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SEISMIC STUDY OF EARTHQUAKES IN THE LAKE MEAD, NEVADA–ARIZONA REGION

By A. M. Rogers and W. H. K. Lee

ABSTRACT

A nine-station telemetered array was installed around the Boulder Basin portion of Lake Mead, Nevada-Arizona. During $1\frac{1}{2}$ years of monitoring, approximately 1,360 events were detected in the magnitude range $-1.0 \leq M_L \leq 2.9$, and half this number were locatable. Many of the events, which ranged in depth from 0 to 13 km, can be associated with mapped faults. In particular, epicenter lineations clearly indicate activity on portions of steeply dipping faults on the east side of Boulder Basin, which generally confirms Carder's earlier work (Carder, 1945, 1948, 1970). The strike of these faults is approximately north. Focal mechanisms are in agreement with this strike and show right-lateral motion on near-vertical faults. The tension axis for this solution is oriented northwest-southeast in agreement with the stress pattern for other parts of the Basin and Range Province.

Although lake load increased 20 per cent during the monitoring period, neither number of events nor energy release shows a correlation with this change. Carder (1970) found similar results for periods after 1949. A higher *b* value (1.45) was obtained than in the past, and lower monthly energy release was observed than in the late 1930's and 1940's when seismic activity at Lake Mead was first recorded. A 2-yr seismicity map of southern Nevada, including the monitoring period, shows that Lake Mead activity is now no greater than that of the surrounding area.

The pre-Lake Mead seismic history is not well known because the founding of Boulder City occurred just a few years before Lake Mead was impounded. The existence of earthquakes in the region before the reservoir was filled has been questioned in the literature. However, a search of the *Las Vegas Review Journal* for felt reports pre- and postimpoundment and compilation of a catalog of the largest events from the literature confirm that there was a significant increase in the number of felt events at Las Vegas after the reservoir was filled.

The results indicate that the filling of Lake Mead has triggered release of tectonic stresses having the same orientation as the regional stress field. These stresses are probably being released in a way that is more dependent on tectonic stress buildup than on small changes in pore pressure (~ 1 bar) due to fluctuating lake level. Given that the shear strength of rock decreases with increasing pore pressure, one might explain the decreasing energy release since the 1940's and the high *b* value as due to a decrease in elastic-energy density of the rock. A test of this hypothesis based on the order of magnitude of energy released seems to support it.

INTRODUCTION

The Lake Mead region has been seismically active for at least the last 37 years. Prior to that time the seismic history is uncertain. Jones (1944, p. 161) stated that "no earthquakes were reported by the few local inhabitants in the 15-yr period prior to the construction of Boulder Dam". Carder and Small (1948) noted, however, that small shocks may have been mistaken for blasting operations during construction (March 1931 to May 1935) and that the area may have been too sparsely populated before that time for earthquakes to have

been detected or reported. A member of the exploration party in Boulder Canyon in 1921 to 1923 reported hearing "earth noises", although at that time they were believed to be caused by rock slides (Carder, 1945). Finally, Raphael (1954, p. 9) reported that the early inhabitants of the area occasionally "reported minor local earth shocks". A portion of this paper presents some additional evidence to clarify the seismic history.

Since the first felt events were reported in September 1936, more than 10,000 recorded earthquakes have been observed at Lake Mead (Mickey, 1973). Table 1 lists all those events of local magnitude (M_L) 4.0, or intensity V, or greater. M_L 5.0 has been estimated from intensity VI at Boulder City in several cases, because this location may be as much as 15 km from the epicentral region. These events were felt at Boulder City, at the dam, and occasionally in Las Vegas. Instrumental magnitudes are not available for all earthquakes, and it is probable, therefore, that the list is not complete. That is, it is likely that some M_L 5 events were felt at less than intensity VI, and a larger number of M_L 4 events were felt at less than intensity V. Hundreds of earthquakes have been felt at Boulder City and Hoover Dam since the lake was impounded, although the seismicity appears to have declined since 1952 (U.S. Earthquakes).

Literature Review

Seismographs have been intermittently recording in the vicinity of the lake for the last 37 years, providing data for several studies. Mead and Carder (1941) were able to obtain the first event locations using data from a Wood-Anderson seismograph placed in service in 1938 at Boulder City and from a tripartite array (vibrometers), about 80 km on each side, that began operation around the lake in 1940. The located events were found to occur on the east side of Boulder Basin in the vicinity of Fortification Hill.

The vibrometers were replaced with three-component Benioff seismographs in 1942, and the Wood-Anderson instrument was moved to the dam in 1943. Jones (1944) evaluated the increase in detection capability due to these changes, devised a local magnitude scale applicable at close-in hypocentral distances, and determined the radius of perceptibility versus magnitude for Lake Mead events.

Carder (1945) located about 400 earthquakes during the period 1940 to 1944. Most events appear to have been associated with the Indian Canyon, Fortification, or Mead Slope faults. Correlation between the lake level and the number of events was found to be poor. For 5 years during the period 1936 to 1944, the peak seismicity occurred when the lake level was falling, several weeks to several months after the seasonal water-level peak. For 3 years in that period, the peak activity occurred when the lake was rising, and 1 year the peak level and peak activity coincided. Because the earthquakes were associated with faults thought to have a history of block faulting, Carder (1945) concluded that the events were the result of downfaulting of the basin due to the weight of the lake.

Carder supported this argument by comparing the energy of subsidence with the total energy release of the largest events. The total earthquake energy was found to be twice the subsidence energy, in reasonable agreement considering that the displacements used to compute the subsidence energy were roughly estimated. Carder and Small (1948) later obtained geodetic data which showed that subsidence had occurred during 1935 to 1941. Because Boulder Basin showed greater subsidence than areas immediately to the southeast and south, they noted that this supported the hypothesis that downfaulting of the Boulder Basin block produced the earthquakes.

Raphael (1954) examined leveling data run in 1935, 1940 to 1941, and 1949 to 1950 and compared these data with theoretical subsidence displacements computed by Westergaard and Adkins (1934). The displacements due to the weight of the lake were resolved

TABLE I

ALL HISTORICAL LAKE MEAD EVENTS WITH $M_L \geqq 4.0$ OR MODIFIED MERCALLI INTENSITY $\geqq V$.

Date	Time (GCT)	Lat. N.	Long. W.	M_L or m_b	Intensity	References and remarks
09/07/36	11:48	36.0	114.8	4.5	IV	S
09/20/36	04:13	36.0	114.8	3.5	V	UF
04/28/37	04:15	36.0	114.8	4.0*	V	UF
04/28/37	06:16	36.0	114.8	4.0**	V**	U
06/18/37	17:18	36.0	114.8	4.0*	V	UF
11/12/37	00:39	36.0	114.8	3.5	V-VI	UF, Felt in Las Vegas
07/28/38	00:01	37.6	115.8	4.0	IV	S, GS, Felt at Boulder City and Hoover Dam, mislocation?
07/28/38	00:39	37.6	115.8	4.5	V	S, GS, Felt at Boulder City and Hoover Dam, mislocation?
12/28/38	04:38	36.8	114.1	4.0	IV	S, GS
05/04/39	20:44	36.0	114.8	5.0	VI	UF, RJ, Felt in Las Vegas
05/04/39	22:37	36.0	114.8	4.0	IV	S, GS
06/11/39	19:15	36.0	114.8	5.0**	VI**	S, Felt by all, rock slides, plaster cracked and fell
06/04/42	15:26	36.0	114.9	4.0*	V	UF
08/11/42	10:14	36.0	114.7	4.0	V	S, GS
09/09/42	05:15	36.0	114.7	5.0*	VI	UF, GS, Felt in Las Vegas
06/11/44	05:19	39.0	116.0	4.0	IV	S, GS, Felt at Boulder City, mislocation?
07/30/47	22:45	36.0	114.8	4.5**	V-VI**	S, U, RJ, Felt by all, dishes rattled, bushes shaken
09/30/47	21:58	36.0	114.8	4.0*	V	S, GS
05/09/48	18:53	36.0	114.8	4.0*	V	S
11/02/48	16:48	35.9	114.8	5.0*	VI	UF
05/07/50	08:36	36.0	114.8	4.0*	V	S
02/08/52	08:59	36.0	114.8	3.4	V	UF
02/20/52	13:41	36.0	114.8	5.0*	VI	UF, Felt in Las Vegas, +
05/24/52	04:15	36.1	114.8	5.0	VI	UF, S, GS, Felt in Las Vegas, +
10/18/52	19:55	36.0	114.8	4.0*	V	U, S
10/20/52	07:26	36.0	114.8	5.0*	VI	S, GS
04/19/58	09:01	36.0	114.9	5.0*	VI	UF
03/25/63	09:29	36.0	114.9	$4.3m_b$	VI	UF, U, Felt in Las Vegas
04/23/63	08:13	36.0	115.0	4.0*	V	UF
09/23/64	17:10	35.9	114.8	$4.4m_b$	V	UF, U, Felt in Las Vegas

Note: Sources of information are U.S. Earthquakes (U), Coffman and von Hake (1973) (UF), Slemmons *et al.* (1965) (S), the *Las Vegas Review Journal* (RJ), Hays *et al.* (1975) (GS).

*Magnitude estimated from intensity.

