Vulnerability of Transportation Systems to Earthquakes--U.S.

Offices of Research
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Washington, D.C. 20590

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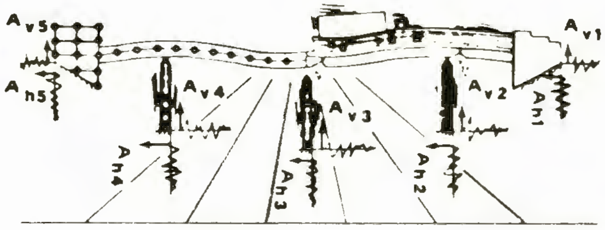
Earthquake Protection
of



Transportation Structures

FOREWORD

This report is the result of staff research conducted by the Federal Highway Administration (FHWA), Office of Research. The report will be of interest to those researchers and engineers concerned with assessing the vulnerability of transportation systems to strong ground motion. Specifically, the performance of transportation structures during previous United States earthquakes are documented.

Copies of the report are being distributed by FHWA transmittal memorandum. Additional copies may be obtained from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

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Director, Office of Research
Federal Highway Administration

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16. Abstract

This report describes the damage to transportation systems during past U.S. earthquakes and correlates the degree of damage with published M.M. isoseismal information for the earthquakes.

The author considers the threshold of critical damage to highways and railroads to start at a Modified Mercalli intensity rating of VIII-IX, although limited damage has occurred in earthquakes with a M.M. intensity as low as VI.

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Thaddeus Nowak, Department of Geosciences, The University of Arizona, furnished a copy of the seismogram used for Figure 2.

All base maps used in this report are United States Geological Survey maps.

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VULNERABILITY OF TRANSPORTATION SYSTEMS TO EARTHQUAKES - U.S.

I. Introduction

1. Subject

The function of a modern transportation system is to allow people, vehicles, and goods to move between places in the shortest time and in the most economical way. When an earthquake interrupts the flow of travel, the transportation system no longer serves its intended function. Also, when large numbers of people in an area are injured, killed, or buried, and the remaining people are unable to cope with the disaster, then the loss of the transportation system becomes a survival-threatening situation.

In modern times transportation is provided by land, sea, and air; essentially through arteries of railroad and highway systems, terminals of air traffic (airports), and terminals of sea lanes (harbors and ports). The objective of this report is to examine from a scientific view the vulnerability of a modern transportation system to perform its function following damage sustained during an earthquake. This report does not deal with the cost effectiveness to reduce vulnerability or of prediction criteria that politically justify which areas are to be retrofitted and in what order.

The following are considered to be the primary tasks of a transportation system following a major earthquake:

A. Serve as routes of travel for people escaping fires and other life threatening dangers.

B. Allow the movement of medical teams and civilian assistance personnel to reach the striken areas and for the removal of the injured to functioning hospitals.

C. Permit mobile fire-fighting equipment, heavy-duty machinery for reconstruction, and earth-loading equipment for clearing streets and excavation in rescue operations to reach their destination.

D. Provide adequate ways for disaster relief agencies to bring in food and water to the devastated areas, thus preventing panic.

E. Enable the police or armed service personnel to guard local businesses, banks, and residential areas from looting, and to control pestilence from the dead.*

In order to assess the ability of the transportation system to provide the above services, we must examine the damage incurred to the components of the system during past earthquakes. We shall restrict our discussion to those earthquakes of the United States where damage to the transportation system has been reported in the literature. The author considers the threshold of critical damage to highways and railroads to start at a Modified Mercalli intensity rating of VIII-IX (Table 1); although limited damage has occurred in earthquakes with an M.M. intensity as low as VI (Table 2). Historically there have been approximately 45 earthquakes reported with intensity VIII-IX or greater (Figure 1), and the distribution has been in many other areas besides the West Coast. Several of these earthquakes occurred prior to the development of our modern transportation

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* During the Agadir earthquake, rescue squads and demolition teams worked in isolation for five weeks, living in a quarantine camp, and surrounded by 5,000 troups to prevent the spread of disease (Andrews, 1963).

