between the subsidence-production relations in the Inglewood field and those in the Wilmington field where a causal relation between oil-field operations and subsidence has been clearly documented, and (8) the recognized relation between subsidence or a tendency toward subsidence and declining reservoir pressure associated with underground fluid extraction.

Consideration of various possible explanations for the increasing rate of subsidence with respect to reservoir fluid pressure decline suggests that measured or calculated down-hole reservoir fluid pressure decline is unrepresentative of average or real fluid pressure decline away from producing wells. The near-linear relations between net liquid production and subsidence are explained by analogy with a tightly confined artesian system of infinite areal extent, where production must derive from liquid expansion and (or) reservoir

compaction. Test data from compaction studies in two other oil fields yield estimates of ultimate compaction of the Vickers zone resulting from a total loss of fluid pressure; the best estimate, based on these data and considerations of late Cenozoic history in the Baldwin Hills area, is about 10 feet.

The centripetally directed horizontal displacements and associated horizontal strain are also attributable to exploitation of the Inglewood oil field owing to: (1) their well-defined spatial and symmetrical associations with the differential subsidence, (2) the similarities between these associations and those developed in and around other subsiding oil fields, and (3) the mechanical compatibility of these movements with subsidence induced by the extraction of subsurface materials.

The earth cracks and surficial fault displacements are attributable largely or entirely to the exploitation of the Inglewood oil field owing to: (1) their spatial and temporal relations to both oil-field operations and the differential subsidence, (2) the similarities of these cracks and displacements to those generated in and around other oil fields and areas from which subsurface materials have been extracted, and (3) surface strain patterns deduced from the measured vertical and horizontal surface movements. The cracks and displacements are explained by a differential compaction model consistent with radially oriented extensional strain and elastic compression of the sedimentary section around the periphery of the subsidence bowl.

Analysis of the history of ground-water extraction within and around the Baldwin Hills and subsidence associated with water-level declines in sediments comparable with those in the Baldwin Hills indicates that the surface movements can be no more than incidentally attributed to changes in ground-water conditions. Similarly, analysis of the history of natural and artificial changes in surface loading indicates that these movements cannot be associated with changes in surface loading.

Considerations of local geologic history and various tectonic associations indicate that it is very unlikely that the differential subsidence and horizontal movements are due to tectonic downwarping. Although there exists a far stronger prima facie argument for tectonic involvement in the earth cracking and associated fault displacements, this argument is disputed by: (1) the spatial and temporal relations of the earth cracks to and their mechanical compatibility with the nontectonic differential subsidence, (2) the absence of displacements on the Inglewood fault in conjunction with those along the earth cracks, (3) the probability that branch or conjugate faulting would be characterized by strike- or oblique-slip displacements, (4) the incompatibility of postulated extensional faulting with contractional strain in the central part of the subsidence bowl, and (5) the absence of any clear temporal relation between crack growth and local seismicity. Because as much as about 10 percent of the local isobase gradient may be unexplained by oil-field exploitation, a small fraction of this gradient, and thus the displacements among the southern group of cracks, may have resulted from tectonic activity. However, this fraction could not have been significant in the absence of the strain pattern produced by nontectonic compaction of the underlying oil measures.

Because nearly all the described surface movements can be fully explained as the products of oil-field operations, yet can be no more than incidentally attributed to changes in ground-water conditions, surface loading, or tectonic activity, we conclude that these movements should be attributed largely or entirely to the exploitation of the Inglewood oil field.

INTRODUCTION

The Baldwin Hills occur within the northwestern part of the Los Angeles basin near the north end of the northwest-trending Newport-Inglewood zone (fig. 1). They occupy about 10 square miles and are roughly equidimensional in plan. Rising gently from the south and east and relatively steeply from the north and west, they stand about 350–400 feet above the surrounding basin lowland. The youthful physiographic character of the hills is clearly evident in their slight to moderate dissection and from the well-defined scarp of the Inglewood fault (frontispiece).

This report describes and analyzes historic surface deformation in the Baldwin Hills that had occurred through 1963. The described deformation includes well-defined differential subsidence centering on the Inglewood oil field, horizontal displacements directed toward the center of subsidence, and earth cracks and associated surficial fault displacements along the eastern margin of the subsidence bowl. Because these movements have been recorded in exceptional detail over a very long period, they comprise one of the most definitive and revealing examples of oil-field-associated surface deformation recognized to date.

The nature and magnitude of the continuing vertical movements have been defined by numerous repeated levelings, which were begun at least as early as 1910. Intelligent use of the resulting data, however, has required a reevaluation of the various datums and adjustments employed in the derivation of the many utilized elevations. Although knowledge of the horizontal movements and earth cracks is less detailed, both can be shown to be spatially and mechanically related to the differential subsidence. Each of the recognized types of surface movement, moreover, is clearly associated in space with operations in the Inglewood oil field. A temporal association with these operations, however, is less well defined, and the possible effects of ground-water extraction, surface loading, and tectonic activity have greatly complicated this analysis.

Abundant circumstantial evidence and various theoretical considerations indicate that both the differential subsidence and the horizontal displacements are due to withdrawal of fluids from the underlying Inglewood oil field. Neither the actual changes in ground-water and loading conditions nor their maximum conceivable effects can explain more than a very small fraction of the differential subsidence. Tectonic activity is considered an equally implausible explanation of the observed subsidence. Comparisons with similar examples elsewhere, limited circumstantial evidence, and mechanical compatibility with both the measured and deduced horizontal strain indicate that the earth cracks and associated fault displacements are also due largely to oil-field operations.

The surface deformation in the Baldwin Hills is compared in detail with that associated with the

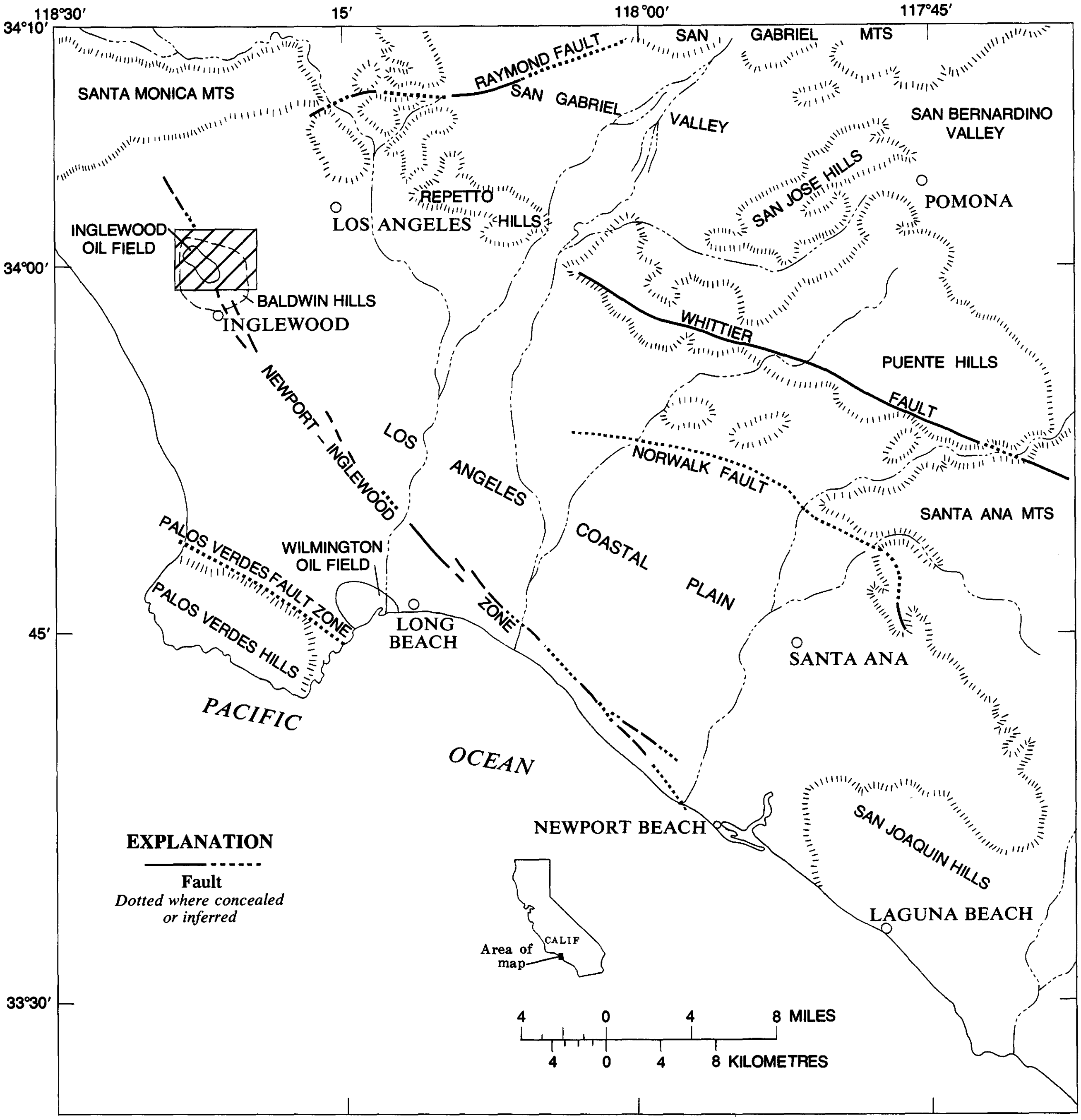

FIGURE 1.—Map of the Los Angeles basin showing location of the Baldwin Hills and major faults and physiographic features. Crosshatched area is shown on plates 2 and 4. Also shown are the approximate locations of the Inglewood and Wilmington oil fields. Modified after Woodford, Schoellhamer, Vedder, and Yerkes (1954, p. 66).

operation of other oil fields in order to evaluate the significance of the association in the Baldwin Hills. This report thus provides a comprehensive review of surface deformation associated with oil-field operations generally.

This paper supersedes an earlier version released as an open-file report (Castle and Yerkes, 1969). It differs from the earlier version chiefly in the presentation of data unavailable to us at the time of the open-file release and because it discusses studies of the problem published since 1969.

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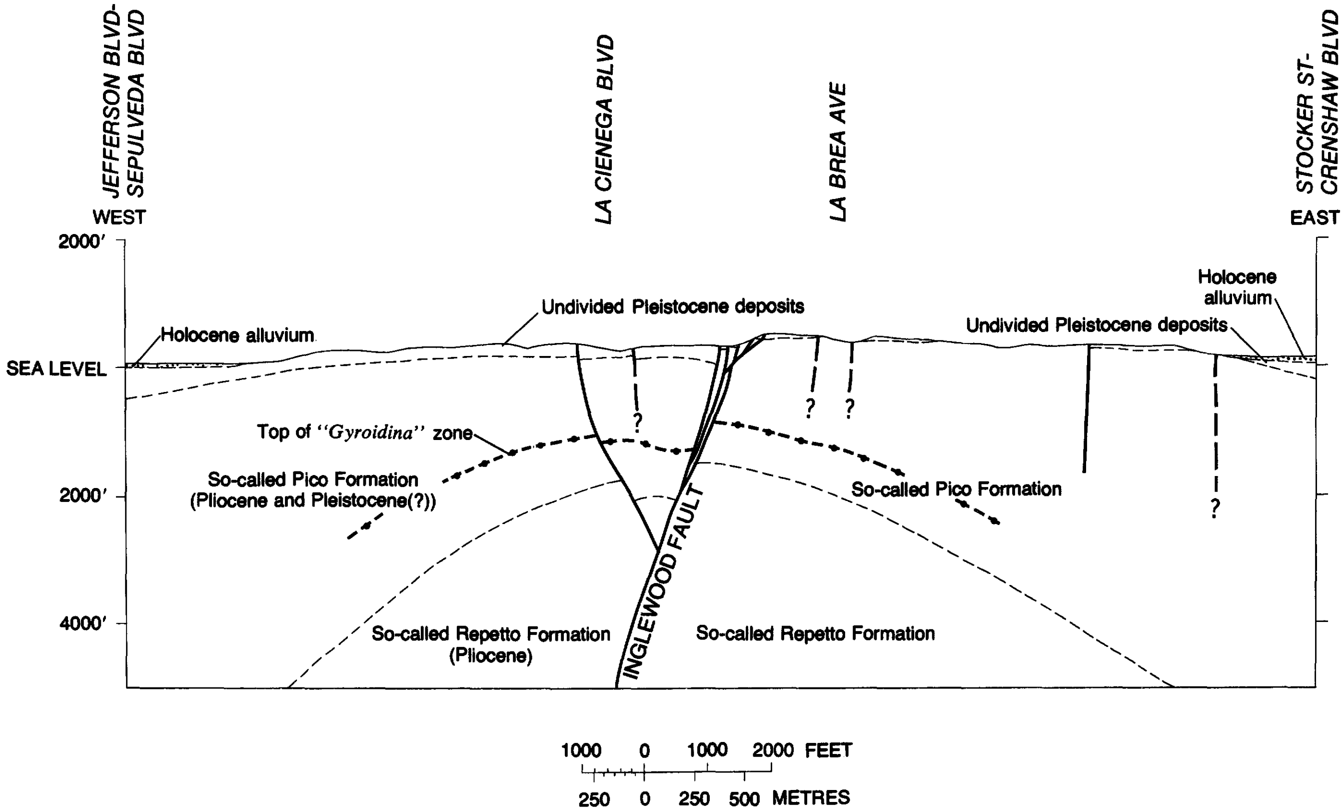

FIGURE 2.—Generalized geologic section of the northern Baldwin Hills normal to trend of the Inglewood fault. Based chiefly on surface mapping by Castle (1960); approximate location of top of "*Gyroidina*" zone, stratigraphic contacts, and major faults at depth projected from sections by Driver (1943, p. 307).

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GEOLOGY

The stratigraphic section underlying the Baldwin Hills is comprised of Tertiary and Quaternary sedimentary rocks and Tertiary volcanic rocks (pl. 1). The crystalline basement complex on which these rest lies more than 10,000 feet beneath the surface (Yerkes and others, 1965, p. A4, pl. 4). Units exposed at the surface consist entirely of Quaternary to uppermost Tertiary(?) sedimentary rocks (fig. 2). The oldest rocks cropping out in the Baldwin Hills are assigned to the so-called Pico Formation of Pliocene and Pleistocene(?) age. They consist chiefly of poorly consolidated marine silts and very fine sands together with local lenses of coarser sand and pebbly materials. This sequence is locally rich in clay, particularly along the northwest flank of the hills, and much of it is thinly laminated; dips exceed 35° locally but average considerably less. Overlying this silty unit, at least in part unconformably, is a predominantly marine sequence of Pleistocene age that is composed of unconsolidated, locally pebbly to cobbly, coarse to medium sand. This unit is characterized by relatively shallow dips of up to no more than 12°. A variety of upper Pleistocene and younger terrestrial deposits unconformably overlies all of these units. These younger deposits consist chiefly of unconsolidated to well indurated, very poorly sorted silts, sands, and gravels.

Deformation in the Baldwin Hills area may have begun during middle Miocene time (Reed and Hollister, 1936, p. 131; Yerkes and others, 1965, p. A48) or even earlier. It has continued at least intermittently through Quaternary time, as indicated especially by prominent fault scarps across the conspicuously arched upper Pleistocene units and the youthful dissection of the hills.

The hills resemble a gently arched, north-northwest-trending dome that has been bisected and offset along the line of the Inglewood fault (frontispiece). The summit of the eastern dome or block is about 2,500 feet south-southwest of bench-mark Hollywood E–11 (frontispiece); a broad, wedge-shaped area lying largely within 5 or 10 feet of the summit elevation extends for about 3,000 feet north and northwest from this highest point. This broad topographic apex is roughly coincident with the structural crest defined by several well-developed stratigraphic horizons of Pleistocene age. The structural crest that is defined by the upper Pliocene stratigraphic horizons is shown in figures 3 and 4; it lies about 5,000 feet south of the Pleistocene crest, and from 3,000 to 5,500 feet south of the physiographic summit area. Similar relations are shown in the western block as well. Hence, we infer that the fold crest may have migrated northward during a late Tertiary-early Quaternary interval.

The pattern of faults and joints developed at the surface (pl. 2) differs in detail from that inferred for the subsurface (figs. 3 and 4). The only difference between the two subsurface interpretations occurs in the southeastern part of the area where subsurface data from recently developed parts of the Inglewood oil field may have aided in the California Division of Oil and Gas interpretation (fig. 4). Significant differences exist, however, between the subsurface interpretations of both Driver (fig. 3) and the Division of Oil and Gas (fig. 4), and the fault pattern mapped at the surface (pl. 2). For example, the Inglewood fault is shown in the subsurface (figs. 3 and 4) as a relatively straight, throughgoing feature, whereas surface mapping (pl. 2) indicates a good deal of structural complexity in the vicinity of the La Brea Avenue–Stocker Street–Overhill Drive intersection. Other discrepancies may be only apparent and may be due simply to inclination of fault surfaces or generalization of the structure at depth.

Displacements of thousands of feet have occurred along the major north-northwest-trending faults in the Baldwin Hills area, whereas displacements on many of the shorter, north to north-northeast-trending subsidiary faults may have been no more than a few feet. Major lateral displacements have been postulated along both the Inglewood fault (Driver, 1943, p. 308) and the Newport-Inglewood fault zone (Hill, 1954, p. 10). Driver has observed that the attitudes of striae in many drill cores indicate a larger component of horizontal than vertical movement, and Hill has deduced right-lateral movement of several miles along the Newport-Inglewood zone on the basis of electric log correlations. Right-lateral displacement along the Inglewood fault of at least 3,000–4,000 feet since middle or late Pliocene time is indicated by the apparent offset of the structural crests on both the top of the "*Gyroidina*" zone (fig. 3) and the nearly stratigraphically equivalent horizon contoured in figure 4. Right-lateral displacement of 1,500–2,000 feet during Quaternary time is suggested by the apparent topographic offset of the hills along the Inglewood fault (frontispiece).

In spite of the fairly abundant evidence of lateral displacements on the Inglewood fault during the geologic past, positive indications of very recent lateral movements have not yet been adduced. Moreover, relatively recent vertical separations of up to at least 200 feet, indicated both by offsets of Pleistocene deposits (Castle, 1960) and the well-developed scarp along the Inglewood fault (frontispiece), imply a possible change in the sense of movement during latest Quaternary time. Right-lateral displacements of 100–150 feet are suggested, however, by offset stream channels along the trace of the Inglewood fault, about 1 mile south of the north edge of the hills. Because the offset stream channels are well incised within the fault scarp, it is likely that right-lateral movements have postdated or accompanied the scarp-forming displacements (whether predominantly dip slip or not). The only other information bearing on the sense of recent movement along the Newport-Inglewood zone derives from examination of seismograms produced by the Dominguez Hills earthquake of 1944 (Martner, 1948). According to Martner (1948, p. 118), "study of the compressions and dilatations of first motion at the various stations* * * is in perfect agreement with the general movement of the region, namely, a differential movement in a northwest direction on the west side and southeast on the east side of the main Inglewood fault zone." Thus, although the data are inconclusive, it is likely that the style of movement along the Newport-Inglewood zone has remained essentially right lateral.

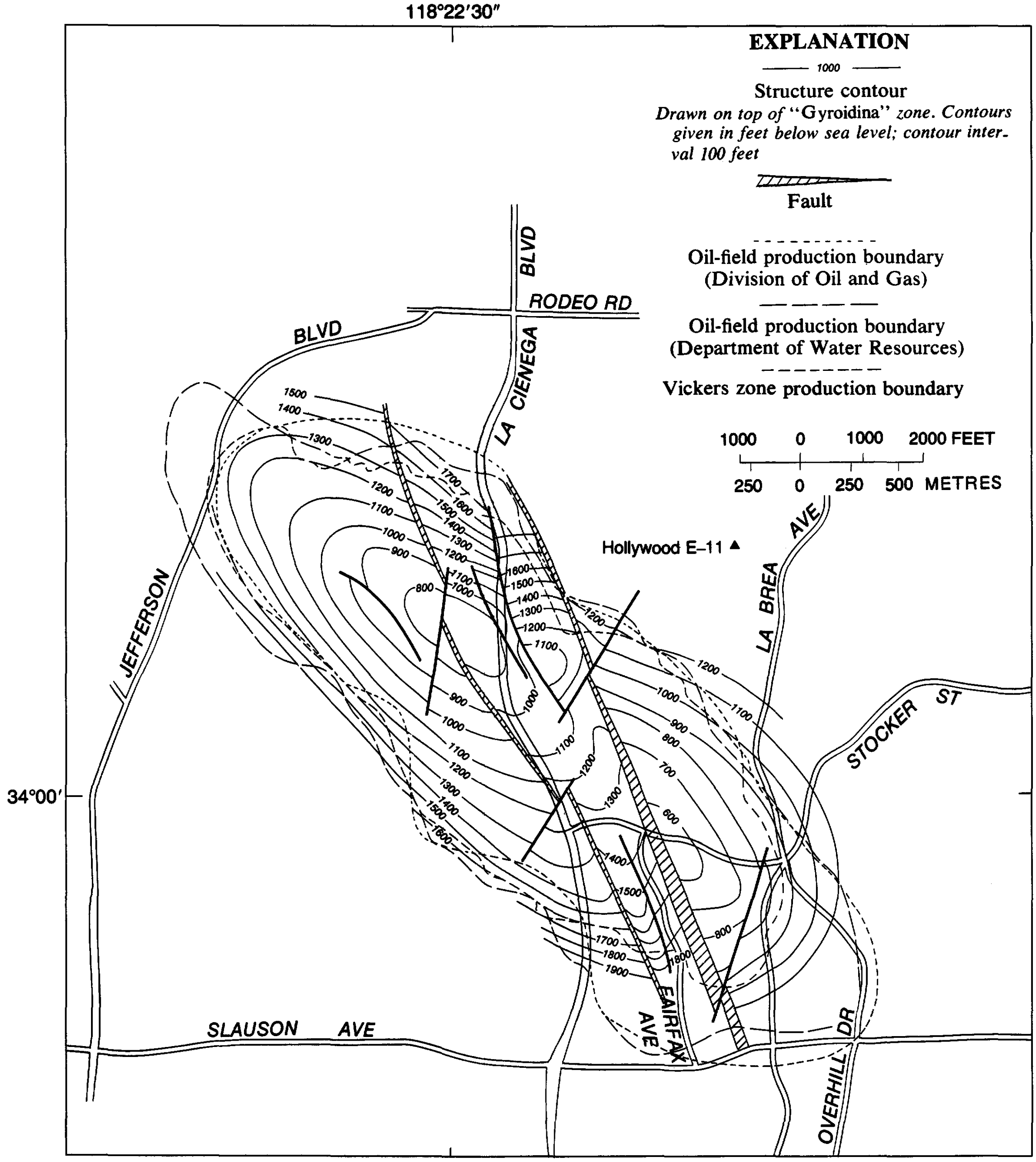


FIGURE 3.—Structure contour map on top of the "*Gyroidina*" zone of the Inglewood oil field (Driver, 1943, p. 307). Oil-field production boundaries after California Division of Oil and Gas (1961, p. 576) and California Department of Water Resources (1964, pl. 8); Vickers zone production boundary after California Department of Water Resources (1964, pl. 16).

SEISMICITY

Although the relation between seismicity and geologic structure in the area of the Los Angeles basin seems to be poorly developed (Allen and others, 1965, p. 769–772, pl. 1), there exists at least one exception to this generalization. Thus, the association between the Newport-Inglewood zone and the seismicity within the Los Angeles basin for the period January 1, 1934–March 31, 1963 is fairly clearly defined, particularly along the southern projection of this zone (pl. 3). Furthermore, of the four largest earthquakes known to have originated in this area prior to 1934 (that is, the 1769 "Olive," the 1812 San Juan Capistrano, the 1920 Inglewood, and the 1933 Long Beach shocks), all but perhaps the "Olive" probably were generated along the Newport-Inglewood zone (Richter, 1958, p. 67, 466, 469, and 472). Hence, the epicenters shown on plate 3, coupled with the distribution of the pre-1934 major earthquakes, identify a band of seismicity that coin-

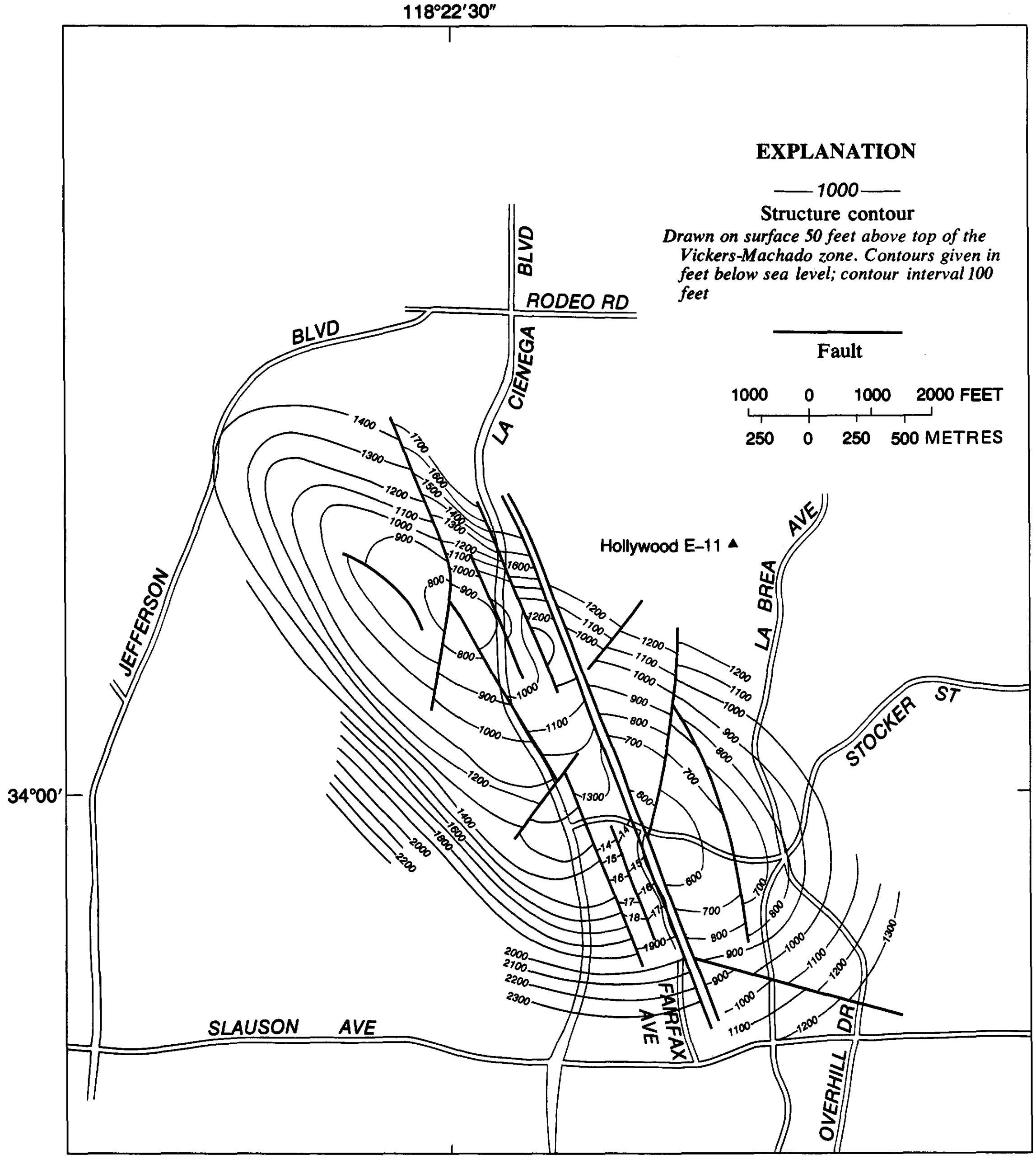


FIGURE 4.—Structure contour map on surface 50 feet above the Vickers-Machado zone of the Inglewood oil field (California Division of Oil and Gas, 1961, p. 576). (Note: Several obvious errors occur near the crest of the structure where contours are either missing or numbered incorrectly or where a fault has been represented improperly. No attempt has been made to investigate the source of these errors since they do not affect the general presentation.)

cides roughly with the Newport-Inglewood zone and attests to continuing tectonic activity along this zone.

The Inglewood earthquake of June 21, 1920, probably was the largest earthquake to have originated in the Baldwin Hills area during historic time. Field investigation by Taber (1920, p. 133) indicated that this shock had an intensity of about "eight and one-half on the Rossi-Forel scale," and its magnitude has been estimated by C. F. Richter (written commun., 1966) at M 5–5½. The epicenter was located in the Inglewood area (Taber, 1920, p. 137), and the shock has been attributed to movement on a major fault within the Newport-Inglewood zone, about 1 mile east of the center of Inglewood (Kew, 1923, p. 158). Richter (1958, p. 67, 474), on the other hand, has attributed the earthquake simply to movement on the "Inglewood fault," or what we identify here as the Newport-Inglewood zone. Taber (1920, p. 137) discovered no evidence of surficial fault

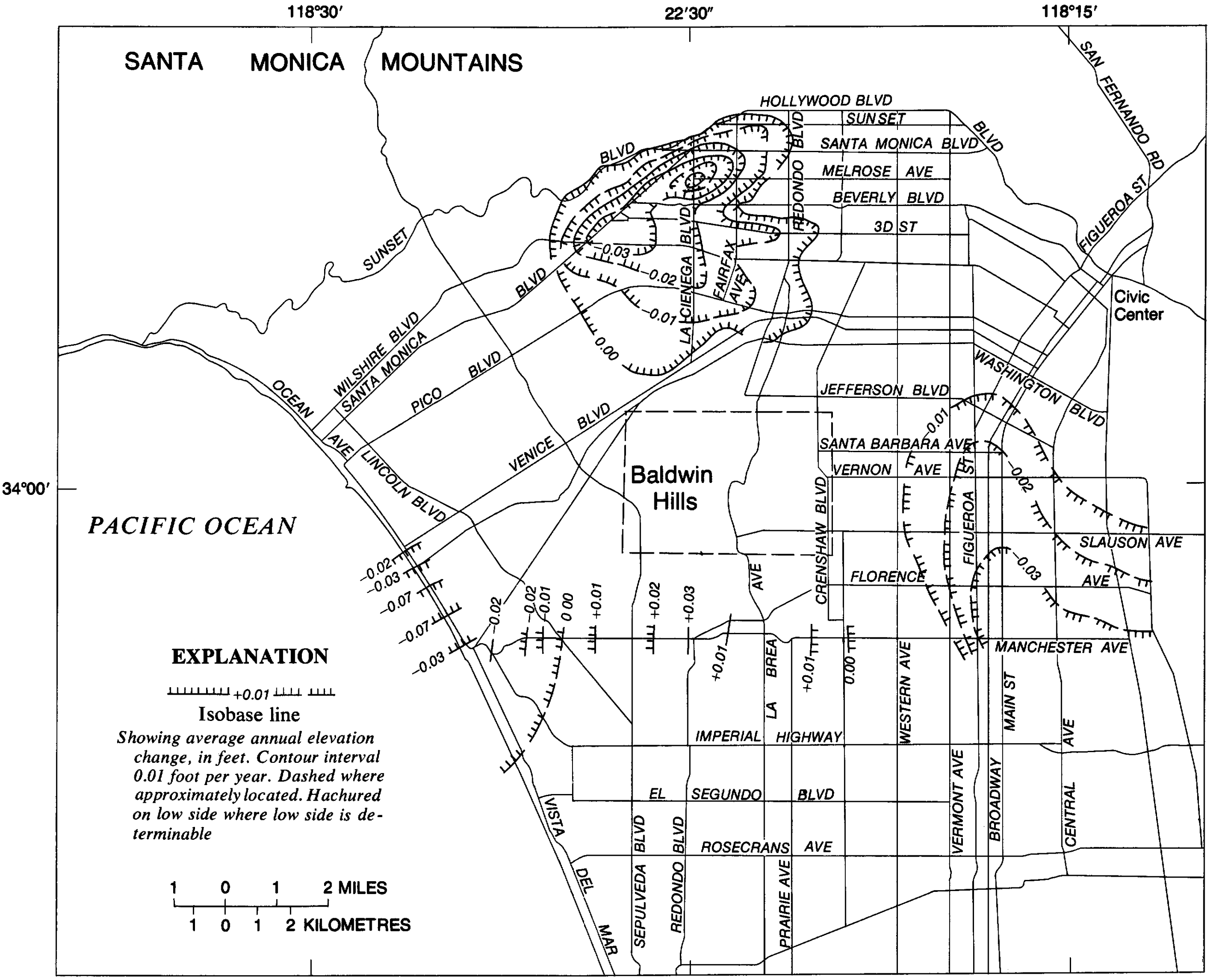


FIGURE 5.—Average annual rates of elevation change of parts of the Los Angeles basin with respect to BM 37–54–26; based on data collected between 1925 and 1938. Modified after Grant and Sheppard (1939). Box shows area of plates 2 and 4.

displacements, nor are there any other reports of surface cracks, mole tracks, or similar ground effects developed during this earthquake. Thus, the most important tectonic event associated with the northern part of the Newport-Inglewood zone during historic time apparently was unaccompanied by surficial faulting or other ground effects that might have simulated faulting.

REGIONAL ELEVATION CHANGES

The historic pattern of vertical movements over large sections of the Los Angeles basin has been described by several writers.[1] Grant and Sheppard (1939), working with very limited data, defined three areas of relative subsidence and one of relative uplift (fig. 5). The average annual elevation changes contoured in figure 5 were calculated with respect to bench mark 37–54–26 (S–32 equivalent—see prefatory note, appendix C), located at the old Los Angeles County Court House. However, the periods of time on which these calculations are based ranged from about 4 to about 12 years. Accordingly, comparisons from point to point within the map area are significant only to the extent that the average rates of vertical movement remained constant over the total period of observation. Although Grant and Sheppard were able to delineate broad areas of subsidence both

[1]The measured elevation changes considered in this paper derive from levelings employing conventional instruments and techniques. All the level lines are assumed to have been surveyed with equal precision. We have made no attempt to evaluate the accuracy of the actual field measurements, despite the fact that the quality of both instrumentation and surveying practices doubtlessly varied. This approach assumes that an unbiased selection of level surveys should produce neither positive nor negative measurement bias. This assumption of equal precision among the separate surveys does not necessarily extend to the applied adjustments or to particular elevation determinations.

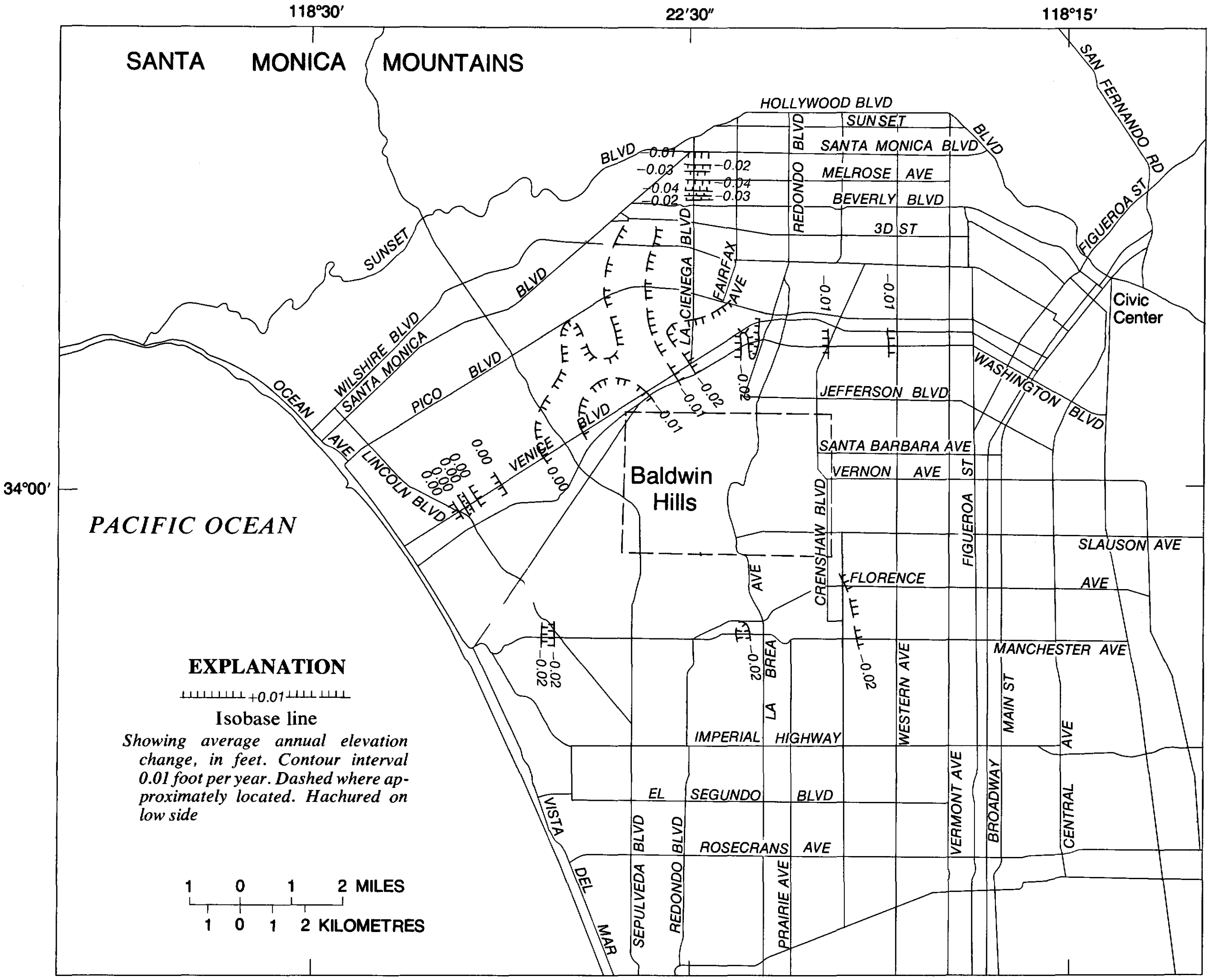


FIGURE 6.—Average annual rates of elevation change of parts of the Los Angeles basin with respect to Los Angeles (City) Bureau of Engineering datum, between 1949 and 1955. Compiled by the writers from record elevations given in the precise bench mark index of the Los Angeles Bureau of Engineering. Box shows area of plates 2 and 4.

north and east of the Baldwin Hills (fig. 5), the part of the basin just northeast of the hills did not appear to be subsiding. The only (relatively) positive movement noted by Grant and Sheppard was detected along the east-west Manchester Avenue line, immediately south of the Baldwin Hills (fig. 5). Because the axis of this positive movement was crossed by only one level line, its trend could not be specified; any extension north of Manchester Avenue, however, would have to be generally north-northeastward or northwestward.

Stone (1961, p. 58) has evaluated the elevation changes deduced from repeated surveys "for more than 9,000 stations leveled over the past 25 years by the Los Angeles City Engineer"; however, neither the datum(s) to which these elevation changes were referred nor the time intervals over which they were observed has been specified. He concluded that in general the areas "within late Quaternary sedimentary basins are subsiding, while some foothill stations are rising" and that "even minor features of local geology affect the rates of movement."

We have calculated elevation changes along selected level lines of the Los Angeles Bureau of Engineering for the period 1949–55 (fig. 6) in order to: (1) examine the later history of movement along several of the lines employed by Grant and Sheppard, and (2) bracket the Baldwin Hills with level surveys that fix the geographic limits of the unusually rapid elevation changes developed there in recent years. The elevation changes shown in Figure 6 and those calculated by Grant and Sheppard were both derived from adjusted record elevations; they differ, perhaps significantly, in that the

1949 and 1955 record elevations of the Los Angeles Bureau of Engineering have been adjusted with respect to two or more datum control points, whereas earlier elevations derived by the Los Angeles Bureau of Engineering in this area were adjusted with respect to a single control point (Los Angeles Bureau of Engineering, Precise Bench Mark Index, p. 4, 20). Because the elevations of the control points themselves may have been changing with respect to each other (changes currently believed to be small—see prefatory note, appendix C), subtle differences can be expected in the apparent patterns of vertical movement shown in figures 5 and 6. Differences in adjustment procedure during the separate survey periods may explain in part, for example, the apparent occurrence of regionally developed subsidence along Manchester Avenue between 1949 and 1955, as contrasted with the gentle uplift developed along this same reach prior to 1939 (compare figs. 5 and 6).

Although detailed point-to-point comparisons of the results of these two comparative elevation studies (figs. 5 and 6) would be futile, a few general observations can be made: (1) the prominent subsidence along La Cienega Boulevard south of the Santa Monica Mountains seemingly has persisted through the two survey periods, even though the area of subsidence has certainly contracted and changed in its general configuration. (2) Elevation changes along Venice Boulevard have remained small through both survey periods. (3) Although generally subsiding since 1949 with respect to the Los Angeles Bureau of Engineering datum, Manchester Avenue has remained free of significant differential subsidence, yet no longer shows evidence of local uplift. (4) The nose or axis of relative uplift that extends southeast from Pico Boulevard toward the Baldwin Hills (fig. 6) may have developed since the first survey period or been unrecognized earlier owing to inadequate data.

The causes of the apparent elevation changes represented in figures 5 and 6 are not understood in detail; these movements are characterized, however, by several revealing associations. (1) When taken together, the positive movement along Manchester Avenue (fig. 5) and the nose of uplift extending southeast from Pico Boulevard (fig. 6) define a north-northwest-trending axis of relative uplift that roughly parallels the Newport-Inglewood zone (fig. 1). Along its southern extension, however, this axis of vertical movement is displaced 1–2 miles west of the Newport-Inglewood zone. (2) The conspicuous subsidence along the coast, between Venice Boulevard and Manchester Avenue (fig. 5), centers on the main producing area of the Playa del Rey oil field; this area probably is not associated with significant reductions in ground-water levels or tectonic downwarping (Grant and Sheppard, 1939, p. 313–319; California Department of Water Resources, 1962, pls. 11A–11C). Grant and Sheppard (1939, p. 319) conclude, accordingly, "that the subsidence in the Venice–Playa del Rey area is a local movement due to the development of the oil field." (3) The area of extensive subsidence east of Western Avenue (fig. 5) lies toward the north end of the flat, featureless Los Angeles plain. Thus the axis of this subsiding area coincides, in a general way, with the structural axis of the basin and the area of most intensive recent alluviation. These considerations suggested to Grant and Sheppard (1939, p. 323–324) that this subsidence might be due to differential compaction of the recent sediments, coupled with some structural downwarp. (4) The subsidence field centering on La Cienega Boulevard, immediately south of the Santa Monica Mountains, is not clearly associated with any single phenomenon. The east-central salient of this subsiding area coincides in part with the old Salt Lake oil field (fig. 7), but the most pronounced subsidence (along La Cienega Boulevard) lies about 2,000 feet north of the nearest oil well in the northwest corner of the field (Grant and Sheppard, 1939, p. 307). Nearly the entire subsidence domain, however, is one in which there may have been major changes in the ground-water regime during the period immediately preceding the levelings from which figure 5 was constructed (Grant and Sheppard, 1939, p. 310) and is one which has since been characterized by large reductions in measured ground-water levels (California Department of Water Resources, 1962, pls. 11A–11C). However, there seems to be little correlation between the area of greatest subsidence and those of either maximum water-level declines—at least within the shallow aquifers (California Department of Water Resources, 1962, pl. 11A, 11C)—or maximum aquifer thickness (California Department of Water Resources, 1961, pl. 3A, 6G). Thus, in spite of the suggestive associations, fluid extraction seems to be an incomplete explanation for the La Cienega subsidence. Grant and Sheppard (1939, p. 311–312) suggest that tectonic forces may have contributed to the origin of this feature, a suggestion strengthened by more recent information. The generally south-sloping buried erosion surface that underlies the surficial deposits of this area, has been folded into an east-northeast-trending syncline that coincides roughly with the northern and most conspicuously developed part of the subsiding area (fig. 7). Hence this syncline, which is bounded on the north by the frontal fault of the Santa Monica Mountains and on the south by the structural high of the Salt Lake oil field, is apparently attributable to relatively recent downwarping between the structures underlying its flanks.

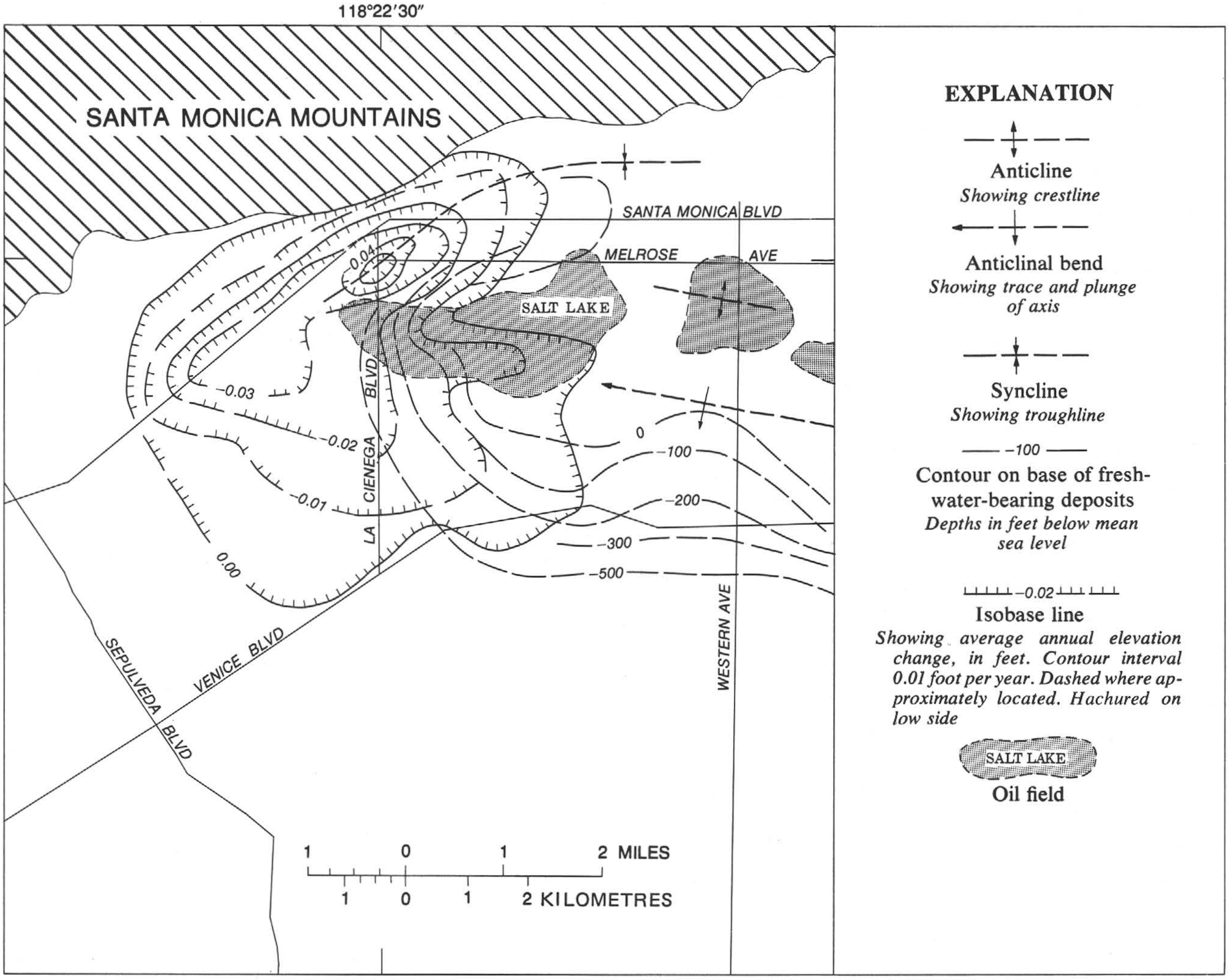


FIGURE 7.—Contours on the base of freshwater-bearing deposits (California Department of Water Resources, 1961, pl. 24A and 24B) and average annual rates of elevation change between 1925 and 1938 in the La Cienega Boulevard area of Los Angeles. (See fig. 5.) Axis of syncline adjacent to Santa Monica Mountains from California Department of Water Resources (1962, pl. 3A). Locations of oil fields from California Division of Oil and Gas (1961, p. 652) and Crowder (1961, pl. 3).

ELEVATION CHANGES ALONG CONTROL LINES THROUGH THE BALDWIN HILLS AND ENVIRONS

During 1939 and 1943 a series of level lines were established or releveled in the Baldwin Hills area by the Los Angeles Department of Water and Power (Hayes, 1943, p. 1–2, 4, 7–8). The locations of the three longest of these lines are shown in figure 8; a detailed history of each of the three is given in appendix A.

Elevation changes along lines A, B, and C (fig. 8) can be related to those elsewhere in the northwestern Los Angeles basin in several ways, but they are related most simply and directly through a U.S. Coast and Geodetic Survey monument located at the intersection of Crenshaw Boulevard with the Atchison, Topeka, and Santa Fe Railway. According to Hayes (1943, p. 5) the Los Angeles Bureau of Engineering "had not detected any appreciable elevation change [at the Crenshaw Boulevard–AT&SF intersection] between the years 1933 and 1936," an observation that accords with the pre-1939 elevation changes shown in figure 5. Because the elevations derived by the Los Angeles Bureau of Engineering for the southern area between 1933 and 1949 were adjusted with respect to the single datum control point at the Civic Center (Los Angeles Bureau of Engineering, Precise Bench Mark Index, p. 20), and because the Crenshaw Boulevard–AT&SF bench mark has remained demonstrably stable with respect to the Civic Center datum control point—at least between the years 1933 and 1936—it follows that elevation changes derived through comparisons with the Crenshaw Boulevard–AT&SF bench mark may be compared directly with those derived from the Civic Center datum control point (that is, those shown in fig. 5). The 1949–55 elevation changes represented in figure 6 are less easily

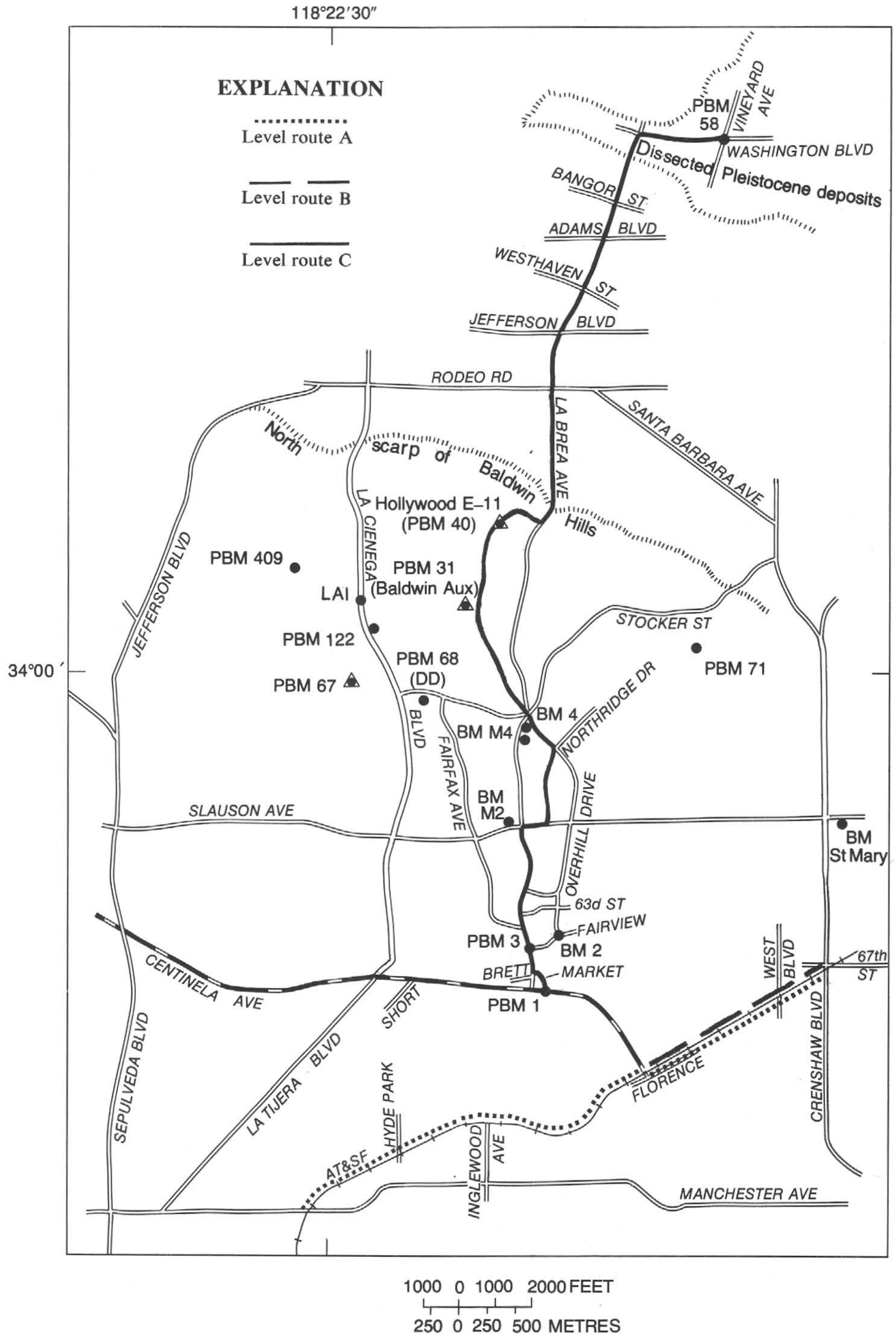


FIGURE 8.—Approximate routes of level lines A, B, and C. After Hayes (1943, fig. 1).

compared with those along the Department of Water and Power control lines for two reasons: (1) the record elevations used in the construction of figure 6 were derived with respect to two or more control points (Los Angeles Bureau of Engineering, Precise Bench Mark Index, p. 20); and (2) they were determined for a period in time (1949–55) relatively remote from the 1933–36 interval of demonstrable stability at the Crenshaw Boulevard–AT&SF intersection.

Level lines A and B (figs. 8, 9, and 10) are tied directly to the Crenshaw Boulevard–AT&SF bench mark; elevation changes along these lines can be compared directly with those derived from the Civic Center control point. Changes along line C (figs. 8 and 11), on

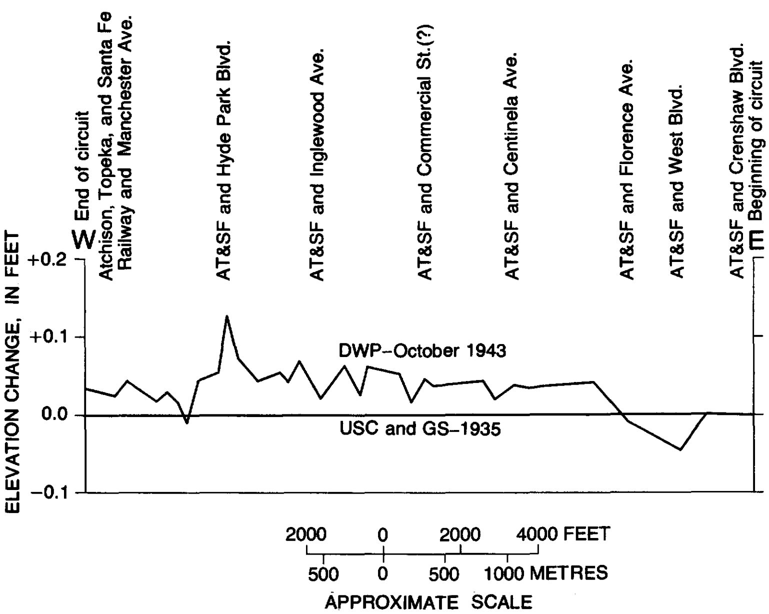


FIGURE 9.—Changes in elevation along level line A between 1935 and 1943. Based on leveling of the U.S. Coast and Geodetic Survey and the Department of Water and Power (formerly the Bureau of Water Works and Supply), City of Los Angeles. After Hayes (1943, fig. 2).

the other hand, can be compared with those determined by the Los Angeles Bureau of Engineering elsewhere in the Los Angeles basin only through the medium of PBM 1 and level line B (or, alternatively, though less simply, PBM 58—see appendix C, PBM 40, II.).

Several generalizations can be made concerning the elevation changes recorded along level lines A, B, and C. Lines A and B (figs. 9 and 10) both show uplift with

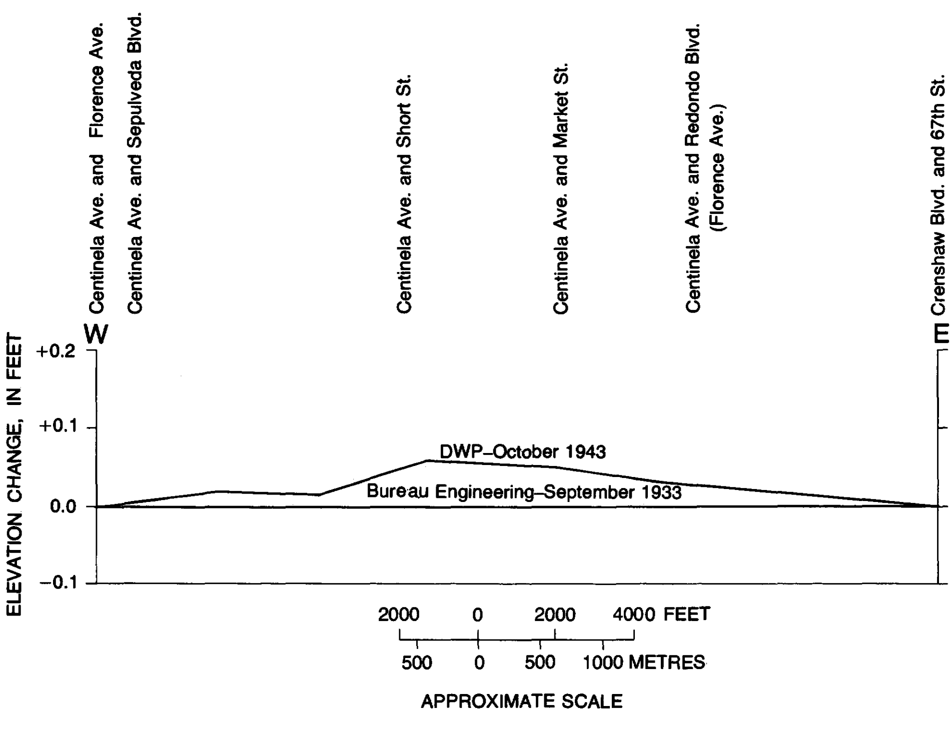
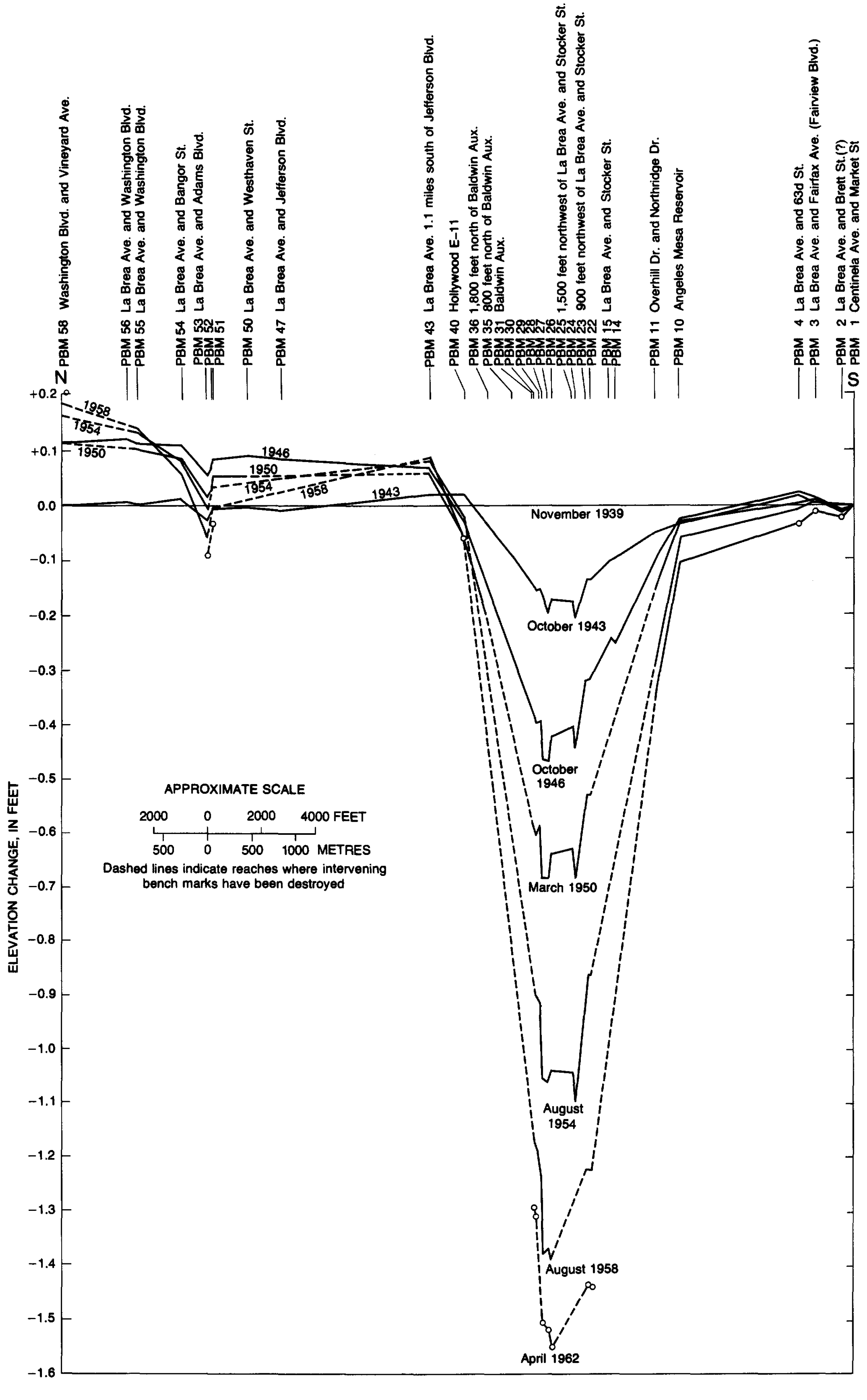


FIGURE 10.—Changes in elevation along level line B between 1933 and 1943. Based on leveling of the Bureau of Engineering and the Department of Water and Power (formerly the Bureau of Water Works and Supply), City of Los Angeles. After Hayes (1943, fig. 3).



N
PBM 58 Washington Blvd. and Vineyard Ave.
PBM 56 La Brea Ave. and Washington Blvd.
PBM 55 La Brea Ave. and Washington Blvd.
PBM 54 La Brea Ave. and Bangor St.
PBM 53 La Brea Ave. and Adams Blvd.
PBM 52
PBM 51
PBM 50 La Brea Ave. and Westhaven St.
PBM 47 La Brea Ave. and Jefferson Blvd.
PBM 43 La Brea Ave. 1.1 miles south of Jefferson Blvd.
PBM 40 Hollywood E-11
PBM 36 1,800 feet north of Baldwin Aux.
PBM 35 800 feet north of Baldwin Aux.
PBM 31 Baldwin Aux.
PBM 30
PBM 29
PBM 28
PBM 27
PBM 26
PBM 25 1,500 feet northwest of La Brea Ave. and Stocker St.
PBM 24
PBM 23 900 feet northwest of La Brea Ave. and Stocker St.
PBM 22
PBM 15 La Brea Ave. and Stocker St.
PBM 14
PBM 11 Overhill Dr. and Northridge Dr.
PBM 10 Angeles Mesa Reservoir
PBM 4 La Brea Ave. and 63d St.
PBM 3 La Brea Ave. and Fairfax Ave. (Fairview Blvd.)
PBM 2 La Brea Ave. and Brett St.(?)
PBM 1 Centinela Ave. and Market St
S
ELEVATION CHANGE, IN FEET
+0.2
+0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
−0.7
−0.8
−0.9
−1.0
−1.1
−1.2
−1.3
−1.4
−1.5
−1.6
1958
1954
1950
1946
1943
November 1939
October 1943
October 1946
March 1950
August 1954
August 1958
April 1962
APPROXIMATE SCALE
2000 0 2000 4000 FEET
500 0 500 1000 METRES
Dashed lines indicate reaches where intervening bench marks have been destroyed

respect to the Crenshaw Boulevard–AT&SF bench mark. Line B shows a seemingly smoother pattern of elevation changes, but the more erratic pattern of elevation changes along line A may reflect either the greater number of stations recorded along this route or its location along the possibly less stable right-of-way of the railway. When taken together, the points of maximum relative uplift along level lines A and B define an essentially north-south line between a point approximately 3,000 feet east-northeast of the Manchester Avenue–AT&SF intersection and a second point approximately 1,000 feet east of the La Tijera Boulevard–Centinela Avenue intersection.

Level line C (fig. 11) has been characterized since 1939 by a general pattern of moderate uplift (with respect to PBM 1) over its northern half and by pronounced subsidence over most of the remainder. The north end of line C (at least since 1946—see appendix A, III.) is identified with down-to-the-south tilting about an axis lying roughly midway between Washington and Adams Boulevards. The southern boundary of this tilted block is marked by a sharp break in the profile of elevation changes, PBM 53 having subsided about 0.07 foot more than PBM 51, which lies several hundred feet to the south. This break coincides with a small differential subsidence trough between Adams Boulevard and Bangor Street. The other narrow subsidence troughs shown in profile C (fig. 11), particularly within the reach of major subsidence between PBM 10 and PBM 43, probably derive from local backward legs in the line of leveling (bench marks PBM 29, PBM 30, and PBM 31, for example, are geographically inverted from their positions as represented in fig. 11—Walley, 1963, fig. 1). Since 1946 there has been an increasing loss of survey stations, such that later relevelings suggest a progressively, smoother pattern of elevation changes.

The elevation changes represented in figures 9, 10, and 11, show several associations comparable with those shown in figures 5 and 6. (1) The essentially north-south line defined by the point of maximum uplift along level lines A and B (figs. 9 and 10) is subparallel to and about 1 mile west of the physiographic and structural axis of the Newport-Inglewood zone. (2) The south end of line C (PBM 1), which has been uplifted moderately with respect to the Crenshaw Boulevard–AT&SF bench mark (fig. 8), lies almost directly over the center of the Newport-Inglewood zone. (3) The uplifted end of the apparently southward tilted block along line C lies somewhat above the general level of the nearby basin, along a roughly east-west trending ridge of dissected Pleistocene fan or terrace deposits. An aeromagnetic profile trending about N. 50° E across this ridge (Schoellhamer and Woodford, 1951) shows a sharp break about 1 mile southeast of PBM 58, coinciding roughly with the scarp along the southern margin of the dissected Pleistocene deposits and suggesting relatively elevated basement rock on the north. A simple Bouguer gravity map (McCulloh, 1957) tends to corroborate the aeromagnetic data; it shows a gradient steepening upward toward the north beyond a line that approximates the southern margin of the dissected Pleistocene deposits. Furthermore, a well drilled in 1960 about one mile east of PBM 58, bottomed in "slate" at the surprisingly shallow depth of 5,506 feet (Popenoe, 1960, p. 913). (4) The zone of prominent subsidence along level line C coincides both with the east edge of the Inglewood oil field (fig. 3) and the most elevated part of the Baldwin Hills.

FIGURE 11.—Changes in elevation along level line C between 1939 and 1962. Line C was not releveled during the 1962 leveling owing to the destruction of many of the original bench marks; elevation changes at remaining points formerly included with level circuit C and now shown by the Department of Water and Power with level line E are indicated by the circled dots of the 1962 survey. PBM numbers refer to precise bench-mark numbers assigned by the Department of Water and Power. Modified after Hayes (1959, fig. 2) and Walley (1963, fig. 2–A).

ELEVATION CHANGES

Elevation measurements in the northern Baldwin Hills date from the end of the nineteenth century (U.S. Geological Survey 15-minute topographic maps of the Redondo, 1896, and Santa Monica, 1902, quadrangles). These early elevation determinations are of limited value, however, for they were derived through relatively inaccurate vertical-angle measurements.

Although a number of level surveys have since been run through the Baldwin Hills, most of these have employed separate datums, thereby precluding direct comparisons among the individual surveys; that is, there is no prima facie basis for assuming that a particular datum control point will remain unchanged in elevation with respect to a second control point. Thus, much of our effort has been directed toward the reduction of pertinent level data to a common datum.

Bench mark S–32 (located in the Los Angeles Civic Center area; see prefatory note, appendix C), together with its resets or nearby derivatives, has been adopted as a primary datum control point because it has proved to be the most convenient (and perhaps the only) control point permitting comparisons among many of the level surveys through the northern Baldwin Hills. However, because the vertical movements recognized in the Baldwin Hills are, in any ultimate sense, relative movements, it is not only sufficient but highly desirable that the measured movements be described with respect to a local control point bordering or immediately external to the described system—in this case, the differential subsidence centering in the northern Baldwin Hills. This control point, in turn, need only have been characterized by a history of relative stability with respect to the framework immediately adjoining the identified system. Attempts to relate the measured vertical movements to "absolute" datums (see, for example, Leps, 1972; Casagrande and others, 1972), such as distant bench marks referred to 1929 Mean Sea Level, are generally no more than exercises in futility. Such attempts compound the imperfections in the method (by increasing unnecessarily the level-line length and enhancing the likelihood of large time gaps at junction points) and obscure the existence of significant intrasystem relative movements (through the inclusion of movements properly assigned to the system of next highest order—in this case, either the Newport-Inglewood zone or the Los Angeles basin).

The elevations of two secondary control points have been used as local datums; vertical movement at these control points with respect to S–32 is determinable through repeated levelings of the Los Angeles Bureau of Engineering and the Los Angeles Department of Water and Power. These secondary control points are: (1) PBM 58 (also designated as 10–W and 12–01050 by the Los Angeles Bureau of Engineering), located at the intersection of Washington Boulevard and Vineyard Avenue in Los Angeles (fig. 8); and (2) Hollywood E–11 (also designated as PBM 40 by the Los Angeles Department of Water and Power), together with its several resets, located near the north edge of the Baldwin Hills (fig. 8).

PBM 58 has served as the northern terminus for level line C, which has been used by the Department of Water and Power since 1939 as a basic elevation control line. It has remained relatively stable through time, having subsided at an average rate of only about 0.00841 ft/yr with respect to S–32 between 1933 and 1960 (see appendix C, Hollywood E–11, II.C.1.). Hollywood E–11 (or one of its resets) has, since 1939, been used as a reference bench mark within the northern Baldwin Hills by the Department of Water and Power (Walley, 1963, p. 2–3). Hollywood E–11 itself was destroyed in 1953; prior to its destruction, however, PBM 40–C was established nearby and "designated as a fixed elevation bench mark for relative studies in this area, as PBM No. 40 likewise had earlier been so designated" (Walley, 1963, p. 3). Because Hollywood E–11 (PBM 40) and PBM 40–C are separated by only about 33.5 feet (Hayes, 1955, p. 4), they are assumed to have remained unchanged in elevation with respect to each other, and Hollywood E–11 has been retained here as a secondary control point even though it was abandoned as a reference bench mark by the Department of Water and Power, beginning with their 1963 report (Hayes, 1959, fig. 1, and Walley, 1963, fig. 1). Accordingly, elevations derived with respect to PBM 40–C are considered identical with those derived with respect to Hollywood E–11.

