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PROBABLE EARTHQUAKE GROUND MOTION AS RELATED TO STRUCTURAL RESPONSE IN LAS VEGAS, NEVADA

December 1980

prepared for
United States Department of Energy
Nevada Operations Office
Under Contract DE-AC08-76DP00099

prepared by
URS/John A. Blume & Associates, Engineers
130 Jessie Street (at New Montgomery)
San Francisco, California 94105

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Roger W. Greensfelder
Frederick C. Kintzer
and
Malcolm R. Somerville

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ABSTRACT

Ground motion parameters are necessary for structural damage assessments and dynamic effects prediction in Las Vegas, Nevada. To develop these, a model of tectonic activity in the southern Basin and Range province was constructed on the basis of late Cenozoic patterns of crustal deformation, estimates of regional strain rates in Holocene time, and historic seismicity. From this information, the region surrounding Las Vegas was subdivided into six seismotectonic zones. Historic seismicity was analyzed on the basis of seismographically recorded earthquakes and compared with long-term seismotectonic activity. Apparent agreement between the two sets of data indicates that the average rates of historic seismicity observed in the areas analyzed are reasonably representative of long-term seismicity.

Magnitude-recurrence relationships were developed for each of the six seismotectonic zones, and probable maximum values of peak ground acceleration in Las Vegas were calculated using a computer program (HAZARD) developed for the study. Probable causative earthquake magnitudes in each source zone, probable values of duration of seismic shaking, and predominant periods likely to be associated with various peak accelerations were also determined.

Longer-period spectral motions important to dynamic engineering of high-rise structures may be much larger than those normally associated with peak ground motions. A review of reports on structural response in Las Vegas due to events at the Nevada Test Site of the U.S. Department of Energy showed that pseudo-relative ground velocities (PSRVs) are amplified considerably in the downtown area. Maximum probable response spectra can be generated for any site in Las Vegas by using an estimated dynamic amplification curve for a reference site.

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ACKNOWLEDGMENTS

This study was sponsored by the Nevada Operations Office of the U.S. Department of Energy as part of an ongoing study of the structural response characteristics of buildings in southern Nevada.

We wish to acknowledge the contributions of Roger E. Skjei, Andrew B. Cunningham, and Humberto T. Contreras, who critically reviewed the manuscript, and Richard Wunderman, who assisted in the compilation of geologic data.

1. INTRODUCTION

The purpose of the study reported here was to estimate the probabilities of earthquake ground motion in Las Vegas, Nevada. The probabilities of peak ground accelerations were derived by means of (1) estimates of long-term seismicity in seismotectonic zones established in this study and (2) statistical analysis of maximum probable peak ground accelerations, using an acceleration-magnitude-distance relationship also developed in this study. These probabilities are useful in predicting the structural response of the low-rise buildings in Las Vegas, an ongoing effort of URS/John A. Blume & Associates, Engineers (URS/Blume), under the sponsorship of the U.S. Department of Energy, Nevada Operations Office (DOE-NV).

Using published analyses of relative response-spectrum amplification among various sites in Las Vegas, this study shows how maximum probable peak accelerations can be used to estimate maximum probable spectral motions at these sites. These response-spectrum predictions will be useful in high-rise damage-prediction studies currently planned by URS/Blume under DOE/NV support.

Construction of a model of seismotectonic activity in the southern Basin and Range province was a major part of this analysis. Late Tertiary and Quaternary faulting styles and apparent relative tectonic activity in late Quaternary time were analyzed in order to assess relative long-term seismicity rates in various parts of the Basin and Range province. Consideration of pre-late-Cenozoic structure and tectonics is useful in defining those features that do not appear to have seismotectonic importance.

Historic seismicity was analyzed on the basis of seismographically recorded earthquakes and was compared with long-term seismotectonic activity. Apparent agreement between the two sets of data indicates that the observed average rates of historic seismicity in the areas analyzed are reasonably representative of long-term seismicity. Thus, it is reasonable to use the observed historic seismicity in probabilistic earthquake hazard prediction.

Probable maximum values of peak ground acceleration, and associated most-probable causative earthquake magnitudes, were calculated with the computer program HAZARD. This report presents the probable values of duration and predominant period that are associated with various peak accelerations.

2. GEOLOGIC OVERVIEW

The first step in the assessment of probable earthquake ground motion in Las Vegas was to examine the geology of the Basin and Range province and adjoining provinces to gain a long-term perspective of regional tectonism. Geologic background data that were developed for regional seismic zonation and evaluation of seismic response of Las Vegas Valley are presented in Appendix A.

The city of Las Vegas is located in the southern portion of the Great Basin physiographic province, which approximately coincides with the northern portion of the Basin and Range tectonic province (see Figure 1). This province is characterized by north-trending mountain ranges and valleys bounded by normal faults. A generalized tectonic map of the Las Vegas region is shown in Figure 2.

Recent faulting and seismic activity have been most pronounced along the western margin of the Great Basin as a combination of distributed right-lateral shear and normal faulting. However, in the rest of Nevada, mechanisms and rates of deformation are not as well understood. Analysis of geologic data and current seismicity suggests that the Garlock-Caliente trend shown in Figure 2 may be the tectonic feature most significant to seismic ground motion calculations for Las Vegas. This lineament coincides with a zone of left-lateral faulting and of contrasts in crustal properties and thickness between northern and southern Nevada.

It is clear that the Las Vegas area lies within a zone of transition between contrasting styles of tectonic behavior. To the west lies the belt of distributed right-lateral deformation between the Sierra Nevada front and the Death Valley — Furnace Creek fault system. In the Mojave Desert, to the southwest, deformation is dominantly right-lateral along northwest-trending faults. This appears to represent a regional right-lateral shear system. To the east of Las Vegas lies the relatively thick, stable Colorado Plateau, bounded by young normal faults. To the north lies the Basin and Range tectonic province of central Nevada, in which generally east-west extension of the crust is occurring.

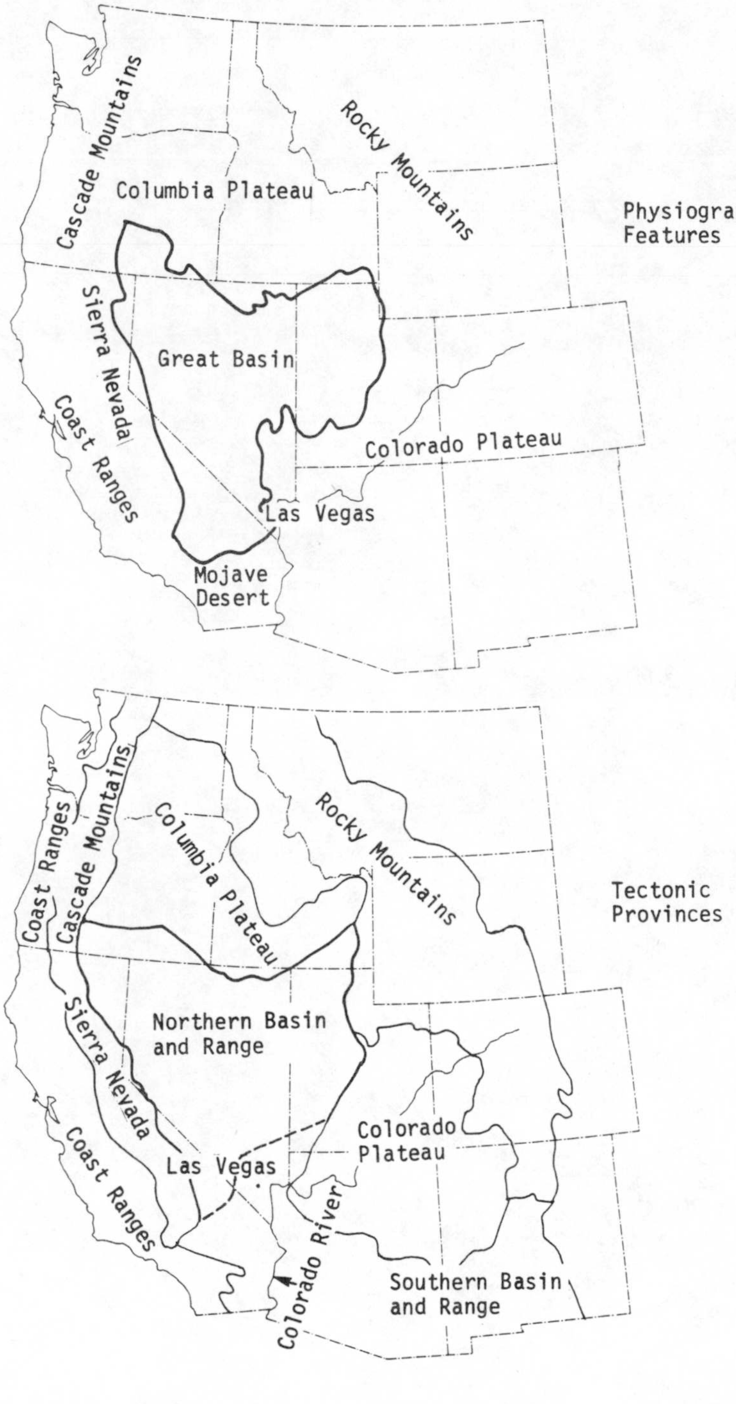
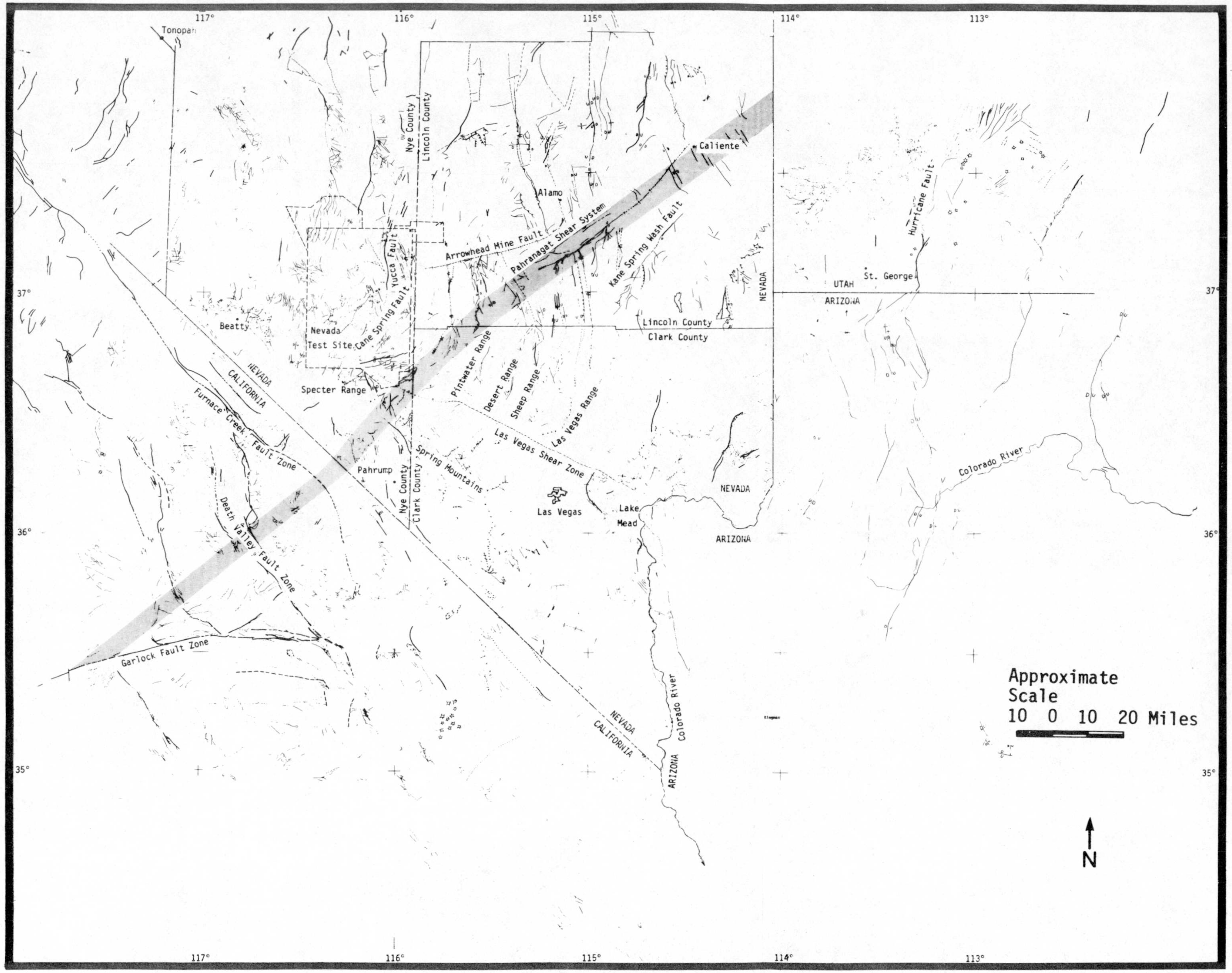


FIGURE 1 MAJOR PHYSIOGRAPHIC FEATURES AND TECTONIC PROVINCES OF THE WESTERN UNITED STATES



LEGEND

Faults with predominant sense of motion, dashed or dotted where poorly located or concealed

Conjectural fault

Low angle faults of Mesozoic age

Anticlinal structures

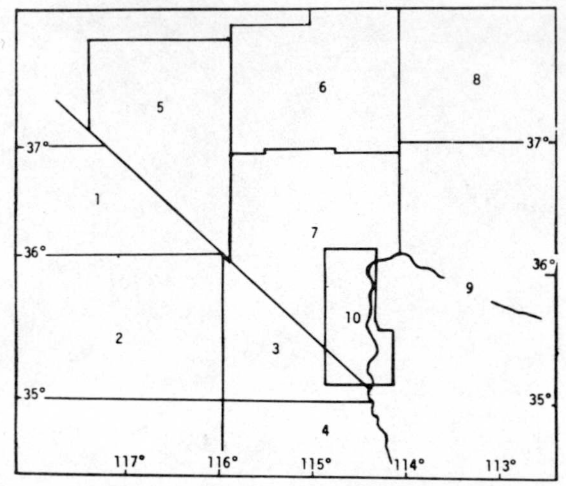
Synclinal structures

Garlock-Caliente Lineament
observed on (ERTS-1) satellite imagery, 1:5,000,000
scale (U.S.D.A. Soil Conservation Service, 1974)

Faults which have late Quaternary or Holocene displacement

Nevada/Utah data from Provisional Map of Active Faults of the Basin and Range Province (Slemmons et al., 1964) - unpublished file data.

Sources of Data



1. - 4. Geologic Map of California, Olaf P. Jenkins Edition, California Division of Mines and Geology, scale 1:250,000, additions from Fault Map of California, California Geologic Data Map Series, Map No. 1, C. W. Jennings, compiler, 1975, scale 1:750,000.
    1. Jennings (1958), Death Valley Sheet.
    2. Jennings, Burnett and Troxel (1962), Trona Sheet.
    3. Jennings (1961), Kingman Sheet.
    4. Bishop (1963), Needles Sheet.

5. Cornwall (1972), Plate 1, Scale 1:250,000.

6. Tshanz and Pampeyan (1970), Plate 3, Scale 1:500,000.

7. Longwell, et al. (1965), Plate 1, Scale 1:250,000.

8. Hintze (1963), Geologic Map of Southeastern Utah, Scale 1:250,000.

9. Wilson, Moore, and Cooper (1969), Geologic Map of Arizona, Scale 1:500,000.

10. Longwell (1963), Plate 1, 1:125,000.

FIGURE 2 GENERALIZED TECTONIC MAP OF THE SOUTHERN GREAT BASIN REGION

Stewart (1971) estimated that the total amount of east-west extension in the Basin and Range province may have been 50 to 100 km. Other estimates have ranged up to 300 km. Thus, the rate of extension has been about 0.3 to 1.7 cm per year over the last 17 million years. Considering ideas developed by Thompson (1965), among others, Stewart suggested that this ongoing deformation is a response of the relatively brittle and thin crustal rocks to movement of a plastically extending substratum below the Great Basin.

The relationship between this concept of regional east-west extension and plate-tectonics theory has not yet been fully clarified, but many workers have contributed to a plausible explanation.

Shawe (1965) attempted to explain the horst and graben structure of the Basin and Range province as the product of a regional system of dominantly strike-slip deformation, consisting of northwesterly trending right-lateral faults and northeasterly oriented left-lateral faults. According to his interpretation, the normal faults of the Great Basin were secondary release features in the larger system of conjugate shears.

Atwater (1970) proposed the concept of a soft continental margin, constituting a broad zone of deformation extending far inland and responding to the stress system that causes the transcurrent motions along the San Andreas fault. The stress system called upon for this model would account for the presence of right-lateral faulting at the western margin of the Great Basin, for example the Death Valley — Furnace Creek fault system and the now-inactive Las Vegas shear zone. The relationships between these systems, the left-lateral Garlock fault, and the San Andreas system can be envisioned in the manner of Shawe (1965).

Scholz, Barazangi, and Sbar (1971), however, objected to the idea of the Great Basin as a passive tectonic region undergoing deformation due to forces transmitted inland from the continental margin. Instead, they proposed that magmatic material has risen from the mantle and spread outward beneath the center of the Great Basin to produce extensional faulting in the overlying continental crust. This upward and outward flow of mantle material could have been generated beginning 30 million years ago following the mutual annihilation of a portion of the East Pacific rise and a subduction zone along the coast of California.

Christiansen and Lipman (1972) described the configuration of the dying subduction zone. The point of intersection and mutual annihilation of the subduction zone and the rise progressed northwestward from southern Arizona into the Great Basin area during Miocene time. This process was accompanied by a rapid change throughout the Cordillera, introducing the modern tectonic regime.

As the compressive stress accompanying subduction was released, a major change occurred in the Basin and Range province, from compressional to extensional tectonics. Therefore, Basin-and-Range-style faulting in the Great Basin was initiated during this period about 17 million years ago, and somewhat earlier in Mexico and southern Arizona (Christiansen and Lipman, 1972). Andesitic volcanism virtually ceased in the Great Basin. After a short period of quiescence from 19 to 17 million years ago, volcanism resumed with a predominantly basaltic composition (McKee, 1971).

Current geophysical data fit the diapir model of Scholz et al. (1971). High heat flow in the Great Basin points to an anomalously hot upper mantle (Roy, Decker, Blackwell, and Birch, 1968). Surrounding regions exhibit more normal heat flows, whereas, to the west in the Sierra Nevada, the heat flow is abnormally low, indicating a profound subcrustal transition beneath western Nevada (Henyey and Lee, 1976).

Seismic refraction data confirm that the higher velocity crustal layer is thinner by about 10 km under the Great Basin than it is in the surrounding regions to the east, north, and west (Prodehl, 1970; Johnson, 1967; and Greensfelder, 1965). This approximate 32-km crustal thickness appears to continue southeastward into the southern Basin and Range province in western and southern Arizona (Langston and Helmberger, 1974).

Crustal structure in southern Nevada and the immediate Las Vegas area has not, however, been adequately resolved. The work of Roller (1964) and data from others cited by Wright (1976) indicate even greater local attenuation of the lithosphere in southern Nevada. Eaton, Wahl, Prostka, Mabey, and

Kleinkopf (1978) analyzed recent geophysical data for the western United States compiled from many sources. Their work shows that there is approximately a 1-km difference in average elevation between central and southern Nevada, although both regions appear to be in isostatic adjustment. A profound change in Bouguer gravity exists north to south across an approximate east-west trend at latitude 37° N north of Las Vegas. This feature is attributed partly to southward crustal thickening and partly to differences in physical properties within the crust that are related to heating and ductile mass flow of rocks under the central portion of the Great Basin.

Late Cenozoic seismicity and volcanism have been concentrated at the margins of the Great Basin where, presumably, tensional stresses have been greatest. The orientation of the stresses and the resultant direction of maximum extension appear to vary with location. From detailed strain measurements at the Nevada Test Site, Carr (1974) deduced that extension of the crust is directed northwest-southeast. The work of Ryall, Savage, and Slemmons (1972) on focal mechanisms of recent earthquakes in the western Nevada seismic zone shows extension generally perpendicular to the large-scale trend of faults. Extension is oriented almost north-south in north-central Nevada but changes to nearly east-west at the northern end of the Owens Valley fault system in California. It is reasonable to expect that, farther south, the direction of maximum extension may be more southwesterly.

The concept of differential extension has been called on to explain tectonic features at the northern and southern ends of the Great Basin. Recently, Lawrence (1976) described large fracture zones trending northwestward across Oregon. He hypothesized right-lateral deformation decreasing in magnitude northward across successive faults in order to explain the northern termination of the Basin and Range province. Davis and Burchfiel (1973) suggested a similar role for the Garlock fault, which takes up differential extension in a left-lateral sense at the southwestern margin of the Great Basin west of Las Vegas. Other left-lateral fault zones in southern Nevada may play a role in distributing differential westward extension along the edge of the Colorado Plateau. Among these are the Hamblin Bay fault system just north of Lake Mead (Anderson, 1973), the Pahranagat shear system in Lincoln County, Nevada (Tschanz and Pampeyan, 1970), and the Cane Spring fault and related faults in the Nevada Test Site (Poole, Elston, and Carr, 1965).

The latter two systems roughly coincide with an alignment that has been associated with a low level of historic seismicity (Smith and Sbar, 1974). A prominent ERTS-1 photo lineament (USDA Soil Conservation Service, 1974) follows this trend from southwestern Utah, southwestward across southern Nevada, to the northern end of Death Valley (see Figure 2). Slemmons (1967) previously noted this lineament, its left-lateral character, and its possible relationship to the Garlock fault. Eaton et al. (1978) noted several Bouguer gravity lineaments parallel to this alignment through southern Nevada.

A major tectonic transition is indicated between central and southern Nevada (Wright, 1976). Although seismic risk in Las Vegas due to local tectonics is apparently low, further investigation of this feature is suggested for a better understanding of the seismicity and tectonics involved. Further geologic mapping and gravimetric surveys of basins and ranges in the vicinity of the alignment would contribute to a tectonic understanding of this little-studied region.

In the Great Basin, published geologic mapping has identified many faults that break Quaternary deposits. However, for most of the Great Basin, maps of active or Quaternary faults have not been compiled. Reliable identification and mapping of Quaternary Basin-and-Range-type faults requires geomorphic study, which is more readily accomplished by means of aerial photography.

3. SEISMOTECTONIC REGIME

3.1 Methods of Analysis

In the western United States, a close relationship is generally observed between the distributions of Quaternary faulting, particularly late Quaternary faulting, and of historic seismicity. This is especially true for the more seismotectonically active areas of California, Nevada, and Utah. Almost invariably, larger earthquakes ($M \geq 6$) of the Cordilleran western United States have been accompanied by surface faulting. These major events, as well as the preponderance of smaller ones ($4 < M < 6$), have occurred in fault systems marked by considerable Quaternary displacement. Therefore, it is reasonable to predict that most future large shocks will occur in these active systems. It is usually not possible, however, to determine the relative activities of particular faults.

Seismic potential in regions that have exhibited little or no historic seismicity is frequently underestimated. This is especially true for portions of the western U.S., for which the historical record is at best only about one century long. Some apparently quiescent or very low-seismicity regions manifest significant late Quaternary faulting, which indicates the occasional occurrence of moderate to large earthquakes over the past 50,000 years. This is true of southern and eastern Nevada and adjacent parts of California and Utah.

It is not yet possible to determine accurately the present-day distribution of crustal strain rates, which should govern long-term seismicity. Therefore, prediction of long-term seismicity must be based on an interpretation of recent seismic and tectonic history.

Most problematic is the matter of sample size. Seismicity is a statistical representation of the rate of elastic strain energy released by earthquakes for a given time and area. Ideally, the sample space (time x area) should be large enough to observe a stable mean frequency of events. Earthquake frequency is a function of stress level, which varies during the cycle of strain accumulation and release (Ryall, 1977, describing the work of

Fedotov). Ideally, therefore, the sample time interval should be at least as long as the strain cycle that affects the areas analyzed. In northern Nevada, this cycle may take some 1,500 years (Ryall, 1977); in southern Nevada, it is probably some 5 to 50 times longer. Although such a record of seismicity is not available, the distribution of late Quaternary faulting may be carefully analyzed according to mechanics and activity level. In this way, regions of coherent strain patterns and rates may be defined, thus providing a basis for extrapolation of observed seismicity in both time and space.

Within the study area, earthquakes of magnitude 4-1/2 and greater have been reliably reported for only 45 years. The representativeness of this record can be judged by comparing it with crustal strain rates estimated from geodetic and Quaternary fault data.

Throughout the following discussion, one underlying assumption governs interpretation. This assumption is that, for any given region, the frequency of occurrence of surface faulting is indicated by the number (or, more precisely, by the total length) of fault breaks in each of several age ranges. For example, the more Holocene faulting in a given area, the greater is the indicated rate of surface faulting. In practice, data are usually so imprecise that only rough estimates of relative frequency, made for the purpose of comparing one area with another, are justified. Nevertheless, such estimates are thought valuable in judging the representativeness of seismicity data and in the geographic extrapolation of historic seismicity.

Regional compilations of Quaternary fault-age data have been found to be more or less imprecise, as they are based upon either published geologic mapping or geomorphologic analysis. In general, only painstaking study of excavations across faults and radiocarbon dating of offset deposits can provide details of fault-movement history. Cost prohibits carrying out such studies for many faults.

Slemmons (1967) has made the only known regional photogeomorphic study of Quaternary faulting in the Great Basin. The study covered all of Nevada, western Utah, and a limited part of the Great Basin of eastern California.

Using available published data, he mapped faults in later Quaternary deposits, as well as Basin and Range faults not cutting Quaternary deposits. In Nevada, three age divisions within late Quaternary time were established, and youngest offsets on faults were mapped accordingly. However, this subdivision of age was not extended beyond Nevada's borders.

For California, Jennings (1975) has compiled all Quaternary faults from the geologic literature and, on the basis of geomorphic and geophysical characteristics, distinguished those that are probably active.

No map compilation of Quaternary fault data has been published for Arizona, although some Basin and Range faults in that state almost certainly have Quaternary displacement.

3.2 Late Quaternary Faulting: Estimation of Regional Strain Rates

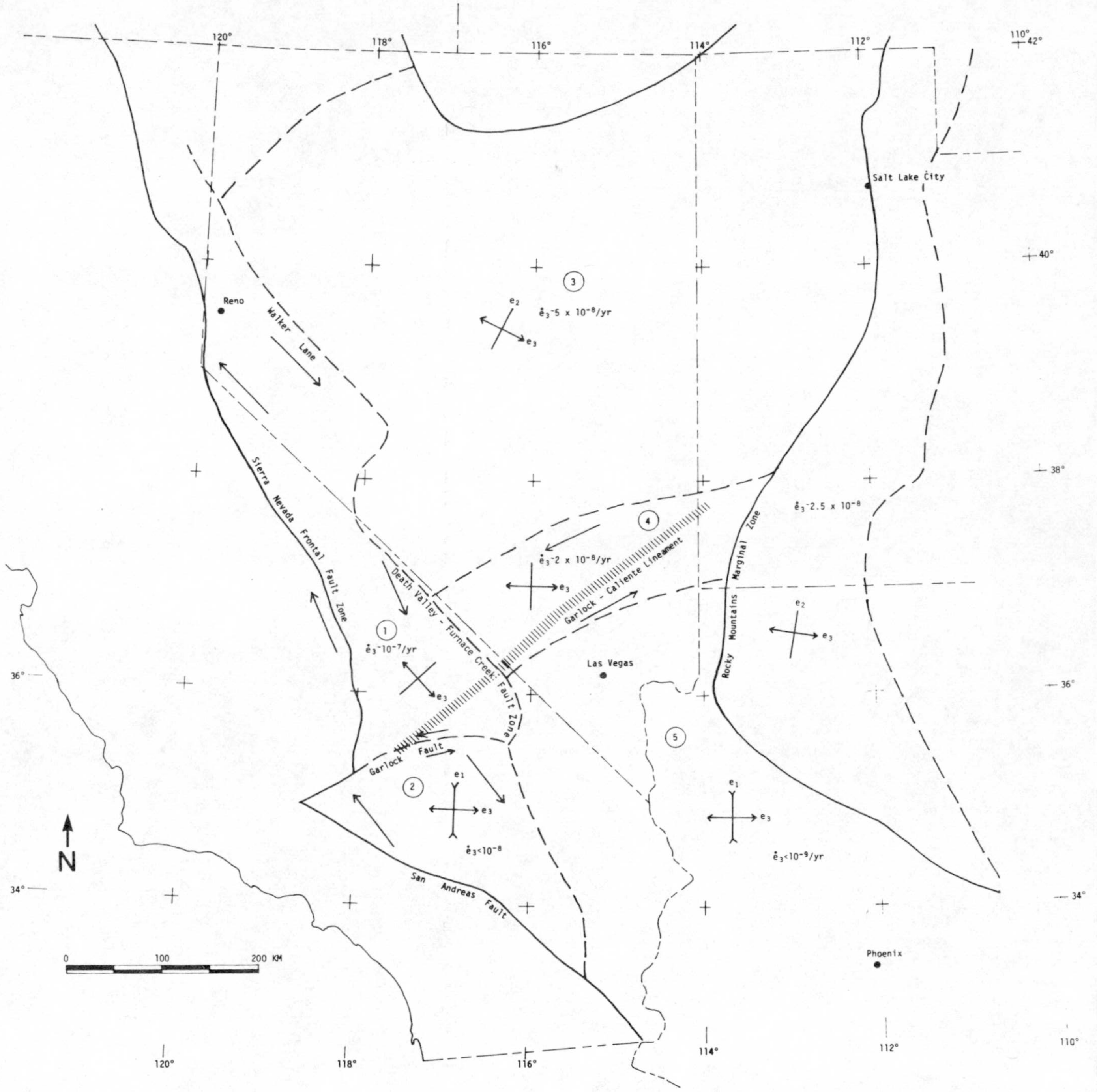
3.2.1 General Aspects.

Late Cenozoic tectonism in the Great Basin fits an overall pattern of crustal extension oriented west-northwest. In western Nevada, faults oriented north-northeast show pure dip-slip displacements. However, faults striking between west-northwest and north-northeast exhibit right-lateral oblique offset, while those striking between east-northeast and east-southeast exhibit left-lateral oblique offset. All of these motions may be explained by a regional stress field wherein minimum compressive stress (or maximum extensional strain) is oriented west-northwest. Such a stress field is confirmed in the Nevada seismic zone by fault-plane solutions and surface-faulting observations for seven major historic earthquakes. These show tensional axes that are oriented between 100° and 140° in azimuth and that plunge between 0° and 20°. Compressional axes plunge from 36° to 80° (Gumper and Scholz, 1971). At the Nevada Test Site, both focal mechanisms of nuclear-test aftershocks and strain-meter measurements show northwest-oriented tension.

Wright (1976) believed that two distinct deformational fields characterize the late Cenozoic tectonics of the Great Basin and that west- to west-northwest-oriented minimum compressive stress is common to both. Wright's Field I, the central Great Basin, is characterized chiefly by steep normal faults, indicating that maximum compressive stress is generally vertical. His Field II, the area south of the Garlock-Caliente lineament, manifests abundant conjugate strike-slip faults, indicating subhorizontal maximum compressive stress. He drew the boundary between the two fields along the Walker Lane and the belt of left-lateral faulting that includes the Pahranagat shear system. Wright postulated that the Sierra Nevada block has moved much further westward, away from the Colorado Plateau, than have blocks immediately north and south of it; the Garlock fault, which bounds the Sierran block on the south, is thought to separate regions of differential extension.

While Wright's most basic concepts relating to differential extension and contrasting tectonic styles were considered acceptable for this study, a somewhat different model was preferred. This preferred model is diagrammed in Figure 3. As illustrated, the Basin and Range province is divided into five tectonic subprovinces, each characterized by its own kinematics and intensity of late Quaternary faulting. Further subdivisions could have been made but were not considered useful for the present study. Characteristic features of faulting in the subprovinces are briefly summarized in the explanation to Figure 3; they are described in detail below.

The Garlock fault appears as an important post-Miocene tectonic boundary. Left-lateral movement on this fault appears to be caused by differing rates of extension in an east-west direction that are much greater to the north than to the south. Eastward from the east end of the Garlock fault, differential extension (increasing northerly) has been accommodated by left-lateral movement along a shear zone that extends from the Specter Range eastward to Caliente. This is included in the Garlock-Caliente lineament seen on 1:5,000,000-scale ERTS satellite photography, as shown in Figures 2 and 3. The shear zone comprises a number of mapped left-lateral, northeast-trending faults, including the Pahranagat shear system, wherein post-Miocene strike slip may total some 15 km. Some of this total slip is of later Quaternary age. It is possible that left slip may characterize the lineament between the Garlock fault and the Specter Range, although this idea is undocumented. The Specter Range — Caliente zone is associated with a broader belt of late Quaternary normal faulting.



EXPLANATION

———	Boundary of Basin and Range province
--------	Boundary of tectonic subprovince and of Rocky Mountain marginal zone
1	Number of subprovince

	Principal Type and Age of Faults
Basin and Range Subprovinces:	
1	Right-lateral-oblique, striking N to NW; intense Holocene activity.
2	Right-lateral, striking NW; few Holocene, but many late Quaternary.
3	Normal, striking NNE; many Holocene.
4	Normal, striking N, and left-lateral, striking ENE; few Holocene, many late Quaternary.
5	Normal, striking N, and right-lateral (?), striking NW; no known Holocene, very few late Quaternary.
Rocky Mountain Marginal Zone	Normal, striking N to NNE; some Holocene, many late Quaternary

e_2 ┼ e_3	Principal strain axes: e_3 is maximum extension; e_1 is maximum contraction; e_2 is intermediate strain axis. Where e_2 is shown, e_1 is vertical, and vice versa; where neither e_1 nor e_2 is shown, they may be variously oriented in the plane normal to e_3.
$\dot{e}_3$	Estimated rate of extension in e_3 direction
⇄	Sense of strike-slip motion; shown where relatively significant

FIGURE 3 TECTONIC SUBPROVINCES OF THE BASIN AND RANGE PROVINCE

Together, these fault patterns suggest a wide zone of distributed left-lateral shear in which north-trending normal faults occur as secondary-release features. This zone marks a transition between two tectonic regimes: the one to the north is featured by much greater extensional strain rate than the one to the south. The difference in the two regimes is well expressed by widely different topographic relief, spatial frequency of Quaternary and Holocene normal faults, and seismicity. All are much greater on the north side than on the south side of the zone. Actually, the southward decrease in strain rate begins somewhat north of the shear zone and is abrupt on the south margin of the zone.

The tectonics of the east margin of the Basin and Range province are dominated by dip slip in a broad belt of north-trending faults that bounds the Colorado Plateau and middle Rocky Mountains. Much of this faulting appears to be pre-late-Quaternary, and seismicity along the belt decreases southward from Cedar City, Utah.

3.2.2 Subprovince 1. Subprovince 1 is bounded by the Sierra Nevada frontal fault system on the west; the Garlock fault on the south; the Death Valley — Furnace Creek fault zone on the southeast; and the Walker Lane on the northeast (from Cedar Mountain north). As noted in Appendix A of this report, this region was subjected to major oroclinal bending, due to distributed right-lateral shear on northwest-trending planes, in pre-middle-Miocene time; the part of the Walker Lane southeast of Cedar Mountain is itself a defunct right-lateral shear zone. However, since Miocene time, right-lateral deformation appears to have become a second-order response, along established planes of weakness, to northwesterly oriented extension. This hypothesis is strongly supported by evidence that oroclinal bending ceased in the Miocene and by the apparently predominant dip-slip nature of Quaternary faulting (note extreme topographic relief of order 3 km).