TABLE 1

HISTORICAL LIST OF U.S. EARTHQUAKES OF M.M. INTENSITY VIII-IX+*

Date	Locality	N. Lat.°	W. Long.°	M.M. Intensity	Data on Isoseismals	Reported Damage to Transp. Sys.
1663 Feb. 5	St. Lawrence River region	47.6	70.1	X	No	
1811 Dec. 16						
1812 Jan. 23	Near New Madrid, Mo.	36.6	89.6	XII	Yes	Yes
1812 Feb. 7						
1812 Dec. 21	Off coast of southern Calif.	34	120	X	No	
1836 June 10	San Francisco Bay	38	122	IX-X	No	
1838 June **	San Francisco Region	37.5	122.5	X	No	Reported similar to 1906 shock.***
1852 Nov. 9	Near Ft. Yuma, Ariz.	33	114.5	VIII-IX	No	
1857 Jan. 9	Near Ft. Tejon, Calif.	35	119	X-XI	Yes	
1865 Oct. 1	Ft. Humboldt and Eureka, Calif.	41	124.5	VIII-IX	No	
1865 Oct. 8	Santa Cruz Mountains, Calif.	37	122	VIII-IX	No	
1868 Apr. 2	Near south coast of Hawaii	19	155.5	X	No	
1868 Oct. 21	Hayward, Calif.	37.5	122	IX-X	No	
1872 Mar. 26	Owens Valley, Calif.	36.5	118	X-XI	No	
1886 Aug. 31	Northwest of Charleston, S.C.	32.9	80	IX-X	Yes	Yes
1887 May 3	Bavispe Sonoro, Mexico	30.7	109.2	IX in U.S.	Yes	
1892 Feb. 23	Northern Baja, Calif.	31.5	116.5	VIII-IX in U.S.	No	
1892 Apr. 19	Vacaville, Calif.	38.5	112.5	IX	No	
1892 Apr. 21	Winters, Calif.	38.5	122	IX	No	
1893 Apr. 4	Northwest of Los Angeles, Calif.	34.5	118.5	VIII-IX	No	
1898 Apr. 14	Mendocino County, Calif.	39	124	VIII-IX	No	
1899 Sept. 3	Yaktutat Bay, Alaska	60	142	XI	No	
1899 Sept. 10	Yaktutat Bay, Alaska	60	140	XI	No	
1899 Dec. 25	San Jacinto and Hemet, Calif.	33.5	116.5	IX	No	
1906 Apr. 18	Northwest of San Francisco, Calif.	38	123	XI	Yes	Yes
1915 Oct. 2	Pleasant Valley, Nevada	40.5	117.5	X	No	
1918 Apr. 21	Riverside County, Calif.	33.8	117	IX	No	Yes
1918 Oct. 11	Northwestern Mona Passage	18.5	67.5	VIII-IX	No	Yes
1922 Mar. 10	Cholame Valley, Calif.	35.8	120.2	IX	No	
1925 June 29	Santa Barbara, Calif.	34.3	119.8	VIII-IX	No	
1927 Nov. 4	West of Point Arguello, Calif.	34.5	121.5	IX-X	Yes	

TABLE 1 cont.

1932	Dec.	20	Western Nevada	38.7	117.8	X	Yes	
1933	Mar.	10	Long Beach, Calif.	33.6	118	IX	No	
1934	Jan.	30	Southeast of Hawthorne, Nevada	38.3	118.4	VIII-IX	Yes	
1940	May	18	Southeast of El Centro, Calif.	32.7	115.5	X	Yes	Yes
1952	July	21	Kern County, Calif.	35	119	XI	Yes	Yes
1954	July	6	East of Fallon, Nevada	39.4	118.5	IX	Yes	Yes
1954	Aug.	23	East of Fallon, Nevada	39.6	118.5	IX	Yes	Yes
1954	Dec.	16	Dixie Valley, Nevada	39.3	118.2	X	Yes	Yes
1958	July	9	Southeastern Alaska	58.6	137.1	XI	No	Yes
1959	Aug.	17	Near Hebgen Lake, Montana	44.8	111.1	X	Yes	Yes
1964	Mar.	27	Southern Alaska	61	147.8	IX-X	Yes	Yes
1971	Feb.	9	San Fernando, Calif.	34.4	118.4	XI	Yes	Yes
1979	Oct.	15	Imperial Valley, Calif.	32.6	115.3	IX	Yes	Yes
1980	Nov.	8	Eureka, Calif.	41.2	129.3	IX	No	Yes

* Data from U.S. Earthquakes and Earthquake History of the United States.

