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Urban Oil Production and Subsidence Control - A Case History, Beverly Hills (East) Oilfield, California

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ABSTRACT

In only a limited number of hydrocarbon producing areas of the United States and elsewhere has the production of oil and related fluids from subsurface reservoirs been correlated with surface subsidence and damage to property in the subsiding area as well as damage to wells and producing facilities as a result of compaction within the productive reservoirs. These limited phenomena have been observed and documented most notably in the Wilmington Oil Field in the southerly portion in the City of Los Angeles and adjoining City of Long Beach.

The City of Los Angeles has permitted urban oil producing operations for the past 20 years in the belief that the risk of significant oil field subsidence is negligible and in the knowledge that should slight negative changes in the surface elevations be noted at or near the outset of production, measures can be taken to abate the condition before damage to surface improvements could occur.

References and illustrations at end of paper.

The Beverly Hills (East) Oilfield was discovered during December 1964, and it soon became apparent that a major hydrocarbon reserve had been found. Within three years production rates exceeded 30,000 BOPD from reservoirs as shallow as 3,600 feet beneath one of the most densely populated portions of the city. Clearly, the situation required assessment of the subsidence prospects.

The Beverly Hills (East) field is located within an east-west trending elongate complexly folded and faulted anticline situated on the northwesterly rim of the Los Angeles Basin at the common boundary between the cities of Beverly Hills and Los Angeles. Productive limits encompass approximately 848 acres within which 6,200 individuals are currently receiving royalty payments. Development drilling has been conducted by two operators - Standard Oil Company of California and Occidental Petroleum Corporation - and by May 1, 1975, 118 wells had been completed of which 26 are water injection wells. As of May 1975, over 61 million barrels of oil and 124 million MCF of gas have been produced. Production during April 1975 averaged 11,000 BOPD and 15,000 MCF of gas per day.

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Early in the life of the field, it was determined that pressure maintenance operations would prove economically attractive and water injection was begun in December 1969. A cooperative venture to monitor precisely the ground elevations over the field area was initiated in 1966 by establishing a network of bench marks to add detail to those bench marks previously established by the City of Los Angeles.

Traditionally, the City of Los Angeles has relied upon precise leveling surveys as a means of determining subtle changes in surface elevations in this tectonically restless geologic province. Such surveys conducted over the surface of the Beverly Hills (East) Oilfield revealed that subsidence rates were relatively uniform from 1960 to 1967, prior to the advent of oil production, and that these rates increased only slightly for the years 1967 to 1969, when production reached its peak. Subsequent precise leveling data recorded decreasing rates of subsidence as a result of declining production and the initiation of a pressure maintenance project.

The water injection program at this time appears to be fulfilling expectations that the project will be economic and is proving effective in arresting the minor amount of subsidence which may be attributable to subsurface fluid withdrawals.

INTRODUCTION

The spectre of surface subsidence, associated with oil field operations, is a matter of continuing concern to those who reside or own property over and adjacent to such operations, despite the fact that damage to surface facilities has occurred only in rare instances and especially where the subsiding area adjoins a body of water. The classic cases most often cited are Wilmington, California; Goose Creek, Texas; and Lake Maracaibo, Venezuela. So dramatic and well known are these examples of oil-field-related subsidence that oil production in urban areas is not permitted without reasonable assurance that similar events will not occur.

Outstanding among local jurisdictions in controlling subsidence is the City of Los Angeles, which depends in large measure upon the following requirements:

"If a zoning administrator determines, after first receiving the report and recommendations from the City Administrative Office, that oil drilling and production activities ... have caused or may cause subsidence ..., then after consulting with recognized experts ... and with those producing hydrocarbons from the affected area, he shall have the authority to require the involved producer(s) to take corrective action, including repressurizing the oil producing structures or cessation of the oil drilling and production."

By means of such an order, the City of Los Angeles has been dealing with problems associated with oilfield subsidence since 1945.

In addition, oil operators have cooperated among themselves to assure that hazardous ground movements will not be allowed to occur. Prior to the commencement of production, Occidental Petroleum Corporation and Standard Oil Company of California, in connection with the development of the Beverly Hills (East) Oilfield, made a thorough preliminary evaluation to define the potential for the subsidence. At the outset, this evaluation consisted of listing those empirical variables that were known to have some control over the magnitude of any earth movement which might occur. A monitoring program was then instituted prior to first production and was structured to yield information concerning the detection and definition of any subsidence which might subsequently occur.

HISTORICAL REVIEW AND REGULATORY FRAMEWORK

The City of Los Angeles is situated squarely on top of one of the great petroleum producing provinces of the world. Viewed from the standpoint of production per acre, the Los Angeles Basin is unequaled in its oil recoveries.

Commercial oil was first produced in the City late in the 19th century, after the discovery of the Los Angeles City Oilfield a short distance from City Hall. Since that time, exploration and drilling have occurred sporadically, as major trends of production have been delineated throughout the Basin (see Figure 1) and as the City has provided a mechanism to authorize drilling and development.

Modern oil operations began in Los Angeles in 1953, shortly after World War II when the City incorporated urban drilling procedures in its Municipal Code (Spaulding, 1971)[1]. The essence of these procedures is the creation of oil drilling districts and approval of "controlled" drilling sites. The latter are one-acre compounds architecturally styled, landscaped, and aesthetically treated in such a way as to eliminate the offensive aspects of a heavy industrial land use in the urban environment. As many as 75 wells have been drilled within one of these island type drill sites.

The most important element of oil well drilling in Los Angeles is the drill site itself, as this is the tangible phase of operations to which residents in its vicinity can relate. In order to provide requisite control of drilling activities, the City relies upon its zoning authorities to impose operating conditions rigid enough to furnish essential protection, yet at the same time flexible enough to achieve environmental compatibility. One of the rigid requirements which is routinely prescribed for all urban drilling operations has been recited in the introduction to this paper.

SUBSIDENCE CONTROL

Each time the City of Los Angeles contemplates a new application for the establishment of an oil drilling district, the question is inevitably asked whether subsidence similar to that at Wilmington may be expected to occur as a consequence of new urban production.

It is fortunate that there is a long record of oil production from the central portion of the City, more than 75 years, and prolific, approximately 170 million barrels from eight oilfields, and is unblemished by any significant subsidence. More than this record, however, the City and urban operators now depend upon their ability to detect and predict subsidence before it reaches damaging proportions with respect to people and properties situated over the oilfield. The basis for such early detection and prediction is precise survey leveling of the land surface. These surveys have the capacity to measure changes in surface elevation within an accuracy of 0.005 of a foot, or 1.5 mm. Recent oil drilling districts now carry as a condition of approval the requirement that precise leveling be done as often as necessary to yield diagnostic information.

URBAN OIL PRODUCING AREAS

Exploration in central Los Angeles reached its zenith in 1965, and was successful in disclosing a number of very substantial oil accumulations. Those of particular interest - because of their size, depth and degree of urbanization - are: Beverly Hills, La Cienegas, Salt Lake, and Los Angeles Downtown. Acting under the authority of the subsidence provisions quoted earlier, the City Administrative Officer commissioned several well-known experts to perform reconnaissance investigations of these oilfields for the purpose of evaluating subsidence prospects or occurrence. The conclusions of the more notable of these studies are illuminating.

Babson and Burns[2], consulting petroleum engineers, concluded by saying: "Based on such data as are available from older Los Angeles Basin oilfields, we would not expect substantial subsidence in the fields in question because of the sharply folded nature of the structures, the prevalence of thrust faulting, the relatively small oil reserves of most of the pools, and the initiation of fluid injection projects in almost all of the fields. It is recognized, however, that many of the factors controlling subsidence are imperfectly known, and the suggestion of increasing subsidence in the Beverly Hills field indicates that the situation in all these areas should be watched carefully."

Babson and Burns had earlier stated that data on subsidence in the Beverly Hills field are derived from bench mark observations recorded by the City Survey Section and the oilfield operators. These records reflected "a relatively consistent rate of subsidence during the period 1960 to 1967 ... production from the east area of the Beverly Hills field was initiated during 1966 and reached a probable peak level during 1968 and 1969. Subsidence rates for most bench marks in the area increased during the period from 1967 to 1969, some reaching a level of approximately 0.05 feet per year," or from two and one-half to five times their former rates. From the distribution of these subsidence rates, it could be seen that the highest rates were measured over the central portion of the field and involved an area of approximately 80 acres.

Babson and Burns have qualified their remarks by pointing out, "While the data ... indicate that increased subsidence rates have occurred over the area in which the hydrocarbon accumulation is widest and the production sands are thickest, definite conclusions in regard to the influence of oil production cannot be drawn without a thorough and detailed study of geology, hydrology and reservoir conditions in order to evaluate the influence of all possible factors."

Mr. Dennis R. Allen, Subsidence Control Engineer for the Department of Oil Properties, City of Long Beach, California, and under retainer to the City of Los Angeles for subsidence studies, has indicated in his report[3] that a particular bench mark during the period from 1949 to 1969 showed a sharp increase in the subsidence rate between the 1967 and 1969 leveling surveys. Mr. Allen further states, "The subsiding area does not coincide in shape or lineation with the oilfield; however, the apparent increase in rate does coincide with oilfield activity. Because of its proximity to oil operations and the apparent increase in rate approximating the period of oil production, this area warrants future review."

HISTORY OF BEVERLY HILLS (EAST) FIELD DEVELOPMENT

The Beverly Hills field was discovered in 1900 when marginal production was obtained from shallow Pliocene sands. By 1926, there was no further development and the wells were eventually abandoned to make way for accelerating population growth.

The Beverly Hills (West) Miocene sand reservoirs were discovered in 1954 from urbanized drill sites within the 20th Century Fox movie studio property. This new drilling did not establish an easterly limit to the field and was terminated when the wells became economically unattractive. In addition, the City of Beverly Hills had no provision for drilling under the City at that time.

The Beverly Hills (East) area was discovered during 1964 by separate core holes drilled by the Occidental and Standard Oil companies. The Standard Oil Company core hole at the Packard Drill Site found the east end of the field, while an Occidental core hole discovered the westerly edge of the field. In September 1965, a Standard core hole drilled in almost the middle of the field delineated the size and extent of the field and confirmed a major discovery. Ultramodern urban drill sites were then erected after establishing the drilling districts, and first production was obtained in 1966. To date, 118 wells have been completed, including 26 water injection wells and 7 wells which have been directionally drilled from a third drill site at the Salt Lake Field to the north.

The well survey map (Figure 2) indicates the status of development as of May 1975. Primary development is considered complete, but drilling for water flood operations is continuing both for producing and water injection wells.