**Intensity and magnitude estimates by authors from felt data.

+ Magnitude 5.0 events not reported in the RJ.

into two components: the displacement due to the elastic compression of a strong granitic upper layer, and the quasi-isostatic displacement due to fluid flow below a depth of 29 km with attendant bending of the granitic layer. Raphael found that the elastic-compression model was in good agreement with the observations. However, the isostatic model produced 3 to 4 times as much displacement as had occurred by 1950. Raphael also noted

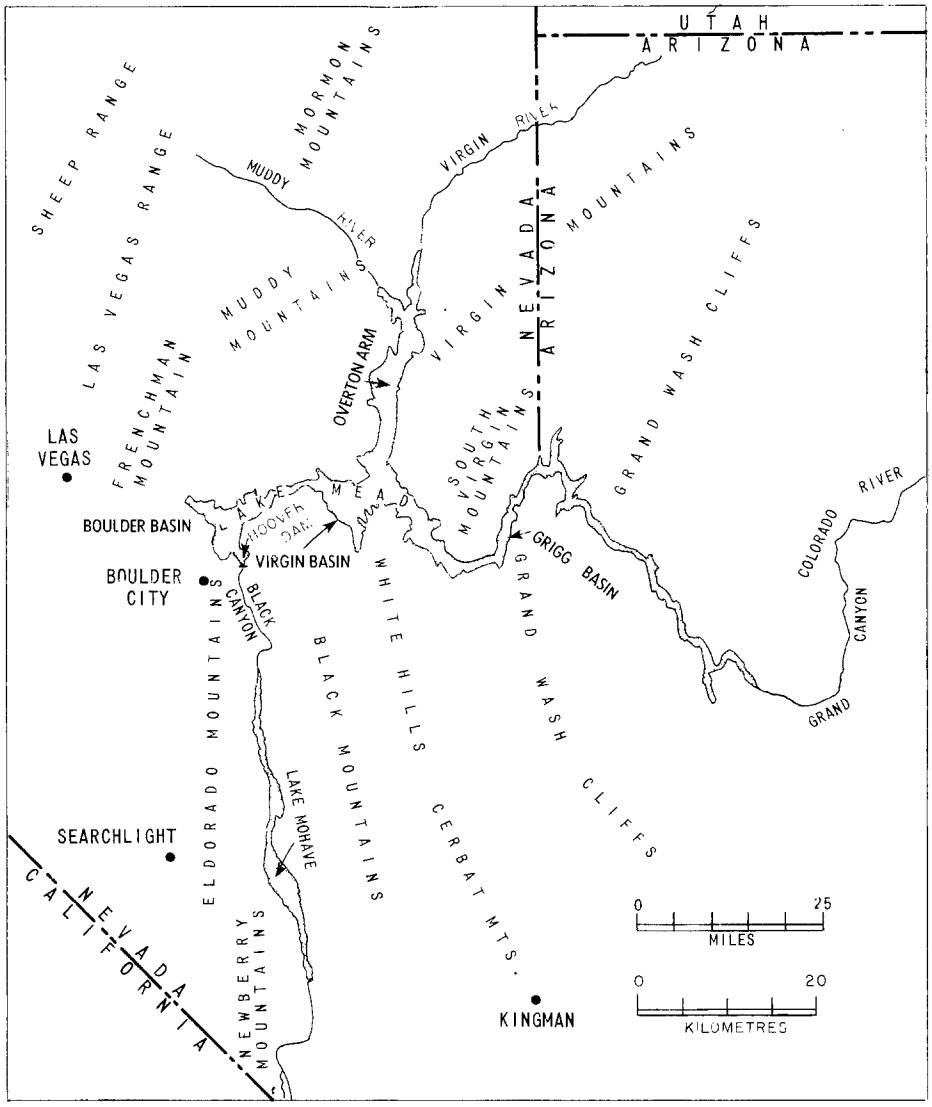

FIG. 1. Map of Lake Mead area, showing schematically major physiographic features.

that the areas of maximum subsidence and earthquake activity did not occur in the same region; furthermore, he found no correlation between earthquake activity and rate of reservoir filling or reservoir load. These observations led Raphael to conclude that the earthquakes were the result of tectonic forces.

Carder (1968, 1970) and Mickey (personal communication) found a positive correlation between seasonal lake load and seismic activity for the years 1938 to 1949; however, subsequent periods showed a negative or zero correlation. The data sample, as a whole,

showed a positive correlation between the water level and seismic activity at a low level of significance (Mickey, 1973). Carder (1970) hypothesized that the crustal adjustment due to loading was satisfied during the first few years after the reservoir was filled. Subsequently, loading or unloading were equally likely to produce earthquakes.

Lara and Sanders (1970), using leveling data obtained in 1963 to 1964, found that rebound occurred at Lake Mead in the interval 1949 to 1963. They suggested that the rebound might be related to a magnitude 5 earthquake that occurred in 1963, just prior to the survey.

In a joint effort to study the present seismicity, Environmental Research Corporation and the U.S. Geological Survey fielded an array of seismometers around the Boulder

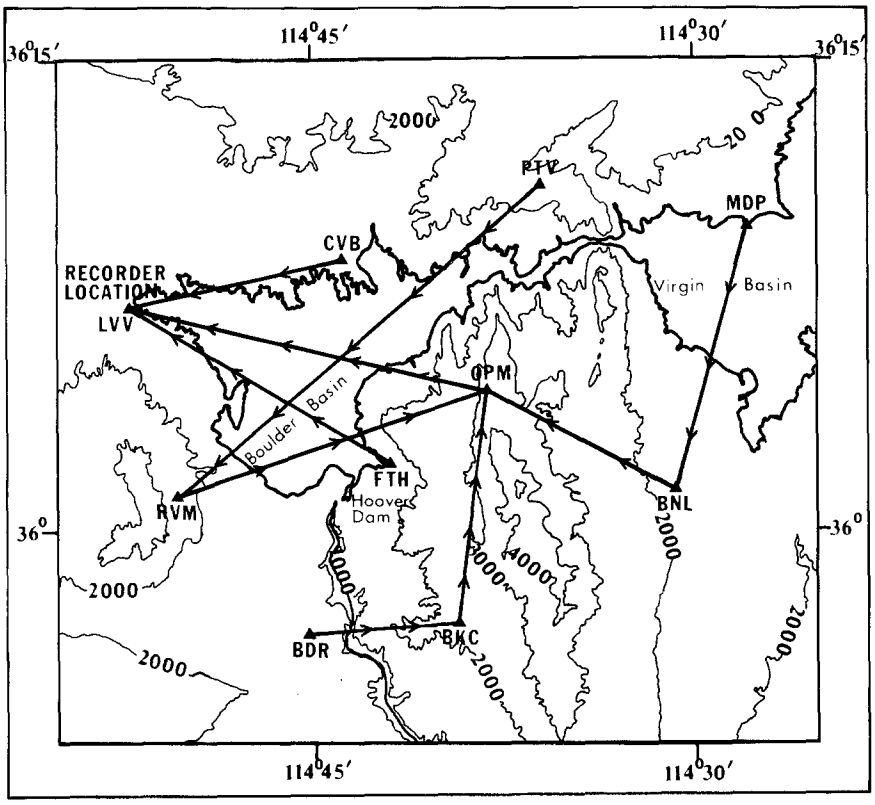

FIG. 2. Topography of Boulder Basin and surrounding area, showing station locations and telemetery paths.

Basin section of Lake Mead in June 1972. The Boulder Basin area was chosen because the majority of previously located earthquakes occurred there. The first seismograms were recorded on July 6, 1972, and the array continued operation until December 5, 1973.

GEOLOGICAL SETTING

Lake Mead is situated near the boundary of two physiographic provinces. It lies within and near the southeast margin of the Basin and Range Province and west of the Colorado Plateau. The lake begins to form where the Colorado River flows out of the Lower Granite Gorge of the Grand Canyon and continues on a largely west course for about 80 km (Figure 1). Lake Mead crosses several north-trending mountain ranges, with intervening broad basins where the widest segments of the lake have formed. The two basins

containing the largest volume of water are the Virgin-Detrital trough and Boulder Basin, where the Colorado River turns to the south and flows into Black Canyon (Figure 2).

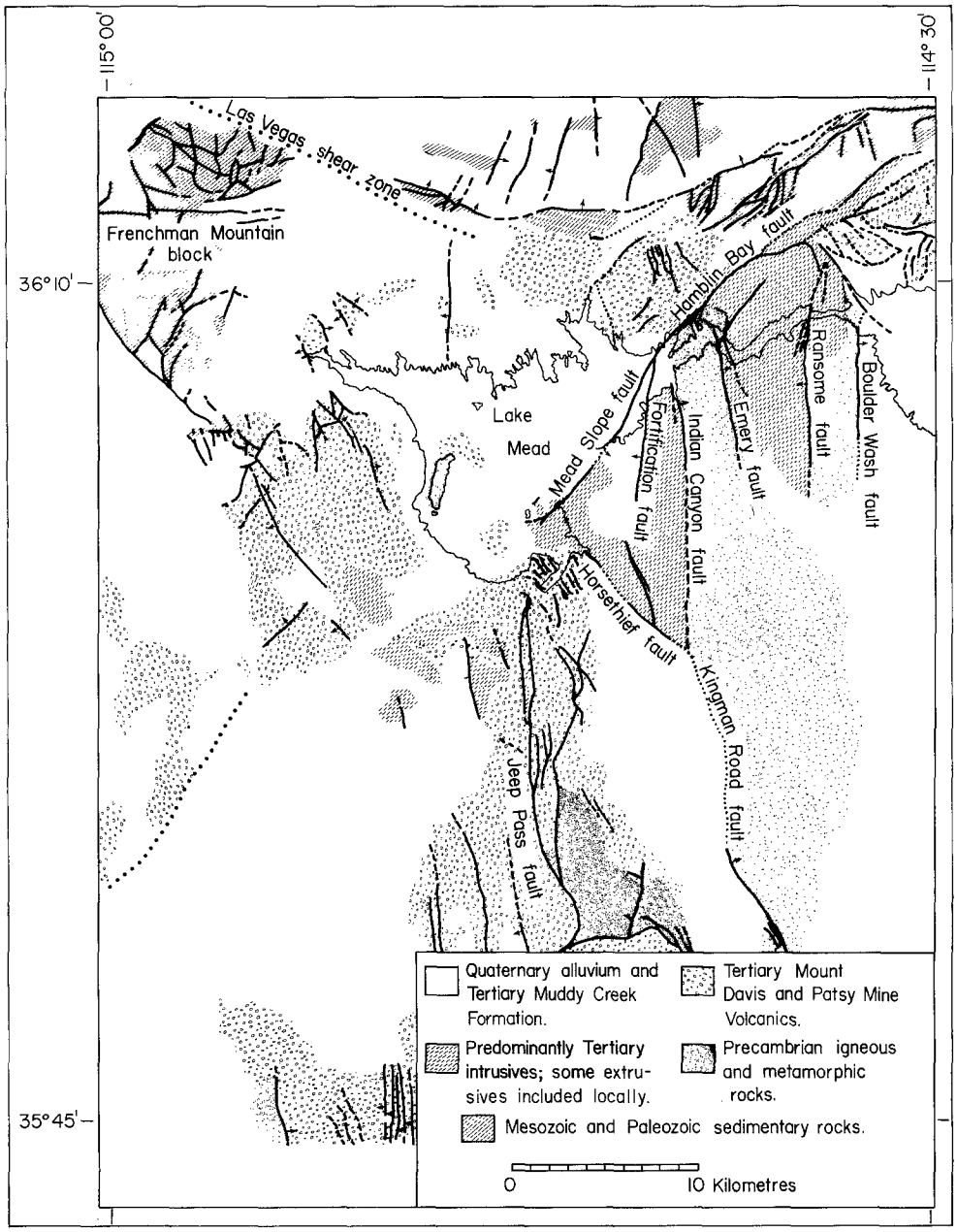

FIG. 3. Tectonic map of Boulder Basin compiled from several sources (Longwell, 1936, 1963; Longwell *et al.*, 1965; Anderson, 1971, 1973b; Anderson *et al.*, 1972).

