ENGINEERING MONOGRAPHS No. 21

United States Department of the Interior
BUREAU OF RECLAMATION

CRUSTAL DISTURBANCES IN THE LAKE MEAD AREA

By Jerome M. Raphael

Denver, Colorado
August 1954 20 cents

United States Department of the Interior

DOUGLAS McKAY, Secretary

Bureau of Reclamation

W. A. DEXHEIMER, Commissioner

L. N. McCLELLAN, Assistant Commissioner and Chief Engineer

Engineering Monograph

No. 21

CRUSTAL DISTURBANCES IN THE LAKE MEAD AREA

By

Jerome M. Raphael

Engineer, Dams Branch*

***Mr. Raphael is now with the University of California**

Technical Information Branch
Denver Federal Center
Denver, Colorado

ENGINEERING MONOGRAPHS are published in limited editions for the technical staff of the Bureau of Reclamation and interested technical circles in government and private agencies. Their purpose is to record developments, innovations, and progress in the engineering and scientific techniques and practices that are employed in the planning, design, construction, and operation of Reclamation structures and equipment. Copies may be obtained from the Bureau of Reclamation, Denver Federal Center, Denver, Colorado, and Washington, D. C.

CONTENTS

LIST OF FIGURES

INTRODUCTION

The designers of Hoover Dam, recognizing that the 41-1/2 thousand million tons of water to be impounded in Lake Mead might be sufficient to cause local deformation of the earth's crust, made theoretical studies to compute the amount and extent of this deformation. Following completion of construction, three series of precise levels were run over a period of 15 years to measure the actual movement of the crust.

The weight of Lake Mead has caused settlement of the general area, which by 1950 had reached a maximum of 7 inches. This settlement is still continuing, but at a decreasing rate; the total may eventually reach 10 inches. The settlement is apparently of the same order of magnitude as that predicted by assuming the earth's crust to be strained elastically, and only about one-third of that computed by assuming that an 18-mile thick crust floats on a liquid base and bends under load. Anomalous settlements have been ascribed to depletion of ground water. No direct connection could be found between earthquake incidence and lake loading. This, together with a regional warping, leads to the conclusion that the Lake Mead settlement, and the anomalous troughs, are superposed on regional deformations which are the surface manifestations of a long-time geotectonic disturbance.

THEORETICAL COMPUTATION OF SETTLEMENT

The theoretical computations to determine the settlement of the Lake Mead area due to the weight of the lake are summarized in Bureau of Reclamation Technical Memorandum No. 422, "Deformation of Earth's Surface Due to Weight of Boulder Reservoir," by H. M. Westergaard and A. W. Adkins, December 26, 1934. In this study, it was assumed that the granitic continental mass lay upon a layer of basalt, and that the basalt in turn rested upon a still denser layer of a somewhat different material. The displacements due to a surface load were resolved into two components: (a) the displacement due to the elastic compression of the strong granitic upper layer, and (b) the quasi-isostatic displacements due to the plastic flow of the deep-seated rock with the accompanying bending of the strong upper layer.

For computing displacements, the reservoir load was resolved into 11 concentrated loads. In computing displacement (a), each of the 11 reservoir loads was assumed to be uniformly distributed over an 11.6-mile square. The displacements at several points were obtained by an integration of Boussinesq's expression for the displacement due to a concentrated load acting normally on the face of a semi-infinite solid. The elastic modulus* was taken at 6,000,000 psi, which was in agreement with laboratory data obtained from specimens of the surface rock at the dam site. This value was taken after considering values which ranged from 6,000,000 psi at the surface to possibly double that value which might be taken as the upper limit of possibility of a near perfect granitic rock. Decision to use the lower value was made assuming that the real earth was weaker structurally than the earth imagined for the computation, and that the greatest deformation would take place near the surface.

For the computation of displacements (b), the reservoir load was resolved into 11 concentrated loads, and the displacements at several points due to each of the 11 loads were obtained from an analysis of a uniformly thick elastic slab of infinite lateral dimensions supported by a perfect fluid. For the slab, the elastic modulus was taken to be 10,000,000 psi and the thickness 18 miles. The density of the underlying fluid was assumed to be 185 pounds per cubic foot. The value of 10,000,000 psi used in the computation of displacements (b) was in accord with data found for the granitic layer by observation of the velocity of propagation of earthquake waves. It was considered that the data for density and elastic modulus for the crustal layer were accurate enough, but the true value of the thickness of the crust was very uncertain, probably much greater than the assumed 18 miles. Also, it was realized that the treatment of the supporting layer as a liquid was open to criticism.

---

*Actually the factor used was $\frac{E}{1 - u^2}$, a modification of the elastic modulus which takes into account bending resistance in two dimensions. This computes to approximately 0.96 E.

A third type of displacement, that due to plastic flow in the strong rock near the surface, was not considered in the mathematical studies. It was assumed that such displacements, if they developed, probably would be proportional to displacement (a) and attain their ultimate values within 2 to 3 years after filling of the reservoir. These displacements would arise from the same phenomenon which causes a concrete test cylinder subjected to a constant load to continue to deform for a long time after application of the load.

Figure 1 shows the vertical settlements which were computed under the assumption that the earth deflected elastically as a solid granitic mass. Figure 2 shows the settlement that might be expected upon complete isostatic readjustment of an 18-mile granitic slab floating upon a basaltic substratum.

THE HOOVER DAM LEVEL NET

Following the completion of Hoover Dam, the Bureau of Reclamation supplied funds to Coast and Geodetic Survey for running three complete lines of levels in the Hoover Dam area to study the deformation of the earth's crust. Figure 3 shows the general vicinity of the Lake Mead Area and the routes of the level net surveys.1/ The base level net was run in 1935, and reruns were made in 1940-41, and in 1949-50. The usual first order level is run to a maximum tolerance of $4\sqrt{K}$ mm between the forward and backward runs, where K is the length of section in kilometers. In this case special instructions were given the level party to use a maximum tolerance of $3\sqrt{K}$ mm. In other words, levels for this particular study were run to one-third higher accuracy than that heretofore required in the most precise leveling to establish permanent bench marks in the United States.

The 1935 leveling was done when the reservoir had just begun to fill and represents the reservoir empty condition. The 1940-41 and the 1949-50 reruns were made when the reservoir was filled nearly to capacity, representing a condition of nearly maximum normal load. The 1935 network of leveling was at first adjusted to the Sea Level Datum of 1929 by holding fixed the elevations resulting from previous adjustments for a ring of junctions on the perimeter of the net. When it was recognized that fitting the network of leveling to the older net resulted in a warping effect on the level network, it was deemed advisable, in view of the continuing nature of this study, that a special adjustment should be made in which only one elevation from the first adjustment was held fixed. Thus in all studies reported in this paper, the changes in elevation from this study are all in relation to an unchanging elevation at Cane Springs, a remote location in a region believed to be stable. The total length of the 1935 level net route was 711 miles, of which all but 83 miles of spur lines entered into the adjustment. The average rate of distribution of corrections for the special adjustment was 0.19 millimeters per kilometer. The maximum rate of adjustment on a line of appreciable length was 0.39 millimeters per kilometer on a line 59 kilometers long.