REGIONAL TECTONIC FRAMEWORK

The Los Angeles Basin exhibits a long history of tectonic subsidence and associated accumulation of sediments from the surrounding high lands, such as the Santa Monica Mountains, the Puente Hills and the San Gabriel Mountains to the north. From subsurface evidence, it is apparent that subsidence and sedimentation have been an almost continuous process, at least since the end of middle Miocene.

The complex network of faulting of the general area has been simplified on Figure 3 to show the major features relative to the area under discussion. The Santa Monica Fault shown at the base of the Santa Monica Mountains extends along the northwesterly edge of the Los Angeles Basin. The Whittier fault trends along the base of the Puente Hills, and in the area of its westerly termination it is lost in the subsurface due to rapid recent burial at the Whittier narrows where the San Gabriel River enters the Los Angeles Basin. The Inglewood Fault trend is a prominent feature in the oilfields shown along its trace and extends at least through the Inglewood Field but seems to dissipate into more than one trace near the Santa Monica Fault.

The tectonic forces which have resulted in the development of these faults probably originate along the San Andreas Fault north of the San Gabriel Mountains[4]. The forces seem to be acting in a southerly direction, resulting in the San Gabriel Mountain mass overriding the adjacent lowlands of the San Fernando and San Gabriel valleys and the Santa Monica Mountain Mass overriding the northwesterly margin of the Los Angeles Basin. The Puente Hills Fault Block is similarly overriding the northeasterly part of the Los Angeles Basin. The Inglewood Fault is the result of the pressure of the Santa Monica Mountain Block against the basinal block and has resulted in right lateral movement. The Santa Monica Fault shows dominantly thrustal movement, but some left lateral movement has occurred.

STRUCTURE AND SEDIMENTATION

Cross Section A-A' (Figure 4) is drawn north-south from the Santa Monica Mountains to the Inglewood Fault and passes through the middle of the Beverly Hills (East) field. The Santa Monica Fault is on the north end of the cross section and separates the intrusives and metamorphic rocks from the basinal rocks to the south. The southerly acting crustal pressure has also generated a complex series of en echelon folds, some of which have ruptured due to the intensity of folding and have developed thrustal faults similar to the Santa Monica Fault. As is indicated on the cross section, these faults are not major faults becoming obscure high in the section, and are apparently limited to Miocene formations.

The anticlines are typically asymmetrical, the northern flanks dipping from 20° to 45° and the southerly flanks overturning to as much as a 75° northerly dip. The small anticline immediately to the south of the Beverly Hills (East) field is the easterly continuation of the plunging anticlinal structure of the Cheviot Hills. It is not a hydrocarbon-bearing reservoir in this particular locality but is oil-bearing up the plunge to the west.

The Miocene sands present at Beverly Hills (East) show minor stratigraphic thinning across the crest of the reservoir and thicken markedly in the Salt Lake Field as the highlands are approached. Sands were deposited during the early Pliocene around the margins of the anticlines, while later Pliocene sands were deposited across the tops of the structures which grew almost continuously throughout the Pliocene deposition. The Pico Formation has not been found oil bearing in the immediate area and is composed primarily of sands and soft shales accumulating to great thickness farther out in the Los Angeles basin.

Covering all is a series of sands, gravels, and shales of Pleistocene age. This series of sediments is fresh water-bearing and apparently all of subaerial deposition. It is noteworthy that La Brea Tar Pits lie just to the east of the line of section and it is probable that some trace of the Santa Monica Fault system accounts for their occurrence.

Cross Section B-B' (Figure 5) is at the westerly end of the Beverly Hills (East) field and shows in larger magnification stratigraphic changes and structural complexities. It may be seen that folding has been more intense than along Section A-A', and the resultant folding is of greater magnitude.

Figure 6 is a type log of the Beverly Hills (East) oilfield. The top is at the left, labeled A, and the bottom is at the right, labeled D. Well depths are not shown on the log because of the wide range of vertical depths to the structure and the highly deviated wells. One hundred foot intervals from a typical penetration are indicated on the centerline of each section. Not shown on Figure 6 are 3,500 feet to 4,500 feet of unconsolidated formations above the shallowest oil sands, including the freshwater-bearing Pleistocene continental sediments and relatively thick Pico (Upper Pliocene) sediments.

The Repetto sands were deposited primarily around the fringes of the anticline in channels or embayments and exhibit moderate compaction. Up to 50% of the sand volume is commonly composed of a breccia of the underlying Miocene shale which was stripped from the crest of the Salt Lake structure immediately to the north. The sands are complexly lenticular, but reservoir continuity is present over limited areas. At no place in the field is the total section productive. The upper sand is productive at the east end, and the lower sand is productive at the west end.

Lying below the Repetto sands is a fairly thick and well compacted Puente shale and siltstone sequence of Upper Miocene Age. The shales are typically fractured and slickensided from the intense folding and frequently have oil and gas within the fractures. There is very little permeability, and the shales do not produce hydrocarbons at economic rates. The series of sands labeled as the "DM" sands are well developed on the south flank of the structure and are occasionally present as thin stringers on the north flank. These sands have been exploited where present in combination with the Main zone.

The Main zone is, as the name implies, the largest oil reservoir in the field. These well compacted sands are relatively continuous in the upper part of the zone but become quite lenticular toward the base. The shale bodies within the zone are widespread over the field and constitute the best correlation markers. The series of shales below the main zone are also fractured and are much harder than those above. Some oil and gas are present in the fractures.

The Deep zone which consists of a series of hard sands and shales is a gas distillate reservoir with a downstructure oil band. The latter is not commercially attractive alone but has been dually completed with the Main zone for development.

The Nodular Shale, although productive in some areas of the Los Angeles Basin, is not productive here despite containing modest amounts of oil and gas in fractures. It is composed of a series of hard calcareous and phosphatic shales with occasional hard sandstone streaks and is extensively fractured.

A simplified structure contour map drawn at the top of the main zone is represented by Figure 7. This structure is noteworthy in that the southerly flank is vertical to overturned and is characterized by an active natural water drive within the field. The east-west faults are those previously described as ruptures due to the intense folding whereas the north-south faults are probably fractures associated with the Inglewood fault trend.

The West Pico 4 fault separates the area of very complex geology to the west from the relatively simple geology to the east. As will be mentioned later, there is evidence for its presence within the shallow freshwater aquifers. It is east of this fault that waterflooding has been undertaken.

Figure 8 is a structural map at the base of the Repetto zone. The fault pattern is much less complex than in the Main zone and folding is less intense with dips up to 60 degrees in the south flank. However, within some of the sands, due to "draping" effects, dips might be greater above this particular horizon. The productive limits are in some cases marked by downstructure oil-water contacts and in other cases represented by sand pinch-out lines. Waterflooding within these sands has been of marginal economic success.

WATERFLOOD

Early in 1967, Standard and Occidental began negotiations and planning precedent to waterflooding the field. It was eventually agreed that operations should be a cooperative venture and that water injection should be started when Main zone reservoir pressure reached approximately 1,700 psi, which was forecast for January 1971. Standard used the Dykstra-Parsons technique to predict waterflood performance, whereas Occidental based its forecast upon the Buckley-Leverett method. It is noteworthy that both companies arrived at essentially the same answer (see Table 1 for reservoir data), although Standard planned a peripheral flood and Occidental planned a pattern flood.

Agreements for the appropriate lease line injection wells were consummated late in 1969. Water injection for the peripheral flood was initiated in December of 1969 and for the pattern flood in February of 1970. At present, the injectors are located as indicated on the well survey map (Figure 2) which shows locations for both the Main and Repetto zones. Pressure in the Main zone was approximately 1,600 psi upon initiation of the injection. It is the aim of the flood to stabilize and not increase formation pressure.

HISTORY OF EARTH MOVEMENTS

Southern California has long been known as a tectonically restless province. In connection with oil production from an urban area, it is therefore essential that the history of earth movements be reviewed and understood before substantial production is permitted. Fortunately, the record of such movements is both extensive and has been thoroughly investigated[5].

Commencing in 1906, the U.S. Coast and Geodetic Survey developed a network of first-order level lines in the Los Angeles region to complement more random surveys performed late in the 19th century. This network was expanded during the repeated levelings in the years 1920, 1924, 1927, 1932, 1934, 1939, and 1945.

Since 1934 the City[6] and County of Los Angeles have also leveled over this network and enlarged upon it to the extent that it now provides very comprehensive coverage in Southern California. These survey records were used as part of the earth movement evaluation by Occidental and Standard for the Beverly Hills (East) field.

Although available leveling records in the area of study go back to the 1920s, their erratic coverage did not allow for the construction of good regional ground movement maps, but by 1949 the density of level traverse lines in this area was such that one could begin to construct regional maps using the 1949 data as base date. Figure 9 shows the annual rate of ground movement for the period 1949 to 1963. This is prior to any fluid extraction from the Beverly Hills (East) field.

Experience at Wilmington had shown that the quickest and least expensive method for monitoring earth movements due to oilfield operations and other possible causes was through periodic first- and second-order leveling surveys. These records yielded a continuous up-to-date picture of where the subsidence was occurring, how much was occurring, and at what rate it was occurring.

To obtain such information, Occidental and Standard decided to establish their own leveling network over the area of indicated oil accumulation prior to any fluid extraction.

Pafford and Associates[7], a private consulting survey firm, was retained to make the first 1967 leveling, periodic relevelings and to set additional bench marks as needed. Included in this network were as many of the U.S. Coast and Geodetic Survey and Los Angeles City traverse lines as could possibly be used. Even the same datum mean sea level was adopted, thus allowing for past and future utilization of their recorded elevations. Releveling and expansion of the Occidental-Standard net occurred during the years 1969, 1970, 1971, 1972 and 1973.

To evaluate ground movements in West Central Los Angeles, all of the elevation determinations, based on mean sea level, for each bench mark in the leveling network were placed in a computerized data retrieval file. Printouts consisting of tabulations of all bench mark elevation records in graphical plots of elevation versus time for each bench mark in the file were made and reviewed. From this review, selected north-south and east-west profiles of total ground movement were constructed to show total change in elevations since 1949.

It was then determined that for historical background the period 1949 through 1963 could be used. During the review it was discovered from the individual bench mark plots that changes in elevation throughout the area were not always consistent but exhibited marked changes in rates of movement. It was therefore found desirable to construct annual rate of change maps for selected periods of time in order to establish a proper base for future comparisons. By converting the total movement to an annual rate of change, it would also be possible to compare shorter periods of observation with longer periods, thus aiding in the detection of significant changes in surface ground movement which may or may not be related to subsurface fluid withdrawals. Considerable care was taken to separate the larger significant changes in rate of movement from the minor fluctuations which are thought to be largely attributable to surveying error.