The geology of the Lake Mead area has been extensively studied by Longwell (1928, 1936, 1963), Longwell *et al.* (1965), Anderson (1971, 1973b), and Anderson *et al.* (1972). Figure 3 shows a compilation of stratigraphic and tectonic information condensed from these studies.

The oldest rocks exposed in the Lake Mead region consist of Precambrian metamorphic and igneous rocks (about 1,740 m.y. old) (Stewart and Carlson, 1974). These rocks are overlain by nearly 5,000 m of Paleozoic, Triassic, and Jurassic sedimentary rocks deposited in the Cordilleran geosyncline. During late Mesozoic, uplift and ensuing erosion removed all the sediments from the area south of the lake, leaving a featureless

TABLE 2

STATION COORDINATES AND CORRECTIONS

Station code	Latitude (N)	Longitude (W)	Station correction (sec)	Operating period**
		I. LAKE MEAD NET		
BDR	35°56.68'	114°45.37'	+0.03	Jul 10, 1972, to Nov 26, 1973
BKC	35°56.91'	114°39.30'	+0.05	Jul 10, 1972, to Nov 24, 1973
BNL	36°01.16'	114°30.90'	+0.02	Jul 10, 1972, to Dec 5, 1973
CVB	36°08.48'	114°43.90'	+0.06	Jul 10, 1972, to Dec 5, 1973
FTH	36°02.06'	114°42.04'	-0.18	Jul 10, 1972, to Dec 5, 1973
LIV*	36°07.10'	114°52.23'	+0.06	Jul 10, 1972, to Sep 30, 1972
LVV*	36°07.00'	114°52.29'	+0.06	Oct 1, 1972, to Jun 8, 1973
MDP	36°09.47'	114°28.11'	0.00	Jul 10, 1972, to Oct 13, 1972
OPM	36°04.54'	114°38.15'	-0.08	Jul 10, 1972, to Dec 5, 1973
PTV	36°10.81'	114°36.10'	0.00	Jul 10, 1972, to Nov 26, 1973
RVM	36°00.95'	114°50.06'	-0.04	Jul 10, 1972, to Nov 26, 1973
		II. SOUTHERN NEVADA NET		
CPX	36°55.92'	116°03.33'		
LSM	36°44.32'	116°16.68'		
LVW	36°10.20'	115°11.25'		
MCV	36°38.01'	115°59.99'		
NEL	35°42.74'	114°50.61'		
PRN	37°26.50'	115°04.00'		

*Three-component station.
**Lake Mead net was not operating on June 19, 1973 due to change of recording.

Precambrian surface by Late Cretaceous. Cretaceous or lower Tertiary conglomerates indicate the close of geosynclinal depositions.

Tertiary volcanic activity was confined mainly to the upper Miocene and Pliocene. The thickness of these deposits is highly variable, but the trend is to greater thicknesses south of Hoover Dam where accumulations are known to approach 5,000 m. A few kilometers

northeast of Boulder Basin, the volcanics are about 900 m thick. Although less abundant than the extrusive volcanic rocks, Tertiary intrusive rocks are scattered in a complex fashion through the exposed Precambrian igneous and metamorphic and Tertiary extrusive rock. The extrusive rocks are chiefly basalt and andesite lavas and silicic ash-flow tuffs, while the intrusive rocks are quartz monzonite and granodiorite.

In Miocene and Pliocene time, volcanism was accompanied by strike-slip and normal faulting that shaped the present structural pattern of the area. Basins with interior drainage were established, and they received sediments that form the Muddy Creek Formation. These sediments cover extensive areas of the Virgin-Detrital trough and a region to the northwest of Boulder Basin. Deposits of this formation are conglomerates, sandstone, clay, basalt flows, salt, and gypsum. In the Virgin Basin area, salt and gypsum beds have accumulated to perhaps a thousand meters (Mannion, 1963). Sometime after deposition of the Muddy Creek Formation, probably in late Tertiary, a more pluvial climate developed and the modern Colorado River was formed. Since that time, the Colorado River has removed much of the detrital fill and sediment from Boulder Basin, leaving many of the structures well exposed.

The most significant structures at Lake Mead are faults. The two major faults are the northwest-trending, right-lateral Las Vegas shear zone (LV) and the northeast-trending left-lateral Hamblin Bay shear zone (HB). Displacements on both these fault zones are estimated to be about 60 to 70 km. A number of normal, reverse, and oblique faults splay south from the HB fault exhibiting north-south trends (Figure 3). The LV fault may pass through the area concealed beneath Quaternary deposits. Anderson (1973b, Figure 8) and Longwell (1971, 1974) have presented two interpretations of the tectonics of the area, based on the interaction of LV and HB faults and the transport of the Frenchman Mountain block from the South Virgin Mountains (SVM) to its present position (Figure 1). Longwell (1974) postulated that the Frenchman Mountain block was offset from a position south of the SVM along the LV shear zone. This fault was then offset by the HB, or related left-lateral faults, shifting the SVM to the northeast. According to this interpretation, the HB and LV faults intersect in the vicinity of the northeast corner of Boulder Basin. Anderson (1973a, b) favored an interpretation whereby a broad band of rock, including Frenchman Mountain and bounded by LV and HB faults, was shifted southwestward and westward from a position originally north of the SVM.

The relationship between the strike-slip and normal faults is complex, but some strike-slip displacement appears to be translated into normal displacement (Anderson, 1973b). Mead Slope, Fortification, Indian Canyon, Boulder Wash, and Kingman Road faults are the major members of this group. Movements on these faults produced uplift of the Black Mountains block and/or subsidence of the surrounding Colorado River and detrital blocks. The vertical displacements on these faults are cumulatively about 1,800 m.

Seismograph Stations

A nine-station network of short-period seismographs was installed around Boulder Basin, Lake Mead. The equipment at each station is similar to that described by Eaton *et al.* (1970). The data from all stations were radio-telemetered to the collection point at Las Vegas Wash Ranger Station (shown on Figure 2 as Station LVV) where the data were recorded on tape from July 10, 1972 until June 9, 1973. In order to reduce field operation and data processing costs the data were recorded on Develocorder from June 20, 1973 to about December 5, 1973.

Magnification for individual stations was adjusted according to the background-noise

level, resulting in station magnifications of about 100,000 at 1 Hz. In locating some earthquakes in the Lake Mead area, we have supplemented our readings with readings from the Southern Nevada Network operated by the Las Vegas Office of the U.S. Geological Survey. All stations used are listed in Table 2. The Lake Mead stations are plotted in Figure 2.

Data Processing and Analysis

Because two types of recordings were used during the study period, two different procedures for data processing were carried out (Rogers and Gallanthine, 1974; Lee and Matamoros, 1975). During the first period, the magnetic tapes were shipped to Menlo Park for playback. Two types of hardcopy playouts were obtained using a Siemens Jet-Ink oscillograph, which has a flat response from dc to about 400 Hz. A continuous playout of each 5-day magnetic tape was produced at a vertical scale of 1 v/cm and a horizontal scale of about 8 sec/cm. After seismic events were identified on the continuous playouts, a more detailed playback was made on a larger time scale of about 1 sec/cm. The seismic signals as well as the timing signals were also digitized at a sampling rate of 100 samples/sec, starting at a few seconds before the onset of P arrivals and lasting for 30 sec.

The digital tapes were then processed on a CDC 7600 computer, using an Automatic Earthquake Processor program (Stevenson, 1976). This program picked the P arrival times for all seismic stations, indicating the picks on a microfilm plot of the seismic traces and punching cards containing the P arrival times. It then executed a preliminary hypocenter location based on these P arrival times. The punched cards were corrected manually for mispicks, using the plot as a guide. Approximately 20 per cent of the picks were corrected manually. First-motion direction, S arrival times, and duration of the coda were determined manually when possible.

During the second period (June 20 to December 5, 1973), the telemetered seismic data were recorded on 16-mm films. They were processed manually to yield information on first P arrivals, first motions, S arrivals (whenever readable), and signal durations. These data were then processed by computer to give origin time, hypocenter location, magnitude, and fault-plane solution of the earthquakes. Each roll of film contained about 24 hr recording and was processed in the following steps: (1) scanning, (2) timing, (3) checking, (4) preparing punched cards, (5) batch processing by computer program HYPO71, (6) correcting errors, (7) adding data from the Southern Nevada Network, and (8) rerunning HYPO71.

Because seismic data recorded on magnetic tapes were also available from October 13 to December 5, 1973, a procedure similar to that carried out in the first period was also applied to supplement the data processing of the 16-mm films.

In the data processing, local events having signal duration of 10 sec or more were always timed. Durations shorter than 10 sec corresponded to a cutoff at about magnitude 1 or less for earthquakes within the Lake Mead Network. Events with $S-P$ time greater than about 5 sec at any station were noted but not timed. Longer $S-P$ times corresponded to earthquakes located greater than about 50 km from the center of the Lake Mead Network.

Location of earthquakes was based mainly on P arrivals from well-recorded events in the region, although S arrivals were used to supplement the P arrivals whenever possible. The HYPO71 computer program (Lee and Lahr, 1972) was used to locate hypocenters, compute the magnitudes, and plot the first-motion patterns.

A number of seismic-refraction surveys have been conducted in the vicinity of Lake Mead (Diment *et al.*, 1961; Gibbs and Roller, 1966; Roller and Healy, 1963; Roller, 1964;

Johnson, 1965; and J. C. Roller (written communication). From these data, the following crustal model was adopted (Lee and Matamoros, 1975):

Layer	Depth (km)	*P* velocity (km/sec)
1	0 to 0.65	2.8
2	0.65 to 20	6.15
3	20 to 28	7.0
4	below 28	7.8

It was further assumed that the ratio of *P* velocity to *S* velocity is constant and has a value of 1.70. This value corresponds to a Poisson's ratio of 0.23, a reasonable value for the crystalline rocks that occur near the surface at Lake Mead (Rogers and Gallanthine, 1974, p. 21).

Stations corrections were determined using selected events chosen from preliminary locations of all the earthquakes. The epicentral area was divided into 1′ by 1′ areas. One event from each 1′ area was selected on the basis of best solution quality and impulsiveness of the seismic arrivals. A total of 51 earthquakes were selected and then relocated, using the adopted model, to determine average station residuals. The 51 events were again relocated using the average station residuals as corrections; the resulting values for the second set of station residuals were added to the values for the first set to obtain the final station corrections. These values are shown in Table 2.