Quantitative study of deformation of the latest Quaternary deposits in Death Valley (Hooke, 1972) indicates northwest-oriented extension on the Death Valley fault at a rate of about 1 to 2 cm/yr. He observed tilting that appears to have a rate of 0.3 μrad/yr and suggested 7 mm/yr dip-slip movement on the Death Valley fault. Also, Hooke found northeast-oriented grabens that indicate 2 to 4 cm/yr extension, which he interpreted to be the result of right slip on the Death Valley fault. Together, the data indicate a strain rate between 10^{-6}/yr and 10^{-7}/yr; however, a rate near 10^{-7}/yr appears to be best supported by the data.

In Owens Valley, geodetic measurements indicate about 4 mm/yr right-lateral deformation parallel to the Owens Valley fault and extension normal to it at about 1 mm/yr (Savage et al., 1975). In addition, down-to-the-east tilt of the block east of the fault is 0.2 μrad/yr. Together, these data indicate northwest-oriented extensional strain at a rate of about 10^{-7}/yr across Owens Valley. These data are in substantial agreement with fault motions observed for the 1872 Owens Valley earthquake ($M \approx 8$), although dip slip and right slip had comparable magnitudes (~ 5 m).

On the Garlock fault, left-lateral offset in Holocene time has been estimated at about 7 mm/yr at Koehn Lake (Clark and Lajoie, 1974). It is thought that this figure represents extension parallel to the Garlock fault within the region immediately north of it.

Displacement rates in other parts of the region have not been measured but are probably comparable to those listed above. Holocene faulting occurs in Saline, Panamint, and Coso valleys and in northern Death Valley.

Extensional strain rate across the subprovince may be estimated with reference to its southeast corner, the junction of the Garlock and Death Valley faults. Net displacement is 2 cm/yr in the direction N 37° W; this amounts to a strain rate of about 10^{-7}/yr.

3.2.3 Subprovince 2. Subprovince 2 is the western Mojave Desert block, characterized by northwest-striking faults on which displacement appears to be largely right-lateral; low topographic relief between the basins and ranges suggests that dip slip is of lesser magnitude. Jennings et al. (1962) show that all major faults in this area cut Quaternary deposits; however, the age of youngest movements is unknown. The area has moderate seismicity. Relative late Quaternary right slip is observed on the Blackwater fault, which tends northwest. Left slip, associated with a magnitude 7 earthquake, was observed on the east-northeast-trending Manix fault in 1947.

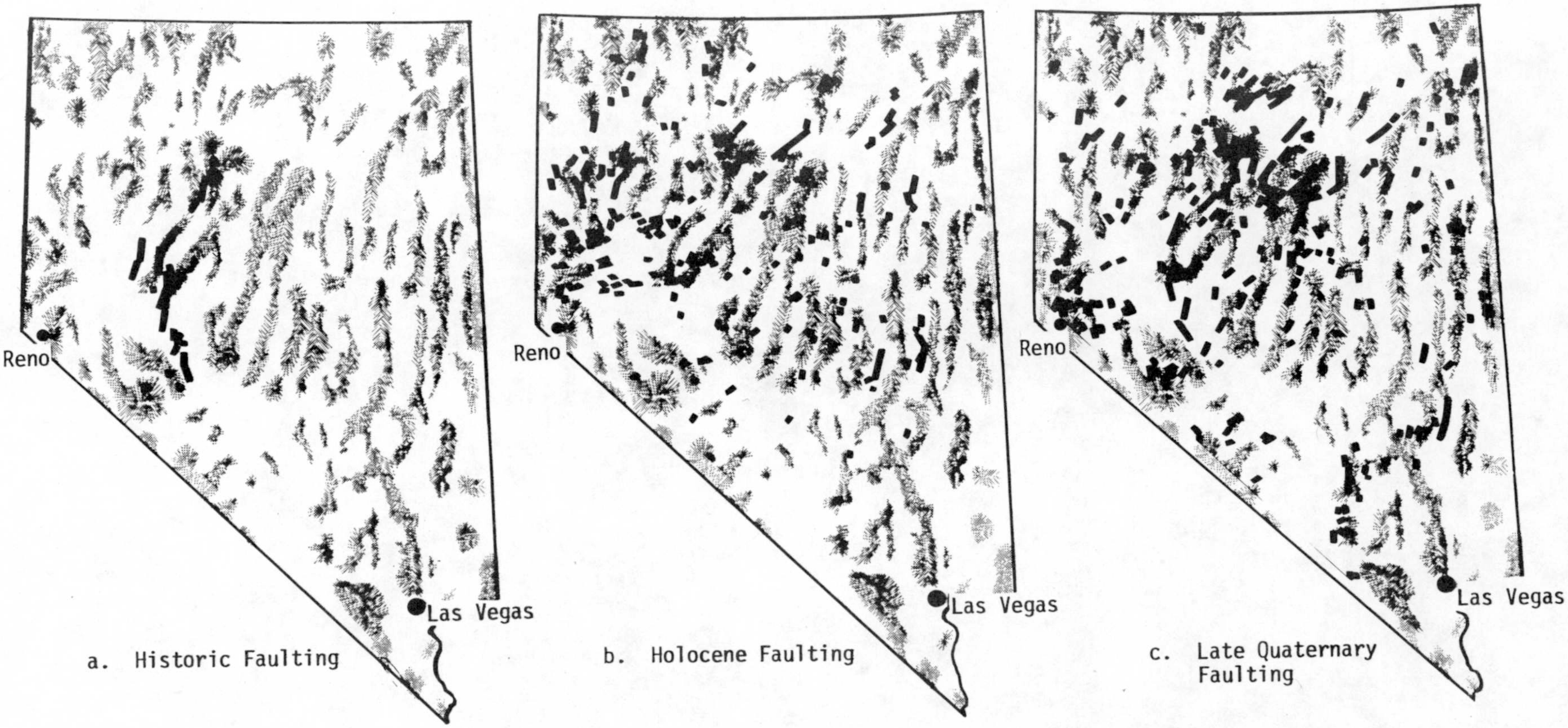
The style of faulting suggests that maximum compressive stress (along strain axis e_1) in this region has a nearly horizontal orientation (see Figure 3); in this regard, it differs markedly from the region to the north, where maximum compressive stress has an average plunge probably near 45°. Strain rate cannot be directly estimated for this region, but it is taken to be of order 10^{-8}/yr or less.

Subprovince 5, immediately east of this region, is tectonically much less active, as described below.

3.2.4 Subprovinces 3, 4, and 5 in Nevada. Slemmons (1967) has classified and mapped faults that offset late Quaternary sediments. Typically, the offset materials are alluvial fans at range fronts; less commonly they are playa deposits formed in Pluvial-period lakes (e.g., lakes Lahontan and Bonneville). The age classification scheme is as follows: historic offsets, less than 100 years old; prehistoric offsets, estimated to be from 100 to several thousand years old (i.e., Holocene); pre-Holocene faulting, from 10,000 to 100,000 years old. Figure 4 shows the distribution of faults in these age ranges in Nevada.

Historic faults form a closely connected chain (Figure 4a) that extends northward from Cedar Mountain to Pleasant Valley. The faulting accompanied eight earthquakes, with magnitudes ranging from 6-1/4 to 7-1/2 between 1903 and 1954. This belt of intense activity is seen in the seismicity distribution of Nevada (Figure 5); a number of the smaller earthquakes ($4 \leq M \leq 6$) in the belt are aftershocks of those that were accompanied by surface faulting. It is noted that the belt is nearly in line with the Owens Valley faulting of 1872, which occurred during an earthquake of magnitude near 8.

Holocene faults appear in Figure 4b. They are spread out rather evenly across northern and central Nevada, in tectonic subprovince 1. Note, however, the sparseness of their occurrence south of latitude 38° N (in subprovinces 4 and 5).



a. Historic Faulting

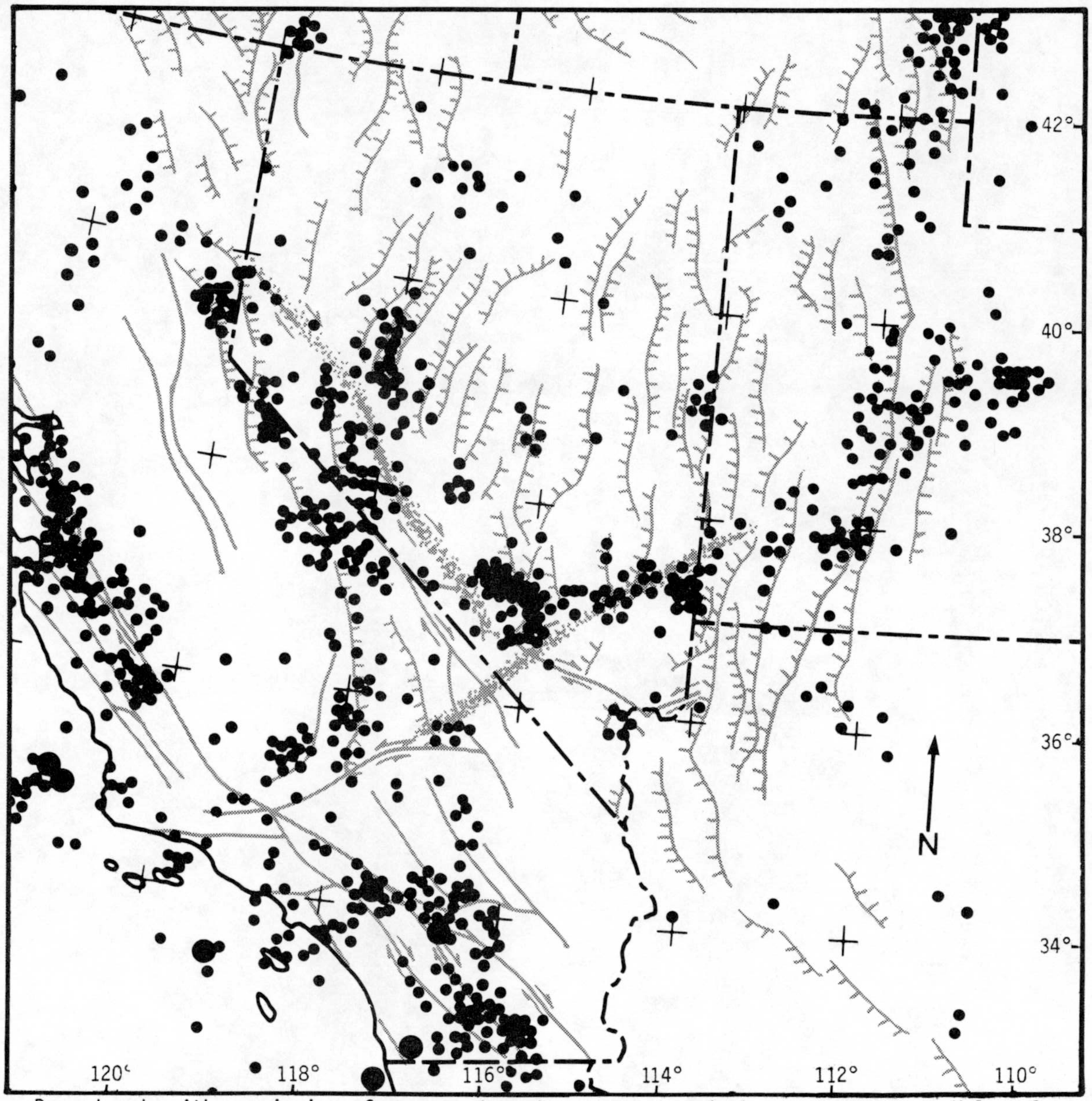
b. Holocene Faulting

c. Late Quaternary Faulting

Note:

Features do not indicate true elevation.

FIGURE 4 HISTORIC, HOLOCENE, AND LATE QUATERNARY FAULTS IN NEVADA
(FROM SLEMMONS, 1967)



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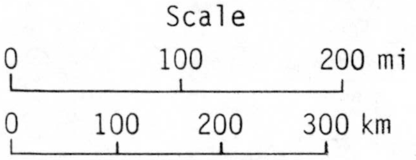

FIGURE 5 SEISMICITY MAP OF THE WESTERN UNITED STATES, 1961-1970, AND LATE CENOZOIC TECTONIC FEATURES (FROM THOMPSON AND BURKE, 1974)

Pre-Holocene faults appear in Figure 4c. They also are more concentrated in the northern and central parts of the state and are generally sparse south of the 38th parallel, except for a diffuse northeast-trending belt of faults in subprovince 4.

After comparing the distributions of faulting in the three age groups, Slemmons (1967) concluded that the historic faulting and earthquake activity are not representative of the long-term (i.e., last 100,000 years) distribution of seismotectonic activity and that future activity may be expected to shift to zones that have been historically dormant. In Slemmons' opinion, however, the historic pattern suggests that, for short time intervals, there may be a tendency for concentrated activity along north-south-trending belts, parallel to the tectonic grain. His conclusions are supported by this study.

In addition, the concentration of pre-Holocene faulting in and near the Specter Range — Caliente shear zone indicates a long-term seismicity rate that is higher than it is in areas adjacent on the north and south. Interestingly, this belt appears as a weak trend of historic seismicity (described in detail below).

In subprovince 3 (northern Basin and Range), normal faults have an average trend of north-northeast. This indicates that the average direction of maximum extension is west-northwest. Strike-slip offsets are generally smaller than dip slip and occur on conjugate trends that fit west-northwest extension. Hence, maximum compressive stress (minimum extension, e_1) is generally vertical in this region.

Dixie Valley, site of two major ($M \approx 7$) earthquakes in 1954, is the basin for which Quaternary tectonics is best known. The axis of maximum extension there trends N 55° W, and the Holocene spreading rate is 1 mm/yr (Thompson and Burke, 1974). This displacement rate is equivalent to a strain rate of 5×10^{-8}/yr across Dixie Valley. This strain rate characterizes much of the subprovince.

Subprovince 4 is characterized by normal faults that trend more northerly than in the region to the north and by major left-lateral faults. The abundance of late Quaternary faults indicates significant tectonism, but the scarcity and shortness of Holocene faults indicates that it is much less than in subprovince 3. The spatial frequency of occurrence of Holocene faults is about 10% to 20% that of subprovince 3. On this basis, the extensional strain rate in this region is estimated to be between 5 x 10^{-9}/yr and 10^{-8}/yr.

Subprovince 5 in Nevada appears entirely devoid of Holocene and latest Quaternary faulting. Also, it is an area of extremely low seismicity. Hence it is thought to have extensional strain rate of less than 10^{-9}/yr -- perhaps as low as 10^{-10}/yr.

3.2.5 Subprovince 5 Outside Nevada. In the Mojave and Colorado deserts of California, east of the 116th meridian, documented Quaternary faulting is practically nonexistent (Jennings, 1975), and no Holocene faulting is known. Current literature reveals little additional information concerning faulting in this region.

Quaternary and Holocene faulting are unknown in the Basin and Range province of northwestern Arizona. But, as in adjacent California, it has not been looked for carefully. Published regional maps (Arizona Bureau of Mines) show no range-bounding faults. Dr. I. Lucchitta (personal communication, 1977), who has worked extensively in the Colorado River country, feels that the ranges may be exhumed pre-Quaternary structures. Certainly they have much lower relief than those in the northern Basin and Range province. Seismicity in this region is extremely low.

From the above, it can be concluded tentatively that extensional strain rate in this entire subprovince is as already estimated from Nevada data: between 10^{-9}/yr and 10^{-10}/yr.

3.2.6 Rocky Mountain Marginal Zone. The Rocky Mountain marginal zone is characterized by north-trending normal faults, many of which exhibit Quaternary or Holocene faulting. Details of recent faulting throughout most of the region are not known. Some movement in the Hurricane fault zone, east of Cedar City, Utah, appears to be late Quaternary and perhaps is Holocene in age.

In Jordan Valley, south of Salt Lake City, the Holocene extension rate has been estimated at 1 mm/yr across the Wasatch fault (Suppe et al., 1975). It is unclear what zone width should be assigned this extension. For the Jordan Valley alone, a strain rate of 5×10^{-8}/yr is implied; for the entire tectonic belt, about 1×10^{-8}/yr. Probably the true value is bracketed by these estimates.

Seismicity is moderate in the belt and decreases southward from Cedar City.

3.3 Historic Seismicity

3.3.1 Regional Pattern. Figure 5 shows the seismicity of the western United States for the period 1961 to 1970, and Figure 6 shows known surface faulting and major earthquakes from 1769 to 1965. Together, they indicate major zones of high seismic energy release for the last two centuries. Within the Basin and Range province, major historic seismicity has been confined to two belts of surface faulting, one in Owens Valley, and another extending from Cedar Mountain to Pleasant Valley, Nevada. Two other important seismicity zones are seen, one in southern Nevada and the other along the margin of the Colorado Plateau.

These historic seismic zones correlate partly with the seismotectonic subprovinces shown in Figure 3, which represent a time span from 100 to 500 times longer. However, it is important to observe that historic seismicity of the Basin and Range province is restricted to portions of subprovinces 1 and 3. It can be concluded from latest Quaternary faulting patterns that this historic configuration is not an adequate representation of long-term seismicity.

3.3.2 Sources and Quality of Data. In this study, the interpretation of historic seismicity is based primarily upon the seismographic record. The record is reasonably complete for shocks of magnitude about 4 or greater that have occurred over much of the study area since 1932. Prior to 1932, the earthquake record is based essentially on felt and damage reports. Because the study region is very sparsely populated, it is thought that many earthquakes with $4 \leq M \leq 6$ went unreported during the historic period 1850 to

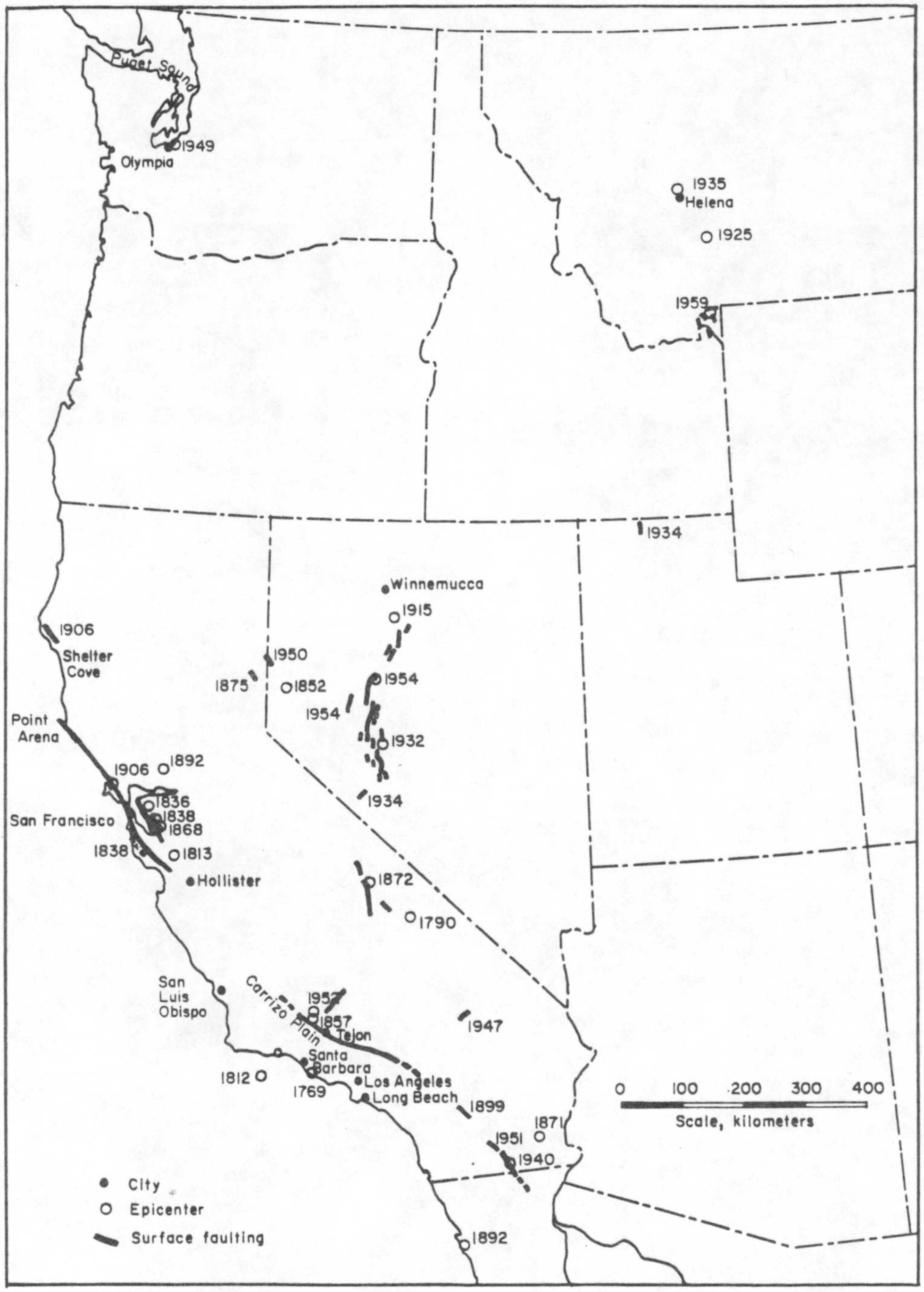

FIGURE 6 HISTORIC SURFACE FAULTING AND MAJOR EARTHQUAKES OF THE WESTERN UNITED STATES, 1769-1965 (FROM RYALL ET AL., 1966)

1931. However, a number of major earthquakes ($M \approx 7$) occurred during this time, and they are considered in the analysis.

For the years 1932 to 1962, the best seismographic record of the study area is assembled from two sources: the California Institute of Technology (CIT) and the University of Nevada, Reno, (UNR) earthquake catalogs (Hileman et al., 1973; Slemmons et al., 1965). These combined data are considered nearly complete for magnitudes greater than about 4. For the years 1963 to present, the catalog of the Environmental Data Service, National Oceanic and Atmospheric Administration (NOAA) is essentially complete for $M \geq 4$; this source is relied upon for the years 1963 to 1973. Also included are microearthquakes recorded and located by the Nevada Special Projects Party (USGS/NOAA) during 1971 to 1973 (Bayer, Mallis, and King, 1972; Bayer, 1973a, 1973b, and 1974). Magnitude data were not available for the microearthquakes.

Figure 7 is an index map showing the geographic areas for which original seismicity data compilations were made for this study; data sources and references to figure numbers of epicenter maps (Figures 8 through 11) are given.

Since 1932, the Seismological Laboratory of the California Institute of Technology has provided apparently complete reporting of southern California earthquakes of magnitude 4± and larger (south of 38° N, east of 119° W). With the addition of a number of new seismograph stations during the 1950s and 1960s, the magnitude threshold of detection in southeastern California dropped from 4± to 3± (Willis et al., 1974). The CIT laboratory has also reported many shocks in southern Nevada (south of 38° N), but probably with less reliability than in California (Hileman et al., 1973). CIT has consistently reported local magnitude, but only to the nearest 1/2 unit until 1943.

Two agencies in the Department of Commerce have maintained earthquake history files for the U.S. since 1928. Until the early 1960s, the U.S. Coast and Geodetic Survey (USCGS) reported intensities routinely, but magnitudes were reported only occasionally, depending on proximity to population centers. Magnitude threshold ranged from as low as 3 to more than 5. Since 1963, NOAA

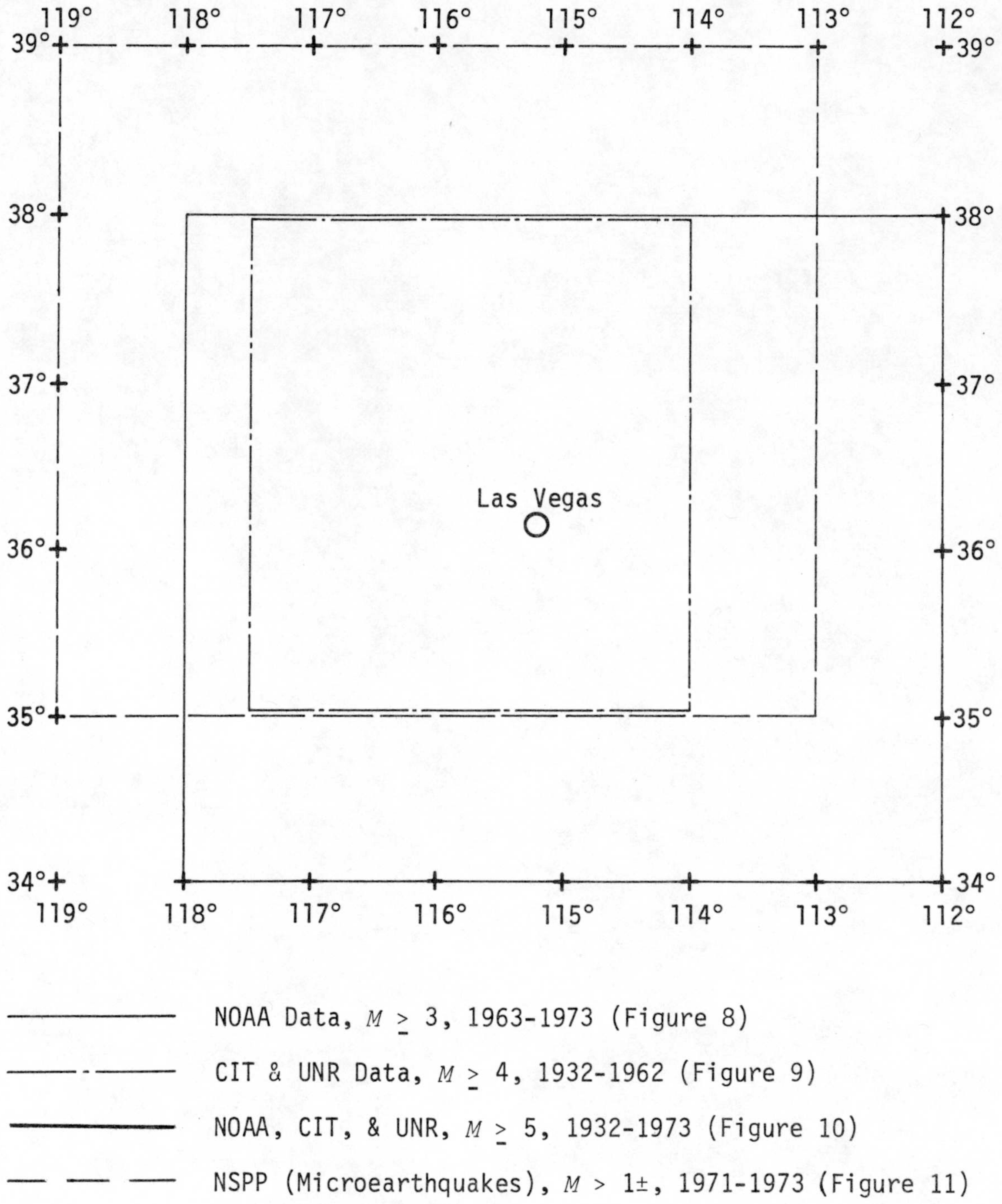

FIGURE 7 INDEX MAP FOR EPICENTER PLOTS OF FIGURES 8 THROUGH 11

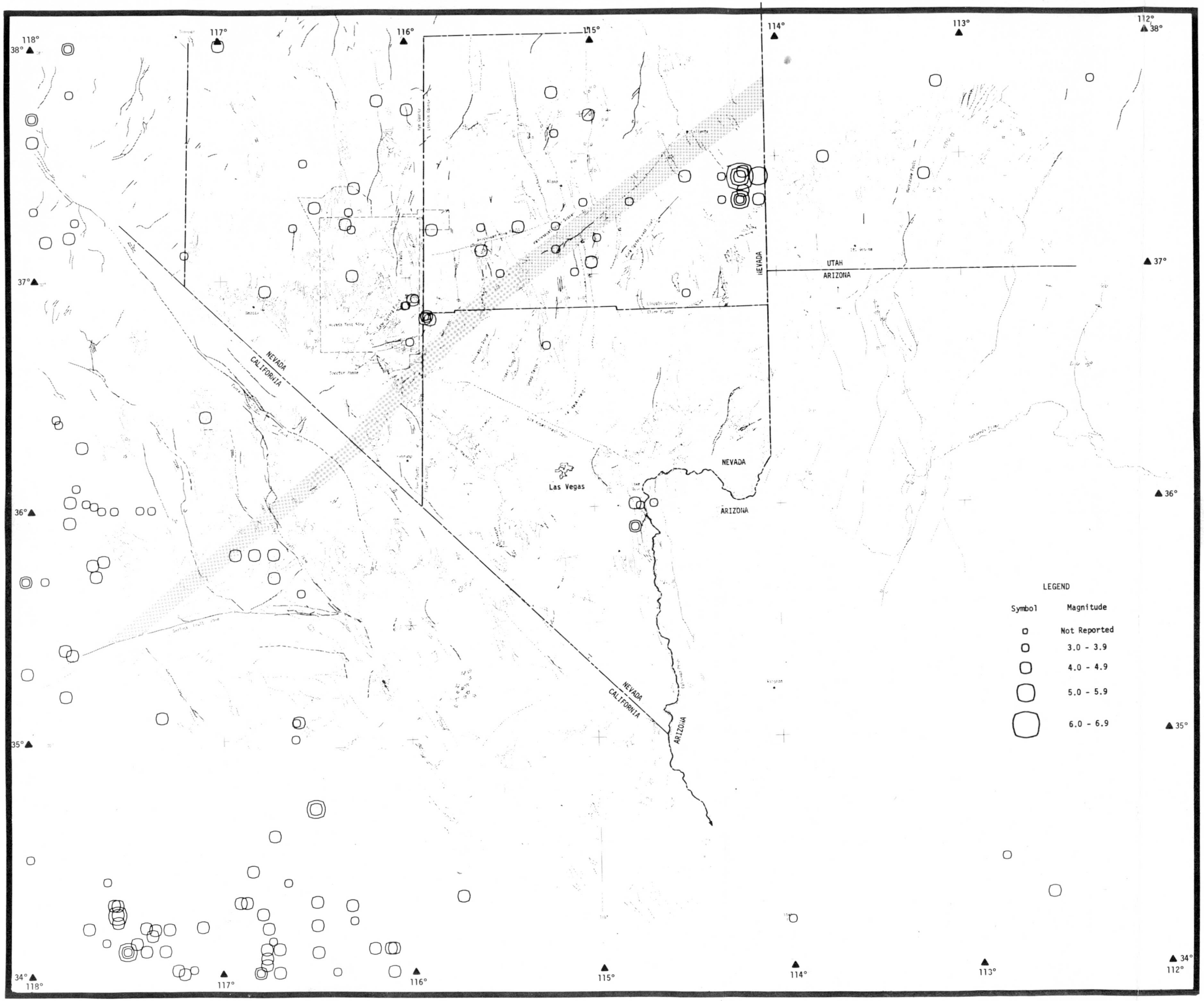

FIGURE 8 EPICENTERS, $M \geq 3$, 1963-1973 (NOAA CATALOG)

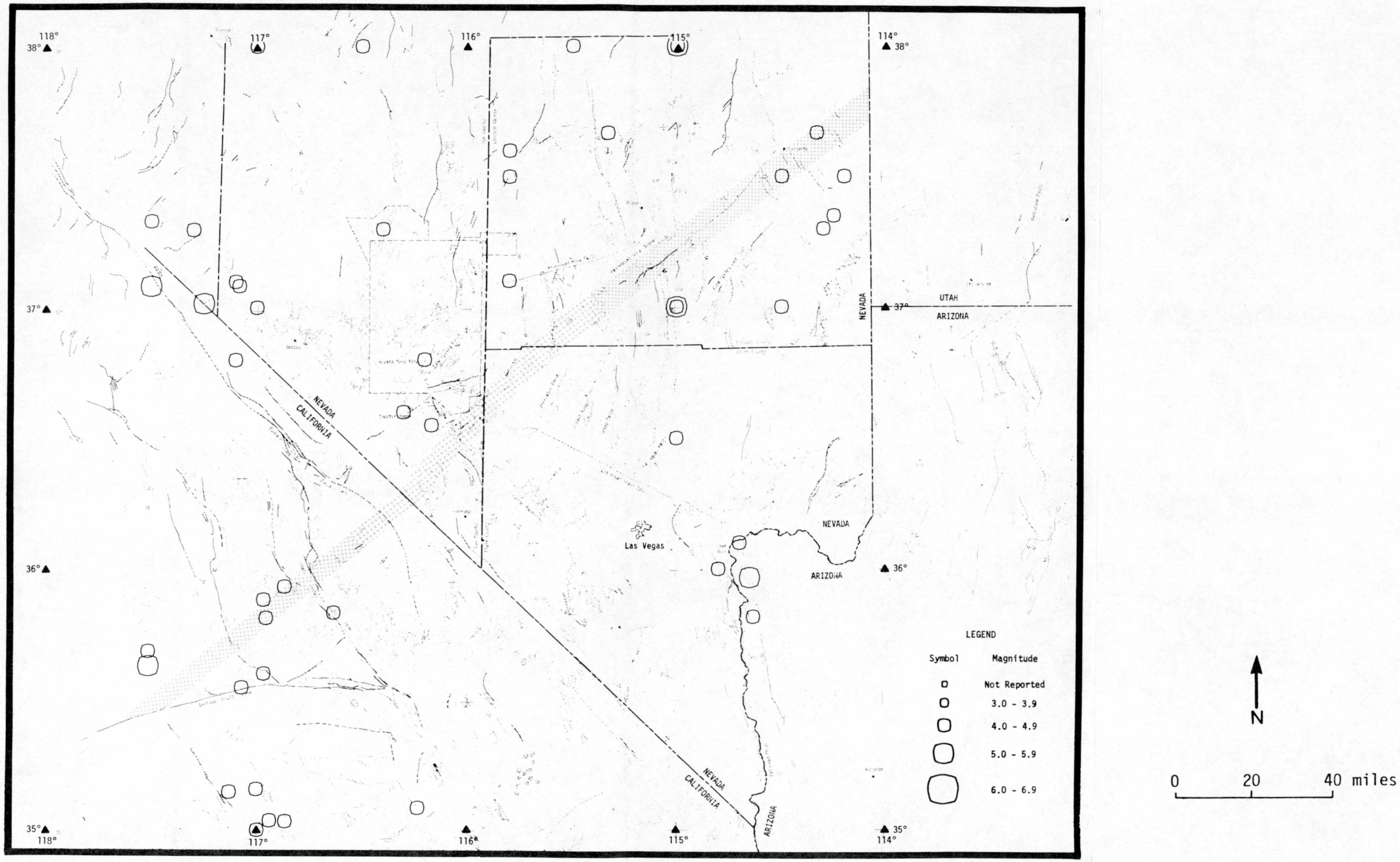

FIGURE 9 EPICENTERS, $M \geq 4$, 1932-1962
(CIT AND UNR CATALOGS,
MERGED AND EDITED)

