Jour. Research U.S. Geol. Survey
Vol. 3, No. 3, May–June 1975, p. 337–343

THE INFLUENCE OF LATE CENOZOIC STRATIGRAPHY ON DISTRIBUTION OF IMPOUNDMENT-RELATED SEISMICITY AT LAKE MEAD, NEVADA-ARIZONA

By R. ERNEST ANDERSON and R. L. LANEY,
Denver, Colo., Phoenix, Ariz.

Abstract.—At Lake Mead, contrasts in permeability of upper Cenozoic sediments show a better correlation with irregularly distributed impoundment-related seismicity than do contrasts in structure. An evaluation of structures developed during the late Cenozoic fails to explain the erratic distribution of seismicity. An evaluation of the late Cenozoic stratigraphy, however, shows a concentration of relatively impermeable evaporite beds and fine-grained clastic strata in the less seismic part of the lake basin; therefore, the authors conclude that a hydraulic connection between the lake water and the deep aquifer system that includes buried faults is needed in the Lake Mead area to cause the release of seismic energy. Where hydraulic connection is prevented by continuous or quasi-continuous upper Cenozoic basin-fill strata of low permeability, as in the eastern basin area, seismicity does not occur.

Lake Mead, one of the major reservoirs of the world, was created in the middle 1930's by the construction of Hoover Dam across the Colorado River at Black Canyon. Soon after Lake Mead began to fill, local earthquakes were felt in the vicinity of the lake (Carder, 1970) and since then over 10,000 events have been recorded.

The impoundment of water in some reservoirs stimulates the release of seismic energy. W. V. Mickey (NOAA Environmental Research Laboratories, written commun., 1973) summarized the impoundment-related seismicity in the United States and found that indirect and inconclusive evidence relating seismic activity to reservoir impoundment is available for more than 40 reservoirs. However, seismic data are available for only 18 reservoirs and at only 10 of these is there an indication of possible cause and effect. Lake Mead is the only reservoir for which there are sufficient seismic data to allow significant comparisons between water impoundment and local seismicity. It is clear that reservoir filling results in increased seismic activity (Carder, 1970).

The Lake Mead area lies along part of the common border of Arizona and Nevada (fig. 1). For purposes of reference the lake can be divided into three parts which, from east to west, are (1) the upper lake, a narrow body that clearly reflects the sinuous course of the Colorado River, (2) the eastern basin, the large body that includes Virgin Basin and Overton Arm, and (3) the western basin north of Hoover Dam (fig. 2). The western basin has been variously referred to as Boulder Basin or Callville Basin.

Carder (1945, 1970) and Carder and Small (1948) prepared maps of earthquake epicenters in the Lake Mead area covering the period from 1940 through 1947.

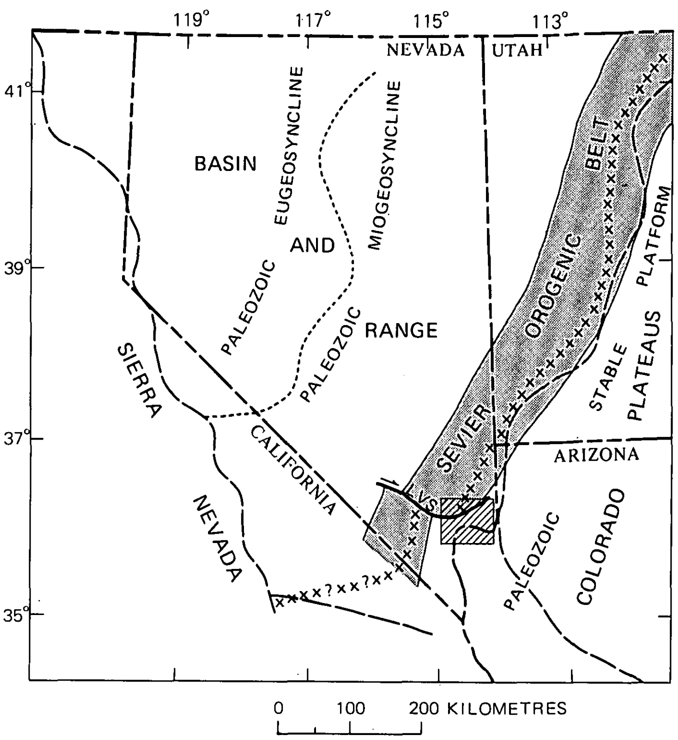

FIGURE 1.—Map showing the location of the Lake Mead area (diagonally ruled) relative to the boundary between the Paleozoic miogeosyncline and stable platform (X's), the Mesozoic Sevier orogenic belt, the boundary between the Colorado Plateaus and Basin and Range provinces (long-dashed line), and the Las Vegas Valley shear zone (LVS).