Although Hollywood E–11 occurs along the edge of an area of intense subsidence (fig. 11), it has sustained little elevation change with respect to reference bench marks outside this differentially subsiding system. Thus between 1939 and 1962 it subsided at an average rate of 0.01098 ft/yr with respect to PBM 58 (appendix C, Hollywood E–11, II.D.2.). Moreover, between 1946 and 1962 it subsided at an average rate of only 0.00794 ft/yr with respect to PBM 58 (appendix C, Hollywood E–11, II.D.2.); this lesser rate obtained, accordingly, during a period in which expanded elevation studies were undertaken in the northern Baldwin Hills and following a period during which adjustments of observed elevations may have produced incorrect determinations of elevation changes along line C (see appendix A, III.). Furthermore, because PBM 58 has been subsiding at about 0.00841 ft/yr with respect to S–32 (appendix C, Hollywood E–11, II.C.1.), Hollywood E–11 has apparently been subsiding at about 0.00841 ft/yr + 0.01098 ft/yr = 0.01939 ft/yr with respect to S–32. The relative stability of Hollywood E–11 is even more significantly demonstrated, however, through comparisons with control points located immediately adjacent to, but clearly beyond the differentially subsiding area identified in figure 11. Between 1939 and 1962 Hollywood E–11 subsided at an average rate of 0.00260 ft/yr with respect to PBM 1 (fig. 11), about ⅔ mile south of the south edge of the differential subsidence bowl; between 1946 and 1962, moreover, Hollywood E–11 subsided at an average rate of only about 0.00169 ft/yr with respect to PBM 1 (fig. 11). Subsidence at Hollywood E–11 with respect to PBM 43, the nearest regularly observed bench mark clearly outside the identified differential subsidence system, averaged about 0.00763 ft/yr between 1939 and 1958 (fig. 11); between 1946 and 1958 subsidence at Hollywood E–11 with respect to PBM 43 averaged about 0.0043 ft/yr (fig. 11). These observations indicate, accordingly, that Hollywood E–11 is certainly an appropriate reference for the description of such vertical movements as have occurred within the limits of the differential subsidence system centering in the northern Baldwin Hills.

SUBSIDENCE AT PBM 67 AND PBM 68

The earliest level surveys through the northern

Baldwin Hills apparently were run in 1910 by the Los Angeles Investment Company. These surveys established the elevations of a large group of Baldwin Hills bench marks, several of which were still in existence at the end of 1963. Derivations of the 1910 elevations of two of these recoverable bench marks, "DD" (or PBM 68) and "HH" (actually its nearby derivative, PBM 67), through the use of the Los Angeles Investment Company elevation control surveys, are given in appendix F; their locations are shown in figure 8. Although these early elevations are actually calculated here (appendix F) with respect to the City of Inglewood datum rather than any of the three control points described above, it can be shown that leveling emanating from either S–32 or the City of Inglewood datum should produce nearly equivalent elevations (see appendix F, prefatory note).

Subsidence at PBM 67 with respect to Hollywood E–11 is calculated to have been 4.324 feet during the period 1910–63 (see appendix G). Subsidence at PBM 67 since 1946 is based on a direct comparison with Hollywood E–11; subsidence between 1910 and 1946, on the other hand, is based on a presumption of stability between S–32 and the City of Inglewood datum, a calculated 1910 elevation of Hollywood E–11, and the acceptance of a 1910 stake elevation adjacent to HH as roughly 0.20 foot less than that of monument HH (see appendix F, PBM 67). In spite of the crude nature of this determination, it is likely that the calculation given in appendix G is a good approximation of subsidence at PBM 67 since 1910 (see appendix H, I.E.).

In 1911 the Department of Water and Power ran an elevation control survey into the Baldwin Hills in connection with the proposed establishment of a reservoir in this area (Hayes, 1943, p. 15); this leveling included concrete monument DD, subsequently designated as PBM 68 by the Department of Water and Power (see appendix B). PBM 68 (fig. 8) is particularly significant here, for it is the only bench mark in the northern Baldwin Hills whose elevation was measured (with respect to an external control point) before 1926 that has been remeasured from time to time since.[2] The November 1911 elevation of PBM 68, as derived through use of the Department of Water and Power control surveys in this area and with respect to both S–32 and Hollywood E–11 as fixed in elevation since 1911, is determined to have been 319.568 feet (see appendix C). This figure accords reasonably well with the 1910 elevation of PBM 68 of 319.778 feet derived through the medium of the Los Angeles Investment Company leveling in the northern Baldwin Hills (see appendix F). Although PBM 68 was releveled in 1917 in connection with surveys that originated locally (see appendix C, PBM 68, I.), there were no elevation measurements made on this bench mark between 1911 and 1943 that could be tied to external control points. Since 1943, however, elevation measurements of PBM 68 with respect to Hollywood E–11 have been repeated more or less quadrennially by the Department of Water and Power (see appendix D).

Differential subsidence at PBM 68 since 1917 and 1911, respectively, is calculated in appendices D and E and illustrated in figures 12 and 13.

Figure 12*A* shows subsidence at PBM 68 since 1917 as determined by the Department of Water and Power (see appendix D, I.). It was assumed in the construction of this graph: (1) that the 1917 elevation of PBM 68 derived through comparison with the elevation of a nearby topographic saddle is identical with that derivable through comparison with Hollywood E–11 as fixed in elevation in 1939 (see appendix D, I.); and (2) that this topographic saddle remained unchanged in elevation between 1911 and 1917 (see appendix C, PBM 68, I.).

Figure 12*B* shows subsidence at PBM 68 since 1911 with respect to Hollywood E–11 as fixed in elevation since 1939 (see appendix D, II). This representation assumes that the 1939 elevation of Hollywood E–11 is the same as that that would have been derived from the control point that produced the 1911 elevation of PBM 68, and that this control point remained unchanged in elevation with respect to Hollywood E–11 between 1911 and 1939. The 1911 elevation of PBM 68 was in fact, however, derived from a control point far removed from and unrelated here to Hollywood E–11, the bench mark from which subsequent elevations of PBM 68 have been derived.

Figure 12*C* shows subsidence at PBM 68 since 1911 with respect to Hollywood E–11 as fixed in elevation in 1911 (see appendix D, III.) The November 1911 elevations of both PBM 68 and Hollywood E–11, with respect to S–32, have been derived here (see appendix C) in order to compare directly the change in elevation between the two since 1911, rather than just since 1943, as is implicit in figures 12*A* and 12*B*.

The representation of subsidence at PBM 68 shown in figure 12*C* is clearly an improvement over that shown in either figure 12*A* or 12*B*, for it is unnecessary to assume that leveling emanating from separate, unrelated

[2] According to the California Department of Water Resources (1964, pl. 15), elevation changes since 1917 are also determinable at four additional bench marks in the Baldwin Hills area. This representation, however, is misleading. One of the four "bench marks" is simply the low point in a topographic saddle; a bench mark as such was never established in this saddle and the 1917 elevation of this point is of doubtful validity and utility (see appendix H, I.A.). Furthermore, no elevations were recorded for any of the three additional bench marks (or any nearby derivatives) before 1926; thus there exists no means of determining elevation changes at the respective bench marks between 1917 and the dates of earliest elevation measurement on these points. This conclusion is actually supported by a statement in the text of the report (California Department of Water Resources, 1964, p. 40) where it is noted "that the subsidence at the center of the [subsidence] bowl [in the northern Baldwin Hills] may have started any time before 1926."

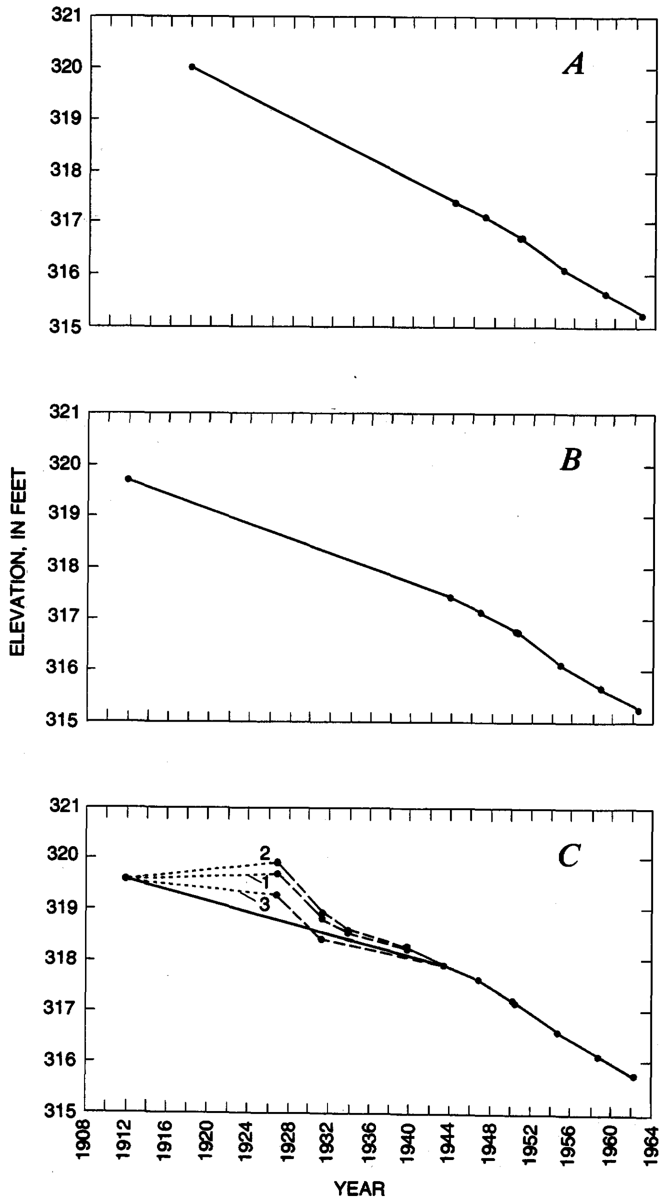


FIGURE 12.—Alternative derivations of the subsidence of PBM 68 with respect to Hollywood E–11. *A*, Since 1917 (Walley, 1963); (see appendix D, I.). *B*, Since 1911; assumes that elevation of Hollywood E–11 has remained invariant with respect to control point from which 1911 elevation of PBM 68 was derived (see appendix D, II.). *C*, Since 1911; based on 1911 elevations of PBM 68 and Hollywood E–11 derived from comparisons with S–32 (see appendix D, III.). Dashed lines show calculated subsidence at PBM 68 between 1926 and 1943; dotted lines include period during which no externally controlled elevation measurements were made in the northern Baldwin Hills. 1. Probable subsidence between 1926 and 1943 calculated from subsidence at PBM 31 and L.A. County BM 4 between 1926 and 1943 and a comparison of subsidence at PBM 68 with that at PBM 31 and the site of L.A. County BM 4 between 1943 and 1958; this representation is clearly the best founded of the three paths shown (see appendix D for details). 2. Maximum probable subsidence between 1926 and 1943 calculated from subsidence at PBM 31 and L.A. County BM 4 between 1926 and 1943 and a comparison of subsidence at PBM 68 with that at PBM 31 and the site of L.A. County BM 4 between 1943 and 1962; based on probably aberrant values for subsidence of PBM 68 versus subsidence of PBM 31 and BM 4 (see appendix D for details). 3. Minimum probable subsidence between 1926 and 1943 calculated from subsidence at L.A. County BM M4 and L.A. County BM 4 between 1926 and 1943 and a comparison of subsidence at PBM 68 with that at the sites of L.A. County BM M4 and L.A. County BM 4 between 1950 and 1958; based on probably aberrant measurement of subsidence at BM M4 between 1931 and 1943 (see appendix D for details).

control points would produce identical elevations of PBM 68. This graph is also based on a more objective derivation of the 1911 elevation of PBM 68 than that employed in figure 12*B* (although the two differ by less than 0.14 foot) since: (1) the questionable adjustment procedures utilized in the original 1911 elevation determination of PBM 68 shown in figure 12*B* have been avoided; and (2) consideration has been given to possible vertical movement of the control point from which the 1911 Department of Water and Power circuit originated (see appendix C, PBM 68). Calculation of the November 1911 elevation of Hollywood E–11 is based in part on the use of average rates of subsidence at Hollywood E–11, with respect to both S–32 and PBM 58, between the years 1939 and 1962. Because the average change in elevation at Hollywood E–11 with respect to S–32 has been fairly uniform and probably no greater than about −0.02 foot/year (at least between 1939 and 1962), any error implicit in this procedure is considered small and probably in a direction that would maximize the difference between the calculated 1911 elevation and the measured 1939 elevation of Hollywood E–11 (see appendix C, PBM 40).

Elevation changes at PBM 68 during the interval 1911–43 (fig. 12*C*—dashed lines) may be calculated through comparisons with measured vertical movements at other bench marks within the Baldwin Hills subsidence field (see appendix D, IV-IX). The probable accuracy of these calculated changes may be judged only through comparisons among the rates of subsidence at these various points through time. Thus, as shown in appendix D, the ratios of subsidence at PBM 68 to subsidence at the several other bench marks employed in these calculations have held fairly constant, except during the interval 1958–62; hence, use of the average ratios derived from measurements recorded through 1958 should lead to approximately valid values of subsidence at PBM 68 between 1926 and 1943.

Figure 13 shows a recalculation with respect to PBM 58 of the most probable subsidence path of PBM 68 shown in figure 12*C* (see appendix E). This graph is neither more nor less accurate than the one shown in figure 12*C*; its chief purpose is to show the change in elevation at PBM 68 with respect to a regularly observed control point outside the Baldwin Hills. This representation (fig. 13), accordingly, eliminates the

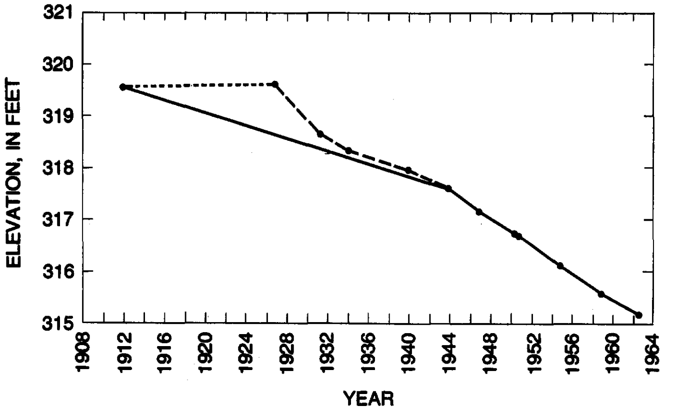


FIGURE 13.—Subsidence of PBM 68 with respect to PBM 58 since 1911. Dashed line shows calculated subsidence between 1926 and 1943; dotted line includes period during which no externally controlled elevation measurements were made in the northern Baldwin Hills. Only the most probable calculated path of subsidence is shown here (see appendix E for details).

effects of the maximum probable subsidence at Hollywood E–11 (with respect to points beyond the area of recognized differential subsidence) on the subsidence path of PBM 68 shown in figure 12*C*.

Subsidence at PBM 68 has been calculated with respect to secondary control points Hollywood E–11 and PBM 58 rather than S–32 for the following reasons: (1) Hollywood E–11 has been used since 1939 by the Department of Water and Power as a primary reference bench mark in its detailed studies of vertical movements in the northern Baldwin Hills (Walley, 1963, p. 3). (2) Since 1939 Hollywood E–11 and PBM 58 are known to have remained relatively stable with respect to PBM 1, which lies well south of the northern Baldwin Hills subsidence field (fig. 11); hence we see no particular advantage in calculating elevation changes at PBM 68 with respect to yet another control point outside the northern Baldwin Hills. (3) The seven Department of Water and Power level surveys run since 1911 that have included PBM 68, have not been tied to S–32 or to any equivalent control point.

The available evidence indicates that the elevation of PBM 68 was unaffected by the Inglewood earthquake of 1920. This is suggested especially by the approximate coincidence between the 1911 record elevation of PBM 68 and its 1926 calculated elevation (fig. 13). This apparent coincidence could, conceivably, have resulted from various combinations of uplift and subsidence. Nevertheless, significant uplift of this bench mark at the time of the earthquake seems most unlikely. Had PBM 68 been subsiding since 1911 at a rate equal to that which has obtained since 1926 or 1943, uplift of 1.8 or 2.2 feet should have been required to produce the elevations indicated for 1926 and 1943, respectively (fig. 13). Uplift of this amount seems unusually large to have been associated with an earthquake of magnitude 5–5½. The maximum measured uplift (with respect to a widely spaced array of bench marks) associated with the Long Beach earthquake of 1933, which was an order of magnitude greater than the Inglewood earthquake of 1920, has been given as 0.610 foot (Gilluly and Grant, 1949, p. 465, 469). (Had PBM 68 been subsiding at rates greater than those that obtained after 1926 or 1943, even greater uplift should have occurred in association with the 1920 earthquake; had it been subsiding at lesser rates, proportionately smaller amounts of uplift could have occurred in 1920, in accordance with the conclusion that little elevation change took place at the time of the earthquake.) Subsidence of PBM 68 at the time of the 1920 earthquake is even more unlikely, for this should require both that no credence be given the calculated 1926 elevation of PBM 68, and that the actual rate of subsidence between 1920 and 1943 was even less than the average rate between 1911 and 1943. The change in the average rate of subsidence after 1943 would then be even more pronounced, and explanations of its origin particularly contrived, for these explanations would seemingly demand a spectacular increase in the average rate of subsidence corresponding with the beginning in 1943 of the period of repeated observations on PBM 68.

It seems likely, then, that little elevation change at PBM 68 can be associated with the 1920 earthquake. This probability is strongly supported by the apparent stability of the City of Inglewood datum with respect to S–32 between 1910 and 1956 (see appendix F, prefatory note). This relative stability suggests that any elevation changes within the epicentral area of the 1920 earthquake must have been slight.

MAXIMUM SUBSIDENCE DURING THE PERIOD 1911–63

The maximum probable subsidence within the Baldwin Hills subsidence field is significant chiefly because it affords an additional basis of comparison with other known areas of differential subsidence. No elevation measurements were made at the approximate center of subsidence prior to 1950. However, maximum subsidence with respect to Hollywood E–11 may be calculated by assuming that the point of maximum subsidence is coincident with PBM 122 (fig. 8). Although the site of greatest subsidence, as determined for various intervals, is known to have shifted somewhat prior to 1964, PBM 122 probably was always within about 600 feet of this spot.

The differential subsidence at PBM 122 between October 1943 and January 1964 is computed to have been about 3.30 feet (see appendix H, II.–VI.). Subsidence at PBM 122 between 1911 and 1943 is less firmly founded; it can be calculated in two general ways. The first is through comparison of the subsidence at PBM 122 with that at an identifiable topographic landmark known as "BM saddle," whose elevation may have been measured in 1911 but is not known to have been tied to PBM 68 until 1917 (see appendix H, I.A.). This procedure was adopted by both the U.S. Geological Survey (1964, p. 12) and the California Department of Water Resources (1964, p. 39) in estimating maximum subsidence between 1917 and 1943. This method produces a calculated value for the subsidence at PBM 122 between 1911 and 1943 of about 4.04 feet (see appendix H, I.A.–I.D.). Adding to this the 3.30 feet of subsidence between 1943 and 1964 leads to a total of 7.34 feet for the entire period November 1911–January 1964. Alternatively, the subsidence at PBM 122 between 1911 and 1943 may be calculated through a direct comparison with that at PBM 68. This comparison indicates subsidence of 2.37 feet at PBM 122 between 1911 and 1943 (see appendix H, I.E.). Thus, the subsidence at PBM 122 over the entire period November 1911–January 1964 is calculated to have been approximately 5.67 feet.

The smaller value (2.37 feet) for the differential subsidence at PBM 122 between 1911 and 1943 is considered the better estimate for several reasons. (1) The first approach requires an assumption of vertical stability between "BM saddle" and PBM 68 (or between some external control point and the bench mark from which the elevation of "BM saddle" was derived) during the period 1911–17. (2) The second method is based on elevation measurements at an established bench mark rather than on estimated elevation changes at an imprecisely defined "low point" in a topographic saddle. (3) The smaller figure more closely accords with that derived through a comparison of the subsidence at PBM 122 with the subsidence at PBM 67 (see appendix H, I.E.4.).

Our best estimate of the 1911–64 subsidence at PBM 122 (5.67 feet) is slightly more than half that (9.7 feet) deduced by the California Department of Water Resources (1964, p. 39–40) for the period 1917–64 and almost exactly half the maximum subsidence (11.6 feet) given by Leps (1972, p. 516–518) for the same period. The California Department of Water Resources estimate, however, is based in part on inaccurate data for the measurement interval 1954–58 (see appendix H, I.C.), a 1917–43 subsidence figure derived through the use of unrelated datums (see appendix H, I.), and elevations measured at "BM saddle." Leps' estimate, moreover, is based on a questionable comparison between the 1917 elevation of the top of an iron pipe (of unknown length) extending upward from the concrete base of bench mark LAI (fig. 8) and the 1943 elevation of the concrete monument itself (see appendix I, III; Castle and Youd, 1973, p. 93–94). Furthermore, because bench mark LAI was destroyed sometime after 1943, we cannot be certain that it was not disturbed between 1917 and 1943. Leps (1973, p. 100–101), on the basis of "personal surveying experience dating back to 1933," rejects even the possibility of an exaggerated estimate for the subsidence at LAI based on the record elevations for this bench mark and contends that determination of the subsidence at several nearby bench marks corroborates his 11.6-foot estimate. In fact, however, Leps' (1972, p. 516–518) estimate of the subsidence at LAI: (1) is at variance with his own subsidence figures for bench marks DD and HH (Castle and Youd, 1973, p. 93); (2) draws upon an alleged similarity between the physical configuration of bench mark LAI (identified with a 3-inch iron pipe) and that of bench marks DD and HH (identified with ¾-inch iron pipes that are indeed characterized by "minimum stickup" of no more than a few inches—Leps, 1973, p. 100); and (3) cannot be confirmed by a procedure that makes use of the disputed 1917–43 LAI subsidence figure of 7.6 feet (or the 1917–64 figure of 11.6 feet) in calculating supposedly supportive cumulative subsidence figures for nearby bench marks (Leps, 1973, p. 101).

GENERAL PATTERN OF ELEVATION CHANGES

The Los Angeles Department of Water and Power began its systematic studies of vertical movements in the Baldwin Hills in 1939 (Hayes, 1943, p. 1–2); it was not until 1950, however, that the area of coverage had been expanded to an extent that the vertical movements could be described over more than a very small part of the northern Baldwin Hills. Since 1950 the approximately quadrennial level surveys of the Department of Water and Power have been expanded to include progressively larger areas, and the station density has been increased to the point that even very local differences in vertical movement can now be detected in the northern Baldwin Hills.

The approximate pattern of average annual elevation changes during the period 1950–54 was the first of the relatively detailed representations of vertical movements in the northern Baldwin Hills produced by the Department of Water and Power (pl. 4). The 1950 and 1954 bench mark elevations, from which these average annual elevation changes have been computed, probably were derived through direct comparisons with contemporary elevations along level line C (figs. 8 and 11). Thus levels emanating from line C presumably were adjusted, if at all, with respect to individual bench-mark field elevations along this line. The pattern of movement between 1950 and 1954 (pl. 4) was generally negative and concentrically disposed about a point roughly 1,000 feet south-southeast of the structural crest of the western block of the Inglewood oil field anticline (figs. 3 and 4). A subsidiary center of negative movement lay about 1,500 feet east-southeast of the structural crest of the east block of the Inglewood oil field anticline. The gross isobase pattern developed for the period 1950–54 (pl. 4) is elongated along a northwest trending line essentially coincident with the axis of the Inglewood anticline (figs. 3 and 4). Several sharp flexures of the isobases occur immediately west of Hollywood E–11; this area is one of relatively good bench-mark control, as well as one in which several north- to northeast-trending faults have been mapped (pl. 2).

The approximate pattern of average annual elevation changes in the northern Baldwin Hills developed by the Department of Water and Power for the period 1954–58 (Hayes, 1959, fig. 1), has been modified here (pl. 4) in order to accommodate an arithmetical error in the calculation of the average annual elevation change at PBM 122. The 1958 bench-mark elevations, like those of 1950 and 1954, apparently were derived from, and probably adjusted with respect to, observed elevations along level line C (Hayes, 1959, p. 10–11); the closures, in any event, were of a "minor nature" (Hayes, 1959, p. 10). The 1958 surveys, however, were run over a 5-month interval—August 1958 to January 1959 (Hayes, 1959, p. 2)—as contrasted with the 1950 and 1954 levelings which were completed within 1-month periods (Hayes, 1955, letter of transmittal). Because any elevation changes that occurred along line C during the 1-month periods in which the 1950 and 1954 surveys were run probably were barely measurable, they are ignored. On the other hand, measurable elevation changes of up to a maximum of about 0.035 foot probably occurred along parts of this elevation control line within the 5-month 1958 survey period (fig. 11). Nevertheless, because the resulting errors in the computed average annual elevation changes arising from the lengthened 1958 survey period almost certainly did not exceed 0.01 foot/year, the annual elevation changes represented in the upper right figure of plate 4 are assumed arbitrarily here to match those that would have been derived if the 1958 circuits had been run entirely within the month of October.

The gross pattern of movement indicated for the period 1954–58 is much the same as that for the period 1950–54; however, there seem to be three minor but possibly significant differences in the patterns of movement shown for these two periods. (1) The rate of subsidence near and for some distance away from the center of the subsiding area declined slightly but measurably (roughly 15 percent) during the 1954–58 interval. (2) East-west profiles in the vicinity of the Stocker Street–La Brea Avenue–Overhill Drive intersection show that the number of isobases per unit of horizontal distance (the isobase gradient) increased sharply in this area after 1954. The narrow trough described by the isobase configuration in this area, moreover, crudely mimics the small "graben" defined by a series of "earth cracks" or contemporary surficial fault displacements that began to develop no later than 1957. The absence of a more precise correlation between the isobase configuration and the earth cracks may be due in part to the timing of the surveys relative to the formation of the earth cracks. (3) A prominent reversal in the sense of movement (with respect to Hollywood E–11) within the area east of Stocker Street and Overhill Drive developed sometime between 1954 and 1958 (see southeast corners of upper figures, pl. 4). This area is depicted as subsiding between 1950 and 1954, whereas only that part immediately adjacent to the Stocker Street-Overhill Drive intersection is shown as subsiding during the period 1954–58 (pl. 4). The apparent change in the rate of vertical movement here, of up to +0.06 foot/year, may have accompanied the initial displacements along the earth cracks generated during the latter part of the 1954–58 interval. Hence the maximum positive average annual elevation change of up to 0.02+ foot/year computed for the entire 1954–58 period was almost certainly no more than one-quarter to one-half that which would have been derived through measurements made within the much narrower 1957–58 time window.

Two interpretations of the elevation changes measured in the vicinity of the Stocker Street–La Brea Avenue–Overhill Drive intersection during the interval, 1958–60 (figs. 14 and 15) have been developed from a special series of level surveys run toward the end of 1960 by the Department of Water and Power. These interpretations differ only in the area extending north-northeast from the Stocker Street–La Brea Avenue–Overhill Drive intersection; one (fig. 15) shows a trough defined by more or less parallel contours of negative movement, whereas the other (fig. 14) suggests no such throughgoing trough. Both interpretations, however, differ significantly from that shown for the period 1954–58 (pl. 4). Between 1954 and 1958 the subsidence apparently decreased north-northeastward away from the intersection (pl. 4), whereas during the shorter 1958–60 period it is represented as nearly uniform or actually increasing to the north along a zone crudely defined by the northward projection of cracks I and IV (figs. 14 and 15).

The latest of the representations of vertical movements in the northern Baldwin Hills prepared by the Department of Water and Power and included with this report, is that for the period 1958–62 (pl. 4). The 1962 benchmark elevations used in calculating the average

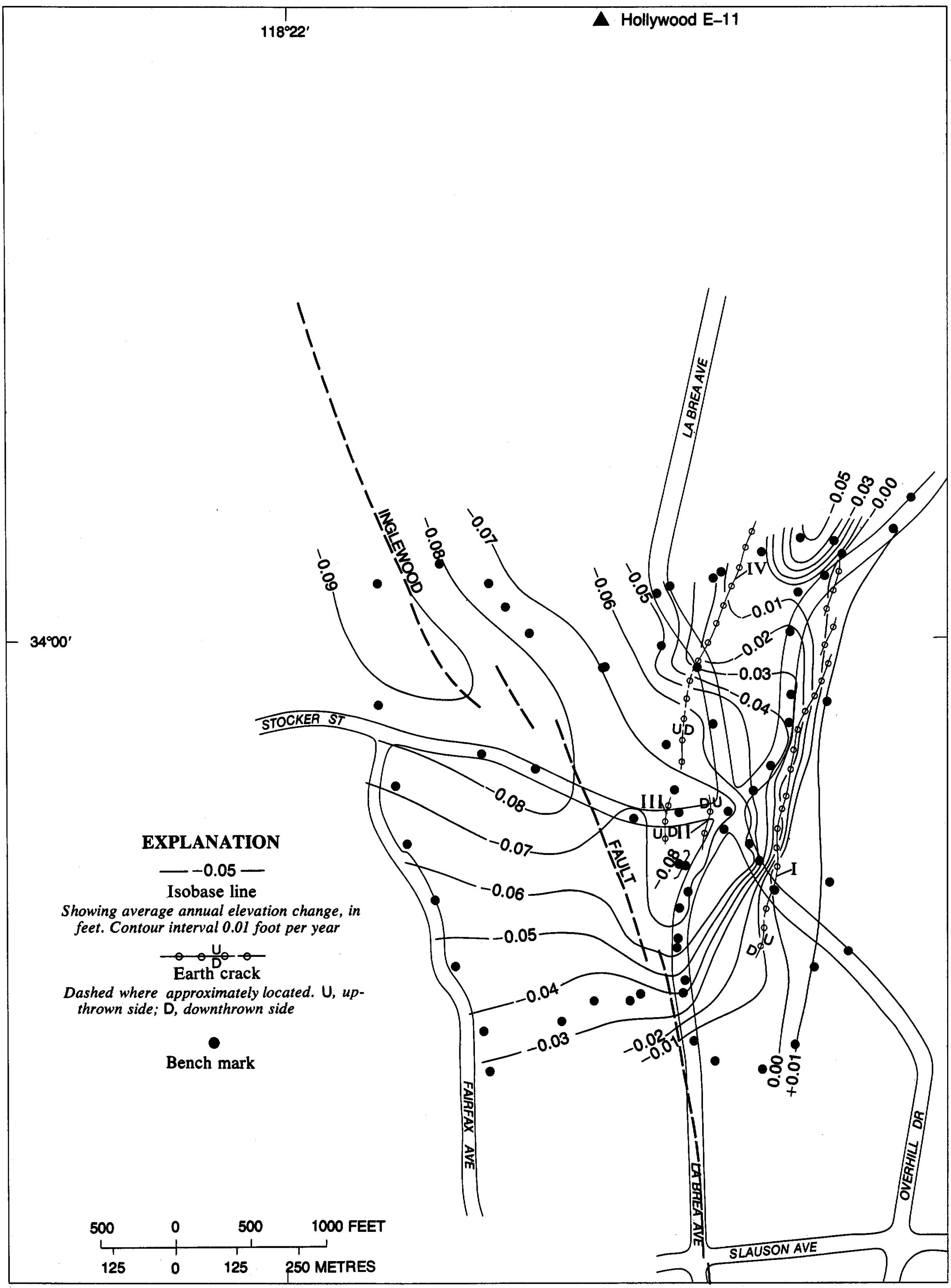


FIGURE 14.—Distribution of earth cracks in the north-central Baldwin Hills as of 1960, and approximate pattern of average annual elevation changes measured with respect to bench-mark Hollywood E-11 for the period 1958–60. Compiled by the Surveys Section of the Water Engineering Design Division of the Department of Water and Power, City of Los Angeles.

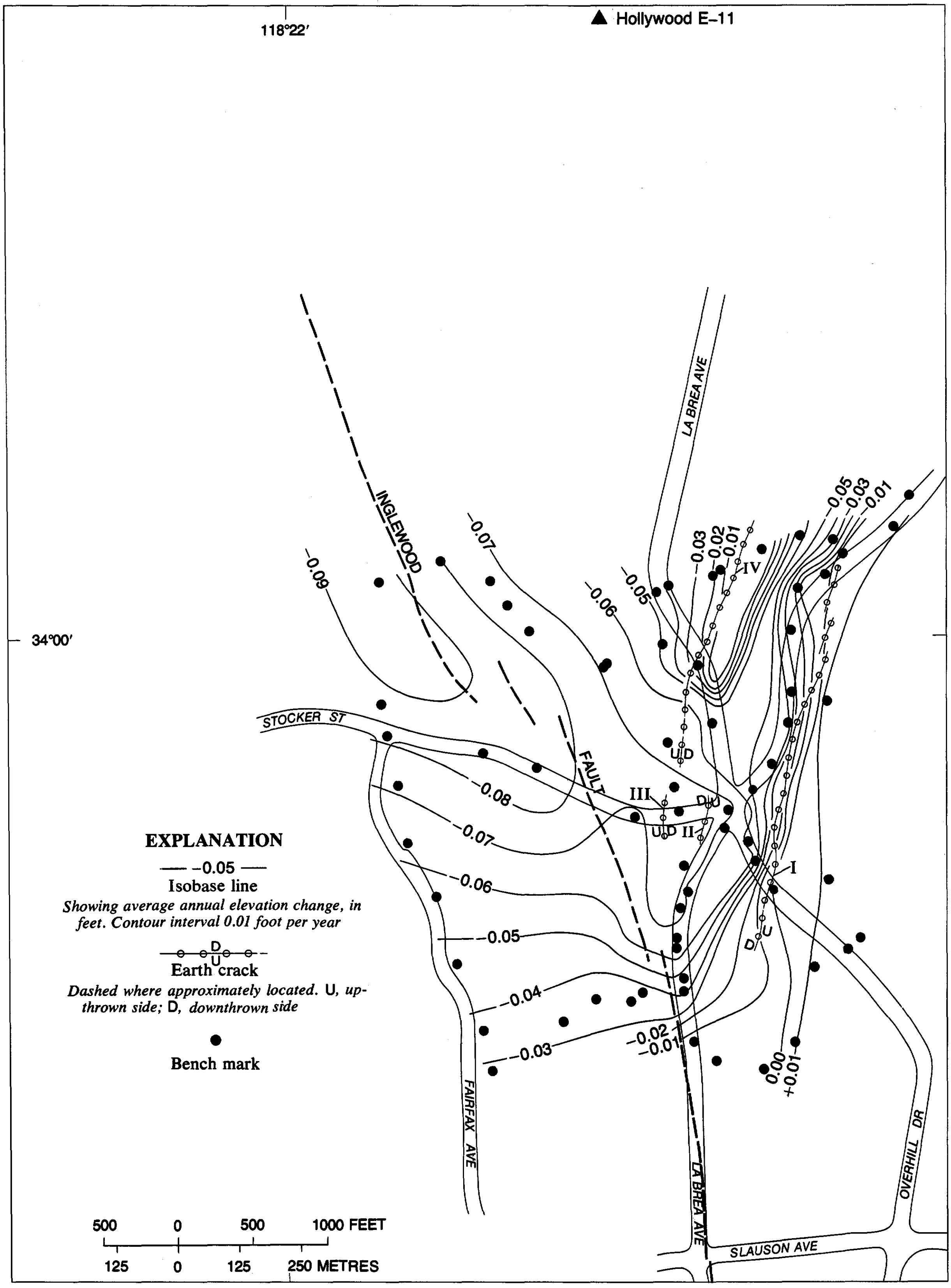


FIGURE 15.—Distribution of earth cracks in the north-central Baldwin Hills as of 1960, and approximate pattern of average annual elevation changes measured with respect to bench-mark Hollywood E–11 for the period 1958–60. A reinterpretation of the same data used in the construction of figure 14.

annual elevation changes that occurred during the interval 1958–62 are based on leveling emanating from an unadjusted Department of Water and Power control survey run in April 1962 (Walley, 1963, p. 14–15, fig. 2–A); this line (level line E) is very nearly coincident with level line C (see fig. 8 and Walley, 1963, fig. 1), such that elevations derived from control points along this line should accord almost precisely with those derivable through comparison with control points along line C. The 1962 leveling was carried out during the period April 1962–January 1963 (Walley, 1963, letter of transmittal). However, even though the 9-month 1962 survey period was almost twice that of the 1958 survey period, maximum comparable errors in the average annual elevation changes probably were of about the same magnitude as those associated with the 1958 leveling (0.01 foot/year), since elevation changes along the 1962 Department of Water and Power control line probably reached a maximum of about 0.038 foot during the 1962 survey interval (Walley, 1963, fig. 2–A). Again, for purposes of this report, the annual elevation changes represented for the period 1958–62 (pl. 4) are assumed arbitrarily to match those that would have been derived had the entire set of 1962 surveys been run within the month of August.

The gross pattern of movement shown for the period 1958–62 is much the same as that indicated for the periods 1950–54 and 1954–58 (pl. 4). The approximately 17 percent-deceleration in subsidence near the center and over much of the rest of the subsidence bowl between the periods 1954–58 and 1958–62 was nearly the same as that which occurred between 1950–54 and 1954–58. Comparison of the pattern of movement shown for the period 1958–62 with the patterns shown for the several preceding intervals, however, reveals several significant changes in the character of the vertical movement during this latest period. (1) A reduction in the rate of positive movement, compared with that of the preceding period, took place sometime between 1958 and 1962 within the block east of Stocker Street and Overhill Drive. This seemingly diminished rate of upward movement, however, may be of only relative significance, for Hollywood E–11 remained essentially unchanged in elevation with respect to PBM 1 between 1958 and 1962, whereas it subsided about 0.04 foot between 1954 and 1958 (fig. 11). (2) During the period 1958–62 the rate of subsidence in the area east of the Inglewood fault decelerated to about 50 percent of that for the period 1954–58; this change in rate was nearly three times the comparable deceleration (17 percent) in the area west of the Inglewood fault. The sharp deceleration in the east block is equally well displayed by the profile of elevation changes along level line C (fig. 11), which is confined entirely to the area east of the Inglewood fault. (3) Comparison of the 1958–62 elevation changes (pl. 4) with the patterns shown in figures 14 and 15 indicates that the pronounced differential subsidence within the narrow trough extending northward from the La Brea Avenue–Stocker Street–Overhill Drive intersection apparently abated and in part reversed sometime between the beginning of 1961 and the end of 1962. The presence during the full period 1958–62 of a broad area of positive isobases of up to +0.01 foot/year toward the north end of the narrow trough of differential subsidence (pl. 4) suggests that measurable subsidence never extended northward beyond the area contoured in figures 14 and 15.

Concern over continuing surface movements in the Baldwin Hills by the Los Angeles County Engineer stimulated an independent subsidence study during the early 1960's (Los Angeles County, Department of County Engineer, 1961a, b); the results of this study consist of a synoptic representation of the average annual elevation changes in the Baldwin Hills area as of June 1961 (lower right figure, pl. 4).

The principal differences between the patterns of vertical movement developed for the several survey intervals by the Department of Water and Power (pl. 4) and that produced by the Department of County Engineer (pl. 4) are due chiefly to questionable treatment of the elevation data in the preparation of the portrayal of subsidence by the Department of County Engineer. (1) In constructing the Department of County Engineer representation (lower right figure, pl. 4), long- and short-term elevation changes were mixed indiscriminately; that is, the calculated average annual elevation changes were based were based on elevations measured over intervals ranging from 3 to 30 years (Los Angeles County, Department of County Engineer, 1961b). Because rates of movement are known to have changed at certain stations, and even in some cases to have undergone slight reversals (Los Angeles County, Department of County Engineer, 1961a), arbitrary combination of long- and short-term averages tends to misrepresent the actual pattern of elevation changes. The magnitude of the misrepresentation implicit in this practice is proportional to the known changes in the rates of vertical movement at the observed bench marks. (2) A second and more serious criticism of this interpretation (lower right figure, pl. 4) stems from the calculation of elevation changes at many of the bench marks from elevations measured with respect to at least two and perhaps a number of unrelated datums (Los Angeles County, Department of County Engineer, 1961a). The type of error inherent in this procedure is illustrated by the calculation of the Department of County Engineer of the average annual elevation change at PBM 409 (Los Angeles County, Department of County Engineer, 1961b), located about 1,200 feet west of La Cienega Boulevard (lower right figure, pl. 4). As shown by the 1961 tabulation of bench-mark elevations (Los Angeles County, Department of County Engineer, 1961a), the −0.25 foot/year isobase at PBM 409 is based on a comparison of a 1961 Department of County Engineer elevation (presumably with respect to Tidal 8) with a 1958 Department of Water and Power record elevation with respect to PBM 1 (Los Angeles Department of Water and Power file card for PBM 409). The possibility that PBM 1 may have subsided with respect to Tidal 8 since its 1939 elevation was fixed by the Department of Water and Power (Hayes, 1943, p. 9–10) apparently was not considered. By way of comparison, the average change in elevation at PBM 409 with respect to the single control point PBM 1 during the period 1958–62 is calculated to have been −0.119 foot/year; the corresponding change with respect to Hollywood E–11 is calculated to have been −0.118 foot/year (Los Angeles Department of Water and Power file card for PBM 409). (The average annual change in elevation at PBM 409 with respect to the Los Angeles County datum between 1958 and 1961 cannot be computed without first deriving the 1958 elevation of PBM 409 with respect to the county datum.) Thus, the utilization of separate datums in the calculation of the average annual elevation changes shown in the lower right figure of plate 4 led to a conspicuous distortion in the configuration of the actual pattern of vertical movements surrounding PBM 409.

INITIATION OF SUBSIDENCE

The beginning of differential subsidence in the Baldwin Hills can be determined only indirectly, for systematic releveling was not begun until the late 1930's, well after the subsidence had begun. Its initiation is most reliably determined by: the history of vertical movement at PBM 68; and the comparative elevations recorded in 1910 and 1917 at four topographic landmarks within the now-recognized subsidence bowl.

The history of subsidence in the northern Baldwin Hills is perhaps best represented by both the measured and calculated vertical movement at PBM 68 (figs. 12 and 13). This bench mark, moreover, has sustained about three-quarters of the maximum amount of subsidence measured within the subsidence bowl; hence its history is probably more representative than are the histories of those bench marks subject to the sometimes aberrant movements produced at the precise center or along the periphery of a subsiding area. In spite of their obvious differences, the four separate interpretations of vertical movement presented in figures 12 and 13 agree in one significant respect: the average and nearly uniform rate of subsidence between 1943 and 1962 was considerably greater than the average rate over the period 1917–43 or 1911–43. Extrapolation of the PBM 68 subsidence curves backward from 1943 at the post-1943 average rates indicates that cumulative subsidence could not have occurred at PBM 68 between the years (1) 1917 and 1921 (fig. 12A); (2) 1911 and 1924 (fig. 12B); (3) 1911 and 1929 (fig. 12. *C*), (4) 1911 and 1928 (fig. 13). The calculated subsidence curves shown in figures 12 *C* and 13 indicate that subsidence of PBM 68 below its 1911 elevation did not take place until 1927 or 1926, respectively. Taken together these observations indicate that subsidence could not have begun until the 1920's and probably did not begin until the middle 1920's.

Although the data are less reliable, owing chiefly to the imprecisely established 1910 elevation of monument "HH" (appendix G); a similar conclusion is suggested by the history of vertical movement at PBM 67 (pl. 4). The average rate of subsidence at PBM 67 between 1943 and 1963 is calculated to have been approximately 0.145 foot/year whereas the 1910–43 rate averaged about 0.046 foot/year (appendix G). Thus the rate of subsidence at PBM 67 changed conspicuously between 1910 and 1943. Backward extrapolation of the average post-1943 rate suggests that there could have been no cumulative subsidence at PBM 67 between 1910 and 1933. Hence this less rigorous determination argues, as above, that subsidence at PBM 67 probably began no earlier than the 1920's.

A series of comparative elevations recorded in 1910 and 1917 within the presently recognized subsidence bowl (appendix I) provide particularly compelling evidence that subsidence could not have begun until after 1917. Thus comparisons between the 1910 and 1917 field elevations of four topographic landmarks indicate 0.025 foot of subsidence with respect to PBM 68 (DD) at two of these, 0.125 foot at a third, and 0.325 foot at a fourth (appendix I.III.B.4). Because the elevation of each topographic feature was recorded to only the nearest tenth of a foot, these elevation changes are regarded as trivial. That is, differences of a tenth of a foot can be reasonably expected in comparing one sequence with the next, even in the absence of any vertical movement. Furthermore, the last-named elevation change stems from elevation measurements recorded at the approximate summit of a very subdued knoll; because it is doubtful that the precise position recorded by the 1910 leveling could have been recovered in the 1917 leveling, the resultant elevation difference is considered equally doubtful. In any case, the 1910–17 elevation changes indicated for the first three features were many times less than the 0.251-foot, 0.119-foot, and 0.340-foot changes derived for these same three points, respectively, over an average 7-year interval between 1950 and 1962 (appendix I, III.B.5). Hence it seems unlikely that there could have been any significant differential movement between PBM 68 and other points within the subsidence bowl during the 1910–17 interval. Thus the apparent absence of differential movement within the subsidence bowl between 1910 and 1917 supports the preceding conclusion: namely, that differential subsidence did not begin until the middle 1920's.

HORIZONTAL MOVEMENTS

Measurements of horizontal surface movements in the Baldwin Hills area have been carried out chiefly by the Department of County Engineer (Los Angeles County, Department of County Engineer, 1961b; Alexander, 1962; California Department of Water Resources, 1964, p. 40, pl. 16) and the Los Angeles Department of Water and Power (Walley, F. J., 1963, p. 9–10; F. J. Walley, written communs. 1964 and 1970). Horizontal movements deduced from triangulation surveys of the Department of County Engineer are shown in the two lower figures of plate 4; length checks assembled under the auspices of the Department of Water and Power are presented in figure 16.[3]

Horizontal movement at triangulation point Baldwin Aux (see pl. 4) during the period 1934–61 was derived by the Department of County Engineer through comparison of its 1961 position with its 1934 position as "determined by the 1934 Cooperative Control Survey of the metropolitan Los Angeles area" (Alexander, 1962, p. 2469). Specifically, "the apparent displacement of 2.21 feet for the 1961 position of Baldwin Aux, compared with that determined in 1934, involves the basic triangle defined by the stations Baldwin Aux, Northwestern, and Southwestern"; the latter two stations define a line of apparent "fixity of length" trending roughly north-south, about 3 miles east of Baldwin Aux (Alexander, 1962, p. 2471, 2473). "From secondary triangulation emanating from the 1961 position of Baldwin Aux, the horizontal movement [over the period 1936–61] of [the] other previously positioned points [shown on pl. 4] was determined and resulting movement vectors were computed" (Alexander, 1962, p. 2469, 2473). The 1961–63 displacements shown on plate 4 presumably were derived through measurements with respect to the same basic control network as that utilized in the 1961 retriangulation; however, no specific statement to this effect is found in the source reference (California Department of Water Resources, 1964).

Horizontal displacements of the six identified triangulation points have been generally toward the center of subsidence (pl. 4). However, there seem to have been slight to moderate deflections of the displacement vectors away from the centripetal direction at those triangulation points whose positions were initially determined prior to 1961. Thus deflection from the centripetal at Baldwin Aux has been counterclockwise; deflections of the after three vectors have been clockwise. We see no evident relation between these deflections of the other three vectors have been clockwise. We see no evident relation between these more specific and probably more significant geometric association is defined by the essentially orthogonal relation between the horizontal movement vectors and the isobases around the triangulation points, especially as shown in the lower left figure of plate 4.

Survey check points were set in March 1958 along the Stocker Street roadway athwart earth crack III (pl. 4) by the Los Angeles Department of Water and Power; the points were spaced at 5- to 10-foot intervals and extended about 30 feet east and west of crack III (Walley, 1963, p. 9). These check points were resurveyed in March 1963 at which time "the maximum horizontal displacement was found to be 0.05 of a foot" (Walley, 1963, p. 10). The "displacement" alluded to by Walley apparently refers to the approximate sum of the maximum northerly and maximum southerly shifts from the original alinement, where the end points are assumed to have remained unchanged. Thus between 1958 and 1963 a check point 2–3 feet west of crack III moved 0.029 foot north and one about 12–13 feet east of the crack shifted 0.028 foot south; the total of the two is 0.057 foot. Length checks were also made along this traverse in 1963. These checks showed that this approximately 50-foot line lengthened by 0.071 foot and that 0.064 foot of this was confined to the 5-foot segment straddling crack III (Los Angeles Department of Water and Power, written commun. 1970).

Following the failure of the Baldwin Hills Reservoir in 1963, length checks were made by the Department of Water and Power along alinement control lines around the four sides of the reservoir (F. J. Walley, written commun. 1964), the center of which lies about 1,600 feet southwest of Hollywood E-11. These checks "showed the east side to have shortened 0.09 ft., the south side to have lengthened 0.23 ft., the west side to have shortened

[3]The precision of the triangulation surveys carried out by the Los Angeles County Engineer has been discussed by Alexander (1962, p. 2473–2474). Comparative surveys revealed adjusted spherical angle changes of up to 27.60 seconds between 1934 and 1961; the maximum probable error in observed direction associated with the 1961 surveys has been given as 0.42 second. Considerations of this sort led Alexander (1962, p. 2473–2474) to conclude "that the bulk of this angular change is due to actual movement of the [primary triangulation] point [Baldwin Aux—see pl. 4], and not to the small discrepancy that normally could be expected in the observation of a triangulation net." Thus, if based on 1961 results, the maximum error in the displacement vector at trianagulation point Baldwin Aux, as determined by observation on triangulation point Denker along a single 30,185-foot line (the longest line involved in the triangulation of Baldwin Aux) nearly normal to the displacement vector, should have been no more than

$$(2)\,(4.2 \times 10^{-1})\,(3.0185 \times 10^{4})\,(4.848 \times 10^{-6}) = 0.123 \text{ foot,}$$

where 4.848×10^{-6} is the number of radians in 1 second of arc.

Length measurements by the Department of County Engineer, the Los Angeles Investment Company, and the Department of Water and Power were apparently read to 0.01 foot.

0.02 ft. and the north side (across the dam) to have lengthened 0.18 ft." since originally measured in 1950 (F. J. Walley, written commun. 1964). The California Department of Water Resources (1964, p. 55) conclude from what we presume to be the measurements described by Walley, that there had been "a progressive elongation of the northeast-southwest [approximately 1,200-foot reservoir] diagonal between 1950 and 1963 of about 0.4 foot"; this elongation corresponds to an average extensional strain of about 0.033 percent. Similar length checks around the Baldwin Hills Reservoir described by Casagrande, Wilson, and Schwantes (1972, p. 581–582) indicate elongation along the northeast-southwest diagonal between 1950 and 1964 of 0.84 foot, or roughly twice that reported by the California Department of Water Resources (1964, p. 55); this greater lengthening corresponds with an average extensional strain of 0.071 percent (Casagrande and others, 1972, p. 581–582). The 1950 surveys used in these two separate determinations of diagonal length change are apparently identical; the subsequent length determinations must have been based on different sets of survey data, for Casagrande, Wilson, and Schwantes (1972, p. 582) recognize no shortening around the reservoir perimeter during the 1950–64 interval. We have no clear basis for choosing between the two cited diagonal strain values; we note, however, that comparative surveys conducted in 1969 indicate post-1950 elongation of the northeast-southwest diagonal of 1.14 feet (Casagrande and others, 1972, p. 581), a figure fully consistent with the reported 0.84-foot lengthening between 1950 and 1964.

One of the most illuminating demonstrations of contemporary horizontal movement in the northern Baldwin Hills is based on length checks along two traverses established initially in 1924 and 1943, respectively (upper right figure, pl. 4 and fig. 16). Taped measurements between survey stations along these traverses were subsequently repeated in whole or in part on six successive occasions. (The latest of these length checks was made in 1969, subsequent to the period of expressed interest—see "Introduction." However, because the 1969 check was the only one to include all the stations incorporated in the several surveys, the resulting measurements are given here.) Thus, between April–May of 1924 and the latest survey in 1969, line DD reset—*A′* apparently shortened by 2.64 feet; similarly, between 1943 and 1969, line *C–C′* shortened by 0.51 feet. However, the greatest change recorded along traverse DD reset—*A′* during the 1924–69 interval occurred over the relatively short segment a–h, which was reduced in length by 4.26 feet (fig. 16). Hence, whether shortening or lengthening occurred was apparently a function of the location of the segment considered. Segments located between a and h, near the center of the subsidence bowl, generally shortened; those located along the northern reaches of line DD reset—*A′*, and thus within the peripheral part of the subsidence bowl, tended to lengthen between surveys. An apparent exception to this generalization is suggested by the first two length checks between stations a and h (fig. 16). This line is represented as having lengthened between each check through 1925; it subsequently shortened by as much as 5.21 feet. The 5.21-foot shortening measured along line a–h between 1925 and 1969 was the maximum change recorded between any two stations along either traverse.

Horizontal strain along lines DD reset—*A′* and *C–C′*, as determined for selected intervals, has been calculated from the successive length checks shown in figure 16. The reliability of these calculations is proportional to the lengths of the lines from which the strain has been calculated. That is, the small errors inherent in the recovery of precisely the same points during successive surveys have a proportionately greater percentage effect on the shorter segments. By way of illustration, all the conspicuously large strains (those greater than 0.3–0.4 percent) stem from measurements over distances of no more than a few feet. Hence, in constructing the interpreted strain profiles, greater weight has been given to data derived from the longer lines. Thus, the maximum extension along line DD reset—*A′* between 1924 and 1969 must have been about 0.05 percent; the maximum contraction during the same interval was apparently about 0.20 percent (fig. 16).

Taken together, the described length checks and associated surveys show that at least the eastern margin of the subsidence bowl has been characterized by extensional horizontal strain along lines roughly perpendicular to the isobases. The strain profiles shown in figure 16 indicate equally clearly that the central part of the subsidence bowl has been identified with contractional horizontal strain. This strain pattern is fully consistent with the centripetally directed horizontal displacements revealed by successive triangulation surveys. The kinematics dictated by these displacements compel that they be associated with a zone of radically oriented extensional strain surrounding a central core characterized by radially oriented contractional strain.

Although the evidence is equivocal, a comparison of the average rates of horizontal movement, as determined for two identified triangulation periods, with the average rates of subsidence at PBM 68 during the same periods (fig. 17) indicates that the centripetally directed horizontal movements (together with the symmetrically related extensional and contractional strain) probably began in the middle 1920's. Backward

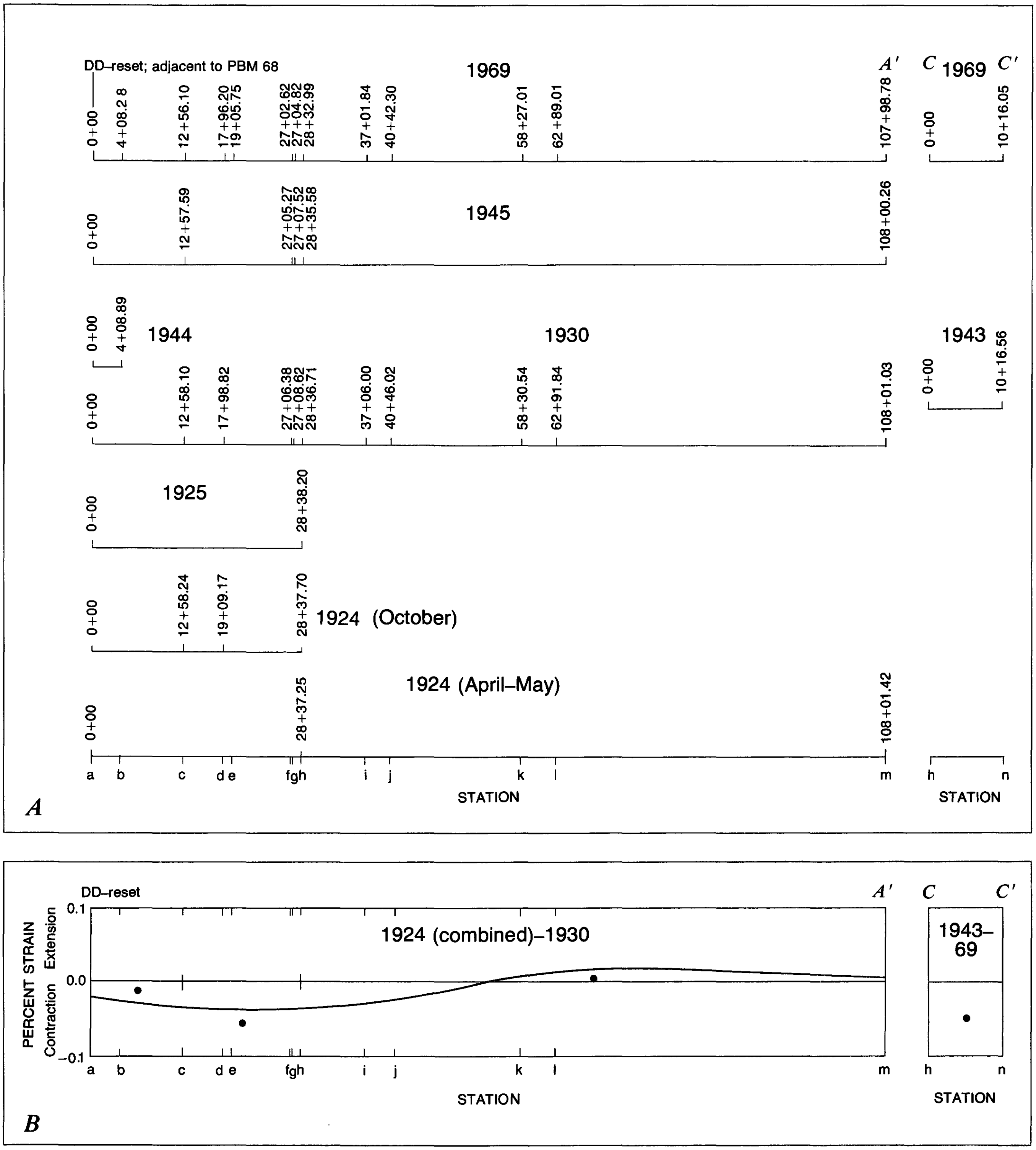


FIGURE 16.—*A*, Taped distances, in feet, measured along lines DD reset—*A′* and *C–C′* (see upper right figure pl. 4). April-May 1924 (Los Angeles County Surveyor's map 8635). October 1924 (Los Angeles County Surveyor's map 8635). 1925 (Los Angeles Investment Company tract map 7937). 1930 (Los Angeles County, Department of County Engineer field book 289, p. 118–123). 1943 (Department of Water and Power field book 2633, p. 60). 1944 (Los Angeles County, Department of County Engineer field book 89-166). 1945 (Department of Water and Power, Power Division field book 771, p. 55–57). 1969 (Department of Water and Power Division field book 3745, p. 2–24, 26). Data courtesy of F.J. Walley and T. M. Leps (written commun., 1970). Station designations (a, b, c, etc.) assigned by writers. *B* and *C*, Calculated horizontal strain along lines DD reset—*A′* and *C–C′* for selected periods between 1924 and 1969. Dots show average strain between indicated stations. Curves estimated by eye; points weighted according to distance between stations.

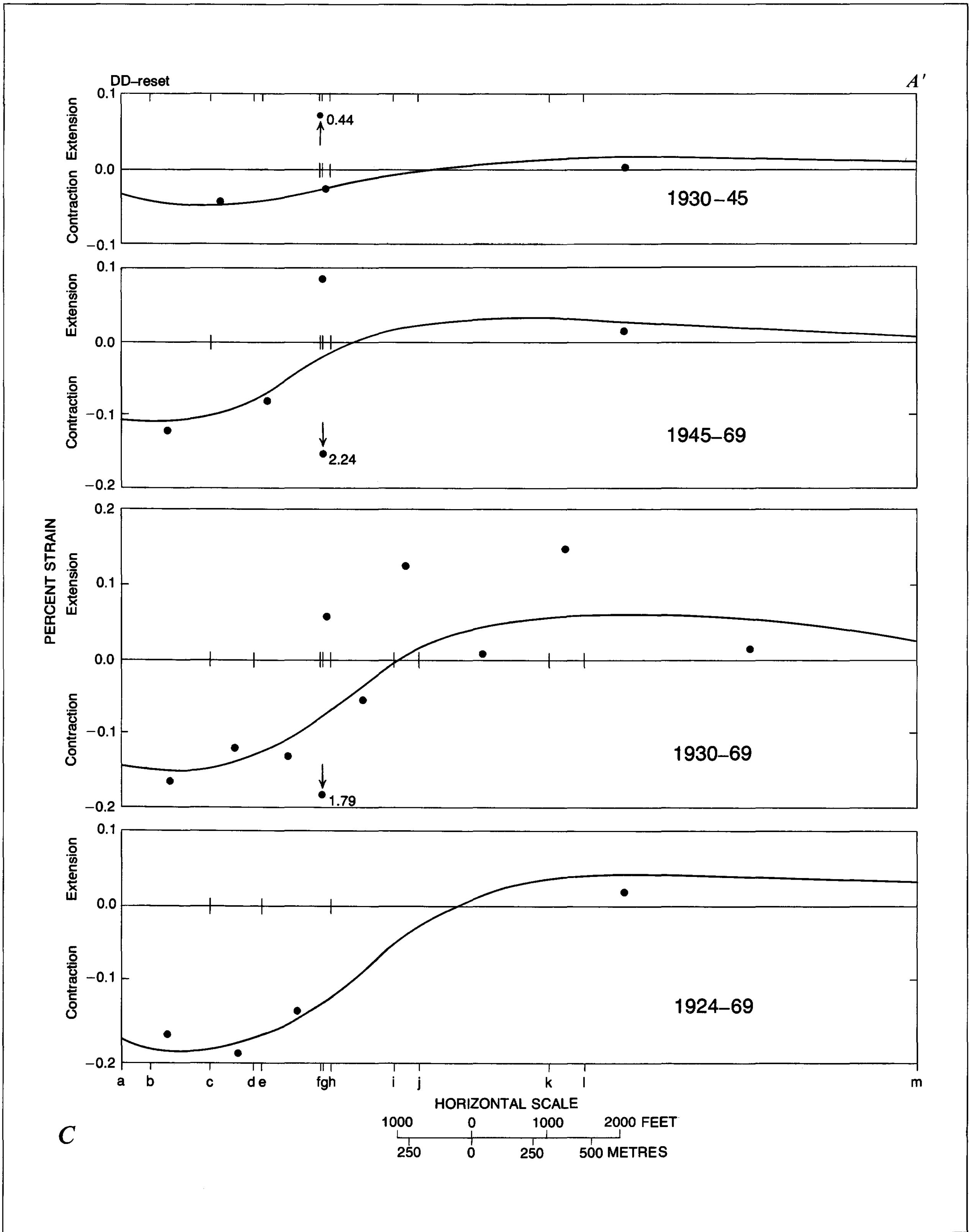


FIGURE 16.—Continued.

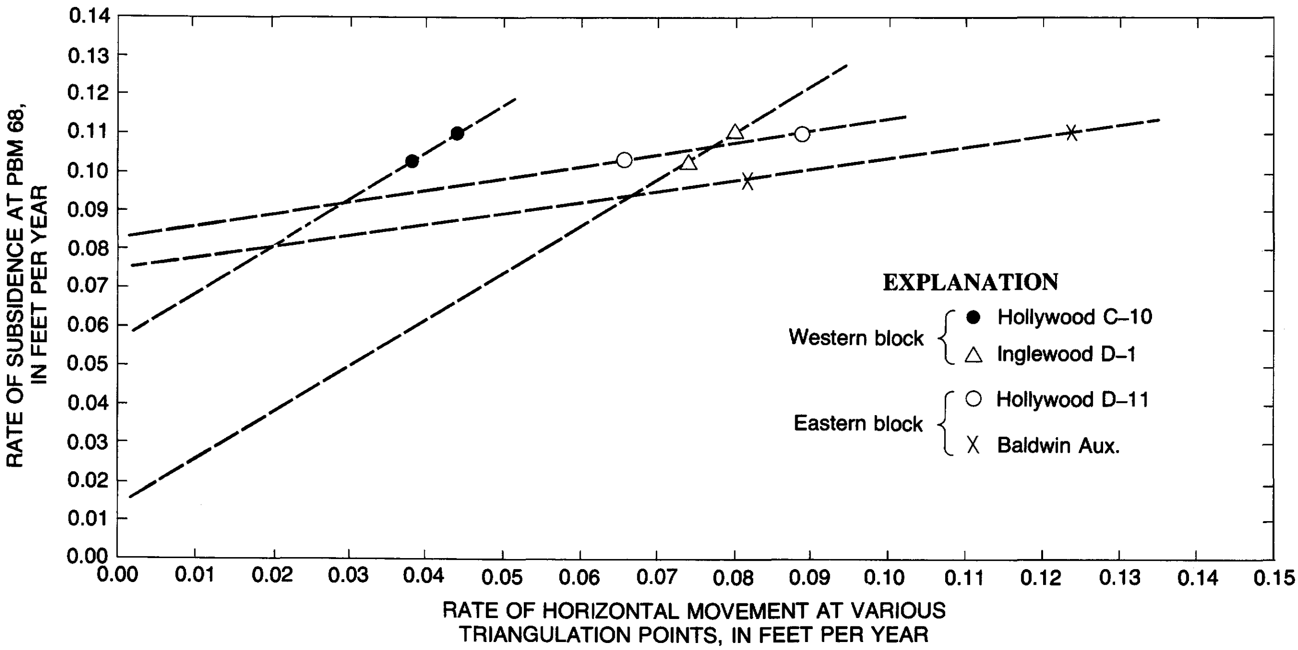


FIGURE 17.—Average rate of subsidence at PBM 68 versus average rate of horizontal movement at four triangulation points within the Baldwin Hills subsidence bowl, as determined for two periods between: (1) 1934 or 1936 and 1961; and (2) May 1961 and August 1963. Data from figure 12 and plate 4, and C. E. Brunty, Los Angeles County, Department of County Engineer (oral commun., 1969).

extrapolation of the lines defined by the plotted pairs shown in figure 17 suggests that horizontal movement at several of the identified triangulation points has varied directly and perhaps linearly with subsidence at PBM 68. This relation is most clearly demonstrated by a comparison of the rates of subsidence at PBM 68 with the rates of horizontal movement at the triangulation point (Inglewood D–1) nearest PBM 68 (pl. 4). That the suggested relation is so much less evident in a comparison of horizontal movements in the east block with subsidence at PBM 68 probably derives from the disproportionately large deceleration in subsidence recognized in the east block during the 1958–62 leveling interval. That is, subsidence at PBM 68 during the 1961–63 period probably was representative of that for the west block only. In any case, because the differential subsidence apparently began in the middle 1920's, the inferred dependence of the horizontal movement rate on the subsidence rate argues that the horizontal displacements began at the same time. Furthermore, although it might be imprudent to suggest that the length checks along DD reset—*A′* indicate that what we now identify as the central part of the subsidence bowl was under extensional strain before 1925, these checks argue forcefully that contractional strain, and thus the radially oriented displacements, could not have begun until 1925 or later.

EARTH CRACKS AND CONTEMPORARY FAULT DISPLACEMENTS

A series of earth cracks, as long as one-half mile and generally associated with measurable dip slip displacements, were recognized along the eastern margin of the Baldwin Hills subsidence field at least as early as 1957. The "cracks" are identified as such here, rather than as faults (which most of them clearly are), in keeping with the terminology of the Los Angeles Department of Water and Power (Walley, 1963, p. 5–13), the U.S. Geological Survey (1964, p. 8–11), and the California Department of Water Resources (1964, p. 41, pls. 17a and 17b), and in order to distinguish them from faults of more conventional recognition that are not known to have been active during historic time.

The earth cracks are generally expressed as simple, single or en echelon ruptures of the ground surface along fairly straight, northerly trends (figs. 18–21). Open "potholes" and irregularly shaped subsurface cavities have been generated along several of these cracks (California Department of Water Resources, 1964, photos 54, 83, and 84, and pls. 22d–22m); both the potholes and the cavities, however, are probably erosional in origin. Open fissures are relatively uncommon along the cracks, but they have been discovered locally (California Department of Water Resources, 1964, photos 55, 57, and 58). Excavations

FIGURE 18.—Extensive, locally broken patching along earth crack I where it passes through school yard north of Overhill Drive. View north-northeast. Photograph taken January 1961.

athwart several prominent earth cracks (California Department of Water Resources, 1964, pls. 22e, 22f, 22g, and 22k) suggest, however, that many of these open fissures are very shallow and probably were caused by (1) the extension and rupture of natural and artificial surface layers in response to vertical displacements along the cracks and(or) (2) desiccation along the upper parts of the opposed blocks. Thus, surficial fissuring and the presence of small subsurface cavities do not in themselves constitute unambiguous evidence of tension

FIGURE 19.—Earth crack II, 200 feet southwest of the center of Stocker Street–La Brea Avenue–Overhill Drive intersection. Vertical separation along crack about equal to height of pocketknife. View northeast. Photograph taken January 1961.

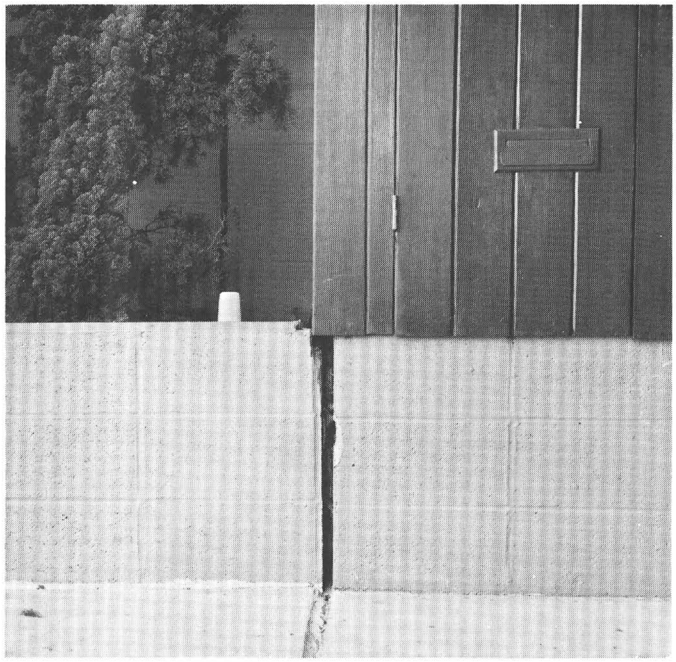


FIGURE 20.—Damaged wall intersected by earth crack I, 235 feet south of Overhill Drive. Photograph taken January 1961.

across the earth cracks.

The earth cracks (pl. 2) are confined almost entirely to the region east of the Inglewood fault and are generally restricted to the eastern margin of the northern Baldwin Hills subsidence bowl. The only reported crack west of the Inglewood fault occurs along the northern margin of the bowl. The cracks are concentrated in two general areas, one centering on the Stocker Street–La Brea Avenue–Overhill Drive intersection and the other forming a narrow zone 1,000–2,000 feet west and southwest of Hollywood E–11. The striking degree of parallelism between the cracks and the faults and joints in their vicinity suggests that the cracks are related to the geologic structure. There is no apparent relation, however, between lithology and the location or character of the earth cracks. Crack I, for example, can be traced through sediments representing the majority of the stratigraphic units exposed at the surface in the Baldwin Hills, including sands, silts, gravels, and artificial fill.