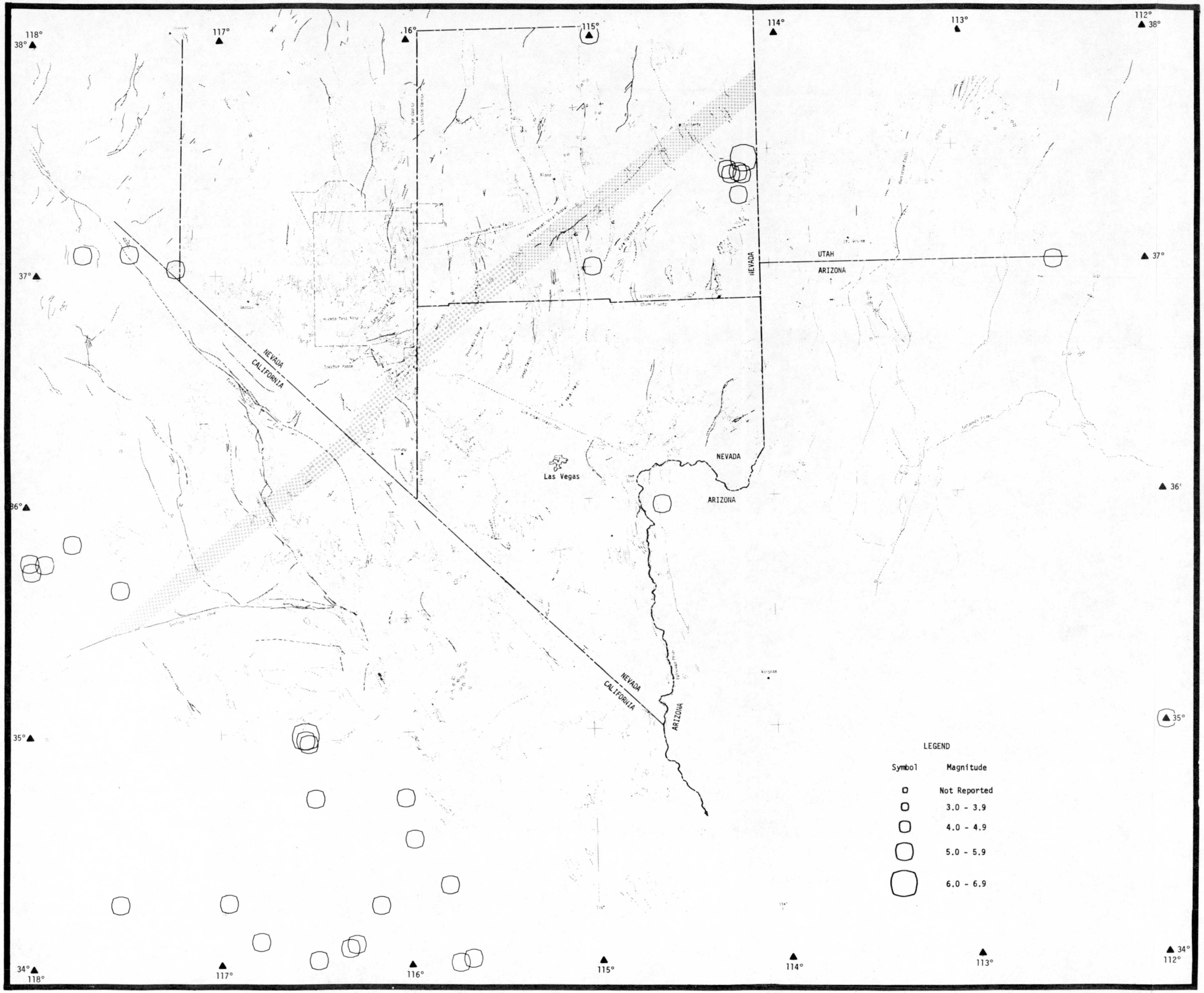

FIGURE 10 EPICENTERS, $M \geq 5$, 1932-1973 (NOAA, CIT, AND UNR CATALOGS, MERGED AND EDITED)

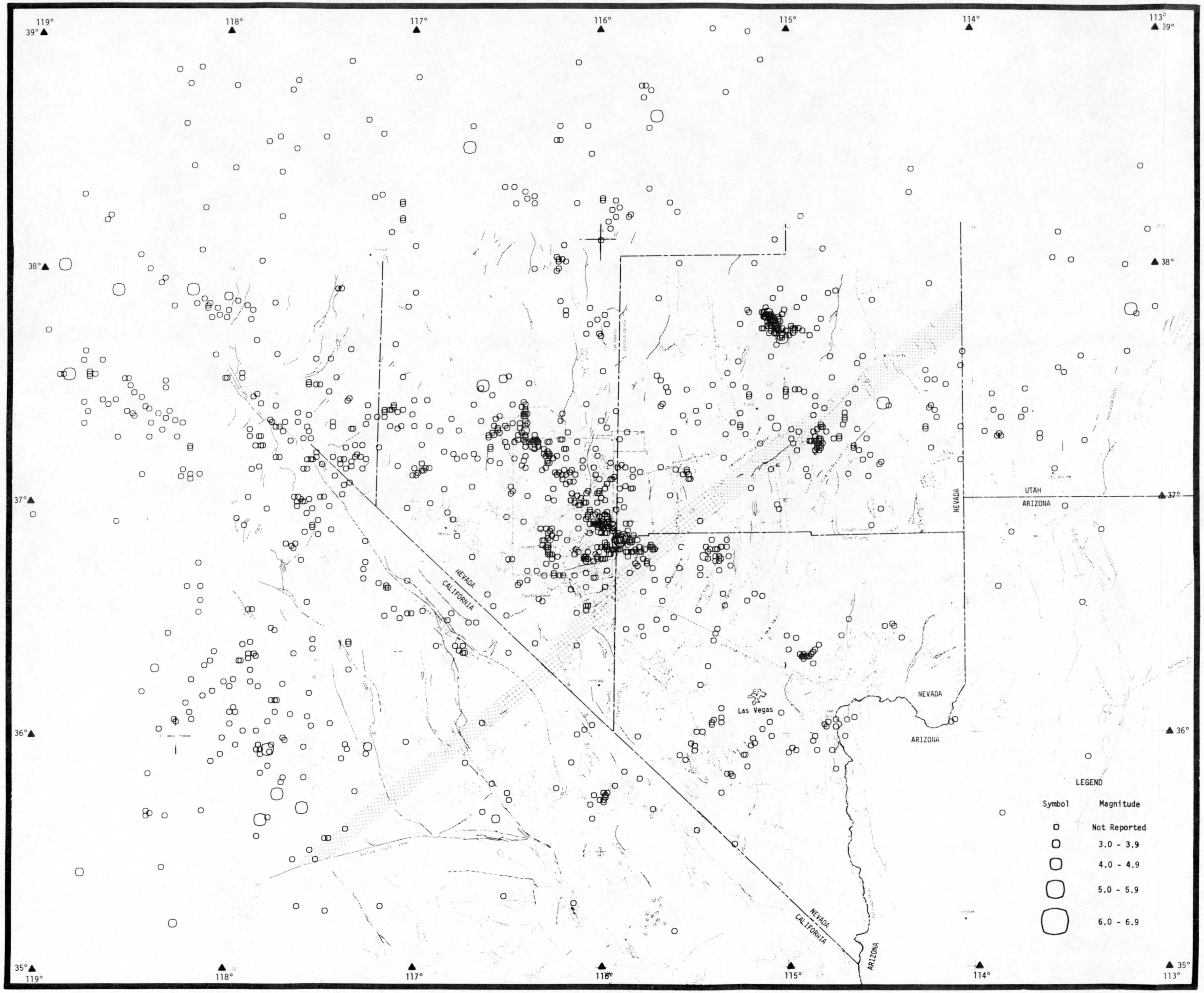

FIGURE 11 MICROEARTHQUAKE EPICENTERS, $M \geq 1\pm$, 1971-1973 (USGS, NEVADA SPECIAL PROJECTS PARTY)

(briefly ESSA) has routinely reported magnitudes (usually M_L) for U.S. earthquakes, and it has apparently reported all shocks of $M \geq 4$ and many of $3 < M < 4$.

Coverage of earthquakes in western Utah and northwestern Arizona is afforded only by the NOAA/USCGS files. Therefore, seismicity data in that sparsely populated region are incomplete for the period 1932 to 1962; shocks with $M < 5\text{-}1/2 \pm 1/2$ were not consistently reported. The lack of magnitude data for this period is a serious handicap for interpretation.

The University of Nevada (Slemmons et al., 1965) has compiled a catalog of Nevada earthquakes for the period 1852 to 1960; all available data were compiled. For southern Nevada, instrumental data comprised essentially just the CIT data. Felt reports were compiled from newspaper articles, as well as from published USCGS lists (*U.S. Earthquakes*, annual series). Because of the sparse population of this area, felt reports are very incomplete for $M < 5$, except for shocks occurring within a few miles of Las Vegas, Boulder City, or a few small towns to the north. With the exception of felt reports of more than 200 small shocks ($M \leq 4\pm$) in the vicinity of Lake Mead, the UNR catalog adds little to the CIT catalog of earthquakes in the southern Nevada area. The combined CIT/UNR catalog may be reasonably complete for southern Nevada earthquakes of $M \geq 4$ since 1932, but this magnitude might be nearer to 5.

Before 1961, no seismograph stations operated in southern Nevada or in adjacent parts of Utah and Arizona. Thus, only rather large shocks were reliably reported in this region prior to 1961. Beginning in 1961, the Atomic Energy Commission (AEC) contracted for the operation of high-gain stations in the area between Las Vegas and Tonopah. Willis et al. (1974) stated that the threshold of reliable detection for this region ranged in magnitude from 4.6 to 5.2 during 1943-1952, from 3.6 to 5.2 during 1953-1962, and from about 2.6 to 3.2 since 1963. However, magnitude-frequency plots, discussed below, suggest that published catalogs are complete for $M > 4$ but are incomplete for $M < 4$, even since 1963. Therefore, it appears that the AEC contract stations either did not record local earthquakes (i.e., did not run continuously) or did not report them to NOAA.

It can be concluded, therefore, that earthquake detection and reporting in the study region have varied significantly in both time and space. The minimum magnitude threshold of reliable reporting ($M_{\min}$) has decreased with time, but has always increased from southwest to northeast; the function $M_{\min}$ (X, Y, t) is not linear, but varies stepwise in time and in space. No attempt has been made to specify this function exactly, although it has been estimated in the above discussion and has been used in isolating relatively complete sets of seismicity data for analysis. For a given sample space, such sets contain only $M \geq M_0$, where M_0 is the maximum value of $M_{\min}$ (X, Y, t) on that space. Some data sets presented here contain $M < M_0$, but M_0 is generally known, so the smaller events may be simply ignored. These data sets are indexed in Figure 7.

Special problems of data quality, particularly for the Rocky Mountain marginal zone, are discussed in the following data analysis.

Identified nuclear detonations and their afterevents (collapses and aftershocks) were removed from the catalog lists and epicenter plots. Identification relied upon published lists. Unidentified events that were not thought to be true earthquakes were also removed.

3.3.3 Geographic Distribution. Figures 8 through 10 present all published epicenter data for the regions and time periods covered (see index map, Figure 7) for $M \geq 4$ (CIT and UNR) and $M \geq 3$ (NOAA); Figure 11 shows all microearthquake epicenters. Earthquakes of $M \geq 3$ are largely confined to seismotectonic subprovinces 1, 2, and 4 and the Rocky Mountain marginal zone. Almost none of subprovince 3 is included within the area of the epicenter plots. Other than the diffuse north-northeast-trending belt in subprovince 4, no obvious alignments of epicenters are evident. Rather, they are scattered through the region outside subprovince 5. In subprovince 5, which includes Las Vegas, the few events plotted are all very near Lake Mead and are believed to be the result of pore-pressure increases induced beneath the lake.

Numerous microearthquakes (Figure 11) are scattered across the entire region, and their distribution shows little relationship to mapped faults. Clustering of events is most pronounced in the Nevada Test Site (NTS), where many are probably unverified afterevents of nuclear detonations. Three earthquake sequences have been identified at the north and east margins of NTS. Most interesting of these is the Silent Canyon sequence (March 1972), which appears as a narrow, north-trending alignment that closely parallels several faults of Pahute Mesa. Two others, Massachusetts Mountain (August to November 1971, maximum magnitude 4.3) and Ranger Mountain (February and March 1973) occurred east of Yucca Flat. They had a swarmlike character and no alignments: all events with $M < 2.9$ were deleted; as a result, only several out of more than 200 located events were plotted. Near Hiko, far to the east of NTS, a diffuse sequence with maximum magnitude 4.8 occurred in December 1971.

Many alignments can be seen, but very few are correlated with mapped fault trends. Near Las Vegas, four northeast-trending alignments of epicenters are seen. Three long ones are located south of Las Vegas and cut across mapped faults trending north to northwest. The shortest is located 30 km northeast of Las Vegas and coincides with a cluster of minor, pre-late-Quaternary faults.

Farther west, in subprovince 1, there is weak clustering of events about the Furnace Creek and Garlock faults. Microearthquake monitoring by the USGS in Death Valley (Papanek and Hamilton, 1972) revealed many events along the Furnace Creek fault zone during a 10-month period.

3.3.4 Magnitude-Frequency Relations. Magnitude-frequency data were compiled and plotted for the five seismotectonic subprovinces and the Rocky Mountain marginal zone. Plots are shown in Figures 12 to 17, and the curve parameters are summarized in Table 1. Data for subprovinces 2, 4, and 5 come entirely from the original compilation prepared for this study; those for subprovince 3 and the Rocky Mountain marginal zone are from published analyses of seismicity (Ryall et al., 1966; Sbar and Smith, 1974). Data for subprovince 1 are from a published analysis (Hileman et al., 1973) and from the present compilation.

Determination of b-values in the empirical relation

$$\log N = c - bM$$

TABLE 1

SUMMARY OF SEISMICITY DATA FOR THE FIVE SEISMOTECTONIC SUBPROVINCES OF THE BASIN AND RANGE PROVINCE AND FOR THE ROCKY MOUNTAIN MARGINAL ZONE

Seismotectonic Subprovince Portion	Area (km^2)	Period	$N_{4.0}$*	b**	$T_{7.0}$***	Data Sources/Comments
1/east of 117.5°W	14,500	1932-1962	0.25	--	--	CIT + UNR
1/east of 118°W	25,000	1963-1973	0.068	1.0‡	13,000	NOAA
1/near ends of 1872 faulting	19,000	1932-1972	0.34	1.0	3,000	CIT; N and b from Hileman et al., 1973
1/south of 38°N	32,000	1932-1973	0.15‡	1.0‡	6,700‡	Log mean of above data
2/all	28,000	1963-1973	0.025	0.91†	22,000	NOAA
2/northern strip	7,700	1932-1962	0.024	--	--	CIT
3/western Nevada	84,000	1932-1969	0.22	0.91	2,200	UNR + NOAA; N and b from Douglas and Ryall, 1975
3/entire Nevada portion	222,000±	1932-1969	0.08‡	0.91‡	6,000‡	Assumes that observed data actually represent activity of entire subprovince
4/all	34,000	1963-1973	0.11	0.96†	6,000	NOAA
4/all	34,000	1932-1962	0.015	1.0‡	77,000	CIT + UNR
4/all	34,000	1932-1973	0.04	1.0‡	25,000‡	Log mean of above data
5/north of 34°N	73,000	1963-1973	0.0037	1.08†	270,000	NOAA
5/north of 35°N, west of 114°W	41,000	1932-1962	0.0070	1.0‡	140,000	CIT + UNR
5/north of 34°N	73,000	1932-1973	0.0052‡	1.0‡	190,000‡	Log mean of above data
Rocky Mountain marginal zone (intermountain seismic belt)	350,000	1961-1970	0.06	0.96†	12,500	NOAA (Sbar and Smith, 1974)
	350,000	1932-1961	0.025 to 0.25	0.96‡	3,000 to 30,000	NOAA (Ryall et al., 1966)
	350,000	1932-1970	0.075‡	0.96‡	10,000	Log mean of above data

Explanation

* number of events $M \geq 4$ per year per 1,000 km^2

** b-slope, in relation $\log N = c - bM$; note that $c = \log N_{4.0} + 4b$

*** modal recurrence time for $M \geq 7$ earthquakes per 1,000 km^2

† b computed using maximum likelihood method

‡ b-value assumed from another subset of data; N-value estimated as geometric (logarithmic) mean of observed data

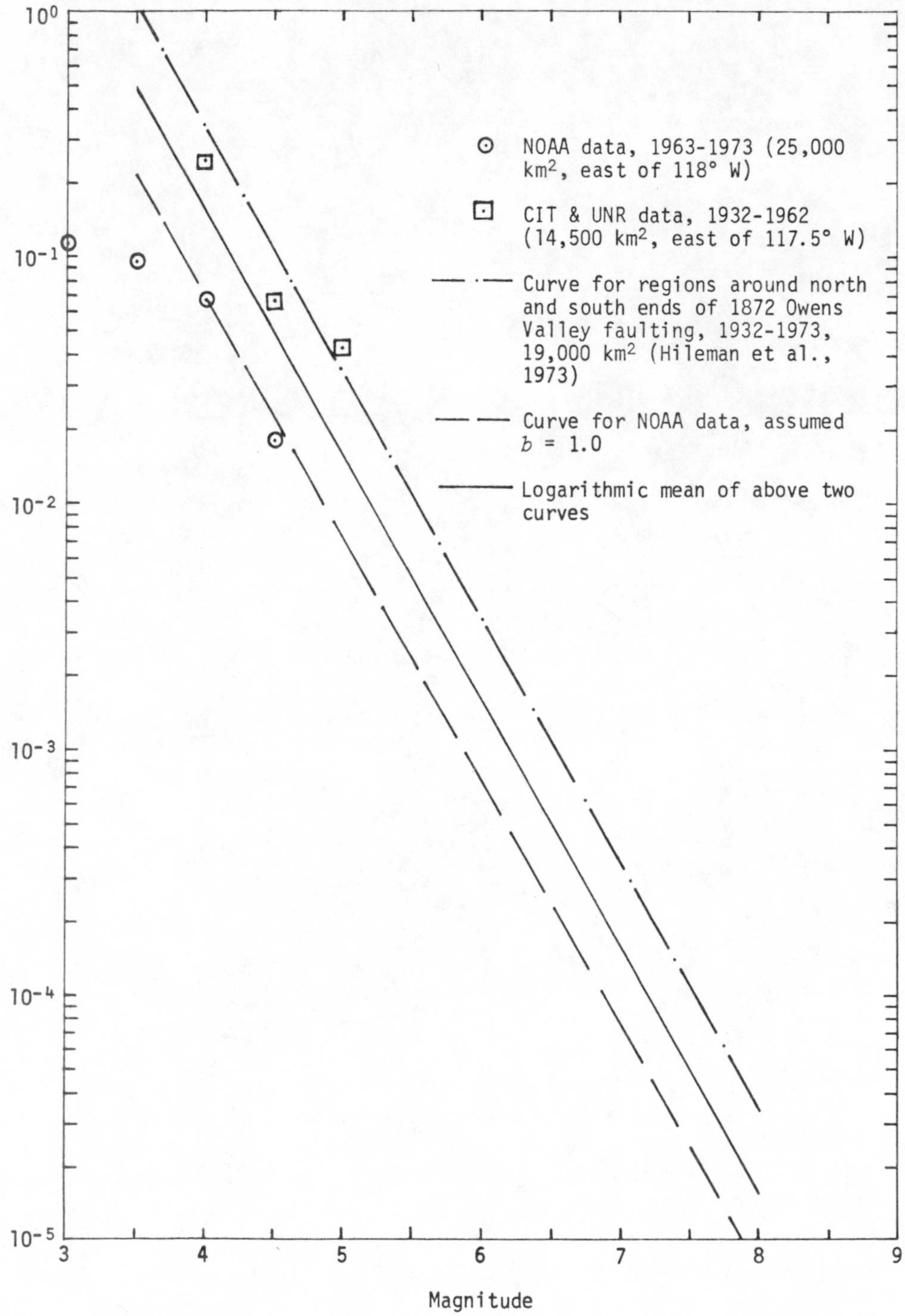

FIGURE 12 MAGNITUDE-FREQUENCY RELATIONS, SEISMOTECTONIC SUBPROVINCE 1 (OWENS VALLEY — DEATH VALLEY REGION), 1932 TO 1973

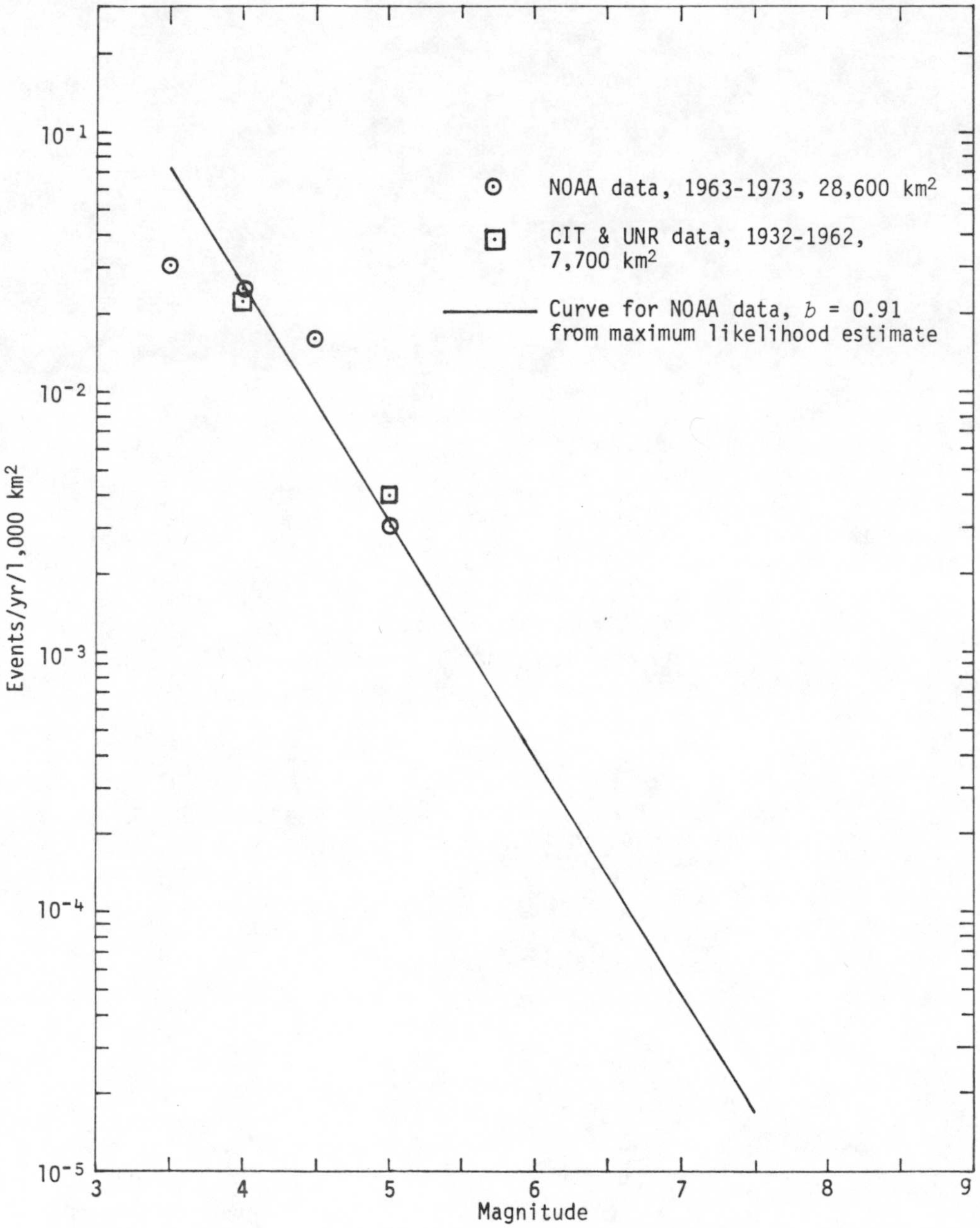

FIGURE 13 MAGNITUDE-FREQUENCY RELATIONS, SEISMOTECTONIC SUBPROVINCE 2 (WESTERN MOJAVE DESERT), 1932 TO 1973

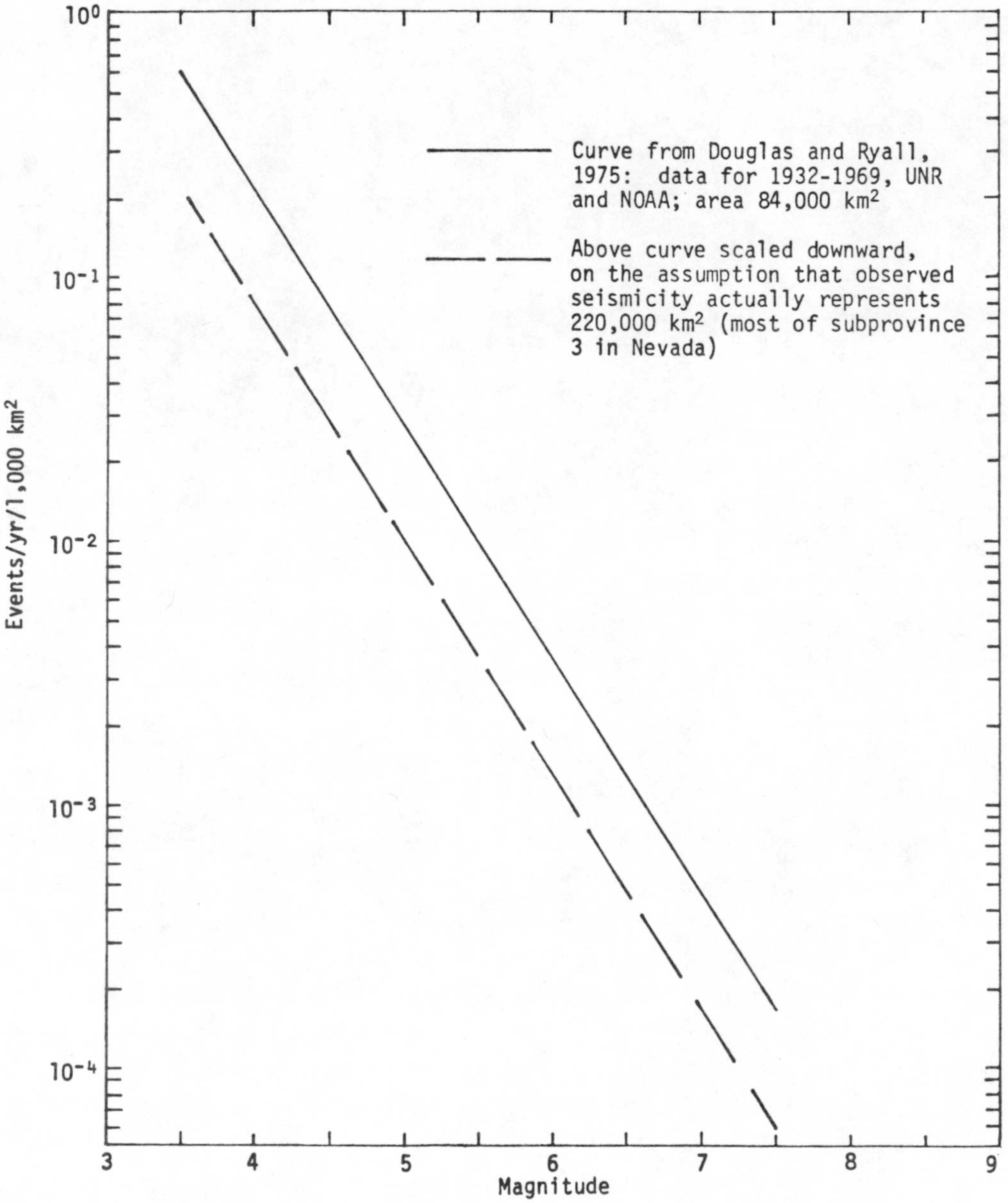

FIGURE 14 MAGNITUDE-FREQUENCY RELATIONS, SEISMOTECTONIC SUBPROVINCE 3 (NORTHERN NEVADA), 1932 TO 1973

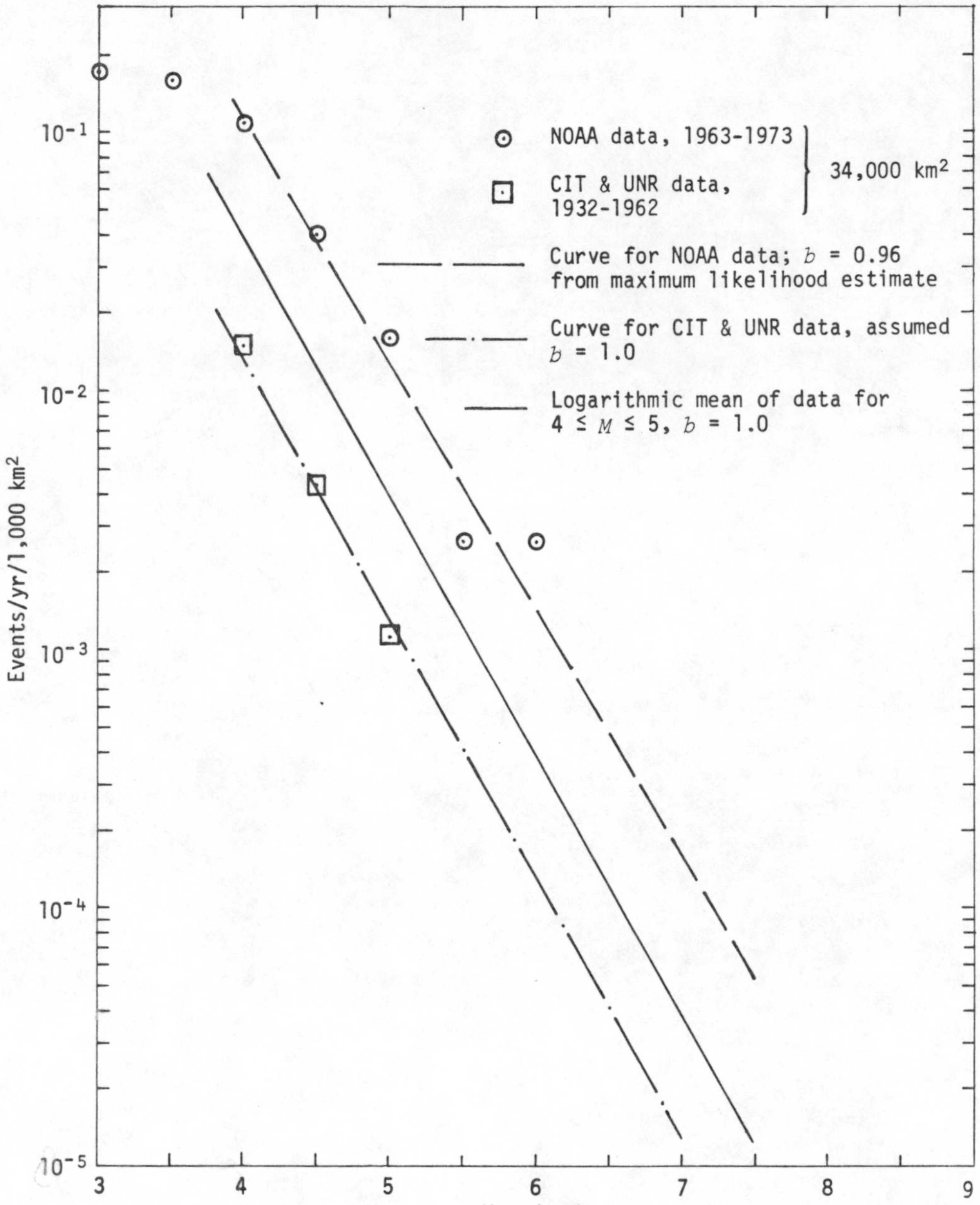

FIGURE 15 MAGNITUDE-FREQUENCY RELATIONS, SEISMOTECTONIC SUBPROVINCE 4 (SOUTHERN NEVADA SEISMIC BELT), 1932 TO 1973

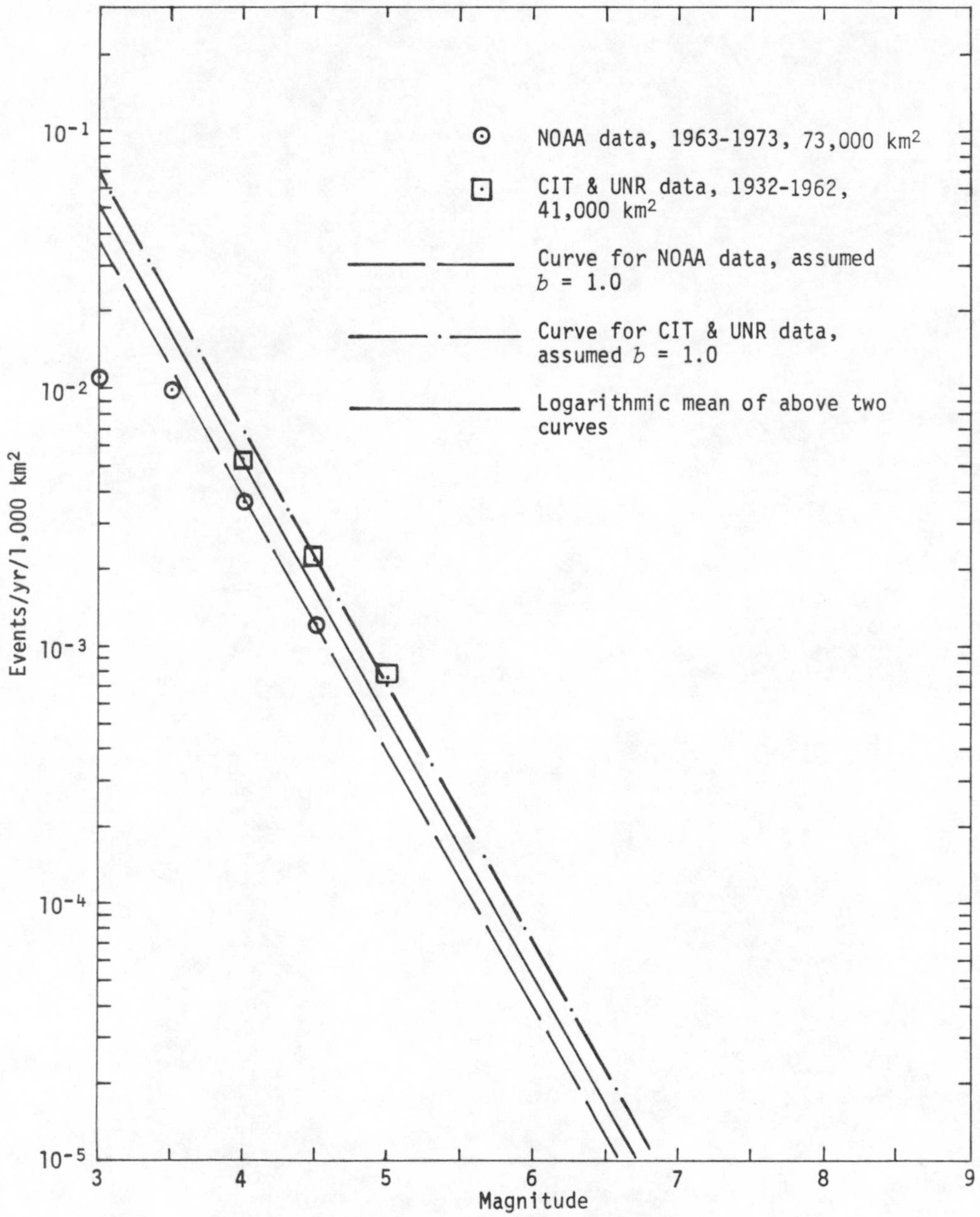

FIGURE 16 MAGNITUDE-FREQUENCY RELATIONS, SEISMOTECTONIC SUBPROVINCE 5 (SOUTHERN BASIN AND RANGE PROVINCE), 1932 TO 1973

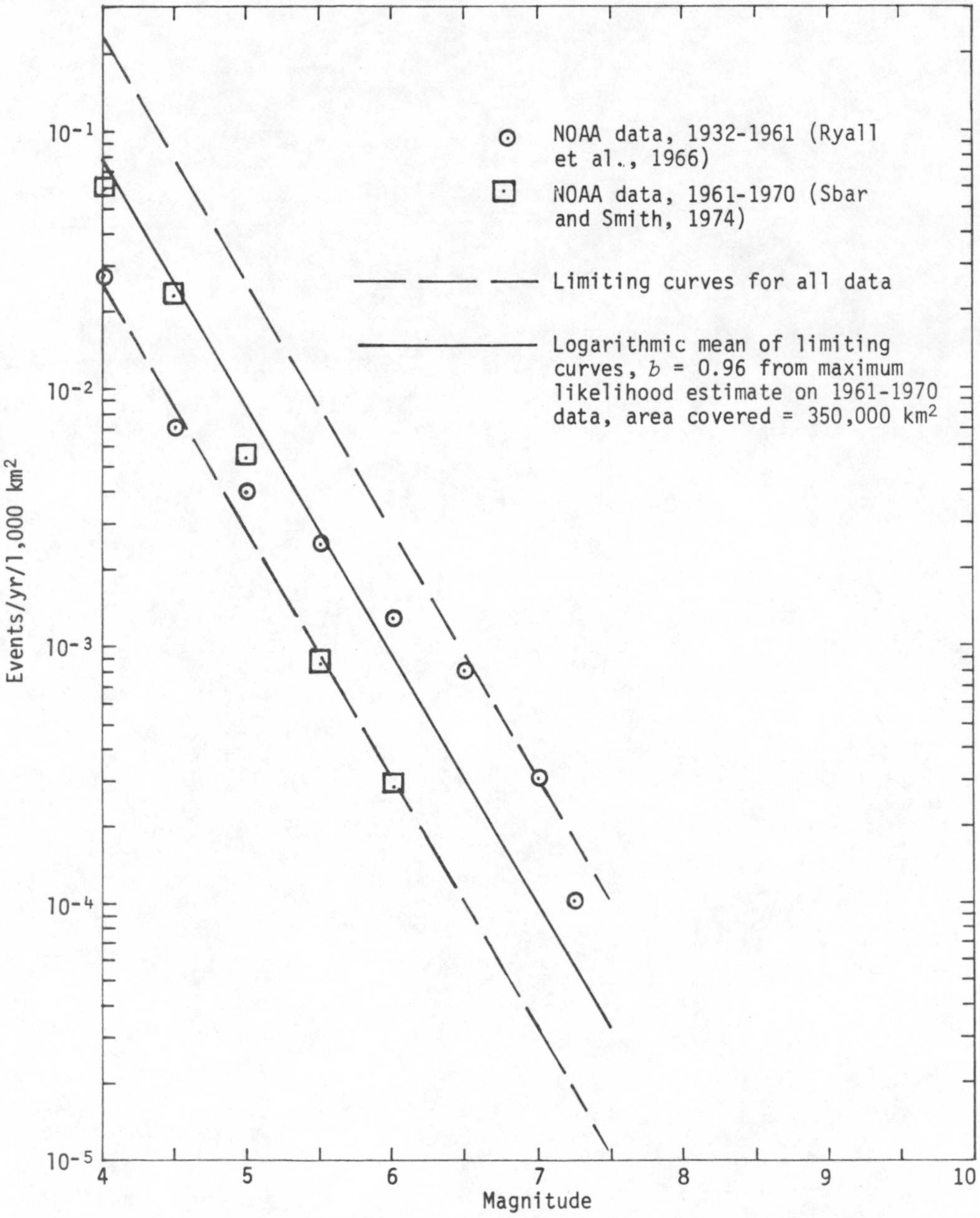

FIGURE 17 MAGNITUDE-FREQUENCY RELATIONS, ROCKY MOUNTAIN MARGINAL ZONE, 1932 TO 1973

is a problem for small data samples, in which stable relative frequencies of events as a function of magnitude may not appear. When the total number of events is sufficiently large (say several hundred), log N is nearly linear in M, with standard deviation less than 0.1 (or ± 25% in N). Also, where N is large and is not overly contaminated by swarm activity, b-values typically are in the range 1.0 ± 0.05. This is true where magnitudes are accurately determined and for complete data sets, that is, for $M \geq M_0$. $M_0 \approx 4.0$ for the data set used in this study because values of log N for $M < 4$ are consistently below the linear relation observed for $M \geq 4$.