The method used for estimating the earthquake magnitude follows that of Lee *et al.* (1972), in which the magnitude is based on the average magnitudes estimated at various stations. Local magnitude (M) is derived from the recorded signal duration (τ) using

$$M = -0.87 + 2.00 \log_{10} \tau + 0.0035\Delta, \tag{1}$$

where Δ is the epicentral distance in kilometers. The signal duration is defined as the duration time in seconds from the onset of the first *P* arrival to the point where the trace amplitude (peak to peak) falls below 1 cm as it appears on the Geotech film viewer ($\times 20$ magnification).

For earthquakes during the first period, originally processed by Rogers and Gallanthine (1974), the signal durations were measured on the magnetic-tape playbacks. Lee and Matamoros (1975) have made a test for some 20 earthquakes where both film and playback existed. Signal durations were measured from both, and their values were found to agree within ± 20 per cent for the same earthquake, corresponding units of ± 0.2 magnitude. Signal durations measured from 16-mm films and magnetic-tape playbacks, therefore, give similar earthquake magnitudes. Consequently, magnitudes for all earthquakes studied were computed using equation (1).

A total of 678 earthquake locations and magnitudes were determined using these procedures. Focal parameters of all the events are listed in Table 2 of Lee and Matamoros (1975).

Results

Figure 4 is an epicenter map for all located events that occurred at Lake Mead during the $1\frac{1}{2}$-yr monitoring period. The standard error in the epicentral location and depth cannot be estimated if less than 5 stations are operating; however, for those events where the errors could be estimated (76 per cent of the events), the standard error in the epicenter and depth are approximately 0.7 and 1.6 km, respectively. Although there is considerable scatter, many of the events can be associated with mapped faults. In particular, epicenter

lineations clearly indicate activity on portions of steeply dipping faults on the east side of Boulder Basin (Fortification and Indian Canyon faults) where the faults intersect the northeast shore. Small clusters of earthquakes which have depths of about 5 km and which

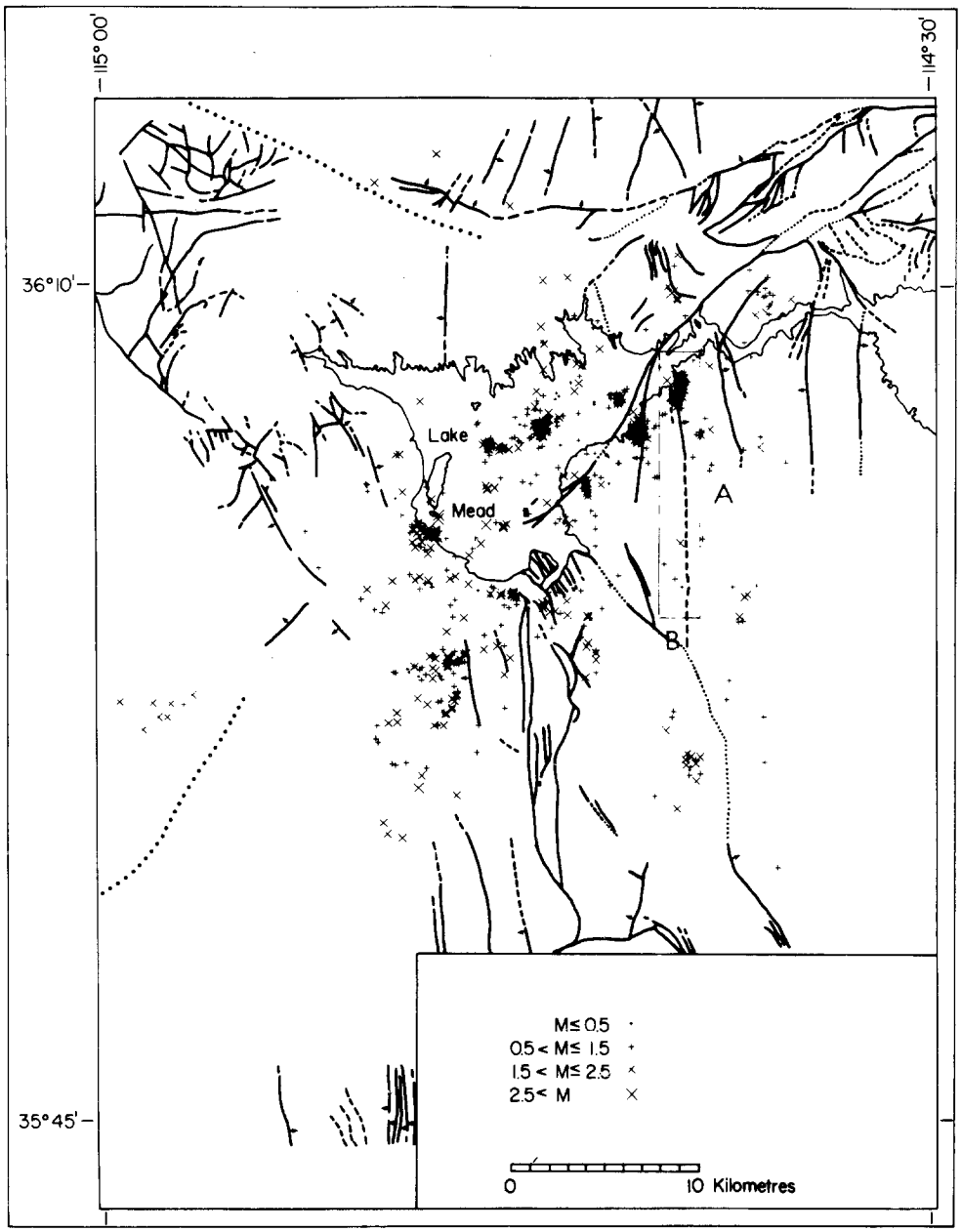

FIG. 4. Epicenter map showing all located events. Vertical sections A and B are shown in Figure 5.

occur northwest of Mead Slope fault may be associated with that fault, although the events are displaced in the wrong direction, given the surface dip that is mapped to the southwest. Alternatively, this group may occur on a hidden fault striking southwest across the center of the lake, where two other clusters of events occur. This lineation also

coincides with a portion of the stream channel before the lake was filled, suggesting that the channel may have been fault-controlled. If the Hamblin Bay fault is not truncated near the northeast corner of the basin, projection of the fault to the southwest would pass through the groups in the center of the lake, the activity south of Saddle Island, and the isolated cluster farther southwest. Association of these groups as a single trend is speculative, however, due to the lack of clear continuity of events. Some faulting evidence

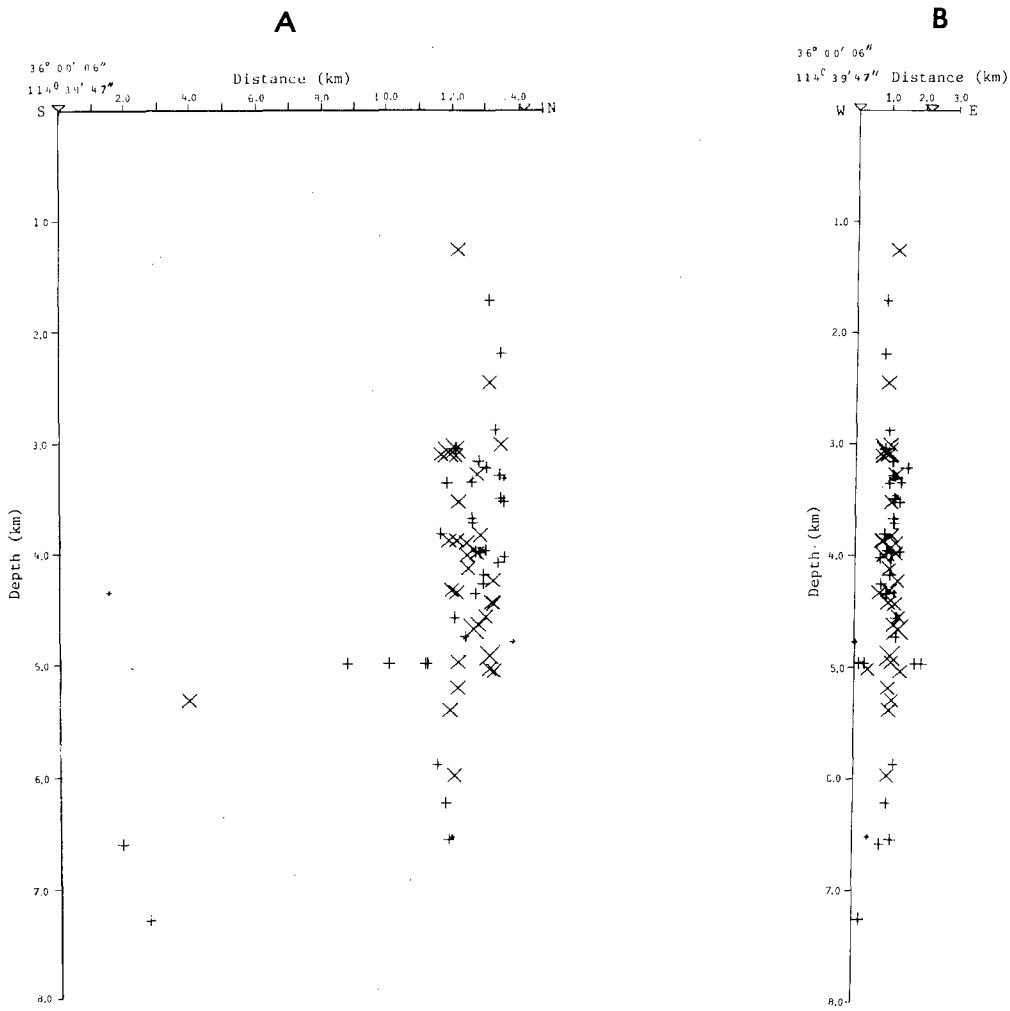

FIG. 5. Vertical section showing activity on the northern portion of the Indian Canyon fault. Symbols are as shown in Figure 4.

for extension of the Hamblin Bay lineation has been found recently and appears in the map compiled by Stewart and Carlson (1974) (not shown in Figures 3 and 4).

Figure 5 shows typical orthogonal vertical sections through the activity on the northern portion of the Indian Canyon fault. The depth of the events is less than 8 km, although the depth of all events ranges from a few tenths of a kilometer to 12 km. The events are highly clustered spatially, occurring on a narrow portion of the fault in an essentially vertical plane. Many of the clusters occur in short time intervals, exhibiting swarm characteristics.