** No day date available.

*** Byerly, p.2.

TABLE 2

U.S. EARTHQUAKES WITH M.M. INTENSITY LESS THAN VIII-IX WHERE DAMAGE TO A TRANSPORTATION SYSTEM WAS REPORTED

Date	Locality	N. Lat.°	W. Long.°	M.M. Intensity	Data on Isoseismals	Reported Damage to Transp. Sys.
1890 Apr. 24	Monterey Bay Region	37	121.5	VII	No	Yes
1906 May 26	Keweenaw Peninsula, Mich.	47.3	88.4	VIII	No	Yes
1906 July 16	Socorro, N. Mex.	34	107	VII-VIII	No	Yes
1925 Feb. 23	Kenai Peninsula, Alaska	62	146	VII	No	Yes
1925 June 27	Helena, Montana	46	111.2	VIII	No	Yes
1932 Mar. 25	South Central Alaska	62.5	152.5	VII	No	Yes
1932 June 6	Humboldt County, Calif.	40.8	124.3	VIII	Yes	Yes
1934 May 14	Kodiak Island, Alaska	57.7	152.2	VI	No	Yes
1934 Dec. 30	South of Calexico, Calif.	32.2	115.5	VI in U.S.	Yes	Yes
1941 June 30	Santa Barbara and Carpinteria	34.4	119.6	VIII	Yes	Yes
1941 Sept. 14	Owens Valley, Calif.	37.6	118.7	VI-VII	Yes	Yes
1942 Oct. 21	Near Borrego Valley, Calif.	33	116	VII	Yes	Yes
1947 Apr. 10	East of Barstow, Calif.	35	116.6	VII	Yes	Yes
1947 June 22	Gilroy, Calif.	37	121.8	VI	Yes	Yes
1947 Oct. 15	Fairbanks area, Alaska	64.5	148.8	VIII	No	Yes
1950 July 29	Imperial Valley, Calif.	33.1	115.6	VIII	Yes	Yes
1954 Oct. 3	Kenai Peninsula, Alaska	60.5	151	VIII	No	Yes
1957 Mar. 9	Andreanof Islands	51.3	175.8	VIII	No	Yes
1957 Mar. 22	West of Daly City, Calif.	37.7	122.5	VII	Yes	Yes
1958 Dec. 11	Southwest of San Francisco	37.7	122.5	VI	Yes	Yes
1959 Sept. 30	Off Coast of Southern Calif.	34.4	120.6	VI	No	Yes
1962 Aug. 30	Northern Utah	41.8	111.8	VII	Yes	Yes
1973 Apr. 26	Hilo, Hawaii	19.9	155.1	VIII	Yes	Yes
1975 June 7	Northern Calif.	40.6	124.1	VII	Yes	Yes
1975 June 30	Yellowstone National Park, Wyoming	44.8	110.6	VIII	Yes	Yes
1975 Nov. 29	Hawaii	19.3	155	VIII	Yes	Yes
1978 Aug. 13	Near Goleta, Calif.	34.4	119.7	VII	Yes	Yes
1980 Jan. 27	Livermore, Calif.	37.7	121.7	VII	No	Yes