Triangulation surveys to determine horizontal ground movement are available for the Los Angeles area (Alexander, 1963[8]). They have not been utilized or enlarged upon for the Beverly Hills (East) field, because they are generally too gross and inaccurate for use in the early detection or subsequent definition of the low magnitude movements encountered.

With this background in hand, Occidental and Standard set about analyzing and describing the various possible causes of the pre-production ground movements that are apparent in Figure 9. This was done in order to develop a technique for recognizing and defining any additional ground movements that might be caused by oilfield fluid withdrawals. Analysis of the causes of these ground movements follows later in this report. Figure 10, an annual rate of earth movement map for the period 1967 to 1971, the period of heaviest production, shows a slight increase in the rate of subsidence over the pre-production background (Figure 9). It was noted that this increase also tended to center over the productive area. To determine how much of this movement might be related to oilfield operations, Bench Mark No. 82 at the corner of Western Ave. and Wilshire Boulevard was selected as a datum. Choice of this bench mark was based on its historical stability and the fact that there are no known subsurface fluid withdrawals anywhere in the immediate area. Figure 11 shows the amount of movement based on mean sea level datum that has occurred in the area of Bench Mark No. 82 between 1967 and 1973 as the possible result of tectonic movement, surveying error, and minor local building or traffic disturbances. Figure 12 shows the annual rates of ground movement for the period 1961 to 1971, based on using Bench Mark 82 as a datum rather than mean sea level as in the case of Figure 10. This new map (Figure 12) probably represents the rate and areal distribution of subsidence related to oil field fluid withdrawals during this period - a rate and amount too small to be considered serious. Figure 13, an annual rate of earth movement map based on Bench Mark 82 as datum for the period October 1972 to October 1973, shows the arresting effect of both the water injection project and declining production.

POSSIBLE CAUSES OF GROUND MOVEMENT

Standard and Occidental have used an empirical approach for predicting potential subsidence wherein each of the possible contributing factors must be considered, weighed and, if necessary, receive further evaluation. Many of the factors causing earth movement are imperfectly known. With sufficient data, however, it has become possible to isolate certain components and determine which may be contributing to the movement. Whenever there are multiple causes, difficulty naturally arises in estimating the quantitative effect of each.

Those variables which the authors considered important in the evaluation of earth movements, particularly oilfield-related, have been organized into the following empirical model and were applied to the Beverly Hills (East) field prior to production in order to estimate the oilfield subsidence potential:

1. Tectonic Activity.
2. Compaction of Sediments due to either Surface Loading or Wetting.
3. Compaction and Consolidation due to Vibration.
4. Subsurface Solution or Cavitation.
5. Subsurface Pore Pressure Reduction.
    - a. Controlling Geologic Characteristics.
        - (1) Regional Structural Conditions.
            - (a) Geologic Structure.
            - (b) Depth of Production.
            - (c) Breadth and Length of Accumulation.
        - (2) Physical Properties of Producing Zones.
            - (a) Porosity.
            - (b) Lithology.
            - (c) Preconsolidation and Cementation.

In the Beverly Hills (East) area, variations in recorded ground movement were too great and too complex to be explained by only one or two causes listed above. By analyzing these recorded ground movements in light of each of the possible causes it can be shown that in this area the movements were resulting from the combined effects of tectonism, near surface freshwater fluid withdrawals and, to a slight extent, recently from deeper oilfield fluid withdrawals. For this empirical approach to be effective, it has become necessary to rely on correlation techniques wherein the survey records are used as the base to which all other factors are compared on a time-of-occurrence basis (i.e., formation pressure decline, earthquake incidence, the lowering of freshwater tables, etc.).

Tectonic Activity

That the Beverly Hills-Hollywood area is and has been tectonically active is readily apparent from the existing folding, faulting and sedimentary patterns. Also, recorded seismic activity (Figure 14), surface physiographic features and the fault displacements of quarternary sediments testify to the restlessness of the region. How much, where, and at what rate the earth has moved as a result of this activity has been revealed by recourse to proper monitoring systems. For example, surface movements have been measured by precise surveying techniques and the seismic activity has been recorded by the seismographs of the California Institute of Technology and the University of Southern California. To date, all of the seismic events recorded by instruments in these two nearby seismograph nets have been associated with movements along geologic features at depths well below the present water flooding project.

Figure 14, a map of earthquake epicenters for the period 1934 to 1973, illustrates regional seismic activity. Most of the events shown on this figure appear to be related to either the Santa Monica Fault zone or the Inglewood Fault zone. Larger earthquakes have also occurred along both of these fault zones during historical times beyond the limits of Figure 14. For instance, quakes of magnitude greater than 6 have occurred further south along the Inglewood Fault zone during 1920 and 1933. Quakes greater than magnitude 5 have occurred during 1855, 1918, 1927, and 1973 along the Santa Monica Fault zone. (U.S. Department of Commerce[9].)

Leveling traverses run prior to first oilfield production show some slow subsidence persisting over the oilfield area which cannot be attributed to shallow groundwater fluid withdrawals (Figures 9 and 15). The most plausible explanation for this movement is slow tectonic subsidence over an area which has received a relatively thick section of sediments throughout recent geologic time. A more subtle expression of this movement can be found by comparing present day topography along La Cienega Boulevard with the annual rate of change in elevation records for the period 1949 to 1963 (Figure 9) and also with the isochore map (Figure 16) of shallow freshwater-bearing sands and gravels. These aspects combine to produce a broad, gentle southerly sloping topographic valley coincident with the greatest subsidence rate and the thickest section of quarternary freshwater-bearing sands and gravels. During the years 1935 to 1953 (Figure 15) when the elevation of the freshwater table was being lowered, some of this surface subsidence has to be attributed to this pressure decline.

Displacement of quarternary sediments and rather prominent fault scarps along the Inglewood and Santa Monica Fault zones are the most conspicuous illustrations of recent tectonic activity. More subtle evidence in the Beverly Hills (East) field is afforded by variations in water table elevations where these faults or their subsidiaries behave as fluid barriers. It has been noted from precise level surveys that subsidence rates may vary between individual fault blocks. When such variations occur, they are usually associated with markedly different variations in the water table of the shallow freshwater aquifers. It has also been noted in several instances that the underlying structural grain is reflected in the surface leveling surveys.

Compaction of Sediments Due to Either Surface Loading or Wetting

There are no indications that any significant part of the present day earth movements in the immediate area of the Beverly Hills (East) field have resulted from surface loading or wetting. The fact that the water table elevation was at one time at or near the present surface precludes shallow compacting from surface wetting in this area (Mendenhall 1905 and Ebert 1921[10]). Very local differential surface settlements of limited duration have been recorded during special leveling surveys in the immediate area of high rise structures under construction. Subsidence of this nature does not appear to be reflected in Figures 9, 10, 12 or 13.

Compaction and Consolidation Due to Vibration

The only events capable of causing subsidence by vibration are earthquakes, although some very minor, local movements may be occurring as a result of surface traffic. Recent leveling traverses east of the Beverly Hills (East) oilfield and along Pico Boulevard showed a marked acceleration in subsidence between level runs in October, 1970 and March, 1971. It is believed that this acceleration resulted from vibratory subsidence set up within the shallow fresh water aquifers by the February 9, 1971 magnitude 6.4 San Fernando earthquake. For example, several bench marks which prior to September, 1970 had consistently subsided for many years at a rate of less than 0.01 foot per year showed an increase to 0.04 foot per year in the March, 1971 survey. A similar acceleration in subsidence appears to have also occurred during the Pt. Mugu earthquake of magnitude 6 on February 21, 1973.

Subsurface Solution or Cavitation

There is no evidence that any of the subsidence over the Beverly Hills (East) oilfield has resulted from subsurface solution or cavitation. The subsurface sediments are not subject to solution, and there has not been a mechanical removal of the subsurface strata in this area.

Subsurface Pore Pressure Reduction (Fluid Withdrawal)

One of the most important criteria related to oilfield subsidence is the reduction or change in pore pressure within the subsurface formations undergoing depletion. When the formation pressure is either reduced or increased, deformation within the particular reservoir will occur. Such a change in formation pressure will result in a load transfer from the fluid phase to the solid matrix or the reverse. The magnitude of the resulting deformation is dependent upon several other variables which interact with each other. Because of the difficulty in adequately defining each of these variables at the time of first hydrocarbon discovery, a rigorous mathematical analysis of the eventual magnitude of deformation is impossible. An early assessment of the potential compaction can, however, be made by using the empirical approach mentioned earlier.

Subsidence has been occurring in the area of the Beverly Hills (East) field for many years prior to the initiation of oilfield operations. Studies discussed earlier have revealed the fact that some of this subsidence was related to shallow freshwater withdrawals. The same controlling geologic characteristics, discussed in considerable detail under Oilfield-Related Subsidence, can also be applied to the shallow freshwater aquifers.

To determine the extent to which shallow groundwater withdrawals were contributing to subsidence, the distribution and thickness of the aquifers were mapped (Figure 16). The changes in water table elevation within this aquifer system[11] were then compared to overlying ground movement measurements. Since the changes in the pore pressure are a reflection of changes in the water table elevation, within the productive formations, it was not necessary to account for discharge or recharge volumes.

Graphical plots of surface movement at bench marks near or adjacent to fluid level recording points were constructed. The longest history of such recordings is shown in Figure 17. This bench mark and observation

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66-9

wells are located southeast of the area of study within what is called the central basin freshwater aquifer, in an area beneath which hydrocarbons have never been withdrawn. This long-term record shows a good correlation since 1926 between surface subsidence and freshwater withdrawals. How much of this movement is due to tectonic activity is unknown. [illegible]

Sediments comprising these aquifers are described as nearly flat-lying, loose, unconsolidated sands and gravels interbedded with silts and clays (Fowler 1961[12]). The same aquifers extend northwesterly across the Beverly Hills (East) field. In Figure 15, surface movements at one of the bench marks centered over the field are compared to fluid level changes in the underlying freshwater aquifer. In this instance, between 1935 and 1953 subsidence was occuring as a result of both freshwater fluid withdrawals and tectonic activity; but it is impossible to discriminate one from the other.