Where the sense of movement along the earth cracks could be determined, it has been almost entirely dip slip. Several cracks, however, showed no differential displacements of any sort; the zone of cracking along what is identified here as crack XIII, for example, seems to have been a rupture of this sort (D. H. Hamilton, oral commun. 1970). The planes along which the movements have occurred are believed to be generally steep; dips on the faults associated with crack IX (figs. 22 and 23), for example, average about 70° W. (California Department

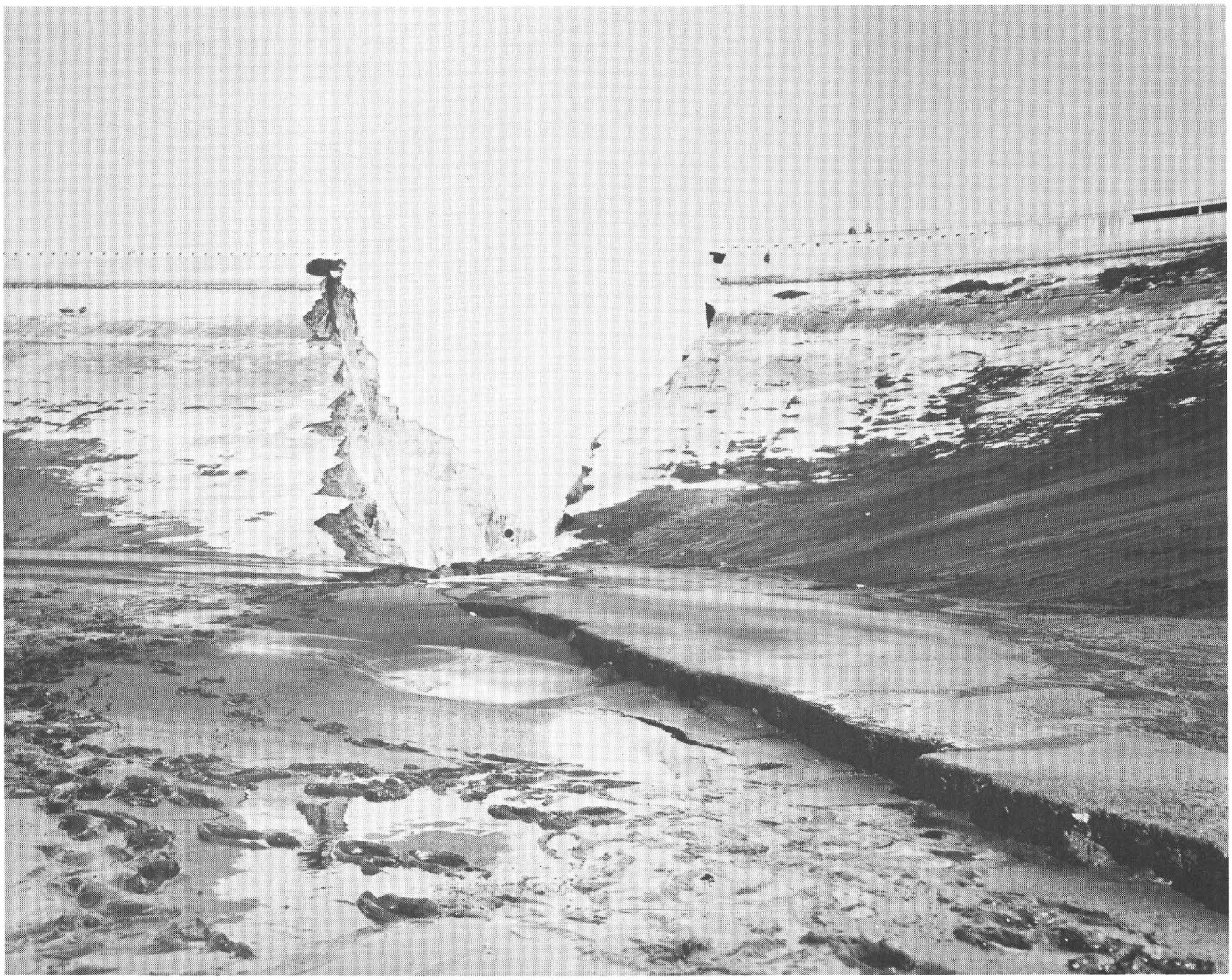


FIGURE 21.—Displacement along earth crack IX. View north (toward ruptured embankment of Baldwin Hills Reservoir). Photograph taken December 1963. Courtesy of the Los Angeles Department of Water and Power.

of Water Resources, 1964, pls. 22d, 22e, 22g, 22k).

Cumulative dip-slip displacements along individual earth cracks have ranged from almost imperceptible to at least 7 inches (California Department of Water Resources, 1964, p. 47). The average displacement, however, has been between 1 and 2 inches. Maximum dip slips or vertical separations (which should be nearly the same owing to the generally steep dips of the planes of movement) along all but one of the earth cracks shown on plate 2 have been measured and tabulated by the California Department of Water Resources (1964, pls. 17a and 17b). Maximum displacement apparently occurred along crack IX where the displacement (or an approximately equivalent vertical separation) has been given as 6 and 7 inches (California Department of Water Resources, 1964, pls. 17a and 17b, p. 47). Displacement on crack IX, however, may have been equalled or exceeded by displacements along cracks I and II. According to one report (D. R. Brown, oral commun. 1962), up to 4 inches of "cracking" had been observed along crack I through the Windsor Hills School yard (east of the Stocker Street–Overhill Drive intersection) by November 1957. During the 1957–63 interval an additional 2 inches of movement occurred along crack I, bringing the total to 6 inches. Four inches of movement had occurred along crack II by the time the photograph in figure 19 was made, and by the end of 1963 total displacement along this crack exceeded 5 inches, nearly that observed along crack IX. There seems to be little relation between displacement and crack length. Cracks I and IX, with 6- or 7-inch displacements, are relatively long. Crack II, on the other hand, which shows a minimum of 5-inches of displacement, is one of the shortest cracks observed in the Baldwin Hills.

Where the earth cracks intersect white lines painted on asphalt surfaces, little if any lateral displacement of

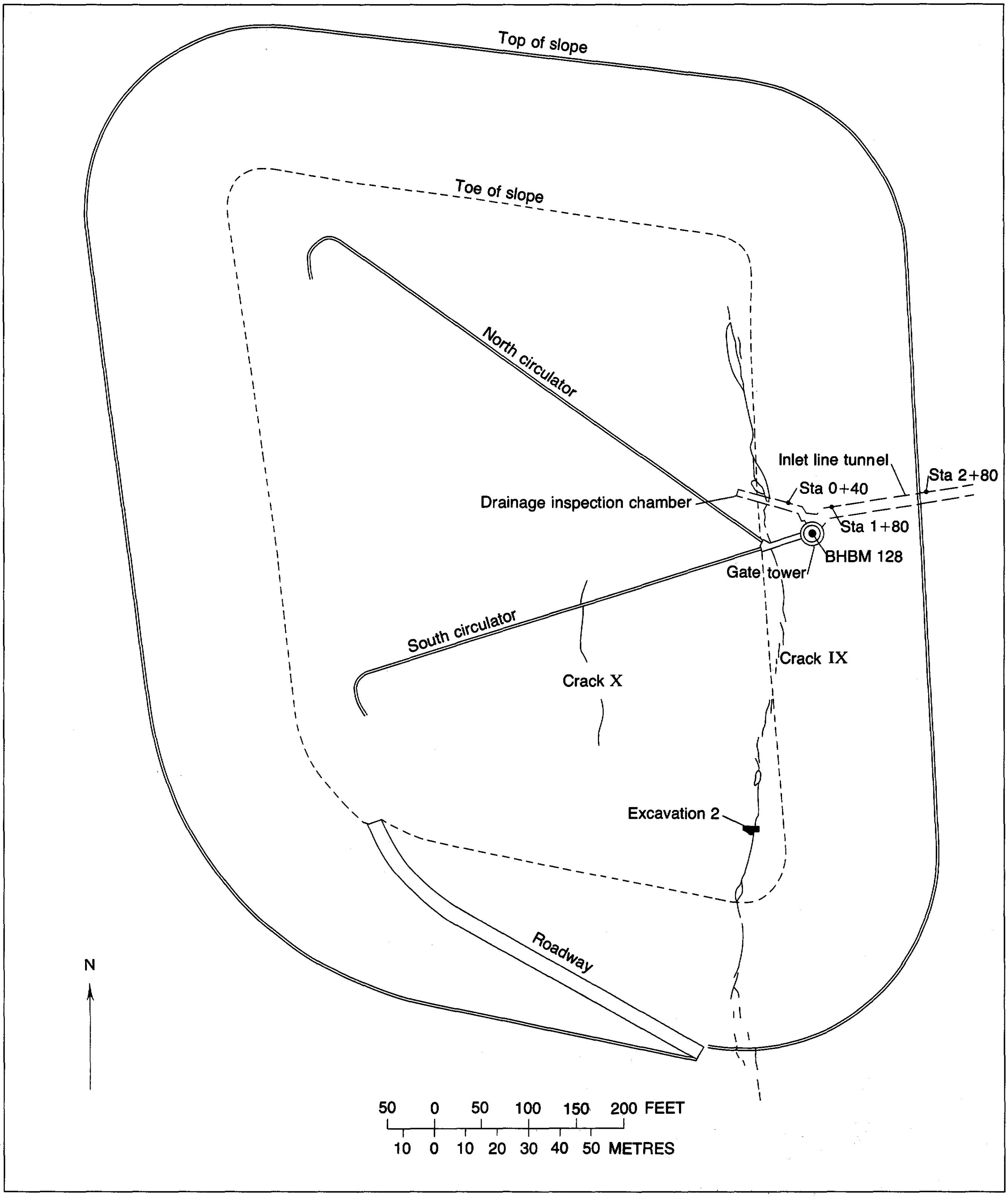


FIGURE 22.—Map of Baldwin Hills Reservoir showing: (1) traces of earth cracks IX and X; (2) location of California Department of Water Resources excavation 2; (3) locations of inlet line tunnel, circulator lines, and drainage inspection chamber of the reservoir. Earth crack IX could not be followed beyond northernmost extent shown on map owing to erosion that accompanied failure of the reservoir. Adapted from California Department of Water Resources (1964, pl. 22a). See plate 2 for location of map area.

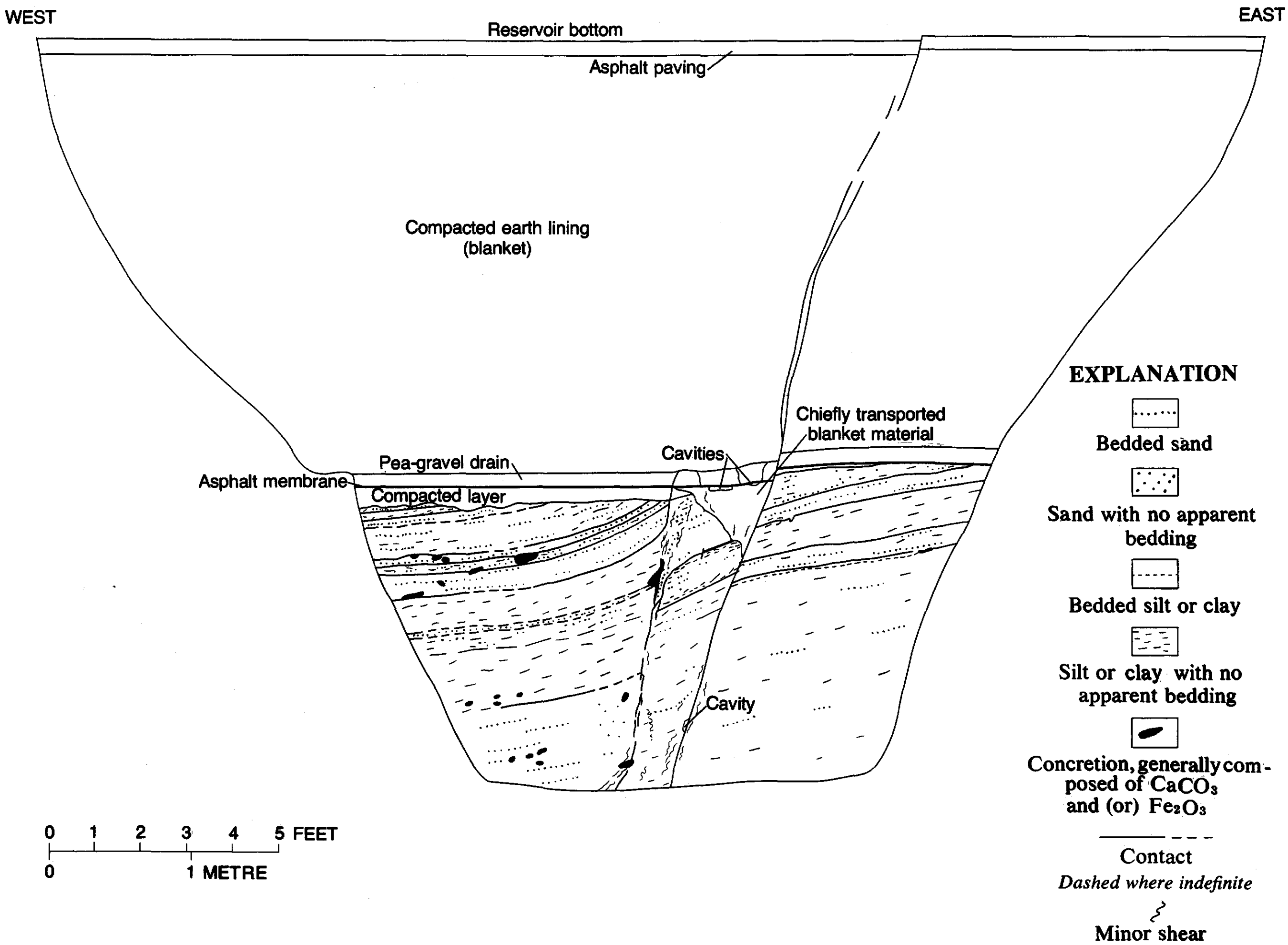


FIGURE 23.—Drawing of north face of California Department of Water Resources excavation 2 intersecting earth crack IX. See figure 22 for location. Modified after California Department of Water Resources (1964, pl. 22e).

the lines can be seen. Curbs and other rigid structures located athwart some of these cracks show minor horizontal displacements that could be interpreted as lateral offsets. However, none of these offsets amounts to more than a very small fraction of the dip-slip component, and they are generally ambiguously expressed. Broken and horizontally offset curbings and other rigid concrete structures occur along or adjacent to the traces of cracks II, IV, VI, VIII, and IX; these offsets, however, average no more than ⅛–¼ inch and range up to a maximum of ½ inch. The sense of lateral movement adduced from offsets of various structures and surfaces is inconsistent from crack to crack and even from place to place along the same crack. Concrete curbings along cracks II, IV, VI, VIII, and IX showed right-lateral offsets, whereas the concrete inspection chamber athwart crack IX was offset left-laterally (California Department of Water Resources, 1964, photo 72). Very slight offsets of white lines on asphalt surface extending across cracks II and IV and the development of feather fractures within the asphalt floor of the Baldwin Hills Reservoir adjacent to crack IX were consistent with left-lateral displacement.

The apparently contradictory indications of the sense of lateral movement along cracks II, IV, and IX may be attributable in part to the manner of failure of rigid structures lying across these cracks. An oblique orientation of the structures with respect to the cracks, or irregular rupturing of surface layers, might result in a rotation of the structures during pure dip-slip movement in such a way as to simulate lateral displacement along the cracks. Furthermore, rigid structures riding athwart a fault along which lateral displacement has occurred may be rotated so as to produce offsets of the structures in a sense opposite to that of the displacement along the fault itself; this passive type of offset is illustrated schematically in figure 24.

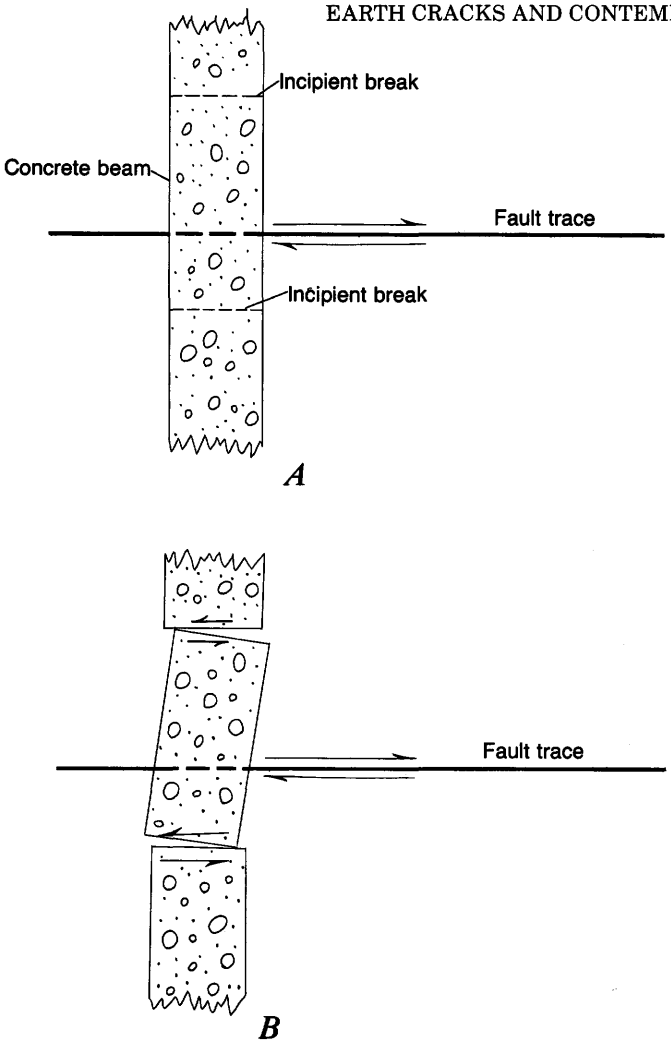


FIGURE 24.—Plan view showing possible horizontal offset of rigid structure intersected by fault along ground surface in sense opposite to that of the supporting crustal blocks.

The depths to which the displacements along the earth cracks may have extended have not been clearly determined, but they are at least tens and possibly hundreds of feet. The only direct evidence of the depth of displacement comes from excavations across cracks IX and X, as logged by the California Department of Water Resources (1964, pls. 22a–22m) (figs. 22 and 23). These excavations revealed measurable offsets within the 8–10 feet of artificial fill lining the bottom of the Baldwin Hills Reservoir (completed in 1951). Because these offsets were clearly evident at the base of the fill (fig. 23), they undoubtedly extended to at least the bottoms of the excavations (that is, 18–20 ft beneath the floor of the reservoir). Several distributional features of the earth cracks also suggest that the displacements continue to depths of more than a few feet or even a few tens of feet. These include: (1) the long linear extent of earth cracks I, IV, and IX; (2) the considerable relief traversed by crack I, which can be traced along the ground surface through elevation differences of about 75 feet between Overhill Drive and Stocker Street; and (3) the apparent consistency in the sense of the vertical separations recorded along a given crack. Oil well damage associated with two small earthquakes that took place in 1963 may also bear on the depth of displacement along the cracks. Two wells (Standard Oil Co. Stocker 5 and 17; pl. 2) are reported to have been damaged within the Vickers zone (pl. 1) during an earthquake on February 18, 1963, and a third well (Standard Oil Co. Baldwin Cienega 27; pl. 2) was damaged at a depth of 1,520 feet in association with an earthquake on March 10, 1963 (California Department of Water Resources, 1964, p. 42). Regardless of the specific mechanism responsible for the damage to the wells, it is significant that: (1) damage to all three wells was confined to the east block of the Inglewood oil field (although Stocker 5 and 17 were spudded in the west block, they pass through the west-dipping Inglewood fault well above the top of the Vickers zone; see California Department of Water Resources 1964, pls. 8, 10); and (2) the location of the well damage is consistent with rupturing or bending of the casings in response to displacements projected to depth along the surface cracks. Thus the described oil well damage affords permissive evidence of earth crack displacements to depths of over 1,000 feet.

Little is known of the history of movement along the earth cracks. Movement along cracks I, II, III, and IV had been recognized by the end of 1958 (Hayes, 1959, fig. 1). Crack XIII was apparently discovered about 1960 (Hamilton and Meehan, 1971, p. 341). Movement along crack V was recognized in 1962 and that along cracks VI and VII was first detected in February 1963. The remaining cracks (that is, VIII, IX, X, XI, and XII) were discovered after the failure of the Baldwin Hills Reservoir in 1963 (California Department of Water Resources, 1964, pls. 17a and 17b). Displacement along many of the cracks has since continued at least intermittently; there has, however, been almost no increase in their length.

The earliest examination of any of the cracks by a trained observer was in May of 1957 when crack I was studied by Professor F. C. Converse (oral commun. 1961), a consulting foundation engineer. Converse first observed crack I in a large compacted fill on the east side of Stocker Street, and within a week or so he discovered that it extended south through the Windsor Hills School yard (fig. 18). It soon became apparent, moreover, that the cracking extended both north and south, well beyond the area of fill and could be traced with local discontinuity through a distance of almost one-half mile. Displacement along crack I may have begun even before 1957, however, for a civil engineer employed by the Los Angeles Department of Water and Power

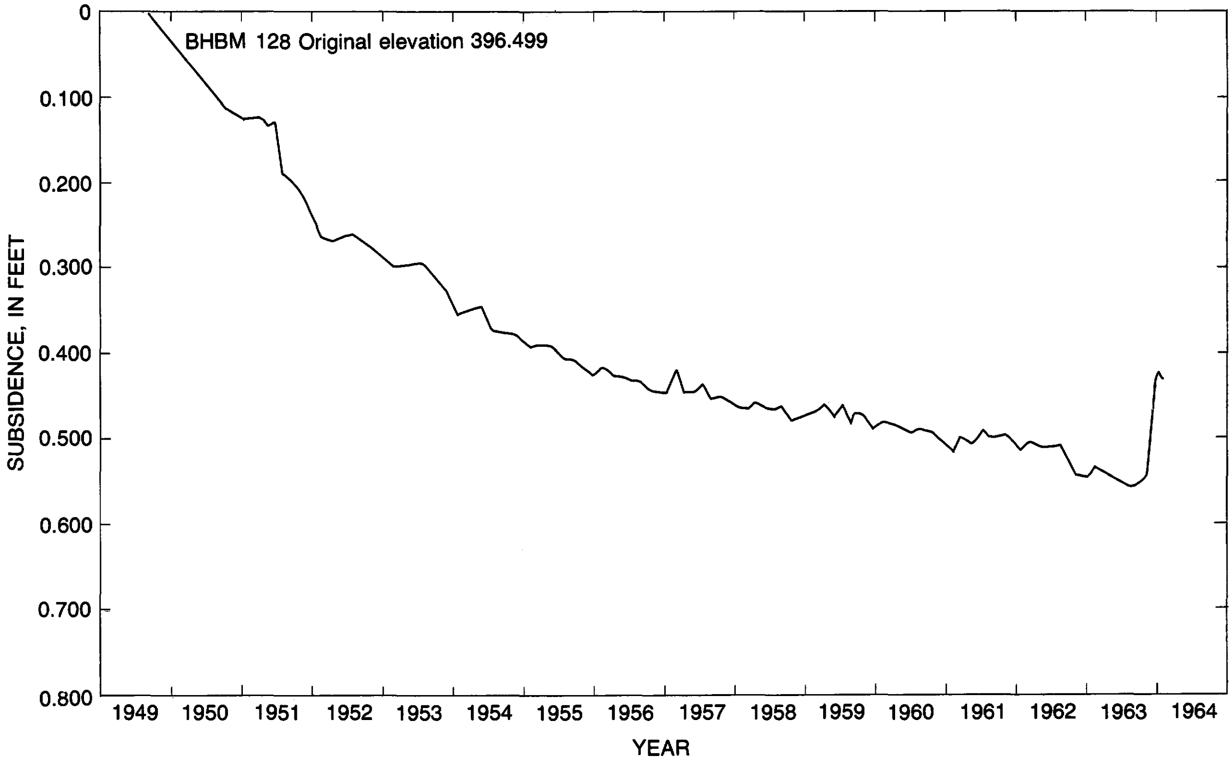


FIGURE 25.—Subsidence of BHBM 128 with respect to Hollywood E–11 (see pl. 4 and fig. 22), 1949–1963 (California Department of Water Resources, 1964, pl. 25d).

reportedly recognized cracks extending across Overhill Drive west of the Windsor Hills School in the summer of 1949 (S. R. Powers, written commun. 1970). Furthermore, according to a memorandum in the files of the Los Angeles County Department of County Engineer (A. G. Keene, written commun., 1970) the janitor of the Windsor Hills School recognized crack I as early as 1955.

Several lines of indirect evidence indicate that movement along crack IX probably began as early as 1950 or 1951. Subsidence of the Baldwin Hills Reservoir gate tower bench mark BHBM 128 (fig. 25), about 50 feet east of crack IX (fig. 22), proceeded at a uniform rate (with respect to Hollywood E–11) of about 0.1 foot/year between July 1949 and the end of 1950, at which time the rate dropped abruptly to about 0.01 foot/year. In July 1951 the subsidence rate increased sharply to about 0.7 foot/year. The initial rate of 0.1 foot/year was resumed in August 1951 and continued until February 1952. At that time the average rate again decreased abruptly to about 0.05 foot/year, but it was interrupted about every 6 months by successive, small reversals. The abrupt change in rate at the end of 1950, as well as the successive reversals after the reservoir was filled (in 1951), may be interpreted as reflections of displacement along crack IX.

The second line of evidence suggesting that movement along crack IX probably began as early as 1951, derives from observations in the drainage inspection chamber beneath the Baldwin Hills Reservoir. In October 1951 a crack 3/32 inch wide was detected within the concrete gallery of the inspection chamber, about 15 feet east of the trace of one of the two faults (R. R. Wilson, written commun., 1964) with which the movement along crack IX seems to have been associated (California Department of Water Resources, 1964, pls. 22d, 22e, 22g, 22h, and 22k). This crack continued to enlarge following its discovery, and additional cracks were discovered within the inspection chamber in 1958 and 1960, west and east, respectively, of the initial break (R. R. Wilson, written commun.,1964). Enlargement of the main crack proceeded somewhat irregularly over the next 12 years, but at an apparently increasing rate (fig. 26). Hudson and Scott (1965, p. 169–171) point out that this graph (fig. 26) shows both an "indication of a definite change in the rate of crack development some time in 1957 and [again in] 1961," and "a pronounced yearly periodicity, with peaks occurring in the spring."

Evidence of early movement along crack IX was also seen in the connector conduit between the gate tower and circulator lines along the floor of the Baldwin Hills Reservoir (see fig. 22), following its failure in 1963. This conduit, which overlies crack IX, showed apparent extension or slippage around a steel bell ring which,

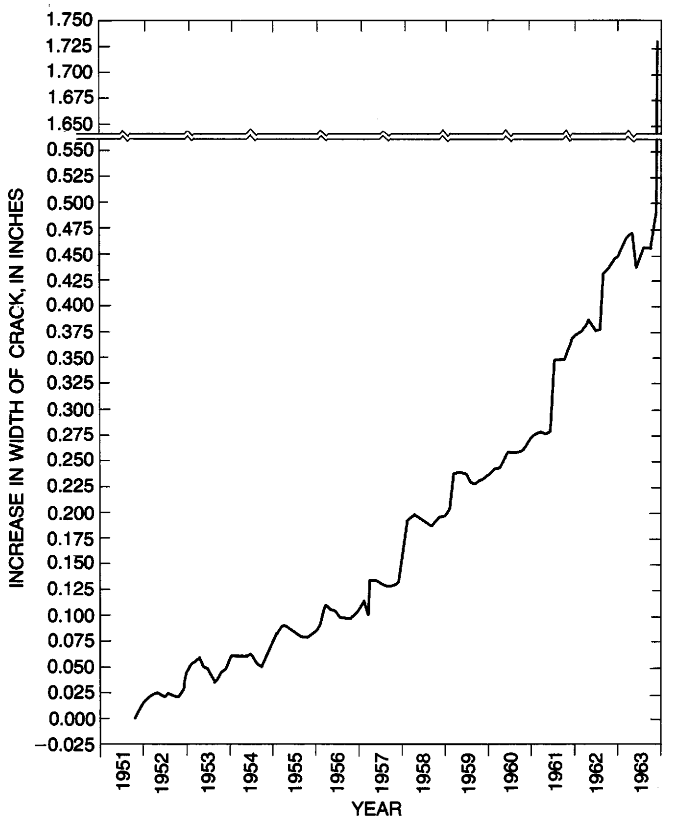


FIGURE 26.—Growth of crack in concrete liner of drainage inspection chamber of Baldwin Hills Reservoir (see pl. 2 and fig. 22), October 1951–December 1963. Average of repeated strain-gage measurements at top of north and south sides of inspection chamber. Adapted from R. R. Wilson (written commun., 1964) and Hudson and Scott (1965, p. 170).

from the character of the corrosion products, was inferred to have been going on for a number of years before the reservoir failed (California Department of Water Resources, 1964, p. 61–62).

The significance of the inspection chamber cracking and the extension of the conduit is not entirely clear. The drainage inspection chamber, for example, "had only minimal temperature reinforcement in the longitudinal direction" (California Department of Water Resources, 1964, p. 61), and the connector conduit probably was not structured to withstand pronounced extension. Hence the cracking and extension cannot be certainly ascribed to displacement along crack IX, and may have been due simply to the general horizontal movement that had taken place across the diameter of the reservoir since its completion. (See preceding section on "Horizontal Movements.") Nevertheless, the localization of the cracks and conduit extension along crack IX, together with the occasional reversals in the gate tower settlement curve, strongly suggest that these phenomena are due to something other than simple horizontal extension across the reservoir: namely, differential displacement along crack IX.

Settlement records around the perimeter and along the circulator lines of the Baldwin Hills Reservoir (California Department of Water Resources, 1964, pls. 25a–25c) suggest that movement along crack X may date back to 1951. Repeated leveling along both the south parapet wall and the south circulator line (California Department of Water Resources, 1964, pls. 25a and 25c) shows a prominent steepening to the west of the vertical movement gradient across crack X (or its projected trace); this steepening is consistent with continuing displacement since 1951 along the fault associated with this earth crack.[4]

Rates of movement along many of the earth cracks varied considerably from the time that they were first observed until the end of 1963. According to reports supplied to the Los Angeles County Department of County Engineer (D. R. Brown, oral commun., 1962), measurements along crack I (within the Windsor Hills School yard) between October and December of 1957 indicated that "movement" was proceeding at about 0.10 foot per month, whereas the vertical separation rate during the 34-month period between December 1957 and October 1960 apparently averaged less than 0.008 foot per month. Again, according to Walley (1963, p. 7), the cracked section of Overhill Drive was resurfaced early in 1959; subsequent displacement along crack I where it crosses this resurfaced area has been less than 0.10 foot. The rate of movement also has varied along crack IV where it crosses La Brea Avenue. La Brea Avenue was resurfaced across crack IV before the close of 1959 and this crack had not reappeared prior to the middle of 1962. By 1963, however, cracking had begun again where crack IV intersects La Brea Avenue. The occurrence of calcium carbonate incrusted fractures in clay-tile drain athwart crack IX (California Department of Water Resources, 1964, p. 58) indicates that displacement within the natural foundation materials locally preceded failure of the Baldwin Hills Reservoir (and, by implication, the relatively large and apparently sudden displacement that is thought to have

[4]The California Department of Water Resources (1964, p. 60) has observed that a "trough of maximum settlement has been defined which crosses the reservoir in a north-south direction and which is parallel to and just westerly of the trace of Fault V [approximately coincident with crack X of this report]*** The settlement trough suggests that foundation deterioration was in progress along Fault I" (approximately coincident with earth crack IX of this report). The trough of differential settlement alluded to here, however, is well defined only along the north wall of the reservoir and the northern part of the reservoir floor; it disappears almost completely toward the south end of the reservoir (California Department of Water Resources, 1964, pls. 25a–25c). The configuration of this settlement trough closely mimics the distribution and thickness of fill placed within the reservoir area (California Department of Water Resources, 1964, pls. 2 and 11). Furthermore, the differential settlement along the north wall of the reservoir with respect to that along the northwest corner (a zone of comparable regional subsidence but relatively limited fill) was more pronounced during the early life of the reservoir (see California Department of Water Resources, 1964, pl. 25a). Thus, although it is not unlikely that part of the settlement along this trough is attributable to a general "foundation deterioration," the described settlement probably is due chiefly to the compaction of fill underlying the northern part of the reservoir.

occurred along crack IX at about the time of failure—see below) by some substantial period of time. Whether this prefailure movement occurred as creep or small, discrete displacements has not been clearly determined. In any case, displacements had not extended upward to the floor of the reservoir by 1957, for it was drained during 1957 and no evidence of displacement was reported at that time from along the traces of cracks IX or X (California Department of Water Resources, 1964, p. 36). "Evidence of increasing displacement [along crack IX prior to the failure of the reservoir] was the presence of ostracods clinging to part of the broken paving surface. The remainder exhibited the lustre of a fresh break, which undoubtedly occurred on the day of the reservoir failure. This lends credence to the conclusion that the paving broke in at least two stages" (California Department of Water Resources, 1964, p. 58). Evidence of continuous, relatively uniform movement is best shown by crack II where it passes through a paved parking lot. This parking lot was resurfaced shortly after January 1961 when the photograph in figure 19 was taken. Rupturing was observed along the trace of this crack several months after resurfacing, and measurable vertical separations exceeded 1 inch by the end of 1963.

Although reversals in the sense of displacement have never been observed along any of these cracks, local reversals in the sense of vertical movement (relative to Hollywood E–11) have been detected within the blocks east of some of these cracks. The reversal east of crack I sometime between 1954 and 1958, for example, has been described already. (See discussion of the pattern of elevation changes in the northern Baldwin Hills.) Reversals in the sense of vertical movement in the block east of crack IX are particularly indicated by both the settlement record of the Baldwin Hills Reservoir gate tower (fig. 25) and the results of periodic elevation measurements along a level line athwart crack IX (see fig. 27). Similarly, repeated leveling around the reservoir perimeter has disclosed at least one episode of prefailure uplift within the block immediately east of crack X (Castle and Youd, 1973, p. 97–98). All these reversals are most reasonably interpreted as rebound accompanying displacement along cracks I and IX.

Because the Baldwin Hills area is seismically active, and because faulting commonly is associated with earthquake activity in other areas, Hudson and Scott (1965, p. 171–173), in conjunction with members of the Seismological Laboratory of the California Institute of Technology, investigated the relation between seismicity and crack growth in the reservoir area. These writers (Hudson and Scott, 1965, p. 171–172) concluded that a "correlation of fault movement and earthquakes is *** dubious, a conclusion which is borne out by a relatively long list of small earthquakes close to the [Baldwin Hills] reservoir which do not appear to be connected with any special features on the crack growth curve" derived from measurements in the drainage inspection chamber (fig. 26). Nevertheless, the association noted earlier between two small earthquakes and oil well damage in the east block of the Inglewood field (California Department of Water Resources, 1964, p. 42) suggests an indirect relation between displacements along subsurface projections of the cracks and earthquake activity. The distances of these earthquakes from the Baldwin Hills Reservoir (6 and 17 miles) given by Hudson and Scott (1965, p. 172), together with their "B" quality epicentral locations (J. P. Nordquist, oral commun., 1969), indicate, however, that these subsurface displacements(?) must have been triggered by seismic waves generated well away from the oil field, as seems to have occurred in the Dominguez and Rosecrans oil fields (Richter, 1958, p. 156, 499).

Although the evidence is in part contradictory, earth crack VII may be no more than the breakaway scar of a small landslide that developed in February 1963 (earth crack 8 of the California Department of Water Resources, 1964, p. 41, pls. 17a and 17b). Thus this crack may be unique among those shown on plate 2, in that none of the remaining cracks (with the possible but unlikely exceptions of VIII and XII) seem to have been generated in response to simple gravity failure. Accordingly, further discussion of movement along the earth cracks excludes that associated with crack VII.

CAUSES OF THE SURFACE MOVEMENTS

Gilluly and Grant (1949, p. 487–488) considered four possible explanations for the prominent differential subsidence in the Long Beach Harbor area. These four possibilities seem to be equally appropriate and inclusive as possible explanations for the surface movements in the northern Baldwin Hills as well. They are: (1) oil-field operations; (2) changes in ground-water conditions; (3) compaction of sedimentary materials in response to artificial or natural surface loading; and (4) tectonic activity. Detailed consideration of each of these possible causes leads to the conclusion that all or most of the subsidence and centripetally-directed horizontal movements, and much or all of the earth cracking and associated surficial faulting, are due to oil-field operations. Tectonic activity may have contributed, in some small measure, to the earth cracking, but it is unlikely that it has contributed significantly to either the differential subsidence or the horizontal movements. Changes in ground-water and loading conditions have been very limited and their effects are thought to have been trivial.

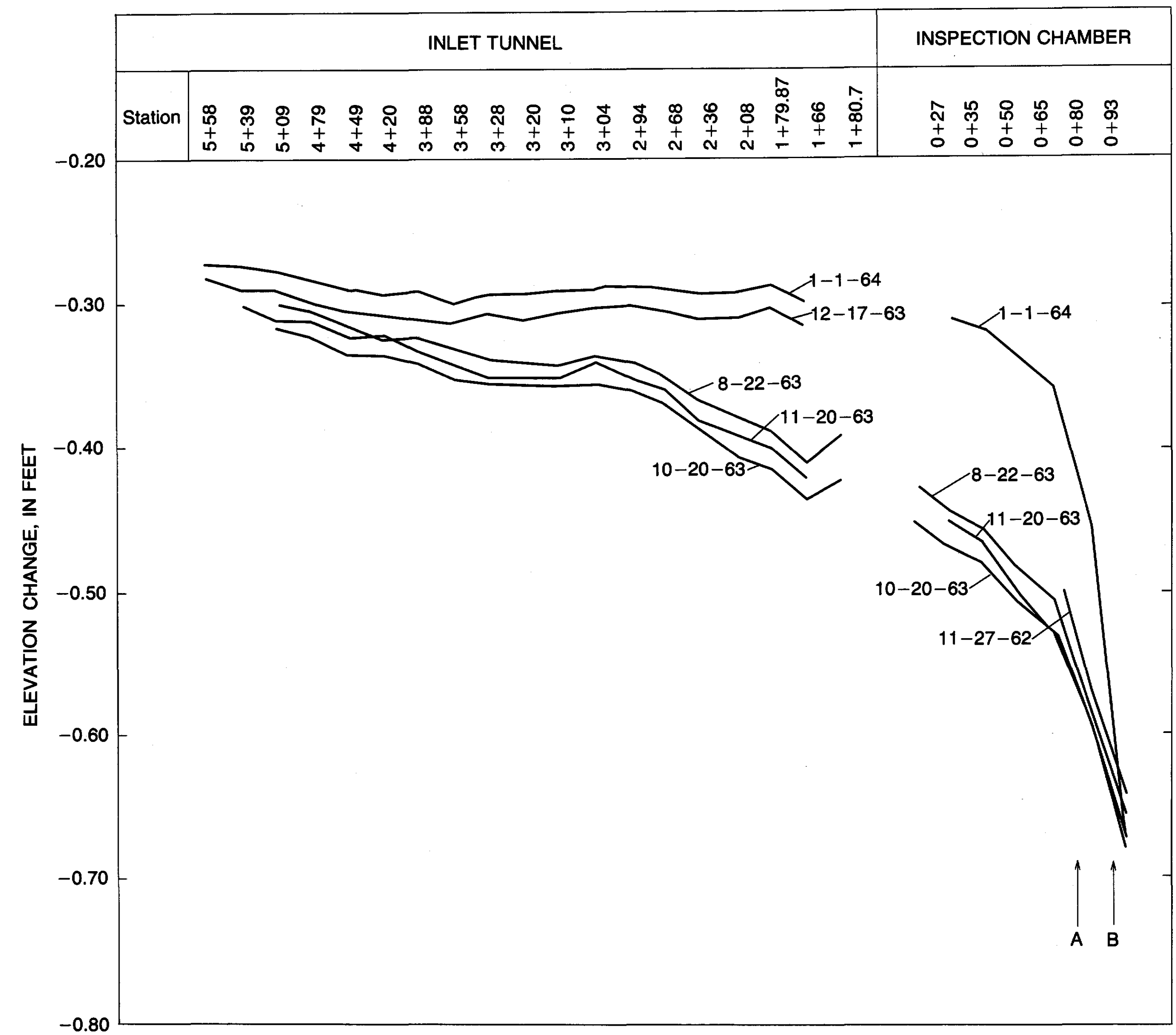


FIGURE 27.—Elevation changes along inlet tunnel and drainage inspection chamber of the Baldwin Hills Reservoir since October 1953, measured with respect to PBM 40–C (Hollywood E–11 equivalent) (adapted from California Department of Water Resources, 1964, pl. 25e). *A*, Approximate location of major crack in concrete liner of drainage inspection chamber (California Department of Water Resources, 1964, photo 72, pl. 22h). *B*, Location of earth crack IX beneath drainage inspection chamber (California Department of Water Resources, 1964, pl. 22h). See figure 22 for location of level surveys.

MOVEMENTS ATTRIBUTABLE TO OIL-FIELD OPERATIONS

Gilluly and Grant (1949, p. 501) have shown that a relation between subsidence and oil withdrawal "is especially suggested [in the Long Beach Harbor area] by the coincidence in both place and time of the rapid subsidence with the exploitation of the [Wilmington] oil field." These writers (1949, p. 463) have also concluded that there exists "a very close agreement between the relative subsidence of the various parts of the field and the pressure decline [developed in response to the extraction of underground fluids], thickness of oil sand affected, and the mechanical properties of the oil sands. This correlation is so close as to constitute conclusive evidence of a cause and effect relation between pressure decline and subsidence." Because great volumes of fluids have been withdrawn in the northern Baldwin Hills in connection with the exploitation of the Inglewood oil field, the relations between surface movements and oil-field operations are examined here first.

DEVELOPMENT OF THE INGLEWOOD OIL FIELD

The discovery well of the Inglewood oil field was completed on September 28, 1924 in the southernmost part of the present field (California Division of Oil and

TABLE 1.—*Petroleum production statistics for the Inglewood oil field by zone through December 31, 1963*

[Conservation Committee of California Oil Producers (1964, p. P). Arranged in approximate order of increasing depth]

Zone	Discovery date	Cumulative production: Oil (bbls)	Cumulative production: Gas (Mcf)
Vickers	Sep. 1924	174,526,000	95,135,000
Rindge	Jul. 1925	22,312,000	20,128,000
Rubel	Aug. 1934	22,694,000	24,513,000
Moynier	Feb. 1932	11,056,000	18,656,000
Bradna	Aug. 1957	1,278,000	2,020,000
Sentous	Sep. 1940	7,578,000	19,493,000
Marlow-Burns	Aug. 1960	1,320,000	3,844,000
Miocene undifferentiated	Mar. 1961	3,000	33,000
Total		240,767,000	183,822,000

Gas, 1961, p. 576–577; Huguenin, 1926, p. 7, pl. II). Reservoir conditions within the upper oil zones were found to be roughly similar in both east and west blocks (Huguenin, 1926, p. 13), and development of the field apparently proceeded rapidly on both sides of the Inglewood fault (Huguenin, 1926, p. 7, pl. II). Peak annual oil production (18,371,536 bbls) and peak annual gas production (13,344,284 Mcf) were attained in 1925, and by June 1926 over 74 percent of the acreage developed to the end of 1963 had been proved (Huguenin, 1926, p. 5; California Division of Oil and Gas, 1963, p. 69). As of January 1, 1964 only slightly more than 1 percent of the cumulative oil production had been drawn from zones discovered after 1940, and little more than 4 percent of the cumulative production had come from zones discovered after 1934 (see table 1).

Large quantities of water have also been produced from the Inglewood field. Cumulative figures are unpublished, but tabulations compiled from summary reports of the State Oil and Gas Supervisor (table 2) indicate that by January 1, 1964 approximately 374,699,000 bbls of water had been produced. The proportion of water, moreover, has generally increased with time (table 2), such that total liquid production has been maintained at high levels, even in later years.

TABLE 2.—*Fluid production and waterflooding statistics for the Inglewood oil field by year*

[Compiled chiefly from summary reports of the State Oil and Gas Supervisor. Gas production statistics for 1924–29 from files of the California Division of Oil and Gas (R. G. Frame, unpub. data, 1962)]

Year	Oil production (in bbls)	Net gas production (in MCF)	Water production (in bbls)	Gross liquid production (in bbls)	Water injected (in bbls)	Net liquid production (in bbls)	Gas/oil (Mcf/bbls)	Gas/gross liquid (Mcf/bbls)	Gas/net liquid (Mcf/bbls)
1924	6,180	6,893	58	6,238		6,238	1.114	1.103	1.103
1925	18,371,536	13,344,284	603,668	18,975,204		18,975,204	.727	.704	.704
1926	17,644,021	13,325,558	1,753,571	19,397,592		19,397,592	.755	.688	.688
1927	12,919,987	9,632,789	1,970,758	14,890,745		14,890,745	.745	.647	.647
1928	10,727,764	7,908,434	2,870,339	13,598,103		13,598,103	.737	.582	.582
1929	8,790,813	6,048,376	3,431,781	12,222,594		12,222,594	.688	.494	.494
1930	6,449,092	4,002,130	3,068,741	9,517,833		9,517,833	.621	.421	.421
1031	5,322,259	2,691,280	3,347,060	8,669,319		8,669,319	.506	.310	.310
1932	4,877,601	2,281,913	3,181,460	8,059,061		8,059,061	.467	.283	.283
1933	4,068,377	1,688,096	3,357,067	7,425,444		7,425,444	.416	.228	.228
1934	3,383,366	1,304,442	2,978,245	6,361,611		6,361,611	.385	.205	.205
1935	4,478,092	1,632,999	3,124,245	7,602,337		7,602,337	.364	.215	.215
1936	4,552,133	1,988,610	2,598,178	7,150,311		7,150,331	.436	.278	.278
1937	5,549,294	3,082,130	2,944,621	8,493,915		8,493,915	.556	.363	.363
1938	5,335,719	3,278,667	3,525,062	8,860,781		8,860,781	.613	.370	.370
1939	4,602,512	2,905,900	3,718,486	8,320,998		8,320,998	.631	.349	.349
1940	4,365,020	2,705,495	3,705,140	8,070,160		8,070,160	.621	.336	.336
1941	4,886,519	3,724,999	3,997,079	8,883,598		8,883,598	.762	.419	.419
1942	6,745,267	5,324,296	7,222,919	13,968,186		13,968,186	.790	.381	.381
1943	6,910,762	6,995,509	7,541,229	14,451,991		14,451,991	1.011	.484	.484
1944	6,460,872	7,487,389	9,194,841	15,655,713		15,655,713	1.158	.478	.478
1945	5,622,703	6,391,438	10,227,989	15,850,692		15,850,692	1.137	.403	.403
1946	4,724,278	4,969,617	10,412,511	15,136,789		15,136,789	1.051	.328	.328
1947	4,332,327	4,039,377	10,850,646	15,182,973		15,182,973	.933	.266	.266
1948	4,376,332	3,917,175	11,278,227	15,654,559		15,654,559	.896	.250	.250
1949	5,061,249	3,800,477	12,085,172	17,146,421		17,146,421	.751	.222	.222
1950	4,853,962	3,679,024	11,889,221	16,743,183		16,743,183	.758	.219	.219
1951	4,929,122	3,770,976	12,165,770	17,094,892		17,094,892	.765	.221	.221
1952	4,932,003	3,763,466	12,352,053	17,284,056		17,284,056	.763	.218	.218
1953	4,892,954	3,954,966	13,506,543	18,399,497		18,399,497	.809	.215	.215
1954	4,658,033	4,007,772	14,154,951	18,812,984	819,242±	17,993,742±	.859	.213	.222
1955	4,356,631	3,436,670	13,867,612	18,224,243	819,242±	17,405,001±	.789	.189	.197
1956	4,435,969	3,342,072	14,544,620	18,980,589	2,237,768	16,742,821	.754	.176	.200
1957	4,632,242	3,518,823	15,293,955	19,926,197	4,475,680	15,450,517	.759	.176	.228
1958	4,413,763	3,441,993	15,939,575	20,353,338	7,019,555	13,333,783	.781	.169	.258
1959	4,242,183	3,323,430	17,538,996	21,781,179	7,272,256	14,508,923	.783	.153	.229
1960	4,557,332	3,527,141	18,384,667	22,941,999	8,565,397	14,376,602	.774	.154	.245
1961	5,769,427	4,583,953	20,282,618	26,052,045	14,373,109	11,678,936	.794	.176	.393
1962	6,729,685	6,957,636	27,240,575	33,970,260	17,795,155	15,995,105	1.032	.205	.435
1963	6,921,366	7,390,448	38,528,470	45,449,836	23,288,351	22,161,485	1.067	.163	.334

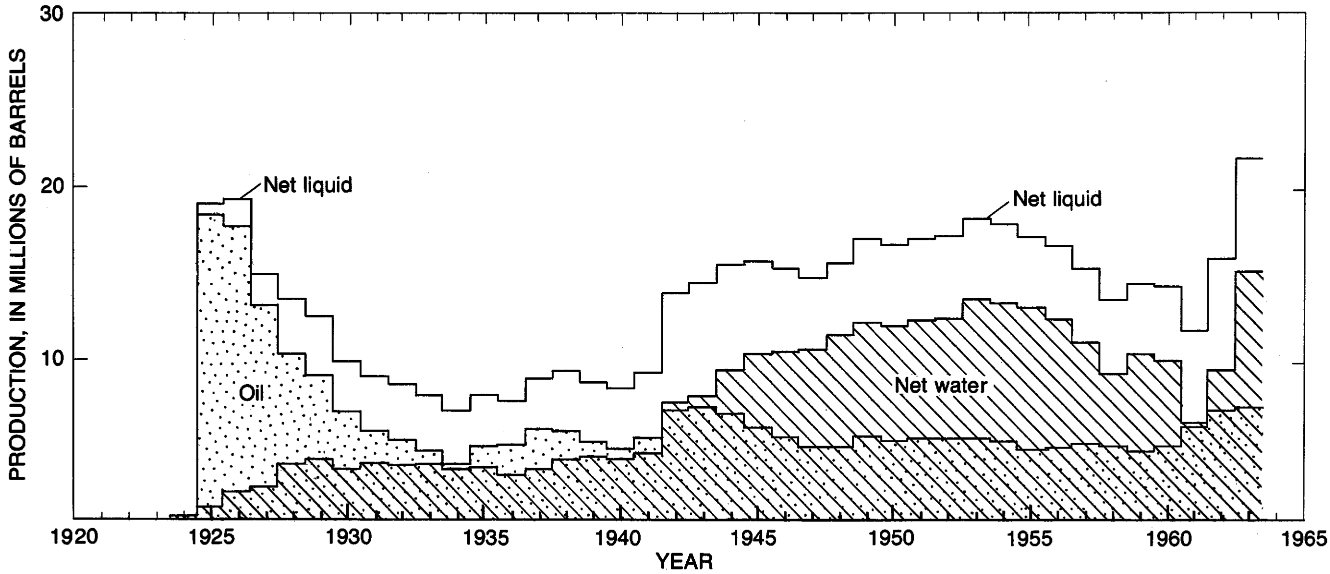


FIGURE 28.—Annual oil, net water, and net liquid production from the Inglewood oil field through 1963. (See table 2.)

Waterflooding was begun in the east block in 1954; flooding in the west block began in 1962 (Oefelein and Walker, 1964; California Division of Oil and Gas, 1963, p. 102). The initial pilot flood was centered about 2,200 feet northwest of the Stocker Street–La Brea Avenue–Overhill Drive intersection (pl. 2); it covered about 3 acres and incorporated a 100-foot section of the Vickers East zone—that is, the Vickers zone east of the Inglewood fault (Oefelein and Walker, 1964, p. 510–511; Walling, 1953, p. 56; Munger Map Book, 1970, p. 165). A second pilot flood, involving a 400-foot section of the Vickers East and covering about 10 acres, was started in 1956 immediately west of the first flood (pl. 2) (Oefelein and Walker, 1964, p. 510–511). About 4.5 million bbls of water were injected during the 3-year pilot flood stage (California Division of Oil and Gas, 1957, p. 94; California Department of Water Resources, 1964, pl. 9). "Full-scale" flooding throughout the entire 1,200–1,300-foot Vickers East interval began in 1957 (Oefelein and Walker, 1964, p. 510–511); it apparently expanded rapidly and by 1963 injection in the Vickers East was proceeding at a rate of over 13 million bbls per year (California Division of Oil and Gas, 1963, p. 102). Although flooding operations in the west block were not begun until 1962, by 1963 approximately 40 percent of the annual injection was going into the Vickers West. Of the total injected to the end of 1963, 79.5 percent went into the Vickers East zone and 84.2 percent went into the Vickers East plus Rubel East zones (California Division of Oil and Gas, 1963, p. 102). The volumes of water injected annually over the field as a whole are given in table 2.

Annual net water, net liquid, and oil production from the Inglewood field are shown in figure 28. Cumulative net-liquid and cumulative gas production through 1963 are presented in figure 29.

Major production from the Inglewood field has been from the Vickers (also known as Vickers-Machado) zone. The Vickers is defined here to include the overlying Investment zone (see pl. 1) as well, for production from this zone has been combined with that of the Vickers by the Conservation Committee of California Oil Producers (W. R. Wardner, written commun., 1967). Although production statistics have not been published for the entire history of this zone, earlier production figures can be deduced from the production history of the field as a whole, the Vickers gas:oil ratio curve (fig. 30), and the Vickers oil production:net water production ratio curve (fig. 31). Thus, about three-quarters of the oil and about

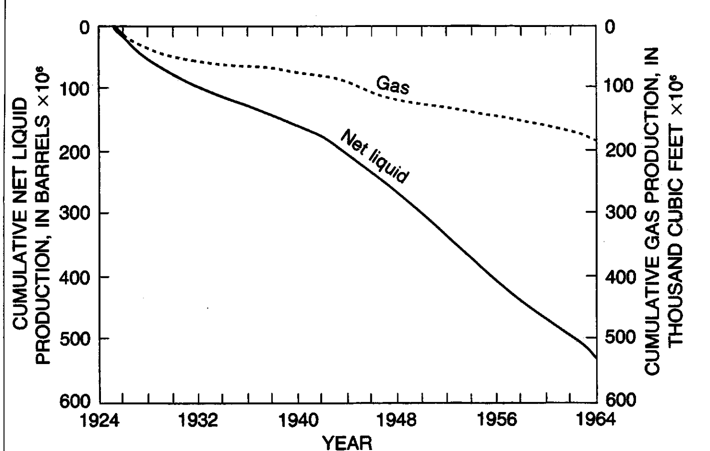


FIGURE 29.—Cumulative net liquid and cumulative gas production from the Inglewood oil field through 1963. Computed chiefly from production statistics presented in the summary reports of the State Oil and Gas Supervisor. (See table 2.)

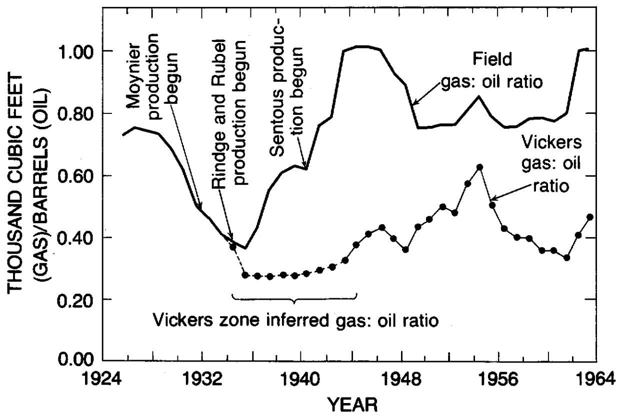


FIGURE 30.—Gas:oil ratios for the Inglewood oil field and the Vickers zone of the Inglewood field. 1924–33 values for the Vickers zone assumed to be identical with those for the entire field; production statistics given in the annual reviews of the Conservation Committee of California Oil Producers indicate that pre-1934 production from zones other than the Vickers was trivial (probably less than 250,000 bbls of oil). 1934–43 values derived through proration of the cumulative gas production for this interval according to annual oil production and extrapolation from earlier and later periods.

four-fifths of the net liquid production from the Inglewood field have been drawn from a zone at a median depth of 2,100–2,200 feet (pl. 1). Annual oil, water and gas production figures for the Vickers zone are given in table 3; curves showing the cumulative net liquid and cumulative gas production through 1963 are presented in figure 32.

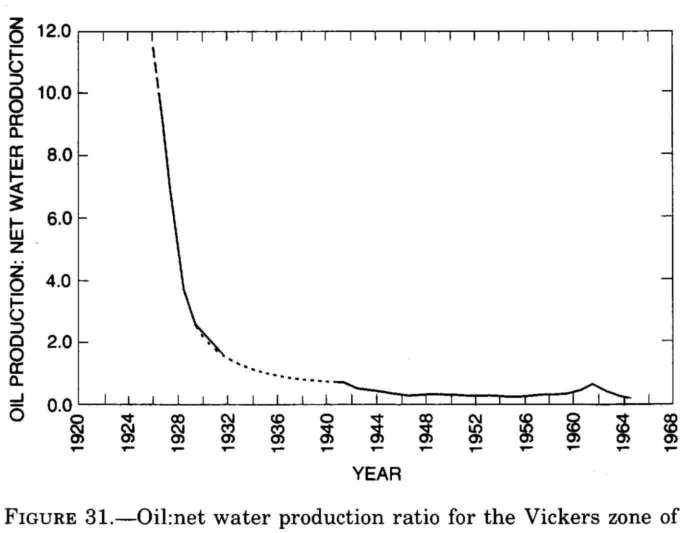


FIGURE 31.—Oil:net water production ratio for the Vickers zone of the Inglewood oil field. 1924–33 values assumed to be identical with those for the entire field; production statistics given in the annual reviews of the Conservation Committee of California Oil Producers indicate that pre-1934 production from all other zones was trivial (probably less than 250,000 bbls of oil). 1934–39 values (dashed line) derived through extrapolation from earlier and later periods.

TABLE 3.—*Fluid production and waterflooding statistics for the Vickers zone of the Inglewood oil field by year*

["Vickers zone" production shown here includes that from the Investment zone (see pl. 1) as well, since production from this zone has been carried with that of the Vickers by the Conservation Committee of California Oil Producers (W. R. Wardner, written commun. 1967). Compiled chiefly from the annual reviews of the Conservation Committee of California Oil Producers. 1924–1933 Vickers figures assumed to be identical with those for the entire field, since the tabulations of the Conservation Committee indicate that pre-1934 production from all other zones was trivial (probably less than 250,000 bbls of oil); 1934–43 gas production figures calculated from the gas:oil ratio curve given in figure 34; 1934–39 water production figures calculated from the oil production:net water production ratio curve given in figure 31]

Year	Oil production (in bbls)	Net gas production (in Mcf)	Water production (in bbls)	Gross liquid production (in bbls)
1924	6,180	6,893	58	6,238
1925	18,371,536	13,344,284	603,668	18,975,204
1926	17,644,021	13,325,558	1,753,571	19,397,592
1927	12,919,987	9,632,789	1,970,758	14,890,745
1928	10,727,764	7,908,434	2,870,339	13,598,103
1929	8,790,813	6,048,376	3,431,781	12,222,594
1930	6,449,092	4,002,130	3,068,741	9,517,833
1931	5,322,259	2,691,280	3,347,060	8,669,319
1932	4,877,601	2,281,913	3,181,460	8,059,061
1933	4,068,377	1,688,096	3,357,067	7,425,444
1934	3,152,812	1,171,894	4,129,800	7,282,612
1935	2,887,442	805,546	2,887,442	5,774,884
1936	1,996,051	544,922	2,193,000	4,189,051
1937	1,851,278	503,548	2,127,000	3,978,278
1938	2,064,361	571,828	2,580,000	4,644,361
1939	2,216,313	616,135	2,805,000	5,021,313
1940	2,297,320	657,034	2,936,000	5,233,320
1941	2,383,535	700,759	3,282,000	5,665,535
1942	3,510,906	1,074,337	6,430,000	9,940,906
1943	3,264,546	1,054,448	6,960,000	10,224,546
1944	3,094,649	1,169,777	7,330,000	10,424,649
1945	2,966,788	1,224,870	8,710,000	11,676,788
1946	2,637,000	1,136,000	8,440,000	11,077,000
1947	2,510,000	985,136	8,215,000	10,725,000
1948	2,701,000	965,175	8,190,000	10,891,000
1949	3,415,000	1,494,000	10,400,000	13,815,000
1950	3,253,708	1,493,452	10,120,000	13,373,708
1951	3,179,000	1,595,908	10,630,000	13,809,000
1952	3,213,000	1,535,857	10,260,000	13,473,000
1953	3,311,000	1,899,000	10,760,000	14,071,000
1954	3,243,000	2,049,000	12,340,000	15,583,000
1955	2,910,000	1,488,000	12,080,000	14,990,000
1956	2,859,000	1,209,000	12,110,000	14,969,000
1957	2,977,000	1,184,000	13,120,000	16,097,000
1958	2,791,000	1,110,000	15,320,000	18,111,000
1959	2,704,000	964,615	14,993,000	17,697,000
1960	2,728,000	980,000	14,606,000	17,334,000
1961	2,951,000	969,000	17,331,000	20,282,000
1962	3,244,000	1,318,000	23,611,000	26,855,000
1963	3,724,000	1,734,000	33,873,000	37,597,000

Year	Water injected (in bbls)	Net liquid production (in bbls)	Gas/oil (Mcf/bbls)	Gas/gross liquid (Mcf/bbls)	Gas/net liquid (Mcf/bbls)
1924		6,238	1.114	1.103	1.103
1925		18,975,204	.727	.704	.704
1926		19,397,592	.755	.688	.688
1927		14,890,745	.745	.647	.647
1928		13,598,103	.737	.582	.582
1929		12,222,594	.688	.494	.494
1930		9,517,833	.621	.421	.421
1931		8,669,319	.506	.310	.310
1932		8,059,061	.467	.283	.283
1933		7,425,444	.416	.228	.228
1934		7,282,612	.372	.161	.161
1935		5,774,884	.279	.139	.139
1936		4,189,051	.273	.130	.130
1937		3,978,278	.272	.127	.127
1938		4,644,361	.277	.123	.123
1939		5,021,313	.278	.123	.123
1940		5,233,320	.286	.127	.127
1941		5,665,535	.294	.124	.124
1942		9,940,906	.306	.108	.108
1943		10,224,546	.323	.103	103
1944		10,424,649	.378	.112	.112
1945		11,676,788	.412	.105	.105
1946		11,077,000	.431	.103	.103
1947		10,725,000	.392	.092	.092
1948		10,891,000	.357	.089	.089
1949		13,815,000	.437	.108	.108
1950		13,373,708	.459	.112	.112
1951		13,809,000	.502	.115	.115
1952		13,473,000	.478	.114	.114
1953		14,071,000	.574	.135	.135
1954	819,242±	14,763,758±	.632	.131	.139
1955	819,242±	14,170,758±	.511	.099	.105
1956	2,237,768	12,731,232	.425	.081	.095
1957	4,475,680	11,621,320	.399	.074	.102
1958	7,901,555	11,091,445	.398	.061	.100
1959	7,272,256	10,424,744	.356	.055	.093
1960	8,565,397	8,768,603	.359	.057	.112
1961	13,022,320	7,259,680	.328	.048	.133
1962	16,556,103	10,298,897	.407	.049	.128
1963	22,661,873	14,935,127	.466	.046	.116

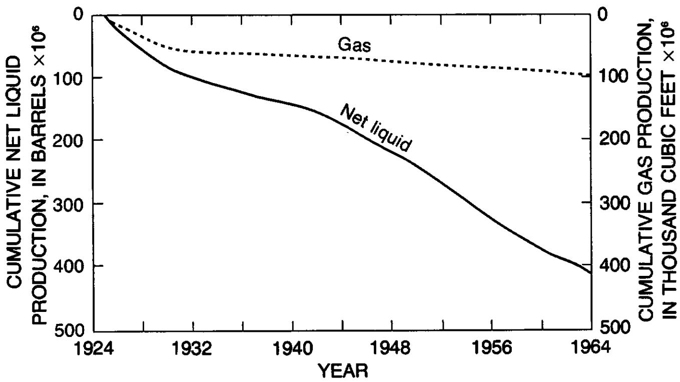


FIGURE 32.—Cumulative net liquid and cumulative gas production from the Vickers zone of the Inglewood oil field through 1963. Computed chiefly from production statistics given in the annual reviews of the Conservation Committee of California Oil Producers. (See table 3.)

Reservoir pressure data from the producing zones of the Inglewood field are not generally available. A single curve showing changing reservoir fluid pressure in the Vickers East zone has been published (California Department of Water Resources, 1964, pl. 9), however, and is reproduced here as figure 33. It should be equally representative of fluid pressure decline within the upper levels of the Vickers West zone as well (at least through 1954 when waterflooding was begun), because: (1) reservoir conditions were initially similar in the east and west blocks, even though these blocks are separated by the nearly impermeable barrier of the Inglewood fault; and (2) development proceeded both uniformly and rapidly in the two blocks. A derived reservoir pressure curve (fig. 34) showing the "average" pressure decline in the Vickers zone in the absence of waterflooding has been constructed from the data of figure 33.

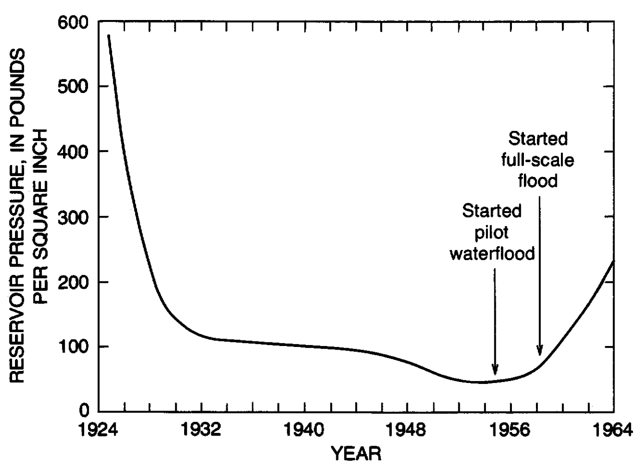


FIGURE 33.—Fluid pressure at −1,330 feet in the Vickers East zone of the Inglewood oil field during the period 1925–63. After California Department of Water Resources (1964, p. 16, pl. 9).

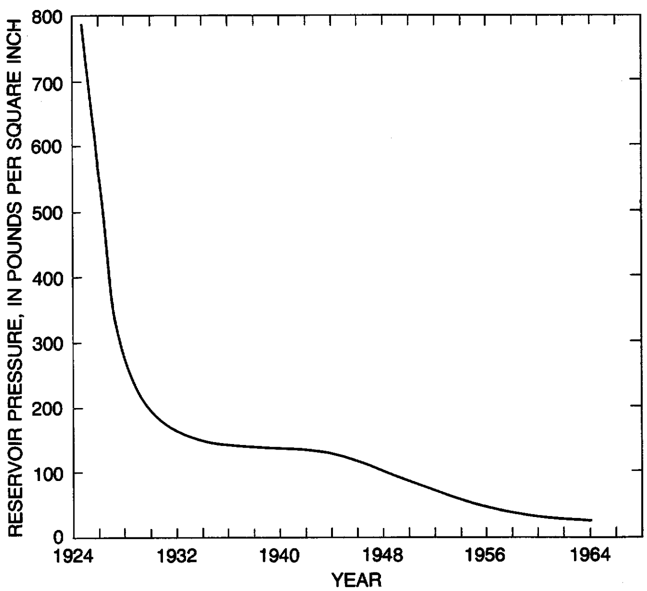


FIGURE 34.—Calculated fluid-pressure decline midway through the central Vickers zone of the Inglewood oil field during the period 1925–63. Derived from figure 33 by proportional extrapolation of data to a depth of −1,850 feet (the approximate midpoint of the Vickers zone) and contingent upon the following assumptions: (1) uniform elevations among correlative intrazone horizons throughout the Inglewood field (a simple, horizontally layered system); (2) a calculated initial reservoir fluid pressure of 790 psi; (3) uniform decline of the fluid-pressure gradient throughout the reservoir column (an assumption supported by the interzone pressure-decline history in the Wilmington field); and (4) an absence of waterflooding effects.

The geographic limits of the Inglewood oil field, the Vickers zone, and the Inglewood oil-field anticline are approximately coincident (fig. 3). The Vickers zone boundary of figure 3 differs from the full field production boundaries only along the south or southeast edge of the field. The southeastern extension of the field beyond the Vickers boundary is apparently due in part, and perhaps entirely, to: (1) production from the Bradna, Sentous, and Marlow-Burns zones, the producing parts of which are restricted to the southeast flank of the structure (California Division of Oil and Gas, 1961, p. 577); and(or) (2) production brought in at the extreme southeast edge of the field in 1957 from beneath the "Bradna Community" lease (Bailey, 1957, p. 87).

SUBSIDENCE

A spatial coincidence between the Inglewood oil field and the well-developed differential subsidence in the northern Baldwin Hills is clearly demonstrated in the frontispiece and through comparison of figures 3 and 4 with plate 4. The patterns of subsidence represented on plate 4 are symmetrically arranged with respect to both the oil-field production limits and the producing structure itself. There is, in addition, an equally well-defined coincidence between the center of subsidence and the approximate center of the Inglewood oil-field anticline; the center of the anticline is inferred, in turn, to coincide with the area of maximum petroleum accumulation and maximum fluid extraction. Spatial coincidence between the Inglewood oil field and the Baldwin Hills subsidence is also shown by the geographical association between the subsidiary and subsidence dish recognized during the 1950–54 interval and the underlying structural crest of the east block (figs. 3 and 4, and pl. 4). Thus the subsidence field and the producing area of the oil field are concentrically centered, identically oriented, and similarly shaped.

Although the Baldwin Hills subsidence field extends well beyond the producing limits of the Inglewood oil field, this feature characterizes a number of other U.S. oil-field subsidence domains. Wherever oil-field-related subsidence fields have been mapped, they are generally at least twice as large as the associated producing areas (Yerkes and Castle, 1970, p. 57–58). Thus the absence of a more precise congruency between the Inglewood oil field and the associated subsidence bowl should not be viewed as detracting from the well-defined spatial coincidence between these features.

The coincidence in time between the onset and development of the differential subsidence in the northern Baldwin Hills and the discovery and exploitation of the Inglewood oil field is less easily shown than the corresponding spatial coincidence. Although Kresse (1966, p. 98) states flatly "that subsidence [in the Inglewood field] is occurring and that it can be compared to oil field development, both in time and space, can be demonstrated," he seems to have had available only that evidence developed by the California Department of Water Resources (1964, p. 44); the synchroneity between subsidence and production cannot be demonstrated with this evidence.

The temporal coincidence between the beginning of exploitation and the initiation of the spatially associated subsidence is shown most convincingly by the relation between the production history and the history of vertical movement at PBM 68. Movement at PBM 68 is an especially significant index of this relation since: (1) PBM 68 is the only bench mark within the subsidence bowl whose elevation was measured with respect to the same or an easily related external datum both before and after exploitation began; and (2) it is probably more representative of the subsidence history than is that at the precise center or along the periphery of the subsidence bowl. Thus the several analyses of movement at PBM 68 all indicate that the differential subsidence probably did not begin until the middle twenties—or at about the time significant production began in 1925. This conclusion is supported both by the history of movement at PBM 67 and by an apparent absence of differential subsidence between 1910 and 1917 within the subsequently recognized subsidence bowl.

The existence of a more general correspondence between production and subsidence can be demonstrated by comparing the calculated and measured paths of subsidence at PBM 68 shown in figures 12*C* and 13 with the cumulative production from the Inglewood field as a whole (fig. 29) and the Vickers zone in particular (fig. 32). The most valid of the subsidence curves (fig. 12*C*, curve 1; fig. 13) indicate that PBM 68 did not subside below its 1911 elevation until 1927 or 1926, respectively; thus, differential subsidence must have begun soon after the start of major production from both the field and its chief producing zone (figs. 29 and 32). The subsidence curves in figures 12*C* and 13 and the liquid production curves in figures 29 and 32 closely mimic each other and indicate, thereby, a close correspondence between rates of liquid production and rates of subsidence. The correspondence between fluid production and subsidence is emphasized, moreover, if the relatively large pre-1932 and, to a lesser extent, post-1942 gas production are also considered (figs. 29 and 32). Thus, it is certainly clear that differential subsidence began soon after production began, and that there has been a very close correspondence between the rates of subsidence and rates of production.