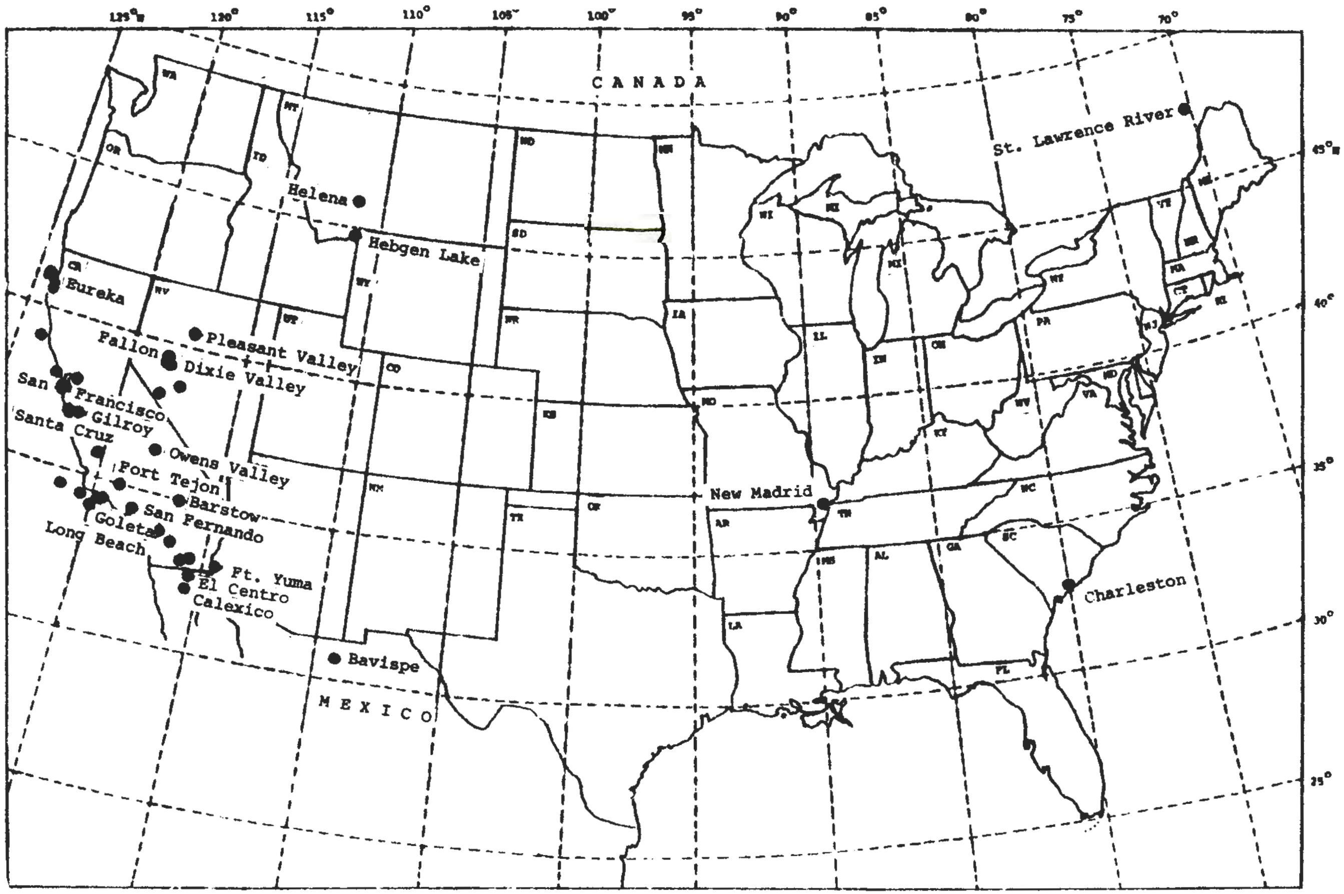


Figure 1. Location of referenced earthquakes in the conterminous United States.

system; therefore, in the present evaluation of vulnerability we need to assess what might happen should the earthquakes reoccur with their same intensity in modern times. We shall get at this kind of evaluation by studying the isoseismal contours for several earthquakes.

2. Background

In the field examination of an earthquake it is useful to examine the effects of an earthquake on the basis of its strength. Three scales have been commonly used in the literature to report strength: the Rossi-Forel (R.F.) scale, the Modified Mercalli (M.M.) scale, and the Richter magnitude (M_L) scale. For correlation purposes from publications using different scales, it becomes important to translate the reports of damage to one scale. This investigation will use the M.M. scale as the basis of evaluation.

Isoseismals are map contours of equal intensities of earthquake shaking. "Intensity is measured by means of the degree of damage to the works of man, the amount of disturbances to the surface of the ground and the extent of animal reaction of the shaking." (Bolt, 1978) As damage information patterns developed from reports of earthquakes, DeRossi in Italy and Forel in Switzerland pooled their sources of information in 1883 and developed the Rossi-Forel scale for seismological reporting of the maximum intensity of the earthquake. This scale given in Table 3 is indicated by the abbreviation "R.F." followed by the Roman numeral of the maximum scale degree. This scale has 10 degrees ranging from I to X, and was used for reporting the intensity of the 1906 San Francisco earthquake in the literature. (Lawson, 1908) An enormous range of intensity was lumped at the highest level of the scale, which would have included the effects of damage to a transportation system.

TABLE 3

ROSSI-FOREL SCALE OF EARTHQUAKE INTENSITIES

(Adapted from Byerly, 1952, p. 6)

R.F. I. Microseismic shock--recorded by a single seismograph, or by seismographs of the same model, but not putting seismographs of different patterns in motion; reported by experienced observers only.

II. Shock recorded by several seismographs of different patterns; reported by a small number of persons who are at rest.

III. Shock reported by a number of persons at rest; duration or direction noted. A SHOCK; A LIGHT SHOCK.

IV. Shock reported by persons in motion; shaking of movable objects, doors and windows, cracking of ceilings. MODERATE; sometimes STRONG; SHARP; LIGHT.

V. Shock felt generally by everyone; furniture shaken, some bells rung.

VI. General awakening of sleepers; general ringing of bells, swinging of chandeliers; stopping of clocks, visible swaying of trees; some persons run out of buildings.