Between 1953 and 1966 when the water table remained essentially static, the overlying surface continued to subside - apparently due to tectonic activity. By again comparing Figures 9 and 16, as was done in the evaluation of tectonically induced subsidence, it can be seen that there is a correlation between the highest rates of subsidence and the aquifer thickness. It also happens that the greatest change in water table elevations have also occurred in the area of greatest aquifer thickness. For example, in the area of the Beverly Hills (East) field where the freshwater aquifer is nearly 800 feet thick, the water table has been lowered approximately 140 feet since the early 1900s.

Prior to production from the Beverly Hills (East) field, it was conceivable that slight subsidence from oilfield production might occur. As a consequence, a network of precise leveling traverses was initiated to detect surface elevation changes at an early date so that corrective measures could be taken if required.

In Figure 15, acceleration and movement at Bench Mark 120 after 1966 is believed to be related in part to oilfield production. This slight increase in ground movement can also be seen in Figure 18, a profile of total ground movements since 1949 along La Cienega Boulevard. During the early life of the oilfield when oil production exceeded 30,000 barrels per day, the subsidence rate from all causes increased to a maximum of 0.12 foot per year during a six-month period in 1969. After March of 1971, it can be seen from Figures 13 and 15 that the subsidence rate has decreased to less than 0.04 foot per year as a result of declining production and the initiation of a pressure maintenance project. These rates of subsidence are insignificant when compared to a maximum annual rate of 2.7 feet per year which occurred at Wilmington.

All reservoirs producing in the Beverly Hills (East) field, with one rather local exception, are of the depletion type with moderate edgewater encroachment. Figure 19 shows a plot of depth versus pressure within the various hydrocarbon-bearing zones at the time of discovery. A normal hydrostatic water and oil gradient was noted for each. Since initial production when original pore pressures were approximately 2,900 psi within the main zone, pressures have declined to approximately 1,400 psi (Figure 20).

Subsidence which might be attributed to oilfield production is depicted in Figures 12, 13 and 15. Notice that the subsiding area is approximately 12,000 feet in radius with a maximum of 4.6 inches of differential subsidence at the center. Stated differently, the regional tilt amounts to about 5 inches in more than two miles.

Beverly Hills (East) field subsidence should be compared with that of the Hollywood syncline area to the north (Figure 18) where nearly 11 inches has resulted from tectonic forces and depletion of shallow aquifers. In neither case, however, has any surface damage been reported from this differential movement.

Controlling Geologic Characteristics

(1) Regional Structural Conditions

The geometry of the trapping structure for the Beverly Hills (East) field varies from a tight asymmetrical fold within the deep Miocene sediments to a broad gentle fold in the shallower lower Pliocene rocks to a nearly flat-lying or gently dipping sedimentary section in the shallow upper Pliocene-Pleistocene sediments. The significant oil accumulations occur within the deep tightly folded section which reflects, along with the associated thrust faulting, strong north-south compression. This configuration should furnish strong arch support within both the producing intervals and the overlying capping rock (Figure 4).

The shallower Repetto hydrocarbon accumulations, which are not as large or as extensive as the Main zone, lie within the more gently folded portion of the structure. Structural support from arching was not expected within these shallower sediments. The overlying younger formations rest nearly horizontally as a dead load on these shallower productive zones.

From the subsurface structural patterns mapped to date and supplemented by density log records and injectivity tests, there is good supporting evidence which indicates that the maximum principal stress direction lies in the horizontal north-south direction, whereas the least principal stress direction lies in the horizontal east-west direction. This places the intermediate stress access in the vertical direction and consists of the overburden load, a gradient of approximately 0.9 psi per foot. (Injectivity tests broke down the Main zone sediments at a fractured gradient of 1.26 psi per foot.)

Other important subsidence controlling factors are the depth to production, breadth and length of the accumulations and the thickness of each productive zone. In the Beverly Hills (East) field, the shallow producing reservoirs are generally thin and limited in areal extent. Some contribution to surface subsidence was anticipated from these zones because of their shallow depth of burial between 3,600 feet and 4,500 feet and their nearly horizontal attitude.

The major producing reservoirs, Main and Deep zones, are considerably deeper within the strongly arched section of the entrapping anticline. The minimum depth to the top of the Main zone is 5,400 feet. The minimum depth to the top of the Deep zone is approximately 6,800 feet. The ratios of breadth of accumulation to depth for each significant zone are listed in Table 1. Thickness of the oil productive Main section is impressive on the south flank where the beds are standing nearly vertical. Oil productive thickness on this flank ranges up to 1,000 feet, whereas on the north flank, which is more gently dipping, the productive section averages about 650 feet in thickness. There is also the strong likelihood that these deeper Miocene reservoirs are more resistive to consolidation due to retained tectonic pre-stressing.

(2) *Physical Properties of the Producing Zones*

The physical properties of the sediments which make up the producing reservoirs have a bearing on the degree of consolidation which may occur when and if a sizable load transfer from the fluid phase to the rock matrix occurs. The principal rock characteristics which appear to exert some control on the amount of consolidation that will occur are:

a. Porosity
b. Lithology
c. Preconsolidation and Cementation

Porosity - All of the commercially productive zones are made up of clastic sediments with intergranular porosity. The porosity versus depth curve for the field has been constructed utilizing both core data and density log information (Figure 21). This plot shows an average reduction in porosity with depth of approximately 2% per 1,000 feet. A further reduction of this available void volume can occur as a result of grain fracturing or rearrangement of the grains which constitute the host rock, or both. In the Beverly Hills (East) field, the shallow Repetto zones with their slightly higher porosities were expected to undergo a greater change per unit volume than were the deeper Main and Deep zones.

Lithology - In intergranular reservoirs, the degree of sorting and mineral content are the principal lithologic variables which control consolidation. From ditch samples, cores and sidewall samples, it was determined that these reservoir rocks are generally poorly sorted, dirty argillaceous arkosic sands which can be physically unstable when subjected to additional loading. This type of lithology is generally more subject to consolidation than are clean, well-sorted quartzitic sands (Meade 1968[13]). This difference is chiefly due to the presence of minerals which either fail rapidly by shearing or yield plastically when additional loads are applied.

Preconsolidation and Cementation - These variables are basically related to depth of burial, maximum loading during geologic time and chemical cementation of the rock matrix by geologic processes. At Beverly Hills, the shallow Repetto sands are not well consolidated and tend to flow quite readily, necessitating

66-11

gravel pack completions. The deeper Main and Deep zone sands show a considerable degree of consolidation and cementation apparently because of depth of burial, greater age and the presence of strong horizontal compressive forces. No significant stripping or removal of shallower sediments appears to have occurred in this area. The stratigraphic column as presented (Figure 6), appears to be one of a normal sequence of deposition interrupted by minor unconformities.

Cementation of the Main zone with secondary mineralization is limited to only occasional lime-cemented stringers. Surface compressibility tests were run on main zone cores and indicated rock compressibilities averaged 4.12 x 10^{-6} PV/PV/PSI for changes in effective overburden pressure between 2,300 psi and 3,900 psi. These determinations do not appear to reflect true subsurface conditions, because the amount of measured subsidence does not approach theoretical predictions, or the difference between theoretical and actual consolidation may reflect inherent structural arch support.

Precision collar logs have been run in four wells with a repeat run in one well. Due to the large number of highly deviated holes, it has been impossible to run as many precision collar logs as desirable to check for subsurface compaction. From the repeat runs (January 30, 1967 and November 6, 1970), negligible compaction was noted opposite the Repetto zones, but this compaction was so small that it was barely within the limits of the accuracy of the measuring instrument. A repeat run through the deeper zone has not been made as of this date.

POSSIBLE EFFECTS OF EARTH MOVEMENT

Surface earth movements which may be associated with oilfield operations in the Beverly Hills (East) field have been insufficient to cause any damage to surface structures. Because of the pressure maintenance program now in progress, future subsidence attributable to production should be substantially less and insignificant. It is certain to be small in comparison with long-term surface movements arising from other causes.

Stresses which accumulated in the subsurface as a result of possible consolidation within the producing zones and overlying cap rock may have caused some casing deformation coincident with the decline in formation pressure. Now that water injection is maintaining formation pressures at a relatively constant level below original formation pressure, further deformation is not expected.

CONCLUSIONS

1. Regulations of the City of Los Angeles have been effective in controlling oil well drilling and production within the City. Not only do they render surface operations compatible with their local environmental settings, but also they are broad enough in scope to encompass unusual oilfield developments such as surface subsidence.

2. The Beverly Hills (East) oilfield is situated in an area undergoing regional subsidence as a consequence of tectonic forces. Imprinted upon this regional downwarping are subsidence components arising from shallow water production and deeper oilfield fluid withdrawals. Singly or in combination, these forces produce subsidence measurable in no more than a few hundredths of a foot per year.

3. Precise leveling surveys conducted by Standard Oil Company of California and Occidental Petroleum Corporation have been effective in detecting and monitoring surface elevation changes over the Beverly Hills (East) oilfield. Similarly, these surveys have demonstrated that subsidence attributable to oilfield operation is being arrested by a program of subsurface reservoir pressure maintenance based on water injection.

4. Oilfield subsidence, which in rare cases has been extremely damaging, can be detected at an early date following the advent of production by precise leveling surveys. Corrective measures can then be instituted to arrest subsidence before damage to surface structures or wells occurs. As a result, the principal problems which have been associated with subsidence can be prevented.

5. Oilfield subsidence may be due to a wide assortment of causes, chiefly geologic in nature, and therefore its prediction may not be quantitatively accomplished. From a qualitative point of view, however, the construction of a model using empirical components may be extremely helpful in forecasting subsidence prospects and estimating their magnitude. Subsurface geologic data, coupled with other related information, are indispensable in the accuracy of such forecasts.