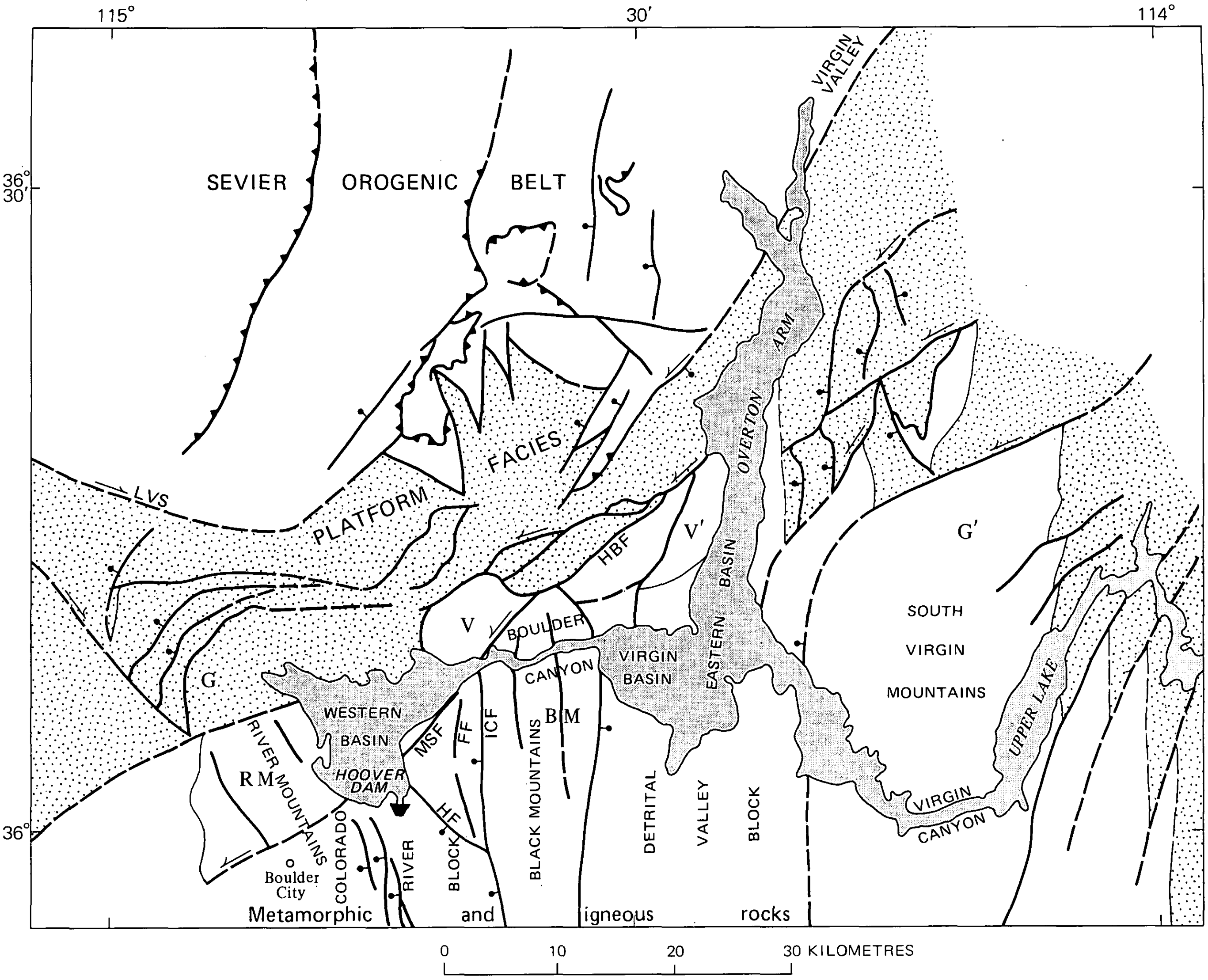

FIGURE 2.—Map showing Lake Mead (shaded) and its principal basins relative to some of the major tectonic features of the area including (1) Sevier orogenic belt and its complexly faulted south boundary, (2) area of Precambrian metamorphic rocks and Cenozoic igneous and volcanic rocks, and (3) structural corridor (stipple pattern) between 1 and 2 composed of tectonically transported Paleozoic platform facies rocks and Mesozoic and Cenozoic strata of continental origin. Two offset parts of a late Cenozoic volcano, indicated by V and V′; the River Mountains (RM) probably represent the offset northern part of the Black Mountains (BM); unique rapakivi granite widely exposed at G′ is found as landslide masses at G, indicating the approximate cumulative displacement on the left-lateral shear system. Las Vegas Valley shear zone, LVS; Hamblin Bay fault, HBF; Mead Slope fault, MSF; Fortification fault, FF; Indian Canyon fault, ICF; Horsethief fault, HF. Faults are dashed where approximately located and have bar and ball on downthrown side; arrow shows relative direction of movement; sawtooth edge indicates east-directed overthrusts.