VII. Overturning of loose objects; fall of plaster; striking of church bells; general fright, without damage to buildings.

VIII. Fall of chimneys; cracks in the walls of buildings.

IX. Partial or total destruction of some buildings.

X. Great disasters; overturning of rocks; fissures in the surface of the earth; mountain slides.

An improved scale was developed in 1902 by Mercalli, an Italian seismologist, at first with ten grades of intensity, later with twelve grades following a suggestion by Cancani who attempted to express these grades in terms of acceleration (Richter, 1958). H.O. Wood and Frank P. Neumann, U.S. seismologists, modified the Mercalli scale in 1931 to fit construction conditions in most of the United States and particularly in California. The modified scale is given in Table 4.

Neither the R.F. or M.M. scales represent the size of an earthquake obtained from measurements made with instruments. If one could make such a measurement then it should be possible to correlate the measurement with the amount of energy released by the quake. In 1935, Drs. C.F. Richter and Beno Gutenberg of the California Institute of Technology developed the technique for defining the magnitude of earthquakes from a seismogram recording. Dr. Richter credits K. Wadati, a Japanese seismologist, with originating the idea in 1931 during the studies of earthquakes in Japan. Dr. Richter defined the magnitude of a local earthquake as "the logarithm to the base ten of the maximum seismic wave amplitude (in thousands of a millimeter) at a distance of 100 kilometers from the earthquake epicenter." Considerable judgment and calculations go into describing the magnitude (M_L) of a local earthquake from field instrument recordings (Richter, 1958, p. 340). Figure 2 shows an approximate method for determining the magnitude M_L from seismogram recordings.

M_L is the magnitude for a local earthquake as given by the equation:

$$M_L = \log A - \log A_o$$

where A is the maximum recorded trace amplitude at a given distance in millimeters on a standard Wood-Anderson seismograph,

TABLE 4

MODIFIED MERCALLI INTENSITY SCALE OF 1931
(Adapted from Wood and Neumann, 1931, p. 277-283)

I. Not felt -- or, except rarely under especially favorable circumstances.

Under certain conditions, at and outside the boundary of the area in which a great shock is felt:

sometimes birds, animals, reported uneasy or disturbed;
sometimes dizziness or nausea experienced;
sometimes trees, structures, liquids, bodies of water, may sway -- doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons.

Also, as in grade I, but often more noticeably:

sometimes hanging objects may swing, especially when delicately suspended;
sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly;
sometimes birds, animals, reported uneasy or disturbed;
sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration.

Sometimes not recognized to be an earthquake at first.

Duration estimated in some cases.
Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away.
Hanging objects may swing slightly.
Movements may be appreciable on upper levels of tall structures.
Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few.

Awakened few, especially light sleepers.
Frightened no one, unless apprehensive from previous experience.
Vibration like that due to passing of heavy, or heavily loaded trucks.
Sensation like heavy body striking building, or falling of heavy objects inside.
Rattling of dishes, windows, doors; glassware and crockery clink and clash.
Creaking of walls, frames, especially in the upper range of this grade.

TABLE 4 cont.

Hanging objects swung, in numerous instances.
Disturbed liquids in open vessels slightly.
Rocked standing motor cars noticeably.

V. Felt indoors by practically all, outdoors by many or most: outdoors direction estimated.
Awakened many, or most.
Frightened few -- slight excitement, a few ran outdoors.
Buildings trembled throughout.
Cracked windows -- in some cases, but not generally.
Broke dishes, glassware, to some extent
Overturned vases, small or unstable objects, in many instances, with occasional fall.
Hanging objects, doors, swing generally or considerably.
Knocked pictures against walls, or swung them out of place.
Opened, or closed doors, shutters, abruptly.
Pendulum clocks stopped, started, or ran fast, or slow.
Moved small objects, furnishings, the latter to slight extent.
Spilled liquids in small amounts from well-filled open containers.
Trees, bushes, shaken slightly.

VI. Felt by all, indoors and outdoors.
Frightened many, excitement general, some alarm, many ran outdoors.
Awakened all.
Persons made to move unsteadily.
Trees, bushes, shaken slightly to moderately.
Liquid set in strong motion.
Small bells rang -- church, chapel, school, etc.
Damage slight in poorly built buildings.
Fall of plaster in small amount.
Cracked plaster somewhat, especially fine cracks, chimneys in some instances.
Broke dishes, glassware, in considerable quantity, also some windows.
Fall of knick-knacks, books, pictures.
Overturned furniture in many instances.
Moved furnishings of moderately heavy kind.