The level net route of 1940-41 followed as nearly as practicable the 1935 route. A new line was added extending from a point 15 miles north of Chloride to a point 6 miles west of Patterson's Well. Tide gages were installed at four locations on the lake shore to provide connections for the lines across the lake, since the lake was filled nearly to capacity at the time of this leveling. All elevations were adjusted to zero at bench mark R1 at Cane Springs in order to produce elevations for comparison with those of the 1935 survey. One line of levels, which included the water connection between the gages at Hualpai Wash and Lake Shore Mine and from that point to the junction 10 miles east of St. Thomas, showed closures which were nearly twice the allowable limit and this line was omitted from the special adjustment. The total amount of leveling in the 1940-41 net was 715 miles, of which 117 miles were not included in the adjustment. The average rate of the adjustment correction was 0.11 millimeters per kilometer and the maximum rate was 0.25 millimeters per kilometer on a line 128 kilometers long.

The latest leveling of the network was done in 1949-50. As shown on Figure 3, several lines included in the previous two surveys were omitted so that the total amount of leveling was 582 miles, of which 39 miles of spur lines were not included in the adjustment.

1/ Numbers correspond to references at end of this monograph.

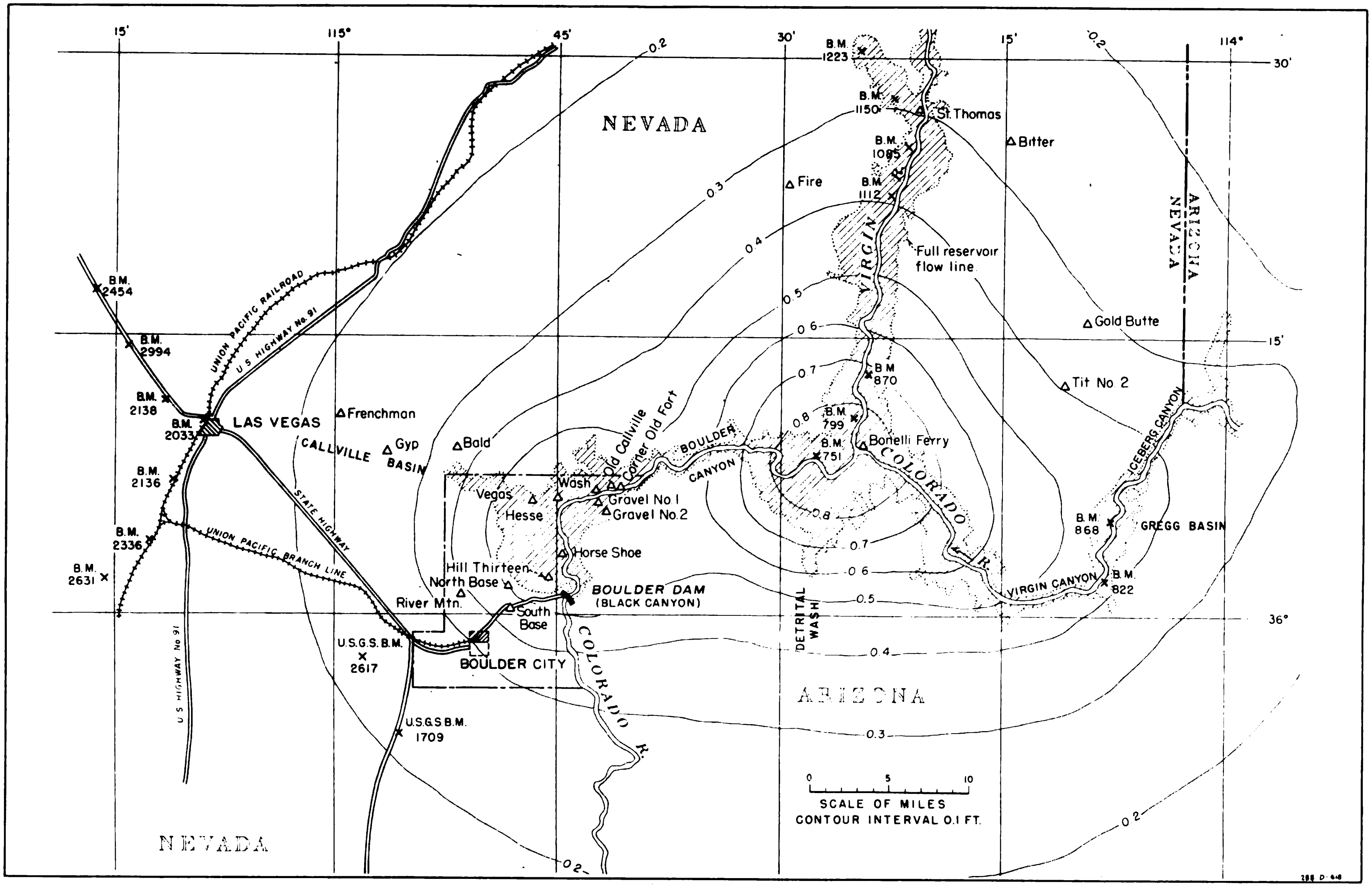

FIGURE 1--Computed vertical settlements assuming earth deflects elastically as solid granitic mass.