The distribution of epicenters is extremely irregular; epicenters are highly concentrated in the vicinity of, and south of, the western basin, with a subordinate concentration in the area of the upper lake (fig. 3). No epicenters are reported in the eastern basin although it contains the largest area and volume of water. According to A. M. Rodgers, Jr. (Environmental Research Corp., written commun., 1973), microearthquakes are now occurring in the western basin area at the rate of one or two per day at depths typically less than 5 km. Most of the epicenters in the vicinity of the western basin lie northeast of Boulder City, Nev., and many are concentrated near four major faults that were described by Longwell (1963, pl. 1)—the Mead Slope fault, the Fortification fault, the Indian Canyon fault, and the Horsethief fault (figs. 2, 3).

Carder (1945) suggested that the irregular distribution of seismicity is related to a contrast in the type of

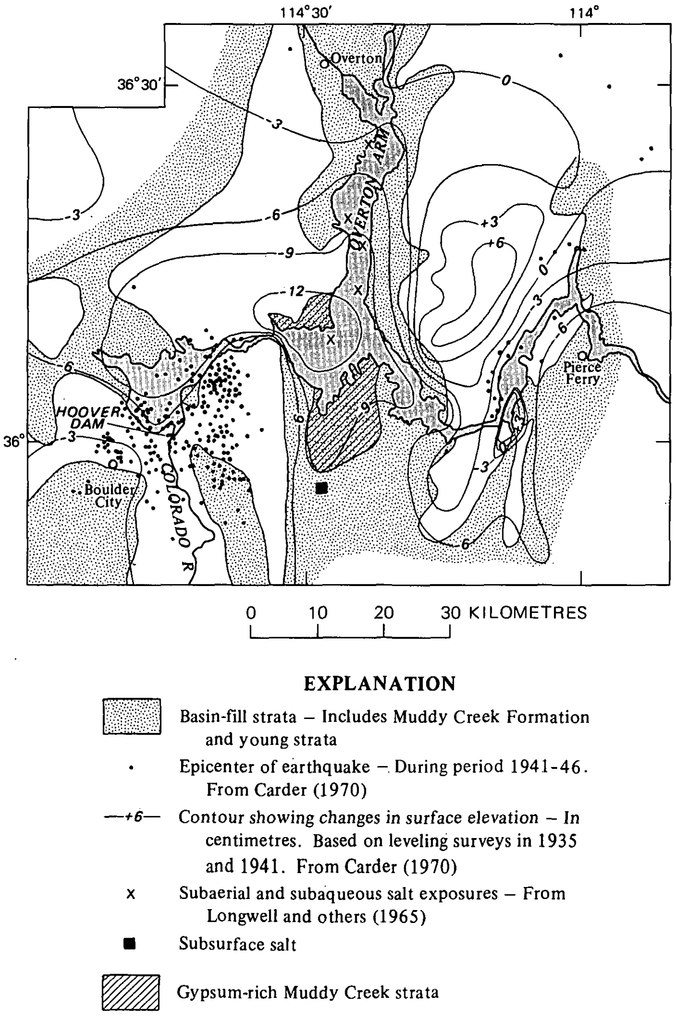

FIGURE 3.—Map of the Lake Mead area showing locations of epicenters, changes in surface elevations, highly generalized distribution of basin-fill strata, occurrences of subaerial and subaqueous salt exposures in the Overton Arm area, location of subsurface salt, and area of gypsum-rich strata in Muddy Creek Formation in Detrital Valley.

impoundment-related deformation between the two major basins: flexuring in the aseismic eastern basin and faulting in the seismic western basin. The purpose of the present report is to summarize the geologic setting and late Cenozoic geologic history of the Lake Mead area, to evaluate Carder's suggestion in terms of that summary, and to suggest, instead, that the irregular distribution of seismicity is related to contrasts in basin stratigraphy and not to structure. In particular, the distribution of relatively impermeable evaporite beds and fine-grained clastic strata in the eastern basin seems to have produced an aseismic area by preventing hydraulic connection between the waters of Lake Mead and the system of faults that is believed to be present beneath the impermeable strata.