In the areas analyzed in this study, the conditions for well-determined b-values are not generally satisfied: N is usually small for $M \geq M_0$, and magnitudes for the pre-1963 period are not always of the best quality. Before 1943, CIT reported magnitude only to the nearest half-unit, which distorts data for the eastern California — southern Nevada area. In the Rocky Mountain marginal zone, magnitudes for the period 1932 to 1960 were generally estimated for maximum reported Mercalli intensities or felt area (Ryall et al., 1966), and the b-slope indicated by these data (about 0.6) is incorrect.

In order to establish optimal c-values from the historic (1932-1973) data, it was assumed that all b-values had to be in the range 0.9 to 1.0, which characterizes better data sets of the western U.S. Where not adopted from the three literature references mentioned above, b-values were estimated using the maximum likelihood method (Aki, 1965), which is considered better than a least-squares approximation for small data sets. When estimated b-values were outside the range 0.95 ± 0.05, a value of 1.0 was arbitrarily assigned. Sources of all adopted b-values are given in Figures 12 to 17 and in Table 1.

Major differences in normalized c-values or $N_{4.0}$-values (number of shocks $M \geq 4$ per year per 1,000 km^2) from different data sets are observed for seismotectonic subprovinces 1 and 4. These differences seem to be related mainly to the time interval analyzed.

In subprovince 1 (Figure 12), the 1932-1962 values are three and a half times greater than the 1963-1973 values. Furthermore, regions around the ends of the 1872 fault rupture zone appear to be some one and a half times as active per unit area as the whole subprovince. A log-mean (geometric-mean) $N_{4.0}$-value is felt to be representative of the entire region.

In subprovince 4 (Figure 15), the 1963-1973 value of $N_{4.0}$ is about seven times greater than the 1932-1962 value. Much of the difference may be explained by the occurrence in 1966 of a large ($M = 6$) earthquake and its many aftershocks (27 with $M \geq 4$). This sort of earthquake series did not occur during the 1932-1962 period. Deleting this event and its aftershocks would lower $N_{4.0}$ for 1963-1973 by 50% to a value only three and a half times that for 1932-1962. The value so obtained is the same as the log mean of the two observed $N_{4.0}$ values and is considered a good estimate for the entire 1932-1973 period.

Magnitude-frequency data for the Rocky Mountain marginal zone (Figure 17) are from published analyses (Ryall et al., 1966; Sbar and Smith, 1974). The highly nonlinear appearance of the 1932-1961 data is probably caused by inconsistent reporting of events and by incorrect magnitudes derived from intensity data. The 1963-1973 data are more linear, but still deviate somewhat from a linear fit. A best-fit curve was found by constructing upper-bound and lower-bound curves (using $b = 0.96$) and then taking the logarithmic mean of these curves.

Interpretation of magnitude-frequency data is presented in the following section.

3.4 Predicted Seismicity

3.4.1 Overview. The regional geographic distribution of historical seismicity has already been outlined in Section 3.3. As noted in that section, historical seismicity (and faulting) has been confined to limited parts of regions that seem to have nearly uniform styles and magnitudes of late Quaternary and Holocene faulting. Because it is assumed that this faulting is indicative of long-term (>10,000 years) geographic distribution of seismicity, the historical record cannot be considered an adequate sample of that distribution. Since this is true for historically active areas measured in tens of thousands of square kilometers, there is little hope that smaller areas could be correctly represented by the historical data. Therefore, it is thought that detailed subdivision of the broad, historically seismic zones would be meaningless for seismicity prediction.

Throughout each of the seismotectonic subprovinces, many faults appear to have comparable rates of late Quaternary displacement. Therefore, it is not possible to state their relative activities with any confidence. Historically, two linear belts of surface faulting accompanied by major earthquakes and by aftershocks lasting for as long as a century (Ryall, 1977) have appeared. One is in subprovince 1; the other is in subprovince 3. Analysis of historic seismicity data indicates that the modal recurrence time for $M \geq 7$ events on individual faults ranges from 2,000 to 6,000 years in subprovinces 1 and 3 and from 140,000 to 270,000 years in subprovince 5 (see Table 1). Therefore, over the next few centuries, it is highly probable that the historically active faults will not rerupture.

It is not possible to say where large earthquakes will occur in the near future, but it is presumed they are rather more likely to occur on younger faults (late Quaternary or Holocene) than on older faults. Time rates of seismic activity per unit area vary among the subprovinces, and hence the spatial probability density of future events should vary similarly. This statement is thought to approach the limit of geographic resolution of long-term and near-future seismicity.

For statistical prediction of earthquake ground motion, estimates of long-term seismicity rates in each of the seismotectonic areas are required. It is shown below that the historical sample may represent future seismicity.

3.4.2 Comparison of Seismicity, Faulting, and Strain Rate. In this section, the historical record of seismicity is compared with crustal strain rates that have been geodetically measured or inferred from spatial frequency of Quaternary fault ruptures.

In section 3.2 of this report, extensional strain rates ($\dot{e}_3$) were estimated for the seismotectonic subprovinces of the Basin and Range province and for the Rocky Mountain marginal zone. For subprovince 1, geodetic strain data for Owens Valley and estimates of Holocene fault displacement rates for Death Valley and the Garlock fault were used. For northern Nevada (subprovince 3) and the Rocky Mountain marginal zone, fault displacement data were used to estimate Holocene strain rates.

For subprovinces 4 and 5 (southern Nevada seismotectonic belt and southern Basin and Range), strain rates were estimated by comparing their Holocene spatial faulting frequency with that of northern Nevada, as

$$\dot{e}_3 \mid_{\text{area } k} = \dot{e}_3 \mid_{\text{area } 3} (\frac{V_k}{V_3}),$$

where V is the spatial frequency of faulting. Because no Holocene faulting is reported in the Nevada portion of subprovince 5 (data are not available for the region outside Nevada), only an upper-bound strain rate could be calculated there; a lower bound was conjectured. Although no Holocene faulting (except for one historic earthquake) is documented in subprovince 2 (western Mojave), it is almost certain to exist; the strain rate in subprovince 2 could only be conjectured.

In Table 2, strain rate estimates are listed for the areas described above, as well as for the Salton Trough. The latter region was included as a check on the others because geodetic strain and seismicity data are considered fairly reliable there. Estimated error factors (EEFs) are stated for both e_3 and $N_{4.0}$ and represent the uncertainty in the seismotectonic activity.

Figure 18 is a plot of log $\dot{e}_3$ against log $N_{4.0}$. A power curve was fitted to five data points: Basin and Range subprovinces 1, 3, and 4; the Salton Trough; and the Rocky Mountain marginal zone. The curve is expressed by

$$\dot{e}_3 = 1.88 \times 10^{-6} (N_{4.0})^{1.64}$$

and has a correlation coefficient of 0.98. It is noteworthy that the curve extrapolates to the middle of the strain-rate range estimated for subprovince 5. Also, the strain-rate range taken for subprovince 2 lies near the curve.

The good fit of the strain and seismicity data is surprising. Although it is reasonable to expect a close relationship between strain rate and seismicity, consideration of the estimated error factors (ranging from 1.5 to 3)

TABLE 2

STRAIN RATES AND SEISMICITY IN THE SEISMOTECTONIC SUBPROVINCES

Province	$\dot{e}_3 (\mathrm{yr}^{-1})^*$	EEF($\dot{e}_3$)†	$N_{4.0}$*	EEF($N_{4.0}$)†	Source of Strain Data
Basin and Range:					
subprovince 1	10^{-7}	2	0.15	2	Geodetic and Holocene fault displacement
subprovince 2	10^{-8} ?	?	0.025	1.5	Conjectured
subprovince 3	5×10^{-8}	1.5	0.08	2	Holocene fault displacement
subprovince 4	7×10^{-9}	2	0.04	3	Spatial frequency of Holocene faulting relative to subprovince 3
subprovince 5	$<10^{-9}$	?	0.005	1.5	
Rocky Mountain marginal zone	2.3×10^{-8}	2	0.075	3	Holocene fault displacement
Salton Trough	5×10^{-7}	1.5	0.50	<1.5	Geodetic (triangulation)

* maximum principal strain rate per year: extensional except in Salton Trough, where compressional

† estimated error factor (or uncertainty) in the logarithmic mean: $\log x = \log \bar{x} \pm \log \mathrm{EEF}$ (where x represents $\dot{e}_3$ or $N_{4.0}$)

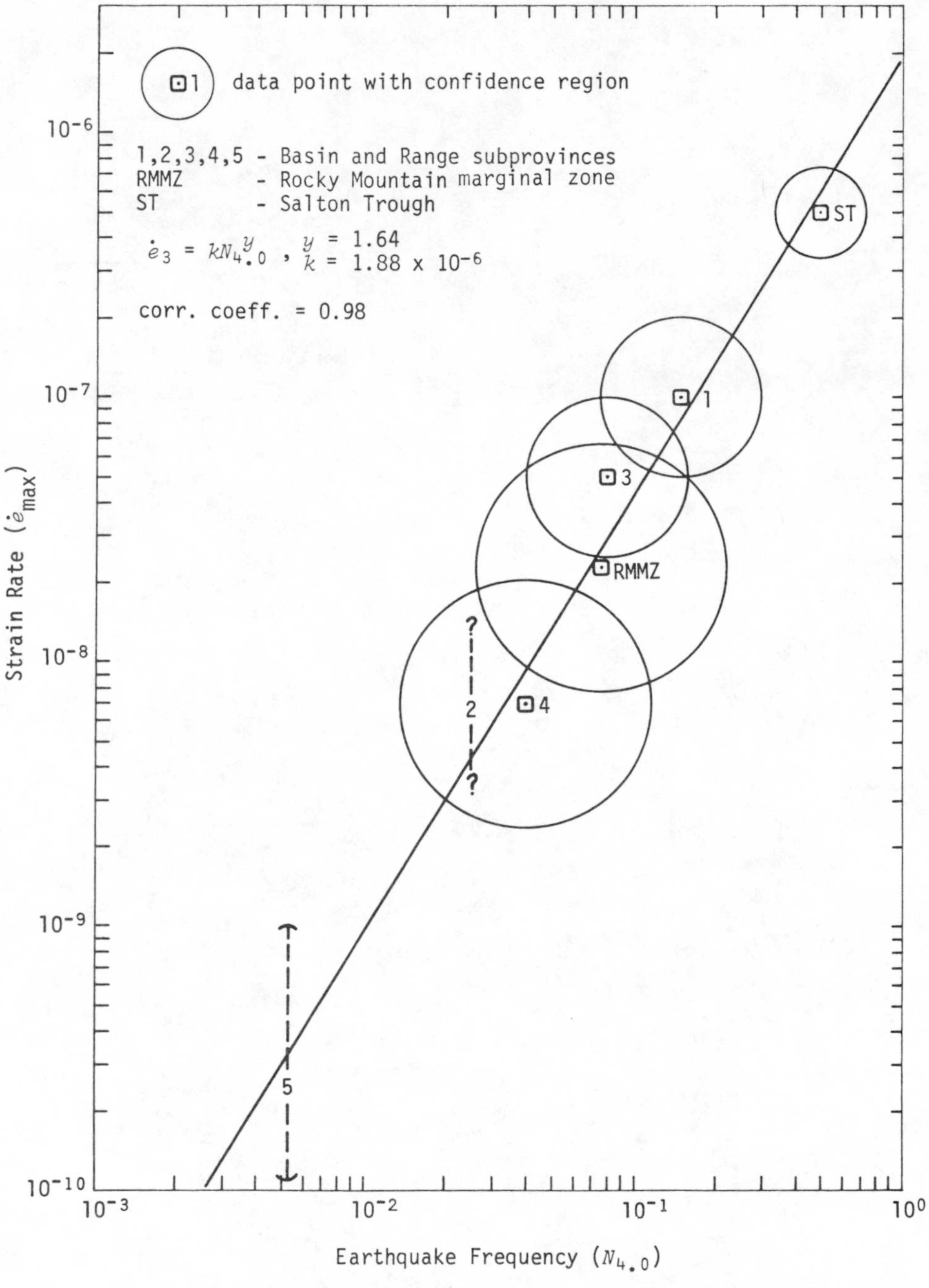

FIGURE 18 CORRELATION OF EARTHQUAKE FREQUENCY AND STRAIN RATE AMONG SEISMOTECTONIC SUBPROVINCES

suggests that an element of chance is involved. Still, it is remarkable that all five data points lie within the range ± log 1.6 from predicted values. This indicates that the seismicity rates observed over a 40-year period may approximate the 10,000-year average within a factor of 2 if it is assumed that (1) strain rate and seismicity really do have a simple, power-curve relationship, and (2) the relationship is not substantially different for strike-slip and normal-faulting modes of strain release.

The correlation observed in Figure 18 suggests that the 40-year seismicity record could represent a much longer period of time rather well. Also, it at least indicates no significant discrepancy in the data, and in itself offers no reason to question the use of the observed seismicity data for prediction. Nevertheless, the estimated error factors of the historic seismicity samples are considered to be realistic assessments of the uncertainty concerning long-term seismicity. Thus, they will be used in evaluating an upper bound of earthquake hazard.

4. PROBABLE GROUND MOTION IN LAS VEGAS

4.1 Method of Analysis

The hazard of earthquake ground motion in Las Vegas is predicted in terms of maximum probable accelerations that result from the regional pattern of long-term seismicity described in the preceding section of this report. Predicted accelerations are for "average" ground conditions, i.e., on alluvium of indeterminate thickness. No attempt has been made to model ground response to incident accelerations in Las Vegas Valley.

4.1.1 Computer Program HAZARD. A computer program named HAZARD was developed for the study to compute annual rates of exceedance of given site accelerations A due to earthquakes of magnitude M or greater for each of the tectonic provinces already described; these effects are summarized as the probability of exceedance of a given site acceleration A in any period of T years. The method was developed independently, but it is similar to that of Douglas and Ryall (1975). A brief description of the theory and computational procedure employed in the program follows. Program HAZARD is listed in Appendix B.

The program considers both line (fault) and area sources. Area sources are specified as portions of annular rings (or whole circles) centered on the site being analyzed. Since source-site azimuth is immaterial, an annular source may be treated as a radial line source whose source density increases as the square of source-site distance. Ground accelerations for given earthquake magnitude and distance are assumed to be lognormally distributed; this distribution has been amply documented in the literature (Murphy and O'Brien, 1977). Calculations proceed as follows. First, consider an arbitrary site acceleration A; then, given the occurrence of an earthquake of magnitude M at distance R from the site on source S, find the probability that the earthquake will cause acceleration $a \geq A$ at the site. This is given by

$$P_S(M,R,A) = 1 - \Phi\left[\frac{\log A - a^*(M,R)}{\sigma}\right],$$

where $a^*(M,R)$ is a central value of the logarithm of site acceleration for an earthquake of magnitude M at distance R; R is the shortest distance from the seismic fault rupture to the site; σ is the standard deviation of $a^*(M,R)$; and Φ is the cumulative normal distribution function.

Because an earthquake of a given magnitude is considered to have uniform likelihood along a particular line source, the probability that any magnitude M earthquake on the line source will cause $a \geq A$ can be computed by

$$P_S(M,A) = \frac{1}{L} \int_0^L P_S[M,R(l),A]\,dl$$

where L is the length of the line source.

In this integration (performed using Simpson's rule), the length of the rupture is taken as two-thirds the length of the aftershock zone of a magnitude M earthquake (Patwardhan and Tocher, 1975).

The probability density (in time) of the rate of exceedance acceleration A with respect to magnitude is given by

$$D_S(M,A) = P_S(M,A) \frac{dN(M)}{dM}$$

where N is the number of events per year of magnitude M or greater. The recurrence relation is commonly expressed in the form

$$\log_{10} N = c - bM$$

so that

$$\frac{dN}{dM} = b(\ln 10)^{c-bM}$$

Then, the rate at which earthquakes of magnitude $M_1 \leq M \leq M_2$ on source S cause $a \geq A$ is given by

$$R_S(M_1,M_2,A) = \int_{M_1}^{M_2} D_S(M,A)\,dM$$

where M_2 is an upper-bound magnitude for S. It appears that, for engineering purposes, all significant accelerations may be included by taking $M_1 = 3$.

Finally, the total hazard at the site is found by summing the rates of the various sources,

$$\nu(A) = \sum_{s} R_S(M_1, M_2, A)$$

Assuming that earthquake occurrence follows a Poisson process, the probability that site acceleration a equals or exceeds A in any period of T years is then

$$P(a \geq A \text{ in } T \text{ yrs}) = 1 - e^{-\nu(A)T}$$

<u>4.1.2 Acceleration as a Function of Distance and Magnitude.</u> Program HAZARD requires that peak site acceleration be specified as a function of source magnitude and source-siting distance. The choice of the function $a^*(M,R)$, a central value of the mean logarithm of site acceleration, is rather critical in the results obtained from HAZARD. Gutenberg and Richter (1956) analyzed much ground-acceleration data for California, including all available strong-motion accelerograph records. For this, they developed an empirical relation for epicentral acceleration (A_0) as a function of magnitude and also for the ratio of site acceleration (A_s) to epicentral acceleration as a function of epicentral distance (R). For $A_0(M)$, they found

$$\log A_0 = -1.63 + 0.81M - 0.027M^2,$$

in which the observed constant (-1.63) was lowered to -2.1. This was done in order to correct the data to a rock datum; however, the value -1.63, appropriate to alluvial sites, will be used here. The attenuation factor, log (A_s/A_0), was tabulated and graphed by Gutenberg and Richter.

In this study, Gutenberg and Richter's (1956) attenuation function for the epicentral distance range of 20 to 100 km has been matched and extended from 100 to 500 km using additional data from the Kern County (1952), Borrego Mountain (1968), and San Fernando (1971) earthquakes. The data have been fit by the equation

$$\log \alpha = \frac{\sqrt{1 + U^2} + U - 2\exp(-\frac{1}{2}W^2)}{5}$$

where

$$\alpha = A_0/A_s$$

$$U = 5(\log R - 1.27)$$

$$W = 4(\log R - 2.40)$$

Using the above two equations,

$$a^*(M,R) = \log A_0(M) - \log \alpha(R), \; 20 \leq R \leq 500 \text{ km}$$

This function, graphed in Figure 19, is used in program HAZARD.

For $R < 20$ km, the acceleration data compiled by Gutenberg and Richter are very limited, and it was necessary to establish $A(M,R)$, utilizing more recent near-field accelerograph data. These indicate much greater near-field accelerations for magnitudes less than about 7 than do the Gutenberg-Richter data and empirical functions. From acceleration data presented by Schnabel and Seed (1973), Page et al. (1972), and Hanks and Johnson (1976), it is found that

$$\log A_0'(M) = -1.97 + 1.31M - 0.089M^2$$

represents a distinct improvement. We have decided to take $A(M,R) \leq 3 \leq A_0'(M)$. For $3 \leq R \leq 20$ km, we compute $a^*(M,R)$ by linear interpolation between $\log A_0'(M)$ and $\log A_S(M,R = 20)$. Thus $a^*(M,R)$ is continuous at $R = 20$ km, as shown in Figure 19.

Major uncertainty is present in the acceleration function described, and the standard deviation (σ) is a critical factor in computation of probabilities of exceedance. Blume (1977) found $\sigma = 0.25$ for $a^*(M,R)$, or a factor of 1.8 for $A_S(M,R)$.

Uncertainty seems to increase with decreasing magnitude and epicentral distance. In the near field (i.e., epicentral distance comparable to source dimension), the "fine structure" of the propagating fault rupture is observed. This appears in higher-frequency body waves (≥ 5 Hz), which are attenuated rapidly with distance. As Hanks and Johnson (1976) have pointed out, short-

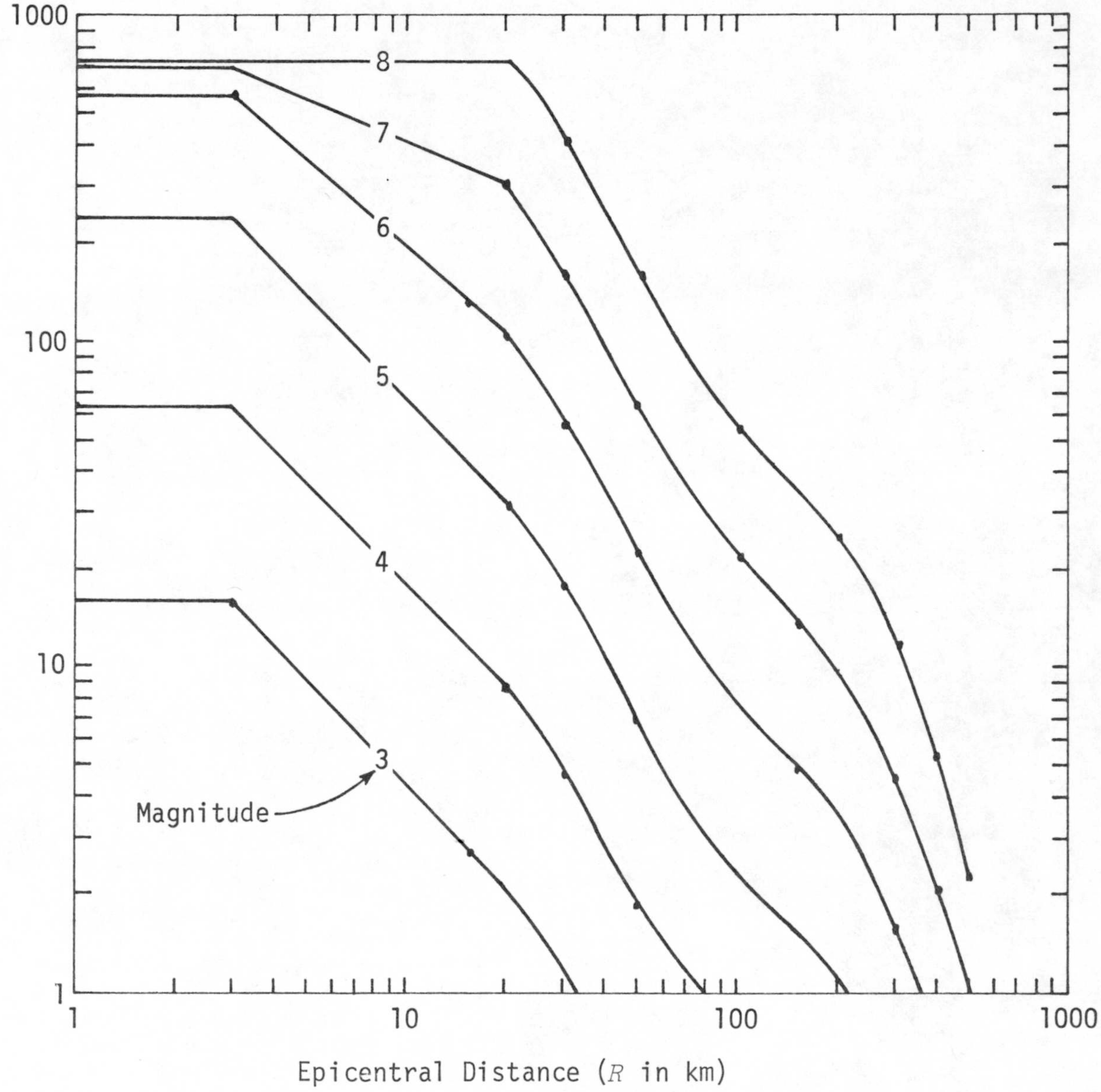

FIGURE 19 ACCELERATION AS A FUNCTION OF DISTANCE AND MAGNITUDE

lived bursts of high-frequency ($\geq$ 10 Hz), high-amplitude energy may be released as the rupture passes through local regions of high effective shear stress. They believe that peak accelerations observed in the near field are determined by the maximum effective shear stresses encountered by the propagating rupture rather than by magnitude. Magnitude generally is determined from lower-frequency ($\leq$ 5 Hz) motions recorded in the far field and is a function mainly of average particle motions along rupture segments at least 1/2 km in length; hence it does not reflect the smaller parts of the source. Therefore, it is not surprising that peak accelerations of up to 0.6g have been observed for M = 4-1/2 shocks at distances of a few kilometers. The point of this discussion is that magnitude is a poor predictor of peak acceleration for smaller-magnitude (M < 4-1/2) shocks at distances less than about 10 to 20 km, and uncertainty in acceleration may approach a factor of ten for these events.

The use of a standard deviation of 0.25 for $a^*(M,R)$ in HAZARD calculations is thought to be realistic for $M \geq$ 4-1/2, but may be too low for $M \leq$ 4-1/2. However, it is important to note that predominant period and duration of motion are very small for these smaller events. Therefore, they are rarely, if ever, of any consequence to structures.

4.1.3 Source Model. Seismic source areas were modeled as a series of annular ring segments that included the previously mentioned seismotectonic subprovinces within a limiting radius of 300 km. In addition, the San Andreas fault was modeled as two line sources -- one north and the other south of Cajon Pass. The segment south of Cajon Pass included all Salton Trough seismicity, i.e., all seismicity of the branching southern San Andreas fault system. Not including area sources beyond 300 km has a negligible effect upon calculated arrival rates of accelerations greater than 0.01g, the minimum value considered in this study. Maximum magnitude was set at 7-1/2 for all sources except subprovince 1 and the northern segment of the San Andreas fault; for these two, it was set at 8 and 8-1/4, respectively.

Seismicity of the area sources was specified and is given in Table 1 in terms of best-estimate c and b. Upper-bound c-values for the two sources most critical to Las Vegas (subprovinces 4 and 5) were also used.

4.1.4 Results and Interpretation. Results of HAZARD calculations are summarized in Figures 20 and 21 and in Tables 3 and 4. Figure 20 is a plot of the mean rates of exceedance per year and mean recurrence time of peak ground accelerations in Las Vegas. The term *mean rate of exceedance* means the average frequency of occurrence, or arrival rate, of ground accelerations exceeding any given value; the term *mean recurrence time* means the average time between occurrences of acceleration greater than or equal to any given value. It is very important to remember that the acceleration corresponding to a particular frequency of occurrence (or recurrence time), sometimes called a maximum probable acceleration, has a 63% chance of exceedance. Thus, Figure 20 shows the distribution of peak accelerations with respect to time, *with a set probability (63%) of being exceeded.*

In order to consider other probabilities of exceedance, the Poisson probability function must be used:

$$P(a \leq A \text{ in } T \text{ yrs}) = 1 - e^{-\nu(A)T}$$

where $\nu(A)$ is the mean arrival rate of accelerations greater than or equal to A (or rate of exceedance of A). In Figure 21, $P(a > A$ in T yrs) is plotted against A for several values of T. The figure shows, for example, that the probability of exceeding 0.10g in 100 years is 8%; for 0.05g in 50 years, it is 15%, and so on.

These results have been checked against observed occurrences of peak accelerations in Las Vegas. Since 1966, three earthquakes have produced peak ground accelerations greater than or equal to 0.003g in Las Vegas: the 1966 Utah-Nevada border earthquake, the 1968 Borrego Mountain earthquake, and the 1971 San Fernando earthquake. The last may be considered as related closely to the northern San Andreas source. The observed rate of exceedance of 0.003g in Las Vegas, therefore, is about 0.3 per year. This is close to the curve of Figure 20, extrapolated to smaller accelerations. Actually, the data point falls on the parallel curve for acceleration less one standard deviation (in acceleration).

The curves presented show that the probability of occurrence of moderate to high peak accelerations is indeed low in Las Vegas compared with other areas

TABLE 3

ANNUAL RATE OF EXCEEDANCE OF GIVEN PEAK ACCELERATIONS IN LAS VEGAS, OCCASIONED BY SEISMICITY IN THE MODELED SOURCES

Acceleration(g)	Source Areas*							Sum A**	Sum B†
	1	2	3	4	5	RMMZ	SAF		
0.01	9.8×10^{-3}	1.7×10^{-3}	5.9×10^{-3}	1.0×10^{-2}	3.7×10^{-2}	6.6×10^{-3}	8.7×10^{-3}	8.1×10^{-2}	4.3×10^{-2}
0.02	2.0×10^{-3}	2.8×10^{-4}	8.2×10^{-4}	2.2×10^{-3}	1.3×10^{-2}	1.1×10^{-3}	9.7×10^{-4}	2.3×10^{-2}	7.4×10^{-3}
0.05	1.4×10^{-4}	9.7×10^{-6}	2.0×10^{-5}	2.0×10^{-4}	2.6×10^{-3}	3.8×10^{-5}	1.7×10^{-5}	3.1×10^{-3}	4.2×10^{-4}
0.10	9.4×10^{-6}	3.0×10^{-7}	4.0×10^{-7}	2.0×10^{-5}	7.0×10^{-4}	1.1×10^{-6}	3.0×10^{-7}	7.3×10^{-4}	3.0×10^{-5}
0.20	3.0×10^{-7}	-	-	4.2×10^{-6}	1.6×10^{-4}	-	-	1.6×10^{-4}	4.5×10^{-6}
0.50	- ‡	-	-	-	1.5×10^{-6}	-	-	1.5×10^{-5}	-

* Numbers 1 through 5 refer to Basin and Range subprovinces, RMMZ is Rocky Mountain marginal zone; SAF is San Andreas fault

** Sum of exceedance rate for all sources

† Sum of exceedance rate for all sources except source 5

‡ Dashes mean less than 10^{-7}

TABLE 4

MOST PROBABLE MAGNITUDES CAUSING GIVEN ACCELERATIONS IN LAS VEGAS, ACCORDING TO SOURCE AREA

Acceleration(g)	Source Areas*						
	1	2	3	4	5	RMMZ	SAF
0.01	6-1/2	6-3/4	7	6	3-1/2	6-1/2	7-1/2+
0.02	7-1/2	7-1/4	7-1/2	6-1/2	3-3/4	7-1/4	7-1/2
0.05	8	7-1/2	7-1/2	7-1/4	4-1/4	7-1/2	7-1/2+
0.10	8	-	-	7-1/2	4-1/2	7-1/2	-
0.20	-†	-	-	-	5	-	-
0.50	-	-	-	-	5-1/2	-	-

* Numbers refer to Basin and Range subprovinces; RMMZ is Rocky Mountain marginal zone; SAF is San Andreas fault

† Dashes mean that rate of exceedance is less than 10^{-6}/yr; thus the event is negligible.