Alternatively, the approximate coincidence between the beginning of subsidence and the beginning of production can be shown through a direct comparison between both the full-field and Vickers zone cumulative liquid production and the measured subsidence at PBM 68 since 1911 (fig. 35). A significant relation emerges from this comparison: both curves (particularly that for the Vickers zone) are very nearly linear, and backward extrapolations of the measured parts (1943–62) of the net liquid production curves pass nearly through the origins of the graphs. Thus subsidence of PBM 68 below its 1911 elevation must have been essentially coincident with the beginning of production, 13 or 14 years later. That the calculated parts of the curves (1926–43) fail to pass precisely through the origins of the graphs probably is due to one or more of at least three possible reasons: (1) The subsidence recorded at PBM 68 stems from comparison with an objectively calculated 1911 elevation of bench mark Hollywood E–11; correction for the likelihood that Hollywood E–11 sustained no differential subsidence (with respect to control points immediately beyond the area of differential subsidence) before production began, would lower all points shown in both figures 12*C* and 35 by a maximum of about 0.14 foot (see appendix C, Hollywood E–11, II.D.). (2) Subsidence at PBM 68 between 1926 and 1943 (fig. 12*C*)

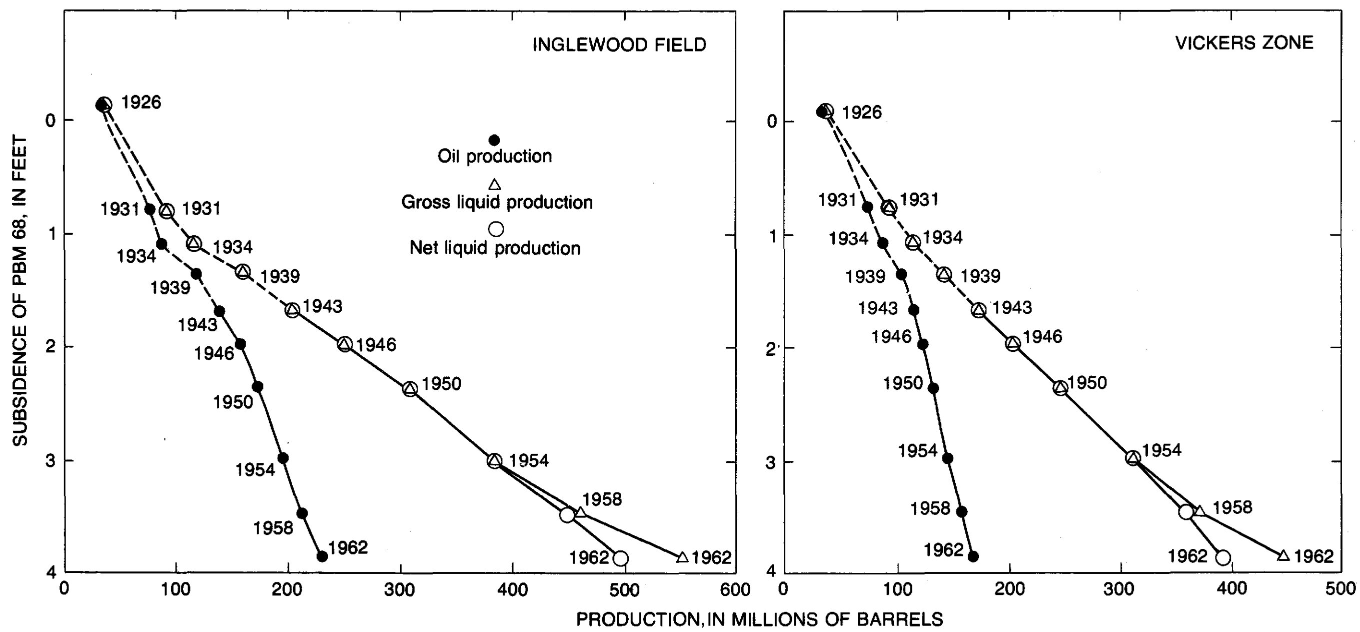


FIGURE 35.—Cumulative oil, gross liquid, and net liquid production from both the entire field and the Vickers zone of the Inglewood oil field versus cumulative subsidence at PBM 68 with respect to Hollywood E–11 since 1911. See figure 12 for explanation of dashed lines. Data from figures 12C, 29, and 32, and tables 4 and 5.

was, of necessity, calculated from comparisons with vertical movements at nearby bench marks; hence the 1926–43 subsidence values may contain cumulative errors of as much as several tenths of a foot. (3) Determinations of subsidence at PBM 68 derive from elevations measured in 1911 rather than 1924, when production began; because differential uplift has been recognized west of the Newport-Inglewood zone in this area (Grant and Sheppard, 1939, p. 302, 319–322), it is conceivable that PBM 68 rose slightly with respect to Hollywood E–11 sometime between 1911 and 1924.

The rate of subsidence and the post-1934 rates of net liquid production from the Inglewood field and the Vickers zone, in particular, have also varied linearly with respect to each other (fig. 36). The calculated pre-1934 subsidence rate probably was greatly influenced by high gas production (which is not reflected in the liquid production), thereby accounting for the two points lying to the right of the points representing later intervals of time. With this qualification, the rate of subsidence clearly is directly proportional to the rate of production.

The relation between subsidence and liquid production from both the Inglewood field as a whole and the Vickers zone in particular may also be shown by comparing various aspects of liquid production with the maximum subsidence or with the volume of subsidence measured over selected time intervals. The data used and the results of these comparisons are tabulated in tables 4 and 5, several features of which require explanation. (1) In calculating fractional parts of the annual production, the total annual production has been treated as if it consisted of 12 equal monthly increments. (2) All production determinations have been made to the first day of the given month. (3) The volumes of subsidence have been calculated on the assumption that the depressed volumes approximate inverted elliptical cones. Measurements of the basal dimensions (a and b) of the cones are somewhat subjective; they are based in part on the projected positions of the zero isobases in both space and time. (4) The figure of 2.37 feet for maximum subsidence during the period 1911–43 has been used in preparing the tables because we consider it the best available estimate.

Examination of the various groups of subsidence-to-production ratios given in tables 4 and 5 shows that the intragroup values have remained fairly uniform over a wide range of time intervals. The most significant ratios, namely those of maximum subsidence and volume of subsidence to net liquid production, extend over ranges of less than 1.3-fold for the full field and about 1.2-fold for the Vickers zone. This range of values may be explained in part by the imprecise measurements of the apparent volumes of subsidence (and, thereby, the ratios based on these volumes) over the successive time intervals. Thus, in the absence of better information, the calculated volume of subsidence over the interval 1911–43 has been based on the assumption that the areal dimensions of the subsidence dish remained unchanged from their inception until 1954. It is likely, however, that the subsiding area over the

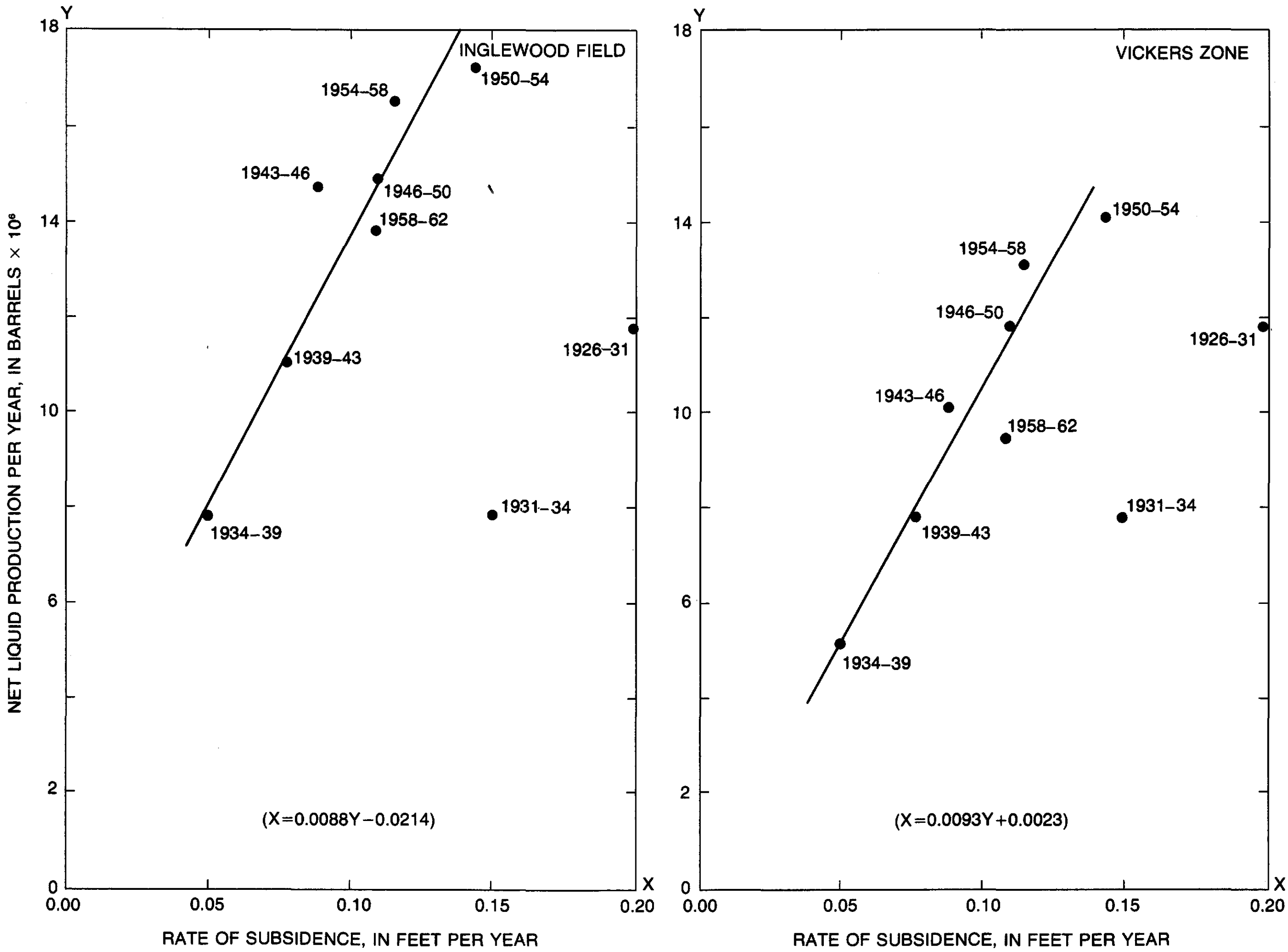


FIGURE 36.—Rate of subsidence at PBM 68 versus rates of net liquid production from the Inglewood oil field and the Vickers zone of the Inglewood field, 1926–62. The points 1926–31 and 1931–34 were not included in least-squares solutions shown in illustration (see text). Data from figures 12*C*, 29, and 32.

Inglewood oil field expanded between 1943 and 1954. This probability is supported by the 14.7 percent increase in proved acreage in the Inglewood field from 850 acres at the end of 1943 (Bush, 1943, p. 20) to 975 acres by the end of 1954 (Musser, 1954, p. 62). Nonetheless, and in spite of the probable changes in the configuration of the subsidence cone and limitations on the measurement of successive subsidence volumes, the generally constant ratios between both measures of subsidence (that is, maximum subsidence and volume of subsidence) and net liquid production (fig. 37) again indicate a nearly linear relation between subsidence and net liquid production, whereby the curves relating subsidence volume to net liquid production project backward to, or close to the origin.

The coincidence in time between subsidence and various aspects of oil-field operations can also be tested by comparing the differences in subsidence and production histories in the east and west blocks of the Inglewood field. Thus, during the 1958–62 interval, the average rate of subsidence in the east block fell to about 50 percent of that which prevailed during the preceding quadrennial period (pl. 4); this pronounced deceleration was about three times that in the west block during the same interval. It was, coincidentally, during this interval that full-scale waterflooding was begun in earnest (table 2). Because approximately 80 percent of the water injected to the end of 1963 was confined to the east block, the preferential reduction in subsidence in this block provides an independent index of the temporal relation between liquid production and subsidence.

The preceding comparisons between subsidence and production demonstrate a temporal coincidence, both generally and in detail, between subsidence and oil-field operations. This coincidence, combined with the clearly defined spatial association, constitutes persuasive evidence of a cause-and-effect relation between fluid extraction and surface subsidence over the Inglewood oil field.

A direct comparison between subsidence at PBM 68 and reservoir pressure decline in the central part of the Vickers zone (fig. 38) shows that these parameters varied directly but nonlinearly during the period 1926–62. Similarly, the average rates of subsidence over successive measurement intervals generally have

TABLE 4.—*Subsidence and production data for the Inglewood oil field*

[The data that have been deduced, extrapolated, interpolated, grouped or otherwise modified by the writers are indicated by reference to "this report." See appendix H for details of the calculation of maximum subsidence.]

Discovery date	September 28, 1924	California Division of Oil and Gas (1961, p. 577)
Maximum subsidence (d) relative to Hollywood E–11		
Nov. 1911–Oct. 1943[1]	2.37 ft	Hayes, 1943, fig. 6; Hayes 1955, fig. 1; Walley, 1963, fig. 1; this report.
Oct. 1943–Mar. 1950	.99 ft	Walley, 1963, subsidence chart for PBM 68; DWP file card for PBM 122; this report.
Mar. 1950–Aug. 1954	.89 ft	DWP file card for PBM 122; this report.
Aug. 1954–Oct. 1958	.67 ft	Do.
Oct. 1958–Aug. 1962	.55 ft	Walley, 1963, p. 5; this report
Nov. 1911–Aug. 1962	5.47 ft	This report.
Approximate dimensions (a and b) of semimajor and semiminor axes of subsiding area simplified to elliptical shape		
Oct. 1943	a=7,000 ft; b=5,500 ft	Hayes, 1955, fig. 1; this report.
Mar. 1950	a=7,000 ft; b=5,500 ft	Do.
Aug. 1954	a=7,000 ft; b=5,500 ft	Do.
Oct. 1958	a=7,000 ft; b=5,500 ft	Hayes, 1959, fig. 1; this report.
Aug. 1962	a=6,600 ft; b=5,200 ft	Walley 1963, p. 5.
Volume of subsidence ($\pi abd/3$)		
Nov. 1911–Oct. 1943	95,552,000 ft^3	
Oct. 1943–Mar. 1950	39,900,000 ft^3	
Mar. 1950–Aug. 1954	35,860,000 ft^3	
Aug. 1954–Oct. 1958	27,020,000 ft^3	
Oct. 1958–Aug. 1962	19,760,000 ft^3	
Nov. 1911–Aug. 1962	218,092,000 ft^3	
Volume of oil produced[2]		
Nov. 1911–Oct. 1943	138,256,000 bbls 776,500,000 ft^3	Bush 1942, p. 36; this report.
Oct. 1943–Mar. 1950	33,115,000 bbls 185,900,000 ft^3	Bush, 1949, p. 23; this report.
Mar. 1950–Aug. 1954	21,540,000 bbls 120,700,000 ft^3	California Division of Oil and Gas, 1950, p. 26; Musser, 1954, p. 62; this report.
Aug. 1954–Oct. 1958	18,675,000 bbls 104,800,000 ft^3	Musser 1958 p. 79; this report.
Oct. 1958–Aug. 1962	19,685,000 bbls 110,500,000 ft^3	California Division of Oil and Gas, 1962, p. 107; this report.
Nov. 1911–Aug. 1962	231,152,000 bbls 1,298,000,000 ft^3	Musser, 1961, p. 84; this report.
Volume of water produced		
Nov. 1911–Oct. 1943	62,949,000 bbls	California Division of Oil and Gas production statistics; this report.
Oct. 1943–Mar. 1950	67,918,000 bbls	Do.
Mar. 1950–Aug. 1954	56,190,000 bbls	Do.
Aug. 1954–Oct. 1958	61,558,000 bbls	Do.
Oct. 1958–Aug. 1962	76,072,000 bbls	Do.
Nov. 1911–Aug. 1962	324,800,000 bbls	Do.
Volume of water injected		
Nov. 1911–Oct. 1943	0 bbls	California Division of Oil and Gas production statistics.
Oct. 1943–Mar. 1950	0 bbls	Do.
Mar. 1950–Aug. 1954	477,500 bbls	California Division of Oil and Gas production statistics; this report.
Aug. 1954–Oct. 1958	13,140,000 bbls	Do.
Oct. 1958–Aug. 1962	42,450,000 bbls	Do.
Nov. 1911–Aug. 1962	56,070,000 bbls	Do.

TABLE 4.—*Subsidence and production data for the Inglewood oil field* —Continued

Discovery date	September 28, 1924	California Division of Oil and Gas (1961, p. 577)
Gross liquid production[2]		
Nov. 1911–Oct. 1943	201,205,000 bbls 1,130,000,000 ft^3	This report.
Oct. 1943–Mar. 1950	101,033,000 bbls 567,600,000 ft^3	Do.
Mar. 1950–Aug. 1954	77,730,000 bbls 436,500,000 ft^3	Do.
Aug. 1954–Oct. 1958	80,233,000 bbls 450,600,000 ft^3	Do.
Oct. 1958–Aug. 1962	95,757,000 bbls 537,700,000 ft^3	Do.
Nov. 1911–Aug. 1962	555,952,000 bbls 3,120,000,000 ft^3	Do.
Net liquid production[2]		
Nov. 1911–Oct. 1943	201,205,000 bbls 1,130,000,000 ft^3	This report.
Oct. 1943–Mar. 1950	101,033,000 bbls 567,600,000 ft^3	Do.
Mar. 1950–Aug. 1954	77,250,000 bbls 433,000,000 ft^3	Do.
Aug. 1954–Oct. 1958	67,093,000 bbls 376,600,000 ft^3	Do. Do.
Oct. 1958–Aug. 1962	53,307,000 bbls 299,800,000 ft^3	Do.
Nov. 1911–Aug. 1962	499,882,000 bbls 2,803,000,000 ft^3	Do.
Maximum subsidence/gross liquid production		
Nov. 1911–Oct. 1943	0.210×10^{-8}/ft^2	
Oct. 1943–Mar. 1950	$.175 \times 10^{-8}$/ft^2	
Mar. 1950–Aug. 1954	$.204 \times 10^{-8}$/ft^2	
Aug. 1954–Oct. 1958	$.149 \times 10^{-8}$/ft^2	
Oct. 1958–Aug. 1962	$.102 \times 10^{-8}$/ft^2	
Nov. 1911–Aug. 1962	$.175 \times 10^{-8}$/ft^2	
Maximum subsidence/net liquid production		
Nov. 1911–Oct. 1943	0.210×10^{-8}/ft^2	
Oct. 1943–Mar. 1950	$.175 \times 10^{-8}$/ft^2	
Mar. 1950–Aug. 1954	$.205 \times 10^{-8}$/ft^2	
Aug. 1954–Oct. 1958	$.178 \times 10^{-8}$/ft^2	
Oct. 1958–Aug. 1962	$.184 \times 10^{-8}$/ft^2	
Nov. 1911–Aug. 1962	$.195 \times 10^{-8}$/ft^2	
Maximum subsidence/oil production		
Nov. 1911–Oct. 1943	0.305×10^{-8}/ft^2	
Oct. 1943–Mar. 1950	$.532 \times 10^{-8}$/ft^2	
Mar. 1950–Aug. 1954	$.737 \times 10^{-8}$/ft^2	
Aug. 1954–Oct. 1958	$.639 \times 10^{-8}$/ft^2	
Oct. 1958–Aug. 1962	$.497 \times 10^{-8}$/ft^2	
Nov. 1911–Aug. 1962	$.421 \times 10^{-8}$/ft^2	
Volume of subsidence/gross liquid production		
Nov. 1911–Oct. 1943	0.085	
Oct. 1943–Mar. 1950	.070	
Mar. 1950–Aug. 1954	.082	
Aug. 1954–Oct. 1958	.060	
Oct. 1958–Aug. 1962	.037	
Nov. 1911–Aug. 1962	.070	
Volume of subsidence/net liquid production		
Nov. 1911–Oct. 1943	0.085	
Oct. 1943–Mar. 1950	.070	
Mar. 1950–Aug. 1954	.083	
Aug. 1954–Oct. 1958	.072	
Oct. 1958–Aug. 1962	.066	
Nov. 1911–Aug. 1962	.078	
Volume of subsidence/oil production		
Nov. 1911–Oct. 1943	0.123	
Oct. 1943–Mar. 1950	.214	
Mar. 1950–Aug. 1954	.297	
Aug. 1954–Oct. 1958	.258	
Oct. 1958–Aug. 1962	.179	
Nov. 1911–Aug. 1962	.168	

[1]Figure based on the acceptance of 1911 elevations of points "DD" (PBM 68) and Hollywood E–11 as true elevations with respect to S–32.

[2]Volume in cubic feet based on conversion factor of: 1 bbl = $\frac{42 \times 231}{12 \times 12 \times 12}$ = 5.615 ft^3.

TABLE 5.—*Subsidence and production data for the Vickers zone of the Inglewood oil field*

[The data that have been deduced, extrapolated, interpolated, grouped, or otherwise modified by the writers are indicated by reference to "this report." See appendix H for details of the calculation of maximum subsidence.]

Discovery date	September 28, 1924	California Division of Oil and Gas (1961, p. 577)
Maximum subsidence (d) relative to Hollywood E-11		
Nov. 1911–Oct. 1943[1]	2.37 ft	Hayes, 1943, fig. 6; Hayes, 1955, fig. 1; Walley, 1963, fig. 1; this report.
Oct. 1943–Mar. 1950	.99 ft	Walley, 1963, subsidence chart for PBM 68; DWP file card for PBM 122; this report.
Mar. 1950–Aug. 1954	.89 ft	DWP file card for PBM 122; this report.
Aug. 1954–Oct. 1958	.67 ft	Do.
Oct. 1958–Aug. 1962	.55 ft	Walley, 1963, p. 5; this report.
Nov. 1911–Aug. 1962	5.47 ft	This report.
Approximate dimensions (a and b) of semimajor and semiminor axes of subsiding area simplified to elliptical shape		
Oct. 1943	a=7,000 ft; b=5,500 ft	Hayes, 1955, fig. 1; this report.
Mar. 1950	a=7,000 ft; b=5,500 ft	Do.
Aug. 1954	a=7,000 ft; b=5,500 ft	Do.
Oct. 1958	a=7,000 ft; b=5,500 ft	Hayes, 1959, fig. 1; this report.
Aug. 1962	a=6,600 ft; b=5,200 ft	Walley, 1963, p. 5.
Volume of subsidence ($\pi abd/3$)		
Nov. 1911–Oct. 1943	95,552,000 ft³	
Oct. 1943–Mar. 1950	39,900,000 ft³	
Mar. 1950–Aug. 1954	35,860,000 ft³	
Aug. 1954–Oct. 1958	27,020,000 ft³	
Oct. 1958–Aug. 1962	19,760,000 ft³	
Nov. 1911–Aug. 1962	218,092,000 ft³	
Volume of oil produced[2]		
Nov. 1911–Oct. 1943	113,988,000 bbls 640,041,000 ft³	This report.
Oct. 1943–Mar. 1950	18,680,000 bbls 104,891,000 ft³	Do.
Mar. 1950–Aug. 1954	14,307,000 bbls 80,335,000 ft³	Do.
Aug. 1954–Oct. 1958	12,325,000 bbls 69,205,000 ft³	Do.
Oct. 1958–Aug. 1962	11,019,000 bbls 61,872,000 ft³	Do.
Nov. 1911–Aug. 1962	170,139,000 bbls 955,332,000 ft³	Do.
Volume of water produced		
Nov. 1911–Oct. 1943	58,175,000 bbls	This report.
Oct. 1943–Mar. 1950	54,715,000 bbls	Do.
Mar. 1950–Aug. 1954	47,292,500 bbls	Do.
Aug. 1954–Oct. 1958	44,747,000 bbls	Do.
Oct. 1958–Aug. 1962	64,535,000 bbls	Do.
Nov. 1911–Aug. 1962	278,643,000 bbls	Do.
Volume of water injected		
Nov. 1911–Oct. 1943	0 bbls	California Division of Oil and Gas production statistics.
Oct. 1943–Mar. 1950	0 bbls	Do.
Mar. 1950–Aug. 1954	477,500 bbls	Do.
Aug. 1954–Oct. 1958	13,140,000 bbls	Do.
Oct. 1958–Aug. 1962	40,285,000 bbls	Do.
Nov. 1911–Aug. 1962	53,886,000 bbls	Do.
Gross liquid production[2]		
Nov. 1911–Oct. 1943	172,163,000 bbls 966,692,000 ft³	This report.
Oct. 1943–Mar. 1950	73,395,000 bbls 412,116,000 ft³	Do.
Mar. 1950–Aug. 1954	61,599,000 bbls 345,822,000 ft³	Do.
Aug. 1954–Oct. 1958	67,072,000 bbls 376,608,000 ft³	Do.
Oct. 1958–Aug. 1962	75,554,000 bbls 424,236,000 ft³	Do.
Nov. 1911–Aug. 1962	448,782,000 bbls 2,519,914,000 ft³	Do.

TABLE 5.—*Subsidence and production data for the Vickers zone of the Inglewood oil field*—Continued

Discovery date	September 28, 1924	California Division of Oil and Gas (1961, p. 577)
Net liquid production[2]		
Nov. 1911–Oct. 1943	172,163,000 bbls 966,692,000 ft³	This report.
Oct. 1943–Mar. 1950	73,395,000 bbls 412,116,000 ft³	Do.
Mar. 1950–Aug. 1954	61,118,000 bbls 343,200,000 ft³	Do.
Aug. 1954–Oct. 1958	53,932,000 bbls 299,500,000 ft³	Do.
Oct. 1958–Aug. 1962	35,269,000 bbls 198,038,000 ft³	Do.
Nov. 1911–Aug. 1962	394,896,000 bbls 2,217,342,000 ft³	Do.
Maximum subsidence/gross liquid production		
Nov. 1911–Oct. 1943	$0.245 \times 10^{-8}/ft^2$	
Oct. 1943–Mar. 1950	$.240 \times 10^{-8}/ft^2$	
Mar. 1950–Aug. 1954	$.258 \times 10^{-8}/ft^2$	
Aug. 1954–Oct. 1958	$.178 \times 10^{-8}/ft^2$	
Oct. 1958–Aug. 1962	$.129 \times 10^{-8}/ft^2$	
Nov. 1911–Aug. 1962	$.217 \times 10^{-8}/ft^2$	
Maximum subsidence/net liquid production		
Nov. 1911–Oct. 1943	$0.245 \times 10^{-8}/ft^2$	
Oct. 1943–Mar. 1950	$.240 \times 10^{-8}/ft^2$	
Mar. 1950–Aug. 1954	$.259 \times 10^{-8}/ft^2$	
Aug. 1954–Oct. 1958	$.224 \times 10^{-8}/ft^2$	
Oct. 1958–Aug. 1962	$.276 \times 10^{-8}/ft^2$	
Nov. 1911–Aug. 1962	$.247 \times 10^{-8}/ft^2$	
Maximum subsidence/oil production		
Nov. 1911–Oct. 1943	$0.370 \times 10^{-8}/ft^2$	
Oct. 1943–Mar. 1950	$.945 \times 10^{-8}/ft^2$	
Mar. 1950–Aug. 1954	$1.110 \times 10^{-8}/ft^2$	
Aug. 1954–Oct. 1958	$.969 \times 10^{-8}/ft^2$	
Oct. 1958–Aug. 1962	$.889 \times 10^{-8}/ft^2$	
Nov. 1911–Aug. 1962	$.573 \times 10^{-8}/ft^2$	
Volume of subsidence/gross liquid production		
Nov. 1911–Oct. 1943	0.099	
Oct. 1943–Mar. 1950	.097	
Mar. 1950–Aug. 1954	.104	
Aug. 1954–Oct. 1958	.072	
Oct. 1958–Aug. 1962	.047	
Nov. 1911–Aug. 1962	.087	
Volume of subsidence/net liquid production		
Nov. 1911–Oct. 1943	0.099	
Oct. 1943–Mar. 1950	.097	
Mar. 1950–Aug. 1954	.105	
Aug. 1954–Oct. 1958	.090	
Oct. 1958–Aug. 1962	.100	
Nov. 1911–Aug. 1962	.098	
Volume of subsidence/oil production		
Nov. 1911–Oct. 1943	0.149	
Oct. 1943–Mar. 1950	.381	
Mar. 1950–Aug. 1954	.447	
Aug. 1954–Oct. 1958	.391	
Oct. 1958–Aug. 1962	.320	
Nov. 1911–Aug. 1962	.228	

[1]Figure based on the acceptance of 1911 elevations of points "DD" (PBM 68) and Hollywood E-11 as true elevations with respect to S-32.

[2]Volume in cubic feet based on conversion factor of: $1 \text{ bbl} = \frac{42 \times 231}{12 \times 12 \times 12} = 5.615 \text{ ft}^3$.

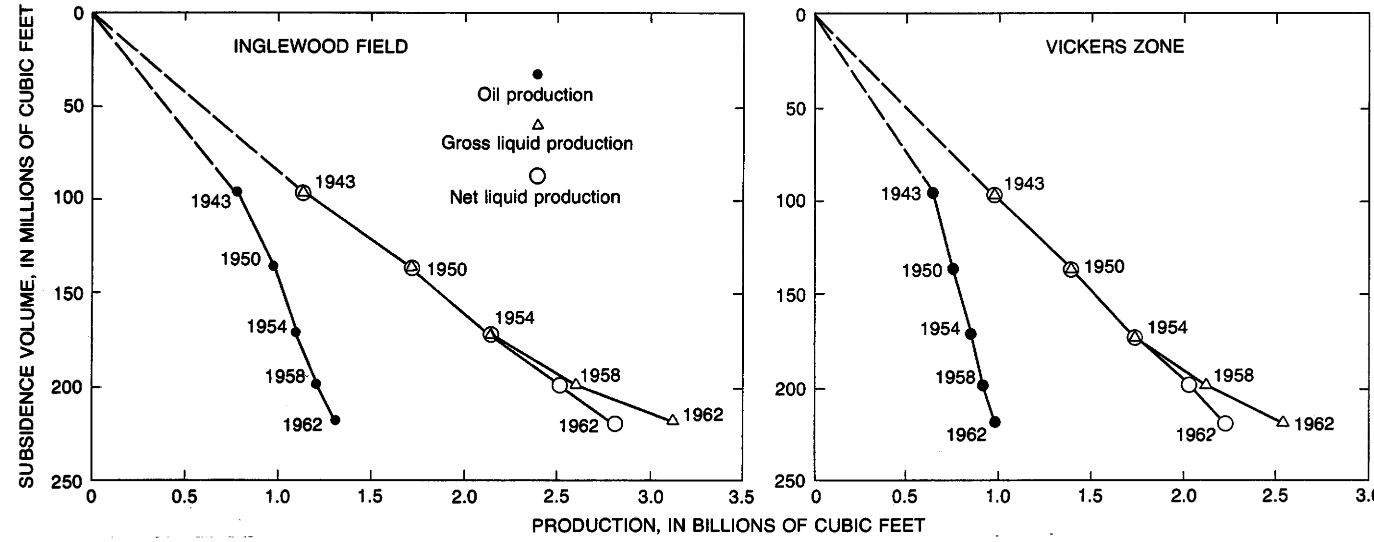


FIGURE 37.—Cumulative oil, gross liquid, and net liquid production from both the entire field and the Vickers zone of the Inglewood oil field versus cumulative volume of subsidence over the field since 1911. Calculation of successive volumes of subsidence based on the assumption that their shapes have closely approximated inverted elliptical cones. (See tables 4 and 5.)

varied directly but also nonlinearly with (both accelerations and decelerations in) the average rates of reservoir pressure decline over the same intervals (fig. 39). Although this relation seemingly broke down temporarily around 1950, reservoir pressure had by this time declined to about 10 percent of its original value (that is, from about 790 psi to 80 psi at −1,850 feet). Thus, small errors in measured fluid pressure after the middle 1930's could have imparted relatively large percentage changes in the pressure-decline rate, such that apparent departures from the normally direct relation between pressure-decline rate and subsidence rate may be of little significance during the later production years. The first of the observed correlations (between subsidence and reservoir pressure decline) is consistent with a a cause-and-effect relation between reservoir pressure decline in the Vickers zone and subsidence over the Inglewood oil field; the second (between subsidence rate and pressure-decline rate) is both consistent with and supports such a relation. Both relations, however, particularly the first, are less convincing evidence of the connection between oil-field

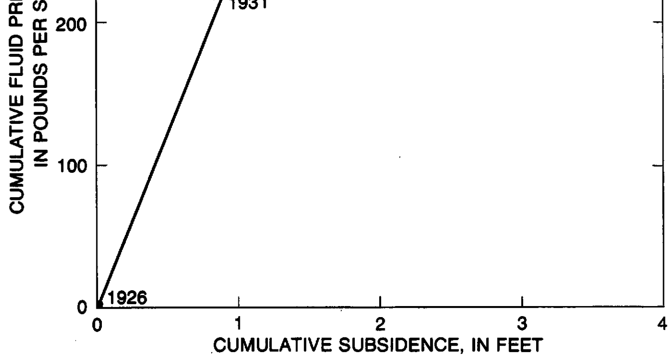


FIGURE 38.—Cumulative subsidence at PBM 68 versus cumulative pressure decline in the Vickers zone of the Inglewood oil field for the period 1926–62. Data from figures 12C and 34.

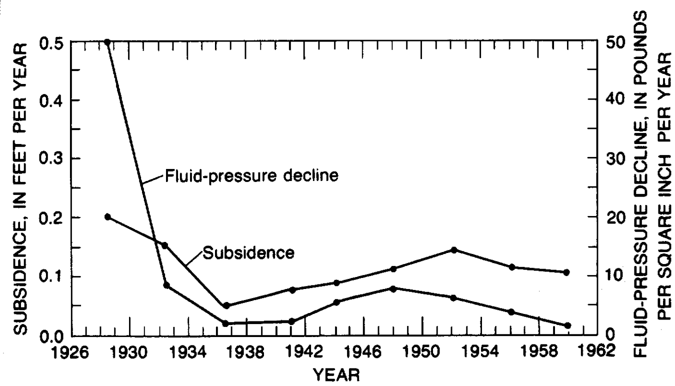


FIGURE 39.—Annual average subsidence at PBM 68 and annual average pressure decline in the Vickers zone plotted against time. Data from figures 12C and 34.

operations and subsidence than the previously cited comparisons between production and subsidence.

SUBSIDENCE IN OTHER OIL FIELDS

A number of examples have been reported to date of differential subsidence associated with producing oil fields. Poland and Davis (1969, p. 199), moreover, have observed in their recent review of this subject that "doubtless many oil fields away from the ocean or other large water bodies have subsided as much as several feet, but without repeated precise leveling such subsidence may pass unnoticed."

The geologic similarities between many of the oil and gas fields in which there has been major surface subsidence are especially significant. Among the nine subsiding, or formerly subsiding, oil and gas fields cited by Poland and Davis (1969), production has been chiefly or entirely from rocks of Cenozoic (mainly late Cenozoic) age and generally from relatively shallow (3,000–4,000 feet or less) horizons (see in addition Pratt and Johnson, 1926, p. 584, and California Division of Oil and Gas, 1961). Most of the domestic examples of differential surface subsidence identified with oil fields occur in California; examples outside California include the Goose Creek (see fig. 48), Mykawa, South Houston (Weaver and Sheets, 1962, figs. 1 and 2), and Saxet fields in Texas. Well-defined subsidence has now been reported in seven other California oil fields in addition to the Inglewood field: Playa del Rey (Grant and Sheppard, 1939, p. 313–319); Long Beach (Grant, 1944, p. 148–149); Huntington Beach (Gilluly and Grant, 1949, p. 526; Estabrook, 1962, p. 8–9, fig. 2); Santa Fe Springs (Gilluly and Grant, 1949, p. 527); Wilmington (Gilluly and Grant, 1949; Grant, 1954); Torrance (Golzé, 1965, p. 100); and Buena Vista (Whitten, 1961, p. 319; 1966, p. 74; this report, fig. 49). Recent investigations have also disclosed at least localized differential subsidence over 10 other California fields: Dominguez, Edison, Fruitvale, Greeley, Kern Front, Midway-Sunset, Paloma, San Emidio Nose, Tejon North, and an unnamed field in Orange County (Yerkes and Castle, 1970, p. 57–58). Nearly half of the California examples lie within the Los Angeles basin and three of these (Long Beach, Huntington Beach, and Dominguez) occur along the Newport-Inglewood zone. Thus, if it is accepted that the fields listed above have subsided in response to oil-field operations, the Inglewood field, simply on the basis of its location and reservoir characteristics, should be regarded as one with a high potential for exploitation-induced subsidence.

The number of oil fields in which a temporal relation can be established between subsidence and production is considerably fewer than the number in which a spatial association is evident, for the repeated levelings required to establish this relation have not generally been carried out. Thus, of the five oil and gas fields cited by Poland and Davis (1969) in which there is at least a suggestion of a coincidence in time between exploitation and subsidence, all occur in low-lying coastal environments where potential inundation by the sea constitutes an evident and sensitive indicator of subsidence and repeated levelings are less necessary. These few examples suggest, nevertheless, that the close correlation in time between subsidence and production in the Inglewood field is not simply fortuitous.

There are, exclusive of the Inglewood field, only two domestic oil or gas fields in which a coincidence in time between subsidence and exploitation has been demonstrated—Goose Creek, Texas, and Wilmington, California. The Goose Creek oil field was discovered in 1917. By 1918 the Gaillard Peninsula near the center of the field had begun to submerge, and by no later than 1926 the entire peninsula had disappeared beneath the waters of San Jacinto Bay (Pratt and Johnson, 1926, p. 577–579). Because the Gaillard Peninsula had persisted essentially unchanged in outline and had shown no direct evidence indicative of subsidence for nearly a century prior to 1917 (Pratt and Johnson, 1926, p. 589), it is certainly clear that oil-field operations and subsidence began at about the same time. The relation through time, however, between the rates of subsidence and the rates of oil, gas, water, and sand production, to which the subsidence has been attributed (Pratt and Johnson, 1926, p. 577), is unknown.

Repeated level surveys in the Los Angeles and Long Beach harbor areas show that differential subsidence centering on the Wilmington field was absent or inconspicuous before development began in 1936 (Gilluly and Grant, 1949, p. 465–469, 482), yet was well advanced by 1941 (Gilluly and Grant, 1949, p. 469–471). Marigrams taken from the harbor area, moreover, indicate clearly that measurable subsidence of the oil field had begun by 1937 (Gilluly and Grant, 1949, p. 478–481). Finally, a fair correlation between rates of subsidence and rates of oil production, and a much better correlation between rates of subsidence and rates of net-liquid production, have also been shown for the Wilmington field (see Poland and Davis, 1969, p. 205; Hudson, 1957, fig. 23).

COMPARISON WITH THE WILMINGTON OIL FIELD

The subsidence over the Wilmington oil field is probably the best and most carefully studied example of this phenomenon in the world. To the extent that the Wilmington and Inglewood examples are similar, this similarity supports the conclusion that the generally accepted explanation for the subsidence over the Wilmington field (see Harris and Harlow, 1947; Gilluly and Grant, 1949; Miller and Somerton, 1955, p. 68, 70;

Poland and Davis, 1969, p. 201) applies equally to that over the Inglewood field.

The Wilmington and Inglewood oil fields are grossly similar in the following ways: (1) Both oil fields lie within the western part of the Los Angeles basin (fig. 1). (2) In each case petroleum occurs chiefly within relatively unconsolidated clastic rocks ranging in age from middle Miocene through Pliocene (California Division of Oil and Gas, 1961, p. 576–577, 686–687). (3) Major productive horizons occur at relatively shallow depths of from about 2,000 to 4,000 feet in the Wilmington field (California Division of Oil and Gas, 1961, p. 576–577; Poland and Davis, 1969, p. 207) and about 1,000 to 3,500 feet in the Inglewood field. (4) Both fields occur within large, open anticlines broken into two or more major blocks by faults that have acted as barriers to fluid migration (Gilluly and Grant, 1949, p. 483; California Department of Water Resources, 1964, p. 14–15).

The Wilmington and Inglewood fields are dissimilar in the following ways: (1) The Wilmington field lies entirely within a large, relatively stable crustal block bounded by the Newport-Inglewood zone on the northeast and the Palos Verdes Hills fault zone on the southwest (Yerkes and others, 1965, p. A5), whereas the Inglewood field lies athwart the active Newport-Inglewood zone (fig. 1). (2) Structural arching in the Wilmington field, in which limbs at depths between −2,300 and −3,300 feet dip at angles of up to about 20° (California Division of Oil and Gas, 1961, p. 684), is somewhat gentler than that in the Inglewood field, in which limbs at depths between −800 and −1,200 feet dip at angles of up to about 25° (fig. 3). (3) The Wilmington field, much larger than the Inglewood field in both area and production, produced 884,534,330 barrels of oil over a 24-year period, whereas the Inglewood field produced only 221,463,251 barrels of oil during a 36-year period (California Division of Oil and Gas, 1961, p. 577, 687). Annual fluid production, water flooding, and various gas/liquid ratios for the Inglewood and Wilmington fields can be compared in tables 2 and 6. The annual liquid production from the two fields can be compared in figures 28 and 40.

A comparison between cumulative production and cumulative maximum subsidence in the Wilmington field shows: (1) that differential subsidence did not begin before production began in 1936; and (2) that periods of major subsidence have generally coincided with periods of heavy production (fig. 41). The relatively low subsidence rate during the early years of exploitation, moreover, correlates with a period of generally low gas production. This correspondence between production and subsidence broke down, however, during the later production years. Thus, by the end of 1958 the slope of the production curve had actually reversed, whereas the subsidence continued (although at a slower rate). The slope reversal in the production curve derives from the onset of massive waterflooding in 1957 and 1958 (see table 6 and fig. 40); because the initial repressuring was concentrated chiefly in the southern part of the field (Poland and Davis, 1969, p. 211), and up through 1960, at least, was nonuniform with respect to both producing area and producing zone (Musser, 1960, p. 133–134), the cumulative production and cumulative maximum subsidence curves should not be compared for the years after 1957. In any case, and regardless of the fidelity of the correspondence, it is evident that the maximum subsidence over the Wilmington field has varied directly with net-liquid production.

Comparisons between various aspects of liquid production and maximum subsidence in the Wilmington field show that between 1945 and the initiation

TABLE 6.—*Fluid production and waterflooding statistics for the Wilmington oil field by year.*

[Compiled from summary reports of the State Oil and Gas Supervisor]

Year	Oil production (in bbls)	Net gas production (in Mcf)	Water production (in bbls)	Gross liquid production (in bbls)
1936	91,089	unknown	6,609	97,698
1937	14,047,340	3,480,000	159,137	14,206,477
1938	34,021,599	17,700,000	379,036	34,400,635
1939	31,091,297	25,360,000	419,526	31,510,823
1940	30,237,750	25,750,000	759,856	30,997,606
1941	30,683,188	25,650,000	1,734,025	32,417,213
1942	33,378,681	31,108,935	2,648,562	36,027,243
1943	34,298,354	32,951,165	3,933,020	38,231,374
1944	36,892,094	38,497,054	5,658,850	42,550,944
1945	36,173,033	38,153,281	6,801,978	42,975,011
1946	40,175,993	40,491,653	7,850,817	48,026,810
1947	47,686,643	51,714,619	9,251,923	56,938,566
1948	48,320,459	55,920,765	11,510,109	59,830,568
1949	43,495,989	49,261,566	13,390,295	56,886,284
1950	46,227,417	49,597,076	14,631,504	60,858,921
1951	50,786,902	53,550,889	17,571,264	68,358,166
1952	48,105,364	42,566,775	20,695,450	68,800,814
1953	44,341,298	36,889,300	22,446,183	66,787,481
1954	41,561,100	34,018,746	24,330,956	65,892,056
1955	38,879,018	31,210,293	25,960,920	64,839,938
1956	36,799,908	29,704,516	28,929,099	65,729,007
1957	32,427,190	26,215,132	30,634,598	63,061,788
1958	29,676,471	25,033,097	31,881,762	61,558,233
1959	26,944,459	20,462,403	34,615,165	61,559,624
1960	27,550,499	17,522,921	48,740,374	76,290,873
1961	27,971,235	12,997,816	58,403,025	86,374,260

Year	Water injected (in bbls)	Net liquid production (in bbls)	Gas/oil (Mcf/bbls)	Gas/gross liquid (Mcf/bbls)	Gas/net liquid (Mcf/bbls)
1936		97,698	----	----	----
1937		14,206,477	0.248	0.245	0.245
1938		34,400,635	.520	.514	.514
1939		31,510,823	.815	.805	.805
1940		30,997,606	.852	.832	.832
1941		32,417,213	.836	.792	.792
1942		36,027,243	.923	.863	.863
1943		38,231,374	.961	,862	.862
1944		42,550,944	1.043	.905	.905
1945		42,975,011	1.054	.889	.889
1946		48,026,810	1.008	.843	.843
1947		56,938,566	1.084	.908	.908
1948		59,830,568	1.157	.935	.935
1949		56,886,284	1.132	.866	.866
1950		60,858,921	1.072	.815	.815
1951		68,358,166	1.054	.783	.783
1952		68,800,814	.885	.618	.618
1953	651,700(?)	66,135,781(?)	.832	.552	.558
1954	1,414,971	64,477,085	.819	.493	.528
1955	4,378,704	60,461,234	.803	.482	.517
1956	9,368,272	56,360,735	.807	.452	.527
1957	13,862,295	49,199,493	.807	.416	.533
1958	30,813,528	30,744,705	.843	.407	.813
1959	87,185,762	−25,626,138	.759	.332	----
1960	133,555,117	−57,264,244	.636	.230	----
1961	154,282,971	−67,908,711	.465	.150	----

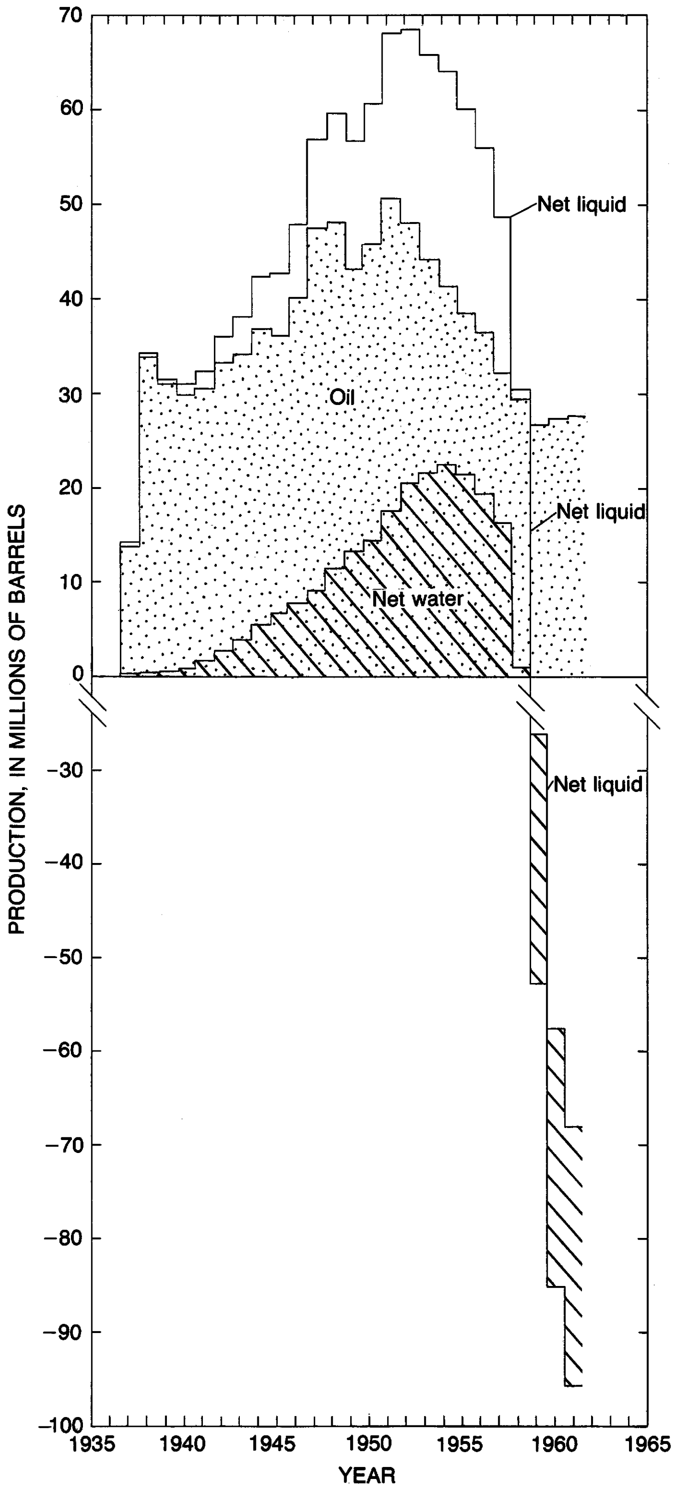


FIGURE 40.—Annual oil, net water, and net liquid production from the Wilmington oil field through 1961. (See table 6.)

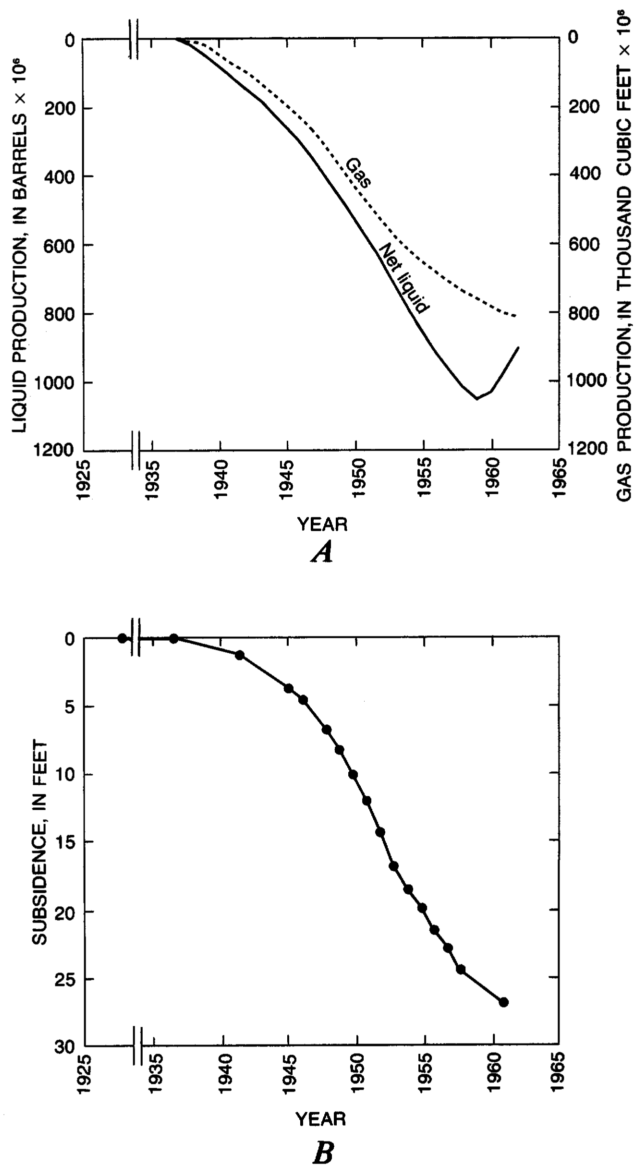


FIGURE 41.—*A*, Cumulative net liquid and cumulative gas production from the Wilmington oil field through 1961. Compiled from production statistics given in the summary reports of the State Oil and Gas Supervisor. *B*, Cumulative maximum subsidence within the Wilmington oil field subsidence bowl between 1928 and 1960. Based on data presented by Gilluly and Grant (1949, p. 471–473, 527), Hudson (1957, table V), and Bailey (1957, p. 89; 1960, p. 140); assumes in part that the maximum subsidence is approximated by that at bench mark 8772, near the center of the subsidence bowl.

of full-scale waterflooding in 1957, there existed a near-linear relation between net liquid production and maximum subsidence (fig. 42). Because cumulative net liquid production during the 12-year period 1945–57 accounted for 70 percent of that produced through 1957, this relation probably is more representative than is suggested by the short period of observation.

Hudson (1957, fig. 23) has demonstrated a general correspondence between measured rates of maximum subsidence (specifically, that at B.M. 8772) and rates of both gross liquid production and oil production from the Wilmington field during the interval 1946–55. These

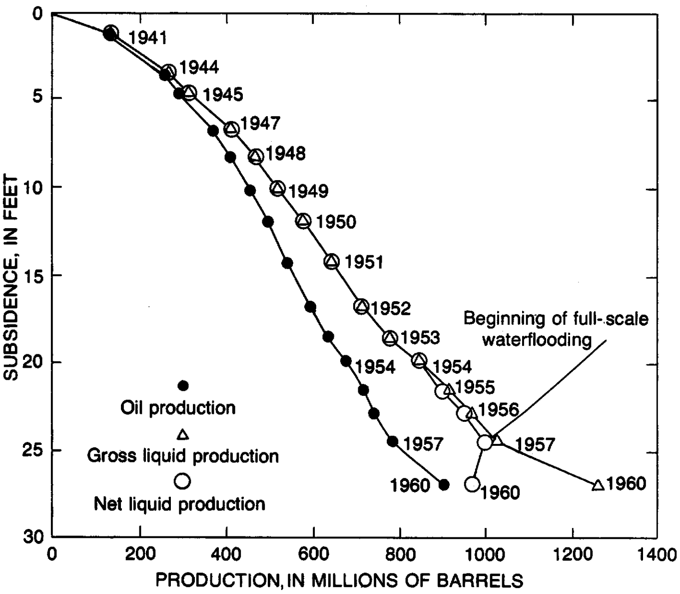


FIGURE 42.—Cumulative oil, gross liquid, and net liquid production from the Wilmington oil field versus cumulative maximum subsidence, 1928–60. Data from figure 41 and table 6.

data (Hudson, 1957, fig. 23) also show that the response of the rate of subsidence to changes in the rates of liquid production was excellent; the inflection points in the subsidence curve, however, lag behind those of the production curves by about one-half year.

The relations between subsidence and liquid production in the Wilmington field may also be shown by comparing production and subsidence over selected time intervals (table 7). The calculated intragroup subsidence-to-liquid production ratios given in table 7 range between extremes of 0.279–0.768, a factor of 2.8 (in the case of the maximum subsidence/volume of oil production), and 0.375–0.626, a factor of 1.7 (in the case of maximum subsidence/gross-liquid and net liquid production). If the pre-1946 period of relatively limited production is excluded, the most significant of these ratios, namely those of maximum subsidence/net liquid production and volume of subsidence/net liquid production, extend over much less than a 1.7-fold range (table 7). However, even the larger ranges in the several ratios of subsidence to net liquid production seem remarkably restricted, particularly if allowance is made for the difficulties in estimating successive volumes of subsidence over the Wilmington field (table 7). Thus these calculated ratios again demonstrate that subsidence has varied directly, and perhaps almost linearly, with net liquid production.

Gilluly and Grant (1949, p. 501–502) concluded "that there is no evident relation between the volume of oil produced from a given [fault] block [within the Wilmington field] and the volume of subsidence within it." They based this conclusion on subsidence volume/oil production ratios calculated for four naturally defined "production blocks" during the period 1934–45. These ratios ranged from 0.207 to 1.346 and indicated that "subsidence is seemingly not due in any significant degree to settling into voids left by the extraction of oil from the field" (Gilluly and Grant, 1949, p. 502). Even though the 7-fold range in these ratios suggests no immediately evident relation between the volume of oil produced from and the volume of subsidence over a particular block, it furnishes no basis for concluding that fluid production and the volume of subsidence over the full field are unrelated. In the first place, barring actual rupture of the ground surface along the production block boundaries, differential compaction within one block will certainly impose a drag upon adjacent blocks, thereby obscuring the intrablock relation between subsidence and production. Secondly, the relation between subsidence and net liquid production, rather than just oil production, may be more significant. Although water production from the Wilmington field through 1944 was relatively limited (table 6), its distribution in space may have contributed in part to the 7-fold range in the subsidence-production ratios for the four blocks examined by Gilluly and Grant. In any case, as we conclude above, the restricted range of successive subsidence to net liquid production ratios taken over the Wilmington field as a whole, indicates, in contrast to the conclusion of Gilluly and Grant, a clear and perhaps almost linear relation between liquid production and subsidence.

The relation between liquid production and subsidence is also indicated by the effects of waterflooding in the Wilmington field. Full-scale flooding was begun in the central part of the south limb of the subsidence bowl in mid-1958 and was accompanied by an almost immediate deceleration in the rate of subsidence (Allen, 1968, fig. 7; Poland and Davis, 1969, p. 210–213). Similar effects were observed after flooding was begun in the area to the west. These experiences again indicate clearly the dependence of subsidence on net liquid production.

Gilluly and Grant (1949, p. 523) predicted the ultimate expectable subsidence over the Wilmington oil field on the basis of a relation whereby subsidence is inferred to have varied directly with reservoir pressure decline. The existence of this relation is supported by a comparison of maximum subsidence with measured reservoir pressure decline in the two most prolific (and most compactive) of the Wilmington oil zones (fig. 43). However, although subsidence over the Wilmington field seems to have varied directly with measured reservoir pressure decline, this variation clearly has been nonlinear.

Summarizing, the Wilmington and Inglewood fields

TABLE 7.—*Subsidence and production data for the Wilmington oil field.*

[The data that have been deduced, extrapolated, interpolated, grouped, or otherwise modified by the writers are indicated by reference to "this report"]

Discovery date	January 26, 1932; rapid development begun December, 1936	California Division of Oil and Gas, 1961, p. 687
Maximum subsidence (d)		
1933–Mar. 1946	4.5 ft	Gilluly and Grant, 1949 p. 473.
Mar. 1946–Nov. 1951	9.9 ft	This report.
Nov. 1951–Aug. 1957	10.1 ft	Do.
1928–Nov. 1951	14.4 ft	Hudson, 1957, table V; this report.
Aug. 1928–Aug. 1957	24.5 ft	Bailey, 1957, p. 89; this report.
Approximate dimensions (a and b) of semimajor and semiminor axes of subsiding area simplified to elliptical shape		
Mar. 1946	a=12,250 ft; b=8,850 ft	Gilluly and Grant, 1949, p. 473; this report.
Nov. 1951	a=13,000 ft; b=9,750 ft	Hudson, 1956, fig. 10; this report.
Aug. 1957	a=17,000 ft; b=12,500 ft	Hudson, 1957, fig. 10; this report.
Volume of subsidence		
1934–1945[1]	550,000,000 ft^3	Gilluly and Grant, 1949, p. 502; this report.
1933–Mar. 1946	656,000,000 ft^3	Gilluly and Grant, 1949, p. 502; Long Beach Harbor Department, drawing B-247; this report.
	512,000,000 ft^3	$\pi abd/3$
Mar. 1946–Nov. 1951	1,168,000,000 ft^3	Long Beach Harbor Department, drawing B–247.
	1,312,000,000 ft^3	$\pi abd/3$
Nov. 1951–Aug. 1957	1,068,000,000 ft^3	Long Beach Harbor Department, drawing B–247.
	2,243,000,000 ft^3	$\pi abd/3$; this report.
1928–Nov. 1951	1,824,000,000 ft^3	
	1,824,000,000 ft^3	(sum $\pi abd/3$)
Aug. 1928–Aug. 1957	2,892,000,000 ft^3	
	4,067,000,000 ft^3	(sum $\pi abd/3$)
Volume of oil produced[2]		
1934–Jan. 1945	245,425,158 bbls 1,361,000,000 ft^3	Bush, 1944, p. 15.
1933–Mar. 1946	287,400,000 bbls	Bush, 1945, p. 30; this report.
Mar. 1946–Nov. 1951	262,400,000 bbls 1,470,000,000 ft^3	This report.
Nov. 1951–Aug. 1957	234,400,000 bbls 1,315,000,000 ft^3	Do.
1928–Nov. 1951	549,800,000 bbls 3,084,000,000 ft^3	Bush, 1951, p. 17; this report.
Aug. 1928–Aug. 1957	784,200,000 bbls 4,415,000,000 ft^3	Musser, 1957, p. 66; this report.
Volume of water produced		
1934–Jan. 1945	15,698,621 bbls	California Division of Oil and Gas, production statistics; this report.
1933–Mar. 1946	23,800,000 bbls	Do.
Mar. 1946–Nov. 1951	69,980,000 bbls	Do.
Nov. 1951–Aug. 1957	143,120,000 bbls	Do.
1928–Nov. 1951	93,780,000 bbls	Do.
Aug. 1928–Aug. 1957	236,900,000 bbls	Do.
Volume of water injected		
1934–Jan. 1945	0 bbls	California Division of Oil and Gas, production statistics; this report.
1933–Mar. 1946	0 bbls	Do.
Mar. 1946–Nov. 1951	0 bbls	Do.
Nov. 1951–Aug. 1957	23,900,000 bbls	Do.
1928–Nov. 1951	0 bbls	Do.
Aug. 1928–Aug. 1957	23,900,000 bbls	Do.

TABLE 7.—*Subsidence and production data for the Wilmington oil field* —Continued.

Discovery date	January 26, 1932; rapid development begun December, 1936	California Division of Oil and Gas, 1961, p. 687
Gross liquid production[2]		
1934–Jan. 1945	261,123,779 bbls 1,463,500,000 ft^3	This report.
1933–Mar. 1946	311,200,000 bbls 1,747,000,000 ft^3	Do.
Mar. 1946–Nov. 1951	332,400,000 bbls 1,863,000,000 ft^3	Do.
Nov. 1951–Aug. 1957	377,500,000 bbls 2,125,000,000 ft^3	Do.
1928–Nov. 1951	643,600,000 bbls 3,610,000,000 ft^3	Do.
Aug. 1928–Aug. 1957	1,021,100,000 bbls 5,735,000,000 ft^3	Do.
Net liquid production[2]		
1934–Jan. 1945	261,123,779 bbls 1,463,500,000 ft^3	This report.
1933–Mar. 1946	311,200,000 bbls 1,747,000,000 ft^3	Do.
Mar. 1946–Nov. 1951	332,400,000 bbls 1,863,000,000 ft^3	Do.
Nov. 1951–Aug. 1957	353,600,000 bbls 1,989,600,000 ft^3	Do.
1928–Nov. 1951	643,600,000 bbls 3,610,000,000 ft^3	Do.
Aug. 1928–Aug. 1957	997,200,000 bbls 5,599,600,000 ft^3	Do.
Maximum subsidence/gross liquid production		
1933–Mar. 1946	$0.258 \times 10^{-8}/ft^2$	
Mar. 1946–Nov. 1951	$.531 \times 10^{-8}/ft^2$	
Nov. 1951–Aug. 1957	$.476 \times 10^{-8}/ft^2$	
1928–Nov. 1951	$.399 \times 10^{-8}/ft^2$	
Aug. 1928–Aug. 1957	$.427 \times 10^{-8}/ft^2$	
Maximum subsidence/net liquid production		
1933–Mar. 1946	$0.258 \times 10^{-8}/ft^2$	
Mar. 1946–Nov. 1951	$.531 \times 10^{-8}/ft^2$	
Nov. 1951–Aug. 1957	$.507 \times 10^{-8}/ft^2$	
1928–Nov. 1951	$.399 \times 10^{-8}/ft^2$	
Aug. 1928–Aug. 1957	$.437 \times 10^{-8}/ft^2$	
Maximum subsidence/oil production		
1933–Mar. 1946	$0.279 \times 10^{-8}/ft^2$	
Mar. 1946–Nov. 1951	$.673 \times 10^{-8}/ft^2$	
Nov. 1951–Aug. 1957	$.768 \times 10^{-8}/ft^2$	
1928–Nov. 1951	$.466 \times 10^{-8}/ft^2$	
Aug. 1928–Aug. 1957	$.555 \times 10^{-8}/ft^2$	
Volume of subsidence/gross liquid production[3]		
1934–Jan. 1945	0.379	
1933–Mar. 1946	.375 (0.292)	
Mar. 1946–Nov. 1951	.626 (.704)	
Nov. 1951–Aug. 1957	.502 (1.056)	
1928–Nov. 1951	.505 (.505)	
Aug. 1928–Aug. 1957	.504 (.713)	
Volume of subsidence/net liquid production[3]		
1934–Jan. 1945	0.379	
1933–Mar. 1946	.375 (0.292)	
Mar. 1946–Nov. 1951	.626 (.704)	
Nov. 1951–Aug. 1957	.537 (1.128)	
1928–Nov. 1951	.505 (.505)	
Aug. 1928–Aug. 1957	.516 (.732)	

are similar in general lithology, depth of reservoir, and in general structural configuration; they are dissimilar in physical size and size of production, in location relative to the regional structural framework, and in volume of subsidence relative to volume of production. A detailed comparison shows that for each field: (1) differential subsidence coincided with fluid production in both space and time; (2) subsidence has varied

TABLE 7.—*Subsidence and production data for the Wilmington oil field* —Continued.

Discovery date	January 26, 1932; rapid development begun December, 1936	California Division of Oil and Gas, 1961, p. 687
Volume of subsidence/oil production[3]		
1934–Jan. 1945	0.407	
1933–Mar. 1946	.407 (0.317)	
Mar. 1946–Nov. 1951	.795 (.893)	
Nov. 1951–Aug. 1957	.812 (1.706)	
1928–Nov. 1951	.592 ((.592)	
Aug. 1928–Aug. 1957	.655 (.927)	

[1]Owing to the absence of offshore control and the presence of interfering subsidence domains (Gilluly and Grant, 1949, p. 270; Poland and Davis, 1969, pl. 1; J. M. Buchanan, written commun., 1969), calculation of successive volumes of subsidence over the Wilmington field is, even with detailed onshore measurements, a subjective procedure.

A Long Beach Harbor Department curve, which shows cumulative volume of subsidence over the Wilmington oil field versus time (D. R. Allen, written commun., 1969, Long Beach Harbor Department drawing No. B–247), dates from 1946. Because the Long Beach Harbor Department estimate of the volume of subsidence to 1945 exceeds that of Gilluly and Grant (1949, p. 502) by at least two times and our own maximum estimate by about 1.5 times, the Gilluly and Grant values have been used here in estimating this initial (1936–45) increment of the volume of subsidence. Post-1945 increments are essentially those of the Long Beach Harbor Department.

Although shown for the sake of comparison, subsidence volumes modeled on inverted elliptical cones are considered unreliable in this case for the following reasons: (1) the cross-sectional configuration of the depressed volume changed from one approximating that of a cone in 1948 to one strongly concave downward in 1954 (Hudson, 1957, fig. 16); (2) the offshore part of the depressed area is not known to conform with an elliptical shape; (3) interfering subsidence domains have complicated the peripheral configuration of the subsidence bowl; and (4) the dimensions of the depressed area generally could not be defined beyond the 1-foot isobase (or its projection), which was, therefore, taken as the boundary for successive elliptical areas.

[2]Volume in cubic feet based on conversion factor of:

$$1 \text{ bbl} = \frac{42 \times 231}{12 \times 12 \times 12} = 5.615 \text{ ft}^3$$

[3]Figures in parentheses based on subsidence volumes modeled on inverted elliptical cones.

directly and almost linearly with net liquid production; (3) the volume of subsidence has varied directly and almost linearly with net liquid production; (4) the rates of subsidence have varied directly with the rates of net liquid production; (5) changes in subsidence rate have been associated with corresponding changes in gas production rate; and (6) subsidence has varied directly but nonlinearly with changes in measured reservoir pressure.

Thus, despite prominent dissimilarities in physical size and magnitude of production and subsidence, the many other physical similarities, and the strong similarities between the several measures of subsidence versus fluid production are sufficiently striking that the subsidence over each field can be attributed to the same cause or causes. Published investigations of the Wilmington subsidence attribute it unanimously to compaction following withdrawal of fluids during oil-field operations (Harris and Hawlow, 1947; Gilluly and Grant, 1949; Miller and Somerton, 1955, p. 68, 70; Poland and Davis, 1969, p. 201). Hence, the various cited similarities between the Inglewood and Wilmington examples support the conclusion that the subsidence over the Inglewood field is also due to withdrawal of fluids associated with oil-field operations.

PHYSICAL RELATIONS

THEORETICAL AND EXPERIMENTAL BASES

Poland and Davis (1969) have summarized briefly the application of consolidation theory to the analysis of surface subsidence. The general principles outlined by

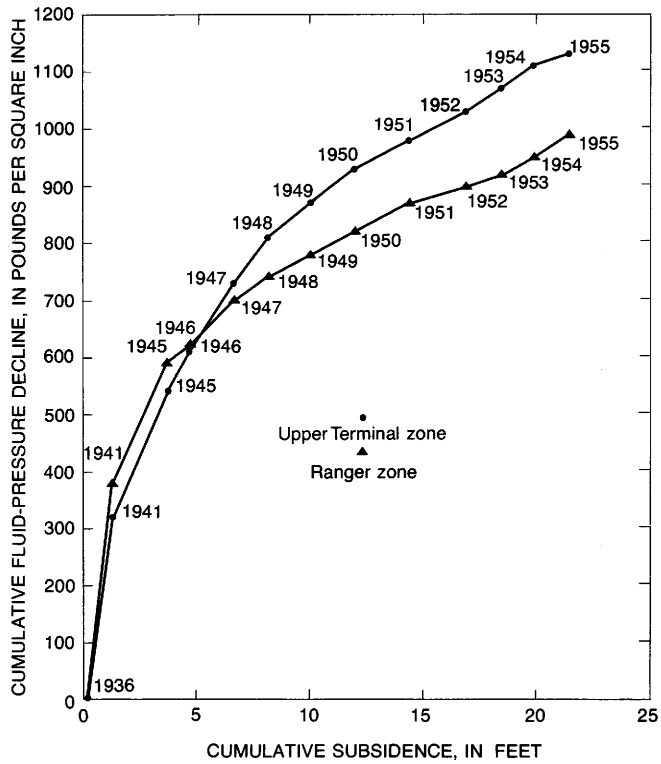


FIGURE 43.—Cumulative maximum subsidence versus cumulative measured pressure decline in the Ranger and Upper Terminal zones of the Wilmington oil field. Data from figure 41 and DeGolyer and MacNaughton Core Laboratories (1957, charts 3 and 4).

these writers provide the framework for the following discussion.

Central to the arguments of Poland and Davis (1969, p. 193–197) is 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 (porewater, reservoir, neutral, internal) stress or pressure.[5] In a confined water system in which the compressibility of water is disregarded, unit head decline (which may be equated with reduction in fluid pressure) 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 the loss of fluid mass from the system (Poland and Davis, 1969, p. 193–196). Because the overburden is supported by both fluid and effective pressure, decrease in fluid pressure to a point approaching zero will increase the effective pressure to a value approaching

[5]Fatt (1958, p. 1926, 1930) has found experimentally that for actual in situ conditions in porous rock, the relation may be closer to $p = p' + nu$, where n is a function of p and the compressibility of the solid materials, being close to unity in the 1,000 psi range.

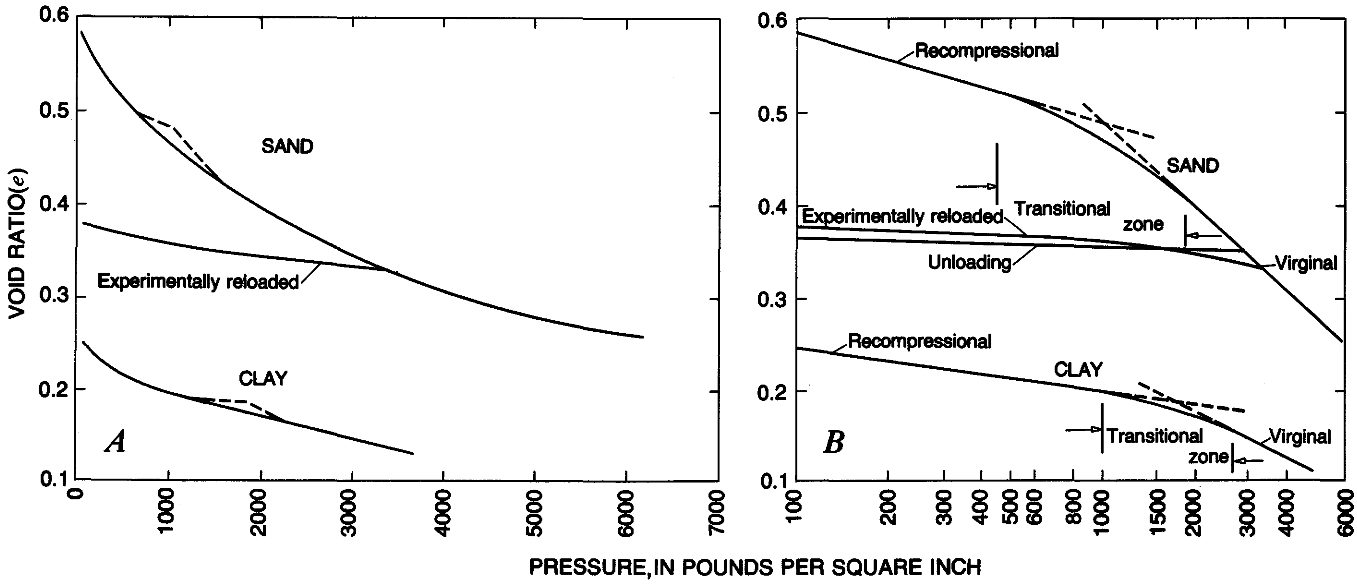


FIGURE 44.—Void ratio as a function of applied pressure for adjacent sand and clay samples from a post-Eocene Bolivar Coast formation at a depth of 3,100 feet; dashed lines show hypothetical relations in the absence of any transitional zone. *A*, Natural scale. *B*, Semi-logarithmic *e*-log *p* plot. After van der Knaap and van der Vlis (1967, p. 89).

that of the lithostatic pressure; the resulting compression will be proportional to the magnitude of the increase in effective pressure (Poland and Davis, 1969, p. 193–196).