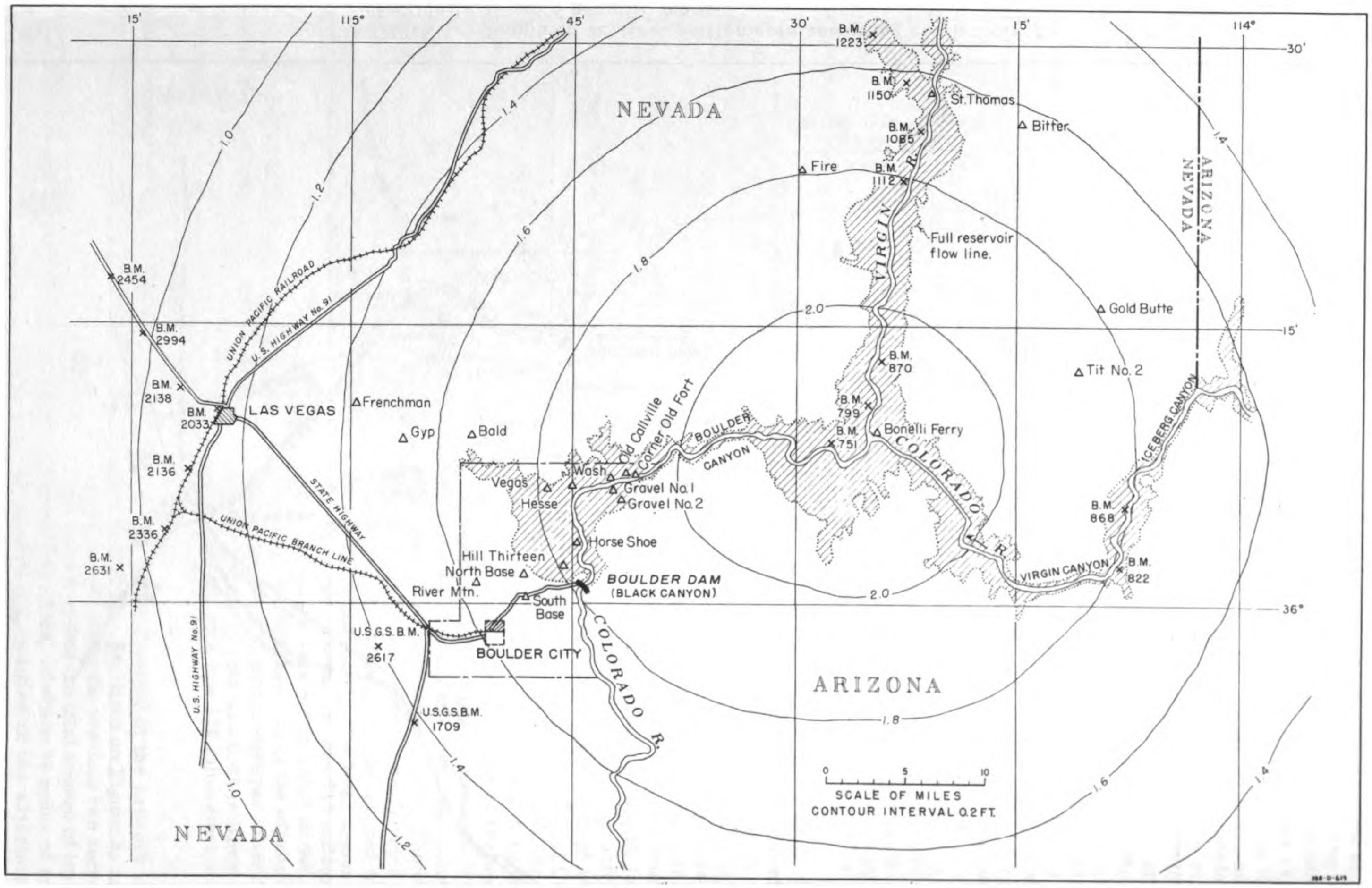

FIGURE 2--Computed vertical settlement assuming granitic slab floating on basaltic substratum.

floating on basaltic substratum.

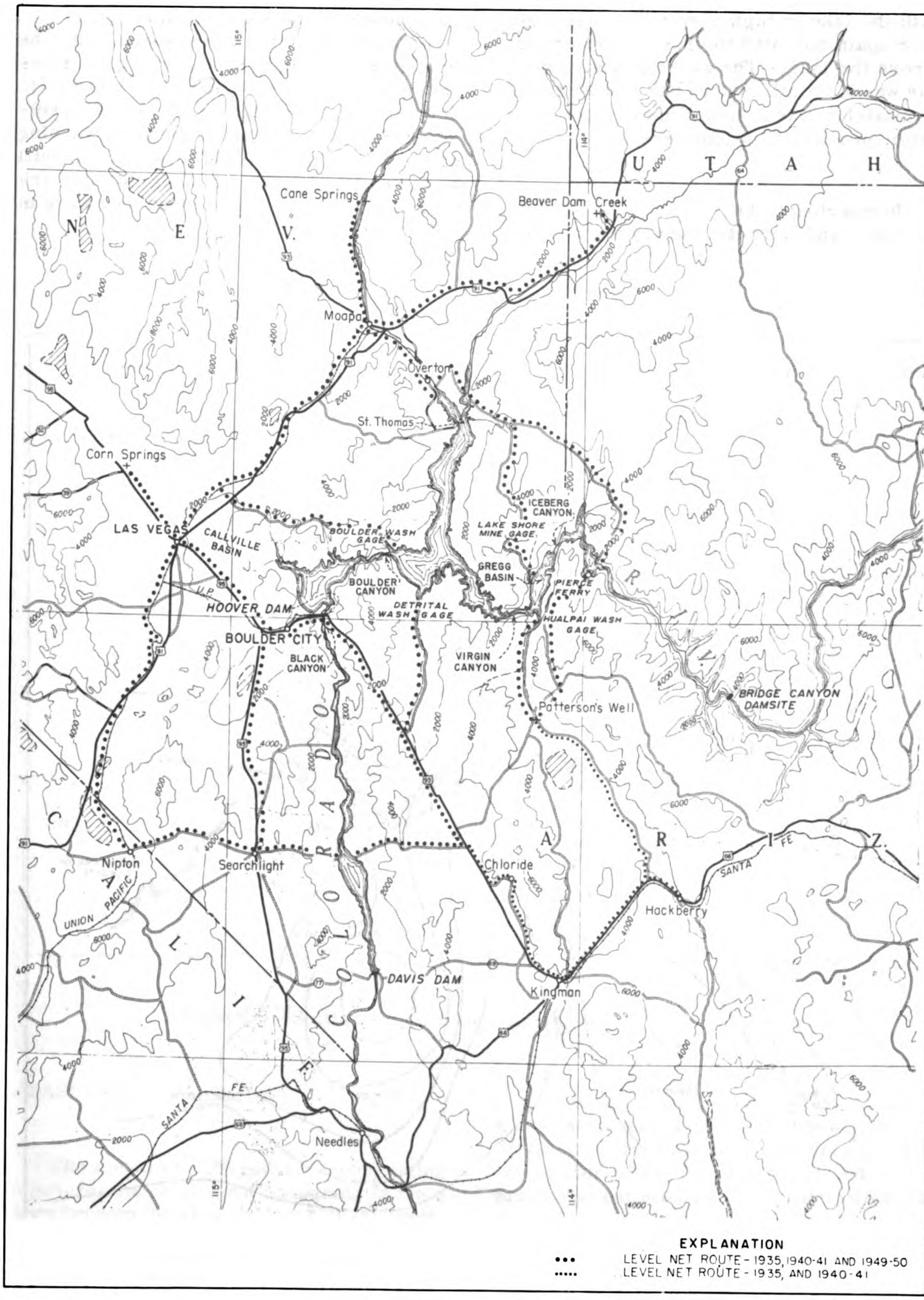

FIGURE 3--Routes of level net surveys.

With the lake at high elevation, tide gages were again operated to provide connections across the lake. The average distribution rate was 0.14 millimeters per kilometer and the maximum was 0.29 millimeters per kilometer on a line 29 kilometers long.

In reporting on the results of the leveling, the Coast and Geodetic Survey warned that caution was advised against drawing definite conclusions from the divergences along the line from the Lake Shore Mine to 10 miles east of St. Thomas because of the high rate of correction distributed on the 1940-41 leveling of this line. No corresponding warning was given for the 1949-50 leveling. As will be seen later, elevations along this line are generally higher in 1940-41 than they were in the original leveling of 1935.