VII. Frightened all -- general alarm, all ran outdoors.
Some, or many, found it difficult to stand.
Noticed by persons driving motor cars.
Trees and bushes shaken moderately to strongly.
Waves on ponds, lakes, and running water.

TABLE 4 cont.

Water turbid from mud stirred up.
Incaving to some extent of sand or gravel stream banks.
Rang large church bells, etc.
Suspended objects made to quiver.
Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc.
Cracked chimneys to considerable extent, walls to some extent.
Shook down loosened brickwork and tiles.
Broke weak chimneys at the roof-line (sometimes damaging roofs).
Fall of cornices from towers and huge buildings.
Dislodged bricks and stones.
Overturned heavy furniture, with damage from breaking.
Damage considerable to concrete irrigation ditches.

VIII. Fright general -- alarm approaches panic.
Disturbed persons driving motor cars.
Trees shaken strongly -- branches, trunks, broken off, especially palm trees.
Ejected sand and mud in small amounts.
Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters.
Damage slight in structures (brick) built especially to withstand earthquakes.
Considerable in ordinary substantial buildings, partial collapse racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling.
Fall of walls.
Cracked, broke, solid stone walls seriously.
Wet ground to some extent, also ground on steep slopes.
Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers.
Moved conspicuously, overturned, very heavy furniture.

IX. Panic general.
Cracked ground conspicuously.
Damage considerable in (masonry) structures built especially to withstand earthquakes;
Threw out of plumb some wood-frame houses built especially to withstand earthquakes;
Great in substantial (masonry) buildings, some collapse in

TABLE 4 cont.

large part; or wholly shifted frame buildings off foundations, racked frames.
Serious to reservoirs; underground pipes sometimes broken.

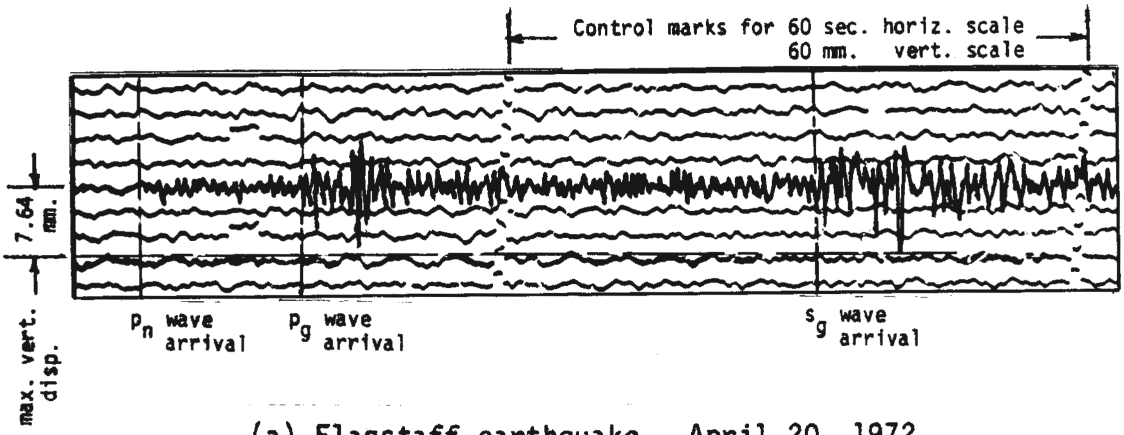
X. Cracked ground, especially when loose and wet, up to widths of several inches, fissures up to a yard in width ran parallel to canal and stream banks.
Landslides considerable from river banks and steep coasts.
Shifted sand and mud horizontally on beaches and flat land.
Changed level of water in wells.
Threw water on banks of canals, lakes, rivers, etc.
Damage serious to dams, dikes, embankments.
Severe to well-built wooden structures and bridges, some destroyed.
Developed dangerous cracks in excellent brick walls.
Destroyed most masonry and frame structures, also their foundations.
Bent railroad rails slightly.
Tore apart, or crushed endwise, pipe lines buried in earth.
Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material.
Broad fissures, earth slumps, and land slips in soft, wet ground.
Ejected water in large amount charged with sand and mud.
Caused sea-waves ("tidal waves") of significant magnitude.
Damage severe to wood-frame structures, especially near shock centers.
Great to dams, dikes, embankments, often for long distances.
Few, if any (masonry), structures remained standing.
Destroyed large well-built bridges by the wrecking of supporting piers, or pillars.
Affected yielding wooden bridges less.
Bent railroad rails greatly, and thrust them endwise.
Put pipe lines buried in earth completely out of service.