ACKNOWLEDGMENTS

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66-13

Zone	Repetto	Miocene Main	Miocene Deep
Year of First Production	1967	1966	1967
Reservoir Area (Acres)	–	840	–
Depth to Top of Zone (ft.)	3200	5350	6750
Maximum Width (ft.)	2000	3300	2300
Ratio of Depth/Width*	1.8	1.6	2.9
Net Sand Thickness at Crest (ft.)	535	465	425
Average Porosity (% bulk volume)	28.6	23.1	20.3
Average Permeability (millidarcies)	265.0	108.0	22.0
Interstitial Water (% pore space)	22.0	22.7	26.0
Original Oil in Place (barrels/acre–feet)	1349	990	710
Original Solution Gas–Oil Ratio (standard cubic feet/barrel)	500	665	1040
Initial Formation Volume Factor (volume[1]/volume)	1.283	1.40	1.64
Original Reservoir Pressure (psig)	2200	2850–2920	3300
Saturation Pressure (psig)	2200	2680–2975	3300
Datum (feet subsea)	4700	5700	7000
Reservoir Temperature (°F)	170	200	215
A. P. I. Gravity of Oil (°)	30–35	22–30	40–45

*Ratio of Depth/Width at Wilmington Ranger Zone 2300/15000 = .15

Table 1 – Beverly Hills (East) Reservoir Data

66-14

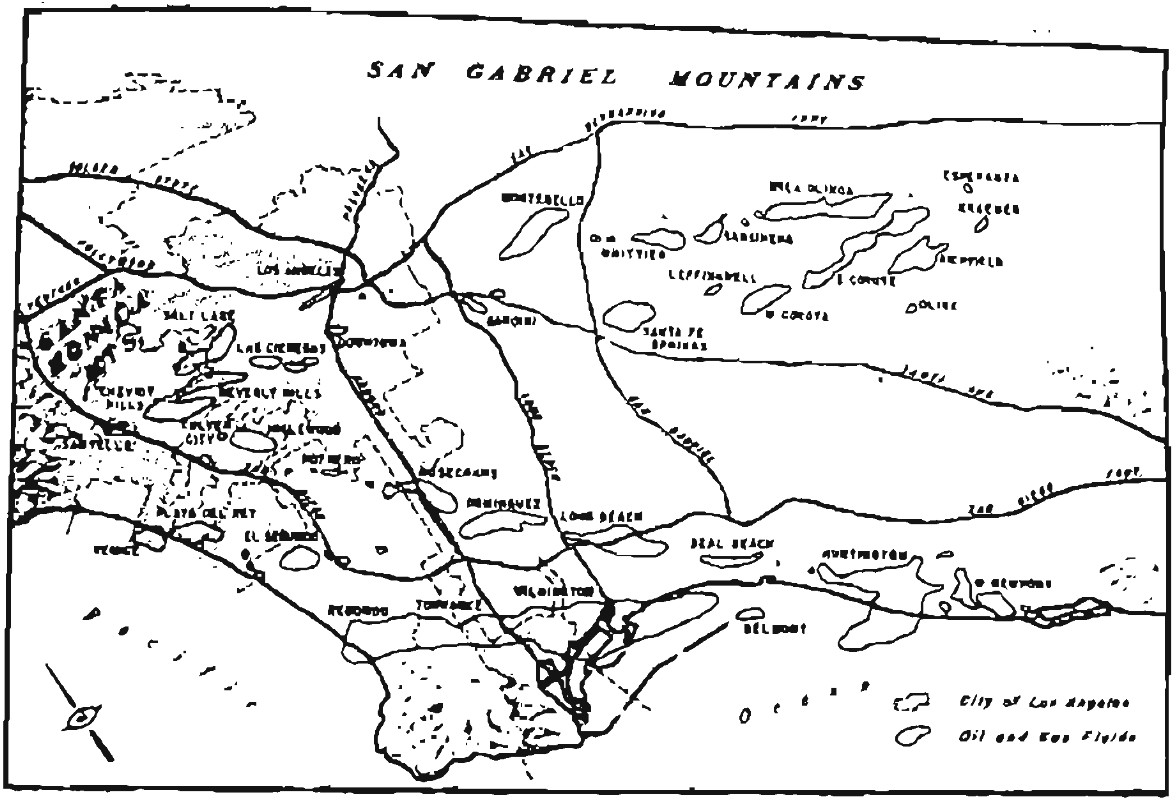

Fig. 1 - Location Map

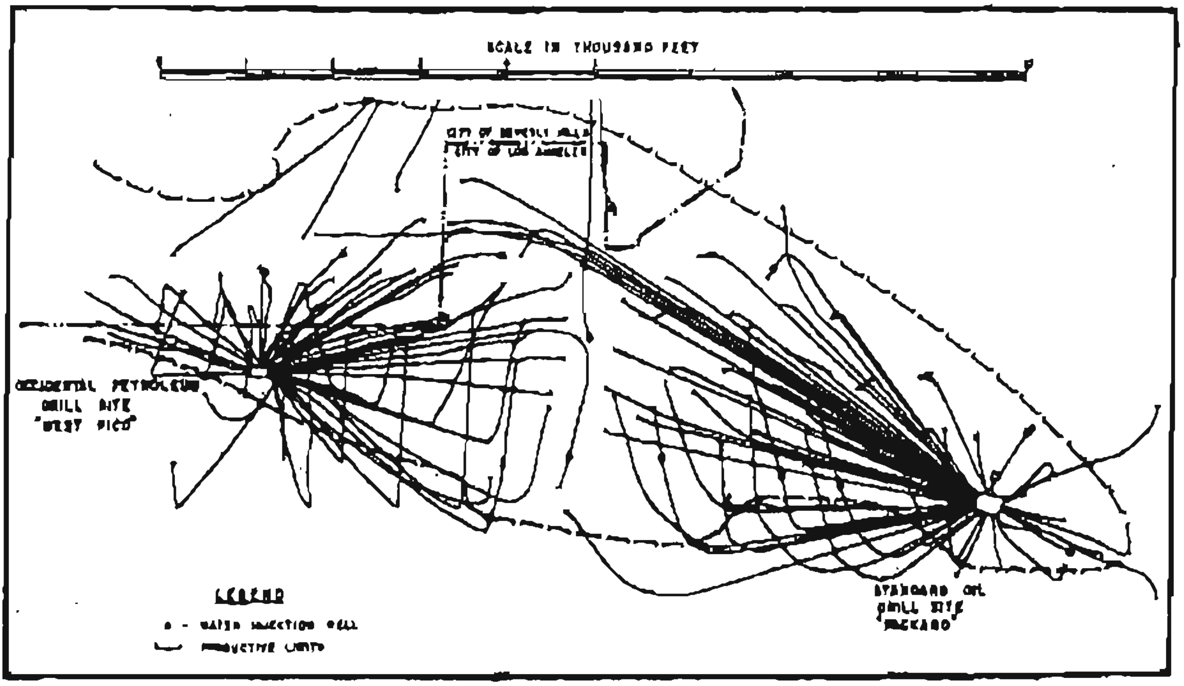

Fig. 2 - East Beverly Hills field well survey map.

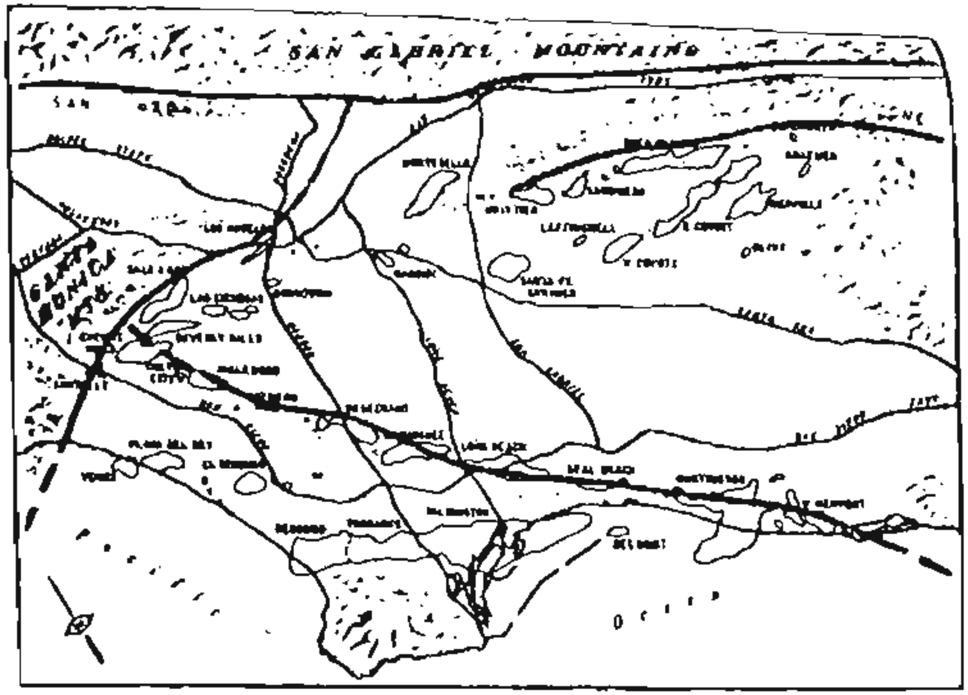

Fig. 3

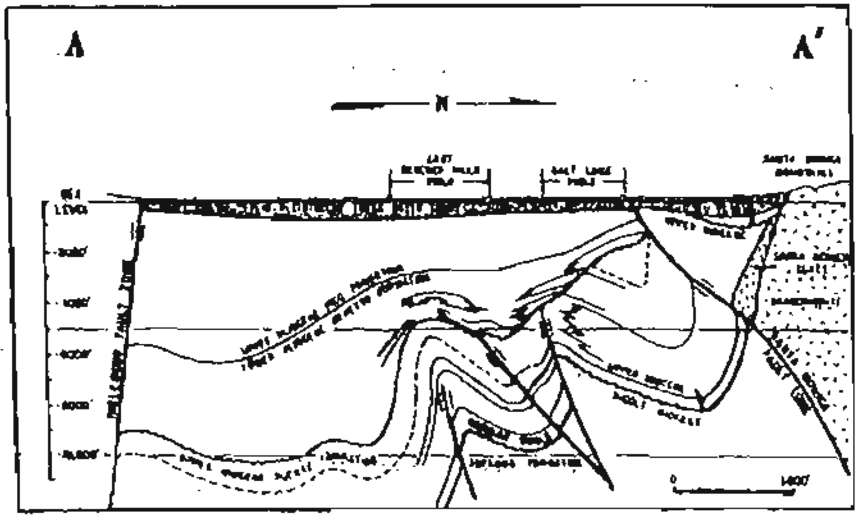

Fig. 4 - Inglewood to Santa Monica mountains cross section.