Number of events, lake level, and per cent of stations operating are plotted versus time

as shown in Figure 6. Each quantity has been averaged over a 10-day interval. The average number of stations operating is computed by multiplying the number of stations operating by the number of days they operated in a 10-day interval, summing, and dividing by 10. There is an an apparent positive correlation between the number of events and lake level in Figure 6; however, the data are contaminated by the number of stations operating. When the stations operating are high, greater numbers of events are detected. Fewer stations were operating in the first 6 months relative to the remainder of the period, when the lake level had risen 7 per cent (a 20 per cent increase in lake load). Thus, although an apparently significant correlation of 0.48 can be calculated between number of events and lake level, and the test of the hypothesis that the correlation coefficient is zero can be rejected at the 1 per cent significance level (Crow *et al.*, 1960, p. 159), a lower correlation coefficient would be obtained if the data could be corrected for the number of stations

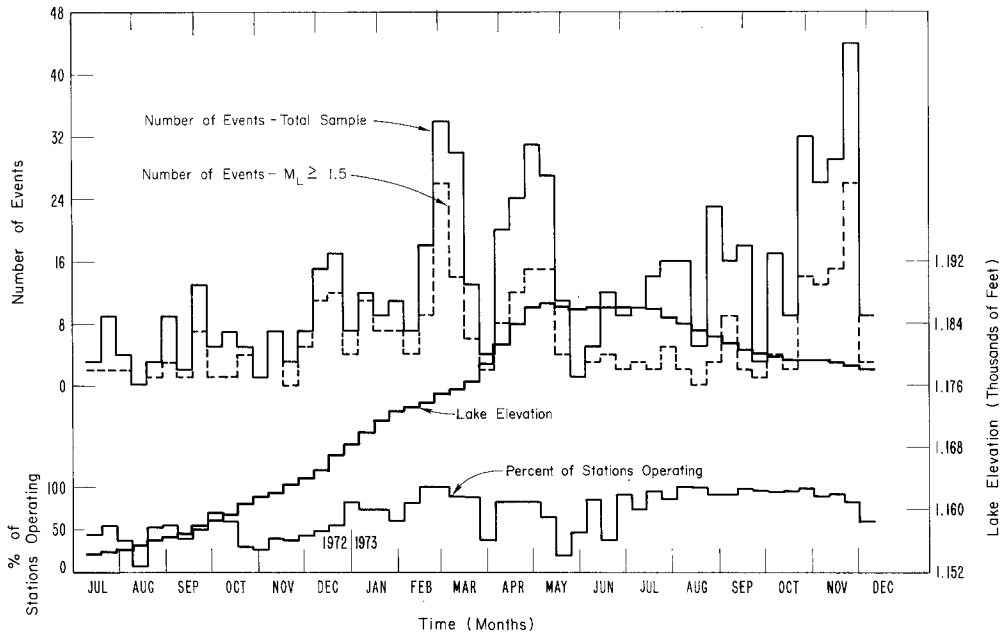

FIG. 6. Number of events, lake level, and per cent of stations operating versus time. Quantities are averaged over 10-day intervals.

operating. The station effect is also reflected in the comparison of the total sample with the occurrence of events larger than $M_L \geqq 1.5$ which shows a disproportionate decrease in the number of events in the second half of the period relative to the period in 1972 and early 1973 (Figure 6). Is it possible, then, to distinguish lake-level effects from station-operation effects in these data? To answer this question it is necessary to discuss the effects that might result in each situation individually.

We expect that changes in the number of stations operating will have little or no effect above a certain threshold magnitude, if we are only detecting events. Ideally, we also expect no effect on the number of located events for events above the threshold magnitude if at least three well-placed stations are working. Practically, however, for periods when only three stations are operating one might expect a small decrease in the number of located events above the threshold magnitude depending on the stations involved. Below the threshold, we would expect large decreases in the number of located events as the number of stations operating decreased. In comparing the recurrence curves for a period

of high station operation (HSO) versus a period of lower station operation (LSO), we would expect that above the threshold magnitude the recurrence curves would have approximately the same slope, although the HSO curve might lie slightly above the LSO curve. Below the threshold, however, the HSO curve should show much higher levels of activity.

On the other hand, we would expect periods of high lake level (HLL) to produce different effects on the number of events occurring and the recurrence curves relative to periods of low lake level (LLL). For reasons discussed below, one might expect HLL to increase activity at all magnitudes and to increase the b value relative to LLL. These effects should be distinguishable from those of station operation effects. The frequency of recurrence curves for periods of high average station operation (after February 25, 1973) and lower average station operation (before February 25, 1975) are shown in Figure 7. These curves seem to reflect the type of results one would expect for HSO and LSO because there is no change in the recurrence line fit for $M_L \geqq 1.6$. Tests of the hypotheses

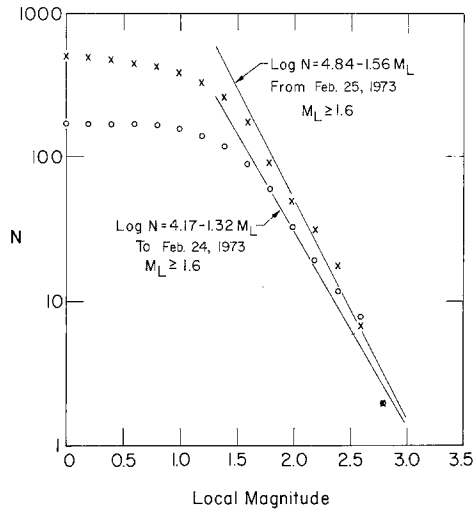

FIG. 7. Frequency of recurrence for the first and last half of the monitoring period. X-symbols indicate the last half-period and O-symbols indicate the first half-period. The lines are least-squares fits to the data in each interval. N indicates the cumulative number of events.

that the slopes and intercepts of the two lines are equal cannot be rejected at the 5 per cent significance level (Wine, 1964). The probability value, that is, the probability that the difference in the b values is as large as observed, assuming that the difference is zero, is 0.66 (Wonnacott and Wonnacott, 1972, pp. 189–191). In conclusion, if lake level has affected the seismic rates during this monitoring period the effects are smaller than the station operation effects and cannot be distinguished from them.

The frequency of recurrence relation for the entire period is

$$\log_{10} N = 4.84 - 1.45 M_L \qquad M_L \geqq 1.6. \quad (2)$$

The b value is currently higher than in any previous monitoring period. Jones' (1944) data can be used to derive a b value for 1942 to 1943 of 1.2 for events ranging from magnitude 2 to 4. Carder (1970) found b values for 1950, 1951, and 1952 of 1.0, 0.73, and 0.85 (estimated from Carder's Figure 5), respectively, for events ranging from magnitude 0 to 2.5. Comparison of these and current values implies an increasing proportion of small-to-large events. The decrease in average energy release supports this change. In the period 1938 to

1950, the mean energy release, computed from

$$\bar{E} = 10 \exp(\Sigma_i \log_{10} E_i/N), \tag{3}$$

averaged 4.3×10^{15} ergs/10 days (Carder, 1970, Figure 2) compared with 6.3×10^{13} ergs/10 days (Figure 8) in the period covered by this study. These two values are not directly comparable because Carder (1970) used the magnitude energy relation

$$\log_{10} E = 11.8 + 1.5M \tag{4a}$$

whereas in this study we have used (Richter, 1958)

$$\log_{10} E = 9.9 + 1.9M_L - 0.024M_L^2. \tag{4b}$$

Carder's value can be compared with the average energy release given here by correcting his value for the difference in formulas used. The corrected value is

$$\log_{10} \bar{E} = \log_{10} [4.3 \times 10^{15} \text{ ergs/10 days}] - 0.9$$
$$= 14.733$$
$$\bar{E} = 5.4 \times 10^{14} \text{ ergs/10 days}$$

where 0.9 is the difference between (4a) and (4b) for $M = 3.0$. Assuming the logarithm of the mean energy release is normally distributed, the hypothesis that the corrected mean 10-day energy release in Carder's study equals that in this study can be rejected at the 0.1 per cent significance level (Crow *et al.*, 1960, p. 53). Comparison of the energy release calculated from Table 1 for the 17-yr period 1936 to 1952

$$\bar{E} = 7.9 \times 10^{16} \text{ ergs/10 days}$$

or the most recent 23-yr period, 1953 to 1975

$$\bar{E} = 9.0 \times 10^{15} \text{ ergs/10 days}$$

with the 1972 to 1973 monitoring period shows a continuing decline in energy release in the last $3\frac{1}{2}$ decades. Poor detection of events in past years due to sparse instrumentation would act to make the apparent energy difference smaller than it actually is. Furthermore, the decline in felt events supports the energy decrease. In the interval 1938 to 1950, 5 to 10 felt events occurred per month (Carder, 1970), whereas in the interval 1965 to 1975, only one felt event occurred on December 25, 1973 (local date).

Figure 8 also shows that there is no correlation between the logarithm of the energy release and lake level. Correlation of $\log_{10} E$ with lake level yields $r = 0.25$. The hypothesis that this value is zero cannot be rejected at the 5 per cent significance level. Thus, the largest events are considered to be occurring independently of lake level.

Figure 9 shows the seismicity in the southern Nevada region for a 2-yr period encompassing the Lake Mead monitoring (King, 1974). This map indicates that seismicity in the vicinity of the lake is no greater than in some of the surrounding areas. There are no events occurring in Virgin Basin, and few events occur anywhere east of Boulder Basin. There are some exceptions; for instance, the events at the north tip of Overton Arm and one event in Griggs Basin mark areas that Carder (1970) also found to be active. At least one area of activity on this map may be related to mining activities; namely, the events shown 30 km north-northwest of Boulder Basin, which occur near the site of a lime mine engaged in blasting. Explosions are unlikely within the array, because it is located within a national recreation area.