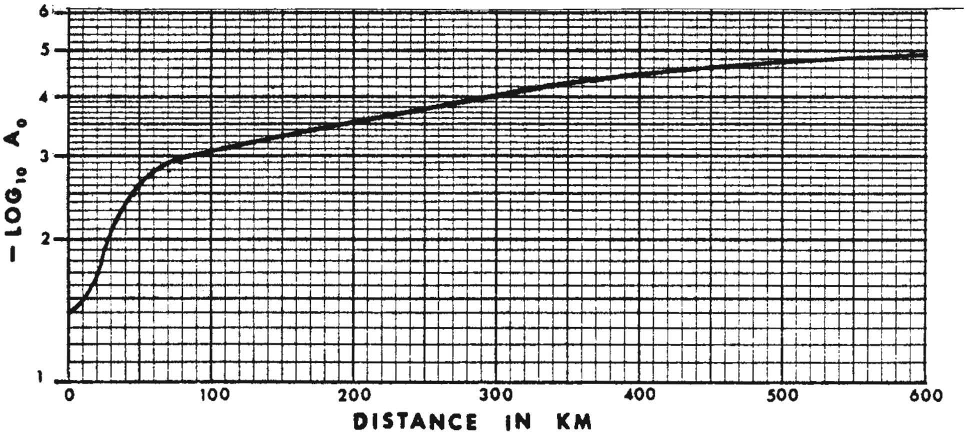
XII. Damage total -- practically all works of construction damaged greatly or destroyed.
Disturbances in ground great and varied, numerous shearing cracks.
Landslides, falls of rock or significant character, slumping of river banks, etc., numerous and extensive.
Wrenched loose, tore off, large rock masses.
Fault slips in firm rock, with notable horizontal and vertical offset displacements.

TABLE 4 cont.

Water channels, surface and underground, disturbed and modified greatly.
Dammed lakes, produced waterfalls, deflected rivers, etc.
Waves seen on ground surfaces (actually seen, probably, in some cases).
Distorted lines of sight and level.
Threw objects upward into the air.



(a) Flagstaff earthquake - April 20, 1972.



(b) Logarithms of amplitude for earthquakes of zero magnitude. Magnitude magnification factor V = 2800.

Example: $M_L = \mathrm{LOG}_{10}\ A - \mathrm{LOG}_{10}\ A_0$

Albuquerque record magnification = 100,000

Max. disp. = 7.64 $\left(\frac{2800}{100{,}000}\right)$ = 0.214. Log_{10} (0.214) = -0.670

Distance Flagstaff to Albuquerque = 457 km.

From Figure b, $-\mathrm{Log}_{10}$ (457 km.) = -4.60

M_L = -0.670 - (-4.60) = 3.93

Figure 2. Approximate method for determining magnitude M_L from seismogram recordings.

(Base record is from the USGS World Wide Standard Station network at Albuquerque, New Mexico. Seismogram courtesy of Thaddeus Nowak, Dept. of Geosciences, Univ. of Arizona. Figure b is based on tabular information from Richter, C.F., Elementary Seismology, W. Freeman and Company, San. Francisco, 1958, p. 342.)

and A_O is the predicted trace amplitude of the standard earthquake in millimeters at the same epicenter distance. (Berlin, 1880) M_L was intended for earthquakes within an epicenter distance of 600 km. In 1936, Beno Guterberg and C.F. Richter using horizontal surface waves with periods near 20 seconds, expanded the M_L scale to shallow earthquakes originating at distances over 1000 km (teleseisms) and recorded by different types of seismographs as given by equation:

$$M_S = \log A - \log B + C + D$$

where M_S is the teleseismic earthquake magnitude, A is the sum of the north-south and east-west computed ground amplitudes in microns for surface waves near 20 seconds, B is the same information as A for a zero magnitude earthquake at the same epicentral distance, and C and D are local constants for each seismographic station. Figure 3 shows the relationship between energy and magnitude based upon the two equations above and also shows the correlation between M_S values of several earthquakes and the M_S curve. (Berlin, 1980)

Table 5 shows an approximate correspondence among the R.F., M.M., and M_L scales. (Wood and Newman, 1931) (Bolt, 1978)