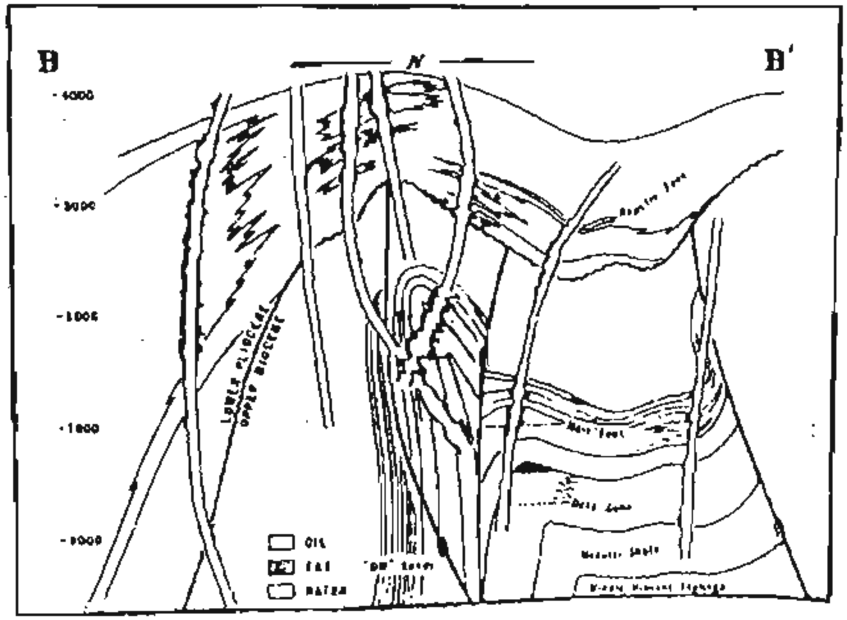

Fig. 5 - Beverly Hills (East) field structure cross section.

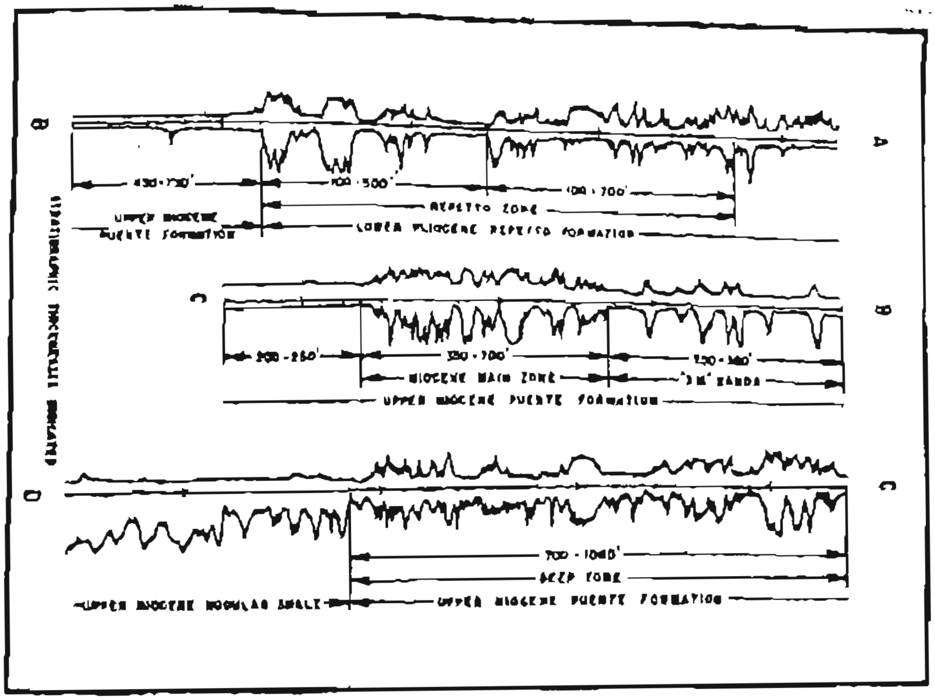

Fig. 6 - Beverly Hills (East) field, type log.

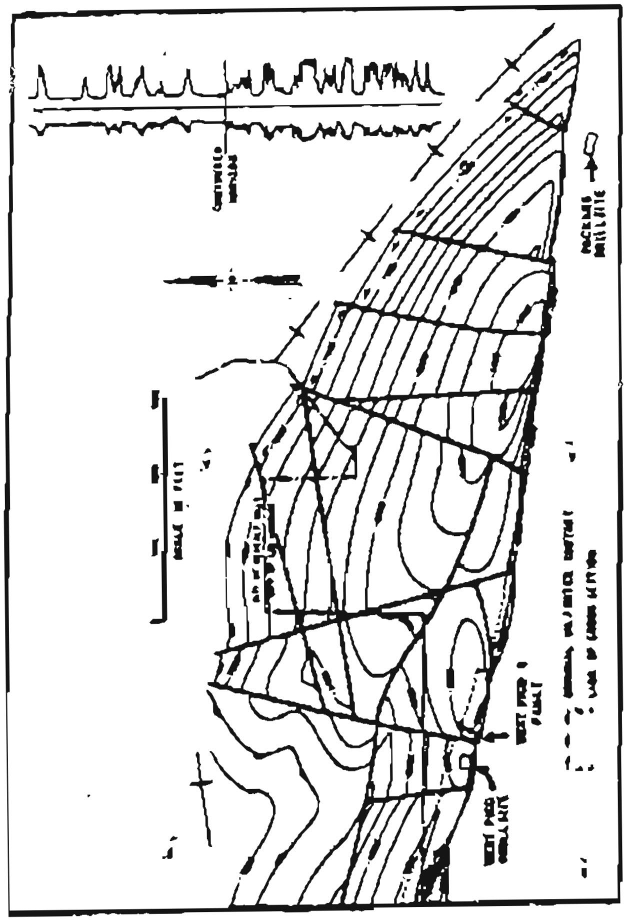

Fig. 7 - Beverly Hills (East) field, structure contour map on top Miocene Main zone.

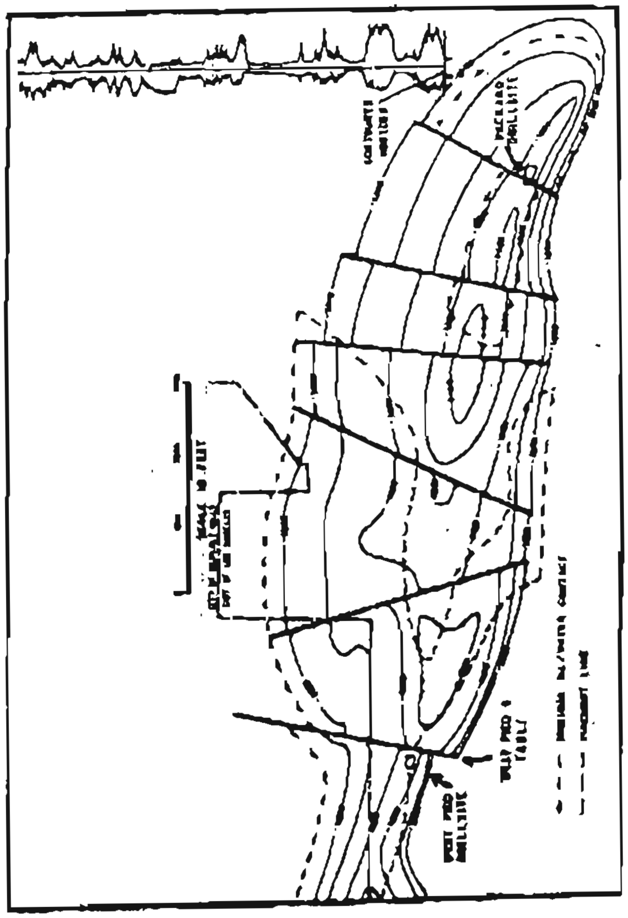

Fig. 8 - Beverly Hills (East) field, structure contour map on base Repetto sands.

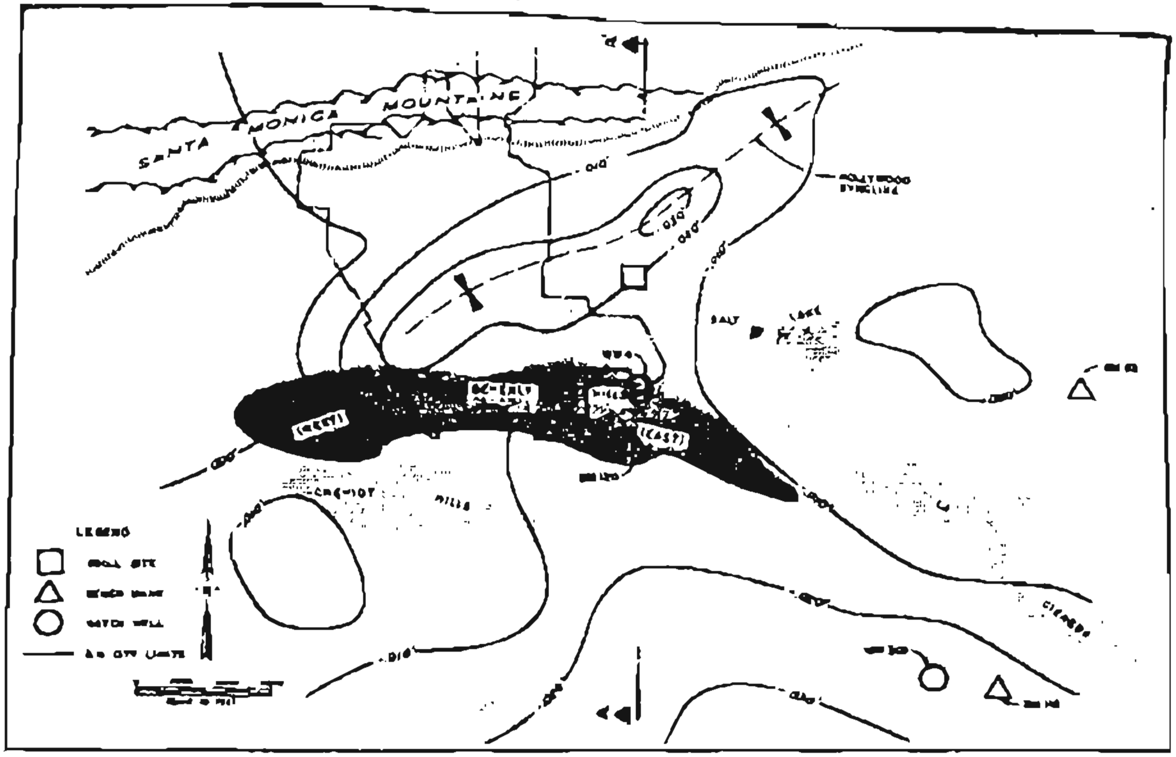

Fig. 9 - Annual rate of earth movement for the period 1949 to 1963.