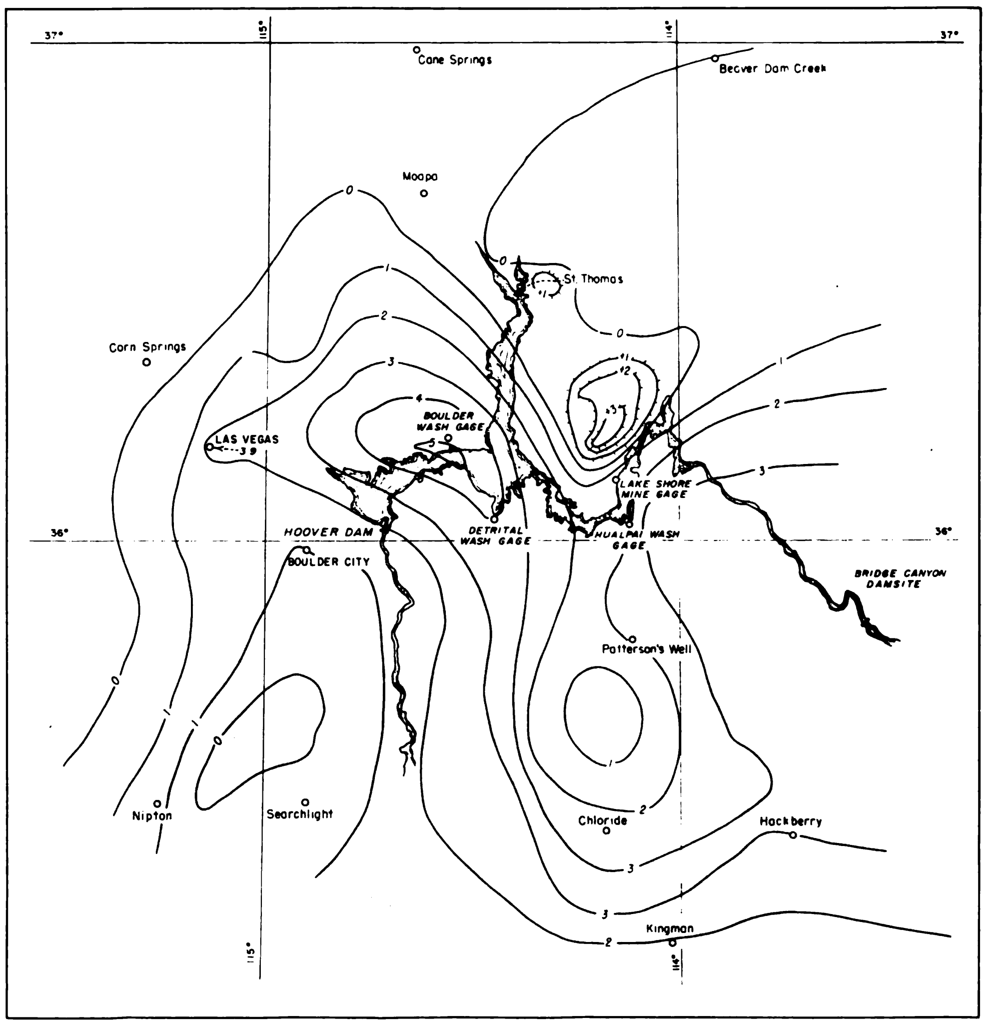

FIGURE 4--Settlement in inches between 1935 and 1940-41.

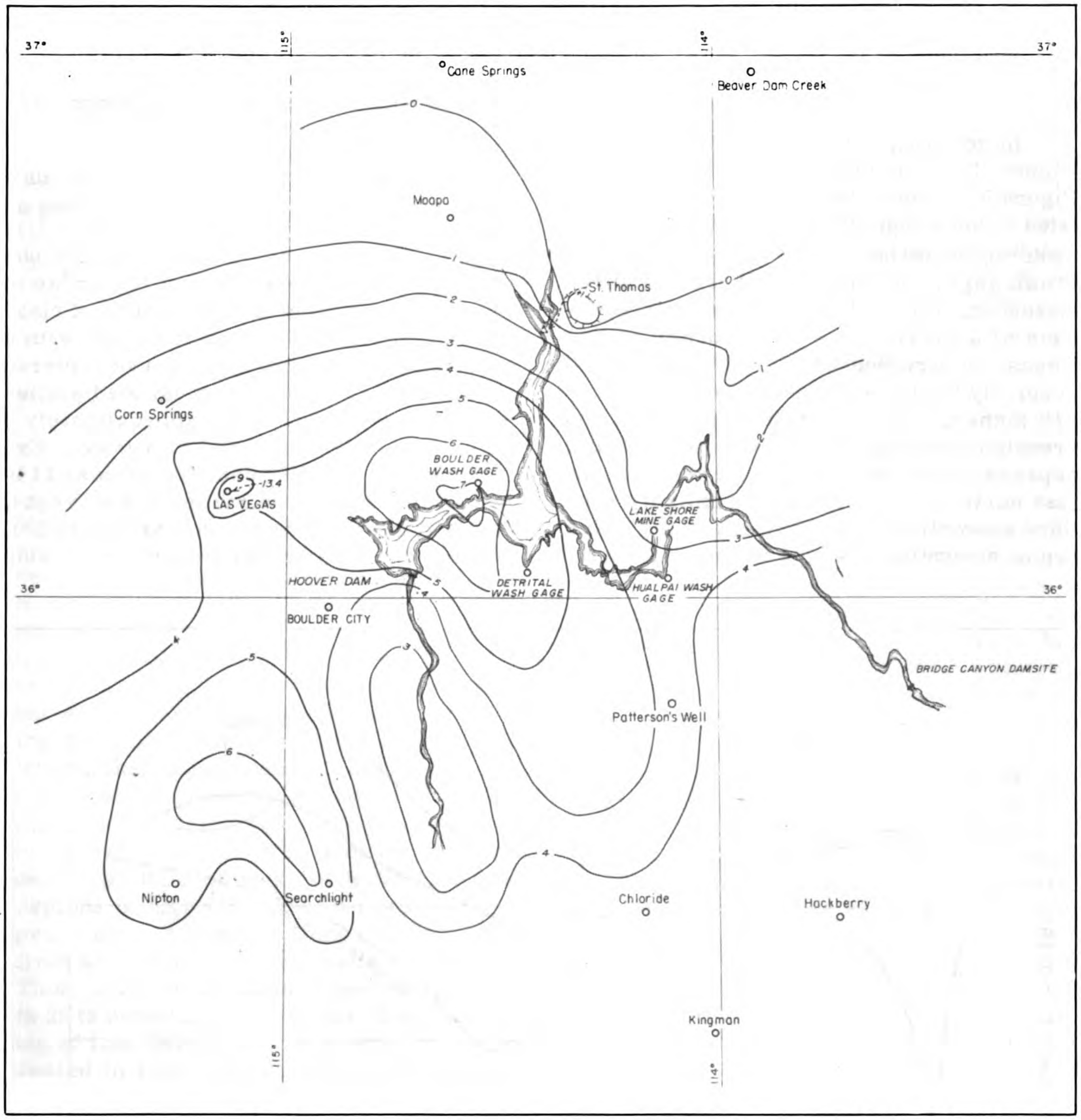

FIGURE 5--Settlement in inches between 1935 and 1949-50.