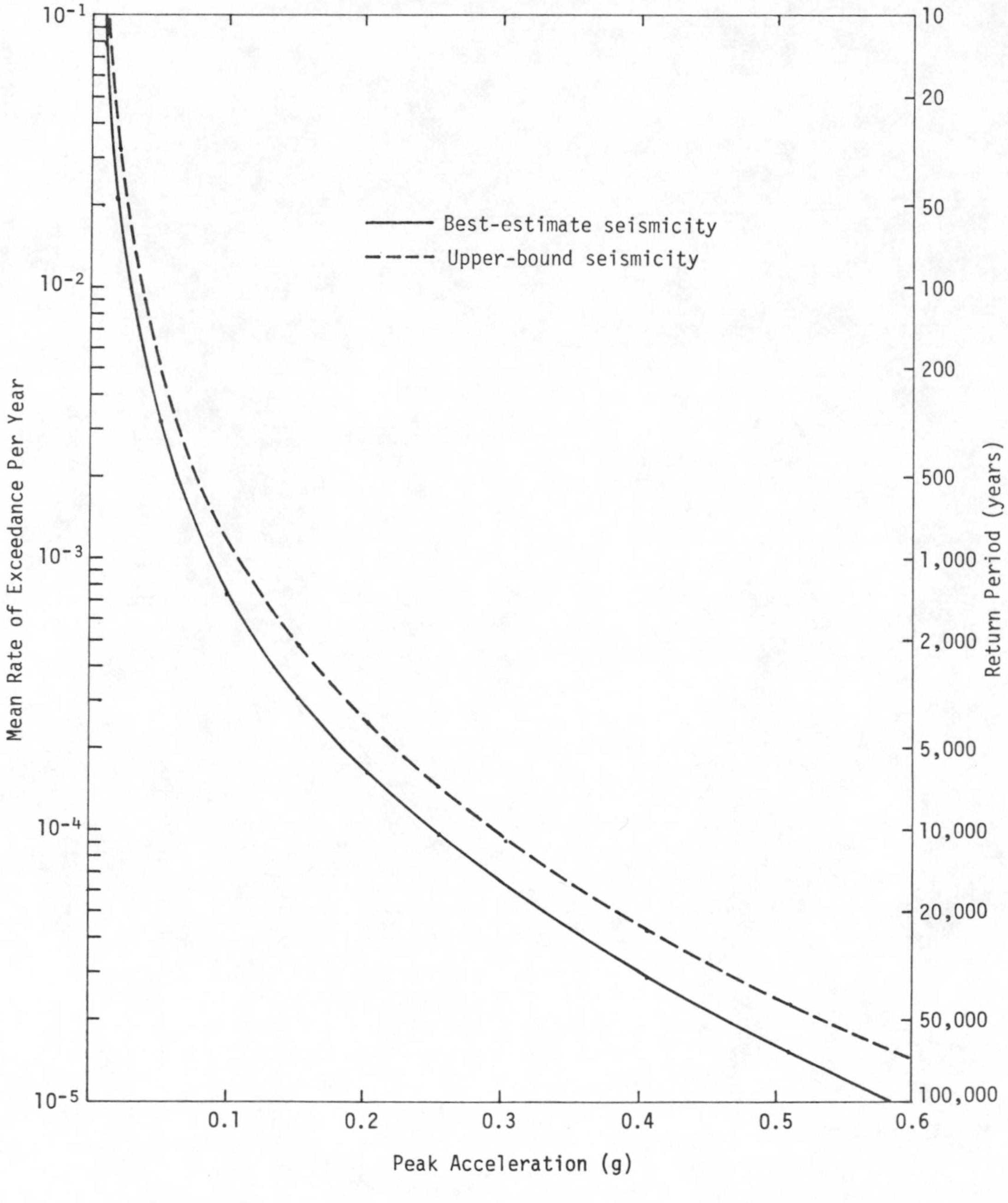

FIGURE 20 MEAN RATE OF EXCEEDANCE AND MEAN RECURRENCE TIME OF PEAK ACCELERATIONS IN LAS VEGAS

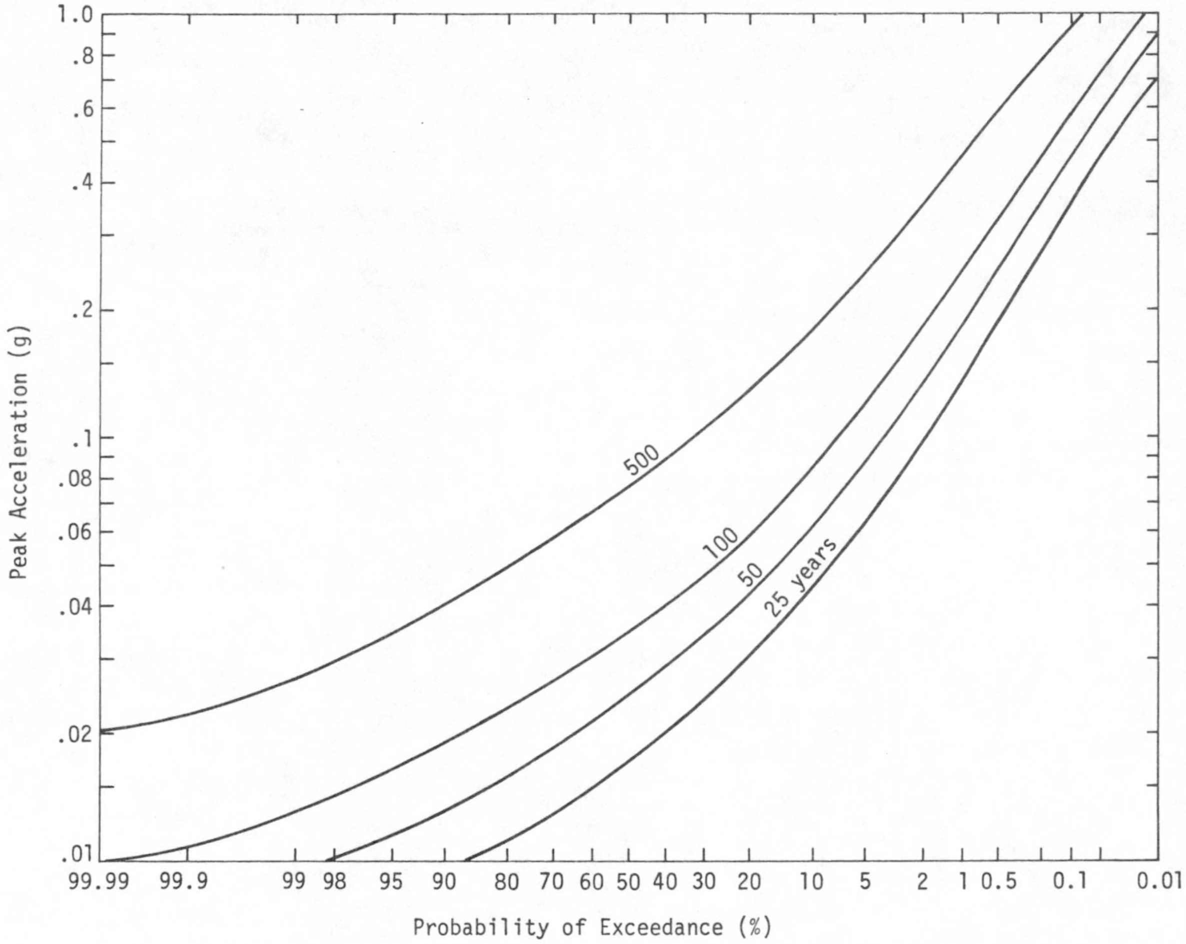

FIGURE 21 PROBABILITY OF EXCEEDANCE OF PEAK GROUND ACCELERATION IN LAS VEGAS FOR GIVEN PERIODS OF TIME

in the Far West. In 100 years, there is only a 7% chance of exceeding 0.1g and a 1% chance of exceeding 0.25g. There is a 50% chance of exceeding 0.035g in 100 years or 0.025g in 50 years; the mean recurrence time for 0.01g is 12 years. However, these small, rather frequent accelerations could be damaging to high buildings when associated with ground motion of long period and duration, especially where there is significant site resonance.

Peak acceleration alone is not very well correlated with earthquake damage potential; spectral character, which can be crudely stated in terms of predominant period and duration, also has an important influence. Characteristics of ground motion at longer periods (i.e., >1.0 sec), which are pertinent to high-rise damage prediction, are discussed in terms of predicted response spectra in the next section of this report. Table 5 presents estimates of the most probable predominant periods and durations to be associated with given accelerations. These were derived by listing, for each of the seismicity sources, the most probable magnitudes that give rise to given accelerations (Table 4) and comparing these with the rate of exceedance of those accelerations (Table 3).

Examination of Table 3 shows that accelerations of 0.01g to 0.02g are as likely to result from local shocks (in subprovince 5) as from distant shocks (Sum B, for all shocks outside subprovince 5). Table 4 shows that the most probable events causing such accelerations are local shocks of magnitude 3-1/2 to 3-3/4 and distant shocks of magnitude 6 to 7-1/2. Weighted-mean magnitudes are given in Table 5; corresponding values of predominant period and duration are from Gutenberg and Richter (1956) and Housner (1970).

It is important to note that accelerations exceeding 0.05g are much more likely to result from local shocks than from distant shocks: for 0.05, 0.10, and 0.20g, the odds are 6:1, 23:1, and 35:1, respectively; for 0.50g they are more than 10^7:1. While the probability of exceeding 0.10g is 7% in 100 years, the associated predominant period and duration are 0.2 sec and 1.0 sec, respectively (Table 5). Therefore, such local events may have very little engineering significance. While 0.5g is associated with a duration of 6.0 sec, its probability of exceedance is extremely small -- only 0.15% (0.0015) in 100 years.

TABLE 5

MOST PROBABLE DURATION AND PREDOMINANT PERIOD OF GROUND MOTION ASSOCIATED WITH GIVEN ACCELERATION IN LAS VEGAS

A	M	d	T
0.01	6-1/2 or 3-1/2*	18.0 or 0.2*	0.5 or 0.2*
0.02	7-1/2 or 3-3/4*	30.0 or 0.3*	0.5 or 0.2*
0.05	4-1/2	0.7	0.2
0.10	4-1/2	1.0	0.2
0.20	5	2.0	0.25
0.50	5-1/2	6.0	0.30

* The two values shown have nearly equal probabilities

Note: A = acceleration (g)
M = magnitude
d = duration of strong motion (sec)
T = predominant period of ground motion (sec)

The probability of exceeding 0.02g in 30 years as a result of distant seismicity occurring outside subprovince 5 is 25%. This acceleration has associated duration of 30 sec and predominant period of 0.5 sec. Site-dependent spectral amplification (resonance) in Las Vegas, described below, is such that spectral acceleration in downtown Las Vegas could exceed 0.08g at 0.5-sec period and 5% damping; spectral velocity at 3.0-sec period could exceed 55 cm/sec.

4.2 Response Spectra

4.2.1 Response Spectral Ratios. It is well known that the amplitudes of seismic ground motion at a particular site depend upon frequency and the properties of underlying earth materials. In particular, the shear modulus and damping properties of the uppermost few thousand feet seem to be controlling factors.

Many underground nuclear explosions at the NTS have been recorded by seismographs at several locations in Las Vegas. These data have been extensively analyzed and published in reports by Environmental Research Corporation. Four reports deal exclusively with the variations of ground motion spectral character among various Las Vegas sites.

Ground motion in Las Vegas resulting from NTS explosions was first described by Davis and Lynch (1970), who found that peak spectral (pseudo-relative) particle velocities, or PSRVs, were consistently higher in the downtown area than in the outskirts of the city. Ratios of PSRVs at several sites with respect to station SE-6, on the University of Nevada campus, were computed for a number of periods, resulting in intrasite amplification spectra. Ratios significantly greater than 1.0 were in the period range 0.4 to 2.5 sec (frequencies of 2.5 to 0.4 Hz). Squires Park station seemed to represent the downtown area and had PSRV ratios as large as 2.2. Analyses of arrival times and periods of peak motions showed that peak PSRV ratios are associated with body shear waves (S) and surface waves (apparently both Love and Rayleigh).

Two later reports on this subject (West, 1971; Davis, 1972) reached similar conclusions using data from additional explosions and recording stations.

Murphy and Hewlett (1975) extended these studies in their preliminary microzonation of Las Vegas. Their findings were summarized in 12 contour maps, showing PSRV ratios relative to station 801 in each of 12 period intervals, ranging from 0.16 to 6.0 sec. Station 801, the reference site, was located near the intersection of West Charleston and Decatur boulevards. The maps show ratios of radial, transverse, and vertical components of motion. Ratios of horizontal motion in the downtown area average more than 2 for periods between 0.5 and 6.0 sec and reach a maximum of 7.5 at 3.0 sec; ratios of vertical motion are always smaller. Locations of the recording stations mentioned above are shown in Figure 22.

Table 6 presents PSRV data at period bands relevant to seismic engineering of high-rise buildings; these data were interpolated from the maps of Murphy and Hewlett (1975). The response patterns described above are demonstrated in Table 6. Site amplification relative to Station 801 increases toward the downtown area of Las Vegas (e.g., Station 805 and the Squires Park station). These trends are especially pronounced for ground motion periods greater than about 1.0 sec. Thus, potential exists for damage to high-rise structures even at relatively low peak accelerations. Peak acceleration defines only the high-frequency (short-period) end of a response spectrum.

The geographic variation in ground motion shown by Murphy and Hewlett is strikingly large for an area that would seem to have fairly uniform subsurface geology. Davis (1972) speculated that variations in both thickness and compaction of alluvium control spectral characteristics of ground motion in Las Vegas. Published data on alluvium thickness (Figure A10 of Appendix A) do not demonstrate correlation with PSRV ratios. However, the correlation with land subsidence (Davis, 1972, Figure 4.5), presumed due to groundwater withdrawal, is impressive: maximum subsidence occurs in the same area as maximum PSRV ratios. In general, because of ground motion amplitude and acoustic impedance are inversely correlated, the PSRV anomaly indicates an area of relatively low density and velocity in the valley alluvium. Subsidence could be expected to be greater where the density is lower and the compaction potential therefore higher.

4.2.2 Predicted Ground Motion Spectra. In earthquake engineering of high-rise buildings and other sensitive structures, prediction of site ground

TABLE 6

PSRV RATIOS OF RADIAL COMPONENT OBSERVED RELATIVE TO STATION 801 IN LAS VEGAS

Station	Period Band (sec)						
	0.30-0.40	0.55-0.74	1.00-1.35	1.35-1.82	1.82-2.46	2.46-3.33	3.33-4.48
824	1.1	0.9	0.8	0.8	0.7	0.7	<1.0
Squires Park	0.9	1.7	2.1	3.2	3.5	4.5	6.5
805	0.8	1.4	2.0	2.5	3.3	5.1	4.2
818	0.8	1.3	1.9	1.9	1.8	2.3	3.0

Note: Data interpolated from response maps published by Murphy and Hewlett (1975).

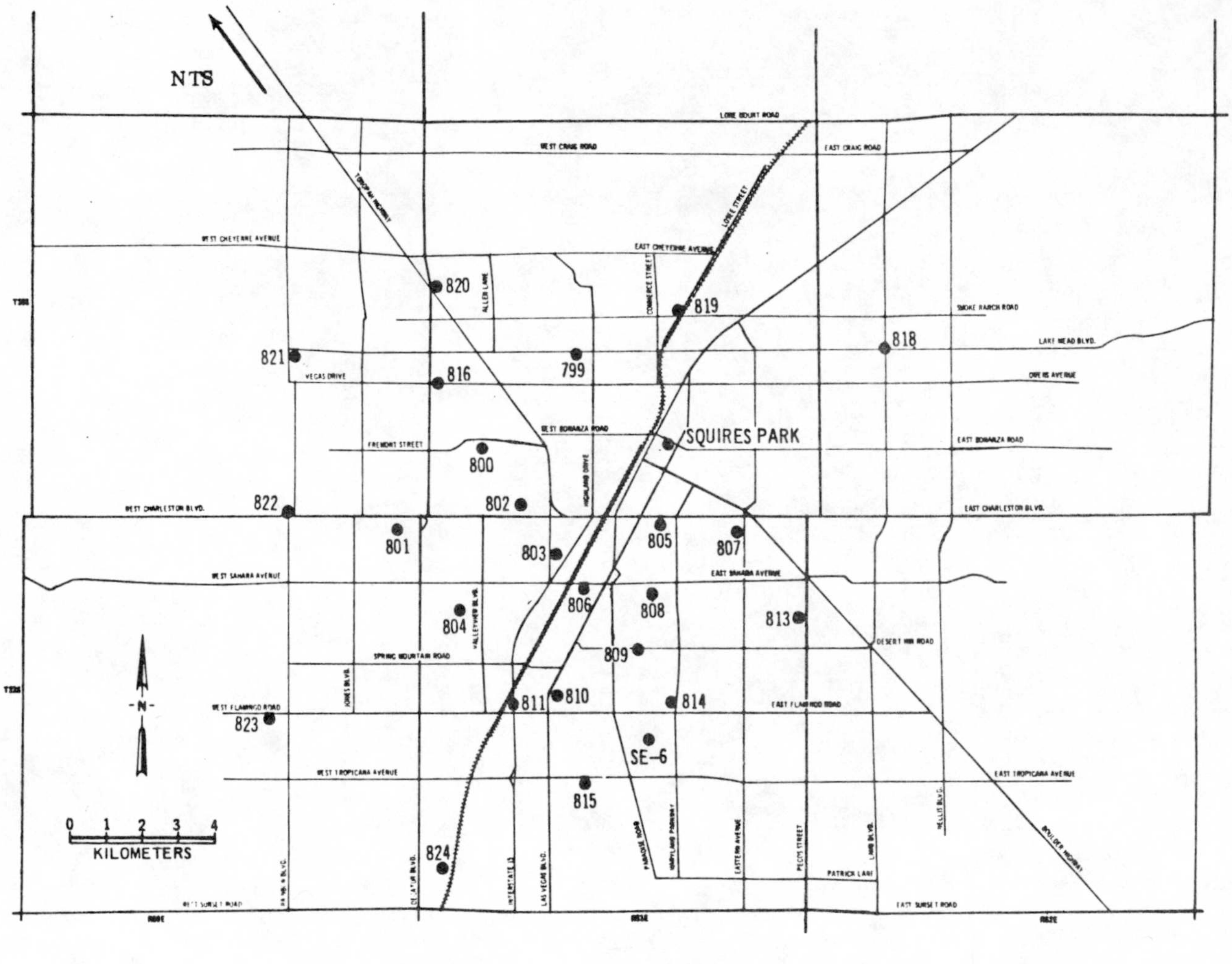

FIGURE 22 LOCATIONS OF GROUND MOTION STATIONS IN LAS VEGAS (FROM MURPHY AND HEWLETT, 1975)

motion is often done by normalizing an appropriate response spectrum to the peak acceleration predicted for the site. With the predicted peak accelerations (Section 4.1.4) and the well-known response spectral variations in Las Vegas outlined above, maximum probable response spectra for any site in the city can be readily predicted if an appropriate response-spectral shape, or dynamic amplification factor (DAF) curve, can be established for the reference site (station 801).

In order to estimate a reasonable DAF curve for the reference site, response spectra for five nuclear detonations (West, 1971) were compared with typical earthquake spectra. All spectra were normalized to a period of 0.03 sec, below which the DAF is nearly 1.0, and damping factors of 5% were used. Results are shown in Figure 23. It can be seen that, for periods less than about 2.0 sec, the spectrum shape recommended for seismic design of nuclear facilities (Newmark et al., 1973) and the shape characterizing an average alluvial site (estimated from Mohraz, 1976) agree fairly well with the observed mean spectrum for station 801.

The five nuclear explosions had yields between 20 and 200 kt, corresponding to earthquake magnitudes (m_b) of 5 ± 1/2. The earthquake spectra correspond to generally larger ($m_b \geq 6\text{-}1/2$) shocks, and so have larger spectral values at periods greater than 2.0 sec. So that magnitudes of at least 6 could be considered, the spectra of three events in the megaton range were also compared. These were recorded at station SE-6 but not at station 801. Allowing for the known response difference between stations 801 and SE-6, the spectral shape of the larger events at the reference site was substantially the same as for the smaller events for periods less than 2.0 sec. However, response in the period range from 2.0 to 3.0 sec was significantly greater and paralleled that for earthquakes. It can thus be concluded that, to a period of at least 3.0 sec, average earthquake spectra and nuclear event spectra at the Las Vegas reference site have substantially the same shape.

Considering the above, it can be assumed that the design spectrum shape (DAF curve) of Newmark et al. (1973) is appropriate to the reference site, station 801. Using this assumption, together with predicted peak accelerations given here and response ratios presented by Murphy and Hewlett (1975), maximum probable response spectra van be constructed for any site in Las Vegas.

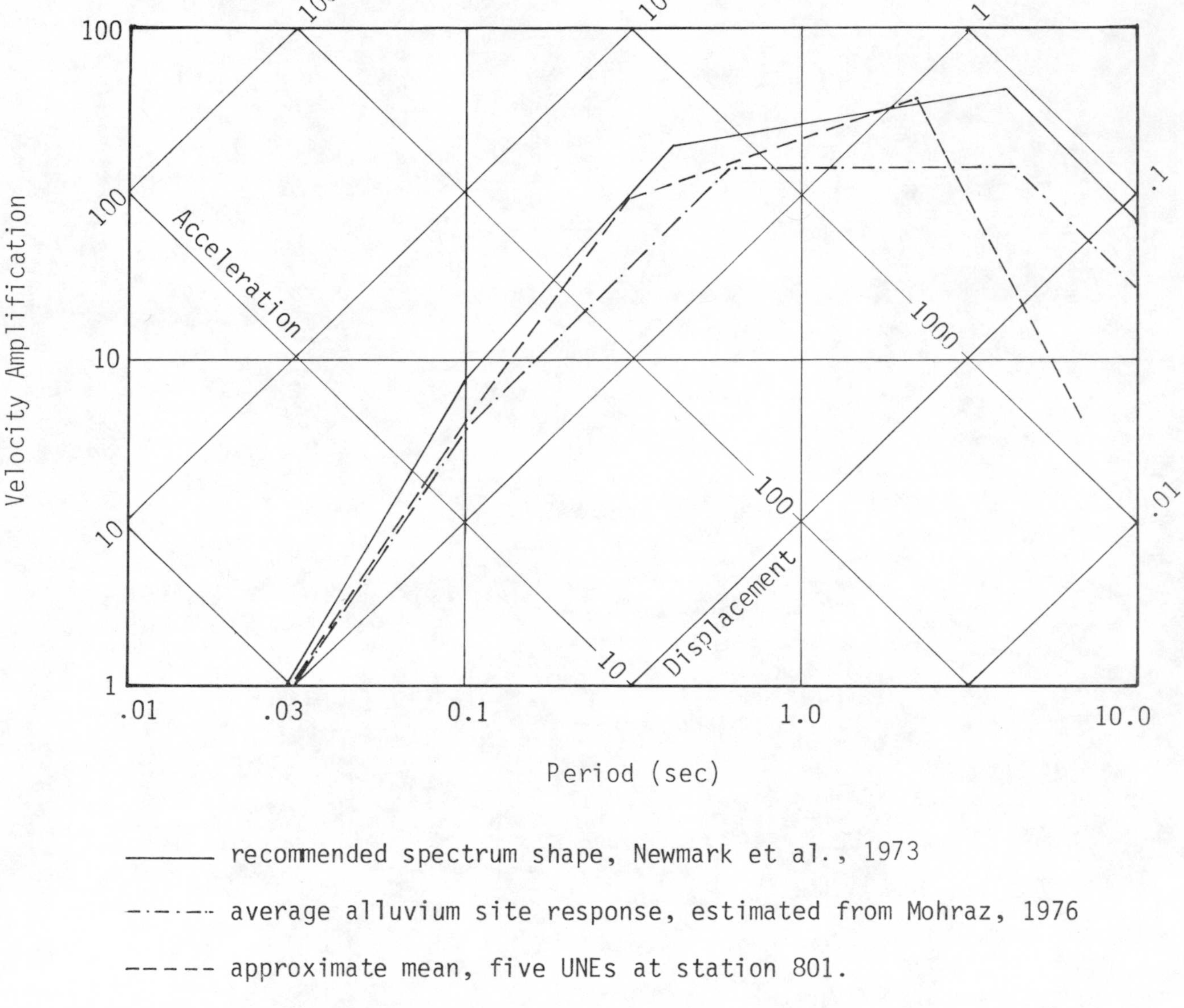

FIGURE 23 AVERAGE HORIZONTAL SPECTRAL AMPLIFICATIONS AT ALLUVIAL SITES (FOR EARTHQUAKES) AND AT STATION 801 IN LAS VEGAS (FOR UNDERGROUND NUCLEAR EXPLOSIONS): SPECTRAL ACCELERATION NORMALIZED AT 0.03 SEC PERIOD; DAMPING RATIO = 5%

Finally, the confidence limits of estimated site response spectra can be analyzed. If the logarithms of the DAF at the reference site and PSRV ratios are normally distributed, independent variables (assumed here), the variance of their sum is given by

$$\sigma_X^2 \;=\; \sigma_V^2 + \sigma_R^2$$

where $V(T)$ is the DAF for velocity at station 801 and $R(T)$ is the PSRV ratio of site X with respect to station 801. Mohraz (1976) found the standard deviation for the DAF (σ_V) for acceleration σ_A by scaling σ_A to the velocity axis (multiplying by $\sqrt{2}$), yielding $\sigma_V = 0.23$. Murphy and Hewlett (1975) give $\sigma_R = 0.11$. Therefore, σ_X is 0.25, for a standard error factor of 1.8. The probable error is 0.16, for a probable error factor of 1.4.

5. SUMMARY AND CONCLUSIONS

This study presents a probabilistic derivation of the occurrence of seismic ground motion in Las Vegas at levels that might cause damage to structures. Seismotectonic activity is regionalized on the basis of late Cenozoic geotectonic structure, Quaternary faulting, and apparent present-day crustal strain rates and seismicity.

Mesozoic and early Cenozoic tectonism in the Cordileran region was characterized by compressive and vertical crustal deformation, as well as by major right-lateral oroclinal shearing in the northwest-trending Walker Lane and to the west. In southern Nevada, many thrust faults, trending from north to northeast, were formed during this period. Available geologic and seismologic data show that the compressive stresses that produced these features are no longer present. However, modern right-lateral deformation and high seismicity along the west margin of the Great Basin may be localized on planes of weakness established by pre-Miocene shearing.

Present-day seismotectonic patterns probably emerged in middle-Miocene time, when the tectonic regime in the Great Basin region became one of east-west extension, forming the Basin and Range tectonic province. This province is characterized by northerly trending normal faults that formed during and since Miocene time, many of which are still seismically active.

A major conclusion of this study is that, since Miocene time, the rate of crustal extension has been much greater in the northern part of the Basin and Range province than in the southern part. The transition zone between these two different regimes is a broad, roughly east-west belt uniquely characterized by Pliocene and younger lateral faulting and by normal faulting, which may be a secondary response to left-lateral shear at depth. The zone is some 100 km wide, trends about N 70° E, and is traversed by a major lineament that extends northeast from the Garlock fault and includes the Pahranagat left-lateral system. This zone is significant because it separates regions of widely different Holocene and present-day seismotectonic activity. Las Vegas lies in the southern, much less active region.

Long-term seismotectonic activity was assessed on the basis of post-Miocene fault patterns, topographic relief, crustal thickness, and late Quaternary faulting; the assessment led to a subdivision of the Basin and Range province into several seismotectonic subprovinces. Crustal strain rates were estimated for each of the subprovinces using data on late Quaternary faulting and geodetic strain measurements. Average historic seismicity rates were derived for each of the subprovinces and were found to correlate very well with the late Quaternary crustal strain rates. Therefore, historic seismicity rates may represent rather well a period more than 10,000 years long.

The computer program HAZARD was used to calculate probabilities of exceedance of various peak ground accelerations in Las Vegas. The calculations were based on the historic seismicity rates that characterize six seismotectonic source regions within 300 km of Las Vegas; the San Andreas fault was also included as a source. Results indicate that Las Vegas is subject to low seismic risk relative to much of the western United States. In any 100-year period, the probability of exceeding 0.1g is only 7%, and the mean recurrence time for 0.1g is 1,400 years. Because these accelerations result from local, small ($M \approx$ 4-1/2) shocks, their likely duration is only about 1 sec.

Las Vegas is located in a region of locally low seismicity that is flanked by regions of much higher seismicity. It is concluded that accelerations from 0.01g to 0.02g are as likely to result from small, local shocks as from large, distant earthquakes. Thus, ground motion events of 0.02g are apt to have predominant periods of either 0.5 sec or 0.2 sec and durations of either 30 sec or 0.3 sec. The events with longer period and duration have a mean return period of some 100 years.

Data on site-dependent spectral amplification in Las Vegas show that pseudo-relative ground velocities (PSRVs) in the downtown area may be from two to seven times as large as those in outlying areas for periods between 0.5 and 6.0 sec. The lowest observed PSRVs appear to represent average alluvial sites, as do the computed peak ground accelerations. Hence, longer-period spectral motions in the downtown area may be much larger than those normally associated with the peak ground motions given in this report.

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APPENDIX A

Geologic Background

CONTENTS

TABLES

FIGURES

CONTENTS (Continued)

GEOLOGIC BACKGROUND

A.1 Physiographic Setting

Las Vegas is located in southern Nevada near the Arizona border, which follows the course of the Colorado River, passing through Lake Mead Reservoir. This area lies within the Great Basin physiographic province near the western margin of the Colorado Plateau. The Great Basin approximately coincides with the northern part of the larger Basin and Range tectonic province in eastern California, western Utah, and most of Nevada. It is distinctive because the many streams and rivers flowing into the Great Basin form inland lakes that have no ultimate outlet to the sea.

The Basin and Range province is characterized by generally north-trending, broad, flat valleys spaced 15 to 20 mi apart and separated by fault block mountain ranges, often with relief of 3,000 ft or more. In contrast to this northerly regional trend, Las Vegas Valley strikes in a northwest-southeasterly direction and cuts across the north-trending Basin and Range structures. Over its 50-mi length, the valley widens from about 10 mi at its northwest end to about 20 mi at its southeast end near Las Vegas. The valley floor slopes southeastward at an average descent of about 35 ft/mi from an elevation of over 3,000 ft in the northwest portion of the valley to an elevation of less than 2,000 ft southeast of Las Vegas. Stream courses are normally dry, and only during rare heavy rainfall does natural runoff pass down Las Vegas Wash and into Lake Mead.

The mountains forming the northeast side of Las Vegas Valley are the Desert Range, the Sheep Range, and the Las Vegas Range. These mountain ranges trend southerly and intersect Las Vegas Valley at large angles. Their elevations vary from about 6,000 to 10,000 ft. The southeastern end of the valley is formed by Frenchman Mountain, the River Mountains, and the McCullough Range (Figure A1).

The valley is bounded on the west by the Spring Mountains, a range of high relief, in which the highest point, Charleston Peak, rises to an elevation of 11,912 ft.

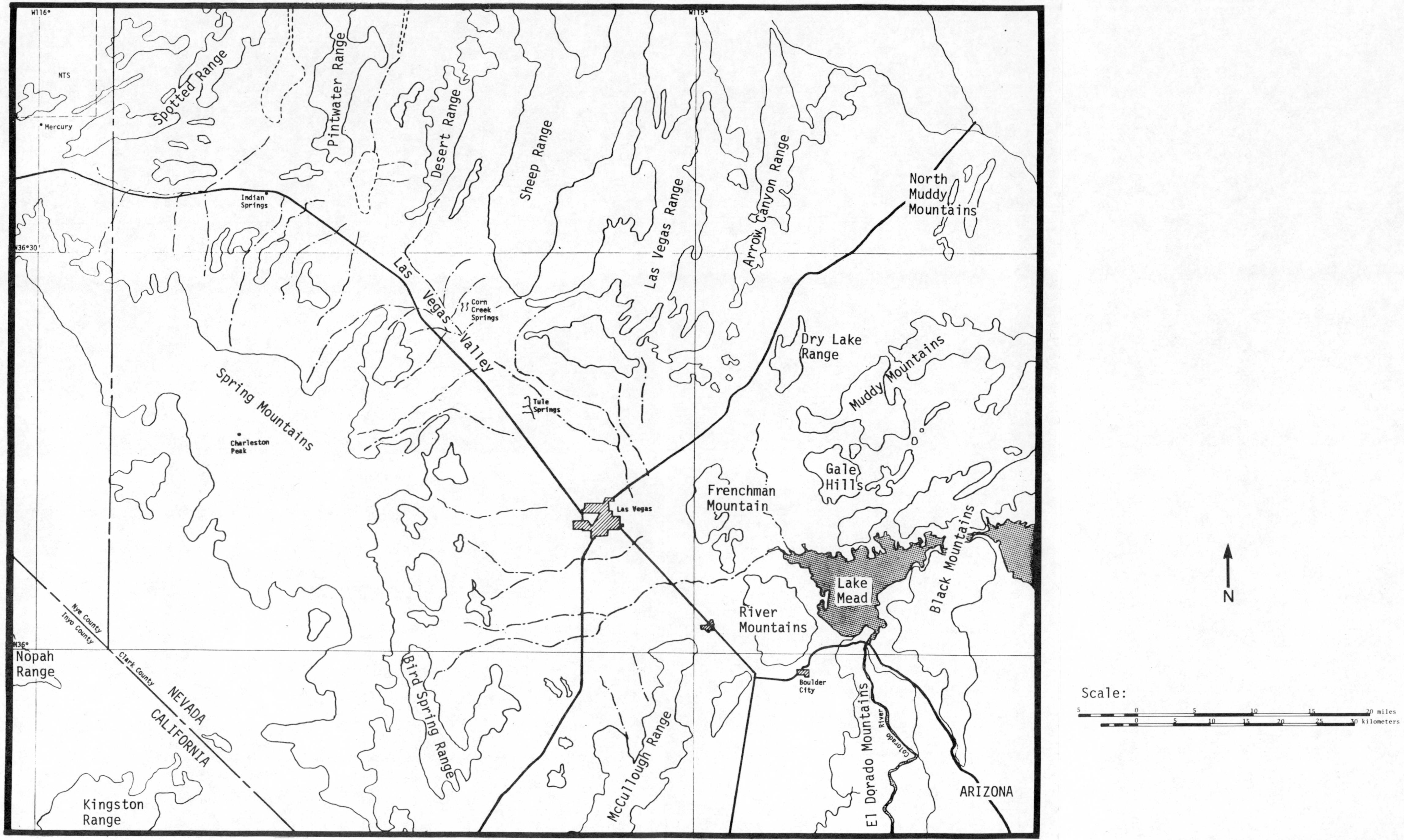


FIGURE A1 PHYSIOGRAPHY OF THE LAS VEGAS REGION

Debris from the mountains bordering Las Vegas Valley has formed gently sloping alluvial fans that merge almost imperceptibly into the valley floor. The fans at the front of the Spring Mountains extend as far as 15 mi into the valley, whereas those of the other mountain ranges are less well developed.

The climate of southern Nevada is arid to semiarid. Lowlands such as Las Vegas Valley normally receive 3-1/2 to 4-1/2 in. of precipitation per year (Malmberg, 1965), enough to support only sparse desert vegetation. The winters are mild, and the summers are long and hot, producing extremely high evaporation rates. Strong winds may occur at any time of the year.

A.2 Geologic History

The geologic record of the southern Great Basin region is long and remarkably complete, extending from early Precambrian time to the present. Several orogenic events, widespread igneous activity, and a complicated history of folding and faulting have imposed a great deal of local complexity on the regional picture (Table A1).

In late Precambrian time, approximately 850 million years ago, the Cordilleran geosyncline developed along the length of North America (Stewart, 1972). The trend of this trough was generally northward through Nevada, with its shallow eastern margin in the vicinity of Las Vegas.

The initial sediments deposited in the geosyncline were coarse clastics derived from the metamorphic and igneous terrain to the east. By Middle Cambrian time, deposition of carbonates had begun in a shallow marine or miogeosynclinal environment. The miogeosyncline persisted throughout most of the Paleozoic era in central and southern Nevada, and a thick sequence of predominantly carbonate rocks was deposited.

These Paleozoic carbonate rocks grade westward into the more siliceous and volcanic rocks of the eugeosynclinal assemblage of California along a narrow north-trending transitional zone in western Nevada and southeastern California (Figure A2a).