Anderson (1973a) has attributed the low seismicity in the Virgin Basin area to the

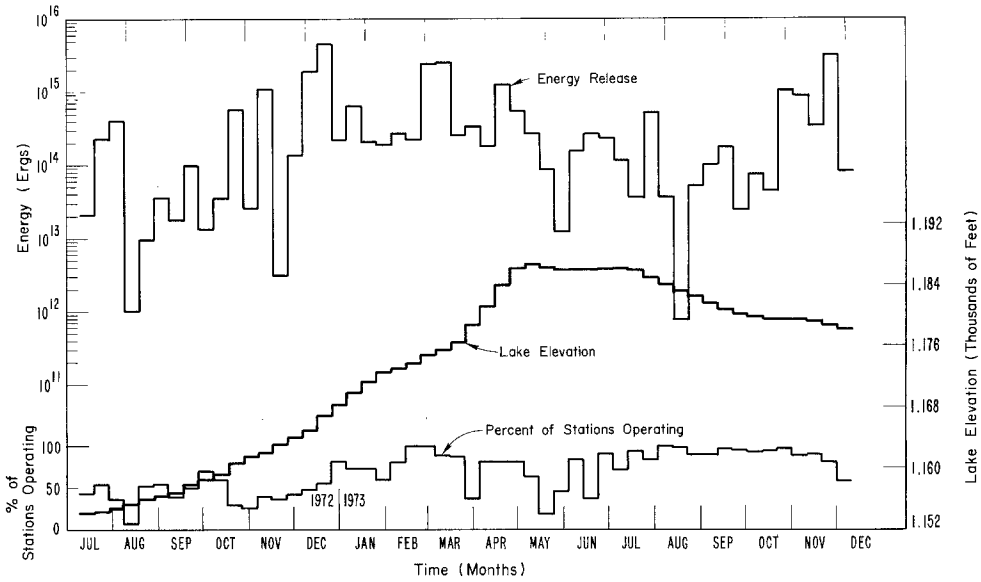

FIG. 8. Energy release, lake level, and per cent of stations operating versus time.

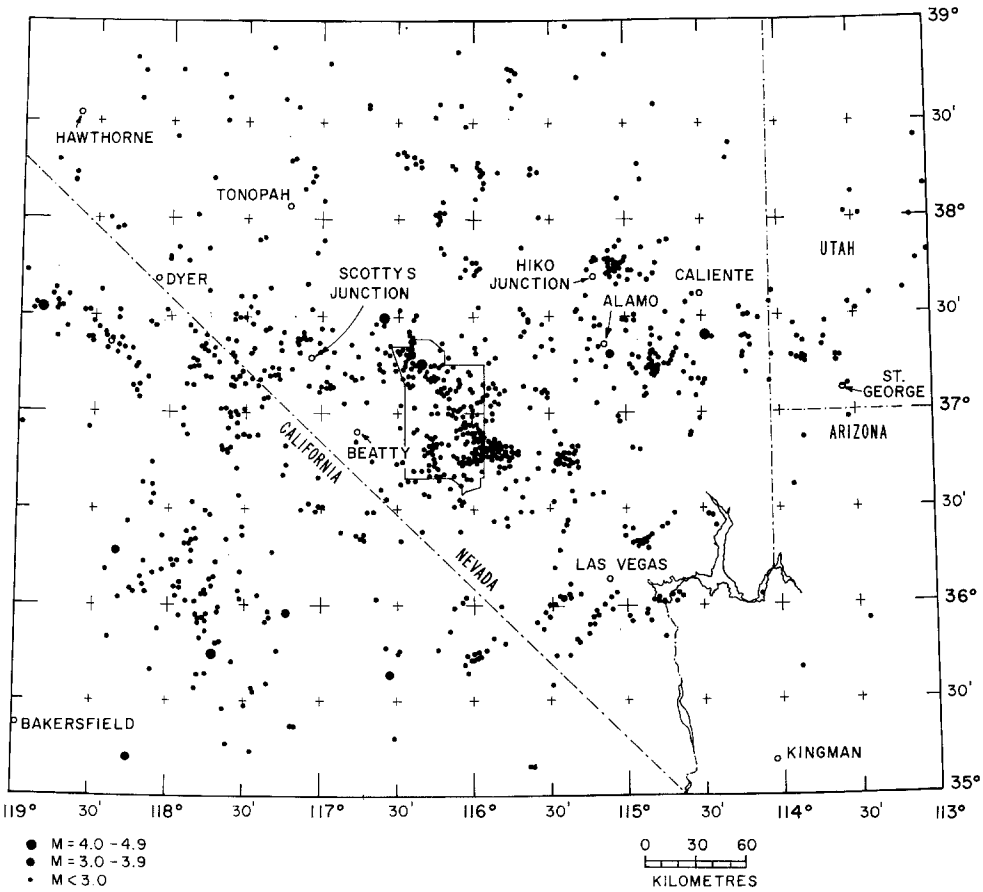

FIG. 9. Seismicity of southern Nevada from December 22, 1971, through June 1973. These events were located by the U.S. Geological Survey, Las Vegas office, using data from the Southern Nevada and Sandia seismic network (K. W. King, written communication).

presence of thick salt deposits. These deposits might form a barrier to penetration of water into the fractured basement rock, thereby preserving the strength of the rock.

Focal Mechanism

In the standard analysis of the Lake Mead seismic data, the program HYPO71 (Lee and Lahr, 1972) also gave plots of first motions of *P* arrivals on an equal-area projection of the lower focal hemisphere. We examined over 200 such plots and attempted fault-plane solutions whenever possible. Because we had only eight or nine seismograph stations, it was not possible to obtain unique fault-plane solutions for many of these earthquakes. However, we attempted to select events in seven subregions to represent some typical fault-plane solutions. Whenever individual fault-plane solutions were not possible, solutions were attempted based on composite plots of first motions from several earthquakes that occurred closely in space and time. The results are summarized in Table

TABLE 3

Summary of Fault-Plane Solutions

Sub-Region		Date	N	Hypocenter Coordinates			Fault-plane Solutions		Alternative Fault-Plane Solution	
				Lat (N)	Long (W)	Depth (Km)	S_1	S_2	S_3	S_4
R1	a	10/5/73 to 10/9/73	5	36°7.2'	114°39.0'	3.4	α=N4°E δ=90°	α=N86°W δ=90°		
	b	11/28/73	5	36°6.6'	114°39.2'	4.1	α=N3°E δ=90°	α=N87°W δ=90°		
R2	a	10/30/73	5	36°5.6'	114°40.7'	6.4	α=N4°E δ=90°	α=N86°W δ=90°		
	b	11/20/73 to 11/21/73	6	36°5.6'	114°40.7'	6.2	α=N4°E δ=90°	α=N86°W δ=90°		
R3	a	5/1/73 (00:15)	1	36°4.0'	114°42.5'	6.5	α=N12°W δ=90°	α=N78°E δ=90°		
	b	5/2/73 (22:14)	1	36°4.0'	114°42.5'	6.7	α=N10°W δ=90°	α=N80°E δ=90°		
R4	a	3/5/73 (09:24)	1	36°5.7'	114°44.1'	5.3	α=N59°E δ=40°NW	α=N59°E δ=50°SE	α=N9°E δ=90°	α=N81°W δ=90°
	b	3/11/73 (05:37)	1	36°5.8'	114°44.1'	5.3	α=N59°E δ=40°NW	α=N59°E δ=50°SE	α=N8°E δ=90°	α=N82°W δ=90°
R5	a	5/4/73 (02:01)	1	36°5.2'	114°46.0'	3.4	α=N53°E δ=40°NW	α=N53°E δ=50°SE	α=N1°E δ=90°	α=N89°W δ=90°
	b	5/7/73 to 5/8/73	3	36°5.2'	114°46.0'	4.2	α=N50°E δ=40°NW	α=N50°E δ=50°SE	α=N1°E δ=90°	α=N89°W δ=90°
R6		5/7/73 (18:54)	1	36°0.8'	114°45.1'	3.5	α=N8°E δ=90°	α=N82°W δ=90°		
R7		12/9/72 (06:46)	1	36°2.5'	114°48.1'	3.1	α=N52°E δ=20°NW	α=N52°E δ=70°SE		

*N is the number of earthquakes used in composite first-motion plots; α is the strike of fault plane; δ is the dip of fault plane.

3. Figure 10 illustrates 12 fault-plane solutions corresponding to Table 3. For subregions 1, 2, 3, 4, and 5, we have presented two first-motion plots each to show that the solutions are similar. Results shown in Figure 10 are summarized in Figure 11.

Fault-plane solutions for earthquakes along the Indian Canyon (R1) and Fortification (R2) faults indicate right-lateral, strike-slip motions with north-south strike similar to that of the mentioned faults. Fault-plane solutions for two earthquakes near the Mead Slope fault (R3) indicate either north-south, right-lateral, strike-slip motions or east-west, left-lateral, strike-slip motions. In either case, the strike does not agree with that of the Mead

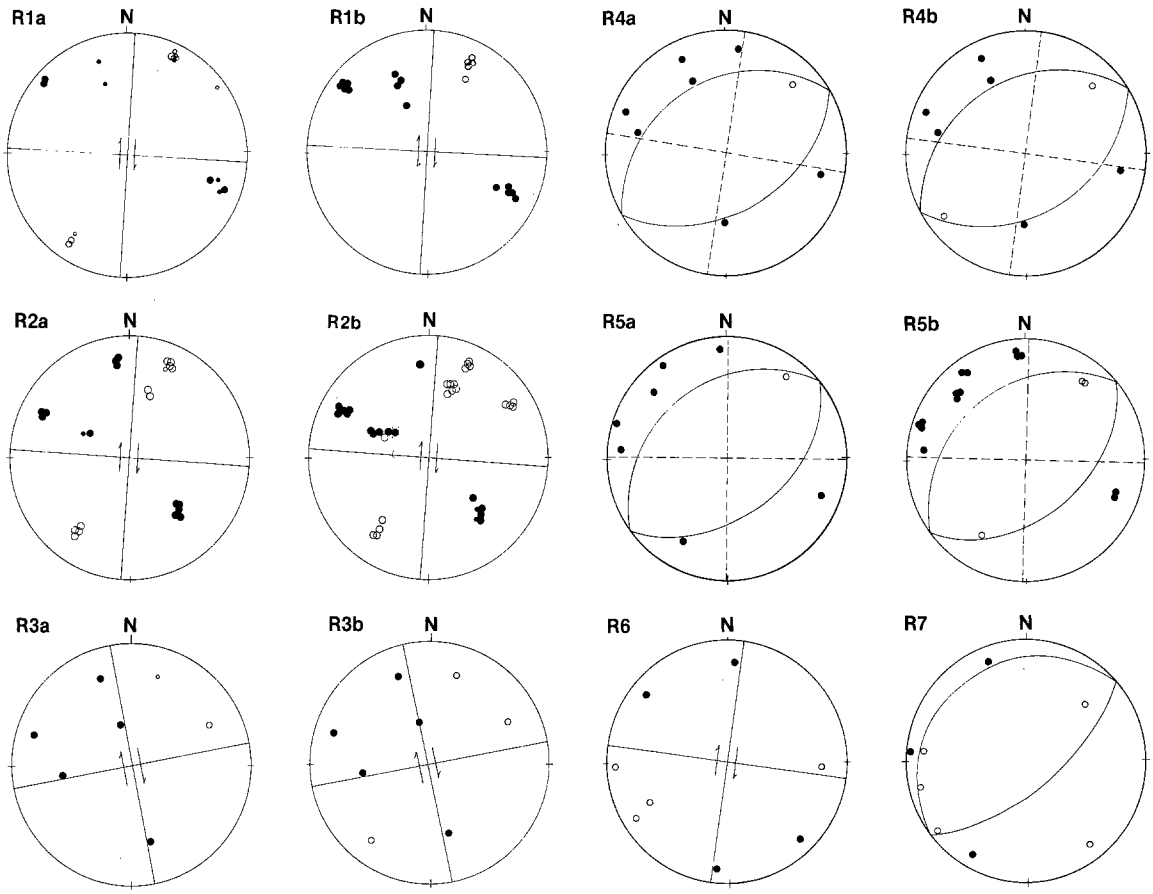

FIG. 10. Fault-plane solutions constructed from first-motion of *P* arrivals. Diagrams are equal-area projections of the lower focal hemisphere. Solid circles indicate compression; open circles, dilatation. Small circles (either open or solid) indicate poorer quality of *P* arrivals. Letter and number coding indicates events from particular regions shown in Table 3, and Figure 1.