MEASURED SETTLEMENT

The elevation differences representing in general the settlement occurring in the 5 years between the 1935 and the 1940-41 leveling are shown as contour lines on Figure 4. The corresponding figure showing differences in elevation as contours in the 15 years between the original survey of 1935 and the latest of 1949-50 is shown in Figure 5.

In comparing the two figures, it can be seen that in general the center of depression of the Lake Mead area appears very close to the center of depression predicted by the mathematical studies. It is also noted that the sinking has been continuous over 15 years and that the rate of sinking is decreasing, indicating some mechanism akin to plastic flow. It is also to be noted that the upward displacement just north of the Lake Shore Mine gage at the end of 5 years as shown on

Figure 4 is in the region in which the measurements were described as doubtful by the Coast and Geodetic Survey.

In general, tendencies established in Figure 4 are confirmed and amplified in Figure 5. A definite settlement pattern related to the weight of Lake Mead can be seen centering somewhere in the vicinity of Boulder Wash gage. In addition, there are three anomalies. One is the deep and sharp depression of a maximum 13-1/2 inches at Las Vegas, in a region which is characterized generally by depressions of the order of 4-1/2 inches. Another is the continuing depression to the south of Las Vegas so that a depression amounting to 6 inches is found just north of Nipton and Searchlight. The third anomaly is an evident tilt of the whole region amounting to 4 or 5 inches in the hundred miles from Cane Springs to the latitude of Searchlight and Chloride. Hoover Dam itself had sunk 2 inches in 1940, and 5 inches by 1950 with relation to Cane Springs.

Figure 6 shows a comparison of the theoretical and observed settlement along an east-west line through the center of Las Vegas. It can be easily seen that the observed displacements are of the order of those computed under the assumption of elastic deformation of a granitic crust with a superposed deep draw-down curve centered in Las Vegas. The maximum load settlement was observed to lie approximately 6 miles west of the computed maximum. Except for the doubtful positive area at 114° 10' and the negative anomalies at Las Vegas, the settlement curves are nearly parallel, showing 2 to 3 inches settlement over a wide

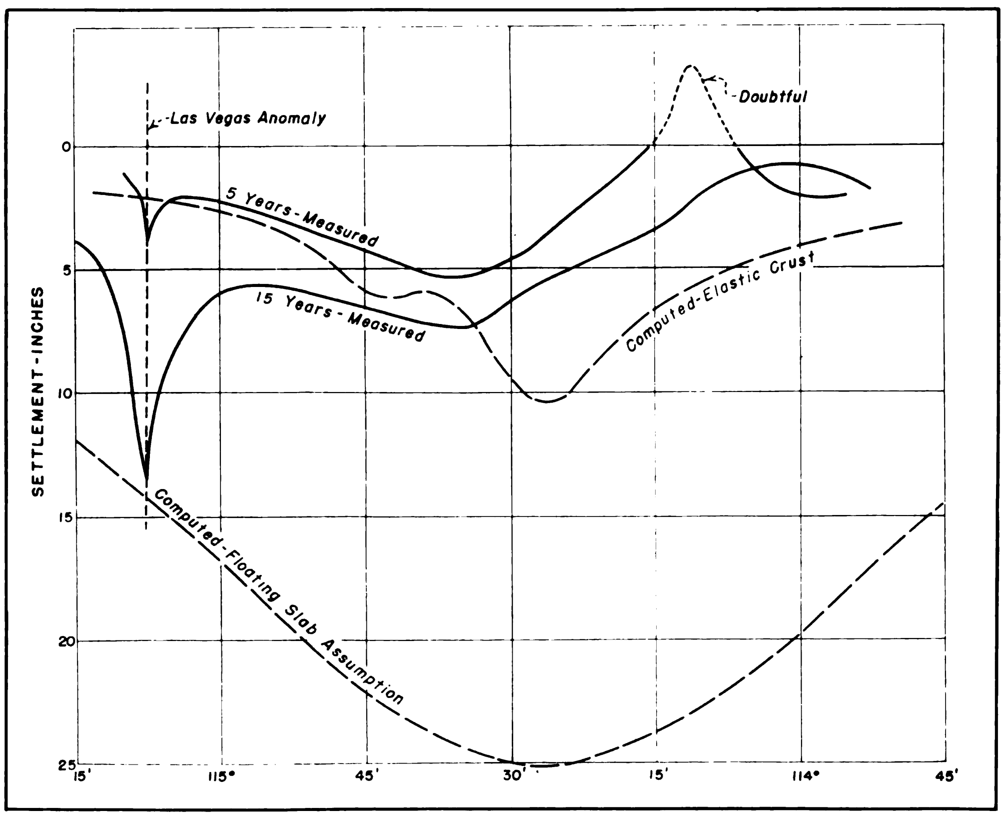

FIGURE 6--Theoretical and measured settlement--East-West profile through Las Vegas.

area in the past 10 years. The computed settlement assuming the crust floating on a liquid base seems unrelated to the observed behavior.

The physical causes underlying this variegated pattern of settlement are not understood. If a logical meaning to the settlement pattern can be found, then we will know what to expect in the way of bench mark changes if similar circumstances prevail in another location.

ISOSTATIC ADJUSTMENT

Isostatic adjustment has been mentioned as a possible major mechanism of the Lake Mead settlement. "Isostasy," a Greek term signifying "equal standing", has been used to describe a concept of balance between segments of the earth's crust. The English mathematician, Airy, gives a common illustration of the way this principle applies. A series of copper blocks of equal cross section but unequal lengths are considered to be floating in a pool of mercury. Depending on their length, they sink to unequal depth, and also rise to unequal height. As this principle applies to the earth, segments of the earth's crust are considered to be in effect floating in deeper portions of rock which can flow from regions of high pressure to regions of low pressure, or in other words, behave as a fluid according to Archimedes' principle. Thus, if weight is added to one segment, as in delta deposition, or, in this case, the filling of Lake Mead, the segment could be expected to sink until equilibrium was again reached. Conversely, if weight were removed, as in the weathering of mountain masses or the retreat of a glacier, the segment could be expected to rise to a new equilibrium.