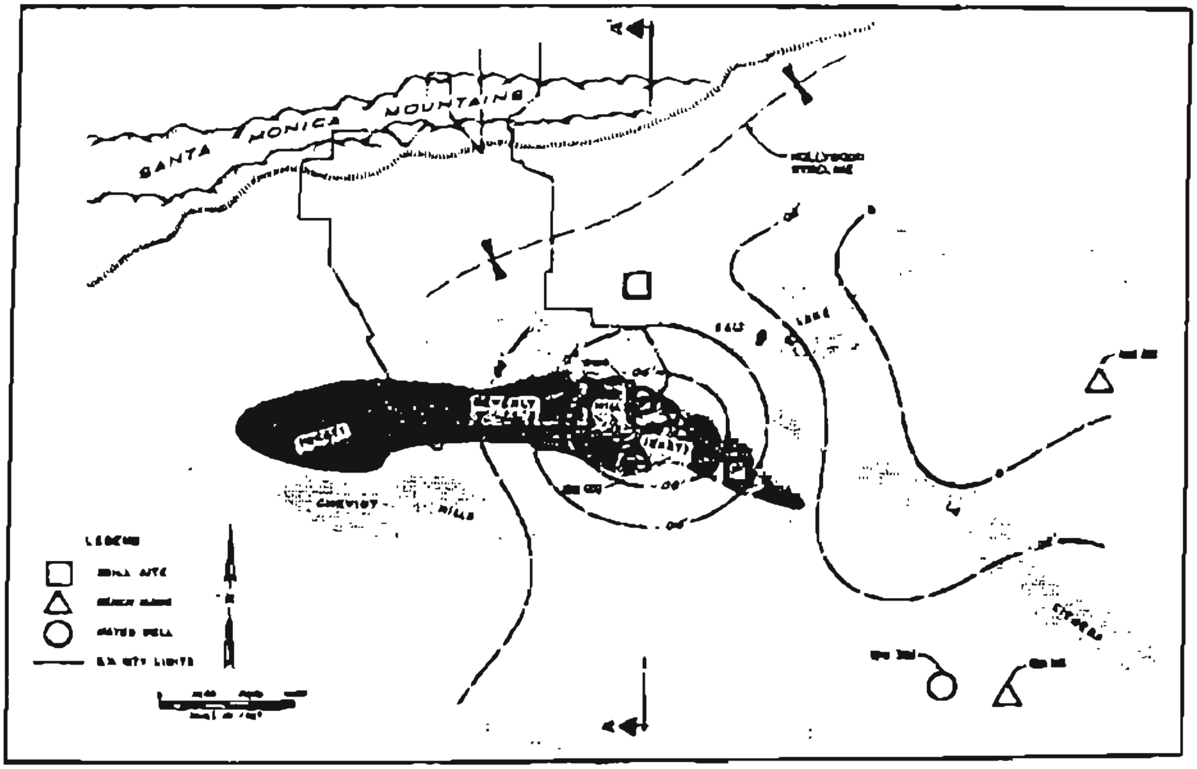

Fig. 10 - Annual rate of earth movement for the period March 1967 to March 1971, based on a mean sea level datum.

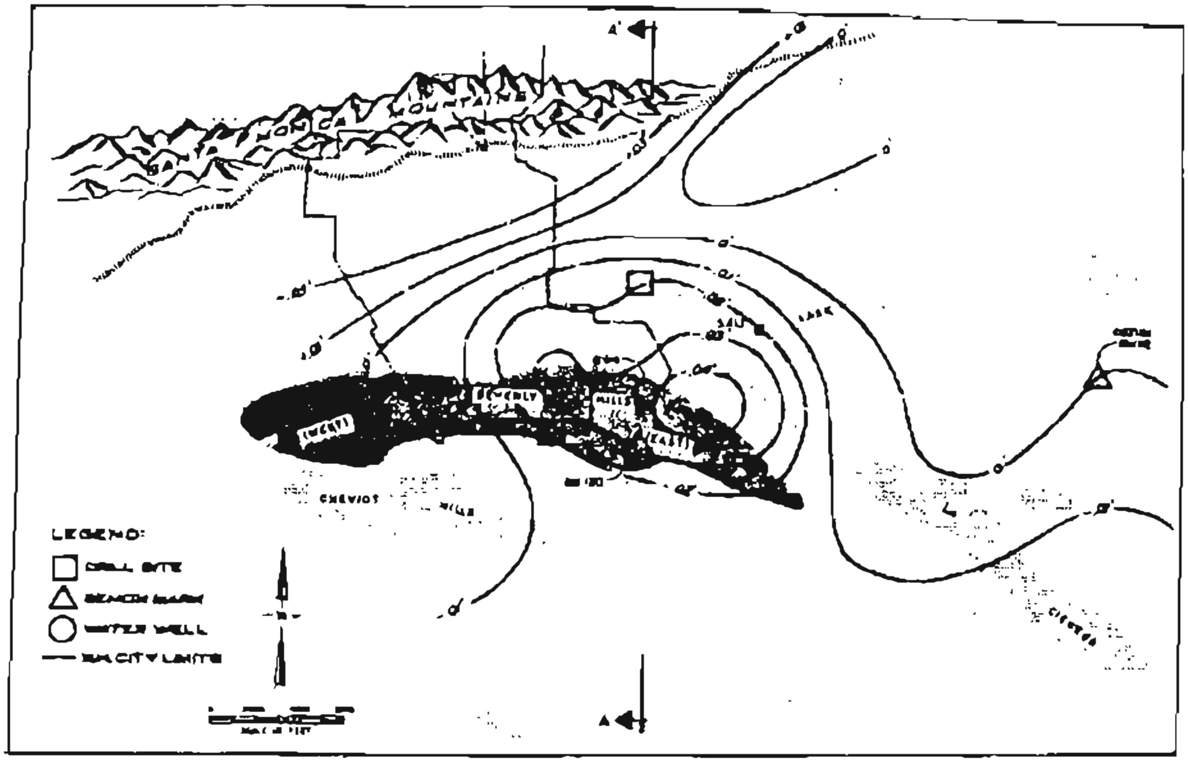

Fig. 13 - Annual rate of earth movement for the period October 1972 to October 1973, based on B.M. No. 82 as datum.

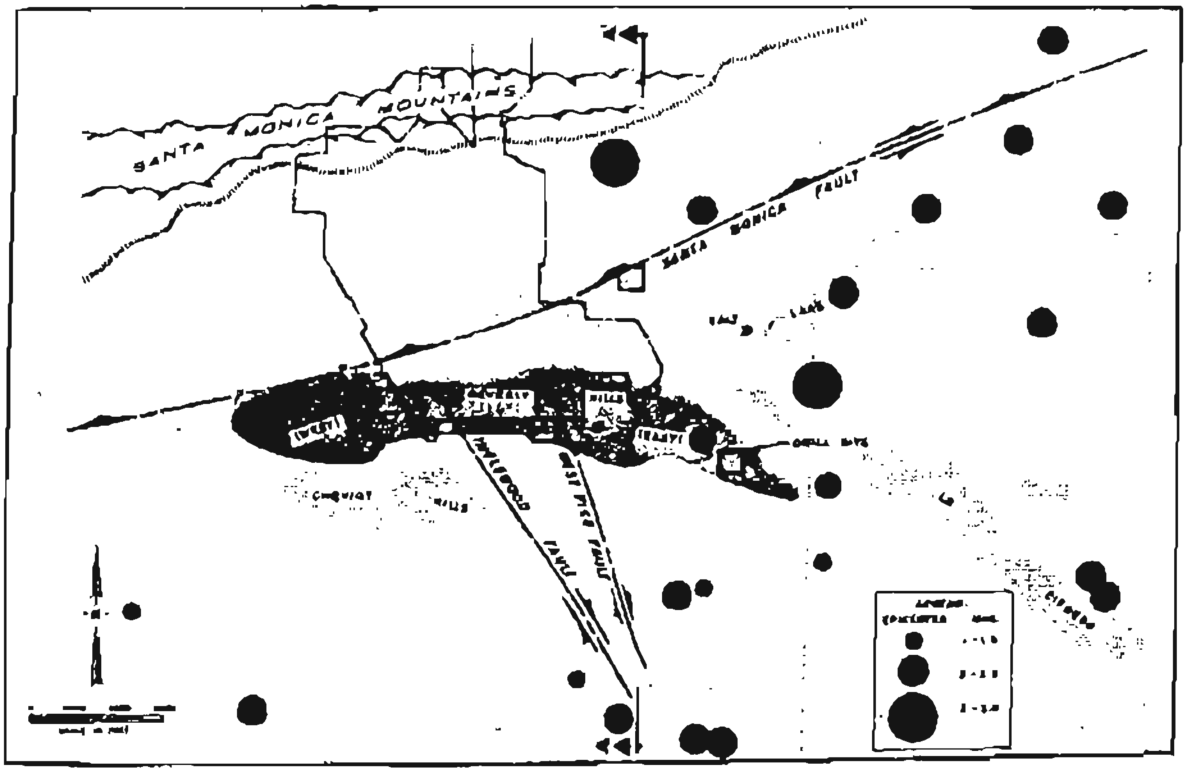

Fig. 14 - Earthquake epicenter map for the period 1934 to 1974 data from California Institute of Technology and USC Geophysical Lab.

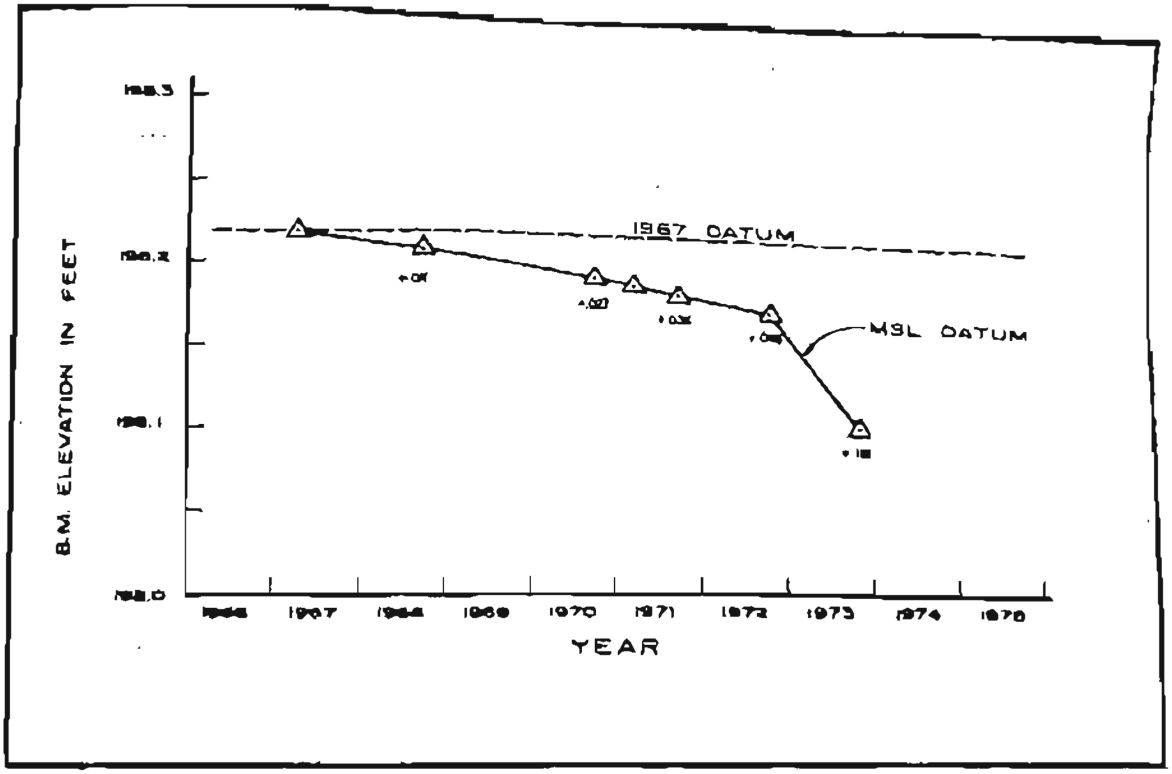

Fig. 11 - Adjustment of B.M. No. 82 to a constant datum as of March 1967.