Slope fault, although the north-south solution does agree with the short north-south lineation of epicenters there, suggesting that the events fall on an unmapped fault. Fault-plane solutions (R6) for one earthquake along the Jeep Pass fault indicate north-south, right-lateral, strike-slip motions with strike similar to that of the fault.

Fault-plane solutions for earthquakes in the Boulder Basin (R4, R5) indicate slippage on either normal faults that strike northeast or strike-slip faults that strike north. We have selected the former case as more probable, because a fault-plane solution of an earthquake on the southwestern edge of the Boulder Basin (R7) indicates normal faulting with

northeast strike. This strike would be consistent with an extension of the Hamblin Bay fault, as suggested by Anderson (1973b).

In summary, most earthquakes in the Lake Mead area have fault-plane solutions that support right-lateral, strike-slip motions along nearly vertical faults striking north-south. However, for some earthquakes, normal faulting striking northeast along fault planes dipping about 45° is also possible. Although our results suggest a stress pattern similar to that of the broader Nevada area, the lack of sufficiently large numbers of seismograph stations preclude us from making definitive focal-mechanism solutions.

Discussion

These data suggest a tectonic source for Lake Mead seismicity and raise some doubt as to whether a relation exists between Lake Mead and local earthquakes. Examination of

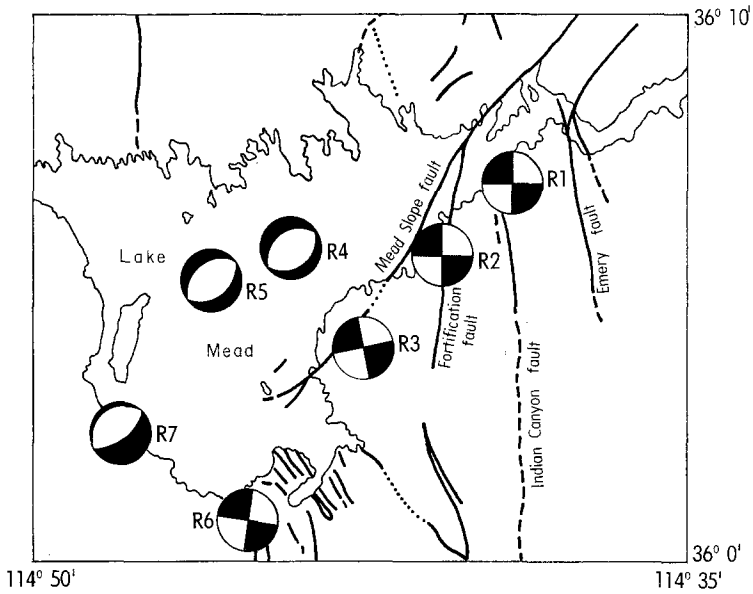

FIG. 11. Map showing fault-plane solutions derived from Figure 10. Black quadrant denotes compression; white quadrant, dilatation.

the seismic history of the reservoir, however, produces strong evidence for a causal relationship. During the period 1932 to 1936, the *Las Vegas Review Journal* reported several felt shocks due to earthquakes in California, northern Nevada, and Imperial Valley, Mexico. In the 1932 description of the Cedar Mountain, Nevada, shock the newspaper stated (*Las Vegas Review Journal*, December 21, 1932) that this event was "Las Vegas first earthquake in somewhat over fifteen years." Presumably this reference is to the Pleasant Valley, Nevada, event of 1915. On the average, one Lake Mead event was felt in Las Vegas every 4 to 5 years during the period 1936 to 1964 (Table 1), after the reservoir was filled. Thus, although it appears that tectonic stresses are responsible for current activity, one must contend with evidence that felt earthquakes were uncommon in the region prior to the filling of the reservoir.

Past hypotheses that the weight of the lake and resulting subsidence were causing earthquakes appear unlikely in light of faulting mechanics and reservoir-induced stresses. The shear strength of a vertical fault in a homogeneous half-space is

$$\tau = \tau_0 + \mu g \rho z \gamma / (1 - \gamma), \tag{5}$$

where

μ = coefficient of friction,
g = acceleration of gravity,
ρ = rock density,
z = depth,
γ = Poisson's ratio,
τ_0 = cohesive strength

(Gough and Gough, 1970b). Neglecting τ_0 and assuming $\mu = 0.5$, $g = 980\,\mathrm{cm/sec^2}$, $\rho = 2.7\,\mathrm{gm/cm^3}$, and $\gamma = 0.25$, the shear strength at 2-km depth is about 90 bars. Vertical shear stresses induced by the weight of the lake are on the order of 1 bar near the surface and decrease with depth (Gough and Gough, 1970a). These stresses are too small, therefore, to cause earthquakes, although existing tectonic stress might be triggered by these small additional stresses.

The geodetic data shown in Figure 12 (Lara and Sanders, 1970) indicate subsidence in the immediate vicinity of the reservoir that is probably due to the added lake load. Subsidence near Las Vegas is due to ground-water withdrawal (Mindling, 1971). Comparison of these data with predictions of Westergaard and Adkins' (1934) (also Carder and Small, 1948 or Raphael, 1954) elastic-compression model, described previously, indicates good agreement. At least the greatest portion of these elevation changes, therefore, are probably unrelated to fault movement.

Most of the "elastic" elevation changes can be removed to reveal other trends. Because the greatest subsidence occurred before 1949, effective removal of these displacements is achieved by considering the interval from 1949 to 1963, shown in Figure 13. Some subsidence continued to occur in that interval and is probably due to the increasing sediment load; at some basin locations sediments from 15 to 30 m thick have accumulated. In addition to the uplift and tilt to the north, there are four areas of anomalous localized movement. Pockets of relative subsidence occur between Las Vegas and Moapa and near Cane Springs. A small area of relative subsidence also occurs southwest of Boulder Basin, and an area of uplift occurs northeast of this basin. Although these localized movements may have been related to faulting, the preponderance of elevation changes appear to be due to lake subsidence and regional uplift. The strike-slip focal mechanisms observed for the current seismicity tend to support this argument. If the subsidence or uplift in these two pockets of anomalous movement closest to Lake Mead are considered to be about 20 cm, the displacements could be related to two magnitude 4.0 earthquakes (Bonilla and Buchanan, 1970).

Rising pore pressure and consequent decreasing rock strength have been postulated as the cause of reservoir seismicity at other locales (Raleigh and Healy, 1973). That is, earthquakes are triggered when pore pressures reduce the effective normal stresses on existing fractures and the shear strength of the rock is reduced. If the tectonic shear stress on the fracture is near the rock strength, a small reduction in effective normal stress can trigger slip. Given this model, one might explain the decreasing energy release since the late 1930's as due to a decrease in elastic-energy density of the rock. The addition of the lake may have gradually raised the pore pressure in the rock under the reservoir by as much as 19 bars (assuming an increase in the height of the water table of 200 m), depending on the depth to the original water table. The resulting weakening of the rock lowered the tectonic stress that it was capable of sustaining, and the excess stored stress was relieved by a temporary increase in the rate of fault movement.

Support for this hypothesis is obtained by a check of the order of magnitude of the

expected and observed energy release. The shear strength on a vertical fault in a porous permeable, water-saturated half-space is given by (Gough and Gough, 1970b)