TABLE A1

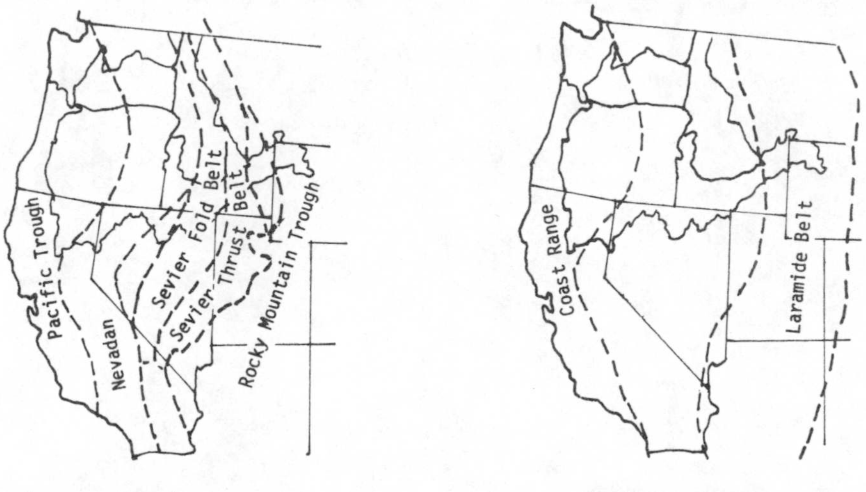
GEOLOGIC HISTORY OF WESTERN NORTH AMERICA

ERA	PERIOD	EPOCH	MILLION YEARS BEFORE PRESENT	MAJOR EVENTS AFFECTING THE GREAT BASIN		GROSS LITHOLOGY SOUTHERN NEVADA
CENOZOIC	QUATERNARY	RECENT	10,000 years	Renewed uplift in Sierra Nevada, glaciations, uplifting of Colorado Plateau	Basin-and-Range-style extensional tectonics	Gravels, sands, silts, clays
		PLEISTOCENE	1.8			
	TERTIARY	PLIOCENE	5.0	Continuing uplift in Sierra Nevada and formation of modern Rocky Mountains. Volcanic activity extensive in western North America.		Volcanics, sandstone, shale minor conglomerate, very minor limestone; latter is in Moenkopi Fm (early Triassic)
		MIOCENE	225			
		OLIGOCENE	37.5			
		EOCENE	53.5			
		PALEOCENE	65			
MESOZOIC	CRETACEOUS		136	LARAMIDE OROGENY Uplifting of the Rocky Mountains		
	JURASSIC		190-195	NEVADAN OROGENY Uplift along Pacific Border. Thrust faulting across southern Nevada.		
	TRIASSIC		225	Aridity and volcanism		
PALEOZOIC	PERMIAN		280	SONOMA OROGENY Uplift in eastern California. Thrust faulting in west-central Nevada.		Top of Paleozoic limestones
	PENNSYLVANIAN		320	ANTLER OROGENY Uplift in northwestern Nevada. Thrust faulting in central Nevada.		Gross estimate: sandstone and shale (75%); limestone (25%)
	MISSISSIPPIAN		345			
	DEVONIAN		395	Deposition in the Cordilleran geosyncline		Predominantly limestone and dolomite Minor sandstone and finer clastics
	SILURIAN		430-440			
	ORDOVICIAN		500			Gross estimate: sandstone and finer clastics (70%); limestone (30%)
	CAMBRIAN		570			
PRECAMBRIAN			900	Beginnings of Cordilleran geosyncline		
			3,600+	Primitive crust		Basement (metamorphic and igneous rocks)

a. Late Precambrian to Late Devonian

b. Antler Orogeny, Late Devonian through Middle Pennsylvanian

c. Sonoma Orogeny, Late Permian and Early Triassic



d. Nevadan - Sevier Orogeny, Jurassic

e. Cretaceous and Tertiary Orogenic Belts

FIGURE A2 MAJOR PHASES OF THE CORDILLERAN GEOTECTONIC CYCLE (AFTER ROBERTS, 1972)

The only major interruption in the carbonate sequence occurred during Late Devonian to Early Pennsylvanian time about 310 to 360 million years ago. During this episode, coarse detrital sediments were shed from western Nevada eastward into the miogeosyncline as a result of the Antler orogeny (Figure A2b). The trend of the Antler orogenic belt corresponds to the transitional zone that marked the boundary between the Paleozoic miogeosynclinal basin of Nevada from the eugeosynclinal basin of California (Roberts, 1972). Large-scale thrust faulting with displacements of tens of miles in a southeastward direction is recorded along a sinuous north-northeastward trend from Mineral County to Humboldt County, Nevada (Silberling and Roberts, 1962). This deformation apparently did not affect Nye and Esmeralda counties, but Mississippian rocks in these counties and areas farther to the south and east document the temporary existence of the Antler highland source of detrital sediments.

The Sonoma orogeny produced a second episode of folding and southeastward thrusting in Permian to Early Triassic time. The Sonoma fold belt emerged somewhat farther to the west (Figure A2c) and did not interrupt late Paleozoic miogeosynclinal deposition in the southern portion of the Great Basin.

The Mesozoic era, beginning about 225 million years ago, brought a regional change toward continental styles of deposition. Outcrops of Mesozoic rocks are scattered and demonstrate a history of progressive uplifting and isolation of the depositional basins in Nevada.

Volcanic deposition, possibly originating from a rising island arc to the west in California, took place in northwestern Nevada from the time of the Sonoma orogeny into the Late Jurassic (Stanley, Jordan, and Dott, 1971).

Very shallow marine carbonates continued to be deposited across most of Nevada throughout the Triassic. In southern Nevada, continental conditions predominated by Late Triassic time, resulting in lacustrine and fluviatile deposits of irregular thicknesses.

The last of the conformable Mesozoic rocks -- a thick eolian deposit, the Aztec Sandstone -- was laid down across eastern Nevada probably early in the

Jurassic period, prior to the Sevier orogeny.

The most important orogeny in the geologic history of the southern Great Basin occurred along what Armstrong (1968) termed the Sevier orogenic belt (Figure A2d). This wide belt of deformation trends generally north to northeastward across southern Nevada and into western Utah. Within this belt are found several bands of deformation showing a similar style of contemporaneous folding and thrusting towards the southeast. Deformation probably took place in several pulses, along different thrust faults, during the period from Late Triassic to Late Cretaceous time.

The Nevadan orogeny resulting in the initial elevation of the Sierra Nevada was contemporaneous with the Sevier orogeny of the Basin and Range province. Stewart, Ross, Nelson, and Burchfiel (1966) and Hall (1971) noted the close association between Mesozoic thrusting and plutonism east of the Sierra Nevada. Both orogenic events terminated approximately 80 million years ago in Late Cretaceous time, probably due to a major change in the subduction process at the edge of the North American plate (Smith and Sbar, 1974).

As a result of the Sevier orogeny, the Great Basin became a highland subject to erosion. A great deal of sediment was stripped from the uplifted area and into the flanking Pacific and Rocky Mountain troughs. Throughout Cenozoic time, the region has continued to be a highland with sedimentation taking place in isolated basins (Figure A2e).

Minor volcanism had begun in the Great Basin apparently as early as Late Triassic time, but the major episode of activity began abruptly about 40 million years ago in Eocene to Oligocene time (McKee, 1971). Tertiary volcanism was predominantly silicic and spread outward from a core area in east-central Nevada. This evolution to many eruptive centers occurred in roughly concentric rings over about 20 million years (Armstrong, Ekren, McKee, and Noble, 1969). According to McKee (1971), there was a brief lull in volcanic activity during mid-Miocene time 17 to 19 million years ago, after which volcanism resumed. Since then, volcanism has been predominantly basaltic and confined almost exclusively to the margins of the Great Basin.

Basin-and-Range-type normal faulting began about 16 to 17 million years ago, approximately the same time as the arrival of the basalts. Many lines of evidence point to this period as the time of emergence of the modern tectonic regime.

Right-lateral deformation along the Las Vegas shear zone, and possibly the southern projection of the Walker Lane (south of Tonopah), had importance from about 17 to 11 million years ago. However, major strike-slip faulting is now occurring farther to the west, principally between the east margin of the Sierra Nevada Mountains and the Death Valley — Furnace Creek fault zone.

Rapid changes in relief, due to Basin and Range normal faulting, increased the rate of sedimentation into narrow downfaulted basins. By 10 million years ago, near the end of Miocene time, the Great Basin had become a region of interior drainage with physiography similar to that seen today.

The southern Colorado Plateau, which had been a relative lowland, emerged to its present elevation during Pliocene time, between 5 and 10 million years ago (McKee and McKee, 1972). The Colorado River cut approximately its present course between 5 and 3.3 million years ago, by means of headward erosion from the subsiding Salton Trough — Gulf of California area (Lucchitta, 1972).

Largely as a result of the Pleistocene glaciations and pluvials, great thicknesses of lacustrine sediments, fanglomerates, and unconsolidated Holocene alluvium were deposited in the intermountain basins. Most of the valleys of the Great Basin contained shallow impounded lakes during the Pleistocene epoch. Existing lakes and playas such as the Great Salt Lake, Walker Lake, and Badwater in Death Valley are mere remnants of what were once extensive bodies of water. Several large lakes existed in the northwestern reaches of Las Vegas Valley between Indian Springs and Corn Creek (Snyder, Hardman, and Zdenek, 1964). Tilting and disruption of playa sediments such as these throughout the southern Great Basin are expressions of the continuing tectonic activity of the region.

A.3 Geologic Units

<u>A.3.1 Precambrian Metamorphic and Igneous Complex</u>. The oldest rocks in the

southern Great Basin are granites, strongly folded and metamorphosed schists, and gneisses of Precambrian age. Radiometric dates from Clark County indicate that the metamorphism and intrusion took place about 1.1 to 1.7 billion years ago (Stewart, 1964). Principal outcrops are in the ranges south and east of Las Vegas; for example, in the Newberry Mountains, at Frenchman Mountain, and in the Virgin and South Virgin mountains (Longwell, Pampeyan, Bower, and Roberts, 1965).

A.3.2 Precambrian and Lower Cambrian Sedimentary Rocks. These rocks outcrop throughout the southern Great Basin, lying with angular unconformity upon the metamorphic basement rocks. Originally, they formed a thick sedimentary wedge that was deposited progressively westward across a subsiding continental shelf. The most complete exposures of these initial geosynclinal rocks are concentrated near the southeastern California-Nevada border. Principal outcrops are found in the Las Vegas and Desert ranges, in the northwest Spring Mountains in Clark and Nye counties, and in the Panamint Range and White Mountains in California.

The lithology of upper Precambrian and Lower Cambrian rocks has been studied in great detail by Stewart (1970). His work discloses that individual strata develop and grade westward across the southern Great Basin from the coarse clastic facies of southeastern Nevada into finer-grained equivalents progressively richer in carbonates.

The principal rock types of this age in the eastern part of the region (i.e., east of Las Vegas) are coarse quartzite and conglomeratic quartzite of the Tapeats Sandstone and Pioche Shale, equivalent to the Bright Angel Shale of the Grand Canyon.

The most dramatic westward thickening occurs in the central part of the region from the Spring Mountains to Death Valley. Rock types are fine to coarse quartzite, siltstone, and minor amounts of limestone and dolomite. The most widely recognized formational names are given in Table A2.

In east-central Nevada and in western Utah, the names Prospect Mountain Quartzite and Pioche Shale are used for strata correlated with the upper

TABLE A2

SUMMARY OF PALEOZOIC AND PRECAMBRIAN STRATIGRAPHIC UNITS IN THE SOUTHERN GREAT BASIN (Principal Reference: Langenheim and Larsen, 1973)

AGE	Millions of Years	DEATH VALLEY-PANAMINT AREA (Hall, 1971; Hunt and Mabey, 1966)	SOUTH NYE COUNTY AND NTS (Cornwall, 1972; Johnson and Hibbard, 1957)	WESTERN CLARK COUNTY (Longwell et al., 1965; Hewett, 1956)	SOUTH LINCOLN AND EASTERN CLARK COUNTIES (Tschanz and Pampeyan, 1970; Longwell et al., 1965)
PERMIAN	225	Owens Valley Formation	not exposed	Kaibab Limestone	
				Toroweap Formation	
				red beds	Coconino Sandstone red beds
		Keeler Canyon Formation	Bird Spring Formation	Bird Spring Formation	Callville Limestone
PENNSYL-VANIAN	280	Lee Flat Limestone	Tippipah Limestone		
MISSIS-SIPPIAN	320	Rest Spring Shale	Eleana Formation		
		Perdido Formation			Chainman Shale
		Tin Mountain Limestone		Monte Cristo Limestone	Rogers Spring Limestone
DEVONIAN	345	Lost Burro Formation	Devil's Gate Limestone	Sultan Limestone	Pilot Shale
			Nevada Formation		Muddy Peak Limestone
					Guilmette Formation
		Hidden Valley Dolomite		Goodsprings Dolomite	Simonson Dolomite
					Sevy Dolomite
SILURIAN	395		Lone Mountain Dolomite		Laketown Dolomite
			Roberts Mountain Formation		
ORDOVICIAN	430	Ely Springs Dolomite			
		Eureka Quartzite			
		Pogonip Group			
UPPER CAMBRIAN	500	Nopah Formation			limestone and dolomite undivided
		Bonanza King Formation			
					Peasley Limestone
MIDDLE CAMBRIAN		Carrara Formation			Chisholm Shale
					Lyndon Limestone
LOWER CAMBRIAN					Pioche Shale
		Zabriskie Quartzite			Prospect Mountain Quartzite and Tapeats Sandstone
		Wood Canyon Formation			
UPPER PRECAMBRIAN	570	Stirling Quartzite			hiatus
		Johnnie Formation			
		Noonday Dolomite	(base covered)		
		Pahrump Group			
PRECAMBRIAN	850	Gneiss and Schist			

half of this section (Tschanz and Pampeyan, 1970). Equivalent strata in the western part of the region (e.g., Esmeralda County, Nevada) consist of siltstone, limestone, dolomite, and fine-grained quartzite.

The thickness of the upper Precambrian and Lower Cambrian sequence increases westward from a thickness of less than 400 ft at Frenchman Mountain just east of Las Vegas (Burchfiel, Fleck, Secor, Vincelette, and Davis, 1974), to approximately 13,000 ft at the Nevada Test Site (Ekren, 1968), and to about 21,000 ft in the vicinity of the White Mountains, California (Stewart, 1970).

A.3.3 Paleozoic Carbonate Series. Early to Middle Cambrian rocks belong to a marine clastic sequence that began in the late Precambrian. The Carrara Formation grades upward into a thick carbonate sequence indicating a gradual change toward a shallow-water depositional environment in Middle Cambrian time. This predominantly carbonate series is virtually continuous upward into Permian strata. The names of major Paleozoic formations currently used in various parts of the southern Great Basin are shown in Table A2.

Outcrops of these Paleozoic miogeosynclinal rocks constitute the cores of most of the mountain ranges in western Clark County, Nevada (Longwell et al., 1965), and Lincoln County (Tschanz and Pampeyan, 1970). A few large outcrops are found in southern Nye County in the Spring Mountains, at Bare Mountain, and in the Eleana Range at Yucca Flat (Cornwall, 1972). West of the California-Nevada border, extensive outcrops are found in the Nopah Range (Jennings, Burnett, and Troxell, 1962), in the southern Funeral Mountains and the Panamint Range (Jennings, 1958), and in the Inyo Mountains (Noble and Wright, 1954).

Middle Cambrian through Devonian rocks are remarkably uniform in lithology across the southern Great Basin. They consist almost entirely of limestones and dolomites, with minor amounts of shale, quartzite, siltstone, and chert. The most continuous of these strata are the Ordovician rocks, which include the Pogonip Group, the Eureka Quartzite, and the Ely Springs Dolomite. These formations have been studied and correlated (Ross, 1964) over a wide area from the Panamint Range in California to central Utah. The Eureka Quartzite is the only notable clastic formation within the lower

Paleozoic sequence. It has served as an excellent reference horizon for regional structural studies because of its consistent lithology and thickness (about 300 ft) throughout the southern Great Basin.

Uppermost Devonian and Mississippian rocks are also predominantly carbonates but contain greater proportions of shale and sandstone than other Paleozoic rocks, especially in the miogeosynclinal area. For example, the Eleana Formation of southern Nye County is a thick sequence of shale, argillite, quartzite, conglomerate, and minor limestone. Equivalent strata to the south and east are progressively finer grained, grading into formations composed primarily of limestone (Cornwall, 1972). Similar trends are found within the Monte Cristo Limestone in the Spring Mountains (Longwell et al., 1965). The widespread occurrence of clastics, such as the distinctive, dark Chainman Shale from Lincoln County, Nevada, and the southern Inyo Mountains, California (Merriam and Hall, 1957), confirms that a temporary highland source for these detrital rocks existed to the northwest of Nye County during Mississippian time (Figure A2b).

Pennsylvanian and Permian rocks are composed predominantly of limestones that are frequently dolomitic, silty, or sandy and interbedded with shale, sandstone, and cherty limestone. In Clark County, this upper portion of the Paleozoic sequence is typified by the very thick Bird Spring Formation. Immediately above this formation lie the sandstones and reddish shales of the Permian red beds and the Toroweap and Kaibab formations, which consist of massive-bedded limestone, some shale and sandstone, and considerable gypsum.

Measurements of the total thickness of Paleozoic rocks show thickening in a general westward direction across the southern Great Basin. In the central Grand Canyon area of northwestern Arizona, the total thickness is approximately 4,000 ft, thinning to about 1,000 ft 80 mi to the southeast (McNair, 1951). From the Virgin Mountains at the Arizona-Nevada border to the ranges northwest of Las Vegas Valley, the thickness of Paleozoic rocks increases from 7,000 ft to 26,000 ft (Longwell et al., 1965). Total thicknesses have been estimated at more than 17,000 ft in the Nopah and Resting Springs ranges (Hazzard, 1937) and about 23,000 ft in the Inyo Mountains, California (Merriam, 1954).

A.3.4 Mesozoic Rocks. Outcrops of Mesozoic sedimentary rocks are extensive on the Colorado Plateau; however, in the southern Great Basin region, they are virtually restricted to Clark County, Nevada. Triassic and Lower Jurassic rocks were probably widespread before suffering the erosional effects of the Sevier Orogeny and burial by extensive Tertiary volcanism. Cretaceous outcrops are extremely scattered and reflect the regional change to deposition within localized inland basins.

In southern Nevada, Mesozoic sedimentary rocks are associated with the leading edge of the Sevier thrust belt. Outcrops are found in the Spring Mountains and Frenchman Mountain near Las Vegas, in the Muddy Mountains, the South Virgin Mountains, and a small area in the southeastern corner of Lincoln County.

The Moenkopi Formation is the oldest of the sequence of Mesozoic strata summarized in Table A3. The Moenkopi Formation rests uncomformably on Permian rocks and contains a basal conglomerate, often with fragments of Permian limestone, that is succeeded by shales, limestones, gypsum-rich units, and sandstones. Unlike the overlying formations, the Moenkopi Formation contains marine fossils. It is Early to Middle Triassic in age and represents the last invasion of the sea in the southern Great Basin (Longwell et al., 1965).

The Chinle Formation of Late Triassic age was deposited on flood plains and in localized lakes; therefore its lithology and thickness are variable. The basal Shinarump Member consists of conglomerate and coarse-grained sandstone with frequent petrified wood. The upper part of the Chinle Formation consists of shale and sandstone with considerable gypsum. Scattered deposits of bentonitic clay within this formation indicate volcanic activity during Late Triassic time.

The Aztec Sandstone of Early Jurassic age rests conformably on the Chinle Formation. It consists of a homogeneous fine- to medium-grained sandstone with weak cementation and distinctive reddish coloring. This formation is probably a western extension of the Jurassic Navajo Sandstone of the Colorado Plateau. The Aztec or Navajo Sandstone was the last formation to be laid

TABLE A3

MESOZOIC STRATIGRAPHIC UNITS IN THE SOUTHERN GREAT BASIN

Age	Millions of Years	North and West of Las Vegas	Las Vegas, Eastern Clark County, and Colorado Plateau
Cretaceous	65	Scattered Plutonic Rocks (sedimentary rocks virtually absent)	
			Baseline Sandstone
			Willow Tank Formation
Jurassic	135		
			Navajo Sandstone
Triassic	190		Chinle Formation
			Shinarump Conglomerate
			Moenkopi Formation
	225		

down continuously over an area of large extent within the southern Great Basin.

Mesozoic plutonic rocks consisting of quartz monzonite and granodiorite associated with metavolcanic rocks are found in southern Nye County and west of the California-Nevada border. These igneous rocks were probably emplaced during the Sevier and Nevadan orogenies.

A.3.5 Late Cretaceous and Early Tertiary Clastic Sediments. Late Cretaceous to Tertiary sediments are sparsely distributed in the southern Great Basin. Outside of Clark County, they are practically nonexistent. The largest deposits are in the Muddy Mountains and at Frenchman Mountain just east of Las Vegas. Scattered outcrops lie near the northwest corner of Clark County (Longwell et al., 1965, Plate 1).

These deposits all rest in angular unconformity upon older formations. They consist predominantly of clastic deposits derived from local sources; for example, conglomerates, sandstones, coarse fanglomerates, freshwater limestones, and tuffaceous sediments.

Correlation among these scattered and variable units has been very difficult. In most cases, the ages have not been well resolved. The scarcity of this age group of sediments is attributable to burial by Tertiary volcanics and widespread erosion initiated by Basin and Range faulting in Miocene time.

A.3.6 Cenozoic Volcanic Rocks. Tertiary volcanic rocks are extremely abundant in the Basin and Range province. They are evenly distributed, covering about one-third of the area of the southern Great Basin. In general, Tertiary volcanic rocks outcrop in highland areas along with older basement rocks on the upthrown blocks of the youngest Basin and Range structures. Deep drilling shows that they also occupy the expected position buried beneath the valley floors.

Two of the most prominent eruptive centers within the region lie in southern Nye County at the Nevada Test Site and south of Lake Mead at the edge of the Colorado Plateau.

In southern Nye County, seven major eruptive centers have been delineated surrounding buried or collapsed inactive calderas. The largest of these are the Timber Mountain, Silent Canyon, and Black Mountain centers in the Nevada Test Site. Eruptions were predominantly ash flows that resulted in welded tuffs of rhyolitic and quartz-latitic composition. Within the Nevada Test Site, ash-flow tuffs constitute most of the Tertiary composite section of over 30,000 ft (Ekren, 1968). Extensive radiometric dating studies in this area summarized by Kistler (1965) indicate that volcanism occurred in four or five brief, isolated events over a span of 20 million years, between approximately 26 million years and 6 million years ago.

In northern Clark County, volcanic outcrops are very sparse. However, the southernmost part of the county, southeast of Las Vegas, and the adjoining part of Mojave County, Arizona, is another area of extensive Tertiary igneous activity. Here volcanics lie directly upon Tertiary intrusive bodies and Precambrian basement rocks with little else of the stratigraphic record being preserved. Most of the eruptions were of intermediate composition with minor rhyolite. Volcanic rocks of an aggregate thickness of about 17,000 ft in the Eldorado Mountains have been reported by Anderson (1971). Radiometric dating (Anderson, Longwell, Armstrong, and Marvin, 1972) shows that volcanism and plutonism occurred in this location within the period 18 million to 12 million years ago, apparently overlapping the initiation of Basin-and-Range-type normal faulting.

Armstrong et al. (1969) established that centers of silicic volcanism spread outward in roughly concentric fashion from a core area in north-central Nevada. The progression was most distinct in a southwestward direction across Nevada. Volcanic rocks in the southern Great Basin confirm this pattern in a very general way. There has been negligible volcanism in Quaternary time in southern Nevada. Quaternary activity has occurred farther west, between the Owens Valley and Death Valley — Furnace Creek fault zones and in the Mojave Desert.

McKee (1971) has shown that Quaternary volcanic rocks are preponderantly basaltic, while pre-mid-Miocene volcanic rocks are largely silicic, and predate normal faulting (Figure A3). Indeed, the few eruptions that took

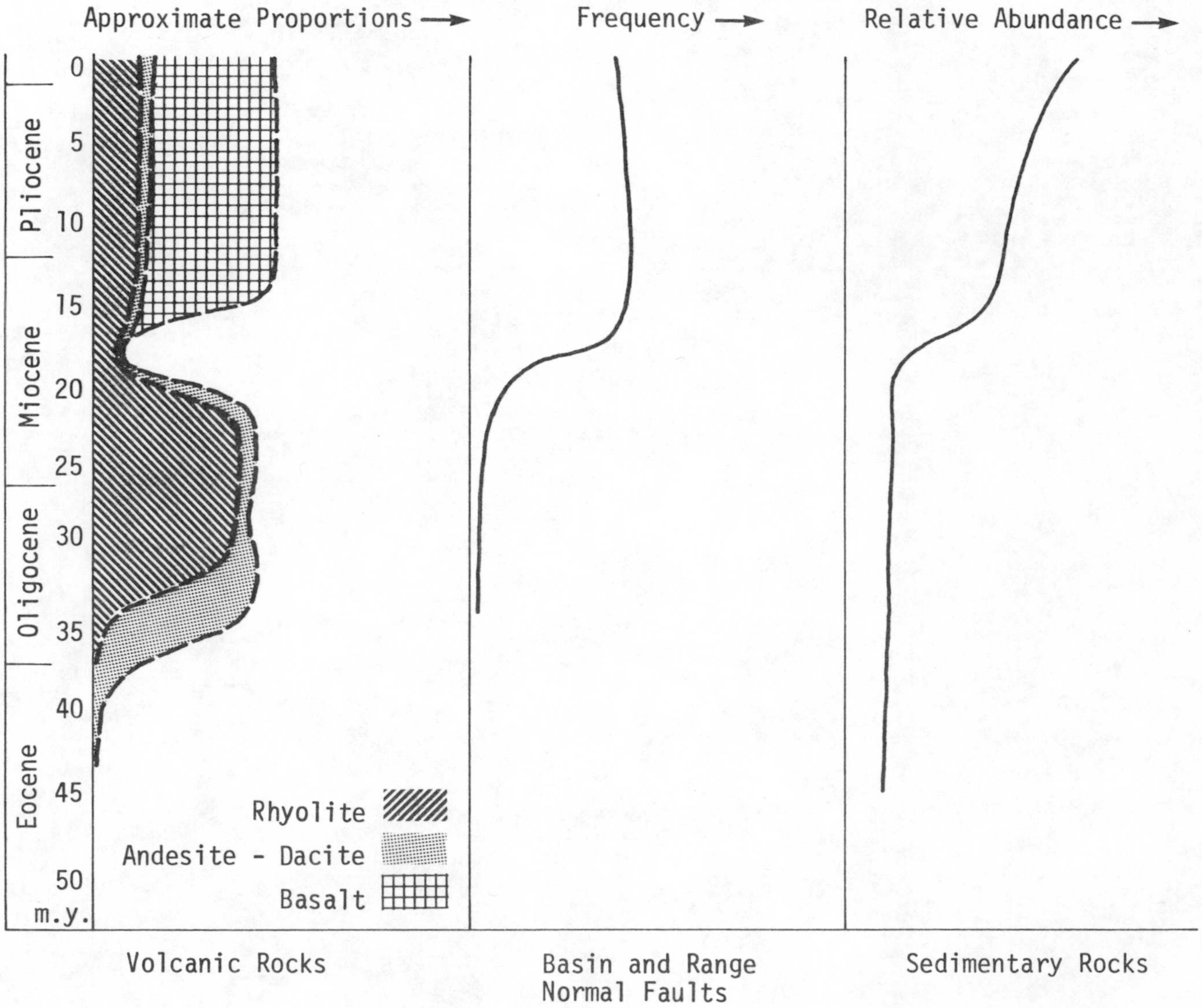


FIGURE A3 AGES AND RELATIVE ABUNDANCES OF CENOZOIC VOLCANIC ROCKS, NORMAL FAULTS, AND SEDIMENTARY ROCKS (REFERENCE: McKEE, 1971) place in the Las Vegas area in Pliocene time were basaltic.

A.3.7 Late Tertiary and Quaternary Sedimentary Rocks. Practically no sediments are to be found in the southern Great Basin with ages between 40 and 17 million years. However, deposition accelerated in Miocene time in narrow, closed valleys produced by block faulting (see Figure A3). These sediments fill the modern basins to depths of up to several thousand feet.

Typically, these deposits grade rapidly finer toward the center of the basin. Valley-margin facies usually consist of coarse conglomerates reworked from older bedrock, locally elevated due to faulting. Central-basin facies consist of fine-grained clastics intercalated with saline or tuffaceous sediments and lacustrine limestone. Throughout the region, late Pliocene sediments occupy approximately the same centers of deposition as Pleistocene and Recent sediments. Late Cenozoic formations in Las Vegas Valley are described in Table A4.

Several large, shallow Pleistocene lakes occupied the northern part of Las Vegas Valley between Indian Springs and Corn Creek (Figure A4). Outwash and lacustrine deposits of this age are locally designated the Las Vegas Formation.

Lake sediments were deposited in the Tule Springs area as recently as 15,000 years ago (Haynes, 1967). Recent alluvial fans, sand dunes, and playas now cover about 40% of Las Vegas Valley.

A.4 Regional Structure

A.4.1 General. The southern Great Basin is a region of highly complex geologic structure. Since Precambrian time, a succession of tectonic events with contrasting deformational styles has affected this region. Briefly, these events may be classed as vertical-tectonic during Paleozoic orogenies; uplift and east- to southeast-oriented crustal shortening, which produced geosynclinal-marginal thrusting during late Mesozoic and earliest Cenozoic time; and east-west-oriented crustal extension during late Cenozoic time, including the present.

TABLE A4

CENOZOIC SEDIMENTARY FORMATIONS, LAS VEGAS VALLEY (FROM TABOR, 1970)

AGE			FORMATION	SECTION		LITHOLOGY	OBSERVATIONS (Distribution, correlations, environments, etc.)	
M.Y.								
10,000 yr.	QUATERNARY	Recent	Quaternary Alluvium	Unit thicknesses not known; aggregate thickness possibly 2,000' or more.		Unconsolidated gravels, sands, silts and clays of present-day river beds, washes, fans, dunes, talus slides	Recent debris of this type covers about 40% of Las Vegas area.	
		PLEISTOCENE	Las Vegas Fm.			Clays and silts: Light-colored, thin regular bedded gravels and sands. Las Vegas is only Quaternary unit sufficiently distinct in lithology to warrant formational mapping.	Isolated outcrops in Las Vegas Valley. Early floodplain-and-river milieu followed by lake conditions as coalescing fans blocked valleys. May correlate with Chemehuevi Fm farther south.	
						Gravels and sands: Carbonate-cemented coarse debris along washes tributary to Colorado River.	Older than Pleistocene beds in Las Vegas Valley but younger than Muddy Creek Fm.	
						Gravels and sands: Carbonate-cemented debris exposed in walls (some 100' - 200' high) of stream courses cutting fans.	Many such deposits occur on divides as high as 9,000', indicating that range, formerly nearly buried, has undergone uplift and strong stream-downcutting (still in progress). Deposits are older than Pleistocene beds of Las Vegas Valley but younger than Muddy Creek Fm.	
1.8						Gravels-sands-silts: Hills of carbonate-cemented debris existing as uplifted terraces.	Some terraces hundreds of feet above present-day stream bottoms. Deposits probably early Pleistocene but some may be of Pliocene age.	
5 11	TERTIARY	PLIOCENE	Muddy Creek Fm. (Frenchman Mt. area)	1,400'+/-		Sandstone-siltstone-clays: Tan, buff, yellowish. Gypsum, occasionally in large bodies, is abundant in the Fm. Caliche caps Fm top in some areas. Intercalated basalt flows in some areas. Stated thickness (1,400') is for Frenchman Mt. area. Absent in Spring Mt. area. Lower basalt dated ± 11 m.y. (Longwell, 1974)	Fm, nearly flat-lying, is coarse near mountain borders, but grades to fine-grained material in flatlands. Fm forms walls and bluffs of canyons and mesas. Deposition in interior basins prior to through-flow of Colorado River.	
		MIOCENE	Horse Spring Fm. (Pintwater Range)	4,200'-6,200'		Frenchman Mt.: Fm mainly limestone, some clastics (4,000'). Pintwater Range, NW corner of Las Vegas area - Base of Fm: conglomerate, minor sandstone & siltstone (3,000' - 5,000'), successively overlain by volcanic sediments & pumice (1,000') and conglomerate (200') at top. Basalt flows in Fm of some areas.	Intrusions of graphitic magmas (Tki) in late Cretaceous(?) and early and later Cenozoic times. Volcanic action (Tv) preceded some of these intrusive episodes.	Horse Spring Fm deposited on rugged terrain during active crustal movement. The Fm in nearly all areas is severely faulted. Lavas and volcanic ash in Horse Spring Fm east of Frenchman Mt. indicate contemporaneous igneous activity.
17			Thumb Fm. (Frenchman Mt. area)	2,000'-3,000'		Clastics, occasional lava flows and volcanic Ash: Red-brown sandstone, siltstone, conglomerate, freshwater limestone. Numerous lenses of sedimentary breccia (to 300'). Dated ± 17 m.y. (Anderson, et al., 1972)		Volcanic ash at top of Thumb Fm. Sedimentary breccia of Fm probably derived from erosion of rising scarps. Upper part of Thumb Fm of Frenchman Mt. area is equivalent Overton fangolmerate of Muddy Mts. area; lower part=Baseline Sandstone and Willow Tank Fm of that area. No Cretaceous sediments known to occur in western part of Las Vegas area.
				25'-100'		Conglomerate		

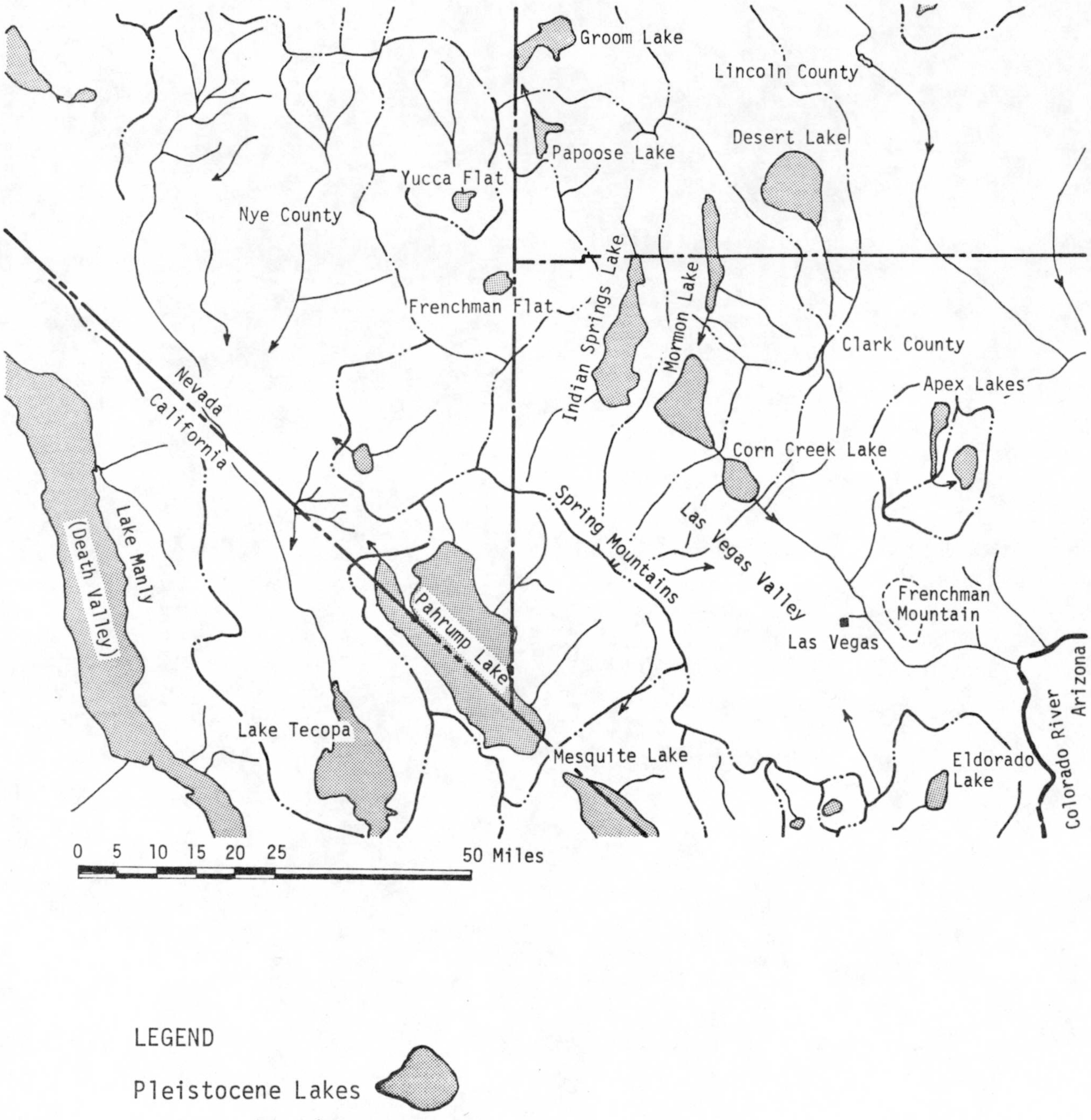


FIGURE A4 PLEISTOCENE LAKES AND DRAINAGE, SOUTHERN GREAT BASIN REGION (AFTER SNYDER ET AL., 1964)

It is noteworthy that a generally north-south-oriented continental margin has persisted since Precambrian time as recorded in the bedding planes of geosynclinal rocks and trends of Paleozoic orogenic belts. Wright (1976) stated that planes of weakness along these trends have undoubtedly influenced the orientation of Cenozoic faulting throughout the Great Basin. Thus, an understanding of ancient structures of the Great Basin may help to explain the present pattern of seismicity and active faulting.