The principles outlined above indicate that reductions in reservoir (fluid) pressure accompanying withdrawal of fluids will increase effective pressure on the skeletal materials of the reservoir. This increase may be treated as an externally applied load; the resulting compression (compaction) is a function of both the magnitude of the load and the compressibility of the skeletal materials (Poland and Davis, 1969, p. 196–197).

One-dimensional consolidation tests on a variety of natural and artificially reconstituted sedimentary materials show that compaction (commonly expressed as changes in void ratio) or strain varies directly with applied load (Terzaghi and Peck, 1967, p. 65–68; Johnson and others, 1968, p. A17–A19; van der Knaap and van der Vlis, 1967, p. 88–89; Allen and Mayuga, 1970, p. 415). Compaction per unit load, moreover, generally decreases with increasing load, much as shown in figure 44*A*. (See also Terzaghi and Peck, 1967, p. 65–68.) Test data ordinarily are plotted, however, in a semilogarithmic manner, whereby void ratio (*e*) is graphed against the log of the applied pressure (*p*); such graphs generally have the form shown in figure 44B. The resulting curves, depending on the consolidation history of the sample, commonly are divisible into three parts (see fig. 44): (1) a steeply sloping "virginal" part representing a range of applied pressures to which the sample had not been subjected previously; (2) a gently sloping recompressional or preconsolidated part representing a range of applied pressures to which the sample had been subjected previously; and (3) a zone transitional between these two (Terzaghi and Peck, 1967, p. 73–78; Johnson and others, 1968, p. A19; van der Knaap and van der Vlis, 1967, p. 89). At elevated pressures and over limited pressure ranges, particularly within those parts of the *e*-log *p* plots represented by the transitional zone, compaction commonly varies nearly linearly with applied pressure, as plotted at natural scale (Taylor, 1948, p. 216; Gilluly and Grant, 1949, p. 512; Terzaghi and Peck, 1967, p. 65–67; fig. 44, this report).

Thus, in the general case compaction increases linearly or at progressively decreasing rates with respect to increasing load. The inverse relation (that is, one in which compaction increases at progressively increasing rates with increasing load) is much less likely and probably occurs only within the transition zone between preconsolidated and virginal pressures. The likelihood of the occurrence and the prominence of the effect of this inverse relation is a function of the contrast between the slopes of the recompressional and virginal parts of the *e*-log *p* curve, the initial slope of the recompressional portion, and the radius of curvature of the transitional zone. Because the curves for dense sands generally show less contrast in slope between recompressional and virginal parts, the effect is more apt to be expressed in surficial deposits than in such materials as oil sands (Terzaghi and Peck, 1967, p. 67).

In order to examine the extent to which the compressibilities of oil-field reservoir materials may increase with increasing load, we have prepared natural-scale *e*-*p* plots for two Bolivar Coast (Lake

Maracaibo) samples (fig. 44*A*), seven arbitrarily selected Wilmington samples from depths of between 2,500–4,500 feet (Witucki, 1959, unnumbered figures), and an "average" (2,000 to 4,000-foot) Wilmington sand (Allen and Mayuga, 1970, p. 415). The plots for the two Bolivar Coast samples shown in figure 44*A* indicate that any reversal in the generally decreasing rate of change in void ratio with respect to increasing stress is so slight as to be undetectable. Of the seven Wilmington samples (three sands and four clays or shales), two showed no inflection in the *e-p* curves, four showed very slight, almost undetectable inflections, and the seventh (the shallowest clay) showed a marked inflection; the "average" Wilmington sand showed no inflection. The "transitional zones" between the experimentally reloaded and virginal parts of the *e*-log *p* curves were, in all of the examined cases, very sharp. This sharp transition may more nearly approximate the in situ condition than does the generally smooth transition between recompressional and virginal parts of the curve developed from laboratory studies. However, barring the nearly complete absence of a smooth transitional zone, increases in the compaction rate (with respect to pressure) within the transitional zone generally do not even begin to compare with the average compaction rate over the curve as a whole. Hence we conclude as a close approximation, that compaction of the clastic sedimentary materials that make up these reservoirs varies directly and at constant or progressively decreasing rates with respect to increasing pressure.

Relations Between Reservoir Pressure Decline and Subsidence

The preceding discussion indicates that compaction in idealized or hypothetical reservoir systems (where the effects of time may be disregarded on the assumption that drainage is rapid) varies directly and generally at constant or progressively decreasing rates with increasing effective pressure (declining fluid pressure). That is, $\frac{dC}{dE}$ either remains constant or decreases with increasing effective pressure ($\frac{d^2C}{dE^2} \leq 0$), where C is compaction and E is effective pressure. The observational evidence (figs. 38 and 43), however, indicates that subsidence over (or compaction in) the Inglewood and Wilmington fields has increased at progressively increasing rates with respect to declining fluid pressure (increasing effective pressure).[6] That is, $\frac{dS}{d\Delta P}$ has increased with declining fluid pressure ($\frac{d^2S}{d\Delta P^2}>0$), where S is subsidence and ΔP is pressure decline. A similar, direct but nonlinear relation between subsidence and reservoir pressure decline has also been recognized in an unnamed Bolivar Coast oil field (van der Knaap and van der Vlis, 1967, p. 93–94). This seeming inconsistency between the pressure decline-subsidence relations associated with actual examples and those predicted for an idealized system may be explained by one or more of the following:

1. Terzaghi's principle of effective stress may be inapplicable in multifluid reservoirs;
2. The relation between decreasing reservoir pressure and surface subsidence may have been obscured by creep effects;
3. Compaction generated after the first 5 or 10 years of production may be due chiefly to dewatering of fine-grained interbeds, to which the measured fluid pressures do not apply;
4. The compressibility of certain oil-field reservoir materials may increase with increasing stress;
5. Small declines of liquid level in each of many layers of a multilayered reservoir, such as the Vickers zone, lead to small losses in fluid pressure and equivalent small increases in effective pressure. The resulting, individually small increments of compaction may lead, however, to large cumulative values of compaction for the entire zone;
6. Measured and calculated reservoir-pressure-decline curves, such as those in figures 33 and 34, may not be representative of the average or true reservoir fluid pressure decline.

Terzaghi's effective stress equation has been investigated chiefly in connection with laboratory studies of foundation problems; its applicability remains untested over the wide range of fluid pressures within the multifluid environments that characterize producing petroleum reservoirs. Hence, the possible inapplicability of Terzaghi's equation to this system could explain in part why the observed relation between pressure decline and subsidence (fig. 38) is inconsistent with that predicted by our hypothetical model.

Bishop (1961, p. 38–46) and Skempton (1961) have verified experimentally a general two-phase form of the effective stress equation, first proposed by Bishop in 1955, and considered applicable to volume changes (compaction) in oil-plus-water systems (Bishop, in British National Society, International Society of Soil Mechanics and Foundation Engineering, 1961, p. 63); thus,

$$p' = p - u_a + \chi(u_a - u_w),$$

[6]Pressure decline in the Vickers zone (fig. 34) is considered representative of that for the field because: (1) through 1963 about 72.5 percent of the oil and about 78 percent of the net liquid production (but only about 50 percent of the gas) had come from the Vickers zone; (2) about two-sevenths of both the measured subsidence in the northern Baldwin Hills and the liquid production from the Inglewood field between 1911 and 1963 had been generated by 1934, up to which time there had been almost no production from zones other than the Vickers; (3) variations in production from the remaining zones of the Inglewood field are very doubtfully related to changes in subsidence rate, whereas there is an excellent correspondence between liquid production from the Vickers zone and subsidence (See Conservation Committee of California Oil Producers, 1964, p. P; this report, figs. 12*C*, 13, and 32).

where u_a and u_w are the pore pressures of air and water, and χ varies directly with the degree of saturation. For dry soils $\chi = 0$ and for completely saturated soils it equals 1. In both limiting cases the general expression reduces to Terzaghi's equation, $p' = p-u$. The term "(u_a-u_w)" is an expression of "capillary pressure" and varies directly with effective pressure; thus, in an air-water system changes in the moisture content (and therefore changes in the "capillary pressure") will necessarily lead to changes in effective pressure. However, because measurable fluid pressures in petroleum reservoirs may be indistinguishable from one or the other of the partial fluid pressures, and because we are unable to assign values to χ and the partial fluid pressures in such systems, we are unable to apply this modified equation to petroleum systems. (It should be noted, however, that the invalidation of the unmodified form of Terzaghi's equation of effective stress, as applied to petroleum systems, would not in itself contribute to an explanation of the roughly linear relation between subsidence (compaction) and liquid production.)

Creep phenomena provide a second possible explanation for the observed relation between pressure decline and subsidence in the Inglewood oil field (fig. 38). Van der Knaap and van der Vlis (1967, p. 91), for example, have observed that the full effects of compaction in the producing layers need not be instantaneously propagated to the surface. Thus an exact correspondence between pressure decline and subsidence need not be expected. Subsidence over the Inglewood field, moreover, tended to lag behind pressure decline during the first decade of production (figs. 12*C*, 13, 33 and 34). Creep effects, accordingly, may provide a partial explanation for the absence of a correspondence between pressure decline and subsidence more in keeping with that predicted for an idealized system. It is unlikely, however, that the progressively increasing subsidence with respect to the very limited pressure decline after 1933–34 can be more than incidentally attributed to creep. (Again, moreover, this explanation for the observed relation between subsidence and pressure decline contributes in no way toward an explanation of the essentially linear relation between fluid production and subsidence; creep effects may, in fact, account for the absence of an even more precisely linear relation between these two parameters.)

Compaction generated in response to dewatering of shaly interbeds suggests a third possible explanation for the observed relation between subsidence and reservoir pressure decline in the Inglewood oil field (fig. 38). Thus in a system such as the Vickers zone, where the reservoir sands are interlayered with fine-grained and relatively impermeable shales, and a stable hydraulic gradient is presumed to have existed between sands and shales prior to exploitation, any rapid drop in reservoir pressure will produce fluid-pressure gradients across the sand-interbed boundaries. If reduced fluid pressures are maintained within the reservoir sands over long periods of time, pressure equilibration between the sands and shale interbeds will lead to dewatering and resultant compaction of the shales. Dewatering of the shales will be inhibited by the low permeability of these materials; hence, most of the subsidence generated after the initially large and seemingly nearly total loss of reservoir fluid pressure could have developed as a result of slow compaction of the shaly interbeds.

Although a part of the total Vickers zone compaction is almost certainly due to interbed compaction, it is unlikely that this mechanism has accounted for nearly all of the post-1932 subsidence. Laboratory studies by van der Knaap and van der Vlis (1967, p. 92), for example, have shown that Bolivar Coast clay beds 5 feet or less in thickness will, in response to an instantaneous (unspecified) drop in fluid pressure, consolidate to 80 percent of their ultimate consolidation in about 2 years or less. Thus over short intervals of time (generally less than those that have obtained between repeated level or casing collar surveys in the Inglewood and Wilmington oil fields), the compaction of clay layers 5 feet or less in thickness should be nearly indistinguishable from that of the reservoir sands; that is, for any given reservoir pressure drop, both sands and clay layers no more than 5 feet thick can be expected to have attained nearly their maximum compaction within 2 or 3 years. Therefore, because only about 28 percent of the Vickers zone consists of shale beds more than 5 feet thick, assignment of the post-1932 compaction to interbed compaction suggests that nearly all the post-1932 subsidence is due to the compaction of only about 28 percent of the section. Hence if this subsidence (about 75 percent of that which occurred through 1963—see figs. 12*C* and 13) is due to interbed compaction, it implies that the compressibility of the shales is about six or eight times that of the reservoir sands. Inasmuch as van der Knaap and van der Vlis (1967, p. 85, 90) have shown that both sands and clays from Bolivar Coast fields compact ultimately to almost the same extent, the occurrence of such relatively high shale compressibilities is considered unlikely. This conclusion is supported in part by the studies of Allen and Mayuga (1970) who report that 67.6 percent of the compaction within the upper four producing zones of the Wilmington field (where the compactible sands comprise 242 m out of a total section more than 470 m thick) has occurred within the reservoir sands, whereas only 32.4 percent has occurred within the shales or siltstones.

A second consideration that argues against the attribution of the post-1932 compaction to interbed compaction, derives from the roughly exponential relation that obtains between thickness and compaction of clay layers in at least some oil fields. For example, whereas ten 4-foot Bolivar Coast clay layers will compact to about 80 percent of their ultimate compaction in about 1 year, two 20-foot layers and one 40-foot layer will compact to the same degree in about 25–30 and 110–120 years, respectively (van der Knaap and van der Vlis, 1967, p. 92). Thus, because about 74 percent of the Vickers zone shale beds over 5 feet thick consist of beds over 20 feet thick, it is likely that any interbed compaction due to a nearly total loss of reservoir pressure before 1932 was confined largely to the small percentage of shale beds between 10 and 20 feet thick (roughly 170 feet out of a total section of 2,300 feet).

Changing consolidation characteristics provide a fourth possible explanation for the increasing rate of subsidence with respect to declining reservoir fluid pressure in the Inglewood field (fig. 38). Grant (1954, p. 23) has, in effect, argued that accelerated subsidence may begin at some critical, threshold value of reduced reservoir pressure, which reflects in turn the maximum effective pressure to which the reservoir skeleton had been previously subjected. Accordingly, should the effective pressure increase above this threshold value in response to a substantial reduction in reservoir pressure, compaction per unit pressure increase might be considerably greater than that within the preconsolidated range.

Several considerations indicate that changes in compressibility probably cannot explain the subsidence-reservoir pressure decline relations in the Inglewood field nor can they explain the similar relation recognized in the Wilmington oil field.

The development of a prominent angular unconformity between the so-called Pico Formation and the overlying Pleistocene sands and gravels, as shown in figure 2, suggests the removal of a substantial thickness of the pre-Pleistocene section (Robertson and Jensen, 1926, p. 35–39). The amount removed cannot be precisely determined; however, a crude estimate of the section eroded from the structural crest of the east block may be obtained by projecting westward (in vertical section) the so-called Pico-Pleistocene sand contact from a point immediately west of the Crenshaw Boulevard–Stocker Street intersection, where the two units seem to be nearly conformable (see Castle, 1960). This projection suggests that about 1,600 feet of section was removed from the crest before the Pleistocene materials were deposited. This implies in turn that the pre-Pleistocene section centering on the structural crest of the east block has been overconsolidated by an amount approximating the lithostatic equivalent of 1,600 feet of brine saturated, hydraulically continuous section, minus that attributable to the roughly 50 feet of overlying and seemingly unsaturated Pleistocene sands (whose load effect may be taken here as approximating that of 100 feet of saturated, hydraulically continuous section).[7] Thus, it is concluded that the Vickers zone probably has been overconsolidated by at least

$$\frac{(1600-100)\,(62.5)\,(0.70)\,(1.7)}{144} = 775 \text{ psi},$$

where

- $1600-100$ = equivalent thickness in feet of hydraulically continuous materials removed from the post-Vickers section,
- 62.5 = weight of 1 cubic foot of water in pounds,
- 0.70 = volume ratio of grains to the total volume of sediments (T. H. McCulloh, written commun. 1966),
- 1.7 = density of grains minus buoying effect of water, and
- 144 = number of square inches per square foot,

(see Gilluly and Grant, 1949, p. 502). Therefore, if the average reservoir pressure at the beginning of production may be taken as 790 psi (see fig. 38), it is unlikely that the change in effective pressure has ever exceeded the preconsolidation pressure, for the average reservoir fluid pressure probably has declined by no more than about 750 psi over the entire productive history of the Vickers zone (see fig. 34).

The average reservoir pressure in the Vickers zone is calculated to have declined about 600 psi between 1925 and 1930; it declined over the next 30 years by no more than about 150 psi (fig. 34). If it is accepted that the relatively limited subsidence that accrued during the initial period of rapid pressure decline was due to compaction within the preconsolidated range, then it follows that the diminished, but substantial subsidence (about 1 foot at PBM 68 between 1931 and 1943; see fig. 12*C*) that occurred after this period of rapid pressure decline derived from compaction within the "virginal" range, for it was seemingly associated with an almost negligible reduction in pressure decline (about 40 psi between 1931 and 1943; see fig. 34). This explanation, however, suggests that the achievement of the preconsolidation limit was coincident with the sharp break in

[7]It is assumed that the land surface and the position in space of the fluid-pressure gradient bore the same relation to each other when erosion began as they do now, since the post-"Pico" surface must have been moderately elevated above sea level in order that erosion might ensue and fluid pressures within the Cenozoic formations in this area probably have remained closely adjusted to normal hydraulic gradients established with respect to prevailing sea levels. However, the critical erosion surface may have stood at an even higher elevation and the degree of preconsolidation may have been correspondingly greater (owing to a corresponding drop in fluid-pressure levels); this possibility is supported by the recognized sea-level lowerings associated with Pleistocene glaciation, maximum values (with respect to present sea level) of which have been given as 525 feet (Donn and others, 1962, p. 212–214) and 418 feet (Curray, 1965, p. 725).

TABLE 8.—*Measured reservoir-pressure decline in selected zones of the Wilmington oil field*

[Data from DeGolyer and MacNaughton Core Laboratories (1957, p. 11, charts 2, 3, and 4). Psig = pounds per square inch gage]

Interval	Tar zone		Ranger zone		Upper Terminal zone		Unweighted average percentage decline of initial pressure
	Reservoir pressure decline		Reservoir pressure decline		Reservoir pressure decline		
	psig	Percent	psig	Percent	psig	Percent	
1936–1/1/45	1,120–940	16	1,350–755	44	1,455–925	36.5	31.8
1/1/45–11/56	[1]940–390	49	[1]755–290	34.5	[1]925–280	44.5	42.6
9/26/45–11/15/49	905–730	15.5	720–535	13.5	880–575	21	16.7
11/15/49–4/11/57	[1]730–365	32.5	[1]535–280	19	[1]575–265	21.5	24.4

[1]Estimated

reservoir pressure decline (fig. 34). Had it been achieved much earlier, the amount of subsidence between 1926 and 1931 should have been proportionately larger; had it been reached much later, the subsidence should have nearly ceased during the decade of negligible pressure decline after 1930, whereas, in fact, it apparently proceeded at a reasonably rapid rate. Moreover, if the post-1930 subsidence was due chiefly to compaction within the virginal compression range, it is difficult to account for the accelerated subsidence that began about 1942 or 1943 and continued at an approximately uniform rate through 1962. The rate of pressure decline seems to have accelerated slightly around 1944 or 1945 (to no more than one-tenth that which prevailed during the 1925–31 period), but it must have quickly dropped to a rate that should have promoted a subsidence rate no greater and probably much less than that which obtained during the 1932–42 period (roughly half that of subsequent years).

Accelerated subsidence over the Wilmington field apparently began during the early or middle 1940's (fig. 41). It could be argued, accordingly, that this acceleration was simply coincident with the achievement of effective pressures within the virginal compressional range and, hence, accelerations in the rates of compaction (even in the absence of comparable accelerations in the decline of reservoir pressure within the compacting zones). This argument is refuted, however, by a comparison of measured reservoir pressure decline with compaction over two intervals beginning in 1945 (9/26/45–11/15/49 and 11/15/49–4/11/57; see tables 8 and 9). Measured reservoir pressure declines in the Ranger and Upper Terminal zones during the first interval very nearly equalled those that occurred during the second interval, whereas reservoir pressure in the Tar zone declined by a factor of two during the second interval. Compaction, on the other hand, more than doubled during the second interval in both the Ranger and Upper Terminal zones and increased by an infinite factor in the Tar zone. This apparent increase in the rate of compaction with respect to reservoir pressure decline (or increased effective pressure) within the

TABLE 9.—*Casing collar surveys of compaction in upper three producing zones of the Wilmington oil field over two selected time intervals*

[After Poland and Davis, 1969, p. 207–208]

Interval	Tar zone (compaction in ft)	Ranger zone (compaction in ft)	Upper Terminal zone (compaction in ft)
9/26/45–11/15/49	[1]−0.02	1.77	2.78
11/15/49–4/11/57	1.49	3.79	6.46

[1]Tension.

virginal compressional range is, however, inconsistent with the results of modern laboratory investigations which show that compaction entirely within the virginal range increases at linear or progressively decreasing rates with respect to increasing effective pressure. Thus, the observed relation between subsidence and reservoir pressure decline in the Wilmington, as well as the Inglewood field, is seemingly unexplained by the suggestion that increasing compressibilities of the reservoir materials should or could be associated with increasing effective pressures.

The preceding considerations indicate that the relation between reservoir pressure decline and subsidence over the Inglewood field (and, by extension, compaction of the Vickers zone) cannot be attributed to major differences in the preconsolidated and "virginal" compaction characteristics in the Vickers zone.

Buoyancy losses within the multilayered reservoir system respresented by the Vickers zone, following an initially large decompression, provide a fifth possible explanation for the increasing rate of subsidence with respect to reservoir pressure decline in the Inglewood field (fig. 38). Poland and Davis (1969, p. 193–196) have shown in connection with simple water systems, that the increase in effective pressure ($\Delta p'$) developed during reservoir depletion may be separated conceptually into two stages: that due to artesian head decline in a confined system and that due to buoyancy loss associated with liquid-level decline (once the desaturation point is reached) in an unconfined system. Artesian head decline in a confined system may be likened to decompression through the production of dissolved gas in the liquid-saturated petroleum system, whereas water-level decline in an unconfined system may be compared to liquid production from a petroleum reservoir once a free gas phase has developed. Although neither primary nor secondary gas caps have been reported from the Vickers zone (Oefelein and Walker, 1964, p. 510), the initial solution GOR (gas:oil ratio) of 90 ft^3/bbl at 570 psi and 100°F given by Oefelein and Walker (1964, p. 511) indicates that a widely disseminated free gas phase probably was generated very early in the production history of this zone (Standing, 1947, p. 97).

The coexistence of a relatively incompressible liquid (water), a relatively compressible liquid (oil), and gas, under conditions in which these fluid proportions have been constantly changing, seemingly invalidates direct comparisons with water systems. If, however, the reservoir pressure decline curve presented in figure 34 is representative of fluid pressure decline in the Vickers zone, then the maximum increase in effective pressure ($\Delta p'$) due to decompression of the liquid-saturated system should be approximately equal to the specified reservoir pressure decline (that is, since p changes only slightly with loss of fluid mass, it should amount to perhaps 95 percent of the pressure decline), and thus analogous to that developed in response to a specified artesian head decline in a simple water system. In any case, by the time that a free (albeit disseminated) gas phase had developed, the reservoir could no longer be viewed as liquid saturated. Because the Vickers zone had not been uniformly depleted during its primary recovery stage (Oefelein and Walker, 1964, p. 511), a direct analogy with the liquid-level decline stage in a simple water system may seem inappropriate. However, the magnitude of the increased effective pressure arising from a comparable effect may be estimated by treating the entire Vickers zone as a single unit divisible into a finite number of mechanically independent subunits of equal thickness.

The decompressed Vickers system may be visualized as a series of superposed or stacked reservoir units of small thickness, within which fluid pressures had by 1930 declined to small fractions of their preexploitation values, but which remained just liquid-saturated up to the beginning of liquid-level decline and buoyancy loss. That is, fluid pressure within each layer was characterized by a normal hydrostatic gradient increasing downward from zero at the top. Changes in effective pressure resulting from liquid-level decline through a single-unit equivalent of the Vickers zone may be calculated through use of an expression modified from one derived by Poland and Davis (1969, p. 195). Thus, as shown in appendix J: (1) the cumulative increase in effective pressure due to liquid-level decline or loss of buoyancy in this simplified, single-unit system could have been no greater than about one-half that due to decompression, even if it is falsely assumed that the entire increment attributable to decompression occurred before 1930; and (2) the effects of liquid-level decline or loss of buoyancy on the increase in effective pressure were inordinately greater during the early production years than they were after about 1940–45. Hence the acceptance of this scheme suggests that about 70 percent of the increase in effective pressure should have occurred during the first 10 years of production, and buoyancy losses during later years could have accounted for no more than about one-fourth of the cumulative change in effective pressure.

In order to simplify the treatment, the calculations of average increase in effective pressure attributable to liquid-level decline (appendix J) have been based on the assumption that an unlayered, hydraulically continuous system is mechanically equivalent to the described system—that is, one divisible into an unspecified number of equithick layers separated by rigid, impermeable membranes of zero thickness and characterized by normal hydrostatic gradients increasing downward from zero at the top. In fact, however, the average increase in effective pressure generated in response to liquid-level decline through such a system is inversely proportional to the number of layers in the system.[8] Therefore, the actual average increases in effective pressure due to buoyancy losses are only $1/\ell$ times those tabulated in appendix J, where ℓ equals the number of layers in the system. Because the Vickers zone is divisible into at least 10 seemingly hydraulically independent layers (see pl. 1 and Oefelein and Walker, 1964, p. 510), buoyancy losses probably have accounted for no more than 2 or 3 percent of the increased effective pressure due to fluid production from the Vickers zone. Accordingly, the seeming aberration in the subsidence-reservoir pressure decline relation developed in the Inglewood field (fig. 38) can be no more than incidentally attributed to buoyancy losses during the post-1930 production years.

[8] The average change in effective pressure in an unconfined system, in which liquid level has declined from the top to the base of the reservoir, may be given as

$\Delta p' = \gamma_\ell (1-n+n_\ell)(T/2)$, where

$\Delta p'$ = average change in effective pressure,

γ_ℓ = unit weight of liquid,

n = reservoir porosity

n_ℓ = liquid retained above the saturation level expressed in percent of total volume, and,

T = reservoir thickness.

This expression is modified from one given by Poland and Davis (1969, p. 195); their equation is divided by 2 because it permits calculation of the change in effective pressure at the base of the drained column only, whereas the average change in effective pressure is sought here. Hence, for the two specified systems, let

$\Delta p_1'$ = the average increase in effective pressure developed in response to liquid-level decline through an unlayered reservoir of thickness T, characterized by a normal hydrostatic gradient increasing downward from zero at the top, and

$\Delta p_2'$ = the average increase in effective pressure developed in response to liquid level decline through each of ℓ layers of equal thickness t, characterized by normal hydrostatic gradients increasing downward from zero at the top and comprising a total thickness T; $\Delta p_2'$ is a function of the thickness t and, in this idealized system, independent of the total thickness T.

Then

$$\frac{\Delta p_1' = (\gamma_\ell)(1-n+n_\ell)(T/2)}{\Delta p_2' = (\gamma_\ell)(1-n+n_\ell)(t/2)}$$

and since $T = \ell t$

$$\frac{\Delta p_1'}{\Delta p_2'} = \ell.$$

The effects of mass loss are disregarded here, for it can be shown that liquid-level decline through the full 1,650-foot, single-unit Vickers zone equivalent would decrease the average geostatic pressure by only about 23 psi.

The possibility finally remains that the pressure decline curves presented in figures 33 and 34 are not representative of the true or average reservoir fluid pressure decline for the Vickers zone as a whole. Thus, in the general case, curves of this sort may, at best, be representative only of fluid pressure decline in the immediate area of the well (or wells) from which the data derive.

Pressure sinks, analogous to cones of depression developed in simple water systems, are generally formed around producing oil wells (Glenn, 1950; van der Knaap and van der Vlis, 1967). These sinks usually become "deeper and wider as time goes on" (van der Knaap and van der Vlis, 1967, p. 91). Gilluly and Grant (1949, p. 518) have indicated that "both common sense and hydrodynamic theory show that the pressure drop is greatest at these points [of well penetration] or the oil would not continue to flow to them and that the pressure drop diminishes away from the wells. Accordingly, the pressure decline curves are maximal curves and by no means represent the average pressure decline throughout the oil sand. On the average the pressure decline over the area of the producing part of the field must be considerably less." Thus in considering this problem in the Wilmington field, Miller and Somerton (1955, p. 68, 70) observed that "reductions in average [or true] pressures in the reservoir are virtually impossible to determine with a satisfactory degree of accuracy" and there is, accordingly, some "question as to whether average static reservoir pressures should be used in the analysis [of subsidence]."

Permissive evidence from the Inglewood field strengthens the conclusion that the curves shown in figures 33 and 34 are not representative of the actual or average fluid pressure decline in the Vickers zone. Oefelein and Walker (1964, p. 511) have described an infill drilling program in the Vickers east pool which was begun in 1947, and during which "several of the infill wells drilled on 2-acre spacing, produced 100 to 200 BOPD initially despite large cumulative withdrawals from nearby older wells which were averaging 25 B/D [BOPD]. This initial rate can be attributed to incomplete drainage of all sands in the complexly faulted, long vertical section." Thus production from the separate fault blocks may have proceeded without having significantly affected reservoir pressures in the adjacent blocks. Although the pressure decline curve shown in figure 33 was based on observations at more than one well (R. C. Erickson, oral commun. 1967) and might thus be expected to incorporate the effects shown by the infill wells, it is possible that these effects were not incorporated and that the initial (1947–54) reservoir pressures characteristic of these younger wells approached those that obtained within the Vickers in 1925.

Because pressure sinks centering on producing wells are an expected consequence of production, and because the Vickers zone may have been characterized by the preservation of areas of relatively high fluid pressures, it is likely that the pressure decline curves presented in figures 33 and 34 are not representative of the true or average fluid pressure decline in the Vickers zone.

We have considered six possible explanations for the seeming inconsistency between the reservoir pressure decline-subsidence relations in the Inglewood field (fig. 38) and those predicted for an idealized system. There exist unresolved questions concerning the applicability of the unmodified form of Terzaghi's effective stress equation to petroleum systems and the influence of creep with respect to the effects of reservoir compaction at the surface. However, neither the invalidation of Terzaghi's equation nor the possible operation of creep contribute to an understanding of the approximately linear relations between liquid production and various measures of subsidence (figs. 35, 36, and 37). On the other hand, the likelihood that net fluid withdrawals more accurately reflect true or average reservoir fluid pressure reductions than do actual reservoir pressure measurements (see Miller and Somerton, 1955, p. 70), leads directly to an explanation of this relation. Thus it is the sixth explanation that seems the likeliest: namely, that the curves presented in figures 33 and 34 are representative of fluid pressure decline developed only at certain producing wells and are not representative of the average fluid pressure decline within the compacting zones of the Inglewood oil field.

Relations between Liquid Production and Subsidence

The identification of a linear relation between various aspects of liquid production and subsidence in the Inglewood oil field (figs. 35, 36, and 37) was unexpected, for Gilluly and Grant (1949, p. 501–502) rejected the occurrence of a similar relation in the Wilmington field. Subsidence in the Wilmington oil field generally has been considered directly proportional to measured reservoir pressure decline or to various logarithmic expressions of liquid production (Gilluly and Grant, 1949, p. 463, 502–518; Miller and Somerton, 1955; Hudson, 1957, p. 43–59). However, although there are very few examples of oil fields in which both production and subsidence are well enough known to be compared over extended periods, linear relations between liquid production and subsidence may be more characteristic of subsiding oil fields than heretofore suspected (Castle and others, 1970).

Castle, Yerkes, and Riley (1970) have compared production and subsidence in the Inglewood, Wilmington, Huntington Beach, and three unidentified Bolivar

Coast oil fields. These comparisons demonstrate recognizable linear relations between cumulative net liquid production and one or more measures of subsidence in all six fields. This relation, moreover, is far less linear if subsidence is compared only with oil or gross liquid production. Departures from linearity seem to have characterized the early production stages in at least five of the six fields. Subsidence rates in the Bolivar Coast and Wilmington fields were, in proportion to their production rates, relatively low during the early years of development; subsidence rates over the Inglewood field (and perhaps the Huntington Beach field as well) are believed to have been relatively high during the early production years.

Although the approximately linear relation between net liquid production and subsidence is still not fully understood, a general explanation is suggested by simple analogy with a tightly confined artesian system of infinite areal extent (Castle and others, 1970). Thus the artesian coefficient of storage may be defined as the volume of water released from storage within a column of aquifer underlying a unit surface area during a decline in head of unity; in an artesian system that is hydraulically isolated from any free-water surface, the volume of water represented by the storage coefficient will be derived entirely from the expansion of the confined water and compaction of the reservoir skeleton. Therefore, the total volume of reservoir compaction must be linearly related to cumulative production, provided only that the bulk modulus of elasticity of the water and the modulus of compression of the reservoir skeleton remain invariant over the relevant stress interval. In the case of a well field in which the liquid-extraction flux is very high (that is, one characterized by closely spaced wells and high production rates) and hydraulic diffusivity[9] is (for whatever reason) very low, fluid-pressure decline will be expressed chiefly as mutually interfering cones of depression surrounding individual wells and will be largely confined to the main body of the well field. Thus production will be obtained chiefly from liquid expansion and reservoir compaction within the areal limits of the well field itself rather than by extraction and consequent but almost unmeasurable, subsidence from an extensive peripheral region. Under these circumstances, then, the average fluid pressure decline anywhere within the field (and the consequent increase in effective pressure and resultant compaction) will tend to become linearly related to cumulative production.

[9]Hydraulic diffusivity, a term analogous to thermal diffusivity, is defined as the transmissivity of an aquifer (hydraulic conductivity times thickness) divided by its storage coefficient. This ratio describes the rate at which a head change propagates through the aquifer.

The system described above becomes directly analogous to an oil field if two restrictions are imposed on the oil-field model: (1) the proportion of gas in the produced fluid must remain constant (it is assumed that the expansive effect of the gas is a function of its concentration in the fluid system); and (2) the compressibilities of both brine and oil in the reservoir state must be virtually identical (alternatively, the oil:net water ratio must remain constant, in which case the relation between oil production and subsidence, as well as between net liquid production and subsidence would tend to be linear). The second restriction is the most vulnerable feature of this model.

Although departures from linearity during the early production years may be associated with changes in liquid or skeletal compressibilities, it is likely that they are due chiefly to changes in the produced gas:net liquid ratio. Thus relatively low gas production from the Wilmington and Bolivar Coast fields during their initial development was associated with relatively low subsidence rates. The early development of the Inglewood field, on the other hand, was characterized by both high gas production and relatively rapid subsidence (figs. 12*C*, 29 and 32).

Compaction

Estimates of expectable compaction of the Vickers zone provide reasonable limits on the amount of subsidence that might occur over the Inglewood oil field. However, because we have been unable to determine average or real drops in reservoir pressure over given production intervals, we may calculate no more than the ultimate compaction that might develop in response to a total loss of reservoir fluid pressure. Furthermore, the absence of consolidation test data from the Inglewood field, plus a general insufficiency of consolidation test data over relevant pressure ranges, severely restrict approaches to this problem. Accordingly, estimates of compaction must be based on the following assumptions: (1) compaction has been confined to the reservoir sands and to shale layers less than 5 feet thick; (2) both sands and shale have experienced comparable compaction in response to comparable increases in effective pressure; (3) compaction within the compacting materials is independent of time; and (4) consolidation test data developed in other oil-field studies (specifically those of the Wilmington field and one Bolivar Coast field) are applicable to the Vickers zone of the Inglewood oil field. The last of these assumptions is considered especially questionable. Nevertheless, the measured compression indices from both the Wilmington and the Bolivar Coast fields are in close agreement (appendix K), suggesting that compacting Cenozoic petroleum reservoirs may possess similar consolidation characteristics. Furthermore, because the Wilmington and Inglewood sediments were derived from and deposited within similar geologic environments, it is likely that they are at least petrographically similar.

The calculated estimates of compaction of the Vickers zone (appendix K) range over an order of magnitude. This range derives chiefly from major differences in the inferred compaction history, as indicated by differences between recompressional and virginal parts of the *e*-log *p* curves.

The Vickers zone parameters, coupled with the test data presented in appendix K, lead to several estimates of compaction, all of which exceed the subsidence measured through 1963. However, because the Vickers zone is believed to have been largely or entirely preconsolidated (see section on "Relations Between Reservoir Pressure Decline and Subsidence"), the values of 60–80 feet given in appendix K, which assume no preconsolidation, probably grossly exceed the ultimate compaction of this zone. Accordingly, the figures of 8.71 feet and 9.80 feet (appendix K, II.B.1.) or 7.26 feet and 10.9 feet (appendix K, II.C.1.), which assume preconsolidation and recompressional compaction, are believed to more accurately define the ultimate compaction range and resultant subsidence over the Inglewood field. Because the compression indices used in calculating the recompressional compaction are drawn from test results on experimentally unloaded and reloaded samples in which the testing was begun at relatively high pressures, the resulting estimates probably constitute maximal values of ultimate compaction (Leonards, 1962, p. 152). The fortuitous agreement between these figures and the 8.93 feet of compaction calculated through use of the Tar-Ranger compression modulus (appendix K, I.) probably stems from the testing of these materials at relatively high stress levels (and correspondingly reduced strain rates) or to a degree of preconsolidation within the tested materials prior to sampling.

The tabulated estimates of compaction (appendix K) provide reasonable limits on the ultimate compaction of the Vickers zone and, hence, the ultimate subsidence over the Inglewood oil field. Thus, provided only that use of the Wilmington-Bolivar Coast test data leads to errors no greater than 100 percent in either direction, the estimates presented in appendix K, coupled with our skeletal knowledge of the late Cenozoic history of the Baldwin Hills, suggest that the ultimate compaction of the Vickers zone should be not much less than 5–10 feet nor much more than 10–20 feet.

CONCLUSION

The differential subsidence in the northern Baldwin Hills can be reasonably attributed entirely to exploitation of the Inglewood oil field, as indicated by the following points: the well-defined spatial association between the pattern of subsidence and the outlines of the oil field; the centering of the subsidence bowl over the centers of both the oil field and the producing structure; the approximate coincidence between the beginning of production and the beginning of subsidence; the nearly linear relations between liquid production and subsidence; the sharp deceleration of subsidence in the east block associated with the establishment of a waterflooding program there; the numerous oil fields in which both a spatial and, to a lesser degree, a temporal association between production and differential subsidence can be recognized; the many similarities between the Inglewood subsidence and the exploitation-related subsidence in the Wilmington oil field; and the mechanical compatibility of subsidence with liquid production and attendant reservoir pressure decline.

HORIZONTAL MOVEMENTS

The spatial associations between the centripetally directed horizontal movements, the Inglewod oil field, its producing structure, and the prominent subsidence in the northern Baldwin Hills, are clearly established by their coincident centering and generally symmetrical relations to each other (pl. 4 and figs. 3 and 4). Moreover, although a temporal relation between the horizontal displacements and oil-field production cannot be established directly, its existence is strongly suggested by the apparent coincidence between the onset of the horizontal displacements and the beginning of subsidence at PBM 68 (see section on "Horizontal Movements" and fig. 17). Thus, since both production and subsidence began in the middle 1920's, it seems likely that the onset of the horizontal movements closely coincided with the beginning of exploitation. This conclusion is forcefully supported by the fact that the genetically associated contractional strain identified in the central part of the subsidence bowl could not have begun before 1925 (fig. 16). In any case, the clearly defined and geometrically restricted spatial relations between the horizontal movements and the patterns of differential subsidence shown in the northern Baldwin Hills, together with the indicated temporal association between the subsidence and the horizontal displacements, suggest either that one was derived from the other or, more likely, that both have developed in response to a common cause. Accordingly, if a cause-and-effect relation between oil-field exploitation and subsidence is accepted, a cause-and-effect relation between exploitation and the horizontal movements must be accepted as equally valid.

HORIZONTAL MOVEMENTS IN THE WILMINGTON AND BUENA VISTA OIL FIELDS

There are, in addition to the Baldwin Hills, two well-documented examples in which centripetally or axially directed horizontal surface movements have coincided with oil-field exploitation: the Wilmington and Buena Vista oil fields. Many other examples may exist, but in the absence of appropriate triangulation or trilateration surveys they remain unrecognized. Because the horizontal surface movements at Wilmington and Buena Vista are also associated with differential subsidence centering on these fields, they too are reasonably attributed to oil-field exploitation.

Measured horizontal displacements developed in and around the subsiding Wilmington field have been described by Grant (1954). The movements are symmetrically disposed about both the subsidence bowl and the oil field (Grant, 1954, p. 20; California Division of Oil and Gas, 1961, p. 684). Horizontal displacements of more than 6 feet by 1951 (Grant, 1954, p. 20) and of more than 11 feet by 1966 (Yerkes and Castle, 1970) have been measured over the Wilmington subsidence bowl. These horizontal movements, moreover, have been directed toward the center of the subsidence bowl, and accompanied by contraction in the central part and by extension around the periphery of the bowl (Grant, 1954, p. 20, 23). The horizontal movements described for the Wilmington field suggest, accordingly, a horizontal strain pattern virtually identical with that recognized in the Baldwin Hills.

Horizontal displacements in the Buena Vista oil field (fig. 48) have been discussed by Whitten (1961, p. 318–319; 1966, p. 74–75) and Howard (1968).[10] These centrally directed movements, moreover, again have been accompanied by contraction (and negative dilatation) over the central part of the field and extension (and dilatation) along its flanks (Howard, 1968, p. 750–752). The displacement vectors observed within the Buena Vista oil field are directed less toward a unique "center" than toward the axis of this conspicuously elongate oil field. They are in addition, assymetrically developed across the field. This asymmetry, however, accords with both the apparent pattern of subsidence and the oil field itself (fig. 48)—as shown, for example, by the fact that through 1959 there had been about four times as much oil withdrawn from the "Hills" area as there had been from the "Front" area (California Division of Oil and Gas, 1960, p. 41–43). Thus, although contemporary displacements along the active thrust fault shown in figure 48 may have obscured the relation, the general correspondence between the patterns of production and subsidence and the pattern of horizontal movements indicates that the horizontal movements have indeed been "caused by collapse from the withdrawal of oil" (Whitten, 1966, p. 74).

MECHANICAL BASIS

Several models have been proposed to explain the axially or centripetally directed horizontal movements known to accompany differential subsidence.

The earliest of the models suggested to explain the radially oriented horizontal movements over the Wilmington field has been designated the "tension center" model (Stanford Research Institute, 1949, p. 67–69). It presupposes: (1) the existence of a spherical compacting volume at depth; (2) a homogeneous isotropic earth; (3) elastic behavior of the involved materials; and (4) negligible weight of the removed material. This model has been expressed as an equation which relates horizontal displacement (u) at a specified radius (r) from the center of subsidence, to the differential subsidence (w) at that radius, and the depth (h) to the tension center: $u = rw/h$. By this expression, horizontal displacement varies from zero at the center of subsidence (where $r = 0$), through a maximum, and back to zero at the periphery (where $w = 0$). Thus, according to the model, both horizontal and vertical movements may be considered complementary expressions of the same strain system.

A second model, which was also developed to explain the horizontal movements over the Wilmington field, has been termed the "vertical pincers" model by McCann and Wilts (1951, p. 1) and is attributed to Grant (1954). This model is based on an analogy with a plate or prism which is clamped at both ends and deforms under its own weight (Grant, 1954, p. 19). The bending of such a plate or beam will produce a concave downward configuration toward the distal ends of the plate, and a concave upward configuration toward the central part of the plate; where the two surface configurations merge at the inflection points, rotation of initially vertical elements of the beam and concomitant horizontal displacement should be greatest.

McCann and Wilts (1951, p. 1–3, 12–16) conclude from an analysis of the surface movements in the Wilmington field that the "tension center" model adequately explains the observed horizontal movements, whereas the "vertical pincers" model cannot.

Lee and Shen (1969) have analyzed horizontal surface movements associated with differential subsidence by means of physical model studies and finite element methods. The only source of deformation permitted in these analyses is the subsidence introduced beneath a

[10] Because three of the four apparently stable triangulation points shown in figure 48 are located within active oil fields, significant errors may exist in the pattern of horizontal displacements if their positions were assumed to be stable rather than actually measured with respect to an independent network; the data source (Whitten, 1961) did not permit an evaluation of this possibility.

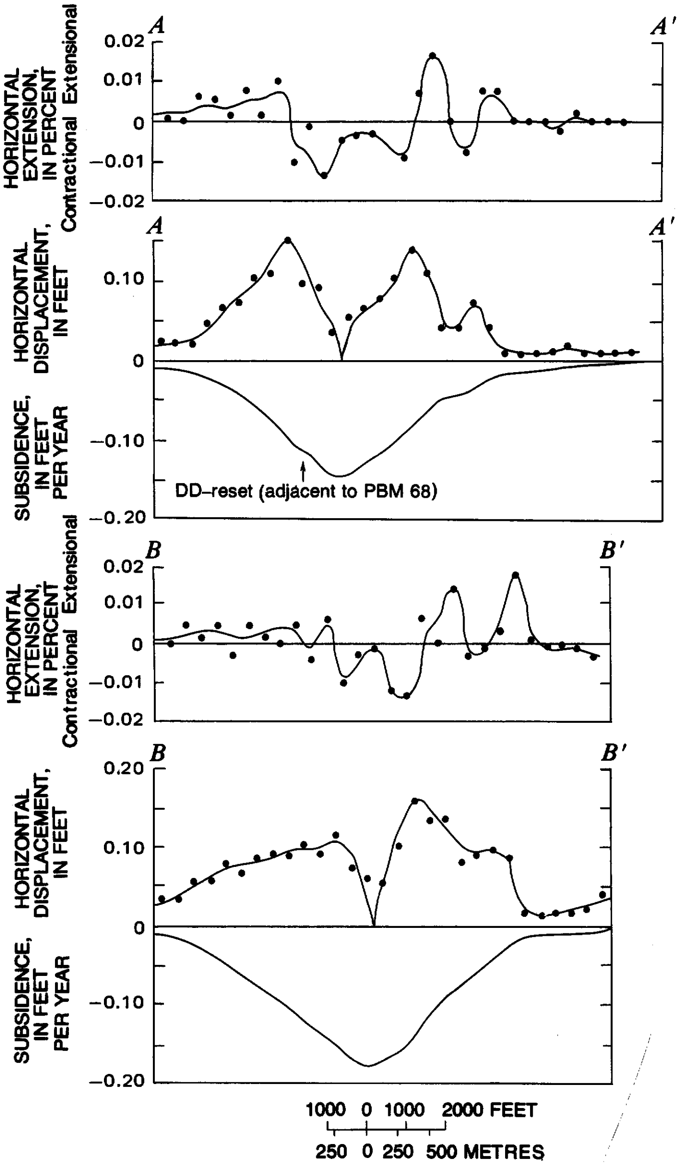


FIGURE 45.—Calculated horizontal displacement and horizontal strain along lines *A–A'* and *B–B'* during the period 1954–58 (see pl. 4). Based on empirical relation developed by Lee and Shen (1969, p. 143–144, 147–148) in which $m = \frac{2}{3} H\alpha$, where m = horizontal movement, H = thickness of the "stiff layer" overlying compacting zone, and α = subsidence slope angle. In this construction H = 875 feet or roughly the average depth to the top of what is defined here as the Vickers zone. Curves fitted by eye.

beam or "stiff" layer designed to represent the overburden above a compacting volume at depth (Lee and Shen, 1969, p. 145–149). Under these circumstances the horizontal displacement, m, is related to the subsidence slope angle, α, by the expression $m = kH\alpha$, where k is a constant derived for the effects of shear and variable modulus and H = the thickness of the overlying "stiff" layer; the physical model and finite element investigations indicate a good fit with the equation where $k = \frac{2}{3}$ (Lee and Shen, 1969, p. 143–144, 147–149). Results of the application of this relation to Baldwin Hills subsidence profiles generated between 1954 and 1958 (and hence generally prior to full-scale waterflooding) (fig. 45) are in general agreement with the observational evidence and support the conclusion that axially or centripetally directed horizontal movements are necessarily associated with differential subsidence. Thus the distribution of the calculated horizontal displacements shown in figure 45 seems to approximate that observed in actual examples of this phenomenon. Moreover, although the calculated strain profiles less faithfully mimic these examples, the form of the calculated profile along line DD reset—*A'* roughly matches that actually measured along this same line (fig. 16). That is, the central part of the bowl is in both cases characterized by contractional (or negative extensional) horizontal strain, whereas the periphery is under extension.

CONCLUSION

The horizontal surface movements in the northern Baldwin Hills can be reasonably attributed entirely to exploitation of the Inglewood oil field, as indicated by the following points: the clearly defined spatial and symmetrical relations between the horizontal surface movements and both the oil field and the essentially coincident differential subsidence bowl; the approximate coincidence between the onset of exploitation and the onset of the horizontal movements; the similarities between these relations and those developed in and around other oil fields; and the mechanical compatibility of this type of horizontal movement with subsidence due to oil-field operations.

EARTH CRACKS AND CONTEMPORARY FAULT DISPLACEMENTS

The earth cracks and associated fault displacements centered on the Stocker Street–Overhill Drive–La Brea Avenue intersection and the Baldwin Hills Reservoir form a third category of contemporary surface movements reasonably attributed to exploitation of the Inglewood oil field. The relation between exploitation and cracking, however, is more obscure than that between exploitation and either the subsidence or the horizontal movements.

A spatial association between the earth cracks and the Inglewood oil field can be seen by comparing plate 2 and figure 3. All the cracks are confined to the oil field or the immediately adjacent, peripheral area; none are known elsewhere in the Baldwin Hills. Many or most of the earth cracks are roughly orthogonal to radii emanating from the approximate center of the field (as well as that of the subsidence bowl); only two (XII and XIII) trend more or less toward the center of the oil field. Although the general restriction of the cracks to the east block seemingly invalidates such conclusions as could be drawn from the spatial or geometrical associations between the earth cracks and the oil field, both the oil field and the history of its exploitation are characterized by asymmetries of various types. For example, until the end of 1963 at least, waterflooding was essentially confined to the east block, thereby destroying any preexisting symmetry of exploitation and the resultant requirement that the cracks be symmetrically distributed with respect to the field. Thus quite the opposite conclusion could be drawn: the apparent asymmetry of exploitation is consistent with the asymmetrical distribution of the cracks. A direct temporal association between exploitation and the generation of the cracks is suggested only by the fact that cracking of this sort was not recognized until the Inglewood field had been in operation for some time.

Earthquake-associated oil well damage (see section on "Earth Cracks and Contemporary Fault Displacements"), which is not known to have occurred before 1963, is consistent with faulting along the subsurface projection(s) of one or more of the earth cracks. Because production from the Inglewood oil field has been overwhelmingly from the Vickers zone, the apparent restriction of damage or inferred rupturing to producing zones no deeper than the Vickers suggests that the subsurface faulting, and hence the surface cracking, are thus related to the exploitation of the field.

FAULTING IN OTHER OIL FIELDS

A number of other examples of faulting associated with oil-field operations have been reported in the literature. These additional examples, located in the Texas Gulf Coast region and the southern San Joaquin Valley, as well as in the Los Angeles basin, support the likelihood of a cause-and-effect relation between the exploitation of the Inglewood oil field and earth cracking in the northern Baldwin Hills.

Faulting along the edge of the Goose Creek oil field east of Houston, Texas (fig. 46), apparently began sometime after 1917, the year development began (Pratt and Johnson, 1926, p. 577–581; Sellards, 1930, p. 29–30). The surficial ruptures at Goose Creek are "compound" or discontinuous in plan (Sellards, 1930, p. 30); the faulting has been characterized by vertical displacements as great as 16 inches and by downdripping of the blocks toward both the nearly coincident center of subsidence and the center of the oil field (fig. 47) (Pratt and Johnson, 1926, p. 578–581; Sellards, 1930, p. 29–30). All the faulting, moreover, has occurred at or beyond the edge of the oil field, along the periphery of the subsidence bowl, and nearly parallel to the subsidence isobases. Movement along the Goose Creek faults probably proceeded unevenly and, in part, as discrete jumps. Direct evidence in support of this inference is lacking, but slight earthquakes were felt locally during a period when movement is known to have been taking place along these faults (Pratt and Johnson, 1926, p. 581), and Sellards (1930, p. 29–30) has

FIGURE 46.—View east along "fracture" on Hog Island near the south edge of the Goose Creek oil field, Texas. After Pratt and Johnson (1926, p. 581).

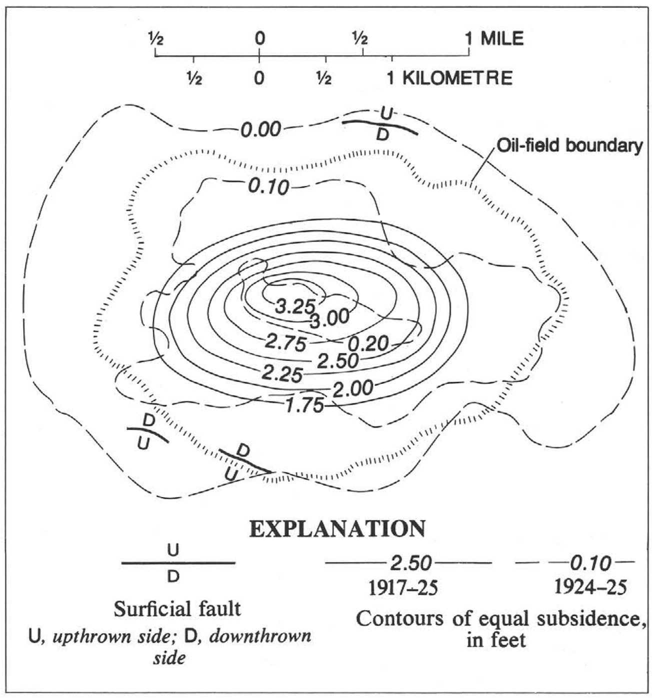


FIGURE 47.—Contours of equal subsidence (in feet) around the Goose Creek oil field. After Pratt and Johnson (1926, p. 582, 584).

indicated that "the drop [or displacement] accompanying the break [along the north edge of the oil field] was necessarily a sudden drop."

Most of the surficial faulting associated with other Texas Gulf Coast oil fields has also occurred in the Houston area. Weaver and Sheets (1962, fig. 1, p. 260, 263) have described contemporary surface faulting within or peripheral to the following metropolitan Houston fields: the Eureka Heights, the Clinton, the Webster, the South Houston, and the Mykawa. Although the nature and history of this faulting have not been described in detail, a well-defined spatial association between much of the faulting and operations in the oil fields listed above is clearly evident. Judging from their map (Weaver and Sheets, 1962, fig. 1), a large part of this faulting is similar to that around the Goose Creek field, and in at least one field (the Mykawa) it is spatially associated with an area of differential subsidence centering on the field (Weaver and Sheets, 1962, figs. 1 and 2). The only other Texas field in which historic surface faulting has been recognized is the Saxet field near Corpus Christi (Yerkes and Castle, 1970, p. 58). This faulting occurred along a 1.5-mile break and was characterized by dip-slip displacements of over 2 feet, in which the downdropped block lay toward the center of the oil field. The Saxet faulting has also been associated with more than 3 feet of differential subsidence (Yerkes and Castle, 1970, p. 58).

Direct associations between oil-field operations and surface faulting have not been firmly established in all these examples, and other phenomena may have contributed to the faulting. The metropolitan Houston area, for example, has been characterized by the withdrawal of large volumes of ground water, and Weaver and Sheets (1962, p. 254) indirectly attribute "the most extensive movement of the surface* * * to the extraction of water." Furthermore, many Gulf Coast oil fields occur over salt domes subject to solution collapse, probably unrelated to the production of petroleum, and various types of surface rupturing have apparently developed in response to such collapse (Sellards, 1930, p. 9–16, 23–28).[11]

The only other reported domestic examples of surficial faulting associated with oil-field operations occur within or around the Buena Vista, McKittrick, and Kern Front fields in the south San Joaquin Valley, and an unnamed field in the Los Angeles basin, all in California.

Faulting in the Buena Vista Hills (fig. 48) is similar to that in the Baldwin Hills chiefly in the sense that it has been unassociated with recognized seismic activity and has been proceeding more or less continually over a period of many years (Koch, 1933, p. 701; Wilt, 1958, p. 169, 171; Nason and others, 1968, p. 101). However, the Buena Vista displacements have been confined to a single surface, and there is no clear evidence indicating that this movement has occurred along a preexisting fault, although a structure section prepared by Koch (1933, p. 707) seems to support such an interpretation.

It is not known when historic movement began on the Buena Vista fault. According to Wilt (1958, p. 169), it was not until 1932, about 22 years after exploitation began (California Division of Oil and Gas, 1960, p. 39), that "it became evident to the oil companies operating in the Buena Vista Hills Field that many wells were being sheared off by an active thrust fault." Koch (1933, p. 701, 709) has indicated that "casing failures referable to the Buena Vista thrust occur at depths ranging from 76 to 794 feet," but these "well failures have occurred only in a narrow shallow zone near the trace, indicating either greatest movement, or most concentrated movement, that is, narrowest fault zone, near the outcrop of the fault." A contour map of the gently north-dipping fault surface (Koch, 1933, p. 702) shows that the active subsurface segment extended no more than 2,000 feet north of the surface trace (fig. 48). Minimum rates of movement along the fault for various periods, as computed by Koch (1933, p. 703–704) from shortening of surface pipelines and deformation of well casings range from 0.139 to 0.266 foot/year and 0.076 to 0.224 foot/year, respectively. The maximum average rate of movement parallel to the dip (as derived from repeated observations of established control points on the surface) is computed to have been only 0.068 foot/year

[11]Although unrelated to oil-field operations, a relevant example of surface faulting associated both spatially and temporally with Frasch-process extraction of sulfur from the caprock of a salt dome is also known from the Texas Gulf Coast (Deere, 1961).

Initial field measurements of both vertical and horizontal surface movements above the salt dome were begun 3 months after mining started (Deere, 1961, p. 59–60). A well-defined subsidence bowl was recognized 9 months after extraction began. Within 31 months it had grown to a diameter of 4,000–5,000 feet and a depth of nearly 5 feet over a central producing area no more than 400 feet wide (Deere, 1961, p. 60–63). After 31 months of operation, centripetally directed horizontal displacements ranging up to 1.3 feet were observed at five triangulation monuments around the subsidence bowl, and horizontal strain (as measured along two lines athwart the subsidence bowl) reached a maximum of 0.65 percent compression at the center of the bowl and 0.20 percent in tension along the flanks (Deere, 1961, p. 62–63).

"A surface crack 2,000 feet long* * * formed suddenly [about 1,000 feet west of the producing zone] during the fifth month of operation in which the ground on the mining side of the crack* * * dropped down from 1 to 4 in." (Deere, 1961, p. 61–62). Displacement apparently continued following initial recognition of the crack, but cumulative figures have not been given. One of Deere's (1961, p. 62) illustrations indicates that the total displacement after 31 months probably was more than 6 inches; furthermore, according to Deere (1961, p. 64), "vertical displacement of the fault [whose trace at the surface is represented by the crack] ranges up to 1 ft. or so." Of particular interest in connection with the northern Baldwin Hills surface ruptures is the fact that the displaced block away from the producing zone showed uplift with respect to a zero datum line established 9 months after production began (Deere, 1961, p. 62–63). This differential uplift, of up to about 0.1 foot, may be analogous in part to that which has occurred east of cracks I and IX in the Baldwin Hills.

The preceding observations show, then, that the extraction of sulfur from a depth of 1,300–1,600 feet below the surface has led to the development of both surficial faulting and a measured surface strain pattern very similar to that which evolved during exploitation of the Inglewood oil field.

Examples of historic surface rupturing have also been reported from within and around several water fields (Robinson and Peterson, 1962; Weaver and Sheets, 1962, Fett and others, 1967; Schumann and Poland, 1970). Most of these examples, moreoever, have been associated with measured differential subsidence. Fault displacements have occurred along a few of the water-field ruptures, but most are expressed simply as open fissures.

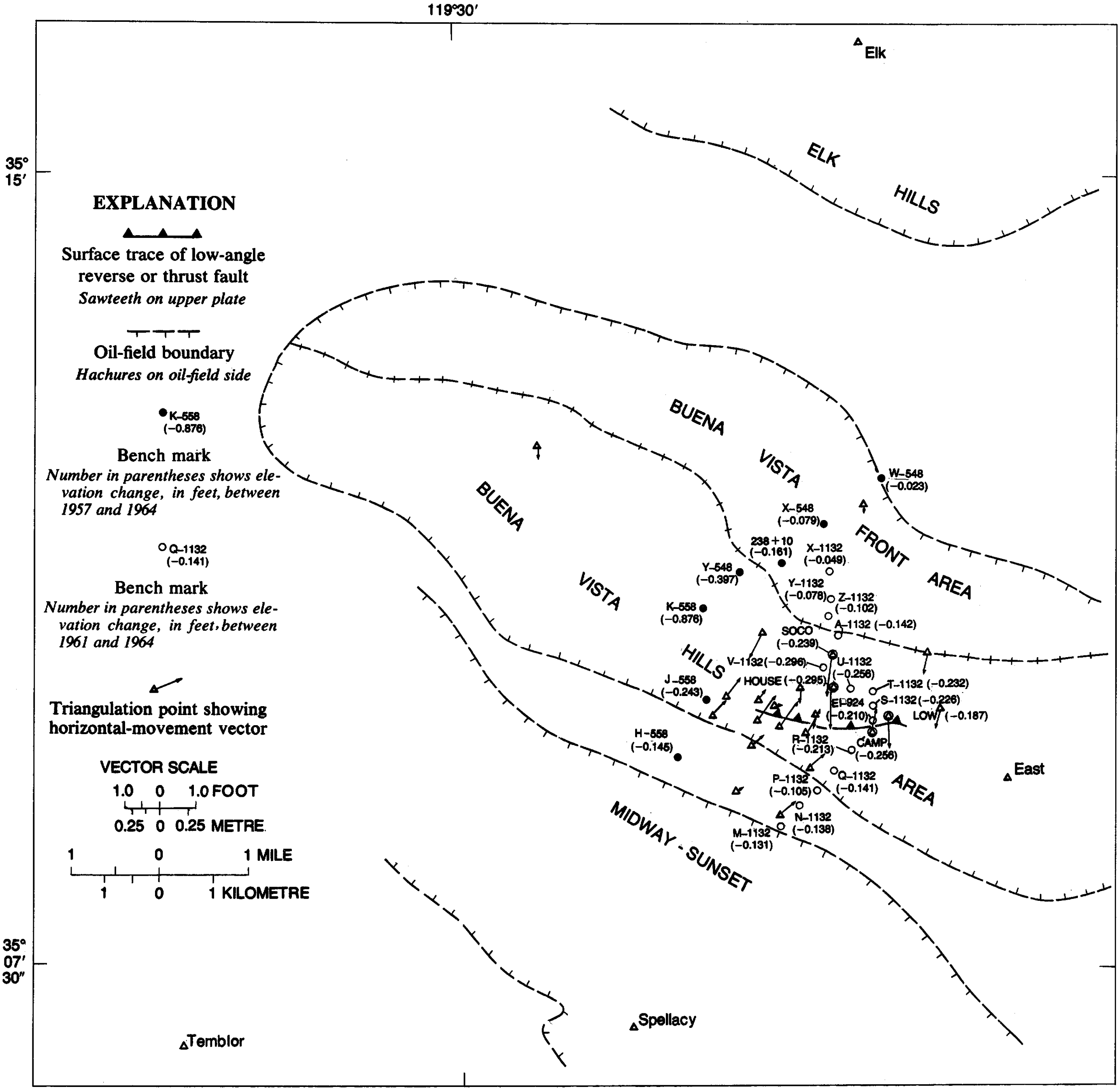


FIGURE 48.—Map of part of the Buena Vista Hills area showing: (1) approximate boundaries of parts of the Buena Vista (divisible into the Buena Vista Front—or flank—and Buena Vista Hills areas), Midway-Sunset, and Elk Hills oil fields (California Division of Oil and Gas, 1960, p. 38, 40, 112, 164); (2) surface trace of historically active fault along south flank of the Buena Vista Hills (Wilt, 1958, p. 170, 172); (3) record elevation changes at selected bench marks in the Buena Vista Hills area (U.S. Coast and Geodetic Survey, 1966, p. 5–6, 18); (4) horizontal movements between 1932 and 1959 relative to undefined network that includes the seemingly stable triangulation points Temblor, Spellacy, East, and Elk (Whitten, 1961, p. 318–319).

(Wilt, 1958, p. 169, 171); continuation of movement at about this rate is supported by observations between 1956 and 1967, which show that the average slippage rate during this interval was approximately 0.083 foot/year (Nason and others, 1968, p. 100).

The location of the fault trace (fig. 48 near the axis of maximum subsidence and the zero-horizontal displacement line (that is, the discontinuity between northerly and southerly directed horizontal displacement vectors) suggests that it lies within the zone of horizontal compression; thus thrust faulting, rather than normal or gravity faulting or simple fissuring, is reasonably expected here.

Neither Koch (1933) nor Wilt (1958) has suggested that the Buena Vista Hills faulting might be other than tectonic in origin. However, because both the subsidence and the horizontal movements have been attributed to oil-field exploitation by Whitten (1961, p. 319; 1966, p. 74), and because the sense of displacement on the fault is consistent with these measured movements, it is likely that the faulting is equally attributable to oil-field operations. This interpretation is supported by Koch's (1933, p. 709) observation with respect to the relatively surficial expression of the faulting: "it seems impossible that the shift in the center of the north flank of the [Buena Vista Hills] anticline could be less than the shift at or near the fault trace." Howard (1968, p. 750–752), moreover, has shown that the area within the southern (footwall) block immediately south of the fault trace has been characterized by extensional and dilatational strain; strain patterns of this type are completely inconsistent with regional tectonic compression.

Historic faulting in the McKittrick oil field has been described by Koch (1933, p. 711) and Yerkes and Castle (1970, p. 57). Koch (1933, p. 711) reported that buckling movements in a concrete highway 1 mile south of the town of McKittrick were proceeding "at the rate of about .8 inch per year." Movement apparently has persisted on this fault for many years, for it showed evidence of recent displacement when visited in 1969.

Surficial faulting associated with the development of the Kern Front oil field (Brooks, 1952; Hill, 1954, p. 11) is more akin to that in the Baldwin Hills than is that in the Buena Vista field. This faulting has been expressed chiefly as dip-slip movements along the probable surface trace of the Kern Front fault which, in turn, marks the east edge of the Kern Front oil field (Brooks, 1952, p. 159). The Kern Front field, moreover, has been identified with differential subsidence of more than 1 foot (Yerkes and Castle, 1970, p. 57). Movement on the fault apparently began no later than 1949 and has been characterized by cumulative displacements of up to 1.2 feet along a 3-mile trace, with downdropping toward the center of the oil field (Hill, 1954, p. 11; Brooks, 1952, p. 159; Yerkes and Castle, 1970, p. 57, 61). Although limits could be placed on the time of the initial major movement in 1949, the seismological stations at Berkeley and Pasadena recorded no seismic activity in the Kern Front area during this limited interval (Hill, 1954, p. 11).

Surficial fault displacements along the north edge of an Orange County oil field within the Los Angeles basin were first recognized in 1968 (Yerkes and Castle, 1970, p. 58). These displacements, which were apparently confined to a single, steeply dipping reverse fault trending at a high angle to the field boundary, ranged up to about 0.2 foot along a surface trace of about 0.22 mile (Yerkes and Castle, 1970, p. 58). No shocks were recorded by the Seismological Laboratory at Pasadena within 20 miles of this location during the month preceding and month following the earliest probable recognition of this faulting on or about October 1, 1968 (J. M. Nordquist, oral commun., 1968).

Several examples of subsurface faulting associated with oil-field operations have been described from the Los Angeles basin. The most unequivocal case of subsurface faulting attributable to exploitation has been recognized in the Wilmington field. According to Frame (1952, p. 5) "nearly horizontal earth movement on two main slippage planes" has taken place within the Wilmington field; "these planes consist of thin shale beds about seven or eight feet thick*** at average depths of 1,550 and 1,700 feet." Resulting oil well damage has been confined to the central part of the subsidence bowl (Frame, 1952, pl. I), but, as shown by Grant (1954, p. 20), it seemingly lay athwart the inflection line—that is, damage occurred within parts of both the extensional and compressional horizontal strain zones measured at the surface (Frame, 1952, pl. I; Grant, 1954, p. 20).

The Wilmington displacements apparently occurred chiefly as sharply defined movements in December 1947, November 1949, August 1951, September (?) 1951, and April 1961 (Frame, 1952, p. 7; Bailey, 1961, p. 118). These movements were accompanied by local earthquakes recorded at Pasadena, 28 miles away, as distinctive seismograms characterized by a relatively large development of long-period motion of a sort attributed to shocks of shallow focus (Richter, 1958, p. 155–156). The maximum horizontal displacements associated with the 1947 and 1949 movements were both about 9 inches (Frame, 1952, p. 7, 9); the maximum 1951 and 1961 displacements are unknown. We have been unable to determine the sense of movement along the slip planes; the upper plate probably moved outward from the center of subsidence (with respect to the underlying block), thereby reducing the accumulated contractional strain observed at the surface (Yerkes and Castle, 1970, p. 60–61) and inferred to extend to depth. This conclusion seems to accord with the views of Grant (1954, p. 22–23). Richter (1958, p. 155), on the other hand, has attributed the movements to "slumping on an enormous scale, incidental to subsidence." In any case, the clearly defined spatial association and less specifically defined temporal association between this faulting and the exploitation-induced subsidence and horizontal movements, leave little doubt that the faulting is

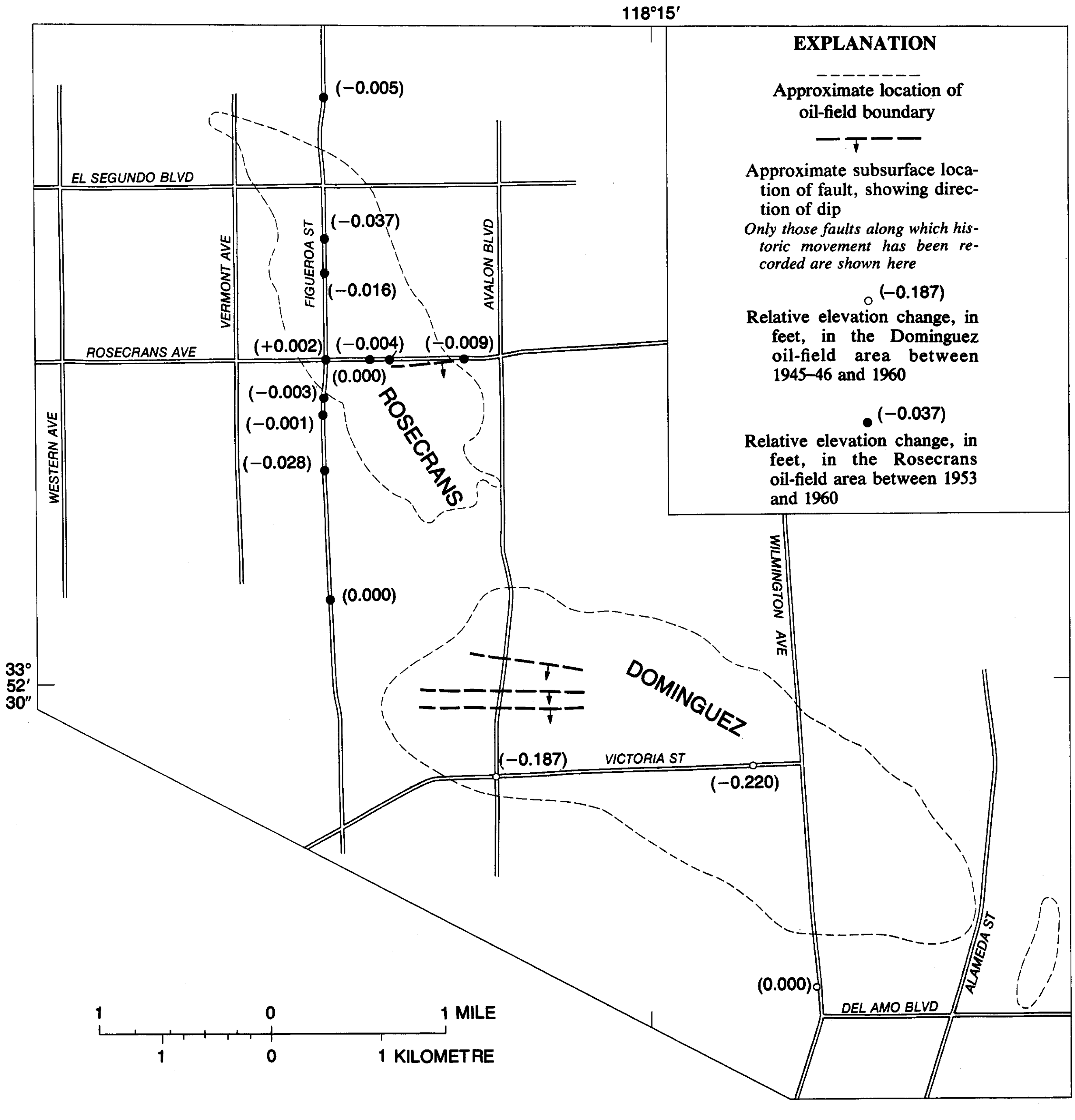


FIGURE 49.—Map of part of the western Los Angeles basin showing (1) Approximate boundaries of the Dominguez and Rosecrans oil fields (California Division of Oil and Gas, 1961, p. 552, 664, 648); (2) location at depth (between 5,000 and 7,000 feet below sea level) of faults along which subsurface displacements are reported to have occurred during historic time (Bravinder, 1942, p. 392; Martner, 1948, p. 112); (3) elevation changes calculated through a comparison of record elevations given for the Dominguez oil field area by the U.S. Coast and Geodetic Survey for 1945–46 and the Los Angeles County Road Department for 1960 and the Rosecrans oil field area by the City of Los Angeles Bureau of Engineering for 1953 and 1960.

equally attributable to the exploitation of the Wilmington oil field.