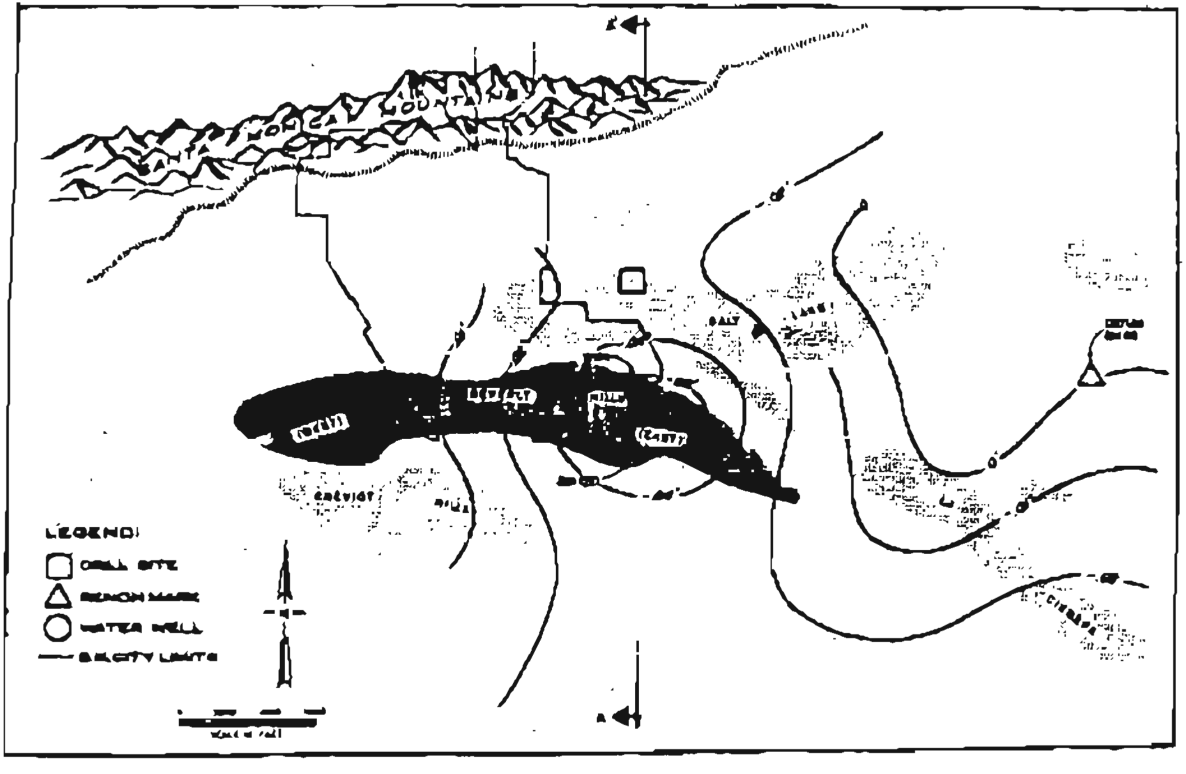

Fig. 12 - Annual rate of earth movement for the period March 1967 to March 1971, based on B.M. No. 82 as datum.

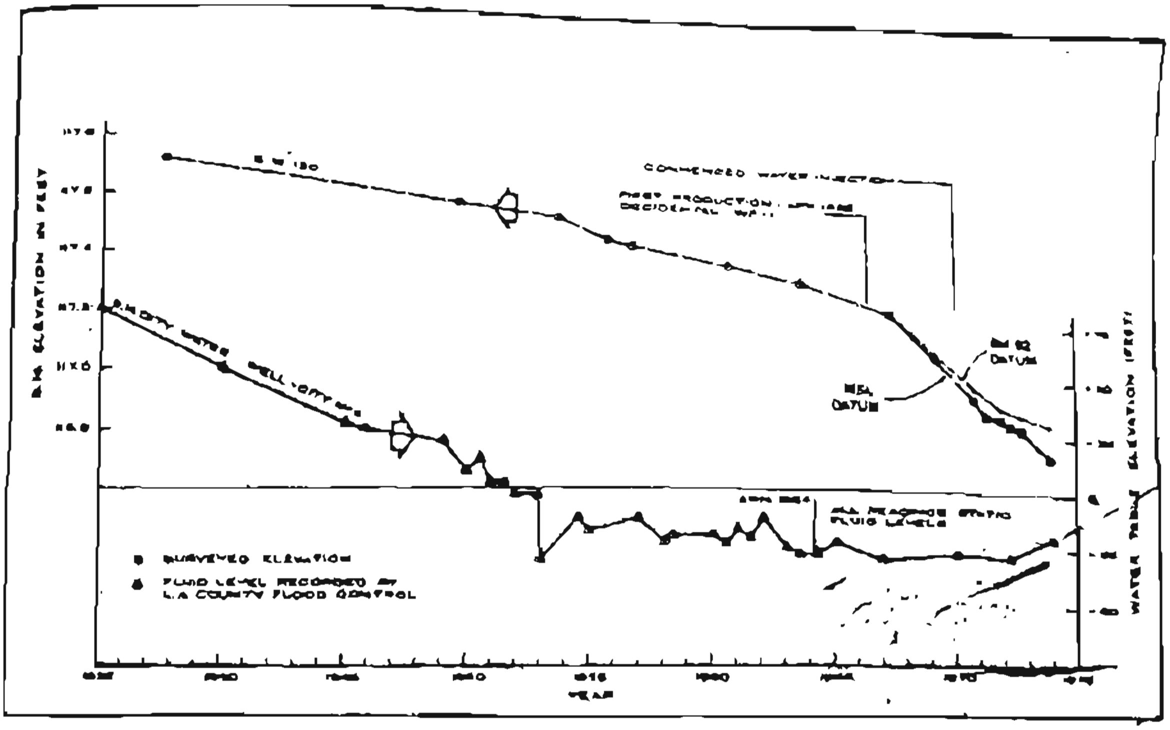

Fig. 15 - Graph of surface change in elevation at B.M. 120 and hydrograph of fluid levels at B.H. City water well No. 4.

FLU
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REC
B
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SOUTH W

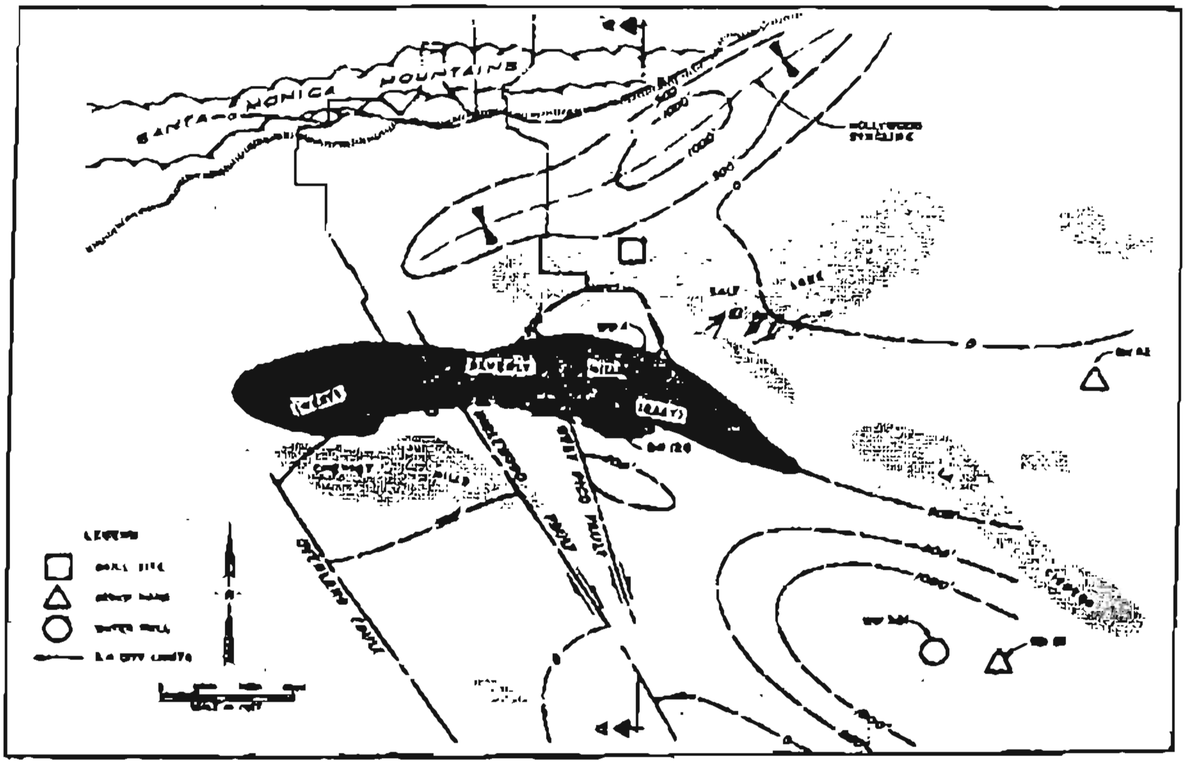

Fig. 16 - Isochore map of fresh water aquifers. Refer to Fig. 4 for stratigraphic position.