GEOLOGIC SETTING

Lake Mead occupies the critical junction of several major geologic features, some of which are offset and others of which either intersect or adjoin in the vicinity of the lake. The location of the lake relative to these features is shown in figures 1 and 2. The boundary between the Paleozoic miogeosynclinal and platform facies rocks projects toward the lake area from the northeast as does the broad belt of east-directed Cretaceous overthrusts, the Sevier orogenic belt. However, neither feature quite reaches the main area of the lake (fig. 1). Both were offset many kilometres to the west during the late Tertiary by displacements on a complex system of faults, one of which is the Las Vegas Valley shear zone (Longwell, 1960; Fleck, 1970). The approximate location of the faulted margin of the Sevier orogenic belt, which embraces the miogeosyncline-platform facies boundary, is shown in figure 2. Although the late Tertiary truncation of these features may be of importance to understanding the geology of the lake area, the features themselves are not and therefore will not be given additional consideration.

The eastern extremity of the upper lake lies across the faulted transition zone between the Colorado Plateaus and the Basin and Range structural provinces (figs. 1, 2). The lake extends westward from the transition zone about 80 km into the Basin and Range province. As the lake reaches westward it transects one basement ridge at Virgin Canyon; farther west the lake lies athwart the northern extremities of two north-trending basins and one intervening range each of which is very well defined for more than 70 km south of the lake (south of the area of fig. 2). From east to west these latter three features are (1) the Detrital Valley downdropped block, (2) the uplifted Black Mountains, and (3) the structural trough that has had much of its sediment fill scoured out by the Colorado River south of Hoover Dam (fig. 2). Bedrock in these areas consists of Precambrian crystalline rocks and Tertiary volcanic and plutonic rocks (Longwell, 1963; Wilson and Moore, 1959). The structural corridor situated between the north ends of these Basin and Range structures and the southern faulted margin of the Sevier orogenic belt (fig. 2) consists of a fantastic array of faulted ridges composed of rocks that were carried into that area from the northeast, piggyback style, on a relatively fast moving current of mantle and lower crustal materials during the late Tertiary (Anderson, 1973). This structural corridor consists of platform-facies Paleozoic strata, Mesozoic strata that include the Moenkopi and Chinle Formations and the Aztec Sandstone, and a thick sequence of continental basin strata, the lower part of which may be as old as Late Cretaceous or early Tertiary.

In summary, the most important stratigraphic units that shape the geologic setting of Lake Mead are (1) the Precambrian and Tertiary metamorphic and igneous rocks in the south and the younger sediment prisms that partially fill the basins that developed there later, and (2) the Paleozoic, Mesozoic, and Tertiary sedimentary strata located in the structural corridor to the north. The most important structures are (1) the faulted transition zone between the Colorado Plateaus and the Basin and Range areas, (2) the Basin and Range structures that extend into the lake area from the south, and (3) the corridor of complex strike-slip structures along which the belt of sedimentary rocks has been shifted many kilometres to the southwest. In the section that follows we attempt to sort out these stratigraphic and structural units in terms of their sequence of development.

LATE CENOZOIC GEOLOGIC HISTORY

The late Cenozoic geologic history of the area can be divided into three main events. During the first episode, which occupied a 7-m.y. period that ended about 13 m.y. ago, there was eruption of predominantly andesite lava to form piles as much as 4,000 m thick, simultaneous emplacement of hypabyssal plutons of batholithic proportions in the southern part of the area, and deposition of clastic, carbonate, and evaporite strata in broad basins to the northeast [1] (Anderson and others, 1972). The plutonism occurred during the latter part of this period and was accompanied by extreme thin-skinned extensional tectonism that continued into the next main event (Anderson, 1971). The Colorado Plateaus and Basin and Range areas probably began to be structurally and physiographically distinguishable during this period. However, all available evidence suggests that drainage was to the north or northeast from the Lake Mead area during most of this period (Lucchitta, 1972).