The only other reported examples of subsurface faulting associated with oil-field operations occurred within the Dominguez (Bravinder, 1942) and Rosecrans (Martner, 1948) oil fields (fig. 49), about midway along the onshore section of the Newport-Inglewood zone. Surface subsidence has been slight over the Dominguez field and almost unmeasurable over the Rosecrans field (fig. 49); it is likely that any centripetally directed horizontal surface displacements have been correspondingly small.

Subsurface fault displacements in the Dominguez oil field occurred on October 21, 1941 (after 18 years of production) and ranged up to at least 7 inches (Bravinder, 1942, p. 388, 391); the displacement or "deflected movement" in the Rosecrans oil field took place on June 18, 1944 (after about 20 years of production) and amounted to "a few inches maximum" (Martner, 1948, p. 105, 116). In neither example is the sense of movement known. Well damage in both fields seems to have occurred chiefly at depths of 5,000–6,000 feet, well above the lowest producing zones (Bravinder, 1942, p. 391, 393–395; Martner, 1948, p. 110–111; California Division of Oil and Gas, 1961, p. 553, 645). The subsurface displacements in both oil fields, moreover, were also associated with earthquakes. However, unlike those that occurred in the Wilmington field, these "earthquakes appear to have originated at the usual depth of about 16 kilometers" such that "the damaging displacements must have been triggered, either by the direct shaking of the earthquake or by the readjustment of the local strain pattern" (Richter, 1958, p. 156). If the strain system relieved by faulting can be attributed to compaction of the producing zones, it should be best developed above the lowest of these zones. Because major well damage and, by inference, maximum displacements, seem to have occurred well above the deepest producing zones, it is likely that the postulated preearthquake strain pattern derived in part from exploitation of the two fields. The limited surface deformation may stem from the resistance to collapse imparted to the entire geologic section by the strong arching shown in both the Dominguez and Rosecrans anticlines (California Division of Oil and Gas, 1961, p. 552, 644).

MECHANICAL BASIS

The generation of the earth cracks may be explained by two separate but conceptually complementary schemes, identified here as the horizontal-tension and elastic-rebound compaction models. Both models are consistent with the existence of a marginal zone of extensional horizontal strain around a recognized subsidence bowl; both are consistent, therefore, with the existence of the vertical and horizontal movement pattern identified in the Baldwin Hills (see section on "Movements Attributable to Oil-field Operations" and Yerkes and Castle, 1970, p. 60–65). It is only the second or elastic-rebound model, however, that seems to explain fully the nature of the observed fault displacements. Because both models require the existence of a surface strain pattern attributable to oil-field operations, their construction is ultimately dependent on the exploitation of the Inglewood oil field.

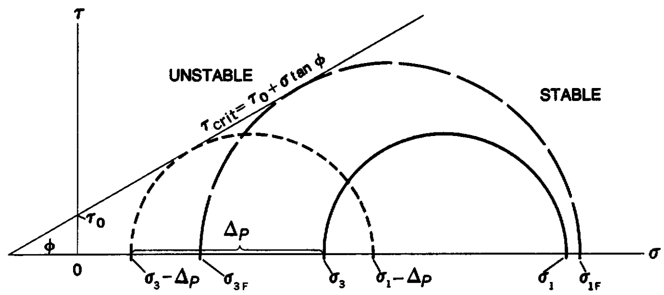


FIGURE 50.—Mohr diagram showing hypothetical states of stress at depth, where: σ = normal effective stress; τ = shear stress; σ_1 = greatest principal effective stress; σ_3 = least principal effective stress; τ_0 = cohesive shear stress; τ_{crit} = shear stress at failure; and ϕ = angle of internal friction. Solid circle shows initial stress conditions. Dashed circle shows stress conditions at failure resulting from increased deviator stress—specifically, an increase in σ_1 and a simultaneous decrease in σ_3. Dotted circle shows stress conditions at failure resulting from fluid pressure increase (Δp) with no change in the deviator stress.

The horizontal-tension compaction model predicts the occurrence of ruptures along steeply dipping surfaces oriented normal to the maximum strain axes (and, hence, to the horizontal displacement vectors, as well) within the zone of extensional horizontal strain; it depends ultimately on stress relations at depth as deduced from the evolving surface strain pattern. We can only speculate on the stress conditions that existed as exploitation began, and can be certain only that they must have been changing as it progressed. However, the contemporary faulting has been generally normal; thus we infer that during some undefined period preceding failure, the greatest principal effective stress, σ_1, was oriented approximately vertically, and the least principal effective stress, σ_3, was approximately horizontal and normal to the strike of the specified fault (Hubbert, 1951). Reductions in σ_3 compel corresponding decreases in normal stress and increases in tangential stress; because increasing extensional horizontal strain must be accompanied by reductions in similarly directed stress, continuing extension ultimately will result in the reduction of σ_3 to some threshold value at which failure will occur (fig. 50). If, as in this example, σ_1 is vertical, faulting will occur ideally on surfaces dipping at 45° + $\phi/2$ (Hubbert, 1951, p. 362–364).

The chronology of cracking seems to fit the horizontal-tension model, for none of the earth cracks had been certainly recognized as surficial fault displacements before 1957, some time after the horizontal strain pattern had become well established. Furthermore, because the identified faults dip generally toward the center of the subsidence bowl, the fact that most of the downdropped blocks lie toward the center of the bowl is consistent with continuing extension and resultant reductions in σ_3. However, the vertical rebound associated with the exterior blocks (that is, those away from the center of the bowl—see below) remains unexplained and must result from the operation of some complementary, unspecified mechanism.

D. R. Brown (oral commun. 1961) has suggested that the cracking and associated fault displacements may have originated as a rebound phenomenon related to the release of elastic strain energy accumulated in association with subsurface compaction. Essentially the same model has been more recently proposed by the California Department of Water Resources (1964, p. 60) to explain displacement along the rupture designated here as crack IX.

The elastic-rebound compaction model requires that compactive or compressive elastic strain energy be accumulated in the marginal blocks around the subsiding oil field as a result of downdrag by the more or less inelastically compacting interior blocks; its principal features are illustrated in figures 50 and 51. Because all, or nearly all, of the reservoir compaction has been confined to the Vickers zone, the effects of any exploitation-induced strain beneath the Vickers zone may be disregarded. We infer again, moreover, that during some finite period preceding failure, σ_1 was approximately vertical and σ_3 was contained within the horizontal and oriented normal to the strike of the identified fault. According to this model, then, as subsidence proceeded within the central part of the compacting oil field, and as extensional horizontal strain continued to increase around the periphery of the field, vertically directed elastic strain tended to increase within the marginal blocks. Thus with continuing fluid extraction and resultant compaction, σ_3 continued to diminish (in association with increasing extensional horizontal strain) while σ_1 increased simultaneously (in association with increasing vertically directed elastic strain) within the marginal parts of the oil field. Both effects tended to enlarge and displace Mohr's stress circle to a position of tangency with Mohr's failure envelope (fig. 50), whereby faulting should occur along steeply dipping surfaces containing the intermediate principal effective stress (Hubbert, 1951, p. 359–364). Thus at some unknown time, but probably at least as early as 1951 and certainly no later than 1957, radially oriented extensional horizontal strain is inferred to have increased to the point that frictional resistance to movement along certain favorably oriented potential failure surfaces was locally overcome by increased tangential stress, due both to reduction of the least principal effective stress and increased vertically directed elastic strain within the marginal blocks, and rupture and displacement of the exterior blocks ensued.

The sense, magnitude, and chronology of the displacements observed along the earth cracks are generally consistent with those predicted by the elastic-rebound model. According to this model, compactive strain (including surface strain) may be viewed as having accumulated within an array of vertical surfaces radiating outward from the approximate center of subsidence, curving only so as to remain parallel to the isobase gradient, and thereby parallel to the horizontal-displacement vectors. Hence any elastic strain release should occur largely within these vertical surfaces with little or no movement at right angles; the generally dip-slip nature of the reported displacements clearly meets this expectation. In those very few cases in

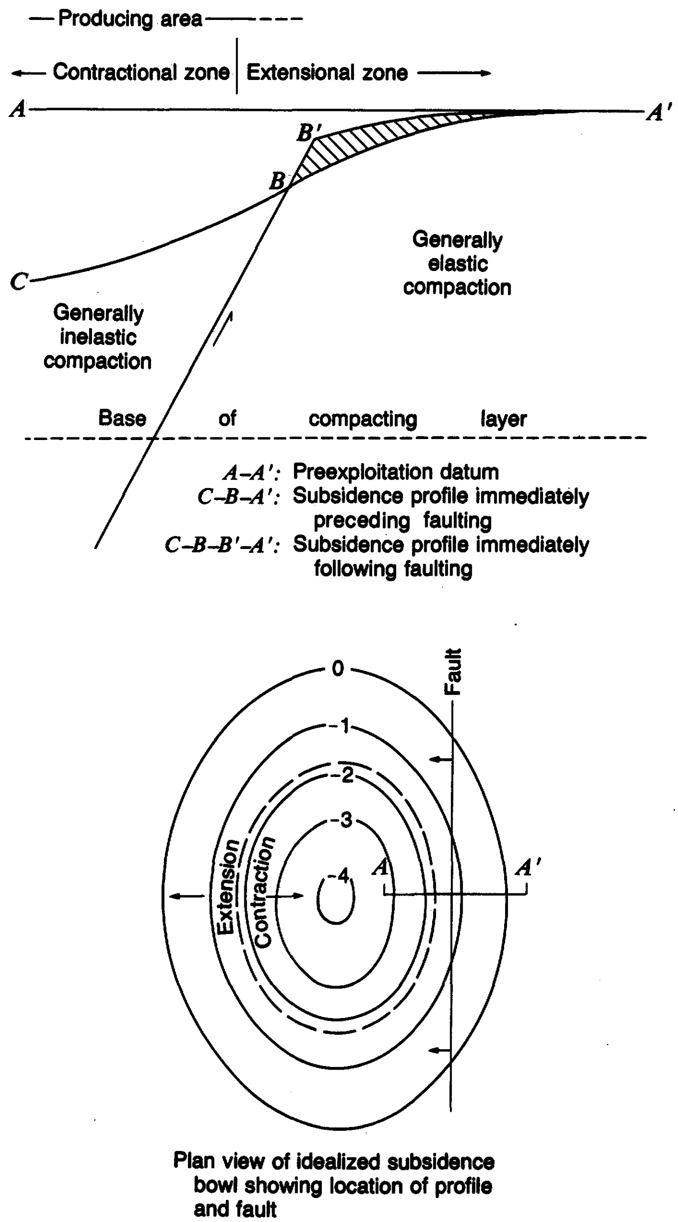


FIGURE 51.—Idealized dimensionless profile showing rebound of elastically compressed block located largely or completely beyond the oil-field producing area but within the zone of extensional horizontal strain around the periphery of the subsidence bowl.

which measurable lateral movements have occurred, the sense of lateral motion has been mechanically compatible with the postulated model. Thus where the strike of an established displacement surface and the trend of the immediately adjacent isobases depart significantly, any fault-block motion should parallel the maximum horizontal strain axis and thus lead to a component of lateral slip toward the center of subsidence. Left-lateral movement on crack IX is an example of this type of slip.

The elastic-rebound model predicts that the downdropped fault blocks should lie toward the center of subsidence and that the peripheral blocks should be uplifted (with respect to control points adjacent to the area of recognized differential subsidence) following rupture. Movements developed along the Baldwin Hills earth cracks generally meet these predictions. The only cracks along which the displacements seem to have been the reverse of that predicted by the model are cracks III and IV near the Stocker Street–La Brea Avenue–Overhill Drive intersection (pl. 2). However, cumulative displacement along both these cracks has been no more than about 1½ inches (California Department of Water Resources, 1964, pls. 17a and 17b), as contrasted with combined displacements of about 10 inches or more along cracks I and II or cracks IX or X. Furthermore, cracks III and IV occur within the western periphery of the subsidiary subsidence bowl developed in the southern part of the eastern block; thus downdropping to the east is construed as consistent with the elastic-rebound model.

The minimum cumulative rebound at the reservoir gate tower bench mark during the period June 1949–January 1964 may be calculated by summing the positive increments shown by the upward jogs in the settlement curve (fig. 25) (which we infer to be expressions of rebound); this summation leads to a figure of 0.318 foot. The additional rebound that probably occurred and would have been measured had elevation measurements been recorded continuously, is estimated to have been at least 0.13 foot. Thus the minimal total rebound of 0.45 foot immediately east of crack IX very nearly matches the vertical separation, 0.50–0.58 foot, along crack IX that must have occurred during this same interval (roughly the life of the Baldwin Hills Reservoir). This very close correspondence between measured displacement and vertical rebound measured immediately east of the fault supports the conclusion that the displacement is nearly exclusively the product of vertical movement of the eastern block only, and hence is clearly consistent with elastic rebound of the peripheral block.

The available data indicate that the magnitudes of the displacements measured along the earth cracks are compatible with those predicted by the elastic-rebound model. The validity of the comparisons between subsidence and rebound outlined below rests on the assumption that the elevations of the interior blocks, immediately adjacent to the earth cracks, remained unchanged during episodes of actual fault movement. This assumption is supported by: (1) the fact that the west end of the level circuit athwart crack IX remained unchanged in elevation between November 1963 and January 1964 (see fig. 27); (2) the excellent correspondence between measured displacement (vertical separation) on crack IX and estimated vertical rebound of the east block adjacent to this crack (see above); and (3) the general occurrence of the cracks beyond the oil-field production limits, such that there should be little tendency toward further compaction and resultant drop of the interior blocks during episodes of displacement.

The patterns of average annual elevation change shown on plate 4 suggest that between 1950 and 1958, a period of relatively uniform although slowly decelerating subsidence, cumulative subsidence immediately east of crack IX (pl. 2) was about 22 percent of that at the center of subsidence. This figure, however, is uncorrected for the likelihood that the block east of crack IX experienced small increments of rebound during this interval (fig. 25). A more realistic figure may be obtained by adding together: (1) the measured positive increments at the gate tower bench mark between March 1950 and October 1958 (0.088 foot); (2) an amount (0.071 foot) based on the probability that rebound occurred instantaneously rather than over the full intervals between levelings, and that subsidence continued over these intervals at rates approximating those of the smoothed subsidence curve; and (3) the total measured elevation change (0.425 foot) between March 1950 and October 1958. This sum is then compared with the subsidence at the center of the bowl over the same interval (see appendix H). The result indicates that between 1950 and 1958 subsidence at the reservoir gate tower bench mark was actually about 37 percent of that at the center of the bowl. Thus, if the cumulative subsidence at the center of the subsidence bowl between 1911 and 1964 was about 5.67 feet, there should have been about (0.22) (5.67 feet) = 1.25 feet or, more likely, (0.37) (5.67 feet) = 2.10 feet of subsidence immediately east of crack IX during this period. A similar calculation based on the single measurement interval 1950–54 shows that the maximum probable subsidence immediately east of crack I between 1911 and 1964 was about 1.8 feet. Therefore, according to the elastic-rebound model, the maximum expectable vertical separations along cracks IX and I between 1911 and 1964 should have been about 1.25 or 2.10 feet and 1.8 feet, respectively. The cumulative vertical separations actually measured along both cracks IX and I through 1963 were about 0.50–0.58 foot, or approximately one-half to one-quarter the predicted maximums; this fractional figure is necessarily based on the implicit assumption that any displacements generated prior to 1950 (and thus preceding construction of the Baldwin Hills Reservoir) were trivial.

Displacements or vertical separations well below the maximum expectable values are almost certainly due either to incomplete recovery by the end of 1963 or the only partly elastic compression of the exterior blocks. Thus the fractional amounts of the maximum expectable recovery (or displacement) actually recorded by the end of 1963 are consistent with those to be expected in a highly compressed, water-saturated, and probably poorly drained sedimentary column. Displacements matching or in excess of the predicted maximum values would seriously dispute the elastic-rebound model.

Castle, Yerkes, and Youd (1973, p. 39–43) have calculated stress changes beneath the Baldwin Hills Reservoir associated with the first 30 years of production and resultant compaction in the Inglewood oil field. The calculated changes are based on measured surface strains within the reservoir area and conservative but realistic values for the modulus of elasticity; these stress changes are thus believed to approximate those that occurred during this same 30-year period along the subsurface projection of crack IX (pl. 2). Necessary assumptions involved in the calculations are: (1) that fluid pressures remained unchanged outside the producing area of the oil field; (2) that no compaction occurred below a depth of 2,500 feet, the approximate base of the Vickers zone; and (3) that the preexploitation horizontal to vertical effective stress ratio (σ_h/σ_v) was 0.5. The results of this simple analysis show that stress conditions consistent with failure, where $\sigma_h/\sigma_v<1/3$, were achieved after 30 years of production down to depths of at least 1,000 feet and probably down to 1,600 feet or more. These calculations thus support indirectly the probable operation of either compaction model, particularly the elastic-rebound model, during the primary recovery phase of exploitation—that is, through the period prior to any waterflooding.

Several possible objections to exploitation-based explanations for the earth cracks are almost self-evident. The most valid of these objections arises from the general restriction of the earth cracks to the east block. This restriction may be no more than apparent, however, and the cracks may not be virtually confined to the east block but may be simply more conspicuous there owing to the relative abundance of paved surfaces, curbings, and other cultural features. They are, nevertheless, certainly concentrated in the area east of the Inglewood fault.

The areal restriction of the earth cracks probably can be attributed chiefly to both the density and the apparent concentration within this same area of steeply dipping faults and joints (pl. 2) oriented more or less normally to the inferred axes of radially oriented strain. Preexisting fractures of this disposition are especially susceptible to compaction-induced failure. Fractures similarly situated with respect to the subsidence bowl also occur in the extreme northwest part of the area (west-southwest of the La Cienega Boulevard–Jefferson Boulevard intersection—pl. 2). However, because there has been relatively little construction there, surficial faulting or cracking might go undetected.

Limitations on fluid migration in the east block provide a second possible explanation for the areal restriction of the earth cracks. Compression of a fluid-saturated reservoir will lead to compaction of the fluid column as well as that of the reservoir skeleton, provided only that no path exists for escape of the fluids, such as laterally along the reservoir beds or out through a producing well. Thus, the vertical recovery potential of the compressed but undrained reservoir should, owing to the increased expansive capacity of the compressed fluid, exceed that of the drained reservoir. Because the east block is much more highly faulted and hence less easily drained than the west block (pl. 2 and figs. 3 and 4), particularly with respect to areas beyond the productive limits of the oil field, elastic rebound is much more apt to occur east of the Inglewood fault.

The initial restriction of waterflooding to the east block has almost certainly accounted in part for either the localization or chronology of movement on the spatially associated earth cracks. Flooding operations, moreover, may have contributed to the cracking and faulting in two conceptually distinct but effectively similar ways.

The disproportionately large deceleration in subsidence and compaction rates in the east block only during the 1958–62 interval is attributed to the injection of disproportionately large volumes of water during this same interval (see p. 39 ff, on "Movements Attributable to Oil-field Operations"). Thus the increasing contrast during this interval in subsidence and compaction rates between the major blocks must have generated disproportionately steepened isobase and compaction gradients over a limited reach of the east limb of the subsidence bowl; we infer that these steepened gradients compelled an increase in the radially oriented extensional horizontal strain developed in the east block to levels generally above those that prevailed elsewhere around the subsidence bowl. Because the probability of rupturing predicted by both the horizontal tension and elastic-rebound compaction models increases with increasing extensional strain and decreasing σ_3, preferential development of the earth cracks in the east block through at least 1963 was certainly a reasonable expectation (Castle and others, 1973, p. 34–35).

The second way in which waterflooding probably has contributed to surface rupturing is through the elevation of pore-water pressures at depth (Hamilton and Meehan, 1971). We have disregarded the effects of changing reservoir fluid pressures on stress conditions in the preceding analyses of faulting, chiefly because such changes have been generally negative and, hence, have decreased the likelihood of faulting (see below). Increasing fluid pressures, however, tend to promote instability and an increased likelihood of faulting. Because fluid pressure is a scalar, and thus directionally independent quantity, application of the principle of effective stress (see section on "Movements attributable to oil-field operations") indicates that increased fluid pressure should result in uniform reductions in the principal effective stresses. It is easily shown through use of a Mohr's diagram in which the coordinate system is defined in terms of effective compressive stress, that uniform reductions in the principal effective stresses compel displacement of the stress circle toward tangency with the failure envelope (fig. 50). Since the deviator stress remains unchanged, this displacement occurs without any concomitant increase in the diameter of the stress circle. Thus decreased stability must derive from the diminished normal stresses that tend to promote frictional resistance to movement (shearing resistance) and, unlike the effect of simply reducing the least principal stress, can in no way be attributed to increased shear stress.

Hamilton and Meehan (1971) have examined the relation between waterflooding and contemporary faulting in the Inglewood oil field and conclude that the faulting is causally related to increased reservoir fluid pressures due to flooding operations. Thus, according to Hamilton and Meehan (1971, p. 339–340), at least two episodes of fault movement along crack IX (deduced from leveling records and the monitored growth of cracks along the trace of this rupture) closely correlate with flooding operations in both space and time. Furthermore, "all recorded episodes of fault movement since 1957 have occurred *after* one or more of the following: initiation of injection in nearby wells, increases of injection pressure, or problems such as dropping fluid pressure concomitant with increases of fluid take, loss of fluid in narrow zones, and so on" (Hamilton and Meehan, 1971, p. 340). The likelihood that artificial elevation of reservoir fluid pressures may have provoked faulting is enhanced by the generation of injection pressure gradients well above the minimal 0.64 psi/foot cited by Hubbert and Willis (1957, p. 162) as necessary for hydraulic fracturing in areas of incipient normal faulting. Hamilton and Meehan (1971, p. 338) show, in this connection, that injection gradients of 0.8 psi/foot or more commonly have been generated in Vickers East flooding operations; this observation is supported by the 0.95 psi/foot maximum operational gradient reported by Oefelein and Walker (1964, p. 512). In any case, massive increases in reservoir fluid pressure may have been unnecessary; any increase in fluid pressure would act to decrease shearing resistance and to increase the probability of faulting.

In spite of the several suggestive associations between waterflooding and cracking, it is unlikely that the localization of the faulting can be attributed solely or even largely to the effects of injection (Castle and others, 1973). Although fully documented evidence of surface cracking dates only from 1957, reports of rupturing along crack I date from 1949 and 1955, and permissive, yet virtually compelling evidence of faulting along crack IX dates from 1951 (see section on "Earth cracks and contemporary fault displacements" and figs. 25 and 26). Moreover, direct evidence of dip-slip movement along crack X also dates from as early as 1951 (see section on "Earth cracks and contemporary fault displacements" and California Department of Water Resources, 1964, pls. 25a and 25c). Waterflooding operations, however, were not begun on even a pilot scale until 1954. Furthermore, although we have no specific data on injection pressures developed during the pilot floods, of the nine injectors known to have been operative at the end of 1957, only two were injecting at gradients above 0.5–0.6 psi/foot (Hamilton and Meehan, 1971, p. 338). Hence it is unlikely that the relatively high gradients of 0.8 psi/foot or more that became commonplace in later years were widely employed before 1958. Moreover, because the nearest pilot injector was separated from crack I by 2,000 feet and several steeply dipping faults (pl. 2), it is very unlikely that the limited injection through 1955 (1,638,484 bbls—see tables 2 and 3) could have provoked the reported rupturing along crack I in 1955. Thus waterflooding is inferred to have accelerated or aggravated a process already in operation and cannot be identified as a major factor in either the activation of the "earth crack" faults or their localization in the east block. Several additional lines of inquiry support this conclusion:

Hamilton and Meehan (1971, p. 338) cite the seemingly striking correlation between the first explicitly documented movement on crack I in May 1957 and the start of flooding in a nearby injector in the same month as evidence that faulting has depended largely on fluid injection at elevated pressures. Close examination of this and similar correlations, however, challenges their implied significance.

According to F. J. Converse, clearly defined cracking along the trace of crack I appeared "early in May, 1957" (S R. Powers, written commun., 1970). Because the indicated injector (Baldwin Cienega–Stocker–LW 281—pl. 2) was placed in operation on May 12, 1957 (Castle and others, 1973, p. 30), this rupturing may have actually preceded the initiation of flooding here. In any case, even if injection had been under way for 3 or 4 months, the lifetime average injection rate for this well of 1,150 bbls/day (Castle and others, 1973, p. 30) suggests that no more than about 100,000 bbls could have been injected before clearly recognized movement began on crack I. This postulated 100,000-bbl volume is certainly insignificant as compared with: (1) the 4.5 million bbls introduced into the Vickers East during the pilot floods; (2) the nearly maximum annual Vickers East injection of 13 million bbls reached in 1961 (Musser, 1961, p. 111); or (3) the approximately 85 million bbls of oil and water and 22 million Mcf of gas extracted from the Vickers East alone before flooding began (as deduced from fig. 32 and Oefelein and Walker, 1964, p. 509). This conclusion takes on even greater significance when it is perceived that: (1) initial injection pressure gradients averaged 0.5–0.6 psi/foot; and (2) injection was conducted under "full-scale" conditions through a section many hundreds of feet thick in which reservoir fluid pressures at 1,300 feet below sea level had declined from an estimated initial value of 570 psi to measured values of 20–100 psi at the start of flooding (see fig. 33 and Oefelein and Walker, 1964, p. 510). Reservoir pressures in simple, finite systems vary directly with increasing volumes of introduced water; hence threshold fluid pressures necessary for failure (faulting) are less readily achieved with the introduction of a fixed volume of water where the initial reservoir pressures are, as in this case, very low. Thus to admit that the injection of 100,000 bbls of water into the pressure-depleted Vickers zone could have provoked movement over a surface on the order of 10^6–10^7 ft^2 simply supports the conclusion that compaction-induced failure had been so closely approached by May 1957 that even very local and otherwise trivial reductions in shearing resistance could trigger faulting. We note in passing, moreover, that the only other injector operating south or east of the pilot floods in May 1957 was BC–LAI–LW 240 (pl. 2); injection began in this well on April 22, 1957 (California Division of Oil and Gas, unpub. data). Because BC–LAI–LW 240 is more than 2,000 feet west of crack I and is separated from it by several steeply dipping faults, it is unlikely that injection through this well could have influenced fluid pressures along the subsurface projection of crack I.

(2) Although flooding was not begun in the west block until 1962, it increased rapidly thereafter. By the end of 1969, flooding in the combined Vickers West-Rindge zones was proceeding at an annual rate of 32,360,506 bbls and cumulative injection had reached 147,468,809 bbls (California Division of Oil and Gas, 1969, p. 101). Flooding operations by the end of 1969, moreover, covered nearly the entire producing area of the west block (Munger Map Book, 1970, p. 165). We have no data on injection pressures utilized in the west block; we assume that they matched approximately those generated in the Vickers East flooding operations.

In spite of the large and apparently expanding waterflooding program (and other secondary recovery operations), the only example of surface rupturing reported from the west block is crack XIII (pl. 2). This crack, which apparently developed around 1960 (Hamilton and Meehan, 1971, p. 341), is atypical, however, in that it trends toward the center of the subsidence bowl and has not been associated with any differential movement. Hamilton and Meehan (1971, p. 341) argue that rupturing along crack XIII is due to increased fluid pressures generated in response to injection through two nearby disposal wells; however, the maximum volume of water that could have been introduced through these wells by the end of 1961 was 202,149 bbls (Musser, 1961, p. 115). Thus if we infer that waterflooding was a major factor in the surficial faulting around the Inglewood field, the injection of 147 million bbls by the end of 1969 (which contrasts significantly with the 8 million bbls injected in the Vickers East through 1957, or even the 73 million bbls injected through 1963—Musser, 1957, p. 83; California Division of Oil and Gas, 1963, p. 102) should have induced at least some additional rupturing in the west block.

(3) Among the 15 domestic oil fields for which we have evidence of historic faulting (see preceding discussion), waterflooding accompanied or preceded faulting in only one other field. Thus the general absence of contemporary flooding or other secondary recovery operations in most of these fields indicates that waterflooding cannot be invoked as a general explanation for faulting associated with oil-field operations. Parenthetically, experience in the Wilmington field suggests that waterflooding may actually inhibit faulting, either by preventing the accumulation of additional elastic strain or by permitting an alternative form of relief for that already accumulated (Castle and others, 1973, p. 39).

A possible objection to models that attribute the rupturing and displacements entirely to the effects of oil-field operations derives from the recognition of relative uplift southeast of the area of previously recognized differential subsidence. If these positive movements are indeed unrelated to exploitation, and if it can be assumed that their magnitude remains unchanged as projected northward into the southeastern part of the Inglewood field, these movements suggest that comparable increments of differential uplift adjacent to crack I (pl. 4 and figs. 14 and 15) may be equally unrelated to exploitation. Thus the prerupture isobase gradient may not be due entirely to exploitation-induced differential subsidence. Because both the horizontal-tension and elastic-rebound models require the achievement of some critical, threshold isobase gradient in order for rupture of occur, there exists some possibility that the rupturing may be due in part to phenomena other than exploitation of the Inglewood oil field. (If these postulated, relatively positive movements were of regional rather than local scope and projected undiminished northward through the entire Baldwin Hills area, they would be of no significance in this context, for this would result simply in uniform elevation of the entire system.)

Direct evidence of relatively positive vertical movements southeast of the area of previously recognized differential subsidence is very limited. Positive vertical movements in excess of 0.01 foot/year, with respect to both Hollywood E–11 and PBM 1, were recognized during the 1958–62 interval in the area extending southeast from Slauson Avenue near Overhill Drive (pl. 4 and fig. 11). Although this area lies beyond the clearly recognized differential subsidence bowl defined by the 1950–54 surveys (pl. 4 and fig. 11), it has not yet been determined whether comparable movements occurred here before 1958. Permissive evidence of such movement derives from the history of vertical movement at PBM 10 (fig. 11), located about 1,200 feet west-northwest of the Slauson Avenue–Overhill Drive intersection (Walley, 1963, fig. 1), and thus about 1,000 feet inside the oil field (fig. 3). During the period 1939–54, PBM 10 subsided at an average rate of about 0.004 foot/year with respect to PBM 1 (fig. 3), a rate 0.01–0.03 foot/year less than that shown by other similarly situated bench marks around the Inglewood oil field. That PBM 10 was subsiding no more rapidly than 0.004 foot/year prior to the recognition of any earth cracks, suggests the occurrence of otherwise unexplained relative uplift in this area.

Although the rebound east of crack I can be fully explained by compaction at depth (see also Deere, 1961, p. 62–63; Lee and Strauss, 1970), the possible occurrence of positive vertical movements of as much as 0.02 foot/year (with respect to PBM 1) within the differential subsidence domain and unrelated to oil-field operations, suggests that a small fraction of the prerupture isobase gradient and associated strain may be unrelated to exploitation. It is unlikely, however, that this fraction could have exceeded the fractional contribution of the postulated positive movements to the average prerupture isobase gradient within the differential subsidence bowl. That is, it is unlikely that it could have been greater than<0.02 foot per year/>0.19 foot per year (compare pl. 4 and fig. 11). This fraction, accordingly, should have been insignificant in the absence of the exploitation-induced differential subsidence.

CONCLUSION

The earth cracks and associated displacements can be reasonably attributed largely or entirely to the exploitation of the Inglewood oil field, as indicated by the following points: the spatial and temporal associations between the earth cracks and both oil-field operations and exploitation-induced subsidence; the similarities in occurrence between these ruptures and displacements and those developed in and around other oil fields; and theoretical considerations which argue that these ruptures and displacements are consistent in form and magnitude with those expectable around the margins of artificially generated subsidence bowls.

MOVEMENTS ATTRIBUTABLE TO CHANGES IN GROUND-WATER REGIMEN

Land subsidence and associated surface deformation due to the extraction of ground water have been recognized in a number of areas around the world, including many in California (Poland and Davis, 1969). Several of these areas, moreover, occur within the Los Angeles basin (Estabrook, 1962, p. 7–8, fig. 1; Miller, 1966, p. 274–275; Gilluly and Grant, 1949, p. 494–497).

GROUND-WATER DEVELOPMENT IN THE BALDWIN HILLS AREA

Systematic exploitation of the ground-water resources of the Los Angeles coastal plain probably began about 1870 (Poland and others, 1959, p. 99); it apparently proceeded rapidly, for Mendenhall (1905, p. 14–15) has indicated that by 1905 formerly flowing wells located near the north end of the Newport-Inglewood zone had ceased to flow and "cheaper" artesian water could no longer be obtained. Poland, Garrett, and Sinnott (1959, p. 99) conclude that a significant increase in ground-water draft in the northwestern Los Angeles basin began sometime after 1919, but detailed data on withdrawals between 1904 and 1930 are unavailable. Ground-water withdrawals between 1931 and 1945 in the Torrance-Inglewood area, south of the Baldwin Hills, and in the Culver City area, north and west of the Baldwin Hills, reached annual maximums of 78,400 acre-feet in 1945 and 12,933 acre-feet in 1940, respectively (Poland and others, 1959, p. 6, 12, 106–107). Between 1934 and 1957 withdrawals from the West Coast basin, which equates roughly with the Torrance-Inglewood area of Poland, Garrett, and Sinnott (1959), reached an annual maximum of 94,100 acre-feet for the season 1952–53, and withdrawals from the Santa Monica basin, which equates roughly with the Culver City area of Poland, Garrett, and Sinnott (1959), reached maximums of 12,000 and 12,400 acre-feet during the 1939–40 and 1950–51 seasons, respectively (California Department of Water Resources, 1962, p. 38–39, 71).

Declines in water table or pressure head probably accompanied withdrawals of ground water from many or most of the aquifers in the northwest Los Angeles basin. Poland, Garrett, and Sinnott (1959, pl. 15) show, for example, that water levels along the Newport-Inglewood zone southward from the Baldwin Hills declined 100–150 feet between the initiation of ground-water development and 1945. They also indicate for the area south of the Baldwin Hills that water levels in the "Silverado zone" declined a maximum of about 30 feet, and those in the shallower "200-foot sand" declined about 8 feet during the period 1933–41 (Poland and others, 1959, pl. 10); water-level declines in the "Silverado zone" immediately north of the Baldwin Hills apparently reached a maximum of about 30 or 40 feet during the somewhat longer interval 1933–45 (Poland and others, 1959, pls. 9 and 12). The California Department of Water Resources (1962, pl. 11C) has shown that over the period 1934–57, water levels in the shallow aquifers only declined a maximum of 30–40 feet in the area immediately west of the Baldwin Hills and about 80 feet both north and southeast of the hills. In short, the development of ground-water resources and resultant changes in ground-water regimen in the northwest Los Angeles basin locally have been both substantial and rapid—and possibly accelerated—during the period in which surface movements have been recognized in the northern Baldwin Hills.

Several considerations, however, indicate that water withdrawals and any attendant changes in ground-water levels have been both relatively insignificant and uniformly distributed within the Baldwin Hills area itself (see frontispiece). (1) Mendenhall's (1905, pls. V and VI) maps reveal concentrations of water wells north, west, and south of the Baldwin Hills; a map compiled some 40 years later (Poland and others, 1959, p. 6–9, pl. 2), shows a generally similar distribution of wells. Only four or five of the scores of water wells shown on these maps could be characterized as "lying within the Baldwin Hills," and even these few occur along the outermost periphery, rather than toward the interior of the hills. Thus there appears to have been relatively little withdrawal of ground water within the Baldwin Hills proper through at least 1943 and virtually no change in the distribution of development activity between 1904 and 1943. These generalizations are strengthened through consideration of progressively smaller areas centering in the hills. (2) Hydrographic contours on maps showing water levels and water-level changes have not generally been extended into the Baldwin Hills (Mendenhall, 1905, pl. 1; Poland and others, 1959, pls. 9, 10, and 12; California Department of Water Resources, 1962, pls. 11A, 11B, 11C, and 12). The absence of these contours, which probably reflects an absence of ground-water development, is consistent with the conclusion of Poland, Garrett, and Sinnott (1959, pls. 9 and 12) that the northern two-thirds of the Baldwin Hills is "largely non-water bearing." (3) The locally thick veneer of Pleistocene sands and gravels overlying much of the Baldwin Hills probably falls chiefly within the vadose zone; changes in the ground-water regimen within these materials are thought to have been minor.

The preceding generalizations may not apply to the "central graben," the structural block bounded by the Inglewood fault on the east and the roughly parallel series of faults 2,000–2,500 feet to the west-southwest (pl. 2). Several water wells, one of which (the Moynier well) was sited about ⅓–½ mile south of the north edge of the hills (Robertson and Jensen, 1926, p. 41, 43), have been drilled within the relatively low central graben area (see frontispiece). The Moynier well, located as far toward the interior of the hills as any known to us, passed "through the lowest Pleistocene conglomerate [and presumably into the clay-silt unit included here with the "Pico"] at 80 feet or 120 feet above sea level" (Robertson and Jensen, 1926, p. 41, 43). Horizontal projection of this "Pico"-Pleistocene contact southward toward the center of the hills suggests that the undifferentiated Pleistocene sands and gravels there may be as thich as 200 feet. These deposits probably are no thicker than 200 feet, however, for the lower Pleistocene so-called San Pedro Formation within the central part of the Inglewood field is represented as ranging from 0 to 200 feet in thickness (pl. 1). Moreover, even if the undifferentiated Pleistocene sands and gravels in the central part of the "graben" are as much as 300 feet thick, they occur largely within a long, dissected ridge about 1,000 feet wide and crop out at elevations of up to 330–340 feet, and thus about 100–150 feet above the surrounding drainageways. Hence, assuming the system to be unconfined, the ground-water table probably could not be naturally maintained at more than 200–250 feet above sea level anywhere within the central graben area, and maximum water-level decline could have been no greater than about 100–120 feet, even with complete evacuation of water. Within the area immediately north of the Baldwin Hills and west of the Inglewood fault, water levels declined about 30 feet in the shallow aquifers between 1934 and 1957, and about 20 feet in the "Silverado zone" between 1933 and 1945 (California Department of Water Resources, 1962, pl. 11C; Poland and others, 1959, pls. 9 and 12). These declines suggest that water-level declines within the central graben have been much less than 100 feet—provided only, as seems likely, that hydraulic continuity between these two areas is unbroken by faults or pinchouts (Castle, 1960) and, as also seems likely, that hydraulic gradients have been no greater than 50 feet/mile (Poland and others, 1959, pls. 9 and 12). This conclusion is supported by the California Department of Water Resources (1964, p. 43), whose studies indicate that the Pleistocene formations within "an area bounded on the west by La Cienega Boulevard, on the northeast by the toe of Baldwin Hills, and on the south by Stocker Street * * * have never been saturated, nor has there been any extraction of ground water from them."

Little is known regarding infiltration of ground water in the Baldwin Hills, but variations in the rates of infiltration may have induced local changes in ground-water levels. Seepage from the Baldwin Hills Reservoir, for example, decreased from about 23 gpm in 1951 to about 9 gpm in early 1963 and then increased again to about 13 gpm by December 1963 (California Department of Water Resources, 1964, p. 56). This seepage may have locally saturated or thoroughly wetted the immediately underlying materials, materials that probably were unsaturated before the reservoir was filled (California Department of Water Resources, 1964, p. 25). Infiltration from other sources, such as tract development, swimming pool leakage, and broken sewerlines may have equalled or exceeded that from the reservoir. However, because both climatic and cultural changes of the sort that might promote variations in infiltration have been felt more or less uniformly over the entire west basin, these variations should have been expressed equally uniformly over the entire area.

The preceding evidence indicates that there has been very little change in ground-water levels in the Baldwin Hills since 1900. Thus changes in ground-water level cannot be cited as likely explanations for the surface movements observed in the northern Baldwin Hills. This is not to suggest that there have been no changes whatever in local ground-water conditions. Whether the greatest conceivable changes in ground-water levels could have induced the observed movements is considered below.

SUBSIDENCE

Substantial declines in water table or pressure head have been recognized over the past several decades within the major aquifers underlying the lowland areas surrounding the Baldwin Hills. These aquifers, moreover, are correlative in part with the undifferentiated Pleistocene sands and gravels within the hills (fig. 2) that have been identified chiefly with the San Pedro Formation and, to a much lesser extent, undivided upper Pleistocene deposits (Poland and others, 1959, pls. 2 and 3). Thus, water-level declines of as much as 60 feet or more occurred within the shallow aquifers between 1934 and 1957, both northeast and southeast of the Baldwin Hills (California Department of Water Resources, 1962, pl. 11C), and declines of about 40 feet were measured within the underlying "Silverado zone" between 1933 and 1945, both southeast of the hills and immediately north of the northern scarp (Poland and others, 1959, pls. 9 and 12). Differential subsidence over these same areas, however, has been slight or nonexistent.

Annual elevation changes along that section of Manchester Boulevard overlying the areas of greatest water-level decline, at about the longitude of Crenshaw Boulevard, ranged from about 0.00 foot/year to +0.01 foot/year during the 1930's (fig. 5) and from less than −0.01 foot/year to about −0.02 foot/year between 1949 and 1955 (fig. 6). If these elevation changes are compared with those over nearly the entire length of Manchester Boulevard, it is clear that differential subsidence over the areas of greatest water-level decline during the 1930's was generally no greater than that elsewhere along Manchester Boulevard (except in the area 2 miles and more east of the Newport-Inglewood axis), and that between 1949 and 1955 it was about the same as that detected over the entire 6- or 7-mile reach examined here.

Similarly limited subsidence seems to have occurred east of Fairfax and north of Jefferson Boulevard, the area of greatest water-table or pressure-head decline north of the Baldwin Hills; reported subsidence there during the 1930's (fig. 5) averaged less than 0.01 foot/year, and that between 1949 and 1955 (fig. 6) was apparently less than 0.03 foot/year. The profiles of elevation change shown in figure 11 indicate that the average rates of subsidence in this area may have been even less than 0.01–0.03 foot/year; subsidence with respect to PBM 1 along La Brea Avenue between the north edge of the hills and Washington Boulevard during the period 1939–62 probably was nowhere more than 0.005 foot/year. Thus, although there seems to be some correlation between subsidence during the period 1949–55 with the area of greatest known pressure-head decline within the "Silverado zone" north of the hills, differential subsidence, as shown by a comparison of elevation changes along Washington Boulevard, probably was nowhere much greater than 0.01 foot/year. In any case, because differential subsidence over the areas of greatest drawdown within the aquifers surrounding the hills has been but a small fraction of that observed within the hills themselves, it is unlikely that the major subsidence in the northern Baldwin Hills can be attributed in any significant degree to reductions in ground-water levels within the local formational equivalents of the aquifers surrounding the hills.

It is very unlikely that water-level or artesian-head decline in the sands and gravels of the "central graben" has been as great as that in the area surrounding the Baldwin Hills. However, even if it is conceded that water-table reductions of as much as 120 feet may have occurred within the central graben area (see preceding section), it is nearly certain that this decline could not have generated surface subsidence of the magnitude measured in the northern Baldwin Hills. Thus, during the period 1933–45 artesian head within the 300-foot "Silverado zone" underlying Dominguez Gap north of Wilmington, declined about 30 feet; this head reduction was associated with 0.354 foot of subsidence over approximately the same interval (Poland and others, 1959, p. 144–145, pls. 9 and 12). If it is assumed: (1) that the materials underlying the aquifers in the Dominguez Gap and central graben areas are similar; (2) that the saturated thickness of the central graben "aquifer" was no greater than 120 feet; (3) that the water table in the central graben area was reduced through its entire 120-foot thickness; and (4) that decrease in geostatic load attributable to water loss was negligible, use of the subsidence-head-decline parameters associated with the extraction of water from the confined aquifers in the Dominguez Gap area permits the following calculation of the maximum conceivable subsidence in the unconfined "aquifer" of the central graben area: $[(0.354\text{ft}/300\text{ ft})/30\text{ft}][120\text{ft}][120\text{ft}/2] = 0.284\text{ ft}$.[12] Hence subsidence due to water-table decline probably could account for no more than about 1/20 of that actually measured over the central graben.

To conclude, it is very unlikely that changes in ground-water conditions have contributed significantly to the differential subsidence recognized in the northern Baldwin Hills, as shown by: the absence of any history of ground-water extraction; the probability that major changes in the ground-water regimen could not have occurred within the Baldwin Hills during historic time; the almost complete absence of measurable surface subsidence over areas of substantial water-table or pressure-head decline in aquifers correlative with the Pleistocene sands and gravels exposed in the Baldwin Hills; the probability that even the maximum conceivable water-table decline would have produced only a small fraction of the observed subsidence in the central graben area; and the absence of any spatial or temporal correlation between the observed subsidence and ground-water development within and around the hills. This conclusion, accordingly, supports that of the California Department of Water Resources (1964, p. 52, 57), who observe that "the formations underlying the Baldwin Hills are devoid of significant quantities of potable ground water, and hence pumpage from water wells has never posed a threat of land subsidence in this area."

There is almost no possibility that the Baldwin Hills subsidence is an example of hydrocompaction or "shallow subsidence" developed in response to infiltration of water into loosely compacted sediments, chiefly because there is no known source for broadly developed, selective infiltration centering on the northwestern section of the hills. Hydrocompaction, moreover, is unknown locally, and the sediments cropping out in the Baldwin Hills are in their mode of origin unlike those subject to this effect (Bull, 1964, p. Al; Lucas, 1965, p. 111–112).

HORIZONTAL MOVEMENTS

The symmetrical and orthogonal relations between the center of subsidence and associated isobases on the one hand, and the centripetally directed horizontal movements on the other hand (pl. 4), indicate that the subsidence and horizontal movements are causally related. Because the differential subsidence cannot be explained by changes in ground-water conditions, the centripetally directed horizontal movements are equally unexplained by such changes.

EARTH CRACKS AND CONTEMPORARY FAULT DISPLACEMENTS

The earth cracks developed in the northern Baldwin Hills occur not only within an area of generally "non-water-bearing" sediments, but also within what is probably the least "water-bearing" part of this area, for it is in the northern half of the east block that the potential water-bearing materials are thinnest. Thus the probability of any substantial changes in ground-water conditions in this very restricted area is even lower than that for the hills in general. Furthermore, because displacements along the earth cracks locally extend well into the underlying rocks, movements along these cracks probably are unrelated to changes in ground-water conditions in the overlying sands and gravels.

The occurrence of the earth cracks within a section of the northwestern Los Angeles basin in which there has been no significant extraction of potable groundwater,

[12]The first term represents the compaction due to a 1-foot drop in pressure head per foot of reservoir section; the second term represents the saturated thickness of the central graben reservoir; the third term represents the average pressure-head decline generated by a 120-foot drop in water level through the unconfined central graben reservoir.

together with the inferred extension to depth of displacements on the earth cracks, indicate that the earth cracks and associated fault displacements cannot be attributed to changes in ground-water conditions.

MOVEMENTS ATTRIBUTABLE TO SURFACE LOADING

Sediments commonly undergo consolidation in response to surface loading. They may also expand following unloading, as suggested, for example, by the 0.03 foot rebound of the Baldwin Hills Reservoir following its drainage in 1957 (California Department of Water Resources, 1964, p. 60).

Loading or unloading may be classified as natural or artificial. It is inferred from both the measured uplift along the Newport-Inglewood zone in this area and the physiographically youthful aspect of the hills, that the Baldwin Hills have been undergoing uplift and denudation during most of late Quaternary time. Thus, because most of the erosion products have been carried out beyond the hills, it is likely that unloading rather than loading has dominated local geologic history throughout the last few thousand years.

Artificial earthmoving activities in the Baldwin Hills over the past three or four decades have been characterized by both loading and unloading. Both have been relatively uniformly distributed over the hills and both have been limited chiefly to cuts and fills measured in tens or hundreds rather than thousands of cubic yards. We recognize, however, three examples of major earthmoving operations within the Baldwin Hills: (1) construction of the Baldwin Hills Reservoir during the late 1940's and early 1950's—which was accompanied by extensive excavation and the placement of about 2 million yards of various locally derived materials (California Department of Water Resources, 1964, p. 24, 26–28); (2) construction of La Cienega Boulevard through the western half of the hills during the early 1950's—which required extensive grading from the area north of Centinela to the north edge of the hills; (3) subdivision development in the southwestern quarter of the hills, chiefly during the 1950's—during which entire drainageways were filled to depths of 25–35 feet over distances of up to about 1 mile.

SUBSIDENCE

Because natural changes in mass distribution in the Baldwin Hills have been dominated by unloading, the pronounced subsidence developed here cannot be explained as a result of natural loading. Similarly, because artificial fill has been distributed fairly uniformly over most of the Baldwin Hills during historic time, and because the three major constructional efforts listed above lie near the edge of the subsidence bowl, it is unlikely that this subsidence can be attributed to artificial loading. This conclusion is supported by the likelihood that the surficial sediments in the Baldwin Hills are relatively insusceptible to compaction. Eagen and Brown (1959, p. 7) report that the "greatest settlement [under load within the Los Angeles basin] usually occurs in lowland areas of lagoon or flood-plain environment in which fine-grained cohesive sediments and organic material have been deposited to a considerable depth." Thus even the filling of the Baldwin Hills Reservoir, the center of which lies about 1,600 feet southwest of Hollywood E–11 had only a slight effect on the subsidence pattern. The settlement record of the reservoir gate tower (fig. 25), which was founded within an excavated section of the reservoir (California Department of Water Resources, 1964, pls. 2 and 11), extends from August 1949—about 1⅔ years prior to filling (California Department of Water Resources, 1964, p. 23, 31; Casagrande and others, 1972, p. 565–567)—through February 1964. This record shows that the average settlement rate (relative to Hollywood E–11) preceding filling was no less and perhaps somewhat greater than that which obtained after the reservoir was filled.

We conclude that the differential subsidence centering in the northern Baldwin Hills probably is unrelated to natural or artificial loading, as indicated by: the geologically recent (and probably continuing) uplift and denudation of the hills; the absence of any apparent spatial or temporal relation between the general pattern of subsidence in the northern Baldwin Hills and the placement of the larger fills; and the relatively unsusceptible nature of the near-surface sediments to continuing compaction.

HORIZONTAL MOVEMENTS

Because the geometric relations between the centripetally directed horizontal movements and the differential subsidence developed in the northern Baldwin Hills indicate that these movements are causally related, the horizontal movements can be no more attributed to loading phenomena than can the subsidence.

EARTH CRACKS AND CONTEMPORARY FAULT DISPLACEMENTS

Although natural unloading in the Baldwin Hills probably has exceeded natural loading during Holocene time, differences between the two during the past several decades probably have been nearly unmeasurable. Moreover, such natural unloading or loading as may have occurred during historic time must have operated relatively uniformly throughout the northern Baldwin Hills. Hence, it is very unlikely that the locally developed earth cracks can be attributed to natural loading effects. Similarly, because artificial cut-and-fill activity has also been more or less uniformly distributed throughout the hills, it is equally unlikely that the cracks and associated displacements are due to artificial loading or unloading. The preceding arguments retain their validity, moreover, even if consideration of loading effects is restricted to areas of high fault or joint density.

A dubious circumstantial argument may be made in support of an association between artificial loading and rupture and displacement along the earth cracks; it cannot apply, however, to the southern group of earth cracks and thus be considered as evidence of a general association between loading and cracking. The chief points of this argument are as follows: (1) the northern group of earth cracks is located in the Baldwin Hills Reservoir area (pl. 2 and fig. 22); (2) cracking of the drainage inspection chamber, which lies athwart crack IX, was first recognized in October 1951 (fig. 26), shortly after the reservoir was filled; and (3) artificial fill and stored water were concentrated in the area west of the earth cracks (California Department of Water Resources, 1964, pls. 2, 11, and 22a). The preceding points suggest that loading in the reservoir area, particularly that associated with the filling of the reservoir, may have compressed the foundation materials differentially with respect to the location of the major earth cracks. Therefore, following this line of argument, drag-induced compression of the materials east of the earth cracks ultimately may have reached some threshold value above which frictional resistance to movement was overcome and rupture and elastic rebound of the east block ensued (figs. 25 and 27). Several considerations, however, dispute this hypothesis. In the first place, because settlement began even before construction of the reservoir (fig. 11) and was no more than slightly accelerated by its filling (fig. 25), the settlement and presumably associated rebound must stem from some other cause. Secondly, there seems to have been little response to unloading west of crack IX subsequent to the reservoir failure and loss of stored water in December 1963 (fig. 27); if the compression of the underlying materials was measurably elastic and due largely to reservoir loading, recovery should not have been so preferentially and exclusively confined to the east block.

There exists a slight possibility that the timing of the displacements in the reservoir area may have been influenced by surface loading. If leakage through the reservoir lining saturated the natural foundation materials, the water load contained within the overlying reservoir may have induced significant increases in pore-water pressure and corresponding decreases in the normal stresses acting across any actual or potential rupture surface. It is unlikely, however, that any displacements could have occurred had there been no accumulation of elastic strain in the underlying materials, which, as shown above, cannot be attributed to surface loading.

Casagrande, Wilson, and Schwantes (1972, p. 573–576) have suggested a complex variation of the preceding argument to explain the faulting in the area of the Baldwin Hills Reservoir. According to these writers, the faulting along cracks IX and X (faults I and V of their description) that preceded failure of the reservoir was the result of "differential settlements*** produced by (1) water and embankment loads applied to the foundation soils which were loosened on the west [downthrown] side of the faults during original faulting, and (2) by wetting and erosion in these loosened masses." The differential movement along crack IX that closely accompanied or followed reservoir failure is attributed to rebound of the east block resulting from release of stress accumulated during a previous tectonic episode; the rebound is considered to have been triggered by the introduction during failure of nearly full reservoir hydrostatic head and resultant loss of shearing resistance along the fault (Casagrande and others, 1972, p. 579–580). The reservoir failure, in other words, is viewed not as an effect of rebound, but rather as its cause.

The Casagrande, Wilson, and Schwantes (1972) model, although conceptually appealing, is deficient in several significant respects. It certainly cannot, for example, be invoked as a general explanation of ground rupturing, for it provides no insight into the fully analogous rupturing in the area of the Stocker Street–La Brea Avenue–Overhill Drive intersection. This hypothesis also requires that the faulting that preceded reservoir failure be explained by active consolidation or compaction of the westerly blocks against passive east blocks (Casagrande and others, 1972, p. 573–576). Our studies, on the other hand, show that displacement along crack IX (and probably along crack X as well) was the product of rebound of the east block against a passive west block throughout the entire operational history of the Baldwin Hills Reservoir. Furthermore, although very localized differential subsidence concentrated west of crack X, in particular, probably is due to differential settlement or consolidation (Casagrande and others, 1972, p. 574), much of this settlement is almost certainly the result of collapse of the natural foundations eroded through piping and continuing consolidation of relatively thick fill west of the earth cracks (California Department of Water Resources, 1964, p. 58, pls. 2, 11, 22f, and 22g); thus the occurrence of such settlement by no means precludes the operation of completely unrelated faulting, which may, in fact, have contributed to its development (California Department of Water Resources, 1964, p. 63). Moreover, the flat determination that "this type of differential settlement could not be explained by displacements of blocks along faults" (Casagrande and others, 1972, p. 574–575) is particularly unwarranted, for it implies that faulting of a conventional nature could not have bounded these narrow zones of differential settlement. In fact, however, vertical movement of this sort is fully consistent with high-angle faulting developed in association with extensional horizontal strain (Cloos, 1968)—such as that recognized in the area of cracks IX and X (Casagrande and others, 1972, p. 581–582). Furthermore, the large survey time windows of 6.4 and 13.1 years that led to the Casagrande, Wilson, and Schwantes (1972, p. 574–575) determination, would both include such movements as may have been associated with reservoir failure and tend to obscure the existence of slight but significant episodes of rebound in the easterly blocks. Finally, the tacit exclusion of any likely mechanical relation between the broadly defined strain system centering on the northern Baldwin Hills and faulting in the Reservoir area (Casagrande and others, 1972) is inconsistent with the very restricted spatial and temporal relations among these features.

To conclude, it is very unlikely that the earth cracks and associated displacements are due to surface loading or unloading, as shown by: the generally random distribution of surface loading or unloading as contrasted with the very restricted development of the earth cracks; and the probability that the observed subsidence and preferential rebound of the east blocks cannot be reasonably explained as a response to surface loading.

MOVEMENTS ATTRIBUTABLE TO TECTONIC ACTIVITY

Southern California is clearly recognized as tectonically active (see sections on "Geology," "Seismicity," and "Regional Elevation Changes"); hence there exists a reasonable basis for assuming that the surface movements in the northern Baldwin Hills are simply manifestations of this apparently continuing activity. Gilluly and Grant (1949, p. 488), however, have focused sharply on the problem of attributing particular movements to specific tectonic forces, for "causes of tectonic movements are so obscure that it is always possible to assert their effectiveness without the possibility of direct disproof; in the nature of the case, the demonstrated adequacy of another mechanism known to be operative and competent to produce the observed effects can only make it unnecessary to appeal to the unknown tectonic forces." In other words, there is a tendency to dismiss as "tectonic" those surface or crustal movements insusceptible to direct analysis.

The effects of continuing tectonic activity in the Baldwin Hills may be expressed in a variety of ways. Rather than examining the full spectrum of tectonic phenomena that may have been operative here, the following discussion considers only those phenomena relevant to the observed surface movements.

SUBSIDENCE

Several partly incompatible lines of evidence could be interpreted as suggesting a tectonic involvement in the northern Baldwin Hills subsidence: (1) the growth of the subsidence bowl within a zone of recognized folding; (2) the apparent northward migration during Quaternary time of the crest of the major anticlinal fold in the Baldwin Hills; (3) the locally developed, ephemeral uplift along parts of the Newport-Inglewood zone west and north of the center of the hills; and (4) the approximate coincidence in space between the "central graben" and the subsidence bowl. Detailed consideration, however, shows that none of these associations is especially significant, either individually or collectively, and none explains the initiation of differential subsidence in the middle 1920's.

There is no doubt that the differential subsidence is spatially associated with a major fold, for it roughly mirrors the underlying Inglewood oil-field anticline (pl. 4 and figs. 3 and 4). Thus, it might be argued that the subsidence simply reflects downfolding along the same axis. Several observations, however, indicate that it is extremely unlikely that the natural sense of folding has been reversed. In the first place, uplift rather than subsidence has dominated the general pattern of vertical movement in this area during late Quaternary time. The relatively elevated nature of the hills, coupled with their mantle of upper(?) Pleistocene debris, suggests that this uplift is continuing. Secondly, the nearby, structurally elevated Cheviot Hills, where until recently any tectonic effects could not have been masked by petroleum exploitation, have been associated with contemporary uplift rather than subsidence. These hills, about 4 miles north-northwest of the Baldwin Hills and about 1⅔ miles east-northeast of the Pico-Sepulveda intersection (figs. 5 and 6), remained unexploited for petroleum until 1958 (Conservation Committee of California Oil Producers, 1964, p. N). Before 1958, moreover, this area had been characterized by at least ephemeral uplift. Thus, as shown in figure 6, the Cheviot Hills structure lies both within a small nose or reentrant of surface uplift in the 1949–55 pattern of isobases and along the boundary of a positive area that seemingly persisted during the late 1920's and through most of the 1930's (fig. 5). This coincidence suggests that in the absence of underground fluid extraction, locally developed and seemingly youthful structural highs have continued to rise through historic time.[13] In any case, the elevation of the very young sediments exposed in the Baldwin Hills, coupled with the recognition of preexploitation positive movement in the Cheviot Hills oil-field area, indicates that tectonically induced reversals in the sense of folding along the Inglewood oil-field anticline should have been very unlikely.

Even were it conceded that there had been no tectonic reversal in the sense of folding of the Inglewood oil-field anticline, it might still be argued that the differential subsidence represents downwarping developed in association with either the postulated northward migration of the major fold axis during Quaternary time, or very recent westward displacement of the axis of the Newport-Inglewood zone. This argument, however, requires not only uplift along the shifted axis, but complementary downwarping along opposite sides of the shifted axis. Because differential subsidence of an order approaching that identified in the northern Baldwin Hills has not been recognized north or west of the hills, this hypothesis is considered invalid.

Finally, it might be suggested that even though the Baldwin Hills as a whole have been undergoing tectonic uplift during Holocene time, this need not preclude an accompanying downdrop of the poorly defined "central graben" (fig. 2 and California Department of Water Resources 1964, pl. 10). The differential subsidence could thus be interpreted as a contemporary expression of the development of the graben. Several arguments, however, refute this postulate. (1) The configuration of the differential subsidence bowl (pl. 4) fails to conform in detail to that of the graben (frontispiece, pl. 2 and figs. 3 and 4). The central graben is a roughly linear feature about 2,000 feet wide and is best developed at the extreme north end of the hills, whereas the subsidence bowl is elliptical, centered about 3,000 feet south of the north edge of the hills, and extends without interruption almost one-half mile northeast and nearly 1 mile southwest of the boundaries of the central graben. The major axis of the subsidence bowl, moreover, intersects that of the graben at an angle of 25–30°. (2) If the 200-foot scarp along the Inglewood fault, which forms the east boundary of the central graben (frontispiece and pl. 2) was generated in response to continuing subsidence of the graben, contemporary subsidence of up to 0.125 foot/year at the fault and up to 0.20 foot/year at the center of the subsidence bowl suggests that the scarp itself may have evolved over a period of about 1,000–1,600 years—an inordinately short interval for the creation of a physiographic feature of this size (California Department of Water Resources, 1964, p. 45). Moreover, if the subsidence resulted from differential vertical movement of the central graben, there should be evidence of contemporary displacement on the Inglewood fault, whereas, in fact, there is none. (3) The presence of contractional horizontal strain (through a 90° range) in the central part of the subsidence bowl (see section on "Horizontal Movements") is completely inconsistent with any tectonic model of graben formation. Tectonically activated normal faulting and associated depression of the blocks that comprise this "graben" (fig. 2 and California Department of Water Resources, 1964, pl. 10) should have been accompanied by extensional horizontal strain, particularly if dispersed and attenuated in propagating to the surface in order to explain the absence of actual surface ruptures along the graben bounding faults (see, for example, Hubbert, 1951); tectonically induced contractional strain is, under these circumstances, mechanically impossible. Thus there appears to be no consistency between the presumably tectonic evolution of the graben and the continuing differential subsidence in the northern Baldwin Hills.

In summary, it is unlikely that the differential subsidence centering in the northern Baldwin Hills can be attributed to tectonic downwarping, as indicated by: the inverse structural relation between the differential subsidence and the underlying Inglewood oil-field anticline; a late Quaternary history of continuing uplift rather than subsidence over the Baldwin Hills as a whole; evidence that the nearby Cheviot Hills had been undergoing uplift rather than subsidence prior to their exploitation for petroleum; the probability that migration of the Inglewood oil-field fold or the Newport-Inglewood axis could not have been accompanied by the asymmetrical development of subsidence athwart either of these axes; and the incompatibility of the subsidence and associated contractional strain with the tectonic evolution of the central graben. This judgment is further supported by the absence of any recognized tectonic event with which the onset of subsidence can be associated.

HORIZONTAL MOVEMENTS

The geometric relations between the pattern of differential subsidence and the centripetally directed horizontal movements indicate that these movements must be genetically related; because the subsidence is probably unrelated to tectonic activity, it is equally unlikely that the horizontal movements are related to tectonic activity.

[13]A comparison of elevation measurements made along Pico Boulevard between 1955 and 1963 by the Los Angeles Bureau of Engineering suggests that uplift over the Cheviot Hills (with respect to bench marks east of the hills) ceased sometime between 1955 and 1960.

EARTH CRACKS AND CONTEMPORARY FAULT DISPLACEMENTS

The earth cracking and associated fault displacements are much more readily attributed to tectonic activity than are the differential subsidence and radially oriented horizontal movements. Tectonic generation of the earth cracks is suggested especially by the following: (1) the cracks are coincident with or nearly parallel to faults known to have been active during Quaternary time; and (2) they occur within the seismically active Newport-Inglewood zone. In spite of these suggestive considerations, it is unlikely that the contemporary separations and displacements along the earth cracks are more than incidentally tectonic.

In the first place, although the earth cracks occur along or parallel to preexisting faults and joints, their relatively specific definition with respect to the subsidence bowl (that is, confined to the periphery of the bowl and roughly perpendicular to radii emanating from its center) suggests that the cracking and displacements are mechanically associated with the subsidence, which is almost certainly of nontectonic origin.

Secondly, most of the domestic examples of clearly tectonic historic surface faulting have been precisely identified with perceptible and generally large earthquakes. Branch and secondary faulting commonly have accompanied these shocks, but always in conjunction with rupturing along the main trace of the primary fault (Bonilla, 1967, table 1). Parenthetically, the two moderate to large earthquakes (the 1920 Inglewood and 1933 Long Beach shocks) that are known to have occurred along the Newport-Inglewood zone are not known to have been accompanied by surface faulting (Taber, 1920, p. 137; Wood, 1933, p. 53). Moreover, all but possibly one of the recognized examples of aseismic tectonic surface faulting have occurred along the main traces of major faults, such as the San Andreas and Hayward (see Bonilla, 1967, p. 17–18, and table 1). Historic precedent suggests, accordingly, that tectonically induced separations and displacements along the earth cracks should have been accompanied by perceptible earthquakes or identifiable displacements on the Inglewood fault, neither of which has been recognized.

Thirdly, the sense of prehistoric movement on those faults paralleling or coincident with the earth cracks apparently ranged through 90°. "At one place on the fault plane [about midway along the length of the fault identified with crack IX]* * * horizontal striae were found showing that the last movement at this location was entirely horizontal with no vertical displacement. At another place on the fault plane, at the toe of the north bank of the reservoir, the striae were along the direction of maximum dip of the fault plane which was S.85°W, dipping 80°" (California Department of Water Resources, 1964, p. 13; Wilson, 1949, p. 25). We have, in addition, measured crudely defined slickensides pitching 50°–70° south along a north-northeast striking fault about one-half mile northwest of the Stocker Street–LaBrea Avenue–Overhill Drive intersection. Thus, because prehistoric movements along these faults have ranged from dip-slip through oblique-slip to lateral-slip, and because the style of faulting along the Newport-Inglewood zone has been characteristically right-lateral, the nearly exclusively dip-slip nature of the contemporary displacements along the earth cracks represents the least expected sense of tectonic displacement on these cracks.

Fourthly, subsurface movements, as indicated by oil-well damage, have not been reported from below the highly productive but relatively shallow Vickers zone. Although this restriction has been attributed by A. J. Horn (as paraphrased by the California Department of Water Resources, 1964, p. 42, 44) to the fact that relatively few wells penetrate deeper zones, 216, or a significant one-third of the 1963 field total of 651 active wells, penetrated zones beneath the Vickers (Conservation Committee of California Oil Producers, 1964, p. P). We suggest, alternatively, that the damaging movements may, in fact, have been confined to the Vickers zone or above (California Department of Water Resources, 1964, p. 44); acceptance of this alternative explanation is incompatible with assertions that faulting or fault-inducing strain have propagated from depth in response to tectonic activity.

Finally, the observed faulting is mechanically inconsistent with tectonic failure generated in a surface strain environment of the sort recognized in the northern Baldwin Hills. If the faulting were purely tectonic it would have to have been: (1) conjugate or shear faulting complementary to that generated along the Inglewood fault; (2) branch faulting; or (3) extensional faulting. If the faulting was either conjugate or branch it should have been chiefly transcurrent in order that it accord with the predominantly right-lateral movement on the Inglewood fault. Conjugate shearing, moreover, probably would have been accompanied by at least minor displacement on the Inglewood Fault. Branch faulting should have been not only predominantly transcurrent, but uniformly right-lateral. Because the historic faulting recognized through at least 1963 was chiefly dip-slip, because there appears to have been no discernible historic displacement on the Inglewood fault, and because at least small components of left-lateral movement were recognized along several of the ruptures (particularly crack IX), it is doubtful that the faulting was either conjugate or branch in nature. The generally dip-slip and seemingly normal character of the faulting, coupled with its high-angle orientation with respect to the axis of the Inglewood oil-field anticline indicates that any tectonic faulting is more likely the product of extension along or parallel to the anticlinal axis. However, the contractional strain measured in the central part of the subsidence bowl effectively destroys this hypothesis.

The coincidence in space between the earth cracks and earthquakes in and around the Baldwin Hills (see pl. 3) is of little apparent significance, for as shown by Hudson and Scott (1965, p. 171–173), there is no evident temporal relation between fault movements at the Baldwin Hills Reservoir site and local earthquake activity. Hudson and Scott have also observed that no significant local seismic events, as indicated by a continually recording seismograph set up at the reservoir site, were recorded during the several weeks following the faulting associated with the reservoir failure. Accordingly, assertions that the earth cracks can be associated with seismotectonic activity would have to be supported by a rigorous statistical study demonstrating not only their spatial coincidence, but a temporal association as well.

Very small increments of relative uplift in the area east of crack I are perhaps the best suggestion of an at least limited tectonic involvement in the earth cracking and associated displacements. As shown in the discussion of earth cracks and contemporary fault displacements attributable to oil-field operations, a probable maximum of 0.02 foot/year of positive movement (with respect to control points outside of the area of previously recognized differential subsidence) in the block east of crack I may be unrelated to oil-field operations, and may have thus accounted for up to about 10 percent of the prerupture isobase gradient there. Accordingly, this postulated tectonic contribution may apply in equal measure to the critical isobase and compaction gradients at which rupturing and displacement could occur. Alternatively, local tectonic effects may have controlled the timing of the rupturing, in that the threshold gradients may have been attained somewhat earlier than in the absence of any such effects. There is, however, no reason to suppose that these suggested increases in the compaction and subsidence isobase gradients could have induced rupturing had not the apparently nontectonic subsidence been proceeding concurrently. Thus, in the absence of oil-field operations, elevation changes within the presently recognized area of differential subsidence probably would have matched very closely those elsewhere in the Baldwin Hills, thereby inhibiting the evolution of abnormally steepened isobase gradients and an associated potential for rupturing.