A.4.2 Mesozoic Thrusts. A series of northeasterly trending Mesozoic thrust systems is superimposed on the generally north-south grain of the basement structure. Within the southern Great Basin are at least three such major bands of thrusting that affected pre-Mesozoic rocks during the Sevier and Nevadan orogenies (Figure A2d). The sense of motion was generally southeastward in all cases.

The Last Chance group of thrusts occurs over a large area in the vicinity of the Inyo Mountains of California (Stewart et al., 1966).

A second group of thrusts is prominent in Nye County, Nevada. This system -- known as the CP-Mine Mountain thrusts -- in the Nevada Test Site placed rocks as old as upper Precambrian upon middle and upper Paleozoic rocks. The resultant foreshortening of the crust was as much as 35 mi southeastward (Barnes and Poole, 1968). Volcanism of predominantly Miocene age covered most of the pre-Tertiary rocks in this area along with possible connections between the CP thrusts and other thrusts in Nye County, such as the Bare Mountain thrust, described by Cornwall and Kleinhampl (1964).

A third series of well-exposed and extensively studied thrust faults belonging to the Sevier system are found in the mountain ranges bordering Las Vegas Valley. This northeasterly trending band is composed of at least four major imbricate thrusts outcropping across northern Clark County and southern Lincoln County, from the Muddy Mountains to the Spotted Range and across the entire length of the Spring Mountains. Thrust faults in the Clark Mountains and the Nopah Range, California, may also be correlated with this system (Burchfiel et al., 1974).

The style of deformation and faulting in the Spring Mountains illustrates the nature of thrust faulting in the Sevier orogenic belt in general. Movement was from northwest to southeast, placing thick miogeosynclinal basin deposits upon thinner marginal facies. This telescoping of beds contributed about half of the apparent northwestward stratigraphic thickening observed in the Spring Mountains (Burchfiel et al., 1974).

A likely value for the total amount of crustal shortening associated with the Sevier orogeny has been estimated by Fleck (1970b) to be between 18 and 32 mi within the Spring Mountains alone. Burchfiel et al. (1974) alternatively arrived at a minimum shortening of 22 to 45 mi. The difference between these two estimates arises from uncertainty in the shape of thrust planes at depth. On the basis of evidence from the Clark Mountains, California, Burchfiel has favored a configuration akin to a décollement in which thrust planes flatten with depth. Fleck, on the other hand, has suggested that the thrust planes maintain their angle with bedding planes or flatten a little until they reach depths at which plastic deformation or flow could compensate for the crustal shortening. Yet more uncertainty arises in accounting for the large amount of shortening due to both broad warping and tight drag-folding pervasive in both the overthrust and lower plates (Fleck, 1970b).

The closest dating of Mesozoic thrusts also comes from the southernmost portion of the Great Basin. On the basis of radiometric dates of plutons in the Ivanpah Mountains, California, and ash deposits in the Muddy Mountains, Fleck (1970b) bracketed the age of thrust faulting as between about 75 and 90 million years ago, entirely within Cretaceous time. Burchfiel et al. (1974), however, present evidence that thrusting began in the Clark Mountains as early as Late Triassic or Early Jurassic time. Thus, deformation may have taken place in several pulses throughout the period from Late Triassic to Late Cretaceous time.

A.4.3 Las Vegas Valley Shear Zone. Considerable evidence indicates the existence of a fault zone with large right-lateral displacement in Las Vegas Valley. As previously noted, structural trends associated with the Sevier orogenic belt are oriented north to northeast across southern Nevada. This structural grain makes a sharp right-angle bend at Las Vegas Valley, a fact that led Longwell (1960) to hypothesize the existence of a buried fault along the length of Las Vegas Valley. According to Longwell's latest interpretation, the axis of the Las Vegas Valley shear zone trends east-southeastward from the northern end of the Spring Mountains, near Mercury, Nevada, to Lake Mead, passing along the north side of Las Vegas Valley, north of Frenchman Mountain and the city of Las Vegas (Figure A5).

In the Spring Mountains, thrust faults and fold axes deviate from their generally northerly trends to more easterly trends as they approach Las Vegas Valley. In the mountain ranges on the north side of the valley, opposite bending is observed. Longwell's mapping in this region has disclosed that bedding plane attitudes strike parallel to the fold axes and also display this bending pattern. Thus, geological structures adjacent to Las Vegas Valley appear to have been oroclinally drag-folded by post-Sevier right-lateral faulting.

Additional evidence arises from regional studies of upper Precambrian and Lower Cambrian formations, such as the Johnnie Formation, the Stirling Quartzite, the Wood Canyon Formation, and the Zabriskie Quartzite (Stewart, 1970). Stewart's isopach maps demonstrate that regular westward thickening of these formations is offset across the Las Vegas shear zone as well as the Death Valley — Furnace Creek fault system. Ross and Longwell (1964) were able to distinguish similar disturbances across the shear zone for the Ordovician Eureka Quartzite.

Seismic refraction data reported by Roller (1964) indicate that crustal thickness increases northward, from 27 to 32 km within a distance of 25 km across Las Vegas Valley. Regional gravity data reflect the gradual northward rise of topography (Mabey, 1960). However, the observed gravity gradient is steeper than that predicted from a change in crustal thickness alone. On the basis of these data, Roller suggested that mean crustal density decreases northward across Las Vegas Valley.

No fault trace definitely belonging to the Las Vegas shear zone has been discovered; however, possible subsidiary traces have been found. The La Madre

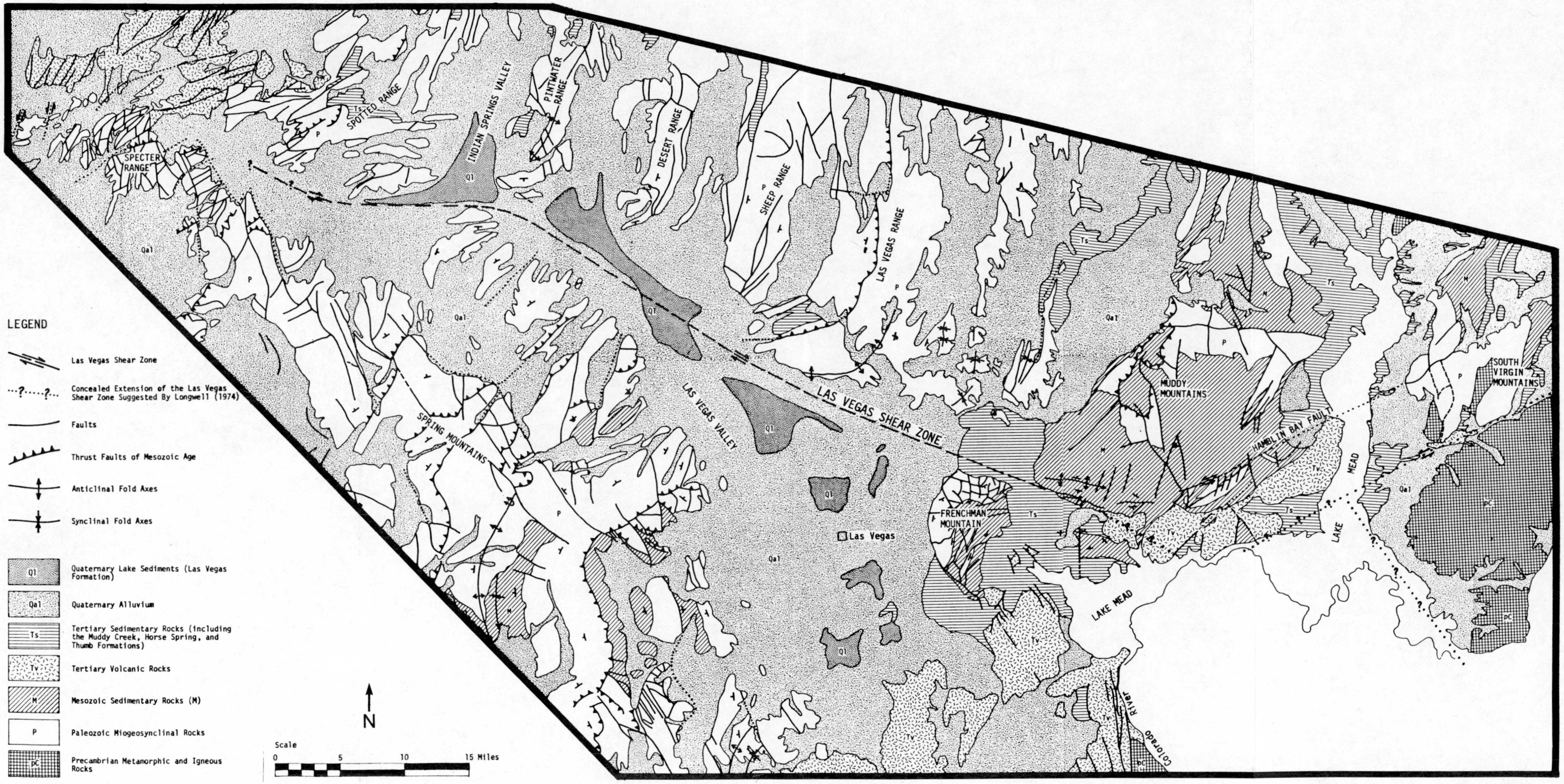


FIGURE A5 GENERALIZED GEOLOGIC MAP OF THE LAS VEGAS REGION, SHOWING LAS VEGAS VALLEY SHEAR ZONE (ADAPTED FROM LONGWELL ET AL., 1965) fault in the Spring Mountains is considered to be a probable branch fault from the main shear zone (Longwell, 1960). It intersects the major thrust plates at nearly right angles (see Figure A5) and displaces structural trends several miles in a predominantly right-lateral sense.

Various estimates have been given for the total displacement on the Las Vegas Valley shear zone. On the basis of a regional study of Ordovician stratigraphy, Ross and Longwell (1964) estimated an offset of 25 to 40 mi. Longwell (1974) has deduced a displacement of approximately 41 mi on the basis of reconstructions of offset and distorted thrust plates and correlation of a distinctive landslide breccia unit at Frenchman Mountain with its probable source area in the South Virgin Mountains.

This breccia is contained within the Thumb Formation, the upper part of which has been dated radiometrically at about 17 million years (Anderson et al., 1972). Radiometric dating of basalt in the lower part of the Muddy Creek formation in the Lake Mead area indicates that the last deformation on the shear zone occurred before 11 million years ago (Longwell, 1974). Previously, it was speculated that this deformation had begun perhaps as early as Mesozoic time. However, these data support the hypothesis that most right-lateral displacement on the Las Vegas shear zone occurred within late Miocene time, over the interval 17 to 11 million years before present. Ekren, Rogers, Anderson, and Orkild (1968), Fleck (1970a), and Anderson et al. (1972) arrived at similar age estimates.

<u>A.4.4 Regional Right-Lateral Deformation.</u> Right-lateral deformation is important in the westernmost part of the Great Basin, in a zone extending eastward from the Sierra Nevada front to the Walker Lane. Most movement probably has occurred since the middle Miocene, although some may have taken place earlier in Tertiary time. Historic surface-faulting characteristics and earthquake mechanism solutions show that right-lateral movement continues in this region today.

Albers (1967) described a belt of sigmoidal bending, which occupies the region between the Sierra Nevada front and the Walker Lane. Within this belt, range trends and structures in rocks as young as early Miocene display

S-shaped arcs. These he called "oroflexes," which are the result of oroclinal bending (i.e., folding about vertical axes) of the earth's crust. They may be the result of regionally distributed right-lateral shear, oriented along northwest-trending planes. Total displacement across the belt is some 80 to 120 mi. Deformation may have begun as early as late Early Jurassic and has apparently prevailed ever since. Bending must have ceased by middle Miocene time, and more recent movements have been restricted to faulting.

The Walker Lane, mentioned above, is a belt of topographic lows, extending southeastward from near Honey Lake, California, to near Mercury, Nevada. Ranges north of it trend predominantly north to north-northeast, while those south of it trend generally northwest. The zone was recognized in the 1930s, but was named by Locke, Billingsley, and Mayo (1940). They, and a number of other writers, have postulated major right-lateral offset along the belt. However, right-lateral faults are documented in only one area -- that of Soda Springs Valley and the Pilot Mountains -- located southeast of Walker Lake. Nielsen (1965) presented strong evidence for some 12 mi of offset in rocks of Permian to Miocene age. Most of the offset appears to have taken place since Miocene time, and physiographic features suggest significant Quaternary movement. Distribution of Quaternary faulting and historic seismicity suggest that the post-Miocene offset in the vicinity of Soda Springs Valley may be more directly related to the now active Owens Valley — Walker Lake — Winnemucca tectonic belt than to the Walker Lane trend.

Stewart's (1967) interpretation also demonstrates a regional system of late Cenozoic right-lateral faulting. His detailed isopach studies of upper Precambrian and Lower Cambrian strata indicate 80 to 120 mi of right-lateral offset from Death Valley to Las Vegas. Most of this offset is accounted for by displacements on the Las Vegas Valley shear zone and on the recently active Death Valley — Furnace Creek fault zone. The remaining offset may have been accommodated by broad regional folds (see Figure A6). Since late Miocene time, about 11 million years ago, when motion on the Las Vegas shear zone ceased (Longwell, 1974), right-lateral deformation has been restricted primarily to faulting in the region west of and including the Owens Valley and Death Valley — Furnace Creek fault zones and to related trends farther south in the Mojave Desert (Jennings, 1975).

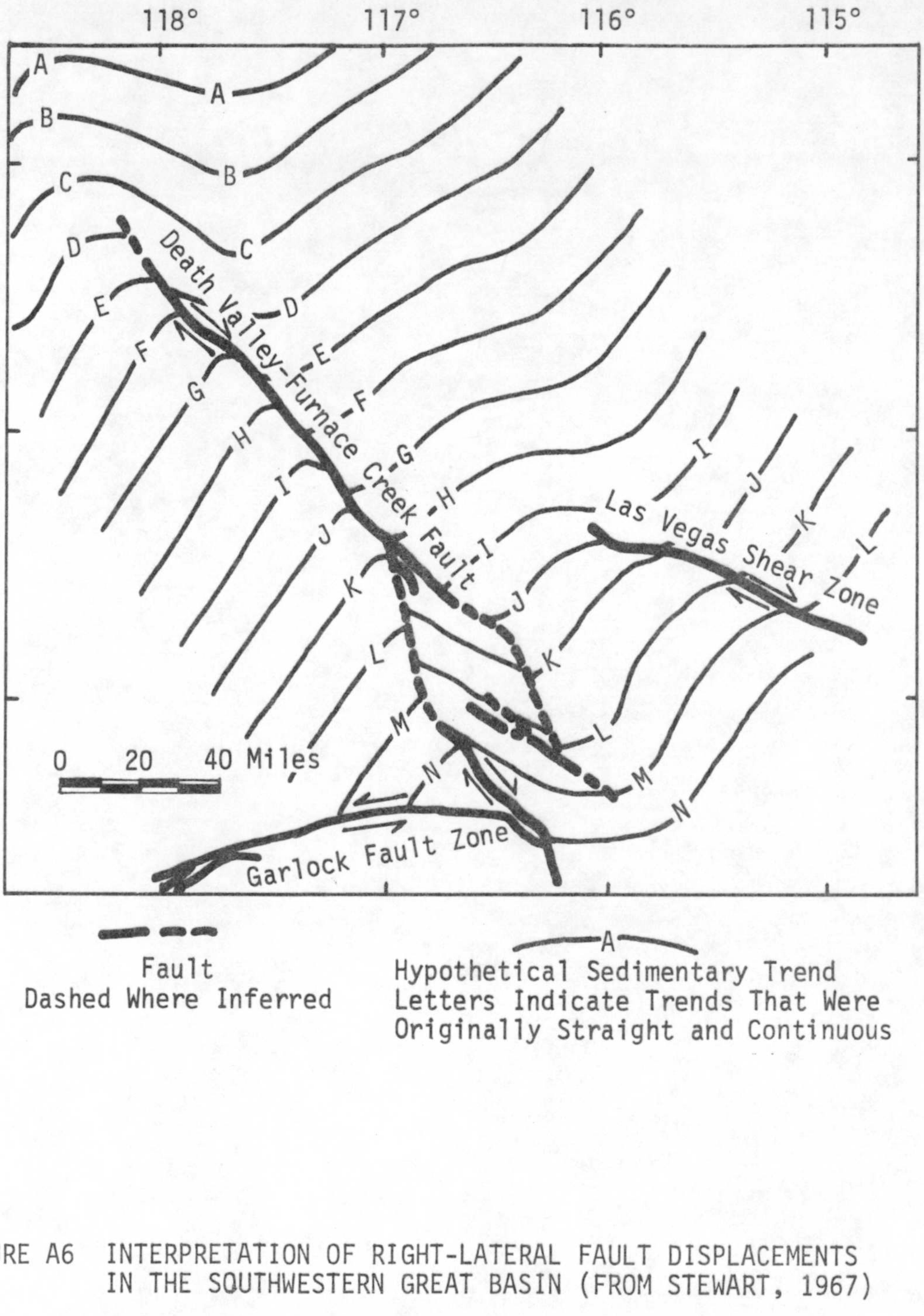


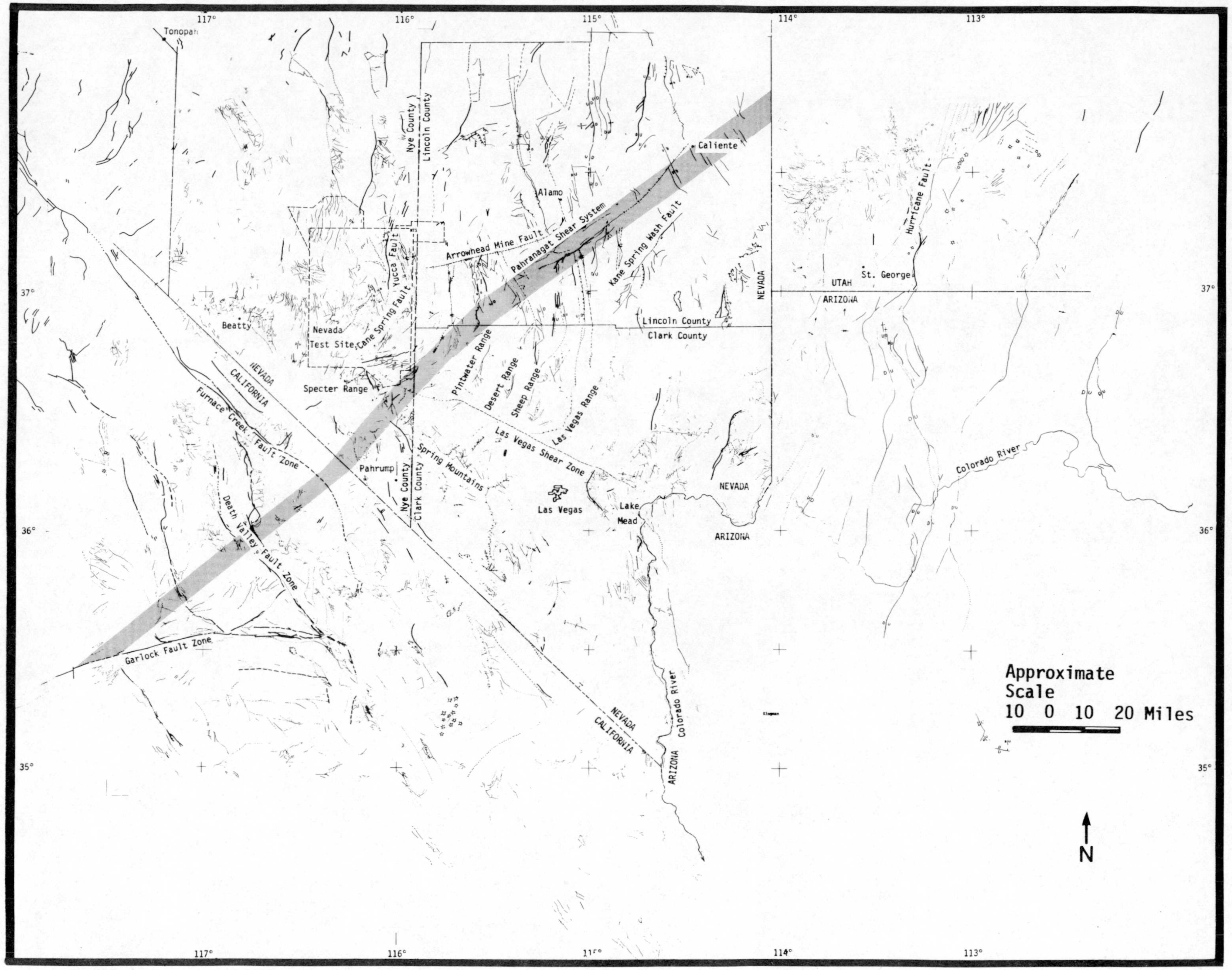
FIGURE A6 INTERPRETATION OF RIGHT-LATERAL FAULT DISPLACEMENTS IN THE SOUTHWESTERN GREAT BASIN (FROM STEWART, 1967)

The extent of the shear zone northwestward and southeastward beyond the ends of Las Vegas Valley has long been a matter of speculation. It seemed natural to connect the shear zone with active faults in west-central Nevada via the Walker Lane. However, little evidence has arisen to support the existence of a continuous right-lateral shear zone as suggested by Shawe (1965). The most doubtful link in the connection between Walker Lane and the Las Vegas shear zone is in southern Nye County, north of the Specter Range and the Amargosa Desert. It is possible that the Walker Lane is an older feature (perhaps pre-late-Miocene) now obscured by late Cenozoic structures.

The Specter Range lies athwart the northwestward extension of the Las Vegas Valley shear zone (Figure A5). Burchfiel (1965) and Moench (1965) have mapped the complex structural geology of this area without finding any clear indications of a large right-lateral shear zone. Both workers have interpreted the structural grain as probably continuous in an easterly trend in the Specter Range and continuous in a north to northwesterly trend in the ranges immediately to the south. Burchfiel suggests that the Las Vegas shear zone either is bent westward through the Specter Range and into the Amargosa Desert or merges into a broad fold. Another possibility, which has not been fully explored, is that the east- to northeast-trending structures are part of a younger left-oblique-slip fault system that has offset the shear zone toward the west. According to Burchfiel, the Walker Lane must be considered as an entirely separate feature from the Las Vegas shear zone.

A.4.5 Late Cenozoic Left-Lateral Faulting. Northeasterly trending left-lateral faults have been mapped in three areas within the southern Great Basin region. These are located as follows: along the north side of Lake Mead, about 25 mi east of Las Vegas; in the southern part of the Nevada Test Site, about 70 mi due northwest of Las Vegas; and in south-central Lincoln County, 70 mi due north of Las Vegas (see Figure A7).

In the first of these areas, immediately north of Lake Mead, Anderson (1973) has mapped a series of left-lateral oblique faults parallel to the Hamblin Bay fault. His interpretation projects this southwesterly trend across the southeastern end of the Las Vegas shear zone. The Las Vegas shear zone apparently does not continue into the Black Mountains, which lie on the



LEGEND

Faults with predominant sense of motion, dashed or dotted where poorly located or concealed

-?--?- Conjectural fault

Low angle faults of Mesozoic age

Anticlinal structures

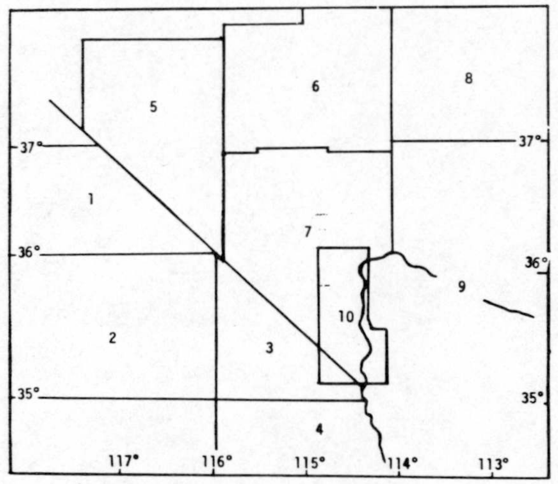
Synclinal structures

Garlock-Caliente Lineament
observed on (ERTS-1) satellite imagery, 1:5,000,000 scale (U.S.D.A. Soil Conservation Service, 1974)

Faults which have late Quaternary or Holocene displacement

Nevada/Utah data from Provisional Map of Active Faults of the Basin and Range Province (Slemmons et al., 1964) - unpublished file data.

Sources of Data



1. - 4. Geologic Map of California, Olaf P. Jenkins Edition, California Division of Mines and Geology, scale 1:250,000, additions from Fault Map of California, California Geologic Data Map Series, Map No. 1, C. W. Jennings, compiler, 1975, scale 1:750,000.

    1. Jennings (1958), Death Valley Sheet.
    2. Jennings, Burnett and Troxel (1962), Trona Sheet.
    3. Jennings (1961), Kingman Sheet.
    4. Bishop (1963), Needles Sheet.

5. Cornwall (1972), Plate 1, Scale 1:250,000.

6. Tshanz and Pampeyan (1970), Plate 3, Scale 1:500,000.

7. Longwell, et al. (1965), Plate 1, Scale 1:250,000.

8. Hintze (1963), Geologic Map of Southeastern Utah, Scale 1:250,000.

9. Wilson, Moore, and Cooper (1969), Geologic Map of Arizona, Scale 1:500,000.

10. Longwell (1963), Plate 1, 1:125,000.

FIGURE A7 GENERALIZED TECTONIC MAP OF THE SOUTHERN GREAT BASIN REGION

Arizona side of Lake Mead between the two basins of the reservoir (Longwell, 1963). In order to explain this configuration, Longwell (1974) postulated the faults shown southeast of Las Vegas in Figure A5.

A system of generally north-trending normal faults approaches the Lake Mead area from the south. Prominent among these are the Eldorado and the Boulder Wash faults. This system appears to be truncated by the left-lateral faults, although interpretation is difficult because they are widely covered by Pliocene and younger volcanic rocks and alluvium. Anderson (1973) believes that many of the normal faults dip at unusually low angles and are genetically related to the left-lateral system.

On the basis of potassium-argon ages, Anderson has inferred more than 12 mi of left-lateral slip on the Hamblin Bay fault system between 12.7 and 11.1 million years ago. The entire zone of parallel left-lateral faults may represent a larger total deformation over a somewhat longer period of time. Anderson et al. (1972) have shown that extensive volcanism occurred along the Hamblin Bay fault concurrently with faulting. For a larger area in southeastern Clark County from Lake Mead to the Eldorado Mountains, most of the volcanism occurred over a longer time span, from about 16 to 12 million years ago.

Other northeasterly left-lateral trends have been mapped in the Nevada Test Site. The complex structural relationships in this area have not been completely resolved. However, some of the left-lateral features, such as the Cane Spring fault near Frenchman Flat, appear to offset all structures except the most recent northerly trending normal faults. These relationships are seen on maps by Ekren and Sargent (1965) and Poole, Elston, and Carr (1965). The east- to northeast-trending left-oblique faults described by Burchfiel (1965) in the Specter Range may be a westward continuation of this system.

The amount of left-lateral offset in this area is unknown. Most movement on the Cane Spring fault probably took place before 11 million years ago, although some probably occurred after 7 million years ago. No left-lateral displacements in Quaternary alluvium have been observed (Ekren, 1972).

Another belt of east- to northeast-trending faults, apparently left-lateral, is centered in southern Lincoln County, east of the Nevada Test Site, and has been described by Tschanz and Pampeyan (1970). Named the Pahranagat shear system, the belt comprises three left-lateral faults and has a length of 25 mi. Total apparent post-Miocene displacement across the system is some 6 to 10 mi. Volcanic units of questionable Pliocene age are only slightly offset, suggesting that the system is less active now than in Pliocene time.

Of the three faults, the Arrowhead Mine fault is by far the most speculative. On the basis of apparent offset of structures in Paleozoic rocks, Tschanz and Pampeyan (1970) suggested that Laramide motion on this fault may have been some 30 mi in a right-lateral sense. They speculated that the entire belt originated in Laramide time as a right-lateral shear zone in basement.

The Arrowhead Mine fault cannot actually be mapped within individual range blocks. However, it, as well as the mapped left-lateral faults immediately south, appears to be almost colinear with part of a major northwest-trending lineament (see Figure A7). The lineament may be seen on 1:5,000,000-scale ERTS satellite photography (USDA Soil Conservation Service, 1974). It appears to be tangent to the Garlock fault and to strike N 50° E, extending across southern Nevada and into the southern Escalante Desert, near Modena, Utah. This lineament might separate regions having different magnitudes of east-west crustal extension, i.e., greater to the north and lesser to the south. If correct, the hypothesis requires left-lateral faulting along the lineament.

A.4.6 Late Cenozoic Normal Faults. The structure of the Basin and Range province is dominated by generally north-trending normal faults. This style of faulting has produced a distinctive physiography of broad, flat, alluvial valleys separated by roughly parallel, north-oriented mountain ranges. The mountain blocks have been elevated by normal faulting along generally parallel lines that are spaced about 30 mi apart in most of the Basin and Range province (Figure A8).

High-angle normal faults are characteristically located along the range

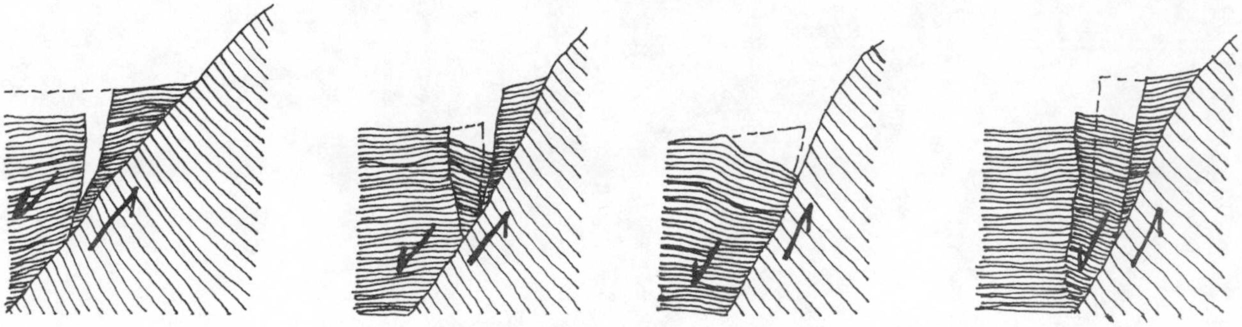


FIGURE A8 DETAILS OF NORMAL FAULT SCARPS IN ALLUVIUM (FROM SLEMMONS, 1957, AFTER GILBERT, 1890)

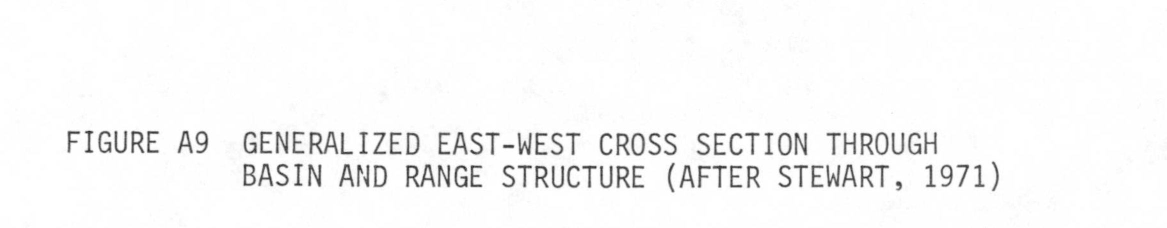


FIGURE A9 GENERALIZED EAST-WEST CROSS SECTION THROUGH BASIN AND RANGE STRUCTURE (AFTER STEWART, 1971) fronts; they are also found some distance from range fronts, buried under valley alluvium. Within this overall pattern are commonly asymmetrical grabens and tilted mountain blocks. The traces of normal faults are linear when viewed on a small scale, but in detail they may be remarkably sinuous. Where normal faulting propagates upward into alluvium, it is commonly observed that fault planes steepen and splay, often forming numerous small grabens (Figure A9).

In certain localities, low-angle normal faults (dipping less than 45°) are abundant. Such faulting has produced almost chaotic structure in the Desert Range north of Las Vegas Valley, the South Virgin Mountains east of Lake Mead (Longwell, 1945), the Black Mountains north of Lake Mead (Anderson, 1973), and the Eldorado Mountains 30 mi southeast of Las Vegas (Anderson, 1971). Anderson (1971) speculated that the origin of these complexly interrelated faults was a distension of the crust accompanied by the emplacement of plutonic masses.

A.5 Las Vegas Valley: Quaternary Deformation and Structure

It may be observed on the geologic maps of Longwell et al. (1965) that normal faulting occurred simultaneously with and overlapped the activity of the Las Vegas shear zone. The trends of mountain ranges at the north side of Las Vegas Valley and the remnants of normal faults that presumably formed during their uplift are clearly bent towards the west. Thus, some normal faulting predated right-lateral faulting on the shear zone.

The Muddy Creek Formation, described in Table A4, is widely exposed in the area surrounding Frenchman Mountain between Las Vegas and Lake Mead. The Las Vegas shear zone passes beneath this area, yet the Muddy Creek Formation is notably undeformed and free of faults.

Outcrops of the underlying Horse Spring and Thumb formations of Miocene age (see Table A4) and all older rocks are severely deformed and cut by normal faults. Thus, shear zone activity and the most intense period of normal faulting must have ended by Muddy Creek time about 11 million years ago.

Geomorphic evidence points to continuing changes in elevation indicative of normal faulting. Tabor (1970) estimated from depositional surfaces in the

Muddy Creek Formation at Frenchman Mountain that about 600 ft of elevation change has occurred in post-Muddy-Creek time. Earlier vertical displacement was more than 4,000 ft.

The configuration of erosion surfaces on Pleistocene alluvium in the Spring Mountains also suggests recent uplifting. Lattman (1971) showed that alluvium in the main canyons leading out of the Spring Mountains into Las Vegas Valley has undergone three stages of successively deeper incision since Pleistocene time. In Lee Canyon, Pleistocene alluvium has been incised to a depth on the order of 400 ft. Range front faulting cannot be concluded from this evidence alone. These geomorphic features could also have been caused by significant fluctuations in runoff volume due to climatic changes.

Haynes (1967) studied the Quaternary stratigraphy of the Tule Springs area in the center of Las Vegas Valley. He concluded that Las Vegas Valley has been tectonically active periodically throughout the last 40,000 years. Lake bed sediments have been tilted possibly as recently as 1,000 years ago.

However, the role of normal faulting in this ongoing deformation is unproven. Range-front normal faults may lie buried in the alluvium bordering Las Vegas Valley. Particularly likely locations are along the east flank of the Spring Mountains in the vicinity of Lee and Kyle canyons northwest of Las Vegas and along the west side of Frenchman Mountain immediately east of Las Vegas (locations shown in Figure A10). These areas have been mapped and discussed by Fleck (1970b), Burchfiel et al. (1974), Longwell et al. (1965), and others.

A gravimetric survey of Las Vegas Valley might aid in detecting the presence of large bedrock discontinuities. Similar studies were instrumental in establishing the unexpected bedrock configuration at Yucca Flat (Healy, 1968). Kane and Carlson's (1964) gravity map of Clark County is inconclusive regarding the detailed bedrock structure of Las Vegas Valley.

No range-front faults have been found in Las Vegas Valley. However, a number of features could bear further scrutiny to assess their relationship to tectonic faulting and whether they constitute significant geologic hazards.