The second episode occurred between 13 and 5 m.y. ago. During the first part of this 8-m.y. period, the intensity of volcanism and thin-skinned extensional tectonism in the southern part of the lake area decreased rapidly. Structural activity changed with time from displacements on low-angle shingling normal faults to displacements on higher angle normal faults that blocked out basins which began to fill with sediments and minor intercalated lavas. More than 1.5 km of vertical displacement eventually developed between the Black Mountains and the flanking basins (Anderson and others, 1972). In the area to the northeast the early formed broad basins were broken up by large-magnitude displacements on interrelated strike-slip and normal fault systems that began to transport the rocks to the southwest. The boundary between the southern metamorphic-igneous area and the central sedimentary corridor (fig. 2) developed early during this period as a major left-lateral strike-slip fault zone that eventually acquired about 60 km of displacement (Anderson, 1973). There was undoubtedly much fault interaction across this boundary because displacements on the strike-slip faults were in part compensated for by simultaneous west-directed extensional tectonics in the area to the south. As in the south, new basins formed in the north and they too began to fill with sediments. The basin-fill sediments in both areas have been mapped widely as the Muddy Creek Formation, which includes coarse to fine clastic rocks, lavas, tuffs, landslide deposits, and more significantly, evaporites and chemical precipitates. Basalt lavas at the top of the Muddy Creek sediments have been dated isotopically at about 5 m.y. (Anderson and others, 1972). These lavas flowed down the flanks of the Black Mountains across the range-front faults and out over the alluviated valleys. The lavas predate the Colorado River in the area and postdate all but a small amount of normal faulting.

The geologic record for the final period, between 5 m.y. ago and the present, is fragmentary largely because much of what might have served as evidence has been removed by erosion. The period may have begun with continued basin sedimentation under conditions of greatly reduced structural activity. Sedimentation was interrupted early and abruptly when the Colorado River entered the area and began breaching the basins and carrying their sedimentary fill southward out of the Lake Mead area. Potassium-argon data reported by Lucchitta (1972) indicate that the Colorado River had cut its channel to approximately its present level by about 3.3 m.y. ago. This age value, together with those reported by Anderson, Longwell, Armstrong, and Marvin (1972), seems to compress the period of canyon cutting by the Colorado River into too short an interval (less than 1.7 m.y.). Nevertheless, the data probably approximate the age of that event, if not its precise duration.

Anderson (1969) reported the presence of the effects of a fossil water table exposed at altitudes more than 0.5 km above present grade of the Colorado River in the vicinity of Hoover Dam. This is undoubtedly the youngest pre-Colorado River feature in the area, but

[1] Although the sedimentary rocks of this period are now located to the north of the western and eastern Lake Mead basins, they were transported to that position tectonically from the northeast and not deposited there (Anderson, 1973). The true nature of the prefaulting transition between predominantly igneous rocks in the south and the sedimentary rocks is not known.

its age has not been precisely determined. Contrasting layers produced by different amounts of water-table-related cementation are traceable for a few kilometres. They are not cut by faults (Anderson, 1969, fig. 2), whereas the youngest nearby basalt lavas are (R. E. Anderson, unpub. data, 1974). These relationships suggest pronounced structural stability over the past 3.3 m.y. in the general area of the most intense impoundment-related seismicity.

The level to which the western basin was filled with sediment near its edges is determined by the level of the fossil water table. Thus, it is clear that a thickness of as much as 0.5 km of basin-fill sediment was stripped from the western basin by the Colorado River. A similar thickness may have been removed from parts of the eastern basin. This denudation event and the accompanying reduction of ground-water level could have acted in the direction of stabilizing the area seismically by reducing hydraulic pressure at hypocentral depths. If this is so, the fact that seismic activity has been triggered by reservoir impoundment would suggest that the rocks at hypocentral depths are maintained in a critical or near-critical state of stress by mild but active tectonic forces. Despite the indications of increased structural stability during the past 5 m.y., the intense late Tertiary tectonism could reasonably be followed by residual tectonic forces of a much lower but still significant magnitude extending to the present.

HYPOTHESIS OF SEISMICITY RELATED TO STRUCTURE

Contoured leveling data reported by Carder and Small (1948, fig. 2) for the period extending from prior to the filling of Lake Mead to 1941 show that the maximum differential displacement measured in the vicinity of the lake occurred between the Detrital Valley block, which subsided 12 cm, and the bedrock area of the South Virgin Mountains to the east, which rose 6 cm (fig. 3). Contours representing changes in elevation for the period from 1935 to 1963 show a similar pattern of subsidence in the area of the Detrital Valley block although some rebound had occurred from 1949 to 1963 (Lara and Sanders, 1970, figs. 2-2 and 2-3). These data, together with the map of epicenter locations reported by Carder and Small (1948), show that impoundment-related deformation was greatest in the aseismic part of the lake area where the largest volume of water occurred. We therefore assume that seismicity is not the direct result of loading by the mass of lake water but instead reflects a reduction in effective stress on fractures in the focal region due to direct hydraulic connection with surface water. Also, if the irregular distribution of seismicity is related to contrasting styles of structural response to loading, as suggested by Carder (1945) and as outlined in the introduction to this report, we should expect to find some contrast in structural setting or pattern between the aseismic and seismic areas.