To conclude, the earth cracks and associated displacements are doubtfully of tectonic origin, as indicated by: their probable mechanical association with the apparently nontectonic subsidence; the absence of displacements on the Inglewood fault in conjunction with displacements along the earth cracks; the absence of surface faulting associated with relatively large earthquakes along the Newport-Inglewood zone; the likelihood that purely tectonic displacements would have been other than essentially dip-slip; the confinement of damaging subsurface movements to relatively shallow parts of the oil field; the mechanical incompatibility between recognized contractional horizontal strain along the axis of the Inglewood oil-field anticline and tectonically-induced extensional faulting; and the absence of a well-defined temporal correlation between the local seismicity and the development of the cracks. Up to about 10 percent of the prerupture isobase and compaction gradients east of crack I and, hence, perhaps 10 percent of the forces responsible for the generation of the earth cracks and displacements there, may be of tectonic origin; this postulated fraction, however, should have been of little significance in the absence of the concurrently evolving nontectonic differential subsidence.

SUMMARY AND CONCLUSIONS

Various expressions of contemporary surface deformation have now been recognized within a wide range of geologic environments. Such deformation, which we define here to include both measured vertical and horizontal movements and surficial rupturing and faulting exclusive of that associated with slope failures, has been attributed to a broad spectrum of artificial and natural phenomena.

Surface movements identified in the Baldwin Hills of southern California comprise a particularly well-documented example of surface deformation associated with oil-field operations. Movements recognized here include well-defined differential subsidence centering on the Inglewood oil field; horizontal movements directed more or less toward the center of subsidence; and earth cracking and associated surficial faulting confined largely to the eastern margin of the subsidence bowl. Although these movements are clearly associated in space with oil-field operations, their temporal associations are less well defined and the possible effects of ground-water extraction, surface loading, and tectonic active have greatly complicated their analysis.

GEOLOGIC FRAMEWORK

The Baldwin Hills are located toward the north end of the Newport-Inglewood zone of folds and faults, where they occur as an isolated physiographic feature elevated about 350–400 feet above the terrace and alluvial deposits of the surrounding Los Angeles basin lowland.

The hills are underlain by a sequence of gently to moderately arched and conspicuously faulted Cenozoic sedimentary and volcanic rocks; this sequence in turn overlies crystalline basement rocks at a depth of over 10,000 feet. Conspicuous displacements have occurred on both the north-northwest trending Inglewood fault, which transects the hills diagonally, and similarly oriented faults elsewhere along the Newport-Inglewood zone. Right-lateral displacements along the Inglewood fault of 3,000–4,000 feet since middle or late Pliocene time and 1,500–2,000 feet during Quaternary time are indicated by offset structures and physiographic features; vertical separations of at least 200 feet during late Quaternary time are clearly indicated in the north-central part of the hills. Displacements along generally north to north-northeast trending branch or cross faults have been only a small fraction of those along the Inglewood fault.

Deformation of the older rocks underlying the Baldwin Hills probably began no later than middle Miocene time. Conspicuous fault scarps developed across upper Pleistocene deposits and the extremely youthful physiographic dissection indicate that this deformation has continued through much of Quaternary time.

Evidence of continuing deformation in and around the Baldwin Hills derives chiefly from the historic seismicity and measured elevation changes. Epicentral locations of earthquakes, as recorded by the Seismological Laboratory at Pasadena since 1934, correlate fairly well with the axis of the Newport-Inglewood zone. Furthermore, the M 5 to 5½ Inglewood earthquake of 1920, the largest earthquake of record in the Baldwin Hills area, is believed to have originated along the Potrero fault, immediately southeast of the hills and en echelon with the Inglewood fault. However, neither this nor any other historic shock along the Newport-Inglewood zone is known to have been associated with surficial fault displacements. Leveling in and around the west and central Los Angeles basin has shown that nearly all stations within the Quaternary sedimentary basin have been subsiding, whereas foothill stations commonly have been rising. The northwestern part of the basin has, in addition, been characterized by several broad and seemingly persistent differential subsidence bowls and a zone of positive movement roughly coincident with the Newport-Inglewood zone.

ELEVATION CHANGES

Repeated levelings through the Baldwin Hills have clearly defined a broad bowl of differential subsidence centering on the northwestern part of the hills. This elliptical subsidence bowl is identified with a northwest-trending long axis of about 2.7 miles and a northeast-trending short axis of about 2.0 miles.

Elevation changes in the northern Baldwin Hills generally have been calculated with respect to control point Hollywood E–11 (PBM 40 of the Los Angeles Department of Water and Power) along the northeast edge of the subsidence bowl. More or less quadrennial levelings along a control line extending northward through and beyond the eastern half of the hills show that Hollywood E–11 has subsided since 1939 at a rate of less than 0.003 foot/year with respect to a bench mark (PBM 1) about ⅔ mile south of the well-defined area of differential subsidence. It has also subsided at about 0.01 foot/year with respect to a control point (PBM 58) about 2 miles north of the hills, and at less than 0.02 foot/year with respect to S–32, about 6 miles east-northeast of the hills and the primary control point for the City of Los Angeles. Thus Hollywood E–11 is identified with a history of relative stability with respect to bench marks well outside the area of differential subsidence.

Reconstruction of successive level surveys with respect to Hollywood E–11 has permitted an evaluation of subsidence since 1910 and 1911 at two points well within the presently recognized subsidence bowl. Bench mark PBM 67 is estimated to have subsided approximately 4.324 feet between June 1910 and February 1963, and bench mark PBM 68 is calculated to have subsided 3.846 feet between November 1911 and June 1962. Maximum subsidence has closely matched the subsidence at bench mark PBM 122; between 1911 and 1963 PBM 122 is estimated to have subsided about 5.67 feet, or only about one-half that of previous estimates of maximum subsidence in the northern Baldwin Hills between 1917 and 1964.

The history of vertical movement at bench mark PBM 68 is particularly significant, for this is the only bench mark in the northern Baldwin Hills leveled before 1926 that has been repeatedly revealed since. Analysis of the leveling data suggests little elevation change at PBM 68 (or elsewhere throughout the Baldwin Hills-Inglewood area) associated with the Inglewood earthquake of 1920. Several independent evaluations show that differential subsidence at PBM 68 probably began in the middle 1920's; the calculated paths of subsidence at PBM 68 indicate little if any subsidence of this bench mark between 1911 and 1926. A comparison of the elevations recorded at four identifiable topographic features within the now recognized area of differential subsidence suggests that there was no subsidence in this area between 1910 and 1917 and, hence, supports the preceding conclusion.

HORIZONTAL MOVEMENTS

Horizontal displacements of six triangulation monuments within the northern Baldwin Hills subsidence bowl have been determined for various times between

1934 and 1963, through comparisons of their positions with respect to a north-south base line about 3 miles east of the hills. These displacements have been directed generally toward the center of subsidence and almost precisely perpendicular to the immediately adjacent isobases of equal elevation change. Maximum movement has been recorded at triangulation point Baldwin Aux, on the northeast limb of the subsidence bowl; this monument was displaced 2.21 feet between 1934 and 1961. Horizontal displacements between 1936 and 1961 at three additional points ranged from 0.95 foot to 1.85 feet. Displacements of 0.10 to 0.29 foot were recorded at all six triangulation monuments during the period 1961–63.

Measurement of interstation distances along several traverses through the area of now recognized subsidence was begun at least as early as 1924. Subsequent length checks along these lines have shown that the eastern margin of the subsidence bowl has been characterized by extensional strain along lines at generally high angles to the isobases of vertical movement. The central part of the subsidence bowl has been similarly identified as a zone of contractional strain. Reliable measurements of horizontal strain range up to maximums of about 0.2 percent in the central contractional zone and more than 0.07 percent in the peripheral, extensional zone.

EARTH CRACKS AND CONTEMPORARY FAULT DISPLACEMENTS

Fully documented contemporary "earth cracking" and surficial faulting in the northern Baldwin Hills dates from at least as early as 1957. This rupturing has been confined largely, if not entirely, to the structural block east of the Inglewood fault and concentrated in two areas centering on the Baldwin Hills Reservoir and the Stocker Street–LaBrea Avenue–Overhill Drive intersection.

The earth cracks are relatively straight, generally continuous features. They commonly trend north to north-northeast and more or less normally to radii emanating from the center of subsidence. The cracks are also oriented subparallel or moderately obliquely to the Inglewood fault and parallel to or coincident with otherwise identifiable faults or joints. Displacements along the earth cracks have been almost entirely dip-slip along steep to nearly vertical surfaces. Cumulative displacements have ranged up to 6 or 7 inches; their magnitudes, moreover, seem to have been independent of the length of cracking. Where lateral movements have been recognized none have been more than small fractions of the corresponding dip-slip components; these horizontal components have averaged about ⅛–¼ inch and have reached a maximum of about ½ inch. Moreover, the apparent sense of lateral movement is ambiguous and actually reverses as traced along several ruptures. Individual fault blocks defined by the earth cracks generally have been downdropped relatively toward the center of subsidence. The contemporary displacements are known to have occurred to depths of at least tens of feet, and indirect evidence indicates that they probably extend several hundred feet beneath the surface. Ruptured or bent oil-well casings on trend with several of the earth cracks comprise permissive evidence of displacements at depths of over 1,000 feet.

Displacements along the earth cracks seem to have been characterized by more or less episodic but continuous creep or small, discrete jumps. A probable exception to this generalization was the several inches of differential movement that took place along a crack through the floor of the Baldwin Hills Reservoir on December 14, 1963. The chronology of movement along the cracks remains poorly known. Thus, even though rupturing was not generally recognized until 1957, the cracking of a concrete structure athwart one of the cracks, the occasional rebound of certain frequently monitored bench marks, and other geodetic evidence of differential movement around the Baldwin Hills Reservoir, suggests that rupturing and displacement probably began at least as early as 1951.

CAUSES OF THE SURFACE MOVEMENTS

The contemporary surface deformation observed in the Baldwin Hills is almost certainly attributable to one or more of the following phenomena: (1) exploitation of the Inglewood oil field; (2) changes in ground-water conditions; (3) compaction of sedimentary materials in response to surface loading; (4) tectonic activity. Detailed consideration of each of these possible causes indicates that all the recent surface movements recognized in the Baldwin Hills are due largely or entirely to operations in the Inglewood oil field.

MOVEMENTS ATTRIBUTABLE TO OIL-FIELD OPERATIONS

Much of the northern Baldwin Hills is occupied by the Inglewood oil field. From the beginning of production in 1924 until the end of 1963, this field produced 224,974,000 bbls of oil, 374, 699,000 bbls of water, and 182,676,000 Mcf of gas. Most of this production has been drawn from the upper Pliocene Vickers zone, which occurs at a median depth of about 2,100–2,200 feet.

Waterflooding in the Inglewood oil field, on other than a pilot scale, began in 1957. It was initially confined to the Vickers zone in the east block; flooding operations in the west block began in 1962.

SUBSIDENCE

A number of considerations indicate that the differential subsidence recognized in the northern Baldwin Hills can be attributed entirely to the exploitation of the Inglewood oil field: (1) the coincidence among the approximate centers of the oil field, the producing structure, and the subsidence bowl; (2) the similar outlines of both the oil field and the differential subsidence domain; (3) the approximate coincidence between the initiation of significant production in 1925 and the onset of differential subsidence around 1926; (4) the generally linear relations between various measures of subsidence and production from both the field as a whole and the exceptionally prolific Vickers zone in particular; (5) the sharp deceleration in the rate of subsidence within the east block of the oil field coincident with the start of full-scale waterflooding there; (6) the many other oil fields in which both spatial and temporal associations between production and subsidence have been recognized; (7) the many similarities between the subsidence-production relations of the Inglewood oil field and those of the Wilmington oil field, where the relation between oil-field operations and subsidence is unequivocal; and (8) the theoretical relations between subsidence, or a tendency toward subsidence, and increased effective pressure associated with the extraction of underground fluids.

In the idealized underground reservoir system, effective (grain-to-grain) pressure increases directly and equally with decreasing fluid pressure. It can also be shown that compaction varies directly and at generally constant or progressively decreasing rates with decreasing fluid pressure or increasing effective pressure. Compaction in both the Inglewood and Wilmington oil fields, however, seemingly has increased at progressively increasing rates with respect to measured down-hole fluid-pressure decline. Of the various possible explanations for the inconsistency between the pressure decline-subsidence relations indicated for these actual examples and those predicted for an idealized system, the most likely is that measured or calculated down-hole fluid-pressure decline is not representative of the average or real reservoir fluid-pressure decline away from producing wells. Hence the fact that the relation between subsidence and measured reservoir pressure decline is the inverse of that predicted from theoretical considerations does not in itself invalidate the conclusion that compaction has proceeded in response to fluid-pressure decline associated with exploitation of the Inglewood oil field.

The nearly linear relations between various measures of net liquid production and subsidence may be explained through analogy with a tightly confined artesian system of infinite areal extent, where production must derive from liquid expansion and(or) reservoir compaction. In a system such as this, the total volume of reservoir compaction must be linearly related to the cumulative production, provided only that the bulk modulus of the liquid and the compression modulus of the reservoir skeleton remain invariant over the relevant stress interval. Use of test data from studies of compaction in two other oil fields yield estimates of the ultimate compaction of the Vickers zone resulting from a total loss of reservoir fluid pressure. Although these estimates range over an order of magnitude, our best estimate, based on these data and considerations of late Cenozoic history in this area, is about 10 feet, or roughly 1⅔ that measured through 1963.

HORIZONTAL MOVEMENTS

The centripetally directed horizontal displacements and the post-1925 horizontal strain recognized in the northern Baldwin Hills may be attributed entirely to the exploitation of the Inglewood oil field. This conclusion stems from: (1) the well-defined symmetrical relations between the horizontal displacements and both the oil field and the associated differential subsidence bowl; (2) the approximate coincidence between the start of production in 1925 and the onset of both the centripetally directed horizontal displacements and centrally located contractional strain in the middle or late 1920's; (3) the similarities between the horizontal movements recognized here and those developed in and around other subsiding oil fields; and (4) the mechanical compatibility of these movements with subsidence induced by the extraction of subsurface materials.

Experimental studies, finite element analyses, and various theoretical models all require that surface subsidence generated through compaction at depth be accompanied by horizontal surface displacements directed toward the center of subsidence. Furthermore, both common sense and strain analyses based on the described horizontal displacements indicate that contractional or compressional strain should be set up in the central or axial region of the subsidence field, and that extensional strain should be generated more or less normally to the isobases of equal elevation change (and thereby parallel to the radially oriented horizontal displacements) within the peripheral part of the subsidence field. Thus, to the extent that the differential subsidence is due to oil-field operations, the associated horizontal movements must be equally due to the exploitation of the Inglewood oil field.

EARTH CRACKS AND CONTEMPORARY FAULT DISPLACEMENTS

The contemporary earth cracks and surficial fault displacements developed around the eastern margin of the subsidence bowl can be attributed largely or entirely to the exploitation of the Inglewood oil field. This conclusion is based on: (1) the well-defined spatial and temporal relations between the surface rupturing and both oil-field operations and the differential subsidence identified with these operations; (2) the similarities between these cracks and displacements and those developed in and around other oil fields or areas of underground materials extraction; and (3) the occurrence of strain patterns, as deduced from the measured vertical and horizontal surface movements, that tend to promote rupturing and fault displacements.

The cracks and displacements may be fully explained by an exploitation-based, elastic-rebound compaction model. This model requires the generation of elastic compression in response to compaction-induced downdrag of the sedimentary sections comprising the upper parts of the structural blocks around the periphery of the subsidence bowl. The sense of faulting is entirely consistent with this model, and the magnitudes of the displacements have been about one-quarter to one-half those predicted for a purely elastic system. As much as about 10 percent of the measured isobase and compaction gradients critical to the construction of this model is conceivably unexplained by exploitation of the Inglewood oil field; it is very unlikely, however, that this fraction could have led to rupturing and displacement in the absence of exploitation.

The almost total restriction of cracking and surficial faulting to the east block probably stems chiefly from the density and generally favorable orientations of preexisting fractures in this area. The elastic-rebound compaction model favors the occurrence of ruptures and displacements along steep surfaces, more or less parallel to the isobases within the extensional horizontal strain zone; preexisting fractures of this orientation are conspicuous in the east block and generally absent in the west block. It is also likely that the initial restriction of waterflooding to the east block aggravated, and conceivably provoked, the faulting there. This flooding, which was carried out at pressures generally above hydrostatic, probably promoted failure in two ways: (1) by increasing the isobase and compaction gradients and, hence, the extensional strain, over a limited reach of the east limb of the subsidence bowl; and (2) by elevating the pore-water pressures along potential failure surfaces.

MOVEMENTS ATTRIBUTABLE TO OTHER CAUSES

CHANGES IN GROUND-WATER REGIMEN

Exploitation of the ground-water resources of the west Los Angeles basin began about 1870 and was certainly in full swing by the turn of the century. However, although great volumes of potable water have been produced from within this area, little has been drawn from the generally nonwater-bearing sediments underlying the Baldwin Hills. The only measurable production has, in fact, come from along the south edge of the hills and from within the northernmost part of the "central graben," an obscurely defined structural feature along the eastern margin of the west block.

We conclude that the differential subsidence and symmetrically related horizontal displacements identified in the Baldwin Hills are no more than incidentally due to changes in ground-water conditions. This conclusion derives from: (1) the absence of any record of significant ground-water extraction from within the hills; (2) the likelihood that no more than minor amounts of ground water could have been drawn from the deposits underlying the hills; (3) the nearly complete absence of measured surface subsidence associated with major head declines in aquifers correlated with the sands and gravels that crop out in the hills; (4) the probability that even the greatest credible drawdowns of water levels could have produced only a small fraction of the recognized subsidence; and (5) the lack of any spatial or temporal correlation between the observed movements and ground-water exploitation within and around the hills.

Several of the points listed above also argue that the earth cracks and surficial fault displacements cannot be due to changes in ground-water conditions. This conclusion is reinforced by the probability that the fault displacements extend well below any potable ground-water horizons.

CHANGES IN SURFACE LOADING

The Baldwin Hills have been undergoing more or less continuous uplift and denudation throughout Quaternary time. Thus because erosion rather than alluviation must have dominated the late Quaternary history, unloading rather than loading has characterized the geologic history of the hills during prehistoric Holocene time. Furthermore, although locally large volumes of materials have been involved, artificial cutting and filling have been distributed more or less equally over most of the Baldwin Hills.

It is very unlikely that the differential subsidence and symmetrically associated horizontal movements are in any way due to either natural or artificial changes in surface load. This conclusion is supported by: (1) the continuing natural denudation of the hills; (2) the absence of any apparent spatial or temporal association between the evolving differential subsidence bowl and the placement of the largest fills recognized in this area; and (3) the fact that the near-surface sediments are relatively insusceptible to load-induced compaction. The earth cracks and surficial fault displacements are equally unrelated to loading, as shown by: (1) the generally random distribution of both cuts and fills as contrasted with the very restricted occurrence of the earth cracks; (2) the apparent absence of any temporal relation between local cut-and-fill operations and the growth of spatially associated earth cracks; and (3) the impossibility of explaining both the settlement and subsequent rebound of the easterly blocks adjacent to the earth cracks as the products of surface loading.

TECTONIC ACTIVITY

The identification of the Newport-Inglewood zone as an active tectonic lineament suggests that the surface movements observed in the Baldwin Hills may be no more than surficial expressions of this continuing activity; consideration of the total evidence, however, indicates that the described movements can be no more than incidentally attributed to tectonic effects.

Although the occurrence of the subsidence bowl within an area of recognized and more or less continuous folding and uplift, together with its approximate coincidence with the "central graben," suggests that it may have evolved in response to tectonic forces generated at depth, it is very unlikely that either the differential subsidence or the symmetrically related horizontal displacements formed through tectonic downwarping. This is indicated especially by: (1) the inverse relation between the subsidence bowl and the underlying Inglewood oil-field anticline; (2) late Quaternary uplift of the hills as a whole; (3) the occurrence of relative uplift over a nearby structurally elevated area, prior, at least, to its exploitation for petroleum; (4) a mechanical incompatibility between the described subsidence pattern and associated horizontal strain on the one hand and the tectonic evolution of the "central graben" on the other hand; and (5) the absence of any recognized tectonic event with which the onset of the subsidence can be associated.

The coincidence or parallelism between many of the contemporary earth cracks and faults known to have been active during Quaternary time and the occurrence of the cracks within a well-defined zone of seismicity are seemingly compelling evidence of a tectonic basis for the contemporary surface rupturing; again, however, it seems very unlikely that the earth cracks and contemporary fault displacements are the result of tectonic activity. This is shown by: (1) the probable mechanical association between the cracks and the apparently nontectonic subsidence; (2) the absence of faulting along the Inglewood fault in conjunction with faulting along the earth cracks; (3) the likelihood, as suggested by local historic precedent, that purely tectonic displacements would have been other than dip-slip; (4) a seeming inconsistency between postulated branch or conjugate faulting and the observed essentially dip-slip movements along the earth cracks; (5) a mechanical incompatibility between postulated extensional faulting developed athwart the axis of the Inglewood oil-field anticline and the contractional horizontal strain recognized in the center of the subsidence bowl; (6) the confinement of damaging subsurface movements to relatively shallow producing horizons; and (7) the absence of any clearly defined temporal relation between crack growth and local seismicity. Up to about 10 percent of the prerupture isobase gradient is conceivably of tectonic origin. Because the elastic-rebound compaction model demands that some threshold isobase or compaction gradient be exceeded in order for displacement to occur, up to perhaps 10 percent of the forces necessary for crack growth may have been of tectonic derivation; this fraction, however, could have been of little significance in the absence of the concurrently evolving and apparently nontectonic subsidence.

CONCLUSION

The various clearly defined spatial and temporal relations between subsidence and oil-field operations that have been demonstrated both for this and other oil fields indicate that the differential subsidence and associated horizontal movements generated in the Baldwin Hills are due to exploitation of the Inglewood oil field. This conclusion is strengthened by various theoretical considerations and a host of experimental studies. Neither the actual changes in ground-water and loading conditions nor the effects of the maximum conceivable changes in these regimens can explain the observed subsidence; tectonic activity is considered an equally implausible explanation of the differential subsidence. Because the earth cracks and associated fault displacements are spatially associated and mechanically compatible with the differential subsidence, because similar phenomena have been recognized around a number of other subsiding oil fields, and because they cannot be related to changes in ground-water conditions or surface loading and are almost certainly no more than incidentally tectonic, we conclude that the contemporary cracking and faulting is also due largely or entirely to the exploitation of the Inglewood oil field.

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APPENDIXES A–K

APPENDIX A

Survey history and adjustments of level lines A, B, and C

I. *Line A*. Level line A (figs. 8 and 9) was established in 1935 by the U.S. Coast and Geodetic Survey; it was releveled in 1943 by the Los Angeles Department of Water and Power (Hayes, 1943, p. 4–5). The 1935 record elevations along line A given by the Coast and Geodetic Survey, and with which the 1943 elevations of the Department of Water and Power were later compared, presumably were adjusted with respect to the Coast and Geodetic Survey primary net, but this was not specified by Hayes. The first part of the 1943 releveling of line A between its east end and Centinela Avenue, a segment over which lines A and B are mutually inclusive, was adjusted to conform with the corresponding retracement of line B; that part westward from Centinela Avenue was left unadjusted (Hayes, 1943, p. 6). Because the closure over the full 22,000-foot length of the 1943 releveling of line B was only +0.007 foot (Hayes, 1943, p. 5), all of line A may be treated as if it had been left unadjusted over its entire length.

II. *Line B*. Level line B (figs. 8 and 10) was established in 1933 by the Los Angeles Bureau of Engineering; it was releveled in 1943 by the Department of Water and Power (Hayes, 1943, p. 7–8, fig. 3). The 1933 record elevations utilized by the Department of Water and Power probably were adjusted with respect to the Bureau of Engineering's Civic Center datum control point, but this was not specified by Hayes. Because, as noted above, the 1943 releveling of line B closed only 0.007 foot high, it too may be treated as unadjusted with respect to the starting bench mark.

III. *Line C*. Level line C (figs. 8 and 11) was established in 1939 by the Department of Water and Power; it was releveled by the Department of Water and Power in 1943, 1946, 1950, 1954, and 1958 (Hayes, 1959, fig. 2). Although this line was not releveled in 1962, bench marks common to line C were incorporated in a more recently established control line (Walley, 1963, p. 15–16, fig. 2–A); elevation changes along line C between 1958 and 1962, accordingly, may be calculated directly from changes along this later survey line.

According to Hayes (1943, p. 9–10), both the 1939 and 1943 levelings along line C were adjusted with respect to a common starting elevation for PBM 1 that was determined through the 1943 leveling of line B (that is, an elevation equal to the 1933 Bureau of Engineering record elevation of PBM 1 plus 0.050 foot). The 1939 and 1943 surveys were adjusted "because it was not believed at the time the levels were of sufficient accuracy to be dependent on the initial bench mark at Centinela Avenue and Market Street, due to the ordinary types of instruments and rods used for leveling. The levels of 1946, 1950, 1954, and 1958, using more refined equipment, were plotted based on the starting bench mark PBM No. 1 at Centinela Avenue and Market Street and allowed to fall where they would without the overall adjustment into the closing bench mark at Washington Boulevard and Vineyard Avenue" (Hayes, 1959, p. 12). Real changes in elevation with respect to PBM 1 along level line C since 1946 (assuming no instrumental bias) can be determined directly from the profile given in figure 11. Elevation changes since 1939, on the other hand, can be determined only through an evaluation of the adjustments applied to the 1939 and 1943 surveys.

A. According to Hayes (1943, p. 10), the 1939 leveling "closed 0.049 of a foot high, while the 1943 circuit closure was 0.038 of a foot high." It could not be determined from an examination of the original field notes, whether these closures were based on the record or "corrected" starting elevation for PBM 1.

1. If the 1939 closure was based on a "corrected" starting elevation (the Bureau of Engineering 1933 record elevation +0.050 foot) and an "uncorrected" 1933 record elevation for PBM 58 (DWP fieldbook 2604, p. 17; LABE-CE fieldbook 16980, p. 1, 6), instrumentally perfect leveling over a line in which PBM 1 and PBM 58 had remained absolutely stable with respect to each other (and where the 1933 record elevations are accepted as valid) should have led to a closure of +0.050 foot; that is, the actual closure may have been only −0.001 foot, and the change in elevation at PBM 58 between 1939 and 1946 should be 0.050 foot less than that represented in figure 11.
2. Alternatively, if the 1939 closure is based on "uncorrected" record elevations for both PBM 1 and PBM 58, and if the leveling were instrumentally perfect, then PBM 58 rose by 0.049 foot with respect to PBM 1, the leveling should not have been adjusted

downward, and the change in elevation of PBM 58 between 1939 and 1946 should be 0.049 foot less than shown in figure 11.

3. In either case, it seems likely that the change in elevation at PBM 58 between 1939 and 1946 probably is exaggerated in figure 11 by perhaps 0.05 foot; a similar exaggeration, diminishing progressively toward PBM 1, may be distributed throughout the profile. However, because the 1939 and 1943 closures on level line C were nearly identical, it is likely that the same adjustments were applied to both levelings such that they may be compared directly with each other. However, neither should be compared directly with subsequent relevelings along line C.

B. Even though elevation changes along line C (as portrayed in fig. 11) may be misrepresented somewhat, no attempt has been made to reconstruct figure 11 on the basis of an uncorrected starting elevation and unadjusted intermediate elevations for the 1939 and 1943 surveys because: (1) changes in the profiles would be slight; (2) a precise reconstruction would require not only a reevaluation of the 1939 and 1943 surveys from the original field data, but replotting of the 1946 and subsequent levelings as well; and (3) elevation changes at critical bench marks may be calculated independently without reconstructing the entire profile.

APPENDIX B

Location of PBM 68 (identified alternatively as DD)

I. Two separate survey points within the northern Baldwin Hills have been identified as "DD." One is a concrete bench mark that is believed to have been set in 1910 by the Los Angeles Investment Company; the second, a triangulation point about 30 feet distant, seemingly was set by the Los Angeles Investment Company sometime between 1910 and 1913. It is necessary that we show: (1) that the existent concrete bench mark occupied and identified in 1943 as PBM 68 by the Department of Water and Power (and not the triangulation point 30 feet distant) is the one occupied and identified in 1911 as DD by the Department of Water and Power; (2) that the same concrete bench mark identified as PBM 68 by the Department of Water and Power is identical with DD as established by the Los Angeles Investment Company in 1910; and (3) that this concrete bench mark has not been moved since it was originally established. Evidence of the existence of two separate survey points named "DD" is as follows:

A. A Los Angeles Investment Company 2-ft contour map dated 1910 shows DD at an estimated elevation of about 313.4± ft.

1. A penciled notation on this same map describes DD as having been moved "30′±" eastward to a point that would place it at an elevation of 316.0+ ft.

B. A Los Angeles Investment Company 5-ft contour map dated April 1913 shows DD at an elevation of about 315.8± ft.

II. Considerations listed below indicate that the concrete bench mark inscribed "DD", which has been utilized by the Department of Water and Power since 1943 as PBM 68 (DWP filecard for PBM 68), is in the same position as originally set by the Los Angeles Investment Company and is identical with bench mark DD occupied by the Department of Water and Power in 1911 (DWP fieldbook 1458, p. 10).

A. According to Mr. William Ball (oral commun., 1965) of the Los Angeles Investment Company, the concrete bench mark inscribed "DD" was never removed from its original position.

B. The ground elevation of a point identified as "DD" on the 1910 Los Angeles Investment Company 2-ft contour map has been estimated at about 313.4± ft; the 1910 elevation of a concrete monument identified as "DD," derived from an adjacent stake elevation established by the Los Angeles Investment Company, is computed here to have been approximately 314.015 ft (LAIC fieldbook 7, p. 3; DWP fieldbook 1458, p. 29). The 1911 elevation of DD given by the Department of Water and Power was 313.930 ft (DWP fieldbook 1458, p. 10); a reevaluation of the leveling data that led to this elevation has shown that it is slightly in error, but almost certainly by no more than about +0.10 ft. The datums employed in these two independent elevation determinations are believed to be nearly identical (see appendix F).

1. Because the elevation of DD measured by the Department of Water and Power in 1911 probably differed by no more than 0.5 ft from that determined in 1910 by the Los Angeles Investment Company, yet was almost certainly more than 1.9 ft below the ground elevation at the apparently relocated position of DD (I.A. and I.B.), it is

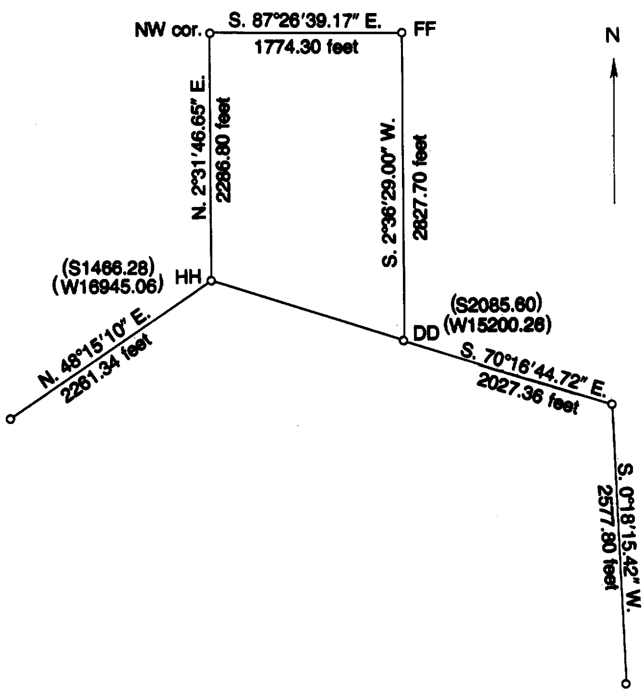

FIGURE 52.—Part of original triangulation net of the Los Angeles Investment Company in the northern Baldwin Hills showing relations between DD (PBM 68) and nearby control points together with the calculated coordinates for points DD and HH (LAIC calculation book, p. 9).

probable that concrete bench mark DD occupied by the Department of Water and Power in 1911 is the same concrete monument set in 1910 by the Los Angeles Investment Company at the original site of DD.

C. The distance between monuments HH and DD (fig. 52) measures about 1,842 ft on a photostat copy of a 1917 topographic map of the old Centinela Reservoir site (Hayes, 1943, fig. 6). The distance HH–DD calculated from coordinates computed from the original survey measurements (fig. 52) of the Los Angeles Investment Company (LAIC calculation book, p. 9) is 1851.4450 ft (F. J. Walley, written commun., 1965), whereas the corrected distance HH–DD calculated from the revised coordinates for HH and DD has been given as 1882.02 ft (LAIC, hill tract calculation worksheet).

   1. Because the distance HH–DD as shown on the 1917 Centinela Reservoir map is probably no greater than and certainly much closer to HH–DD as originally surveyed than it is to the corrected distance HH–DD, it is almost certain that concrete bench mark DD occupied by the Department of Water and Power in 1917 is identical with DD as originally set by the Los Angeles Investment Company in 1910. Because, in addition, the 1917 elevation of DD as derived by the Department of Water and Power through a comparison with the elevation of a nearby topographic saddle that was presumed to have remained unchanged between 1911 and 1917, is given as 314.24 ft (DWP fieldbook 1579, p. 4–5), it is probable that concrete bench mark DD occupied in 1917 is the same as that occupied by the Department of Water and Power in 1911.

D. The distance HH-PBM 68 (identified alternatively as DD by the Department of Water and Power) was taped in 1964 at 1851.44 ft (F. J. Walley, written commun., 1964).

   1. Because the taped distance HH–PBM 68 almost perfectly matches distance HH–DD calculated from the original survey measurements of the Los Angeles Investment Company, concrete bench mark PBM68 is certainly identical with DD as set at the original site of DD by the Los Angeles Investment Company. Furthermore, unless: (1) two virtually identical monuments inscribed "DD" existed within a few tens of feet of each other in 1911; or (2) concrete monument DD was moved eastward 30 feet to the site of triangulation point DD by 1911, and thence back to its 1910 location sometime before 1943, PBM 68 must be identical with concrete monument DD occupied by the Department of Water and Power in 1911.

APPENDIX C

Derivation of the November 1911 elevations of PBM 68 and Hollywood E–11. The November 1911 elevations of PBM 68 (identified alternatively as DD—see fig. 8) and Hollywood E–11 (identified alternatively as PBM 40—see fig. 8) are based here on a comparison with the elevation of S–32 (Civic Center basic control point) established by the U.S. Coast and Geodetic Survey supplemental adjustment of 1933–34 (generally referred to simply as the "1934 adjustment").

NOTE.—Bench marks S–32 reset (located at the Hall of Justice) and 37-54-26 (located on North Broadway 235 ft south of Temple Street) have been used as basic control points by the LABE (Los Angeles (City) Bureau of Engineering) since 1934 (LABE Precise Bench Mark Index, p. 19–20). Primary elevations of the basic control points employed by the LABE since 1934, however, have been determined by the U.S. Coast and Geodetic Survey (LABE Precise Bench Mark Index, p. 17–18, 20). The 1936 elevation of S–32 reset was derived directly from the elevation of S–32 as fixed in the 1934 adjustment (L.A. County level book 719, p. 145–150), so that S–32 and S–32 reset may be treated as precisely equivalent points. Because S–32 reset has been held fixed by the U.S. Coast and Geodetic Survey since 1936 at an elevation subsequently accepted by the LABE (LABE Precise Bench Mark Index, p. 25), it follows that the 1934 elevation of S–32 established by the U.S. Coast and Geodetic Survey has been accepted as unchanged since that time by the LABE; S–32, accordingly, is considered the primary Civic Center basic control point. Because S–32 and 37-54-26 are separated by only about 300 ft, they are assumed to have remained unchanged in elevation with respect to each other. This assumption is supported by observations at the two bench marks between 1953 and 1960 (LABE Precise Bench Mark Index, p. 25); both plus and minus movements of 0.000 to about 0.004 ft/yr of 37-54-26 with respect to S–32 reset have been recorded. Accordingly, S–32, S–32 reset, and 37-54-26 may be treated as coincident points; that is, elevations derived simultaneously from the 1934 adjustment elevations of any of these three points would be virtually identical, equally valid, "true" elevations with respect to S–32.

The LABE 1933–34 general leveling survey (referred to as the "1934 general leveling") for the southern area—defined by the LABE to include nearly all of metropolitan Los Angeles south of the Santa Monica Mountains (LABE Precise Bench Mark Index, p. 4)—had as its basis a single U.S. Coast and Geodetic Survey elevation in the Civic Center of Los Angeles. The 1949 and subsequent general leveling surveys have omitted as a basis the U.S. Coast and Geodetic Survey elevation in the western San Fernando Valley—previously employed as one of two bases for the northern area—and have included instead one in the harbor area (tidal 10, H–768 1946, or tidal 8) as well as one in the Civic Center (LABE Precise Bench Mark Index, p. 19–20). Where more than one control point has been used to establish an adjusted elevation—as has been the case since 1949 for those elevations established by the LABE along its primary network—the difference between the adjusted elevation and the "true" or observed elevation with respect to a single control point is a function of its distance from this single control point; in other words, the closer a point to the Civic Center basic control point S–32, the closer its adjusted elevation will be to its observed elevation with respect to S–32. Precise bench marks in the Baldwin Hills area are much closer to S–32 than they are to the basic control points in the harbor area (PBM 58, for example, is approximately 5.5 miles from S–32 and approximately 20 miles from tidal 8). Moreover, S–32 reset and tidal 8 have had a history of relative stability with respect to each other; closures over the 25-mile course between these two points have been both plus and minus, ranging from a minimum of 0.013 ft to a maximum of 0.18 ft over time intervals of up to three years (Ralph Algranti, LABE, oral commun., 1965). Thus, it is concluded here that those elevations in the Baldwin Hills area given by the LABE as adjusted with respect to both S–32 (or its equivalents) and tidal 8, tidal 10, or H–768 1946, may be treated as the approximate equivalents of those derived through a direct comparison with S–32.

PBM 68 (identified alternatively as DD)

I. The November 1911 elevation of DD has been given as 313.930 ft by the Department of Water and Power (DWP fieldbook 1458, p. 10). Its 1917 elevation has been given as 314.240 ft (DWP fieldbook 1579, p. 5); this figure, however, apparently was derived through a comparison with the elevation of a topographic saddle at the north end of the old Centinela Reservoir site that assumed that this saddle had remained unchanged in elevation between 1911 and 1917 (DWP fieldbook 1579, p. 4–5). There is, accordingly, no firm basis for assuming that the 1917 elevation of DD given above is anything more than a crude approximation, nor is there any basis for concluding that DD actually rose between 1911 and 1917.

A. Elevations of points derived from LABE bench mark elevations established prior to 1925—as was the 1911 elevation of DD—ordinarily are corrected to the datum employed by the LABE since 1925 through the addition of 5.775 ft (LABE Precise Bench Mark Index, p. 17).

1. The November 1911 elevation of DD with respect to the datum adopted by the LABE in 1925 accordingly would be given as: 313.930 ft + 5.775 ft = 319.705 ft.

II. In order to establish the 1911 elevation of DD with respect to the elevation of S–32 as fixed in the 1934 adjustment, the figure of 319.705 ft computed under I.A.1. should be amended as follows:

A. Datum correction:

1. The November 1911 elevation of DD may be treated provisionally as having been derived through a comparison with the elevation of a LABE precise bench mark located at Santa Barbara Avenue and Western Avenue (DWP fieldbook 1458, p. 1). The starting elevation of 136.912 ft at the Santa Barbara-Western precise bench mark utilized in the 1911 derivation of the elevation of DD was adjusted upward from an observed elevation of 136.899 ft, which was derived in March 1908 from the elevation of a LABE precise bench mark located at Wilshire Boulevard and Hoover Street (LABE-CE fieldbook 2726, p. 1); the basis for the adjustment was a closure of −0.015 ft on a precise bench mark whose elevation had been derived in turn from that given for the LABE precise bench mark at Wilshire and Hoover (LABE-CE fieldbook 2726, p. 24). The corrected elevation of the LABE precise bench mark located at Wilshire Boulevard and Hoover Street (LABE-CE fieldbook 2676, p. 30) was derived in turn in March 1908 from the corrected elevation for a U.S. Geological Survey bench mark located on a step at a

courthouse entrance (LABE-CE fieldbook 2676, p. 2). This U.S. Geological Survey bench mark must have been S–32 since its description and elevation (corrected to the post-1925 LABE datum) correspond almost precisely to that given for S–32 by the Geological Survey (Birdseye, 1925, p. 110).

a. 332.822 ft—elevation of S–32 as given by the LABE in March 1908 (LABE-CE fieldbook 2676, p. 2).
   338.631 ft—elevation of S–32 as given in the 1933–34 adjustment by the U.S. Coast and Geodetic Survey (1947, p. 28).

b. 338.631 ft −332.822 ft = 5.809 ft—datum correction to be added to elevations derived from S–32 (as fixed at 332.822 ft by the LABE) in order to bring them into conformity with the 1934 elevation of S–32 since employed by the LABE.

c. Accordingly, the following correction should be made to the 319.705-ft 1911 elevation of DD computed under I.A.1.:
   5.809 ft − 5.775 ft = +0.034 ft.

B. Movement correction for the LABE precise bench mark at Santa Barbara Avenue and Western Avenue:

1. The elevation of the LABE precise bench mark at Santa Barbara and Western was established in March 1908 (LABE-CE fieldbook 2726, p. 19).

2. The following adjusted elevations with respect to S–32 (or its approximate equivalents; that is, the USGS datum adopted in 1925, 37-54-26, S–32 and tidal 8, and so forth) have been recorded by the LABE for a precise bench mark (18–15330) located at the intersection of Santa Barbara and Western Avenues:
   1935—140.791 ft (LABE-CE fieldbook 16901, p. 26)
   1953—140.508 ft (LABE Precise Bench Mark Index)
   1960—140.240 ft (LABE Precise Bench Mark Index)

a. It is concluded on the basis of the longest period of observation at 18–15330, which best records the general history of vertical movement in this area, that the Santa Barbara-Western intersection has been subsiding with respect to S–32 at an average annual rate of about:

$$\frac{140.791\text{ ft} - 140.240\text{ ft}}{25\text{ yrs}} = 0.022\text{ ft/yr.}$$

(Although this computed rate of subsidence probably is the most objective figure obtainable, it is thought to constitute a maximum with respect to earlier periods, for Grant and Sheppard (1939, p. 302) have shown, in a rough way at least, that this same area was subsiding prior to 1939 at a rate of about 0.007 ft/yr.)

b. Accordingly, between March 1908 and November 1911 the LABE precise bench mark at Santa Barbara and Western is calculated to have subsided approximately (3.6 yrs) (0.022 ft/yr) = 0.079 ft below the elevation recorded in March 1908, so that its November 1911 elevation should have been 136.912 ft − 0.079 ft = 136.833 ft.

3. Since the 1911 elevation of DD has been derived in turn from the LABE precise bench mark at Santa Barbara and Western, the following correction should be made to the 319.705-ft 1911 elevation of DD computed under I.A.1.:
   136.833 ft − 136.912 = −0.079 ft.

C. Adjustment correction.

1. Hayes (1943, p. 16) has noted that parts of the level circuit fixing the 1911 elevation of DD "were rerun because of errors; questionable adjustments have been applied in the field notes; and unsound surveying methods were practiced to some extent." This indictment has precipitated a reevaluation of the original level data aimed at (1) a determination of the reliability of the surveying that produced the November 1911 elevation of DD; and (2) a more accurate, objective determination of the 1911 elevation of DD. The level circuit establishing the 1911 elevation of DD actually consisted of two separate loops: The first loop began with the LABE bench mark at Santa Barbara and Western, ran to a bench mark located at St. Mary's Academy (referred to herein as "B.M. St. Mary's") near the Crenshaw Boulevard–Slauson Avenue intersection, and closed on a LABE bench mark at Arlington and Slauson Avenues (DWP fieldbook 1458, p. 1–3, 30); the second loop began with B.M. St. Mary's, ran to DD (as a side shot) and closed on B.M. St. Mary's (DWP fieldbook 1458, p. 3–18, 26–29).

2. a. An elevation of 161.418 ft was derived for B.M. St. Mary's in 1911 through a comparison with the record elevation of

136.912 ft for the LABE precise bench mark located at Santa Barbara and Western (DWP fieldbook 1458, p. 1,3).

(1.) Employment of the above elevation as a starting elevation for B.M. St. Mary's led to a closure of −0.122 ft on a LABE bench mark located at Arlington and Slauson (DWP fieldbook 1458, p. 30). The 1908 record elevation for the Arlington-Slauson bench mark utilized in the determination of this closure (DWP fieldbook 1458, p. 30; LABE-CE fieldbook 2577, p. 16), however, was 0.032 ft below that obtained through a virtually contemporaneous, direct tie with the LABE precise bench mark located at Santa Barbara and Western (LABE-CE fieldbook 2458, p. 17, 39; LABE-CE fieldbook 2577, p. 16). Because both elevations are corrected profile elevations, there is no basis for choosing between them; acceptance of an averaged record elevation for the Arlington-Slauson bench mark leads to a closure of about −0.138 ft.

(2.) Since bench mark 18–14630, located at Van Ness and Slauson Avenues (one block east of Arlington and Slauson), subsided between 1935 and 1956 at an average rate of about 0.359 ft/21 yrs = 0.0171 ft/yr with respect to bench mark 18–15330 located at Santa Barbara and Western (see LABE-CE fieldbook 16901, p. 26 and LABE Precise Bench Mark Index), the Arlington-Slauson intersection is calculated to have subsided about (0.0171 ft/yr) (3.75 yrs) = 0.064 ft with respect to the Santa Barbara-Western intersection between the February 15, 1908, date of plotting of the old LABE bench mark at Arlington and Slauson (LABE-CE fieldbook 2577, p. 1, 16) and November 1911. Therefore, acceptance of the 1908 record elevations for the Santa Barbara-Western and Arlington-Slauson bench marks should have led to an instrumentally perfect closure of about −0.064 ft for a level survey run between these points in November 1911; the "corrected" closure, accordingly, is computed to have been −(0.138 ft −0.064 ft) = −0.074 ft. A prorated adjustment based on the number of turns between B.M. St. Mary's and the Santa Barbara-Western bench mark and B.M. St. Mary's and the Arlington-Slauson bench mark (DWP fieldbook 1458, p. 1–3, 30) leads to an adjusted November 1911 elevation for B.M. St. Mary's of 161.418 ft + (16/22) (0.074 ft) = 161.472 ft.

b. Mr. L. M. Charles (written commun., 1965) of the Department of Water and Power, has carefully reconstructed the circuit B.M. St. Mary's (arbitrarily assigned a starting elevation of 161.540 ft)—DD—B.M. St. Mary's through a coupling of the second run, corrected rod readings for the first part of the circuit (DWP fieldbook 1458, p. 26–30) with the original (and apparently acceptable) rod readings for the second part of the circuit (DWP fieldbook 1458, p. 10–18), as shown below:

+	H.I.	−	Elevation (in ft.)	Adjusted elevation (in ft.)
B.M. St. Mary's Pg. 26:			161.540	
11.030	172.570			
		1.060	171.510	
11.580	183.090			
		0.720	182.370	
9.425	191.795			
		0.835	190.960	
11.540	202.500			
		0.605	201.895	
10.470	212.[365]			
		0.880	211.485	
11.330	222.815			
		0.680	222.135	
9.790	231.925			
		3.195	228.730	
11.810	240.540			
		0.610	239.930	
4.920	244.850			
		11.100	233.750	
9.830	243.580			
		0.620	242.960	
4.035	246.995			
		1.370	245.625	
11.590	257.215			
		0.510	256.705	
11.760	268.465			
		0.545	267.920	
11.162	279.082			
		0.600	278.482	
11.115	289.597			
Pg. 27–Contour-point-check:		4.415	285.182	285.193
		0.510	289.087	
11.395	300.482			
		0.565	299.917	
10.710	310.627			
		0.585	310.042	
11.090	321.132			
		1.770	319.362	
1.820	321.182			
		0.975	320.207	
4.620	324.827			
		5.420	319.407	
11.595	331.002			
		2.660	[3]28.342	
10.885	[3]39.227			

	+	H.I.	–	Elevation (in ft.)	Adjusted elevation (in ft.)
			5.935	[3]33.292	
	11.120	344.412			
			11.290	333.122	
	0.750	333.872			
			7.600	326.272	
	6.590	332.862			
			11.280	321.582	
	2.800	324.382			
B.M. Pg.29:			8.190	316.192	316.211
	5.730	321.922			
			7.610	314.312	
	0.920	315.232			
			1.900	313.332	
	11.000	324.332			
			0.780	323.552	
	11.890	335.442			
			1.130	334.312	
	0.530	334.842			
			11.430	323.412	
	0.470	323.882			
"D.D." Pg. 29:			10.000	313.882	313.906
B.M.-2×2 Stk. marked			8.340	315.542	315.566
"315.675" Pg. 29:			11.660	312.222	
	0.170	312.392			
B.M. #1 Pg. 30:			10.855	301.537	301.562

B.M. #1 300.705 }
B.M. #3 299.925 } Page 10 - F.B. 1458

.780 Difference in elevation

B.M. #1 301.537
.780

B.M. #3 300.757 Elevation relative to B.M. #1 in above circuit

	+	H.I.	–	Elevation (in ft.)	Adjusted elevation (in ft.)
B.M. #3 Pg. 10:				300.757	300.782
	3.930	304.687			
			3.355	301.332	
	0.815	302.147			
			1.805	300.342	
	1.170	301.512			
			1.770	299.742	
	5.035	304.777			
			9.170	295.607	
	10.720	306.327			
B.M. Pg. 11:			3.040	303.287	303.315
			9.080	297.247	
	10.355	307.602			
			0.555	307.047	
	9.775	316.822			
			0.520	316.302	
	10.530	326.832			
			1.370	325.462	
	9.760	335.222			
			1.870	333.352	
	5.345	338.697			
			6.730	331.967	
	4.500	336.467			
			9.630	326.837	
	11.145	337.982			
B.M. Pg. 12:			3.450	334.532	334.566
			0.790	337.192	
	11.950	349.142			
			1.160	347.982	
	11.790	359.772			
			0.630	359.142	
	11.080	370.222			
			0.720	369.502	
	10.660	380.162			
			0.620	379.542	
	11.530	391.072			
			1.590	389.482	
	10.550	400.032			
			0.690	399.342	
	11.790	411.132			
			0.470	410.662	
	10.930	421.592			
			0.790	420.802	

	+	H.I.	–	Elevation (in ft.)	Adjusted elevation (in ft.)
	10.305	431.107			
			0.640	430.467	
	10.850	441.317			
			0.240	441.077	
	11.990	453.067			
			0.685	452.382	
	11.745	464.127			
			0.400	463.727	
	11.770	475.497			
			0.510	474.987	
	11.410	486.397			
			0.790	485.607	
	10.915	496.522			
B.M. Pg. 14:			2.965	493.557	493.602
	0.630	494.187			
			9.370	484.817	
	2.235	487.052			
			8.135	478.917	
	0.680	479.597			
			5.800	473.797	
	5.150	478.947			
			11.295	467.652	
	0.730	468.382			
			10.775	457.607	
	0.450	458.057			
			10.780	447.277	
	2.360	449.637			
			2.210	447.427	
	11.065	458.492			
			1.330	457.162	
	2.580	459.742			
			11.940	447.802	
	2.370	450.172			
			11.060	439.112	
	1.370	440.482			
			11.720	428.762	
	0.390	429.152			
			11.870	417.282	
	0.430	417.712			
B.M. Pg. 15:			11.790	405.922	405.976
	1.095	407.017			
			11.790	395.227	
	0.135	395.362			
			11.330	384.032	
	0.915	384.947			
			11.490	373.457	
	0.790	374.247			
			10.855	363.392	
	0.650	364.042			
			11.245	352.797	
	0.865	353.662			
			11.895	341.767	
	0.905	342.672			
			11.740	330.932	
	0.820	331.752			
			11.405	320.347	
	0.870	321.217			
			11.385	309.832	
	0.380	310.212			
B.M. Pg. 16:			11.765	298.447	298.509
	0.410	298.857			
			10.950	287.907	
	1.025	288.932			
			10.475	278.457	
	6.420	284.877			
			11.330	273.547	
	0.630	274.177			
			10.450	263.727	
	0.310	264.037			
			11.670	252.367	
	0.320	252.687			
			10.080	242.607	
	0.530	243.137			
			10.060	233.077	
	0.565	233.642			
			11.705	221.937	
	0.170	222.107			
			11.590	210.517	
	1.400	211.917			

+	H.I.	−	Elevation (in ft.)	Adjusted elevation (in ft.)
		10.760	201.157	
1.290	202.447			
		9.455	192.992	
1.030	194.022			
		9.175	184.847	
1.060	185.907			
		10.640	175.267	
0.650	175.917			
		9.725	166.192	
2.005	168.197			
B.M. St. Mary's Pg. 18:		6.730	161.467	161.540

161.540
161.467
0.073 = error of closure for 98 T.P.'s
.000745 = plus correction to be applied per T.P.

This procedure, as shown above, leads to a closure of −0.073 ft, thereby providing a measure of the surveying accuracy, and an adjusted elevation for DD of 313.906 ft. Employment of the corrected starting elevation of 161.472 ft deduced above for B.M. St. Mary's would lead to the following corrected elevation for DD:

313.906 ft − (161.540 ft − 161.472 ft) = 313.838 ft.

3. Because the November 1911 elevation of DD derived from the 1908 record elevation for the LABE Santa Barbara-Western precise bench mark has been given previously as 313.930 ft, whereas the November 1911 elevation of DD derived from this same basis is recomputed above to have been 313.838 ft, the following correction should be made to the 319.705-ft 1911 elevation of DD computed under I.A.1.:

313.838 ft −313.930 ft = −0.092 ft.

D. The total correction to be applied to the 1911 elevation of DD of 319.705 ft computed under I.A.1., accordingly, is given as:

+0.034 ft − 0.079 ft − 0.092 ft = − 0.137 ft.

III. The November 1911 elevation of PBM 68 (DD) with respect to S–32 as fixed in the 1934 adjustment, accordingly, is calculated to have been:

319.705 ft − 0.137 ft = 319.568 ft.

Hollywood E–11 (PBM 40)

I. Hollywood E–11 was chosen as a datum control point and its elevation fixed at 470.304 ft as of December 1, 1939 (DWP filecard for PBM 40)

A. The elevation of 470.304 ft for Hollywood E–11 has been employed as the datum elevation (or has in turn fixed the elevation of adjacent bench mark PBM 40–C as the datum elevation) in the calculation of elevations of bench marks subsequently occupied in connection with studies of subsidence in the Baldwin Hills by the Los Angeles Department of Water and Power (Hayes, 1947, p. 8; Walley, 1963, p. 3).

II. In order to establish the 1911 elevation of Hollywood E–11 with respect to the elevation of S–32 as fixed in the 1934 adjustment, the figure of 470.304 ft given under I. should be amended as follows:

A. Adjustment correction:

1. The elevation of Hollywood E–11 of 470.304 ft is an adjusted elevation based on an assumption of stability between PBM 1 (located at Centinela Avenue and Market Street—see fig. 8) and PBM 58 (located at Washington Boulevard and Vineyard Avenue—fig. 8) (Hayes, 1959, p. 12).

However, PBM 1 has been generally subsiding with respect to PBM 58 (10–W; 12–01050) (see profile of elevation changes along level circuit C—fig. 11).

2. An unadjusted 1939 elevation of Hollywood E–11 with respect to PBM 58 may be computed by adding the observed elevation difference between PBM 58 and Hollywood E–11 to the LABE elevation of PBM 58 accepted by the Department of Water and Power in 1939:

a. 470.740 ft − 162.320 ft = 308.420 ft—elevation difference between PBM 58 and Hollywood E–11 (DWP fieldbook 2604, p. 9, 17).

161.860 ft—LABE elevation of PBM 58 accepted by the Department of Water and Power in 1939 (DWP fieldbook 2604, p. 17).

b. 308.420 ft + 161.860 ft = 470.280 ft—1939 elevation of Hollywood E–11 with respect to PBM 58 as fixed at 161.860 ft.

3. The elevation of Hollywood E–11 of 470.280 ft (with respect to PBM 58) is a more objectively determined elevation than 470.304 ft, since it does not assume stability between PBM 1 and PBM 58.

4. Therefore, the following correction should be made to the 470.304-ft 1939 elevation of Hollywood E–11 given under I.:

470.280 ft − 470.304 ft = − 0.024 ft.

B. Datum correction:

1. The record elevation of the Civic Center basic control point 37–54–26 (S–32 equivalent) employed by the LABE in its 1934 general leveling of Los Angeles has been given as 327.306 ft (Grant and Sheppard, 1939, p.

300; LABE Precise Bench Mark Index, p. 20). The elevation of 37–54–26 determined in the 1934 adjustment of the U.S. Coast and Geodetic Survey (1947, p. 28) has been given as 327.309 ft.

a. Accordingly, in order to bring into conformity the elevations established by the LABE in its 1934 general leveling survey with those simultaneously derivable through a comparison with S–32 (37–54–26 equivalent) as fixed in the 1934 adjustment, 327.309 ft − 327.306 ft = 0.003 ft should be added to those elevations derived from 37–54–26 in the LABE general leveling of 1934.

2. The 161.860-ft elevation of PBM 58 (10–W; 12–01050), accepted by the Department of Water and Power in 1939 (DWP fieldbook 2604, p. 17), was established in May 1933 in connection with the LABE 1934 general leveling survey (LABE-CE fieldbook 16980, p. 1, 6).

a. Accordingly, the May 1933 elevation of PBM 58 with respect to S–32 as fixed in the 1934 adjustment is calculated to have been:

161.860 ft + 0.003 ft = 161.863 ft.

3. Because the 1939 elevation of Hollywood E–11 has been derived in turn from PBM 58 as fixed at 161.860 ft (II.A.2.a.), the following correction should be made to the 470.304-ft 1939 elevation of Hollywood E–11 given under I.:

161.863 ft − 161.860 = +0.003 ft.

C. Movement correction for PBM 58:

1. Elevations of PBM 58 (10–W; 12–01050) with respect to S–32 (or its equivalents) have been recorded as:

Date	*Elevation (in ft)*	*Source*
1933	161.863	II.B.2.a. (above)
1949	161.784	LABE Precise Bench Mark Index
1953	161.743	Do.
1955	161.694	Do.
1956	161.684	Do.
1960	161.636	Do.

a. The average annual rate of subsidence of PBM 58 with respect to S–32 for the period 1933–60, accordingly, is calculated to have been:

$$\frac{161.863 \text{ ft} - 161.636 \text{ ft}}{27 \text{ yrs}} = 0.00841 \text{ ft/yr.}$$

2. Extrapolation backwards of the 1933–60 average rate of subsidence of PBM 58 permits the following calculation of subsidence of PBM 58 with respect to S–32 between November 1911 and May 1933:

(0.00841 ft/yr) (21.5 yrs) = 0.181 ft.

a. This calculation of subsidence at PBM 58 may be slightly high. Since, as shown under II.C.1., the apparent rate of subsidence of PBM 58 during the period 1933–49 was roughly half that which obtained during the interval 1949–60, the rate of subsidence over the period 1911–33 may be better reflected by the subsidence that accrued during the immediately following period, 1933–49, than it is by subsidence measured over the entire period 1933–60. (It is not known for certain, of course, whether the apparent increase in the rate of subsidence of PBM 58 between 1933–49 and 1949–60 reflects an actual acceleration of movement or resulted instead from the two-point adjustment procedure used in 1949 and subsequent years; it is assumed to reflect a real increase in rate of movement for reasons brought out in the prefatory note.) Other things being equal, the most objective calculation of the average annual rate of subsidence of PBM 58 should employ the longest period of observation possible; thus the average figure of 0.00841 ft/yr is accepted here as a basis for computation of the subsidence of PBM 58 between 1911 and 1933.

3. Inasmuch as PBM 58 is calculated to have subsided 0.181 ft. with respect to S–32 between November 1911 and May 1933, its November 1911 elevation must have been 0.181 ft greater than that given for May 1933 under II.A.2.

a. Thus, the November 1911 elevation of PBM 58 with respect to the 1933 datum employed by the LABE is calculated to have been:

161.860 ft + 0.181 ft = 162.041 ft.

4. Because the 1939 elevation of Hollywood E–11 has been derived in turn from the elevation of PBM 58 as fixed in May 1933 (II.A.2.), an evaluation of its 1939 elevation with respect to PBM 58 as fixed in November 1911 requires that the following correction be made to the 1939 elevation of Hollywood E–11 of 470.304 ft given under I.:

162.041 ft − 161.860 ft = +0.181 ft.

D. Movement correction for PBM 40 (Hollywood E–11):

1. The profile of elevation changes along level line C shows that Hollywood E–11 has been undergoing measurable changes in elevation with respect to PBM 58 since 1939; it is assumed that comparable changes in elevation took place between 1911 and 1939.
2. The average annual rate of change in elevation of Hollywood E–11 with respect to PBM 58 may be calculated through a comparison of elevation differences between these two points through time.
   a. Elevation differences between Hollywood E–11 and PBM 58 for three separate points in time between 1939 and 1962 are computed as follows:

December 1939:
470.740 ft; observed elevation of Hollywood E–11
(DWP fieldbook 2604, p. 9)
162.320 ft; observed elevation of PBM 58
(DWP fieldbook 2604, p. 17)
308.420 ft; elevation difference between Hollywood E–11 and PBM 58

October 1946:
470.273 ft; observed elevation of Hollywood E–11
(DWP filecard for PBM 40)
161.976 ft; observed elevation of PBM 58
(DWP filecard for PBM 58)
308.297 ft; elevation difference between Hollywood E–11 and PBM 58

April 1962:
456.743 ft; observed elevation of PBM 40–C
(DWP filecard for PBM 40–C)
162.065 ft; observed elevation of PBM 58
(DWP filecard for PBM 58)
294.678 ft; elevation difference between PBM 40–C and PBM 58
13.496 ft; elevation difference between Hollywood E–11 and PBM 40–C (DWP filecards for PBM 40 and PBM 40–C)
308.174 ft; elevation difference between Hollywood E–11 and PBM 58

   b. Use of the longest period over which elevation differences between Hollywood E–11 and PBM 58 have been measured indicates that Hollywood E–11 has been subsiding with respect to PBM 58 at an average annual rate of about:

$$\frac{308.420 \text{ ft} - 308.174 \text{ ft}}{22.4 \text{ yrs}} = 0.01098 \text{ ft/yr.}$$

Were the shorter period of observation, 1946–62, utilized in the above computation, it would lead to a lower rate of subsidence; accordingly, since elevation measurements between Hollywood E–11 and PBM 58 over the period 1946–62 were of a higher order of precision than those obtained prior to 1946 (Hayes, 1959, p. 12), the calculated rate of 0.01098 ft/yr probably represents a maximum average figure for the subsidence of Hollywood E–11 with respect to PBM 58.

3. Extrapolation backwards of the 1939–60 average annual rate of subsidence of Hollywood E–11 permits the following calculation of subsidence of Hollywood E–11 with respect to PBM 58 between November 1911 and December 1939:
(0.01098 ft/yr) (28.09 yrs) = 0.308 ft.
4. Because Hollywood E–11 is calculated to have subsided 0.308 ft with respect to PBM 58 between November 1911 and December 1939, its November 1911 elevation with respect to PBM 58 must have been 0.308 ft greater than that given for December 1939; thus the following correction should be made to the 470.304-ft elevation of Hollywood E–11 given under I.:
470.612 ft − 470.304 ft = +0.308 ft.

E. The total correction to be applied to the 1939 elevation of Hollywood E–11 of 470.304 ft listed under I, accordingly, is given as:
−0.024 ft +0.003 ft +0.181 ft +0.308 ft = +0.468 ft.

III. The November 1911 elevation of Hollywood E–11 (PBM 40) with respect to S–32 as fixed in the 1934 adjustment, accordingly, is calculated to have been:
470.304 ft + 0.468 ft = 470.772 ft.

APPENDIX D

Determinations of subsidence of PBM 68 with respect to Hollywood E–11 (fig. 8).

I. Since 1917, as given by the Department of Water and Power (DWP filecard for PBM 68).

A. The 1917 elevation of PBM 68 was derived from the elevation of a topographic saddle within the area of the old Centinela Reservoir survey (DWP fieldbook 1579, p. 4–5) and can only be assumed to match the 1917 elevation of this point derivable through a comparison with Hollywood E–11; subsequent elevations have been measured with respect to Hollywood E–11 as fixed at 470.304 ft (DWP filecard for PBM 68).

Date	Elevation of PBM 68 (in ft)	Cumulative subsidence of PBM 68 (in ft)
12/1917	320.015	
10/25/1943	317.428	2.587
10/31/1946	317.141	2.874
4/11/1950	316.753	3.262
6/5/1950	316.745	3.270
9/28/1954	316.120	3.895
10/7/1958	315.651	4.364
6/15/1962	315.254	4.761

II. Since 1911.

A. It is assumed here that the 1939 elevation of Hollywood E–11 is the equivalent of one which has been derived from and has remained fixed with respect to the datum control point from which the 1911 elevation of PBM 68 was derived. The 1911 elevation of PBM 68 was derived by the Department of Water and Power through a comparison with a LABE precise benchmark at Santa Barbara and Western Avenues (DWP fieldbook 1458, p. 10) and corrected to the post-1925 Los Angeles city datum (see appendix C, PBM 68 I.); subsequent elevations are with respect to Hollywood E–11 as fixed at 470.304 ft (DWP filecard for PBM 68).

Date	Elevation of PBM 68 (in ft)	Cumulative subsidence of PBM 68 (in ft)
11/1911	319.705	
10/25/1943	317.428	2.277
10/31/1946	317.141	2.564
4/11/1950	316.753	2.952
6/5/1950	316.745	2.960
9/28/1954	316.120	3.585
10/7/1958	315.651	4.054
6/15/1962	315.254	4.451

III. Since 1911.

A. Calculated with respect to Hollywood E–11 as fixed in elevation since November 1911.

1. The 1911 elevation of Hollywood E–11 has been derived through a comparison with S–32 as fixed in the 1934 adjustment and is calculated to have been 470.772 ft (see appendix C, PBM 40). Accordingly, 470.772 ft – 470.304 ft = 0.468 ft have been added to all elevations derived from Hollywood E–11 as fixed at 470.304 ft in order to obtain their elevations with respect to Hollywood E–11 as fixed in elevation since November 1911.

2. The 1911 elevation of PBM 68 has been derived through a comparison with S–32 as fixed in the 1934 adjustment and is calculated to have been 319.568 ft (see appendix C, PBM 68).

Date	Elevation of PBM 68 (in ft)	Cumulative subsidence of PBM 68 (in ft)
11/1911	319.568	
10/25/1943	317.896	1.672
10/31/1946	317.609	1.959
4/11/1950	317.221	2.347
6/5/1950	317.213	2.355
9/28/1954	316.588	2.980
10/7/1958	316.119	3.449
6/15/1962	315.722	3.846

IV. January 4–12, 1934–October 13–25, 1943.

A. PBM 68 and PBM 31 (Baldwin Aux—fig. 8) subsided with respect to Hollywood E–11 between 1943 and 1962 as shown below (DWP filecards for PBM 68 and PBM 31).

PBM 68		Ratio of subsidence PBM 68 / PBM 31	PBM 31	
Time interval	Subsidence (in ft)		Time interval	Subsidence (in ft)
10/25/43–10/31/46 (3 yr ½ wk)	0.287	1.550	10/13/43–10/9/46 (2 yr 11 mo 3½ wk)	0.185
10/31/46–4/11/50 (3 yr 5 mo 1½ wk)	.388	2.155	10/9/46–3/15/50 (3 yr 5 mo 1 wk)	.180
4/11/50–9/28/54 (4 yr 5 mo 2½ wk)	.633	1.906	3/15/50–8/19/54 (4 yr 5 mo ½ wk)	.332
9/28/54–10/7/58 (4 yr 1 wk)	.469	1.892	8/19/54–8/18/58 (4 yr)	.248
10/7/58–6/15/62 (3 yr 8 mo 1 wk)	.397	3.545	8/18/58–4/25/62 (3 yr 8 mo 1 wk)	.112
10/25/43–10/7/58 (14 yr 11 mo 2 wk)	1.777	1.880	10/13/43–8/18/58 (14 yr 10 mo 1 wk)	.945
10/25/43–6/15/62 (18 yr 7 mo 3 wk)	2.174	2.058	10/13/43–4/25/62 (18 yr 6 mo 2 wk)	1.057

1. As shown in the center column above, the ratios of subsidence of PBM 68 to subsidence of PBM 31 held roughly constant during the period 1943–58; the maximum divergence in these ratios (from 1.550 to 2.155) was approximately 39 percent.

2. A sharp change in the relative rates of subsidence of PBM 68 and PBM 31 is indicated for the period 1958–62. The maximum divergence in the ratio of the subsidence of one to that of the other (from 1.550 to 3.545) for the period 1943–62 was approximately 129 percent, about three times as great as that for the period 1943–58.

3. In order to obtain the most representative estimate of the subsidence of PBM 68/subsidence of PBM 31 with respect to Hollywood E–11 for the period 1934–43 through extrapolation backward from the

post-1943 period, the period 1958–62 should be regarded as probably aberrant and excluded from consideration in the calculation of this ratio. (The validity of this approach is reinforced by the fact that the 1958–62 interval is relatively remote from the 1934–43 period of interest).

4. Nevertheless, two sets of figures for the subsidence of PBM 68 between 1934 and 1943 are derived: (A) those calculated from a comparison of the subsidence at PBM 68 with that at PBM 31 between 1943 and 1958; (B) those calculated from a comparison of the subsidence at PBM 68 with that at PBM 31 between 1943 and 1962.
   a. Since the figures associated with set B involve a probable aberration in movement between PBM 68 and PBM 31, the figures associated with set A are considered far more reliable.
5. Therefore, the subsidence of PBM 68 with respect to Hollywood E–11/the subsidence of PBM 31 with respect to Hollywood E–11 (including a correction for the minor differences in the increments of time over which subsidence at the two bench marks was measured) has averaged:

(A) (1943–58)

$$\frac{1.777 \text{ ft}}{0.945 \text{ ft} + 0.006 \text{ ft}} = 1.870.$$

(B) (1943–62)

$$\frac{2.174 \text{ ft}}{1.057 \text{ ft} + 0.003 \text{ ft}} = 2.050.$$

B. PBM 31 subsided approximately 0.404 ft with respect to PBM 71 (W–169—fig. 8) between January 1934 and October 1943 (Hayes, 1943, fig. 5). This is precisely the figure obtained, moreover, through a direct comparison of the elevation differences between PBM 31 and PBM 71 that existed in January 1934 and October 1943 respectively:

January 4–12, 1934; 189.593 ft	(U.S. Coast and Geodetic Survey, 1947, p. 1, 25–26)
October 13–25, 1943; −189.189 ft	(DWP filecards for PBM 31 and PBM 71; DWP fieldbook 2769, p. 26, 51)
0.404 ft.	

1. Elevations of PBM 71 with respect to Hollywood E–11 for the period October 25, 1943, to October 22, 1962, ranged as follows (DWP filecard for PBM 71):

Date	*Elevation in feet*
10/25/43	322.469
11/5/46	322.578
4/14/50	322.587
11/18/54	322.594
11/14/58	322.630
10/22/62	322.612

a. It is concluded, therefore, that for the period 1943–62, PBM 71 changed in elevation with respect to Hollywood E–11 at the average rate:

$$\frac{322.612 \text{ ft} - 322.469 \text{ ft}}{19 \text{ yrs}} = . +0.0075 \text{ ft/yr}.$$

b. Extrapolation of this rate backward in time to the period 1934–43 indicates that PBM 71 rose approximately (9.75 yrs) (0.0075 ft/yr) = 0.073 ft with respect to Hollywood E–11 between January 1934 and October 1943.

2. Therefore, between January 4–12, 1934, and October 13–25, 1943, subsidence of PBM 31 with respect to Hollywood E–11 is computed to have been:

$$0.404 \text{ ft} - 0.073 \text{ ft} = 0.331 \text{ ft}.$$

C. Adoption of the post-1943 ratios of the subsidence of PBM 68 to the subsidence of PBM 31 (IV.A.5.) for the period 1934–43 permits the following calculations of subsidence of PBM 68 with respect to Hollywood E–11 for the period January 4–12, 1934 to October 13–25, 1943:

(A) (0.331 ft) (1.870) = 0.619 ft,
(B) (0.331 ft) (2.050) = 0.679 ft.