$$\tau_1 = \tau_0 + \mu g(\rho - \rho_\omega) z\gamma/(1-\gamma), \tag{6}$$

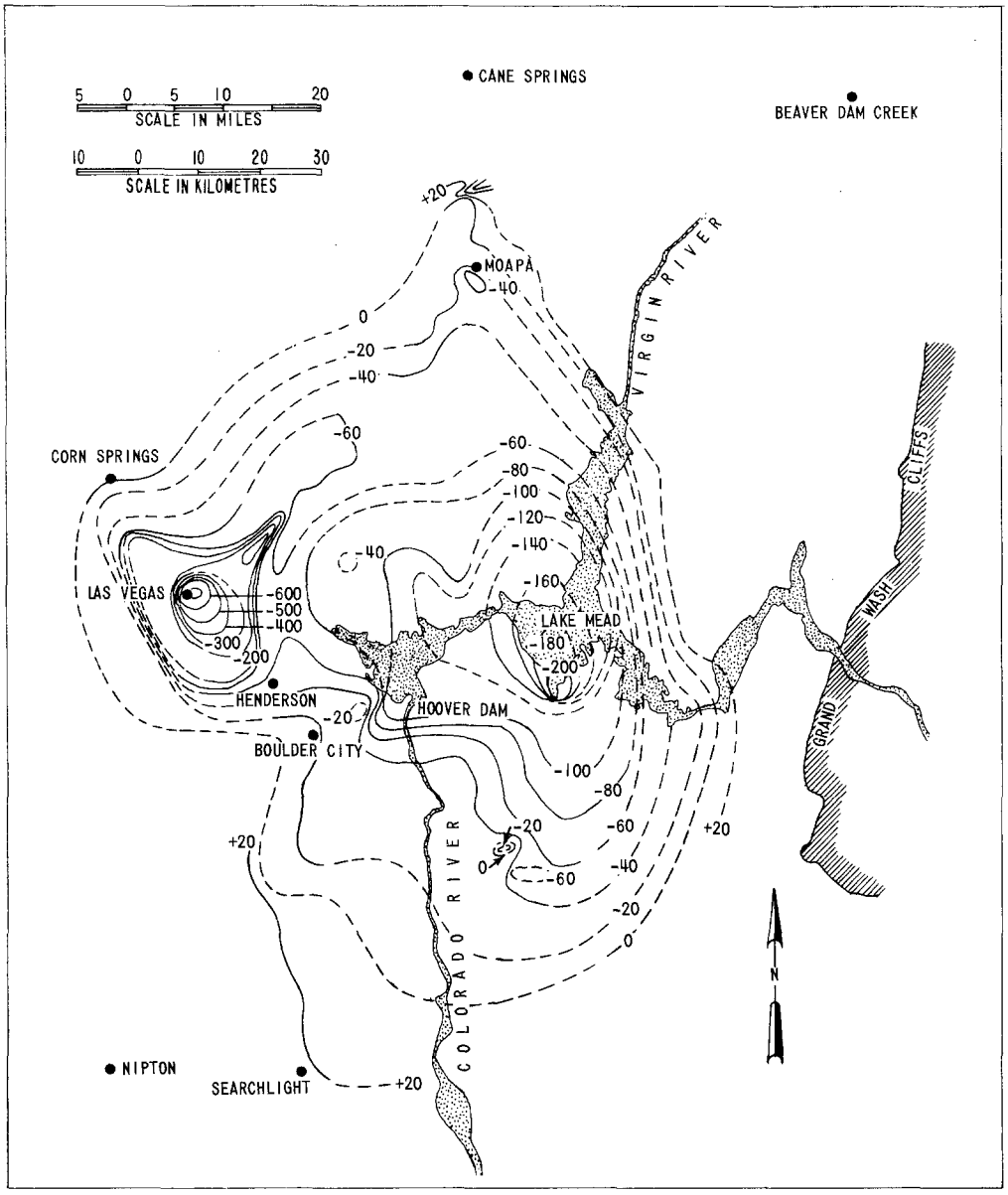

FIG. 12. Contours showing changes in elevation relative to Cane Springs in the interval 1935 to 1963–64. Contours are in millimeters. (Modified from Lara and Sanders 1970.)

with notation as in equation (5) and ρ_ω equal to the density of water. Assuming that the addition of the lake can be represented by a uniform water load of depth h distributed over the half-space, the rock strength becomes

$$\tau_2 = \tau_0 + \mu g(\rho - \rho_\omega) z\gamma/(1-\gamma) + \mu g \rho_\omega h\gamma/(1-\gamma) - \mu g \rho_\omega h. \tag{7}$$

The third term represents the increase in strength caused by the weight of the lake and increased normal stress on the fault. The fourth term is the increase in pore pressure due to the effective raising of the water table. Neglecting the finite extent of the lake boundaries causes the third term to be overestimated, but it would also require a fifth and, probably, a

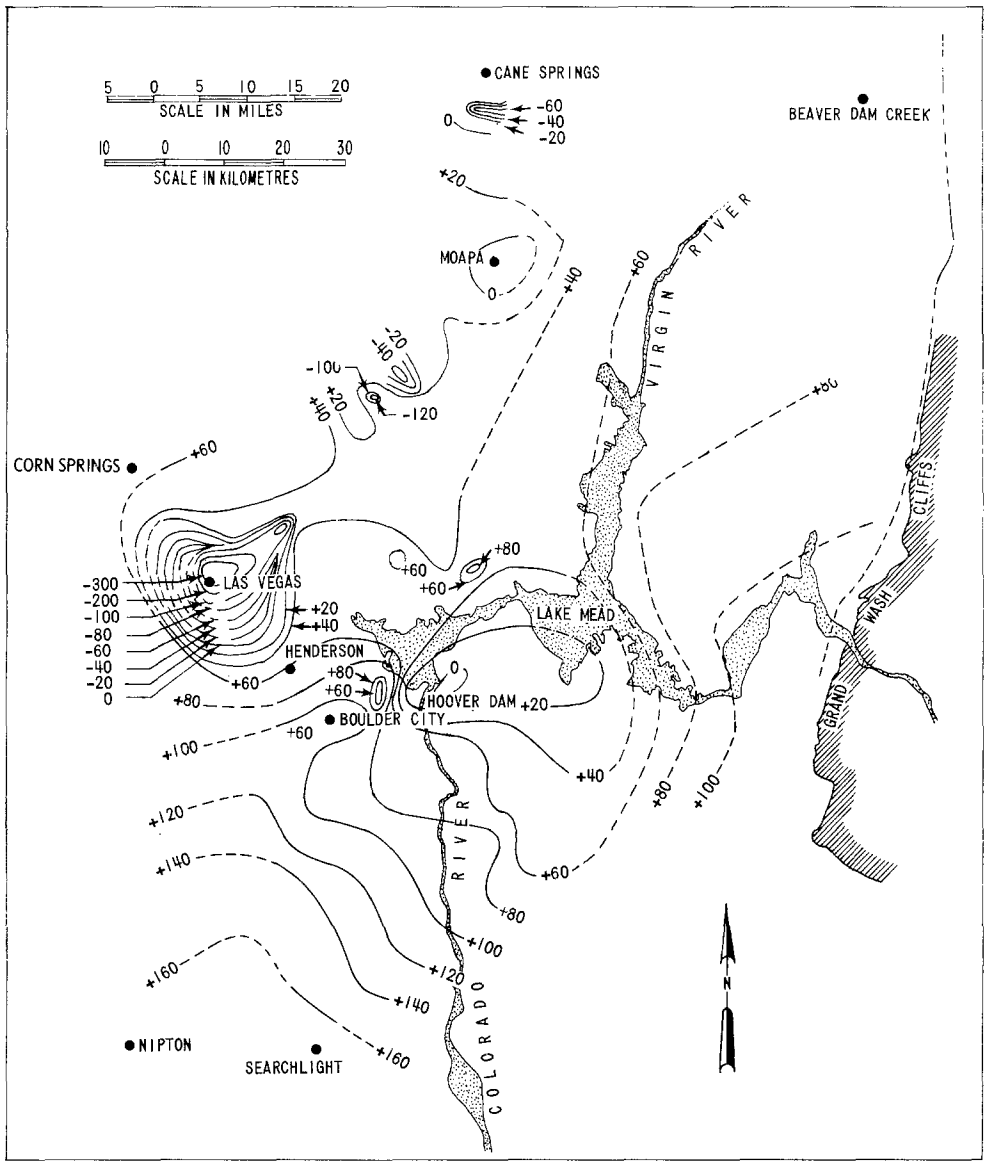

FIG. 13. Contours showing changes in elevation relative to Cane Springs in the interval 1949 to 1963–64. Contours are in millimeters. (Modified from Lara and Sanders, 1970.)

somewhat offsetting factor. That is, the lake load would also contribute an increase in shear stress on the fault. Although highly variable spatially, the maximum shear stress is probably less than 1 bar (Gough and Gough, 1970a). The change in shear strength is

$$\begin{aligned}\Delta S = \tau_2 - \tau_1 &= -g\rho_\omega h\mu(1-2\gamma)/(1-\gamma)\\ &= -3.0 \text{ bars,}\end{aligned} \tag{8}$$

assuming the same values previously used and a mean increase in the height of the water table of 90 m. If the assumed increase in the height of the water table is 200 m, $\Delta S = 6.5$ bars. If the decrease in rock strength was relieved seismically, the energy release can be computed from (Bullen, 1963)

$$\Delta E = V(\Delta S)^2/4G \tag{9}$$

where G is the shear modulus and V is the volume of the source. If the volume of the current seismicity is representative of the volume in which the energy for the eight largest events was stored ($M_L = 5.0$), a parallelopiped $10 \times 30 \times 10\,\mathrm{km}^3$ (area × depth) is appropriate. Letting $G = 3 \times 10^{11}$ dynes/cm^2, ΔE varies from 0.22×10^{20} to 1.0×10^{20} ergs. These values are the same order of magnitude as the seismic energy release of 0.50×10^{20} ergs, calculated from (4b) for eight events. The difference might be accounted for by less than hydrostatic pore pressure throughout the volume, a reasonable supposition for Lake Mead igneous rocks. Aseismic slip or an incomplete list of magnitude 5 events might also account for part of the difference.

Currently one would expect a higher proportion of small to large events (higher b value) because the level of stress the rock is capable of sustaining is lower (Scholz, 1968), but also because a number of quiescent faults have been reactivated and stress can be relieved on these additional faults by small events before it builds up over a large area and is released in a single large event. The period over which the b values have increased may be a measure of the rate of pore-pressure buildup at depth, indicating a duration of several decades. The lack of correlation between lake level and number of events can be explained by this time lag. Furthermore, stresses are probably currently being released in a manner that is more dependent on tectonic-stress buildup than on changes in pore pressure (~ 1 bar) due to fluctuating lake level.

The localization of events at Lake Mead and the pre-impoundment absence of seismicity imply a cause-and-effect relationship. Examination of the data in terms of a pore-pressure model and the triggering of existing tectonic stresses seem to support the model.

Conclusions

The following results concerning Lake Mead seismicity have been obtained:

1. The earthquakes are localized to the vicinity of Boulder Basin, in agreement with Carder's previous work, with the largest clusters of events occurring beneath the lake or within 5 km of the lake boundaries.
2. Two groups of events are clearly associated with steeply dipping mapped faults on the east side of the basin, striking approximately north-south.
3. The majority of events occur at depths of less than 8 km.
4. Neither number of events nor energy release correlated with the 7 per cent increase in lake level. Carder's previous work suggested that the correlation of number of events with lake level was decreasing with time.
5. A b value of 1.45, higher than previously observed at Lake Mead, was obtained.
6. Focal mechanisms with predominantly right-lateral strike-slip on nearly vertical fault planes striking approximately north were obtained. Some events in the middle and southwest portions of Boulder Basin are ambiguous, permitting this strike-slip solution or normal faulting on a northeast-striking fault.
7. Re-examination of geodetic data indicates that only a small portion of the total vertical motions are probably attributable to faulting. The geodetic data are thus in agreement with the focal mechanisms.

8. Re-examination of the historical record shows a significant increase in seismicity after Lake Mead was impounded.

9. Present seismicity at Lake Mead is comparable to that of the surrounding area and has declined significantly since the 1940's.

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U.S. Geological Survey
Box 25046, Denver Federal Center
Denver, Colorado 80225

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