The weight of the reservoir, for all its mass, is considerably less than the weights involved in the wasting away of a mountain mass, or the deposition in an inland sea. It is thus of great interest to see that this man-made weight transfer was of sufficient magnitude to cause some measurable changes in the earth's crust. While the continuing slow movement suggests a plastic readjustment akin to isostatic movements, Figure 6 shows that the magnitude of the disturbance is of the order of the computed elastic deformation. It will be shown later that consideration of earthquake incidence also fails to support a direct connection between lake loading and major crustal disturbance. Thus we tentatively conclude that for this particular loading, isostatic readjustment is not involved, or is too slow to be measured in this fifteen-year loading period. By plotting the settlement of selected locations against time, and extrapolating, it is estimated that ultimate maximum settlement will be of the order of 10 inches.

EARTHQUAKE FREQUENCY

From time to time, the early inhabitants of the sparsely settled Lake Mead area reported minor local earth shocks. During the construction of Hoover Dam, such earth shocks as did occur tended to be obscured by blasting operations. With the completion of the dam, the Seismological Society of America evidenced an interest in determining to what extent the filling of the reservoir would have on the frequency of earthquakes. At a meeting of this society in 1938, a resolution was drawn up to this effect and conveyed to the Bureau of Reclamation. As a result, the Bureau of Reclamation, the Coast and Geodetic Survey, and the National Park Service began a cooperative seismological investigation. In general, the Survey contributed technical services, such as advising on proper instrumentation, training operators, checking equipment, and analyzing records. The Bureau of Reclamation contributed funds, housing for the units, and operating personnel; and the National Park Service operated one station.

Three seismograph stations were established, one at Boulder City, one at Pierce Ferry, and a third at Overton. These were arranged in an equilateral triangle roughly 50 miles on a side. In addition, three strong motion accelerographs were installed in the vicinity of Hoover Dam, one in the dam, one in the Hoover Dam oil house, and one in an intake tower.

Readings from the three seismograph stations were triangulated to locate the epicenters of earthquakes shown in Figure 7. On this figure, each dot represents the epicenter of a quake detected by the three seismographs in the Hoover Dam network. It will be recalled that the epicenter records the trace on the earth's surface of the point of origin of the first motion of an earth shock,

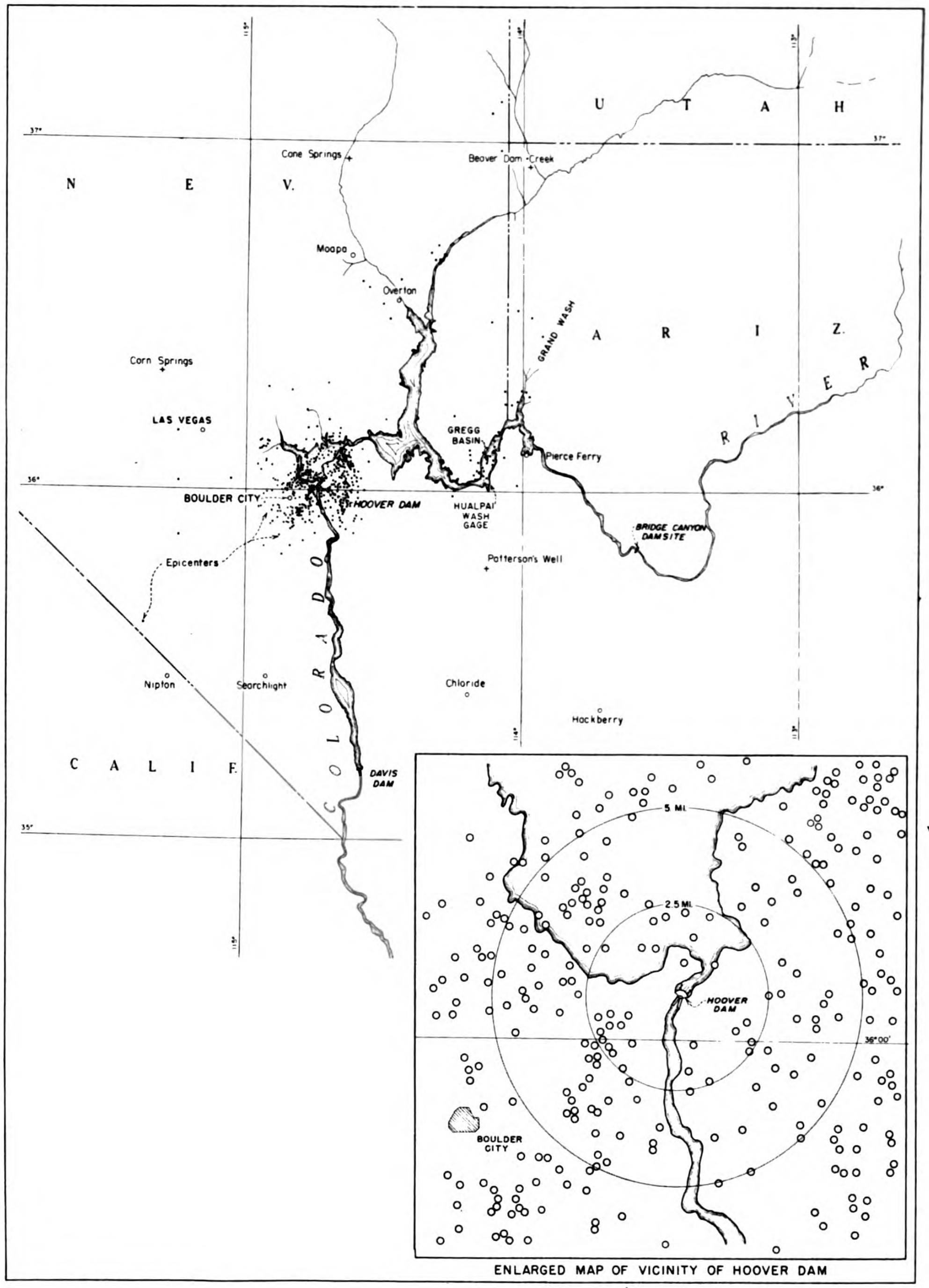

FIGURE 7--Epicenters of earthquakes, 1940-50.

which may act over a considerable area and time. The grouping of the earth shocks shown on Figure 7 is quite striking. The vast majority of earthquake shocks appear to originate within 10 miles of Hoover Dam. A minor grouping is found just to the north of Hualpai Wash gage, in and just to the east of Gregg Basin. The enlarged portion of Figure 7 shows that while most quakes originate within 10 miles of Hoover Dam, the actual vicinity of the dam is singularly free of epicenters. This indicates that the dam is peculiarly well located in an undisturbed block.

By comparison with Figures 4 and 5, it can be seen that the earthquake action is not related directly to the loading, as it occurs not in the region of maximum subsidence but rather in regions of intermediate settlement, characterized by 3 inches of subsidence in 15 years. An attempt was made to correlate earthquake activity with rate of reservoir filling and with total reservoir load, but no direct correlation could be found. It is thus concluded that earthquakes are caused by some geotectonic force of much greater magnitude than the Lake Mead loads, and that the weight of Lake Mead may have hastened the occurrence of earthquakes, by triggering adjustments which would eventually have happened anyway.