High-angle normal faults that cut and bound the Black Mountains block extend beneath the waters of Lake Mead in the aseismic as well as the seismic areas (Longwell, 1936; Anderson, 1973). Individual strike-slip faults also extend into both aseismic and seismic areas. In particular, the southernmost strike-slip fault north of Boulder Canyon (the Hamblin Bay fault of Anderson, 1973) has had about 20 km of left-lateral displacement since about 12.7 m.y. ago (offset indicated in fig. 2). This fault projects beneath the aseismic Overton Arm to the northeast and the seismic western basin to the southwest (fig. 2). Its trace is largely buried beneath strata of the Muddy Creek Formation in the Overton Arm area. Other late Tertiary strike-slip faults having displacements of several kilometres have been mapped in the South Virgin Mountains east of Overton Arm (Longwell and others, 1965; Morgan, 1968). These faults also must extend beneath the lake, although their traces are concealed by basin-fill strata that flank the lake. Late Tertiary normal and related strike-slip faults of large displacement are very abundant along the canyon of the Colorado River south of Hoover Dam (Longwell, 1963; Anderson, 1969, 1971, and unpub. data, 1974). They are visible there only because the river has removed much of the basin fill. Faults of similar size and abundance can be reasonably inferred to exist beneath the aseismic Detrital Valley block where the southern part of the eastern basin is located. Despite the fact that fault locations beneath the eastern basin are highly conjectural or unknown, available geologic maps provide no basis for suggesting that the abundance or pattern of large buried faults is any different there than in the seismic western basin.

INFLUENCE OF SALT BARRIER ON SEISMICITY

Surface exposures of rock salt in the area that is now occupied by Overton Arm (fig. 3) had been studied at several locations prior to the filling of Lake Mead (Longwell, 1936). The specific locations are shown on a mineral resources map of Clark County, Nev. (Longwell and others, 1965, pl. 2). The northernmost occurrence is still exposed along the western lakeshore southwest of Overton Beach (fig. 4).

The salt occurs within the Muddy Creek Formation and is as much as 500 m thick (Mannion, 1963). The Muddy Creek Formation in the area of Overton Arm