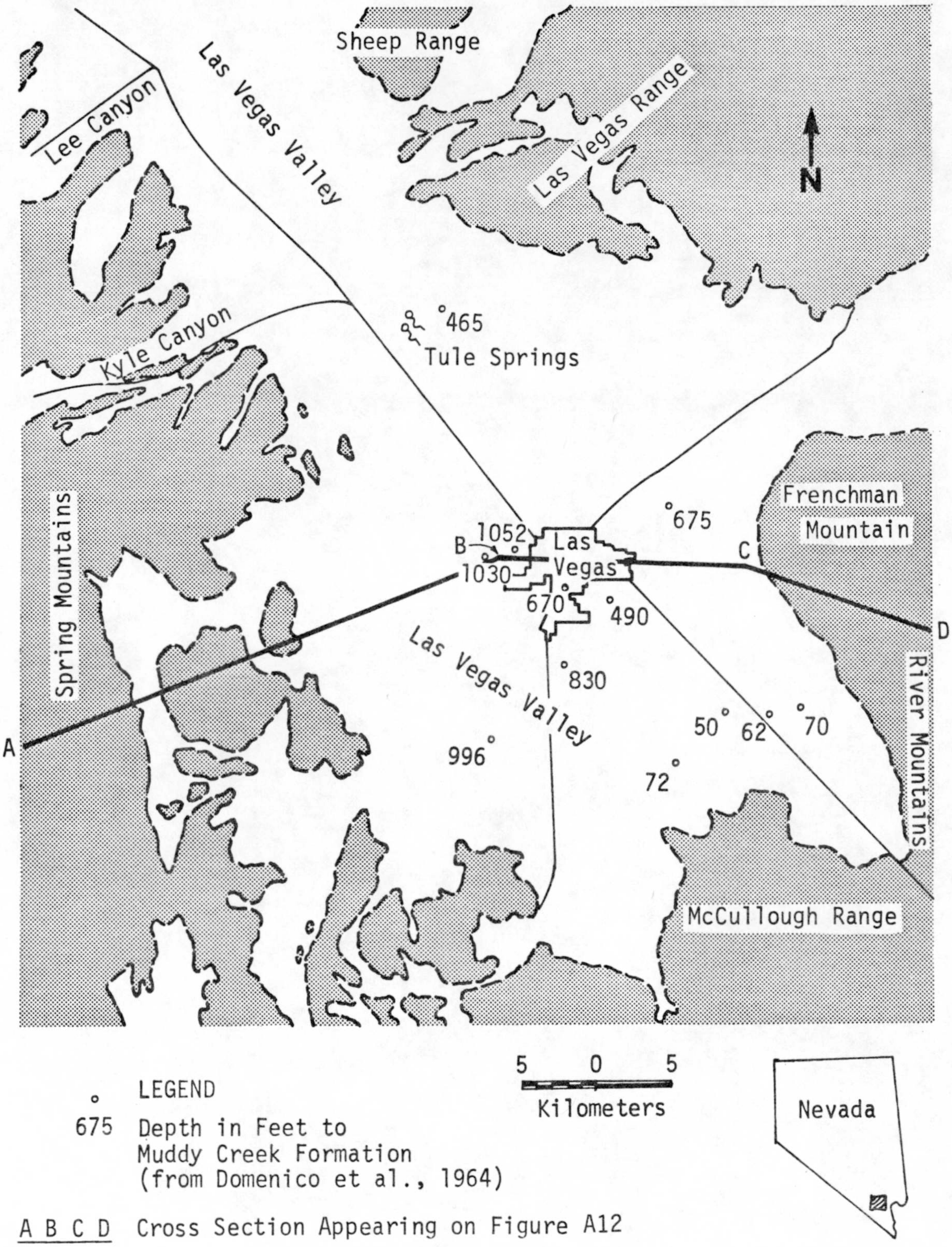


FIGURE A10 ESTIMATED DEPTH TO TOP OF MUDDY CREEK FORMATION, LAS VEGAS VALLEY

Table A5 is a partial list of documented faults, lineaments, and scarps, many of undetermined origin, within a radius of about 70 mi of Las Vegas. The first five entries in Table A5 are recent scarps located in Las Vegas Valley. Suggested origins for these features are water loading in former lakes, wave action, differential compaction, and tectonic deformation (Malmberg, 1964; Price, 1966; and Tabor, 1970).

The Las Vegas compaction scarps trend generally parallel northward through Las Vegas. The faults roughly follow topographic contours with sinuous traces, showing a normal sense of displacement down to the east. Maxey and Jameson (1948) originally suggested that the fault scarps were generated by differential soil compaction. The finer-grained sediments experience greater loss in volume upon compaction, explaining the fact that amount of subsidence and downward faulting increase toward the center of the valley. Conwell (1965) documented the extensive structural damage that has occurred due to subsidence in Las Vegas Valley.

Data presented by Malmberg (1964) indicate that the subsidence is largely due to compaction of the sediments at depth as a result of excessive groundwater withdrawal. Mindling (1965) studied soil parameters, performed laboratory consolidation tests, and calculated expected surface settlements due to subsurface consolidation. He found that the locations and rates of recorded groundwater withdrawals in Las Vegas were consistent with the observed pattern of subsidence.

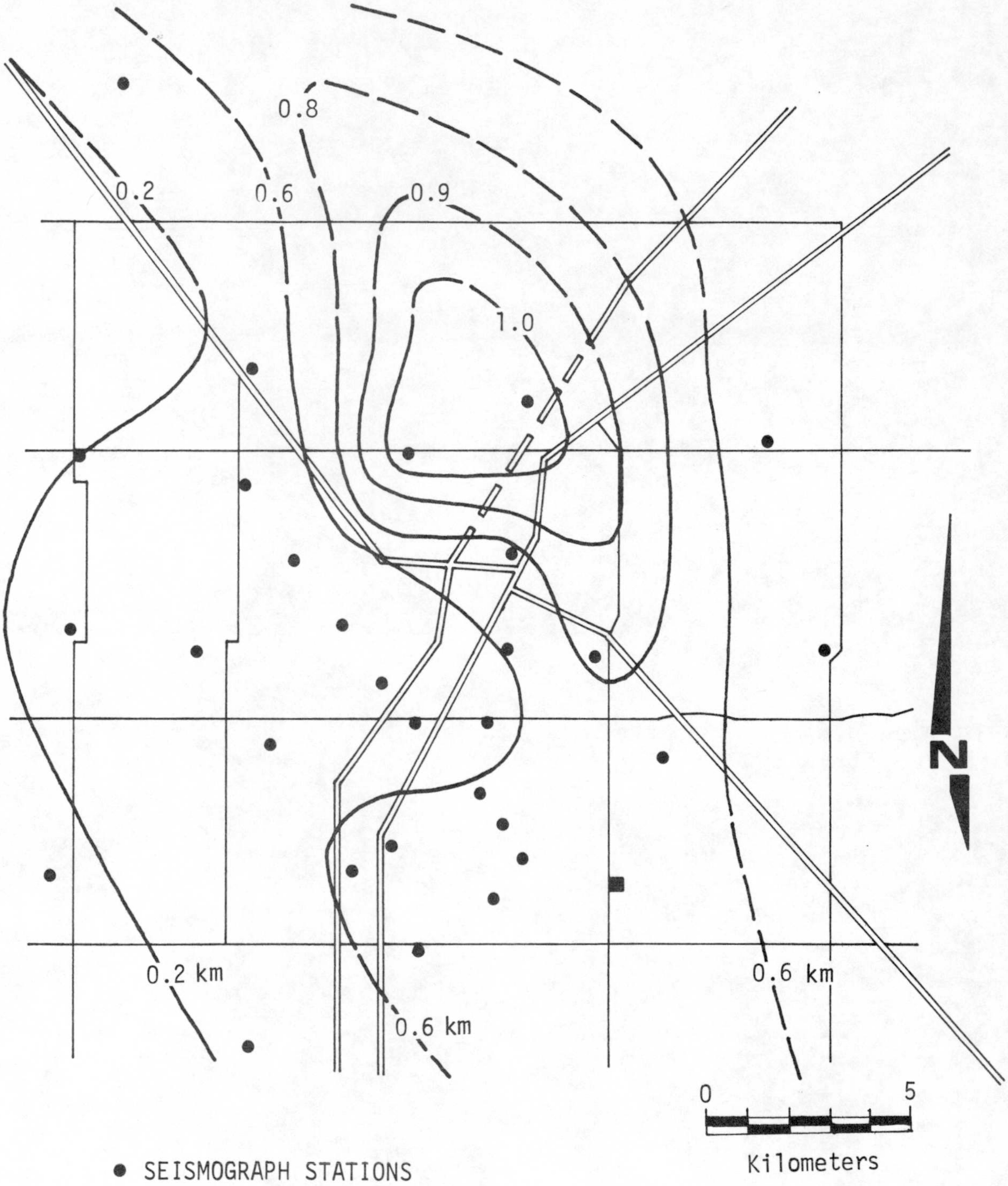
The alluvium of Las Vegas Valley is essentially flat-lying with a low valleyward dip near the surrounding highlands. Unfortunately, very little information concerning the thickness of alluvium and bedrock structures has been published. Domenico, Stephenson, and Maxey (1964) estimated the depth to the top of the Muddy Creek Formation beneath Las Vegas to be approximately 1,000 ft on the basis of many water well logs (see Figure A10). The greatest thickness of alluvium appears to be at the center of the valley, roughly coinciding with the location of thickness contours calculated by Bennett (1974) from ground motion due to nuclear testing (Figure A11).

The difference in magnitude between these two thickness estimates (1,000 ft versus 1 km) points to a lack of knowledge of the subsurface geology and

TABLE A5

POTENTIALLY ACTIVE FAULTS IN THE LAS VEGAS AREA

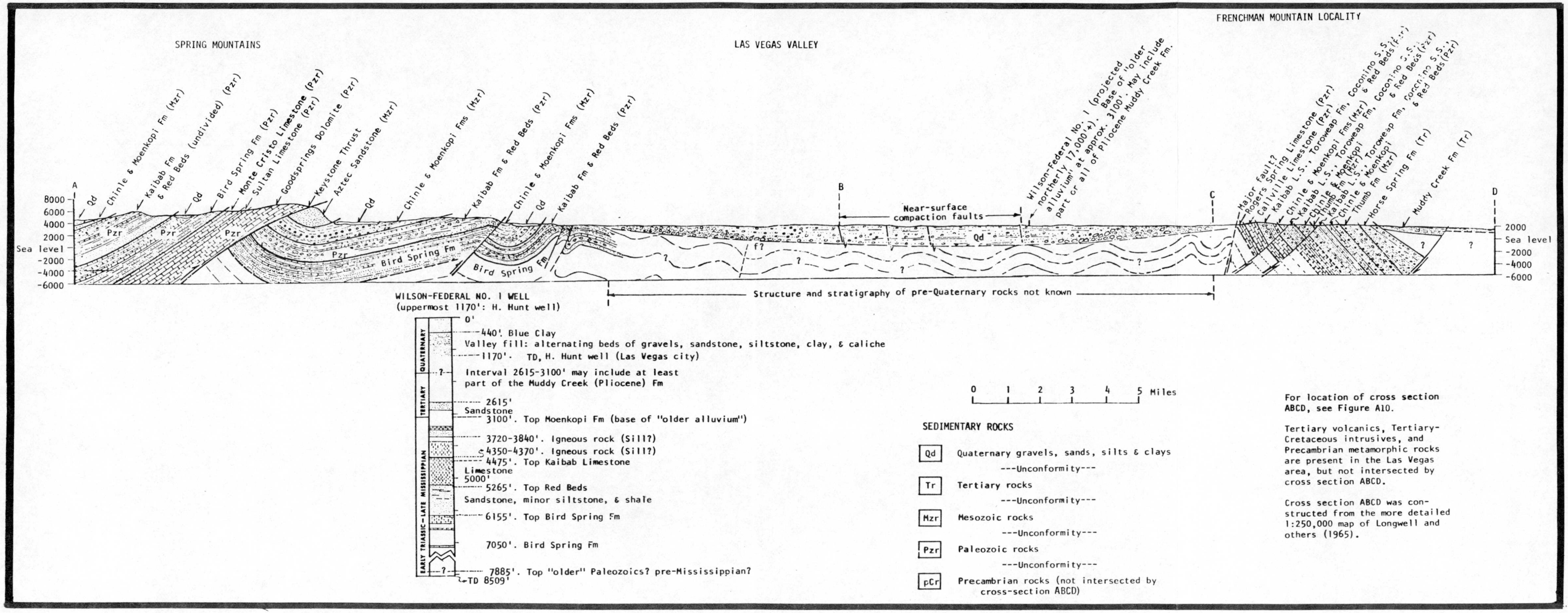
Name	Location Relative to Las Vegas	Description	Estimated Age	Scarp Length	Reference
Las Vegas compaction scarps	within city of Las Vegas	sinuous, normal, down to E	Holocene "active"	5 sinuous traces 5-20 mi long	Maxey and Jameson (1948), Malmberg (1965, plate 3), Conwell (1965), Tabor (1970)
Eglington scarp	6 mi N of Las Vegas	inferred, NE	12,000 to 16,000 yr	4.2 mi	Haynes (1967) ages supported by 80 C^{14} dates
Tule Springs south	10 mi N of Las Vegas	inferred normal, N	abrupt emergence >11,000 yr ago to explain spring	?	Haynes (1967) ages supported by 80 C^{14} dates
Corn Creek fault	24 mi NW of Las Vegas	normal, NW	>11,000 yr horst	4.1 mi	Haynes (1967) ages supported by 80 C^{14} dates
Headquarters fault	24 mi NW of Las Vegas	normal, NW	?	2.4 mi	Haynes (1967) ages supported by 80 C^{14} dates
Fortification fault	south side of Lake Mead, now covered by reservoir, 25 mi E	reverse, N, converges with Mead Slope fault	mostly pre-end of Muddy Creek, covered by Fortification Hill basalt, cuts older Colorado River alluvium in reservoir, Pliocene or Pleistocene	8 mi	Longwell (1936, plate 2), Longwell (1946)
Mead Slope fault and Horse Thief fault	S. Lake Mead, 25 mi E	now partly under water, reverse, NE	Pleistocene or Holocene	2.5 to 5 mi each	Longwell (1963)
Unnamed faults	Echo Wash in Overton Arm, 40 mi E	two faults cutting volcanic and alluvium	?	?	Longwell (1936), cited by Bechtold, Liggett, and Childs (1973)
Unnamed faults	between Gold Butte and Overton	generally N-trending swarm of normal scarps cutting alluvium	Holocene	entire alignment is 20 mi long, individual faults are 1 to 5 mi long	Bechtold et al. (1973)
Epperson fault and Big Blacktop fault	near Lake Mojave, 40-50 mi SE	generally N	?	9 and 2.5 mi	Longwell (1936), cited by Bechtold et al. (1973)
Unnamed	15 mi N of Lake Mohave, 45 mi SE of Las Vegas	small, normal, N-S	?	? nearby lineaments 12 mi long	Hansen (1962), cited by Bechtold et al. (1973)
Unnamed lineaments	70-120 mi SE of Las Vegas near Lake Havasu	motion?, in alluvium	Quaternary?	two faults, each 2 mi long, lineaments 10-30 mi long	Bechtold et al. (1973) from ERTS imagery
Cane Spring fault zone	68 mi NW, in Nevada Test Site	decreasing displacement ~N50°E, left lateral, continuing into normal system at Massachusetts Mountain	Holocene "still active"	6 mi to 8 mi from maps by Poole et al. (1965) and Ekren and Sargent (1965)	Carr, Bath, Healey, and Hazelwood (1975)
Unnamed fault	60 mi NW, west front of Ranger Mountains, in Nevada Test Site	~N60°E, normal, cuts alluvium down to NE	Holocene	1.3 mi maximum, from map by Poole et al. (1965)	Carr et al. (1975)
Puddle Peak system	69 mi NW, in Nevada Test Site	smaller, right lateral, thought to join Yucca fault zone W of Yucca Lake, Cane Spring and Puddle Peak systems drag each other	Holocene, same age as Cane Spring fault	~3 mi from Carr's (1975) map, inferred from gravity and drag evidence	Carr et al. (1975)
Yucca fault	75 mi NW, Yucca Flat, in Nevada Test Site	center of valley, N-S cuts, recent sediments	Holocene	~15 mi, from Fernald's (1968) map	Carr et al. (1975), Fernald, Corchary, and Williams (1968)



● SEISMOGRAPH STATIONS

■ LOCATION OF DEEP WELL

FIGURE A11 CONTOURS OF ALLUVIUM THICKNESS, LAS VEGAS VALLEY (CALCULATED FROM SURFACE WAVE MEASUREMENTS BY BENNETT, 1974) soil parameters such as density and elastic wave velocities. Indeed, it is difficult to decide which horizon in the stratigraphic column should be considered bedrock for seismic response purposes. Current knowledge of the structure of Las Vegas Valley is presented in Figure A12, an east-west cross section through the city of Las Vegas.



For location of cross section ABCD, see Figure A10.

Tertiary volcanics, Tertiary-Cretaceous intrusives, and Precambrian metamorphic rocks are present in the Las Vegas area, but not intersected by cross section ABCD.

Cross section ABCD was constructed from the more detailed 1:250,000 map of Longwell and others (1965).

FIGURE A12 GEOLOGIC CROSS SECTION OF LAS VEGAS VALLEY (FROM TABOR, 1970)

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APPENDIX B

Listing of Program HAZARD

```
      PROGRAM HAZARD(INPUT,OUTPUT)
      DIMENSION A(12),AC(12),B(25),B1(25),E(100),F(12,100),G(100),
     1P(12,12),Q(12,25),R(12,12),RT(12),S(12,25),Y(12),FNAME(10),T(100),
     2SQ(12,25),SS(12,25),SR(12,12)
C      DATA
CARD 0 NRUNS   FORMAT(I5)
C              NUMBER OF SITES TO BE ANALYZED
C
CARD 1         FORMAT(3I5,2F5.2)
C      NF      NUMBER OF EARTHQUAKE SOURCES TO BE CONSIDERED.
C      NA      NUMBER OF ACCELERATIONS FOR WHICH RATES OF EXCEEDANCE ARE TO BE
C              CALCULATED.
C              USE NA = 12 TO AVOID A PRINTOUT BUG.
C      NP      NUMBER OF TIME INTERVALS FOR WHICH PROBABILITIES OF EXCEEDANCE
C              ARE TO BE CALCULATED.
C      RMMIN   SMALLEST MAGNITUDE TO BE CONSIDERED.
C              USE RMMIN = 3.0
C      SIGMA   GEOMETRIC STANDARD DEVIATION ( LOG BASE 10) OF ACCELERATION
C              MODEL.
C              USE SIGMA = .25
C
CARD 2         FORMAT(12F6.1)
C      AC(I)   NA ACCELERATIONS, IN GALS.
C
CARD 3         FORMAT(12F6.1)
C      Y(I)    NP INTERVALS OF TIME, IN YEARS.
C
C
C
C              FOR EACH OF THE NF SOURCES, SPECIFY;
C
CARD A         FORMAT(10A8)
C      FNAME---TITLE CARD--NAME OF SOURCE
C
CARD B         FORMAT(6F10.5,3I5)
C      AR      PARAMETER A IN THE MAGNITUDE - RECURRENCE RELATION.
C              IF, FOR AREA SOURCES, THE RECURRENCE IS NORMALIZED, SET I2 = -1
C              AND SPECIFY REFM AND REFAREA.  THEN AR IS THE NUMBER OF EVENTS
C              OF MAGNITUDE REFM OR MORE PER REFAREA PER YEAR.
C              FOR AREA SOURCES WHICH ARE TO BE DIVIDED INTO SUBREGIONS, AR MUST
C              BE NORMALIZED.
C      BR      PARAMETER B IN THE MAGNITUDE - RECURRENCE RELATION.
C      RMMAX   MAXIMUM MAGNITUDE.
C      DM      MAGNITUDE INCREMENT FOR THE NUMERICAL INTEGRATION.
C              SET DM = .25
C
C              IF THE SOURCE IS A FAULT, LEAVE THE REST OF THIS CARD BLANK.
C
C      REFM    REFERENCE MAGNITUDE.
C      REFAREA REFERENCE AREA, IN SQUARE KILOMETERS.
C      I1       0 FOR FAULT SOURCE
C              -1 FOR AREA SOURCE
C      I2       0 IF THE RECURRENCE PARAMETER AR IS ABSOLUTE.
C              -1 IF AR IS NORMALIZED.
C                 IF THE AREA SOURCE IS TO BE SUBDIVIDED, I2 MUST BE -1 AND AR
C                 MUST BE NORMALIZED.
C      I3      NUMBER OF SUBREGIONS OF THE AREA SOURCE.
C              LEAVE BLANK FOR FAULT SOURCES AND UNITARY AREA SOURCES.
```

```
      RJ1=FLOAT(J1)
      IF (RJ1.EQ.U) GO TO 210
      DO 207 JJ=1,J
      E(JJ)=S(I,JJ)
  207 CONTINUE
      CALL SIMPER(E,H,DM,J)
      R(I,J1)=H
      B1(J1)=RM
  210 CONTINUE
  250 CONTINUE
  300 CONTINUE
      IF (I3.LE.1) GO TO 340
      DO 330 I=1,NA
      DO 310 J=1,M1
      SQ(I,J)=SQ(I,J)+Q(I,J)*AREA
      SS(I,J)=SS(I,J)+S(I,J)
  310 CONTINUE
      DO 320 J=1,M2
      SR(I,J)=SR(I,J)+R(I,J)
  320 CONTINUE
  330 CONTINUE
  340 CONTINUE
  350 CONTINUE
      IF (I3.LE.1) GO TO 390
      DO 380 I=1,NA
      DO 360 J=1,M1
      Q(I,J)=SQ(I,J)/SAREA
      S(I,J)=SS(I,J)
  360 CONTINUE
      DO 370 J=1,M2
      R(I,J)=SR(I,J)
  370 CONTINUE
  380 CONTINUE
  390 CONTINUE
      DO 400 I=1,NA
      RT(I)=RT(I)+R(I,M2)
  400 CONTINUE
      PRINT 1010
 1010 FORMAT(//1X,* PROBABILITY THAT, WHEN A MAGNITUDE M EARTHQUAKE OCCU
     1RS SOMEWHERE IN THE SOURCE, IT WILL CAUSE A SITE ACCELERATION GREA
     2TER THAN A*,/)
      PRINT 1011,(AC(I),I=1,NA)
 1011 FORMAT(7X,*A*,12F10.1/4X,*M*,/)
      PRINT 1012,(B(J),(Q(I,J),I=1,NA),J=1,M1)
 1012 FORMAT(F7.3,3X,12F10.7/F7.3,3X,12F10.7)
      PRINT 1013
 1013 FORMAT(//1X,* DERIVATIVE OF THE RATE OF EXCEEDANCE WITH RESPECT TO
     1 MAGNITUDE*,/)
      PRINT 1011,(AC(I),I=1,NA)
      PRINT 1012,(B(J),(S(I,J),I=1,NA),J=1,M1)
      PRINT 1014
 1014 FORMAT(//1X,* RATE AT WHICH EARTHQUAKES OF MAGNITUDE M OR MORE CAU
     1SE ACCELERATIONS GREATER THAN A*,/)
      PRINT 1011,(AC(I),I=1,NA)
      PRINT 1012,(B1(J),(R(I,J),I=1,NA),J=1,M2)
  500 CONTINUE
      DO 700 I=1,NA
```

```
 2011 FORMAT(4X,*ABSOLUTE RECURRENCE PARAMETER A*,3X,F7.3,/)
      IF (I3.LE.1) GO TO 170
      SAREA=SAREA+AREA
  170 CONTINUE
      M1=M+1
      M2=M/2
      RM=RMMAX+DM
      DO 300 J=1,M1
      RM=RM-DM
      B(J)=RM
      IF (I1.LT.0) GO TO 171
      RL=RLENGM(RM)
      RLN=-RL
      EL=FL-RL
      IF (EL.LE.0.) 20,30
   20 PRINT 1030
 1030 FORMAT(1X,*EARTHQUAKE IS TOO BIG FOR THE FAULT*)
      GO TO 800
   30 CONTINUE
      U=(EL/DL+1.)/2.
      L=2*INT(U)
      IF (L.LT.2) L=2
      U=FLOAT(L)
      DX=EL/U
      L1=L+1
  171 CONTINUE
      V=X1-DX
      W=X1+RL-DX
      DO 200 K=1,L1
      V=V+DX
      W=W+DX
      U=V+W
      X=0.
      IF (U.GE.RL) X=V
      IF (U.LE.RLN) X=W
      Z=SQRT(X**2+D**2)
      CALL ACCEL(AS,RM,Z,K)
      T(K)=X
      DO 150 I=1,NA
      DA=ABS(AS-A(I))/SIGMA
      PHI=(1.+ERFUDGE(DA))/2.
      F(I,K)=PHI
      IF (AS.LE.A(I)) F(I,K)=1.-PHI
  150 CONTINUE
  200 CONTINUE
      DO 250 I=1,NA
      DO 205 K=1,L1
      G(K)=F(I,K)
      IF (I1.LT.0) G(K)=F(I,K)*T(K)
  205 CONTINUE
      CALL SIMPER(G,H,DX,L1)
      Q(I,J)=H/EL
      S(I,J)=Q(I,J)*BR*2.30259*10.**(AX-BR*RM)
      IF (J.LT.3) GO TO 210
      RJ=FLOAT(J)
      U=RJ/2.
      J1=INT(U)
```

```
      IF (I3.LE.1) GO TO 820
      DO 815 I=1,NA
      DO 805 J=1,25
      SQ(I,J)=0.
      SS(I,J)=0.
  805 CONTINUE
      DO 810 J=1,12
      SR(I,J)=0.
  810 CONTINUE
  815 CONTINUE
      SAREA=0.
      GO TO 825
  820 I3=1
  825 CONTINUE
      DO 350 IS=1,I3
      READ 2006,D,X1,X2,DL,THETA
 2006 FORMAT(5F10.5)
      X3=X1
      IF (X1.LT.X2) GO TO 110
      X1=X2
      X2=X3
  110 FL=X2-X1
      IF (I1.LT.0) GO TO 120
      PRINT 1007,FL
 1007 FORMAT(20X,*FAULT LENGTH IS*,3X,F7.3,/)
      PRINT 1008,D
 1008 FORMAT(2X,*NORMAL DISTANCE TO FAULT PLANE IS*,2X,F7.2,/)
  120 CONTINUE
      IF (I3.LE.1) GO TO 130
      PRINT 2009,IS
 2009 FORMAT(/,1X,*SUBREGION*,I5,//)
  130 PRINT 1009,X1,X2
 1009 FORMAT(3X,*COORDINATES OF SOURCE BOUNDARIES*,1X,2F7.1,/)
      IF (I1.GE.0) GO TO 172
      D=.00001
      U=(FL/DL+1.)/2.
      L1=2*INT(U)+1
      IF (L1.LT.3) L1=3
      U=FLOAT(L1)
      DX=FL/U
      RL=0.
      RLN=-RL
      EX2=X2-DX/2.
      EX1=X1+DX/2.
      EL=(EX2**2-EX1**2)/2.
      L=L1-1
      DL=DX
  172 CONTINUE
      PRINT 2008,DL
 2008 FORMAT(16X,*DISTANCE INCREMENTS*,3X,F7.3,/)
      IF (I2.GE.0) GO TO 170
      IF (THETA.LE.0.) THETA=360.
      AREA=(X2**2-X1**2)*THETA/(2.*57.2958*REFAREA)
      AX=ALOG10(AR*AREA)+BR*REFM
      PRINT 2010,THETA,AREA
 2010 FORMAT(3X,*ANGLE AND AREA (REFERENCE UNITS)*,3X,2F7.3,/)
      PRINT 2011,AX
```

```
C
C
C              FOR EACH SOURCE ( AND FOR EACH OF THE I3 SUBREGIONS ), SPECIFY
C              THE FOLLOWING, WITH DISTANCES IN KILOMETERS AND ANGLES IN DEGREES
C
CARD C         FORMAT(5F10.5)
C      D       NORMAL DISTANCE FROM THE SITE TO THE FAULT PLANE.
C              LEAVE BLANK FOR AREA SOURCES.
C      X1,X2   COORDINATES OF BOUNDARIES OF THE SOURCE.
C              FOR FAULTS, MEASURE X1 AND X2 FROM THE NORMAL PROJECTION FROM THE
C              SITE TO THE FAULT PLANE.  DO NOT FORGET MINUS SIGNS.
C              FOR AREA SOURCES, X1 AND X2 ARE THE INNER AND OUTER RADII OF AN
C              ANNULAR SECTOR.
C      DL      DISTANCE INCREMENT FOR THE NUMERICAL INTEGRATION.
C      THETA   ANGLE SUBTENDED AT THE SITE BY AN AREA SOURCE WHOSE RECURRENCE
C              PARAMETER AR IS NORMALIZED.
C              LEAVE BLANK IF AR IS ABSOLUTE.
C
C
      READ 7000,NRUNS
 7000 FORMAT(I5)
      DO 7100  NR=1,NRUNS
      READ 1000,NF,NA,NP,RMMIN,SIGMA
 1000 FORMAT(3I5,2F5.2)
      READ 1001,(AC(I),I=1,NA)
 1001 FORMAT(12F6.1)
      READ 1001,(Y(I),I=1,NP)
      DO 10 I=1,NA
      A(I)=ALOG10(AC(I))
      RT(I)=0.
   10 CONTINUE
      PRINT 1019,SIGMA
 1019 FORMAT(1X,* SIGMA IS*,F5.2,/)
      PRINT 1002,NF
 1002 FORMAT(1X,* NUMBER OF SOURCES IS*,I3)
      DO 500 N=1,NF
      READ 1003,FNAME
 1003 FORMAT(10A8)
      PRINT 1025,FNAME
 1025 FORMAT(////2X,10A8,//)
      READ 1004,AR,BR,RMMAX,DM,REFM,REFAREA,I1,I2,I3
 1004 FORMAT(6F10.5,3I5)
      PRINT 1005,AR,BR
 1005 FORMAT(1X,* RECURRENCE PARAMETERS A AND B ARE*,3X,2F7.3,/)
      IF (I2.GE.0) GO TO 801
      PRINT 2005,REFM,REFAREA
 2005 FORMAT(3X,*REFERENCE MAGNITUDE AND AREA ARE*,1X,2F7.1,/)
      GO TO 802
  801 AX=AR
  802 PRINT 1006,RMMAX
 1006 FORMAT(15X,*MAXIMUM MAGNITUDE IS*,3X,F7.3,/)
      U=((RMMAX-RMMIN)/DM+1.)/2.
      M=2*INT(U)
      U=FLOAT(M)
      DM=(RMMAX-RMMIN)/U
      PRINT 1020,DM
 1020 FORMAT(14X,* MAGNITUDE INCREMENTS*,3X,F7.3,/)
```

```
FUNCTION ACCELM      74/74    OPT=1                                FTN 4.6+433B        01/04/79  11.45.21          PAGE     1

              REAL FUNCTION ACCELM(X)
        C     GUTENBERG - RICHTER 1956
              ACCELM=-1.63+0.81*X-0.027*X**2
              RETURN
              END
```

```
FUNCTION ACCELR      74/74    OPT=1                                FTN 4.6+433B        01/04/79  11.45.21          PAGE     1

              REAL FUNCTION ACCELR(X)
        C     GUTENBERG - RICHTER 1956
              U=ALOG10(X)
              V=5.*(U-1.27)
              W=4.*(U-2.40)
              ACCELR=(SQRT(1.+V**2)+V-2.*EXP(-0.5*W**2))/5.
              RETURN
              END
```

```
FUNCTION AENF        74/74    OPT=1                                FTN 4.6+433B        01/04/79  11.45.21          PAGE     1

              REAL FUNCTION AENF(X)
        C  EPICENTRAL ACCELERATION FROM NEAR-FIELD DATA
              AENF=-.089*X*X+1.31*X-1.97
              RETURN
              END
```

```
PROGRAM HAZARD      74/74    OPT=1                          FTN 4.6+433B        01/04/79  11.45.21         PAGE      6

            A(I)=AC(I)/980.
            DO 600 N=1,NP
            P(I,N)=1.-EXP(-Y(N)*RT(I))
        600 CONTINUE
        700 CONTINUE
            PRINT 1024,NF
       1024 FORMAT(///1X,*SUMMATION OF HAZARD OCCASIONED BY THE*,I3,1X,*FAULTS
          1 AND AREA SOURCES*,//)
            PRINT 1021
       1021 FORMAT(/1X,* RATE PER YEAR OF EXCEEDANCE OF ACCELERATION A*,/)
            PRINT 1022,(AC(I),I=1,NA)
       1022 FORMAT(7X,*A*,12F10.1,/)
            PRINT 1023,(RT(I),I=1,NA)
       1023 FORMAT(2X,*RATE*,5X,12E10.3)
            PRINT 1015
       1015 FORMAT(///1X,* PROBABILITY OF EXCEEDANCE OF ACCELERATION A IN ANY
           1PERIOD OF T YEARS*,/)
            PRINT 1016,(AC(I),I=1,NA)
       1016 FORMAT(7X,*A*,12F10.1/4X,*T*,/)
            PRINT 1018,(Y(N),(P(I,N),I=1,NA),N=1,NP)
            PRINT 1017,(A(I),I=1,NA)
       1017 FORMAT(/8X,*G*,1X,12F10.4)
       1018 FORMAT(F7.1,3X,12F10.7/F7.1,3X,12F10.7)
        800 CONTINUE
       7100 CONTINUE
            END
```

```
SUBROUTINE SIMPER     74/74    OPT=1                          FTN 4.6+433B        01/04/79  11.45.21         PAGE      1

            SUBROUTINE SIMPER(F,W,H,N)
            DIMENSION F(100)
            M=N-1
            L=N-2
            U=0.
            V=0.
            DO 10 I=2,M,2
         10 U=U+F(I)
            IF (L.LT.3) GO TO 30
            DO 20 I=3,L,2
         20 V=V+F(I)
         30 W=(F(1)+F(N)+4.*U+2.*V)*H/3.
            RETURN
            END
```

```
SUBROUTINE ACCEL     7600#7600 OPT=1                                    FTN 4.6+452/034     22 DEC 78 08.39.31  BKY PAGE        1

            SUBROUTINE ACCEL(AS,RM,Z,K)
      C COMPUTES GROUND ACCELERATION AS FUNCTION OF DISTANCE AND MAGNITUDE
      C   FOR Z ,GE. 20, USES GUTENBERG-RICHTER(1956) RELATIONSHIPS TO FIND
      C   LOG(AS) = LOG(A(M)) - LOG(A(R))
      C
      C   FOR Z .LT. 20, INTERPOLATES BETWEEN GUTENBERG-RICHTER AT Z =20 AND
      C   MODERN NEAR-FIELD OBSERVATIONS FOR Z .LE. 10 TO FIND LOG(AS)
      C     INTERPOLATED RESULTS APPROXIMATE  SCHNABEL AND SEED (1972)
            IF(K-1)20,10,20
         10 AEGR=ACCELM(RM)
            AE=AENF(RM)
         20 IF(Z-20.)40,30,30
         30 AS=AEGR-ACCELR(Z)
            GO TO 100
         40 IF(Z-3.)50,50,60
         50 AS=AE
            GO TO 100
         60 AS=1.215*(1.30-ALOG10(Z))*(AE-AEGR+.233)+AEGR-.233
        100 RETURN
            END
```

```
FUNCTION RLENGM      74/74    OPT=1                                     FTN 4.6+433B        01/04/79  11.45.21        PAGE       1

            REAL FUNCTION RLENGM(X)
            Y=(X-5.25)/1.06
            IF (X.LE.6.6) Y=(X-3.28)/2.55
            RLENGM=(2./3.)*10.**Y
            RETURN
            END
```

```
FUNCTION ERFUDGE     74/74    OPT=1                                     FTN 4.6+433B        01/04/79  11.45.21        PAGE       1

            REAL FUNCTION ERFUDGE(X)
      C   COMPUTES ERF(X/SQRT(2))
            Y=0.784*X+0.02408*X**2+0.02696*X**3
            Z=EXP(2.*Y)
            ERFUDGE=(Z-1.)/(Z+1.)
            RETURN
            END
```

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