GEOLOGY OF THE REGION

In spite of various assumptions of a fairly uniform crust which underlay the mathematical determinations of subsidence of the Lake Mead area, the anomalous settlements shown in Figures 4 and 5 and the concentrations of the seismic activity shown in Figure 7 serve as indicators that the region is geologically inhomogeneous. A greatly simplified geology of the Lake Mead area is shown in Figure 8. In this diagram, rocks and formations are grouped

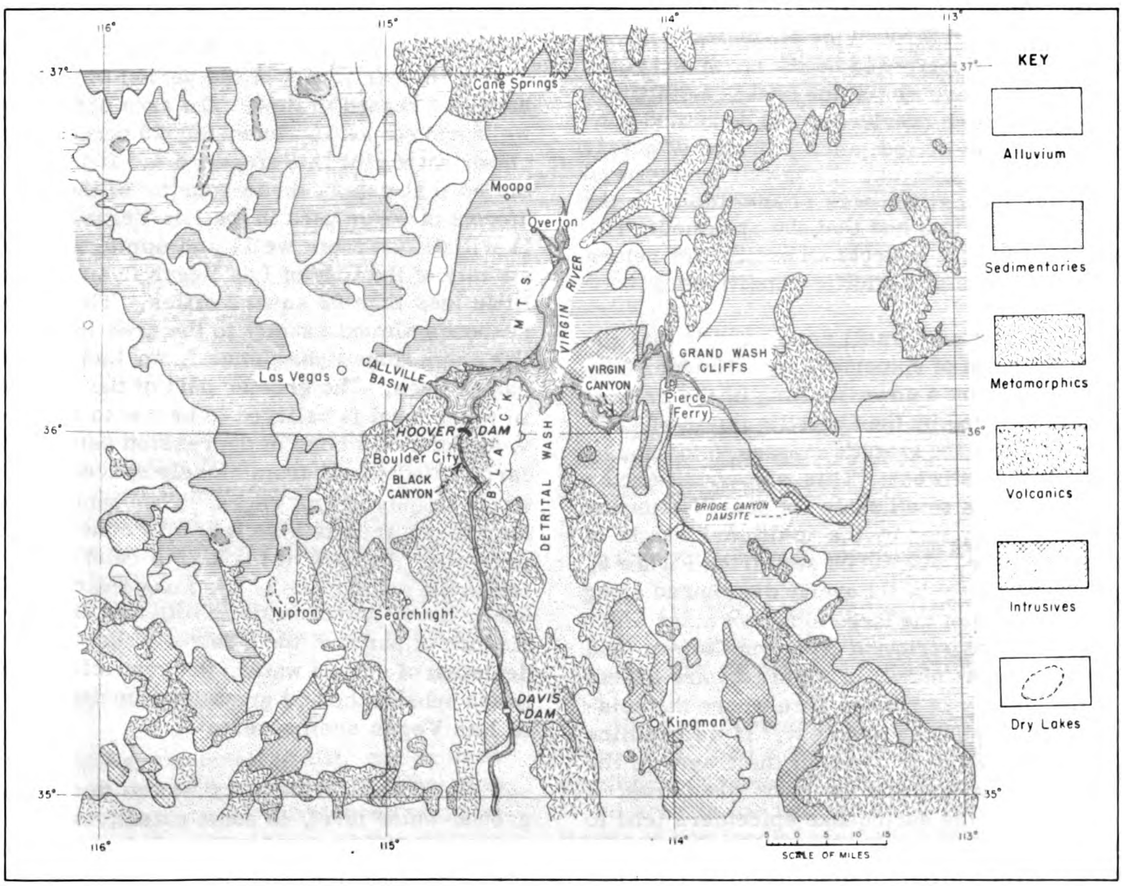

FIGURE 8--Geology of Lake Mead area.

together by method of formation, without regard to the age of the deposit. By this means, seismic activity can be compared with the general rock types.

Longwell has described2/ the Lake Mead area as lying in the eastern part of the basin and range physiographic province. From a 4-month examination of the reservoir area, he concluded that the north and south trending ranges and basins were formed by movements on large faults before the advent of the Colorado River. This arid region is characterized by interior drainage, and thus, as material eroded off the highlands, it was deposited in the adjacent basins. With decreased crustal activity, relief became subdued, although movements continued on some of the faults until a late date. Then followed a period of deposition in the Pliocene time, culminating in limestone deposits which covered the divides between the Grand Wash cliffs and the Virgin-Detrital trough, and which probably overtopped the lower parts of the Black Mountains. In Pleistocene time, as the Colorado River cut down through the basin deposits, its course was superposed on the north and south ranges of more resistant rock. Later, the stream became overloaded and deposited hundreds of feet of sediments, probably nearly filling Black Canyon. Longwell conjectured that the deposition was connected with the latest glaciation; and that the spasmodic removal of the fill reflects an oscillatory return to more normal climatic conditions.

Carder and Small concluded3/ that the concentration of epicenters near Boulder City was caused by a down-faulting of the crustal block occupied by the Callville Basin of Lake Mead against the granitic masses to the southeast and southwest. This was considered a renewal, on a small scale, of pre-Pleistocene activity triggered by the additional weight of the reservoir. As can be seen from Figure 8, seismic activity is not evenly distributed along both margins of the large intrusive mass which causes the constriction at Virgin Canyon, and intrusives, as shown in Figure 6, are absent in the vicinity of Hoover Dam where the seismic activity is the greatest. If we examine Figure 9, which is a plot of the traces of the major known faults in the Lake Mead area, it can be seen the earthquake epicenters tend to locate along a major fault which underlies the floor of the Callville Basin, and another bordering the Gregg Basin. Five north-and-south trending faults are shown in the immediate vicinity of Hoover Dam, crossing the Callville Basin, and two in the vicinity of the Gregg Basin.

Figures 5 and 6 show plainly the anomalous subsidence in the vicinity of Las Vegas. While the general subsidence of the area is of the order of magnitude of 4.5 inches, Las Vegas itself has subsided 13.4 inches. Examination of the detailed map of the Hoover Dam level net, which was the source document from which Figure 6 was drawn, shows that the anomalous subsidence of 9 inches centered in Las Vegas begins roughly 3 to 4 miles from the center of the city, and has the external appearance of a draw-down curve. It is believed that this well-marked subsidence is directly connected with the known depletion of the ground water in the vicinity of Las Vegas.