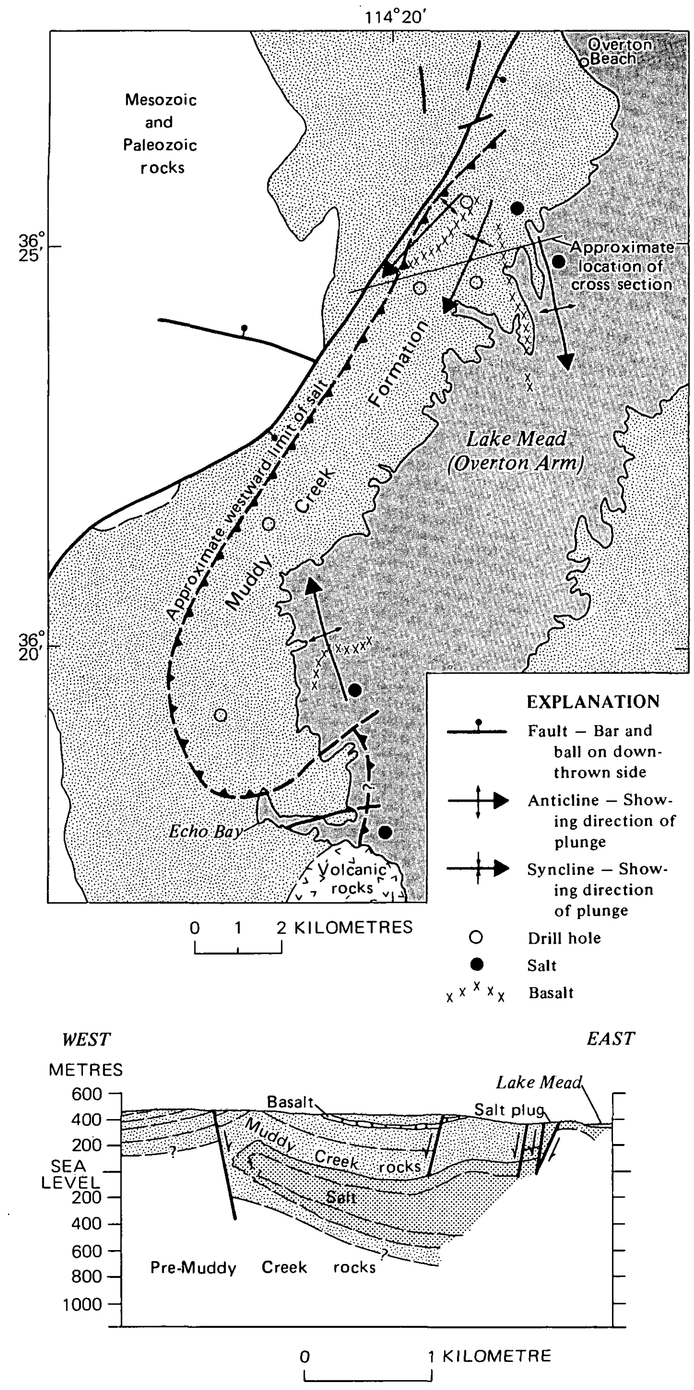

FIGURE 4.—Geologic sketch map of part of the Overton Arm area and generalized cross section south of Overton Beach showing the distribution of subsurface salt. From Mannion (1963).

is more than 800 m thick and consists mainly of siltstone, claystone, and sandstone, all of which are gypsiferous. A conspicuous basalt layer as much as 30 m thick occurs in the upper part of the section above the salt and serves as a useful marker in showing the structural deformation in the area (fig. 4). The salt exposures (all but two are now covered by Lake Mead) occur as domal bulges in the crests of anticlines. The anticlinal structures are complicated by faults, which increase in number and complexity near the salt bodies. Generally the nearly vertical flanks of the salt bulges are marked by high-angle faults. The side away from the axis of the fold usually is downthrown, thus indicating the upward movement of the salt in the anticline.

The entire Virgin Valley–Detrital Valley trough in the vicinity of Lake Mead contains salt deposits. In Detrital Valley about 50 km south of the northernmost exposure of salt in the Overton Arm area, a subsurface salt body has been defined by R. L. Laney using data from 10 drill holes (U.S. Geological Survey, 1972). The subsurface salt there covers an area of at least 13 km^2, is as much as 200 m thick, is within 130 m of the surface in places, and occurs as a northeast-trending mass that is about 2.4 km wide and at least 4.8 km long. The overlying clay, silt, and limestone beds of the Muddy Creek Formation, which are at least 450 m thick in the Detrital Valley block, have been upwarped into a south-plunging anticline. The east flank of the anticline forms a well-defined cuesta. The west flank is mostly concealed by alluvial deposits but, where exposed, appears to be complexly faulted.

To the north of the salt mass, Laney (unpub. data, 1973) mapped more than 90 km^2 where the surface exposures of the Muddy Creek Formation are rich in gypsum (fig. 3). Gypsum-rich beds commonly occur above salt in the Overton Arm area (Mannion, 1963) and in the Detrital Valley block, suggesting that salt may be present beneath the gypsum-rich beds south of the lake. Therefore, it is reasonable to infer from the available data that salt may underlie much of the eastern basin. Salt has not been reported in the western basin nor in the somewhat less seismic area of the upper lake where several large faults cut across the lake.

Salt is one of the least permeable natural rock-forming materials known, and it has a remarkable capacity to deform without fracturing. These physical properties could be responsible for preventing or greatly reducing hydraulic connection across a sequence of salt beds. We suggest that the presence of a continuous or quasi-continuous interval of bedded salt, in conjunction with deposits of gypsum and fine-grained clastic strata of low permeability beneath the eastern basin, is the single controlling factor in producing the aseismic area there; that is, a hydraulic connection between the lake waters and the system of faults in the pre-Muddy Creek rocks is apparently needed in the Lake Mead area to trigger the release of seismic energy by reduction of effective normal stress on fractures that are already sustaining shear stress near the point of failure. Our evaluation of the late Cenozoic geologic setting and history of the Lake Mead area indicates that nowhere should we expect to find a shortage of such fractures at hypocentral depths, but beneath the eastern basin the requisite hydraulic connection is missing.

An alternative explanation of the aseismic character of the eastern basin was suggested to us by R. C. Bucknam (written commun., 1974). The plastic yield of subsurface salt might result in a rather uniform redistribution of the concentrated surface load over the fractured bedrock at potential focal depths. Areas in which the concentrated load is not redistributed owing to plastic flow might be subjected to more localized loading, stress concentrations, and numerous small earthquakes.