V. October 29, 1926–April 7, 1931.

A. PBM 68 and the site of L.A. County BM 4 (not recovered after 1931) (fig. 8), located 185± feet south of Standard Oil Co. well Stocker 8 (L.A. County level book 302, p. 6), which is in turn located about 100 feet south-southwest of the Overhill Drive–LaBrea Avenue intersection, subsided with respect to Hollywood E–11 between 1950 and 1962 as shown below (DWP filecard for PBM 68; Hayes, 1955, fig. 1; Hayes, 1959, fig. 1; Walley, 1963, fig. 1):

Time interval	Subsidence of PBM 68 (in ft)	Calculated subsidence at the site of L.A. County BM 4 (in ft)	PBM 68/BM 4
4/11/50–9/28/54 (4 yr 5 mo 2½ wk)	0.633	0.380	1.666
9/28/54–10/7/58 (4 yr 1 wk)	.469	.286	1.640
10/7/58–6/15/62 (3 yr 8 mo 1 wk)	.397	.148	2.682
4/11/50–10/7/58	1.102	.666	1.654
4/11/50–6/15/62	1.499	.814	1.841

1. As shown in the right-hand column above, PBM 68 and BM 4 subsided at roughly proportionately constant rates during the period 1950–58.
2. A sharp change in the relative rates of subsidence of PBM 68 and BM 4 is indicated for the period 1958–62.
3. In order to obtain the most representative estimate of the subsidence of PBM 68/subsidence of BM 4 for the period 1926–31 through extrapolation backward from the post-1950 period, the period 1958–62 should be regarded as probably aberrant (just as it appeared to be for the subsidence of PBM 68/subsidence of PBM 31) and excluded from consideration in the calculation of this ratio.
4. Nevertheless, two sets of figures for the subsidence of PBM 68 between 1926 and 1931 are derived: (A) those calculated from a comparison of the subsidence of PBM 68 with that at the site of BM 4 between 1950 and 1958; (B) those calculated from a comparison of the subsidence of PBM 68 with that at the site of BM 4 between 1950 and 1962.
   a. Since the figures associated with set B involve a probable aberration in movement between PBM 68 and BM 4, those figures associated with set A are again considered far more reliable.
5. Therefore, the subsidence of PBM 68 with respect to Hollywood E–11/subsidence of BM 4 with respect to Hollywood E–11 has averaged:

   (A) (1950–58); 1.654,
   (B) (1950–62); 1.841.

B. 1. L.A. County BM 2 is located at the intersection of Overhill Drive and Fairview Avenue (L.A. County level book 302, p. 5), about 1,000 feet east of PBM 3. The profile of elevation changes along level line C shows that PBM 3 has remained almost precisely stable with respect to PBM 1.
   a. Since BM 2 lies within this relatively stable zone, its stability is assumed to have matched that of PBM 3, and it is concluded as a corollary that BM 2 has remained unchanged in elevation with respect to PBM 1. The probable stability of BM 2 with respect to PBM 1 may be corroborated in the following manner: Between 1922–26 and 1943 BM 2 is thought to have subsided about 0.003 ft with respect to USGS BM 16 located approximately 3,800 feet south-southwest of PBM 1 (Hayes, 1943, p. 10–11). Between 1933–35 and 1943 BM 16 subsided about 0.026 ft with respect to PBM 1 (Hayes, 1943, figs. 2, 3). It seems unlikely, accordingly, that the elevation of BM 2 has changed with respect to PBM 1 at a rate in excess of about 0.003 ft/yr.
2. The profile of elevation changes along level line C shows that Hollywood E–11 subsided about 0.028 ft with respect to PBM 1 between October 1946 and April 1962.
   a. It is concluded, accordingly, that during the period 1946–62, Hollywood E–11 changed in elevation with respect to PBM 1 at the following average rate:

$$\frac{-0.028 \text{ ft}}{15.5 \text{ yr}} = -0.0018 \text{ ft/yr}.$$

   b. Extrapolation of this rate backward to the period 1926–31 indicates that Hollywood E–11 subsided approximately (4.5 yr) (0.0018 ft/yr) = 0.008 ft with respect to PBM 1 between October 29, 1926, and April 7, 1931.
3. Therefore, between October 29, 1926 and April 7, 1931, Hollywood E–11 is computed to have subsided only 0.008 ft with respect to BM 2.

C. Observed elevations of BM 4 with respect to a fixed elevation of 186.785 ft at BM 2 have been recorded as follows (L.A. County level book 302, p. 4, 6, 196, 198):

   10/29/26 450.085 ft,
   4/7/31 449.530 ft.

1. Accordingly, BM 4 subsided 0.555 ft with respect to BM 2 between October 29, 1926, and April 7, 1931. Hayes' (1943, p. 12) figure of 0.635 ft apparently was based on a comparison between the 1926 observed elevation and a 1931 adjusted elevation that involved a substantial adjustment in BM 2 as well as BM 4.
2. Since Hollywood E–11 is computed to have subsided 0.008 ft with respect to BM 2 during the period 1926–31, BM 4 apparently subsided about 0.555 ft −0.008 ft = 0.547 ft with respect to Hollywood E–11 between October 29, 1926, and April 7, 1931.

D. Adoption of the post-1950 ratios of subsidence of PBM 68 to subsidence of BM 4 (V.A.4.) for the period 1926–31 permits the following calculations of subsidence of PBM 68 with respect to

Hollywood E–11 for the period October 29, 1926, to April 7, 1931:

(A) (0.547) (1.654) = 0.905 ft,

(B) (0.547) (1.841) = 1.007 ft.

VI. November 29, 1939–October 13, 1943.

A. PBM 31 (Baldwin Aux) subsided 0.171 ft with respect to Hollywood E–11 between November 29, 1939, and October 13, 1943 (DWP filecard for PBM 31).

1. Adoption of the post-1943 ratios of subsidence of PBM 68 to subsidence of PBM 31 (IV.A.5.) permits the following calculations of subsidence of PBM 68 with respect to Hollywood E–11 for the period November 29, 1939, to October 13, 1943:

(A) (0.171 ft) (1.870) = 0.320 ft,

(B) (0.171 ft) (2.050) = 0.351 ft.

VII. January 4–12, 1934–November 29, 1939.

A. Subsidence of PBM 68 with respect to Hollywood E–11 between January 4–12, 1934, and October 13–25, 1943, has been calculated at (A) 0.619 ft and (B) 0.679 ft (IV.C.).

B. The subsidence of PBM 68 with respect to Hollywood E–11 between November 29, 1939, and October 13, 1943, has been calculated at (A) 0.320 ft and (B) 0.351 ft (VI.A.1.).

C. Assuming that the average elevation of PBM 68 for the period October 13–25, 1943 matched that which obtained on October 13, 1943, subsidence of PBM 68 with respect to Hollywood E–11 between January 4–12, 1934 and November 29, 1939, may be calculated by difference:

(A) 0.619 ft − 0.320 ft = 0.299 ft,

(B) 0.679 ft − 0.351 ft = 0.328 ft.

VIII. April 7, 1931–January 4–12, 1934.

A. There are no known elevation measurements that can be used in calculating directly the subsidence of PBM 68 for the period April 7, 1931–January 4–12, 1934.

1. Subsidence of PBM 68 with respect to Hollywood E–11 for the period April 7, 1931–January 4–12, 1934, accordingly, is computed here through calculation of the average rate of subsidence of PBM 68 over the intervals of measurement immediately preceding and immediately following this 2.75-year period.

a.

Time interval	Subsidence of PBM 68 (in ft)
October 29, 1926–April 7, 1931	(A)0.905 ft; (B)1.007 ft (V.D.)
January 4–12, 1934–October 13–25, 1943	(A)0.619 ft; (B)0.679 ft (IV.C.)

b. The average rate of subsidence of PBM 68 over the two collective intervals is calculated to have been:

$$\text{(A)}\quad \frac{0.905\text{ ft} + 0.619\text{ ft}}{4.44\text{ yr} + 9.78\text{ yr}} = 0.1071\text{ ft/yr},$$

$$\text{(B)}\quad \frac{1.007\text{ ft} + 0.679\text{ ft}}{4.44\text{ yr} + 9.78\text{ yr}} = 0.1185\text{ ft/yr}.$$

c. Subsidence of PBM 68 with respect to Hollywood E–11 for the period April 7, 1931–January 4–12, 1934 is calculated to have been:

(A) (2.75 yr) (0.1071 ft/yr) = 0.295 ft,

(B) (2.75 yr) (0.1185 ft/yr) = 0.326 ft.

IX. April 7, 1931–October 1943.

A. Subsidence of PBM 68 with respect to Hollywood E–11 between April 7, 1931, and October 1943 may be computed directly through a comparison with the subsidence at the site of L.A. County bench mark BM M4.

1. According to Hayes (1943, p. 11–12), BM M4, a chiseled cross set in an iron bolt at the southeast corner of Standard Oil Co. Stocker 10 derrick (L.A. County level book 302, p. 199), located about 600 feet south-southwest of the LaBrea Avenue–Overhill Drive intersection, subsided 0.517 foot between 1931 and October 1943. Hayes' statement implies that this subsidence was with respect to L.A. County BM 2 (at Fairview Avenue and Overhill Drive), but the datum was unspecified.

a. It is assumed that Hollywood E–11 has subsided with respect to BM 2 at a constant rate of 0.0018 ft/yr (V.B.2.a.). Hollywood E–11, accordingly, is calculated to have subsided about (12.5 yr) (0.0018 ft/yr) = 0.023 ft with respect to BM 2 between April 7, 1931, and October 1943; it is thus concluded that BM M4 subsided 0.517 ft − 0.023 ft = 0.494 ft with respect to Hollywood E–11 during the same period.

b. Inasmuch as the site of BM 4 has undergone subsidence with respect to Hollywood E–11 since 1950 at a rate roughly 1.098 times that which obtained at the site of BM M4 (Hayes, 1955, fig. 1; Hayes, 1959, fig. 1; Walley, 1963, fig. 1), the ratio of the subsidence of PBM 68 to the subsidence of BM M4 should have exceeded that of PBM 68 to BM 4 by the same factor.

c. Therefore, adoption of the post-1950 ratios of subsidence of PBM 68 to subsidence of BM 4 (V.A.5.), times a correction factor of

1.098, for the subsidence of PBM 68 to the subsidence of BM M4, permits the following calculations of subsidence of PBM 68 with respect to Hollywood E–11 for the period April 7, 1931, to October 1943:

(A) (0.494 ft) (1.651) (1.098) = 0.896 ft,

(B) (0.494 ft) (1.841) (1.098) = 0.999 ft.

B. Regrettably, the apparently excellent correspondence between the figures for the subsidence of PBM 68 during the period 1931–43 determined through a comparison with the subsidence at PBM 31 (IV.C.; VIII.A.) and those determined through a comparison with the subsidence at BM M4 (IX.A.1.c.) almost certainly is spurious. This arises from the fact that Hayes' figure of 0.517 ft was determined through a direct comparison between the 1931 adjusted elevation of BM M4 as given by L.A. County and the 1943 adjusted elevation of BM M4 as given by the Department of Water and Power:

443.154 ft (L.A. County level book 302, p. 199)
−442.637 ft (DWP field book 2769, p. 64)
0.517 ft.

Since the above figure does not provide for a difference in datums, it is valid only to the extent that the two datums converge.

1. Calculation of the subsidence of BM M4 with respect to BM 2 for the period 1931–43 may be made, however, through a comparison between either the observed or adjusted differences in elevation between BM M4 and BM 2 for 1931 and 1943.

a. Computation of April 7, 1931, observed difference:

443.235 ft BM M4 (L.A. County level book 302, p. 198)
−186.785 ft BM 2 (L.A. County level book 302, p. 196)
256.450 ft

Computation of April 7, 1931, adjusted difference:

443.154 ft BM M4 (L.A. County level book 302, p. 199)
−186.731 ft BM 2 (L.A. County level book 302, p. 197)
256.423 ft.

b. Computation of October 1943, observed difference:

442.605 ft BM M4 (DWP fieldbook 2769, p. 23, 64)
−186.464 ft BM 2 (DWP fieldbook 2769, p. 17, 66)
256.141 ft.

Computation of October 1943, adjusted difference:

442.637 ft BM M4 (DWP fieldbook 2769, p. 64)
−186.510 ft BM 2 (DWP fieldbook 2769, p. 66)
256.127 ft.

c. Employment of the observed and adjusted differences in elevations between BM 2 and BM M4 shows that between April 7, 1931, and October 1943 BM M4 subsided with respect to BM 2 as follows:

Observed: 256.450 ft (1931)
−256.141 ft (1943)
0.309 ft.

Adjusted: 256.423 ft (1931)
−256.127 ft (1943)
0.296 ft.

2. Subsidence of BM M4 with respect to Hollywood E–11 may be computed by correcting for the estimated subsidence of Hollywood E–11 with respect to BM 2 between April 7, 1931, and October 1943.

a. Hollywood E–11 is assumed to have subsided at a constant rate of 0.0018 ft/yr with respect to BM 2 (see V.B.2.).

b. Accordingly, Hollywood E–11 subsided approximately (12.5 yr) (0.0018 ft/yr) = 0.023 ft with respect to BM 2 between April 7, 1931, and October 1943.

c. Subsidence of BM M4 with respect to Hollywood E–11 for the period April 7, 1931, and October 1943 thus is computed to have been:

Observed: 0.309 ft −0.023 ft = 0.286 ft,
Adjusted: 0.296 ft −0.023 ft = 0.273 ft.

3. Therefore, adoption of the post-1950 ratios of subsidence of PBM 68 to subsidence of BM 4 (V.A.5.), times a correction factor of 1.098, for the subsidence of PBM 68 to the subsidence of BM M4, permits the following calculations of subsidence of PBM 68 with respect to Hollywood E–11 for the period April 7, 1931, to October 1943:

(A) (0.286 ft) (1.654) (1.098) = 0.520 ft
(0.273 ft) (1.654) (1.098) = 0.496 ft,

(B) (0.286 ft) (1.841) (1.098) = 0.578 ft
(0.273 ft) (1.841) (1.098) = 0.552 ft.

C. Because the figures for the subsidence of PBM 68 with respect to Hollywood E–11 for the period 1931–43 determined through a comparison with the subsidence at BM M4 are roughly 0.41 ft less than those determined through a comparison with the subsidence at PBM 31 and (indirectly) BM 4, a question exists as to which set of figures should be accepted.

1. Those derived through a comparison with

PBM 31 are considered the more accurate for the following reasons:

a. PBM 31 is a monument bench mark, whereas BM M4 was simply a cross in an iron bolt set in an oil derrick and thereby more subject to disturbance. The probably undisturbed state of PBM 31, moreover, is corroborated by the almost precisely constant elevation difference maintained between PBM 31 and adjacent bench mark PBM 30 (Baldwin) from 1934 to the present (DWP filecards for PBM 31 and PBM 30).

b. The period of observation covering both PBM 68 and PBM 31 has been much greater than that covering both PBM 68 and the site of BM M4.

c. The comparison with PBM 31 is based entirely on measured elevation changes at PBM 31, whereas the comparison with BM M4 is based in part on approximate elevation changes at the site of BM M4 deduced from the isobase maps for 1950–54, 1954–58, and 1958–62.

d. An apparent aberration exists in the subsidence recorded for another bench mark (BM M2) set at the same time BM M4 was established. According to Hayes (1943, p. 12), BM M2, located 165 ft north of Slauson Avenue and 630 ft west of the Mansfield Drive centerline (L.A. County level book 302, p. 197), subsided 0.538 ft between 1931 and 1943. The subsidence of BM M2 with respect to Hollywood E–11 may have been about 0.23 ft less, as was the case with BM M4, thereby reducing the apparent subsidence at BM M2 to about 0.31 ft. Nevertheless, since 1950 subsidence in the vicinity of this bench mark has ranged between 0.000 ft/yr and 0.017 ft/yr, so that it should have subsided a maximum of 0.2 ft between 1931 and 1943.

e. The approximate ratio of subsidence at the site of BM M4 to that at PBM 31 since 1950 has ranged as follows:

   1950–54; 0.94
   1954–58; 1.06
   1958–62; 1.09.

   Yet between January 1934 and October 1943 subsidence of PBM 31 with respect to Hollywood E–11 is computed to have been 0.331 ft (IV.B.2.), whereas subsidence of BM M4 for the considerably greater period April 7, 1931, to October 1943 is computed to have been no more than 0.286 ft (IX.B.3.). Assuming a uniform rate of movement at BM M4 between 1931 and 1943, the ratio of subsidence at BM M4 to subsidence at PBM 68 for the period January 1934 to October 1943 is computed to have been approximately 0.223 ft/0.331 ft=0.67, almost the inverse of that which has obtained since 1950. This profound divergence in the 1934–43 ratio strongly suggests that for the period 1931–43, measured subsidence at at least one of these two points (PBM 31 or BM M4) was aberrant.

Subsidence with respect to Hollywood E–11 at the site of BM M4 has averaged about:

1931–43; 0.023 ft/yr
1950–58; 0.070 ft/yr

(IX.B.2.; Hayes, 1955, fig. 1; Hayes, 1959, fig. 1). Subsidence of PBM 31 with respect to Hollywood E–11 has averaged about:

1934–43; 0.034 ft/yr
1950–58; 0.069 ft/yr

(IV.B.2., IV.A.). According to these figures, then, the average subsidence of PBM 31 increased by a factor of 2.02 between the periods 1934–43 and 1950–58, whereas the average subsidence at the site of BM M4 increased by a factor of 3.04 between the roughly comparable periods 1931–43 and 1950–58. Since an acceleration in subsidence of the magnitude suggested by the latter figure in particular greatly exceeds any measured increase in subsidence in the northern Baldwin Hills since 1943, the subsidence measured at BM M4 between 1931 and 1943 was more likely aberrant than that measured at PBM 31 between 1934 and 1943.

The probable validity of the 0.034 ft/yr figure for the average rate of subsidence of PBM 31 between 1934 and 1943 may be demonstrated in the following manner:

1934–43:

Subsidence of PBM 31 with respect to Hollywood E–11 between January 1934 and October 1943 (IV.B.2.) is computed to have averaged 0.331 ft/9.75 yr = 0.034 ft/yr.

1939–43:

Subsidence of PBM 31 with respect to Hollywood E–11 between November 29, 1939, and October 13, 1943 (DWP filecard for PBM 31) is computed to have averaged 0.171 ft/3.89 yr = 0.044 ft/yr.

1934–39:

Subsidence of PBM 31 with respect to PBM 71 (W–169) between January 1934 and November 1939 may be computed by assuming that the movement of PBM 71, with respect to the corrected U.S. Coast and Geodetic Survey datum adopted by Hayes (1943, p. 13–14), remained constant between 1934 and 1943. Movement of PBM 71 with respect to the corrected U.S. Coast and Geodetic Survey datum for this period is reported to have been +0.011 ft (Hayes, 1943, p. 14); its movement during the period January 1934 to November 1939, accordingly, is calculated to have been (0.011 ft) (5.9 yr/9.75 yr)=0.007 ft. Since PBM 31 subsided about 0.222 ft with respect to the corrected U.S. Coast and Geodetic Survey datum during this same period (Hayes, 1943, fig. 5), PBM 31 apparently subsided about 0.222 ft + 0.007 ft = 0.229 ft with respect to PBM 71 between 1934 and 1939. Adoption of the 1943–62 average rate of subsidence at Hollywood E–11 with respect to PBM 71 (IV.B.1.a.) indicates that PBM 31 subsided approximately 0.229 ft − (5.9 yr) (0.0075 ft/yr)=0.185 ft with respect to Hollywood E–11 between January 1934 and November 1939. Subsidence of PBM 31 with respect to Hollywood E–11 between January 1934 and November 1939, accordingly, is computed to have averaged 0.185 ft/5.9 yr = 0.031 ft/yr.

Since the average rates of subsidence of PBM 31 for these three separate periods, no one of which depends on measured elevations common to all three intervals, remained roughly uniform throughout the period 1934–43, it is concluded that the aberrant ratio of subsidence of BM M4 to subsidence of PBM 31 for the period 1934–43 is attributable to an aberration in the movement of BM M4 rather than PBM 31.

APPENDIX E

Determination of subsidence of PBM 68 with respect to PBM 58.

I. Since 1911.

A. The 1911 elevation of PBM 68 (fig. 8) has been derived through a comparison with S–32 as fixed in the 1934 adjustment (see appendix C). Subsequent elevations of PBM 68 have been calculated through subtraction of the subsidence at PBM 68 since 1911; the subsidence with respect to PBM 58 (fig. 8) has been computed through algebraic addition of the subsidence at PBM 68 with respect to Hollywood E–11 (appendix D, III.) to the subsidence at Hollywood E–11 with respect to PBM 58 (appendix C, PBM 40, II.A.2., II.D.4.; DWP fieldbook 2769, p. 27, 37; DWP filecard for PBM 40; DWP filecard for PBM 58).

1. Dates of elevation measurements at PBM 58 do not accord precisely with those at PBM 68. However, because Hollywood E–11 has subsided only slightly with respect to PBM 58 since 1939, any elevation changes that Hollywood E–11 may have undergone with respect to PBM 58 over periods of less than 2 months duration are considered negligible.

Date	Elevation of PBM 68 (in ft)	Cumulative subsidence of PBM 68 (in ft)
11/1911	319.568	
10/25/1943	317.616	1.952
10/31/1946	317.178	2.390
4/11/1950	316.762	2.806
6/5/1950	316.754	2.814
9/28/1954	316.118	3.450
10/7/1958	315.585	3.983
6/15/1962	315.166	4.402

II. January 4–12, 1934–October 13–25, 1943.

A. Subsidence of Hollywood E–11 with respect to PBM 58 is calculated to have proceeded at an average rate of 0.01098 ft/yr between 1939 and 1962 (appendix C, PBM 40, II.D.2.b.).

1. Accordingly, between January 4–12, 1934, and October 13–25, 1943, Hollywood E–11 is calculated to have subsided (9.75 yr) (0.01098 ft/yr) = 0.107 ft with respect to PBM 58.

B. PBM 68 is calculated to have subsided 0.619 ft with respect to Hollywood E–11 between January 4–12, 1934, and October 13–25, 1943 (appendix D, IV.C.).

C. Therefore, subsidence of PBM 68 with respect to PBM 58 for the period January 4–12, 1934, to October 13–25, 1943, is calculated to have been:

0.107 ft + 0.619 ft = 0.726 ft.

III. October 29, 1926–April 7, 1931.

A. Hollywood E–11 is calculated to have subsided approximately (0.01098 ft/yr) (4.5 yr) = 0.049 ft (appendix C, PBM 40, II.D.2.b.) between October 29, 1926, and April 7, 1931.

B. PBM 68 is calculated to have subsided 0.905 ft with respect to Hollywood E–11 between October 29, 1926, and April 7, 1931 (appendix D, V.D.).

C. Therefore, subsidence of PBM 68 with respect to PBM 58 for the period October 29, 1926, to April 7, 1931, is calculated to have been:

0.049 ft + 0.905 ft = 0.954 ft.

IV. November 29, 1939–October 13, 1943.

A. Hollywood E–11 is calculated to have subsided (3.87 yr) (0.01098 ft/yr) = 0.042 ft (appendix C, PBM 40, II.D.2.b.) with respect to PBM 58 between November 29, 1939, and October 13, 1943.

B. PBM 68 is calculated to have subsided 0.320 ft with respect to Hollywood E–11 between November 29, 1939, and October 13, 1943 (appendix D, VI.A.1.).

C. Therefore, subsidence of PBM 68 with respect to PBM 58 for the period November 29, 1939 to October 13, 1943, is calculated to have been:

0.042 ft + 0.320 ft = 0.362 ft.

V. January 4–12, 1934–November 29, 1939.

A. The subsidence of PBM 68 with respect to PBM 58 for the period January 4–12, 1934, to November 29, 1939 may be calculated by difference.

1. a. Subsidence of PBM 68 between January 4–12, 1934, and October 13–25, 1943, is calculated to have been 0.726 ft.

b. Subsidence of PBM 68 between November 29, 1939, and October 13, 1943, is calculated to have been 0.362 ft.

2. Assuming that the average elevation of PBM 68 for the period October 13–25, 1943, matched that which obtained on October 13, 1943, subsidence of PBM 68 with respect to PBM 58 for the period January 4–12, 1934, to November 29, 1939, is calculated to have been:

0.726 ft − 0.362 ft = 0.364 ft.

VI. April 7, 1931–January 4–12, 1934.

A. The subsidence of PBM 68 with respect to PBM 58 over the period April 7, 1931, to January 4–12, 1934, is computed here through calculation of the average rate of subsidence of PBM 68 over the intervals of measurement immediately preceding and immediately following this 2.75-year period.

B. The average rate of subsidence of PBM 68 with respect to PBM 58 over the intervals October 29, 1926–April 7, 1931, and January 4–12, 1934–October 13–25, 1943, is calculated to have been:

$$\frac{0.954 \text{ ft} + 0.726 \text{ ft}}{4.44 \text{ yr} + 9.78 \text{ yr}} = 0.1181 \text{ ft/yr}.$$

1. Therefore, subsidence of PBM 68 with respect to PBM 58 for the period April 7, 1931 – January 4–12, 1934, is calculated to have been:

(2.75 yr) (0.1181 ft/yr) = 0.324 ft.

APPENDIX F

Derivation of June-July 1910 elevations of PBM 68 and PBM 67 with respect to S–32. The June-July 1910 elevations of PBM 68 (identified alternatively as DD—see fig. 8) and PBM 67 (triangulation monument Inglewood D–1; adjacent to bench mark HH—see fig. 8) are developed here through the medium of topographic control surveys carried out by the Los Angeles Investment Company.

NOTE—June–July 1910 stake elevations of points adjacent to LAIC bench marks DD and HH were derived through a comparison with the elevation of a bench mark located at Centinela and Eucalyptus Avenues, Inglewood (LAIC fieldbook 7, p. 2). The authority for the starting elevation of 137.973 ft at the Centinela-Eucalyptus bench mark has been given simply as:

"Datum = City of Inglewood
City of Los Angeles +0.013"

(LAIC fieldbook 7, p. 2). Although perusal of pre-1911 City of Inglewood fieldbooks failed to confirm the existence of a City of Inglewood bench mark at Centinela and Eucalyptus, the starting elevation of 137.973 ft is accepted provisionally here as having been derived from a City of Inglewood basic control point. The elevation of the Centinela-Eucalyptus bench mark is assumed to have remained unchanged in elevation with respect to S–32 for the following reasons:

1. Elevation changes with respect to S–32 (or its approximate equivalents) in the vicinity of the Centinela-Eucalyptus bench mark, based on precise leveling carried out prior to 1939, averaged about +0.01 ft/yr (Grant and Sheppard, 1939, p. 302); those based on precise leveling carried out between 1949 and 1955 averaged about −0.01 ft/yr (fig. 6). We conclude, accordingly, that the relatively small positive elevation changes that have accrued in this area have been roughly balanced by comparably small negative changes.
2. The datum correction applied to the pre-1925 LABE elevation of S–32 in order to bring it into conformity with the 1934 elevation assigned to S–32 by the U.S. Coast and Geodetic Survey is +5.809 ft (see appendix C, PBM 68); the datum correction applied to pre-1956 elevations of City of Inglewood bench marks (it is assumed that these bench marks have remained stable with respect to each other over the relatively limited area of Inglewood) in order to bring them into conformity with the elevations assigned to common bench marks by the U.S. Coast and Geodetic Survey (which has held S–32 reset fixed in elevation since 1936—LABE Precise Bench Mark Index, p. 25) is +5.77 ft (Inglewood Municipal Code, Section 7101; 7/17/56). Because the 1910 elevation of the Centinela-Eucalyptus bench mark reportedly departed from that determined through a comparison with the pre-1925 LABE datum by only 0.013 ft, and because the datum

corrections determined for both S–32 and City of Inglewood bench marks through comparison with U.S. Coast and Geodetic Survey elevations of these points (established subsequent to 1933) are very nearly the same, it is likely that, since 1910 at least, S–32 and the Centinela-Eucalyptus bench mark have changed with respect to each other by no more than a few hundredths of a foot.

If S–32 and the Centinela-Eucalyptus bench mark may be treated as having remained unchanged in elevation with respect to each other since 1910, it follows that the City of Inglewood datum correction employed to bring the City of Inglewood bench mark elevations into conformity with those determined by the U.S. Coast and Geodetic Survey may be applied validly at any time after 1910 regardless of when the datum correction was actually made.

PBM 68 (identified alternatively as DD).

I. June–July 1910 elevations of a 2×2 stake set 10 ft east of DD, with respect to the City of Inglewood elevation of the Centinela-Eucalyptus bench mark, have been given as 315.675 ft and 315.66 ft (LAIC fieldbook 7, p. 3, 64), respectively, for an average elevation of:

$$\frac{315.675 \text{ ft} + 315.660 \text{ ft}}{2} = 315.668 \text{ ft.}$$

II. Datum correction.

A. The 1910 elevation of the 2×2 stake set 10 ft east of DD with respect to S–32 as fixed in the 1934 adjustment may be computed through the addition of the standard datum correction applied to all pre-1956 elevations of City of Inglewood bench marks (see prefatory note):

315.668 ft	June–July 1910 elevation of 2×2 stake adjacent to DD with respect to the City of Inglewood elevation of the Centinela-Eucalyptus bench mark.
+ 5.770 ft	City of Inglewood datum correction
321.438 ft.	

III. Monument-stake elevation difference.

A. Concrete monument DD and the 2×2 stake set 10 ft east of DD are assumed to have remained unchanged in elevation with respect to each other.

B. The elevation difference between DD and the 2×2 stake set 10 feet east of DD may be determined as follows:

315.420 ft	1911 observed elevation of 2×2 stake marked 315.675 (DWP fieldbook 1458, p. 29)
−313.760 ft	1911 observed elevation of DD (DWP fieldbook 1458, p. 29)
1.660 ft	(This is within two-tenths of a foot of the ground elevation difference between these two points today.)

IV. The June–July 1910 elevation of PBM 68 (DD) with respect to S–32 as fixed in the 1934 adjustment, as determined through the medium of Los Angeles Investment Company topographic control circuits, accordingly, is calculated to have been:

321.438 ft	1910 2×2 DD stake elevation with respect to S–32
− 1.660 ft	2×2 stake elevation minus DD monument elevation
319.778 ft.	

PBM 67 (triangulation monument Inglewood D–1; adjacent to Monument HH).

I. June–July 1910 elevations of a 2×2 stake set 10 ft north of HH have been given as 378.218 ft, 378.37 ft, and 378.24 ft (LAIC fieldbook 7, p. 10, 57, 74), respectively, for an average elevation of:

$$\frac{378.218 \text{ ft} + 378.37 \text{ ft} + 378.24 \text{ ft}}{3} = 378.276 \text{ ft.}$$

II. Datum correction.

A. The 1910 elevation of the 2×2 stake set 10 ft north of HH with respect to S–32 as fixed in the 1934 adjustment may be computed through the addition of the standard datum correction applied to all pre-1956 elevations of City of Inglewood bench marks (see prefatory note):

378.276 ft	June–July 1910 elevation of 2×2 stake adjacent to HH with respect to the City of Inglewood elevation of the Centinela-Eucalyptus bench mark
+ 5.770 ft	City of Inglewood datum correction
384.046 ft.	

III. PBM 67-HH 2×2 stake elevation difference.

A. Concrete monument HH, the 2×2 stake set 10 ft north of HH, and PBM 67 (approximately 40–50 ft north-northwest of HH) are assumed to have remained unchanged in elevation with respect to each other.

B. The approximate elevation difference between HH and the 2×2 stake set 10 ft east of HH may be determined as follows:

1. Concrete monument HH was set flush with the ground surface (William Ball, Los Angeles Investment Co., oral commun., 1965).

   a. The top of the ¾-inch iron pipe to which subsequent elevations have been referred stands about 0.20 ft above its concrete base.

2. The natural ground surface in the immediate area of HH is smooth and very flat. It is assumed, as a first approximation, that the 1910 ground elevations at HH and the 2×2 stake were identical.

3. LAIC plane table sheet 9, dated August 13 to 24 (1910?), shows the ground elevation at a pinpoint 10 ft north of HH at 378.3 ft (that is, within a few hundredths of a foot of the stake elevation adjacent to monument HH), so that it is probable that the 2×2 stake was set approximately flush with the ground surface.
4. The 1910 elevation of HH, accordingly, is assumed to have been roughly 0.20 ft above the elevation of the 2×2 stake set 10 ft to the north of HH.

C. The elevation difference between HH and PBM 67 may be determined as follows:

375.635 ft 1951 observed elevation of HH (LAIC fieldbook 201, p. 4)
−375.275 ft 1951 observed elevation of PBM 67 (LAIC fieldbook 201, p. 4)
0.360 ft.

D. The PBM 67–HH 2×2 stake elevation difference accordingly is computed to have been:

0.360 ft − 0.20 ft = 0.160 ft.

IV. The approximate June–July 1910 elevation of PBM 67 (triangulation monument Inglewood D–1; adjacent to monument HH) with respect to S–32 as fixed in the 1934 adjustment, as determined through the medium of Los Angeles Investment Company topographic control circuits, accordingly, is calculated to have been:

384.046 ft 1910 HH 2×2 stake elevation with respect to S–32
− .160 ft HH 2×2 stake elevation minus PBM 67 monument elevation
383.886 ft.

APPENDIX G

Determination of subsidence of PBM 67 with respect to Hollywood E–11.

I. Since 1910.

A. Calculated with respect to Hollywood E–11 as fixed in elevation since 1910.

1. The 1911 elevation of Hollywood E–11 has been derived through a comparison with S–32 as fixed in the 1934 adjustment and is calculated to have been 470.772 ft (appendix C, PBM 40). Accordingly, 470.772 ft + [(1.4 yr) (0.00841 ft/yr + 0.01098 ft/yr) = 0.027 ft (see appendix C, PBM 40, II.C., II.D.)] − 470.304 ft = 0.495 ft has been added to all elevations derived from Hollywood E–11 as fixed at 470.304 ft (DWP filecard for PBM 67) in order to obtain their elevations with respect to Hollywood E–11 as fixed in elevation since June–July 1910.
2. The approximate June–July 1910 elevation of PBM 67 has been derived through a comparison with S–32 as fixed in the 1934 adjustment and is calculated to have been 383.886 ft (appendix F, PBM 67).
3. The October 25, 1943, elevation of PBM 67 was not measured; it has been calculated through extrapolation backward to 1943 of the average rate of subsidence at PBM 67 between 1946 and 1950 (DWP filecard for PBM 67).

Comparison with the rate of subsidence at PBM 68 suggests that this calculated value for the subsidence of PBM 67 probably is several hundredths of a foot too large (that is, the calculated 1943 elevation is several hundredths of a foot high).

Date	Elevation of PBM 67 (in ft)	Cumulative subsidence of PBM 67 (in ft)
6–7/1910	383.886	
10/25/1943	382.355	1.531
10/31/1946	381.872	2.014
4/10/1950	381.337	2.549
10/6/1954	380.588	3.298
10/23/1958	380.029	3.757
2/13/1963	379.562	4.324

APPENDIX H

Calculation of maximum subsidence in the northern Baldwin Hills since 1911 with respect to Hollywood E–11.

NOTE—Calculation of the maximum subsidence in the northern Baldwin Hills may be closely approximated by assuming that PBM 122 (fig. 8) is essentially coincident with the point of maximum subsidence. Although the actual center of subsidence in the Baldwin Hills apparently has shifted slightly from time to time, PBM 122 is the only bench mark within the Baldwin Hills that has been observed through more than a single quadrennial measurement period that, since 1950 at least, has been subsiding at a rate no less than 90 percent of the maximum measured rate of subsidence.

I. November 1911–October 1943.

A. Subsidence between December 1917 and October 1943, at the low point of a topographic saddle (herein referred to as BM "saddle") located approximately 725 ft N76°E of PBM 122, was computed by Hayes (1943, fig. 6) to have been approximately 4.2 ft.

1. This computation of subsidence at BM "saddle," however, was based on the following assumptions:

a. The elevation of an unspecified topographic saddle (from which the 1917 elevation was derived) remained unchanged between

1911 and 1917 (DWP fieldbook 1579, p. 4–5).

b. The datums employed in the 1917 and 1943 derivations of the elevation at BM "saddle" were identical.

2. Because the first assumption is not necessarily valid and the second assumption is clearly invalid, the estimated subsidence of 4.2 ft at BM "saddle" between 1917 and 1943 is apparently in error by an unknown factor.

3. Subsidence at BM "saddle" with respect to Hollywood E–11 between November 1911 and October 1943 may be deduced only by making the following assumptions:

a. Any change in elevation at BM "saddle" with respect to PBM 68 between October 25, 1943 and December 9, 1943 was negligible. This assumption is required because the 1943 elevation at BM "saddle" was derived from that of PBM 68 (DD) on December 9, 1943 (DWP fieldbook 2769, p. 74–75).

b. PBM 68 and BM "saddle" remained unchanged in elevation with respect to each other between 1911 and 1917. This assumption is necessary because neither a 1911 measured elevation at BM "saddle" nor a 1917 measured elevation of PBM 68 (with respect to some independent control point outside this immediate area) is known to exist.

B. Subsidence at BM "saddle," with respect to DD, between December 1917 and October 1943 was approximately 4.2 ft − 2.6 ft = 1.6 ft (Hayes, 1943, fig. 6). Because these two points are assumed to have remained unchanged in elevation with respect to each other between 1911 and 1917, subsidence at BM "saddle" with respect to DD between November 1911 and October 1943 must also have been 1.6 ft.

1. Subsidence of PBM 68 with respect to Hollywood E–11 between November 1911 and October 25, 1943 is computed to have been 1.672 ft (app. D, III.).

a. Subsidence at BM "saddle" with respect to Hollywood E–11 between November 1911 and October 25, 1943 accordingly is computed to have been:

$$1.672 \text{ ft} + 1.6 \text{ ft} = 3.272 \text{ ft}.$$

C. Subsidence at the site of PBM 122 since 1950 has exceeded that at BM "saddle" by the following approximate factors:

1950–54; 1.24 (Hayes, 1955, fig. 1)
1954–58; not estimated owing to error in 1954–58 map (Hayes, 1959, fig. 1; DWP filecard for PBM 122)
1958–62; 1.23 (Walley, 1963, fig. 1).

1. The average rate of subsidence of PBM 122 with respect to Hollywood E–11 accordingly has exceeded that at BM "saddle" by the following factor:

$$\frac{1.24 + 1.23}{2} = 1.235.$$

D. Adoption of the above ratio of subsidence of PBM 122 to subsidence at BM "saddle" permits the following calculation of subsidence of PBM 122 with respect to Hollywood E–11 between November 1911 and October 25, 1943:

$$(1.235)\ (3.272 \text{ ft}) = 4.04 \text{ ft}.$$

E. Alternatively, subsidence at the site of PBM 122 with respect to Hollywood E–11 between November 1911 and October 1943 may be calculated through a direct comparison with subsidence at PBM 68.

1. PBM 68 and PBM 122 subsided with respect to Hollywood E–11 between 1950 and 1958 (PBM 122 was not recovered in 1962) as shown below (DWP filecards for PBM 68 and PBM 122).

PBM 68		PBM 122/PBM 68	PBM 122	
Time interval	Subsidence (in ft)		Time interval	Subsidence (in ft)
4/11/50–9/28/54 (4 yr 5 mo 2½ wk)	0.633	1.397	6/7/50–9/29/54 (4 yr 3 mo 3 wk)	0.885
9/28/54–10/7/58 (4 yr 1½ wk)	.469	1.372	9/29/54–9/30/58 (4 yr)	.644
4/11/50–10/7/58 (8 yr 6 mo)	1.102	1.387	6/7/50–9/30/58 (8 yr 3 mo 3 wk)	1.529

2. As shown in the center column above, PBM 68 and PBM 122 subsided at proportionately constant rates during the period 1950–58. Therefore, subsidence of PBM 122/subsidence of PBM 68 with respect to Hollywood E–11 (including a correction for the minor difference in the increments of time over which subsidence at the two bench marks has been measured) between 1950 and 1958 averaged:

$$\frac{1.529 \text{ ft} + 0.033 \text{ ft}}{1.102 \text{ ft}} = 1.417.$$

3. Adoption of the 1950–58 ratio of subsidence of PBM 122 to subsidence of PBM 68 for the period 1911–43 permits the following calculation of subsidence at the site of PBM 122 with respect to Hollywood E–11 for the period November 1911 to October 25, 1943:

$$(1.417)\ (1.672 \text{ ft}) = 2.37 \text{ ft}.$$

4. This lower figure for the 1911–43 subsidence at PBM 122 seems to be corroborated through a comparison with the approximate subsidence at PBM 67 between 1910 and 1943.

a. The average rate of subsidence at PBM 122/average rate of subsidence at PBM 67 for the period 1950–58 is calculated to have been approximately 1.200 (DWP filecards for PBM 122 and PBM 67).

b. The approximate subsidence at PBM 67 with respect to Hollywood E–11 between June–July 1910 and October 25, 1943 is calculated to have been 1.531 ft (app. G); this figure is almost certainly low, but probably by no more than 0.5 ft.

c. Adoption of the 1950–58 ratio of subsidence at PBM 122 to subsidence at PBM 67 permits the following calculation of subsidence of PBM 122 with respect to Hollywood E–11 between June–July 1910 and October 25, 1943:

(1.200) (1.531 ft) = 1.84 ft.

II. October 1943–March 1950.

A. The average annual rate of subsidence of PBM 122 with respect to Hollywood E–11 for the period June 7, 1950–September 30, 1958, is computed to have been:

1.529 ft/8.308 yr = 0.184 ft/yr (DWP filecard for PBM 122).

B. The rate of subsidence of PBM 68, as determined from its subsidence chart (Walley, 1963), for the period 1943–50 was less than that for the period 1950–58 by a factor of 0.557/0.663 = 0.840.

1. Accordingly, if it is assumed that the rate of subsidence at the site of PBM 122 for the period 1943–50 was diminished by the same factor, the average annual rate of subsidence at the site of PBM 122 for the period 1943–50 may be computed as follows:

(0.184 ft/yr) (0.840) = 0.155 ft/yr.

C. Therefore, subsidence at the site of PBM 122 with respect to Hollywood E–11 between October 1943 and March 1950 is calculated to have been:

(6.417 yrs) (0.155 ft/yr) = 0.99 ft.

III. March 1950–August 1954.

A. Subsidence of PBM 122 with respect to Hollywood E–11 for the period June 7, 1950–September 29, 1954, is reported to have been 0.885 ft (DWP filecard for PBM 122).

1. Subsidence of PBM 122 with respect to Hollywood E–11 for the slightly greater period March 1950–August 1954, accordingly, is assumed to have been approximately 0.89 ft.

IV. August 1954–October 1958.

A. Subsidence of PBM 122 with respect to Hollywood E–11 for the period September 29, 1954–September 30, 1958, is reported to have been 0.644 ft (DWP filecard for PBM 122).

1. Subsidence of PBM 122 with respect to Hollywood E–11 for the 2-month period August 1, 1954–October 1, 1954 is computed to have been:

(0.644 ft/4 yr) (1/6 yr) = 0.027 ft.

2. Subsidence of PBM 122 with respect to Hollywood E–11 for the period August 1954–October 1958, accordingly, is calculated to have been:

0.644 ft + 0.027 ft = 0.67 ft.

V. October 1958–August 1962.

A. PBM 420, located approximately 500 ft west of the site of PBM 122, showed the greatest measured subsidence of any point in the northern Baldwin Hills between 1958 and 1962, during which time it reportedly subsided with respect to Hollywood E–11 at an average rate of 0.143 ft/yr (Walley, 1963, p. 5).

1. Adoption of the average annual rate of subsidence of PBM 420 for the period 1958–62 as the average annual rate of subsidence at the site of PBM 122 for this same period permits the following calculation of subsidence at the site of PBM 122 with respect to Hollywood E–11 for the period October 1958–August 1962:

(3.833 yr) (0.143 ft/yr) = 0.55 ft.

VI. August 1962–January 1964.

A. Subsidence at the site of PBM 122 between 1962 and 1964 is assumed to have continued at the rate that prevailed between 1958 and 1962.

1. Therefore, subsidence at the site of PBM 122 with respect to Hollywood E–11 for the period August 1962–January 1964 is computed to have been:

(1.417 yr) (0.143 ft/yr) = 0.20 ft.

VII. November 1911–January 1964.

A. Maximum subsidence at the site of PBM 122 with respect to Hollywood E–11 between November 1911 and January 1964 is calculated to have been approximately:

(1)	or (2)
4.04	2.37
.99	.99
.89	.89
.67	.67
.55	.55
.20	.20
7.34 ft	5.67 ft.

APPENDIX I

Comparative 1910 and 1917 elevations within the area of differential subsidence centering in the northern Baldwin Hills.

I. 1910 elevations.

A. Elevation control surveys emanating from a City of Inglewood bench mark located at Centinela and Eucalyptus Avenues were established in the northern Baldwin Hills by the Los Angeles Investment Company in June and July of 1910 (prefatory note, app. F).

1. Resultant elevations have been recorded in Los Angeles Investment Company fieldbook 7.

2. Additional 1910 elevations (apparently derived from side shots based on the leveling described in LAIC fieldbook 7), measured to the nearest tenth of a foot, were recorded at selected saddles and knolls within the northern Baldwin Hills (LAIC Hill Tract, sheets 1 and 2, October 1910).

II. 1917 elevations.

A. Elevation control surveys emanating from the previously determined elevation of a topographic saddle within the northern Baldwin Hills (and apparently supplementary to 1911 leveling recorded in DWP fieldbook 1458) were established in the northern Baldwin Hills by the Los Angeles Department of Water and Power in December, 1917 (DWP fieldbook 1579).

1. Resultant elevations have been recorded in Los Angeles Department of Water and Power fieldbook 1579.

2. Additional 1917 elevations (apparently derived from side shots based on the leveling described in DWP fieldbook 1579), measured to the nearest tenth of a foot, were recorded at selected saddles and knolls above the 300-foot contour in the northern Baldwin Hills on Los Angeles Department of Water and Power "topographical field map No. D–1769 dated November, 1911" (Hayes, 1943, p. 15, fig. 6).

a. That the indicated elevations are indeed the product of 1917 rather than 1911 leveling derives from the following analysis by Hayes (1943, p. 15): "A minute examination of the topographic field map No. D–1769, dated November 20, 1911 tends to show that the portion of topography mapped above the 300-foot contour elevation was done by a different topographer than that which was mapped below the 300-foot elevation, and probably at a much later date. The style of mapping along the northeasterly side of the [old Centinela] reservoir site is distinctly different from that of the lower portion. The original pencil numerals, still recognizable in the upper portion of the field map, agree precisely with the lettering in fieldbooks containing level circuit and triangulation control surveys conducted at the reservoir site in 1917. It has been assumed, based on convincing evidence, that the reservoir site above the 300-foot elevation was mapped about December 1917."

III. Comparative elevations.

A. The only bench mark common to both the 1910 and the 1917 leveling of which we have knowledge, is concrete monument DD (LAIC fieldbook 7, p. 3 and DWP fieldbook 1458, p. 10, 29—see app. F. III; DWP fieldbook 1579, p. 5), or what is now known as PBM 68.

1. Although bench mark "LAI" (fig. 8) was surveyed in connection with the 1917 leveling (DWP fieldbook 1579, p. 4), both earlier and later elevations on the iron pipe extension to which the 1917 leveling has been referred, remain unknown (for example, DWP fieldbook 2769, p. 63 dated 10/29/43).

a. Thus, the 1917 record elevation of the top of a 3-in iron pipe set on a concrete base marked "L.A.I. Co." has been given as 312.23 ft (DWP fieldbook 1579, p. 4), whereas the 1917 elevation of bench mark LAI read from topographic map D–1769 (Hayes, 1943, fig. 6) was approximately 306 ft. The 1917 record (314.24 ft) and contoured elevations of concrete monument DD, on the other hand, agree almost precisely (DWP fieldbook 1579, p. 5; Hayes, 1943, fig. 6). Hence we conclude: (1) that the 1917 record elevation of LAI was measured on the top of a 3-inch iron pipe that stood an unknown number of feet above the top of the concrete base; and (2) that the 1917 measured elevation difference between LAI and DD affords a very poor basis for determining any differential movements that may have occurred between these identifiable concrete monuments during periods preceding or following 1917.

b. Support for the preceding conclusion derives from the following analysis:

(1.) The 1910 elevation of a temporary

bench mark identified simply as a "2″ × 2″ hub set 10 ft north of corner N.W., near GG" has been given as 309.302 ft with respect to DD as fixed at 314.015 ft (LAIC fieldbook 7, p. 3; DWP fieldbook 1458, p. 29). It is assumed: (1) that the hub was set so as to be no lower than the ground elevation of the identified northwest corner; and (2) that "corner N.W." is identical with the position of LAI as shown on topographic map D–1769. The second assumption is supported by the following considerations:

(a.) A comparison of topographic map D–1769 with Los Angeles Investment Company Hill Tract sheet no. 2, dated October 1910, shows by inspection that LAI and a corner identified on sheet no. 2 as 117 + 14.6 are almost certainly coincident.

(b.) The distance HH–N.W. Corner has been given as 2,286.80 ft by the Los Angeles Investment Company (LAIC Hill Tract calculation worksheet). The distance HH–LAI measures 2,263 ft on a photostat copy of mpa D–1769 (Hayes, 1943, fig. 6); correction for known distortion of the photostat indicates that this distance would measure 2,273 ft on a stable-base copy. Furthermore, if the bar scale appended in 1943 is read as 1″ = 200′ (as seems to have been the intent), the distance HH–LAI measures 2,284 ft on the photostat copy. Hence, "117 + 14.6" is almost certainly identical with "N.W. Corner"; thus LAI and N.W. Corner are equally certainly coincident.

2. All of the evidence tabulated above indicates that the 1917 elevation of concrete monument LAI as (opposed to the 3-inch iron pipe extension) was probably less than 310 feet and certainly several feet below the record elevation of 312.23 ft (with respect to DD as fixed at 314.24 ft). Hence, the 1917 record elevation of LAI is of no value for comparative purposes unless it can be shown that any earlier or later elevations of LAI were measured on the top of the same 3-inch pipe alluded to in the 1917 field notes.

B. 1910 and 1917 elevation differences between DD and four identifiable knolls or saddles, above the 300-foot contour and within the now-recognized subsidence bowl, may be deduced from the record elevations of DD and elevations recorded or estimated to the nearest tenth of a foot on Los Angeles Investment Company Hill Tract map sheets 1 and 2 (1910) and Los Angeles Department of Water and Power topographic map D–1769 (1917). These four topographic features are located as follows with respect to DD (see Hayes, 1943, fig. 6):

(A) 3,105 ft N. 34.8° W.
(B) 1,910 ft N. 43.2° W.
(C) 2,228 ft N. 15.2° W.
(D) 1,740 ft N. 6.6° W.

1. Record elevations of DD are:
   a. 1910—314.015 ft (LAIC fieldbook 7, p. 3; DWP fieldbook 1458, p. 29).
   b. 1917—314.24 ft (DWP fieldbook 1579, p. 5).
2. 1910 elevations of the four identified topographic features read from Los Angeles Investment Company Hill Tract sheets 1 and 2, are as follows:

   (A) 319.8 ft (estimated)
   (B) 327.1 ft
   (C) 327.9 ft
   (D) 331.1 ft.

   a. Thus, the 1910 elevation difference between DD and the indicated topographic features were:

   (A) 319.8 ft − 314.015 ft = 5.785 ft
   (B) 327.1 ft − 314.015 ft = 13.085 ft
   (C) 327.9 ft − 314.015 ft = 13.885 ft
   (D) 331.1 ft − 314.015 ft = 19.085 ft.

3. 1917 elevations of the four identified topographic features read from Los Angeles Department of Water and Power topographic map D–1769 (Hayes, 1943, p. 15, fig. 6), are as follows:

   (A) 320.0 ft
   (B) 327.2 ft
   (C) 328.1 ft
   (D) 333.0 ft.

   a. Thus, the 1917 elevation differences between DD and the indicated topographic features were:

   (A) 320.0 ft − 314.24 ft = 5.76 ft
   (B) 327.2 ft − 314.24 ft = 12.96 ft
   (C) 328.1 ft − 314.24 ft = 13.86 ft
   (D) 333.0 ft − 314.24 ft = 18.76 ft.

4. Elevation changes with respect to DD, between 1910 and 1917 at the four identified

points were, accordingly:

(A) 5.785 ft − 5.760 ft = 0.025 ft
(B) 13.085 ft − 12.960 ft = 0.125 ft
(C) 13.885 ft − 13.860 ft = 0.025 ft
(D) 19.085 ft − 18.760 ft = 0.325 ft.

a. The only seemingly significant elevation change that occurred at any of these points between 1910 and 1917 was that at D. However, because this knoll is a very subdued topographic feature (see Hayes, 1943, fig. 6), it is unlikely that precisely the same point could have been recovered during successive levelings. Hence, the apparent elevation change recorded at D is probably less meaningful than that measured at the other three points.

5. Elevation changes between 1950 and 1962 (with respect to DD or PBM 68) at the four identified topographic features (as deduced from pl. 4) averaged:

(A) 0.033 ft/yr or 0.231 ft/7 yr
(B) 0.044 ft/yr or 0.340 ft/7 yr
(C) 0.017 ft/yr or 0.119 ft/7 yr
(D) 0.014 ft/yr or 0.098 ft/7 yr.

6. Because even this crude analysis indicates that points A, B, and C underwent relative elevation changes ranging from only 0.025 ft through a maximum of 0.125 ft between 1910 and 1917, yet subsided by at least several times these amounts over comparable subsequent periods, it is likely that little, if any, differential subsidence was underway in the northern Baldwin Hills during the period 1910–17.

APPENDIX J

Calculations of average increase in effective pressure in an unlayered equivalent of the Vickers zone.

I. The average change in effective pressure ($\Delta p'$) owing to liquid-level decline through the full thickness of an unlayered, decompressd equivalent of the Vickers zone may be calculated by use of a formula modified from Poland and Davis (1969, p. 193–196):

$$\Delta p' = \gamma_f(1-n+n_f)(z_3-z_1)/2,$$

where

γ_f = unit weight of the liquid,
n = average porosity of the reservoir sand,
n_f = liquid retained in pore space, expressed in percent of total volume,
z_3 = initial elevation of liquid level, and
z_1 = final elevation of liquid level.

NOTE—The expression derived by Poland and Davis (1969, p. 193–196) is divided by 2 here because their equation permits calculation of the increase in effective pressure within the saturated part of the column only, whereas our objective is to obtain an average or distributed value over the entire column (that is, one equivalent to a uniformly developed increase over this same column during artesian head decline or general decompression). Incremental values of the average or distributed increase in effective pressure over the entire column may be obtained through: (1) calculations of the average increase in effective pressure attributable to liquid-level decline through a lower part ($z_2 - z_1$, where z_2 = some intermediate elevation between z_3 and z_1) of the column for pertinent values of z_2, times that fraction of the column through which the drop has been effected ($z_2 - z_1 \div z_3 - z_1$); and (2) subtraction of (a) successive values of $\Delta p'$ obtained through the assignment of successively smaller values to z_2 plus (b) the sum of successive, previously calculated increments of $\Delta p'$ from the total $\Delta p'$ calculated from a reduction of the liquid level through the full column height ($z_3 - z_1$).

II. An approximate value for γ_f may be calculated directly by averaging the stock tank density of the pure oil phase (0.9403), deduced from the 1954 API gravity given by Oefelein and Walker (1964, p. 510), with that of the brine (1.023), deduced from the salinity value given by the California Division of Oil and Gas (1961, p. 577), in accordance with the produced-liquid ratio that obtained at the end of the primary or natural depletion stage; this ratio is estimated to have been 185,000,000 bbls (oil)/267,000,000 bbls (brine). Thus the average specific gravity = 0.990 and γ_f = 0.429. The porosity, n, for the Vickers east zone has been given by Oefelein and Walker (1964, p. 511) as 0.35, but values provided by T. H. McCulloh (written commun., 1966) suggest that 0.30 is a more realistic figure for the zone as a whole. If, as a first approximation, it is accepted that the retained brine-oil ratio is the same as the produced brine-oil ratio, the liquid retained in place (n_f) may be calculated in turn from the estimated original oil in place (2067 bbls/acre × 73,500 acre ft = 151,900,000 bbls) in the Vickers east zone and comparison with the estimated production of oil (33,300,000 bbls) through primary or natural depletion (Oefelein and Walker, 1964, p. 511). Thus, inasmuch as about 78.07 percent of the oil has been retained in place, n_f may be taken as (0.30)(0.7807) = 0.234. The average thickness through which liquid-level decline is considered to have been operative (that is $z_3 - z_1$) has been estimated from the lithologic log presented in figure 2 at about 1,650 feet. This figure has been obtained from the summation of all of the sand units contained within the Vickers and Investment zones, plus all of the shale units 5 ft or less in thickness. The thin shales have been included with the sands because their compactive response to a given pressure increase over time intervals of a year or more is believed to approximate that of the sands. Exclusion of all shale units, however, would decrease this 1,650-foot figure by a maximum of only about 10 percent.

NOTE—It is assumed here that the in situ oil density has remained unchanged during its production. The relatively low reservoir temperature of 100°F, the very low original solution GOR of 0.09 Mcf/bbl (Oefelein and Walker, 1964, p. 511), and the generally low measured reservoir pressures (figs. 33 and 34) tend to support this assumption. In any case, if the reservoir oil underwent any significant increase in density during the productive history of the Vickers zone, it probably occurred during the pre-1930 major decompression (and degassing) period. Because this initial period was one in which liquid-level decline could only have just begun, any oil density increase should have been of minimal significance to the model developed here. If, on the other hand, the in situ oil density declined somewhat during depletion, it is doubtful that the analogy drawn here with liquid-level decline in an unconfined water system would be seriously compromised, for any density drop would operate in the same sense as the liquid-level decline: both would result in a buoyancy loss and, therefore, an increase in effective pressure. For a given volume of produced oil, however, the magnitudes of this increase might differ. If, for example, $n_f \rightarrow n$ or 0, then the production of 50 percent of the recoverable fluid accompanied by a 50 percent decline in liquid level would result in a systemic or average increase in effective pressure amounting to 75 percent of that resulting from 100 percent depletion. The production of an equivalent stock tank volume accompanied by a uniformly distributed 50 percent decrease in fluid density would increase the effective pressure by only 50 percent.

The produced ratio developed at the end of the primary depletion stage is utilized here because it provides a reasonable index of the average liquid composition over a period during which the liquid may be considered to have declined to its lowest levels. If the volume produced in response to secondary recovery efforts is disregarded, this ratio, together with the volumes of oil and brine produced and the year during which primary recovery should have ceased, may be estimated from the natural oil depletion to 1954 (26,200,000 bbls) and the estimated ultimate natural recovery (33,300,000 bbls) given by Oefelein and Walker (1964, p. 511) for the east block only. Because 145,000,000 bbls of oil had been produced from the entire Vickers zone by 1954, and if it is assumed that 78.5 percent (26,200,000/33,300,000) of the naturally recoverable oil had been produced from the eastern Vickers zone by the end of 1954, natural depletion should have ceased with the production of 185,000,000 bbls of oil. This figure was reached in 1966 (Conservation Committee of California Oil Producers, 1967, p. P), by which time the cumulative net liquid production was roughly 452,000,000 bbls.

III. Calculations of $\Delta p'$ developed through buoyancy loss or liquid-level decline are tabulated in table 10. It is assumed that the decompression stage ended at the beginning of 1930, corresponding to the abrupt deceleration in the decline of reservoir pressure (figs. 33 and 34), and that succeeding pressure losses were associated with liquid-level decline. The percent liquid-level decline is based on the assumptions: (1) that this decline began in 1930 at the end of the decompression stage, after the production of 68,460,301 bbls of oil and 10,388,340 bbls of water; and (2) that liquid level would have declined 100 percent by the end of the primary or natural depletion stage, which is estimated to have occurred in 1966 with the production of 185,000,000 bbls of oil.

APPENDIX K

Estimates of compaction of the Vickers zone.

I. The most direct approach to the calculation of reservoir compaction has been described by Gilluly and Grant (1949, p. 511–519). These writers have computed "compression moduli" from compression measurements on a series of sand cores taken from the Wilmington field, which they have then used (in conjunction with measured pressure losses and producing sand thicknesses) to calculate the expected compaction of the several major Wilmington zones over a specified time interval. The compression modulus (a negative quantity) is conceptually similar to Young's modulus and is defined as:

$$E_c \text{ (compression modulus)} = \frac{P_s - P_o}{\frac{L_s - L_o}{L_o}},$$

where

P_s = ultimate stress (in the solid framework),
P_o = original stress (in the solid framework),
L_s = final length of core,
L_o = original length of core;

its utilization assumes a linear relation between stress and strain.

A. Among the Wilmington test data developed by Gilluly and Grant, those of the Tar-Ranger zone are most reasonably applied to the Vickers zone, for in terms of average depth (2,200–2,500 ft) and average age (late Miocene to early Pliocene) (California Division of Oil and Gas, 1961, p. 687), the Tar-Ranger more closely matches the Vickers than do any of the other zones considered by Gilluly and Grant (1949, p. 512, 514). Thus, if the average reservoir fluid pressure loss is 790 psi (fig. 34), the cumulative average thickness of the producing sands is 1,650 feet (see app. J), and the most representative compression modulus (E_c) is [−] 146,000 psi (see Gilluly and Grant, 1949, p. 514), the calculated change in thickness of the Vickers zone generated in response to a total loss of reservoir pressure is given as

TABLE 10.—*Calculations of the average increase in effective pressure attributed to decompression and liquid-level decline through an unlayered equivalent of the Vickers zone of the Inglewood oil field*

Stage	Interval	Vickers zone production: Oil (bbls) interval / cumulative	Vickers zone production: Water (bbls) interval / cumulative	Vickers zone production: Net liquid (bbls) interval / cumulative	Percent estimated net liquid produced during liquid-level decline interval / cumulative	Reservoir pressure: −1,330′ (psi)	Reservoir pressure: Equivalent at −1,850′ (psi)	Increase in effective pressure ($\Delta p'$): Due to decompression (psi)	Increase in effective pressure ($\Delta p'$): Due to liquid-level decline (psi)	cumulative total $\Delta p'$ (psi)
Decompression stage	9/1924–1/1926	18,377,716	589,993	18,967,709	------			232	------	
		18,377,716	589,993	18,967,709		400	558			232
	1/1926–1/1930	50,082,585	9,798,347	59,880,932	------			360	------	
		68,460,301	10,388,340	78,848,641		142	198			592
Liquid-level decline stage	1/1930–1/1935	23,870,141	16,857,341	40,727,482	10.91			------	68	
		92,330,442	27,245,681	119,576,123	10.91	108	149			660
	1/1935–1/1940	11,015,445	12,595,442	23,610,887	6.33			------	36	
		103,345,887	39,841,123	143,187,010	17.24	100	139			696
	1/1940–1/1944	11,456,307	19,608,000	31,064,307	8.33			------	43	
		114,802,194	59,449,123	174,251,317	25.57	91	128			739
	1/1944–1/1950	17,324,437	51,285,000	68,609,437	18.39			------	79	
		132,126,631	110,734,123	242,860,754	43.96	62	86			818
	1/1950–1/1954	12,956,708	41,770,000	54,726,708	14.67			------	47	
		145,083,339	152,504,123	297,587,462	58.63	42	60			865
	1/1954–1/1958	11,989,000	41,295,068	53,284,068	14.28			------	33	
		157,072,339	193,799,191	350,871,530	72.91	------	------			898
	1/1958–1/1962	11,174,000	26,370,472	37,544,472	10.05			------	14	
		168,246,339	220,169,663	388,416,002	82.96	------	------			912
	1/1962–1/1964	6,968,000	18,266,024	25,234,024	6.76			------	6	
		175,214,339	238,435,687	413,650,026	89.72	------	------			918
	1/1964–6/1966	9,785,661	28,564,313	38,349,974	10.28			------	4	
		185,000,000	267,000,000	452,000,000	100.00	------	------			922

$$L_o - L_s = \frac{(P_s - P_o)(L_o)}{-E_c} = \frac{(790)(1650)}{-(-146{,}000)} = 8.93 \text{ ft.}$$

II. A second approach to the calculation of reservoir compaction stems from modern soil mechanics and is based on one-dimensional, drained consolidation tests. Thus, each of the one or more relatively straight-line segments of a standard *e*-log *p* curve (fig. 44) is characterized by a slope identified as the "compression index" (Taylor, 1948, p. 217–218). Taylor (1948, p. 286–288) has derived an expression permitting calculation of compaction through use of measured compression indices and other pertinent properties and changes in the system. This expression is given as:

$$\rho_u = \frac{2H_1}{1+e_1} \frac{p_2 - p_1}{(p_2+p_1)/2} \; 0.435C_c$$

where

ρ_u = total consolidation or settlement,
$2H_1$ = initial thickness,
e_1 = initial void ratio,
p_2 = final average intergranular pressure,
p_1 = initial average intergranular pressure,
C_c = compression index.

A. The initial reservoir thickness ($2H_1$) of the Vickers zone is again taken as 1,650 ft (app. J). The final average intergranular pressure (p_2) may be obtained directly from: (1) the saturated weight of an unbuoyed column of sediments extending 1,850 ft below sea level (to the approximate center of the Vickers zone); plus (2) the nearly dry weight of a column of sediments extending 300 ft above sea level (to a height roughly matching that of the average surface elevation of the Inglewood oil field). The below sea level pressure increment may be computed directly from an expression presented by Gilluly and Grant (1949, p. 502–504) and the overburden increment derives directly from considerations of average sediment density and porosity; thus,

$$p_2 = \frac{0.65 \times 2.7 \times 62.5 \times 1850 + 0.35 \times 64 \times 1850}{144} + \frac{0.65 \times 2.7 \times 62.5 \times 300}{144} = 1922 \text{ psi}$$

The initial average intergranular pressure (p_1) consists simply of the final average intergranular pressure less the initial average reservoir pressure of 790 psi; thus,

$$p_1 = 1{,}922 - 790 = 1{,}132 \text{ psi.}$$

The initial void ratio (e_1) and compression index (C_c) must be read directly from the test results.

1. Because we have no test data from the Inglewood oil field, we have prepared assumed *e*-log *p* curves for the Vickers zone based on the results of test data developed for the Wilmington oil field and a Bolivar

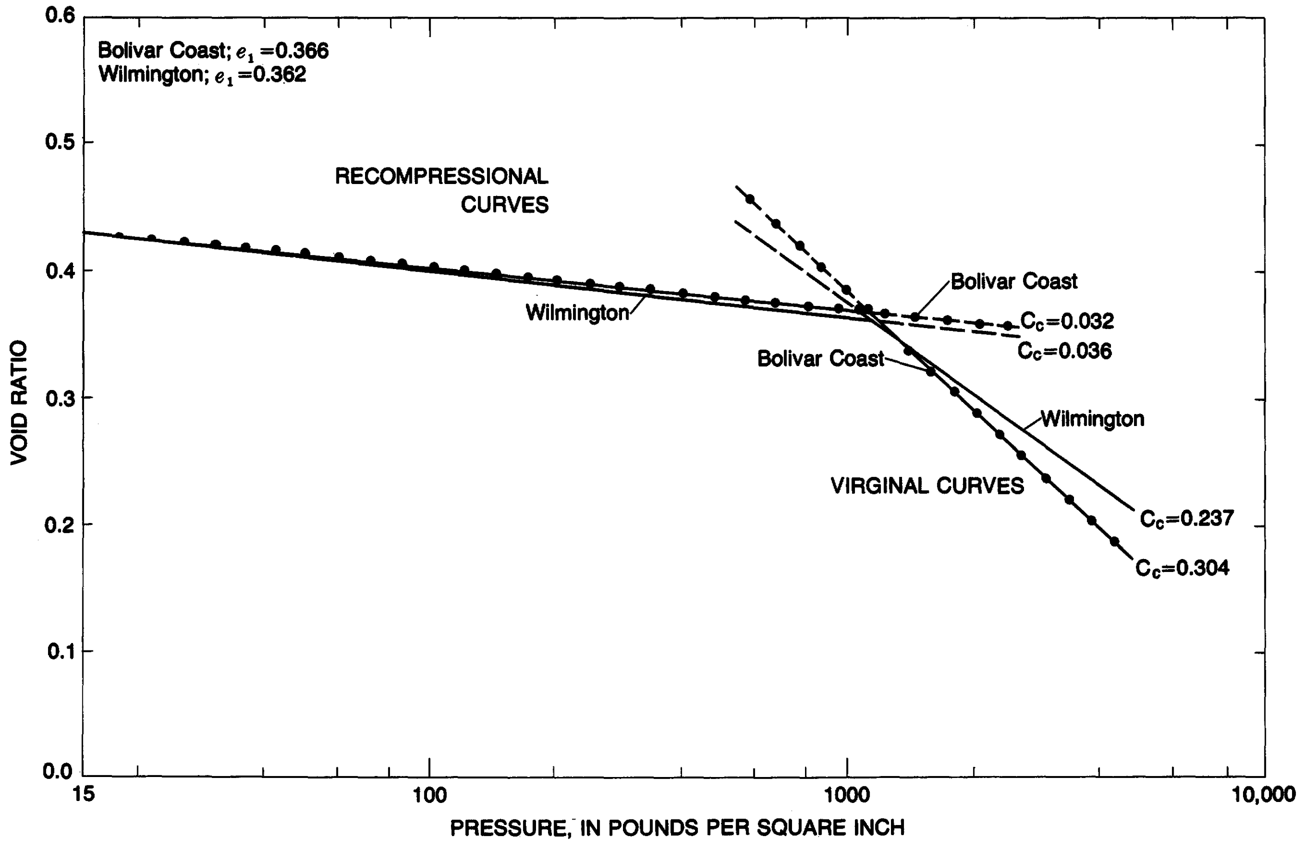

FIGURE 53.—Assumed e-log p curves for the Vickers zone of the Inglewood oil field. Values of C_c for the virginal range assumed to match those for "average" 2,000–4,000-foot Wilmington sand and 3,100-foot Bolivar Coast sand. Values of C_c for the recompressional range assumed to match unloading portion of e-log p curve for "average" 2,000–4,000-foot Wilmington sand and average of unloading and reloaded cycles in the 1,000–3,000 psi range for 3,100-foot Bolivar Coast sand. Data from Allen and Mayuga (1970, p. 415) and van der Knaap and van der Vlis (1967, p. 89).

Coast oil field (fig. 53). The initial in situ void ratios at 1,132 psi were in each case derived from a projection of the recompressional slope at 15 psi and an average measured (laboratory) void ratio of 0.428 (or porosity of 0.30). Utilization of the recompressional parts of the curves, which derive from experimental loading and (or) unloading of the samples, should lead to minimum ultimate compaction figures; utilization of the virginal parts should lead to maximum ultimate compaction figures.

B. Acceptance of the above data as representative of the Vickers zone leads to the following extreme values for the ultimate expected compaction of this zone developed in response to a total loss of reservoir fluid pressure:
   1. Recompressional compaction:
      8.71 ft (Bolivar Coast)
      9.80 ft (Wilmington).
   2. Virginal compaction:
      82.7 ft (Bolivar Coast)
      64.6 ft (Wilmington).

C. Alternatively, compaction may be calculated from the same basic data through use of the expression:

$$\Delta H = \frac{\Delta e}{1+e} \times H,$$

where
   ΔH = change in thickness,
   Δe = change in void ratio between initial and final loads,
   e = initial in situ void ratio, and
   H = original thickness.

Thus,
   1. Recompressional compaction:
      7.26 ft (Bolivar Coast)
      10.9 ft (Wilmington).
   2. Virginal compaction:
      84.6 ft (Bolivar Coast)
      65.4 ft (Wilmington).
   3. Differences between these figures and those calculated from Taylor's formula are attributed to an inherent imprecision in the measurement of Δe (fig. 53).

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