The general decline in ground-water elevation in Las Vegas is well documented in three reports.4/5/6/ The decline in water level in three wells in Las Vegas Valley between 1924 and 1946 was 45 feet, or 2 feet per year. Some wells that flowed prior to and during the early part of the period of record have now ceased to flow. The area of flowing wells has shrunk approximately 25 percent, as shown on a plot in Reference 4. It is estimated that nearly three-fourths of the total amount of water used in the Las Vegas Valley is withdrawn from wells and springs in the vicinity of the City of Las Vegas in an area a little less than 22 square miles. This corresponds almost exactly to the area in which the anomalous subsidence from Las Vegas can be seen. The greater part of the decline in water level is believed to be due to the development of a cone of depression caused by large withdrawals from closely spaced wells in the vicinity of Las Vegas. The shape of the depressed area is also that of a cone of depression. In view of the known relation between the subsidence of the Long Beach area due to heavy withdrawals of oil, and the subsidence of parts of the Central Valley due to depletion of ground water, the connection between subsidence and ground-water depletion in Las Vegas seems certain.

It is also believed that the declining ground-water level, to some extent, explains the anomalous subsidence troughs north of Nipton and Searchlight and between Chloride and Detrital Wash. Evidence of a general regional decline of ground-water levels is

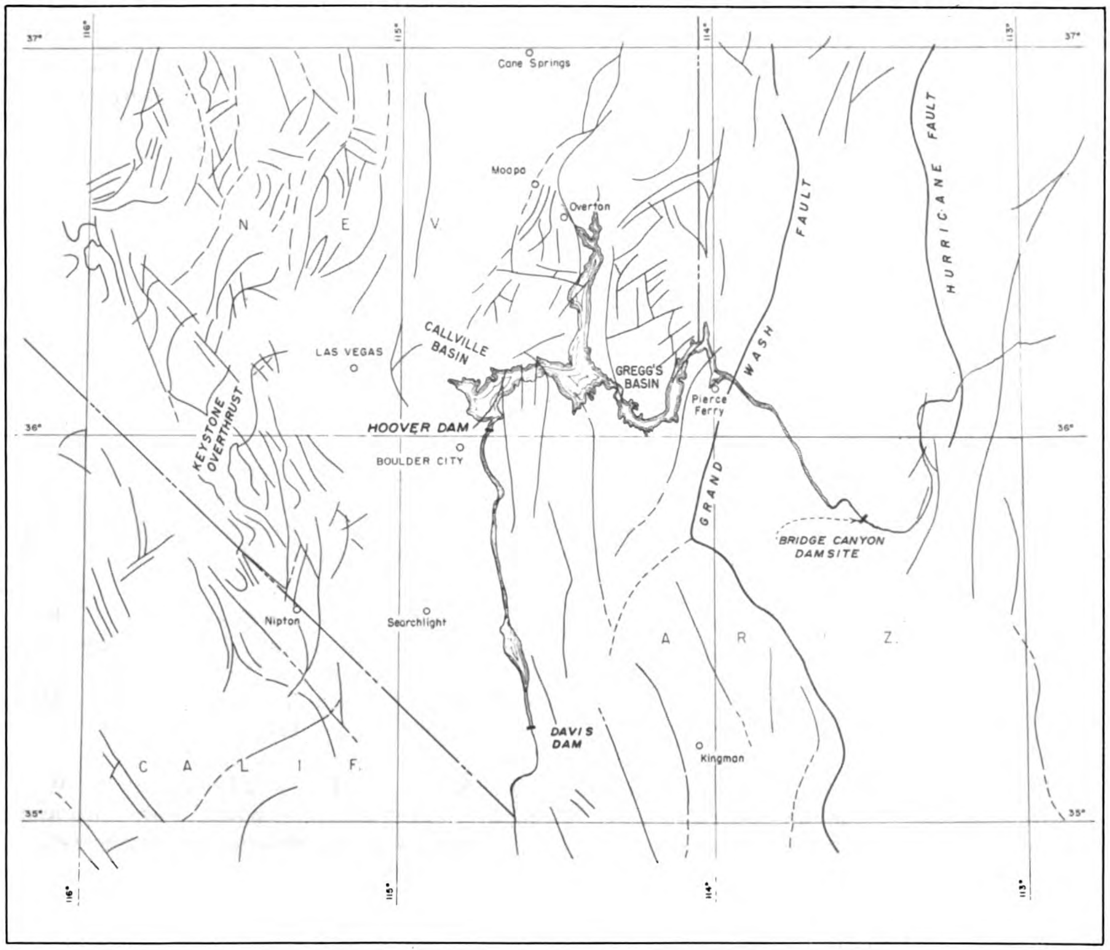

FIGURE 9--Major faults, Lake Mead area.

given by the numerous dry lakes occupying parts of the valley fills. It is believed that this is but another manifestation of the wide-spread evidences of a general warming up of the climate of North America, as evidenced also by a decline of lake elevations in Great Salt Lake, and the retreat of the glaciers in Glacier National Park, to cite a few examples.

REGIONAL WARPING

A regional warping, or tilt, can be seen on further study of Figure 5. This shows that with respect to the zero subsidence taken at Cane Springs, the subsidence at Searchlight and Chloride, 100 miles to the south, is of the order of 4 inches. It is not considered that the regional warping has any connection with the load on the reservoir, but reflects a regional geologic disturbance that has been going on for some time, and presumably will continue in the future.

Two interrelated questions are raised:

(1) Which way is the crust moving--is it tilting up to the north or down to the south; and (2) what is the mechanism?

Upward movements are associated with removal of load such as in the retreat of a glacier or removal of sediments. The Lake Mead area is too remote from the southern limits of continental glaciation to give much credence to this idea. A downwarping to the south could have as a cause the gradually increasing load of sediments in the ancient and modern deltas of the Colorado River. At this time it is perhaps wisest to note that there is tilting, reflecting some geotectonic adjustment, and not speculate as to its cause.

Whatever the mechanism, it is disturbing from an engineering point of view to reflect that bench mark elevations so painstakingly established in this region can be so easily disturbed by natural forces and subject to error in such a short period of time.

REFERENCES

1. Source document: Drawing titled: The Hoover Dam Level Net, revised November 1950, United States Coast and Geodetic Survey

2. Longwell, C. R., "Geology of the Boulder Reservoir Floor," Bulletin Geol. Soc. Am., September 30, 1936, Vol 47, p 1393

3. Carder, D. S., and Small, J. B., "Level Divergences, Seismic Activity, and Reservoir Loading in the Lake Mead Area, Nevada and Arizona," Transactions, American Geophysical Union, December 1948, Vol XXIX, No. 6, p 767

4. Maxey, J. D., and Jameson, C. H., "Well Data in Las Vegas and Indian Spring Valley, Nevada," Water Resources Bulletin No. 4, State of Nevada, 1946

5. Maxey, J. D., and Jameson, C. H., "Water Resources of Las Vegas, Pahrump, and Indian Spring Valley, Clark and Nye Counties, Nevada," Water Resources Bulletin No. 5, State of Nevada, 1948

6. Maxey, J. D., and Robinson, C. W., "Ground Water in Las Vegas, Pahrump and Indian Spring Valley, Nevada, (A Summary)," Water Resources Bulletin No. 6, State of Nevada, 1947

Interior - Reclamation - Denver, Colo.