In the eastern basin–Overton Arm area, the distance to which subsurface salt could tend to redistribute stress is limited by the contact between the bedrock and the basin-fill sediments (fig. 3), and in general it would be somewhat less than that distance. Where known, the actual distance is considerably less than the distance to which epicenters extend into areas of bedrock surrounding the western basin. The strongest vertical deformation reported by Carder (1970) occurred between the eastern basin and the bedrock area of the South Virgin Mountains (fig. 3). The maximum possible distance to which salt could tend to redistribute stress there is less than one-third of the distance to which seismicity extends beneath bedrock in the western basin area. Thus, even if the salt does serve to redistribute stress by plastic flow, the resultant stress would be sufficiently localized to produce seismicity if loading is the main cause of that seismicity. Because of these spatial relationships we favor an explanation related to fluid pressure as stated.

REFERENCES CITED

Anderson, R. E., 1969, Notes on the geology and paleohydrology of the Boulder City pluton, southern Nevada, *in* Geological Survey research 1969: U.S. Geol. Survey Prof. Paper 650–B, p. B35–B40.

———1971, Thin skin distension in Tertiary rocks of southeastern Nevada: Geol. Soc. America Bull., v. 82, p. 43–58.

———1973, Large-magnitude late Tertiary strike-slip faulting north of Lake Mead, Nevada: U.S. Geol. Survey Prof. Paper 794, 18 p.

Anderson, R. E., Longwell, C. R., Armstrong, R. L., and Marvin, R. F., 1972, Significance of K-Ar ages of Tertiary rocks from the Lake Mead region, Nevada-Arizona: Geol. Soc. America Bull., v. 83, p. 273–288.

Carder, D. S., 1945, Seismic investigation in the Boulder Dam area, 1940–1944, and the influence of reservoir loading on earthquake activity: Seismol. Soc. America Bull., v. 35, p. 175–192.

———1970, Reservoir loading and local earthquakes, *in* Adams, W. M., ed., Engineering seismology—The works of man: Geol. Soc. America Eng. Geology Case Histories, no. 8, p. 51–61.

Carder, D. S., and Small, J. B., 1948, Level divergencies, seismic activity, and reservoir loading in the Lake Mead area, Nevada and Arizona: Am. Geophys. Union Trans., v. 29, p. 767–771.

Fleck, R. J., 1970, Age and possible origin of the Las Vegas Valley shear zone, Clark and Nye Counties, Nevada: Geol. Soc. America Abs. with Programs, v. 2, no. 5, p. 333.

Lara, J. M., and Sanders, J. I., 1970, The 1963–64 Lake Mead Survey: U.S. Bur. Reclamation, Rept. REC–OCE–70–21, 162 p.

Longwell, C. R., 1936, Geology of the Boulder Reservoir floor, Arizona-Nevada: Geol. Soc. America Bull., v. 47, p. 1393–1476.

———1960, Possible explanation of diverse structural patterns in southern Nevada: Am. Jour. Sci., v. 258–A (Bradley volume), p. 192–203.

———1963, Reconnaissance geology between Lake Mead and Davis Dam, Arizona-Nevada: U.S. Geol. Survey Prof. Paper 374–E, 51 p.

Longwell, C. R., Pampeyan, E. H., Bowyer, Ben, and Roberts, R. J., 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bur. Mines Bull. 62, 218 p.

Lucchitta, Ivo, 1972, Early history of the Colorado River in the Basin and Range province: Geol. Soc. America Bull., v. 83, p. 1933–1948.

Mannion, L. E., 1963, Virgin Valley salt deposits, Clark County, Nevada, *in* Symposium on salt, Cleveland, 1962: Cleveland, Northern Ohio Geol. Soc., p. 166–175.

Morgan, J. R., 1968, Structure and stratigraphy of the northern part of the South Virgin Mountains, Clark County, Nevada: Albuquerque, New Mexico Univ., M.S. thesis.

U.S. Geological Survey, 1972, Geological Survey research 1972: U.S. Geol. Survey Prof. Paper 800–A, p. A43.

Wilson, E. D., and Moore, R. T., 1959, Geologic map of Mohave County, Arizona: Arizona Bur. Mines, scale 1:375,000.

JOURNAL OF RESEARCH

OF THE U.S. GEOLOGICAL SURVEY

MAY-JUNE 1975
VOLUME 3, NUMBER 3

Scientific notes and summaries of investigations in geology, hydrology, and related fields

U.S. DEPARTMENT OF THE INTERIOR