II. Evidence of Earthquake Damage

1. Introduction

Isoseismal contours (as will be shown later) do not always follow a circular pattern about the epicenter of an earthquake. Some contours follow a ripple pattern because of changes in the topography. Magnitude does not take into account the local variation of topography and is therefore of limited use in comparing damage to a transportation system. Correlating isoseismal curves and damage to transportation systems as

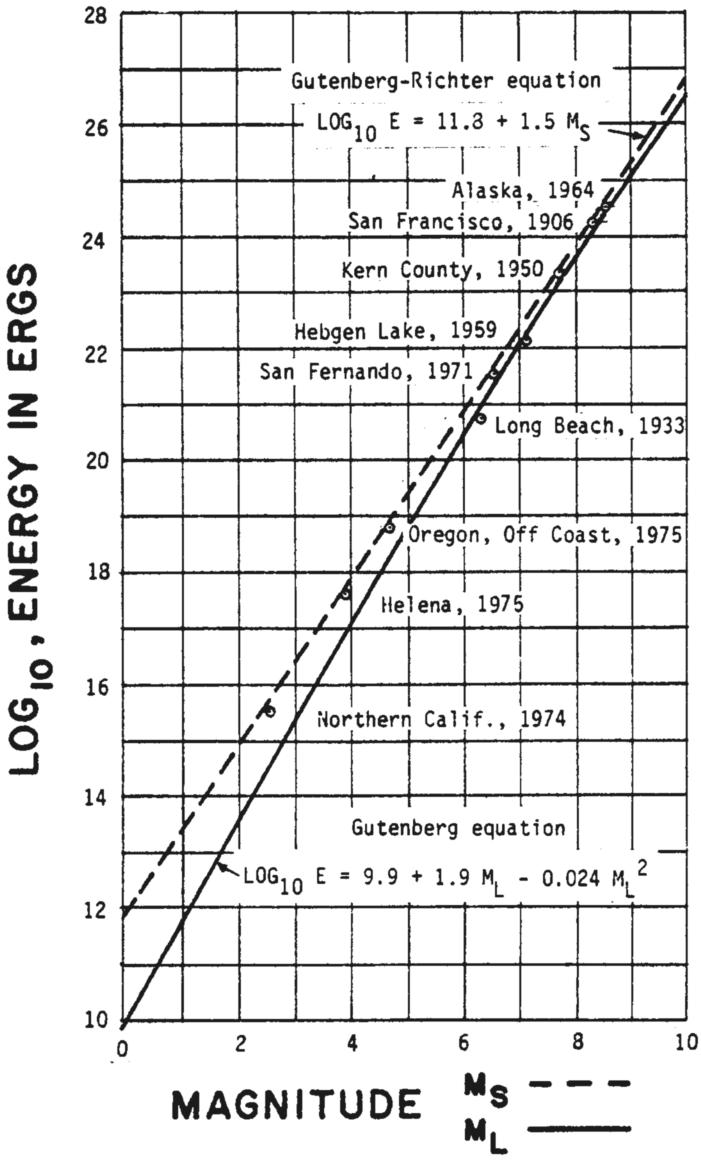


Figure 3. Comparison of earthquake magnitude and earthquake energy. (After Berlin and after Hodgson)

TABLE 5

PUBLISHED COMPARISONS OF INTENSITY AND MAGNITUDE

Rossi-Forel Scale, R.F.	Modified Mercalli Scale, M.M.	Average Peak Acceleration	Magnitude M_L
I	I		2
I - II	II		2
III	III		3
IV - V	IV	0.015g - 0.020g	
V - VI	V	0.030g - 0.040g	4
VI - VII	VI	0.060g - 0.070g	5
VIII-	VII	0.100g - 0.150g	5 - 6
VIII+ - IX-	VIII	0.250g - 0.300g	6
IX+	IX	0.500g - 0.550g	7
X	X	Above 0.600g	7
X	XI		*
X	XII		

(Adapted from Wood and Neumann, 1931, p. 278-282; and from Bolt, 1978, Appendix C) reported in the literature seems to be the best method of measuring damage done to transportation systems. Therefore from the point of view of this investigation, only the information extracted from the literature that can be translated into M.M. intensities (particularly those intensities VIII-IX to XII) will be considered. It is now necessary to describe the effects of several past earthquakes in detail.

2. The New Madrid Earthquakes - December 16, 1811; January 23, 1812; February 7, 1812. All three shocks were of Intensity XII.

The New Madrid earthquakes rank among the great earthquakes of the world, and certainly they were of the greatest intensity to date recorded in the United States. Why then are they not feared with the same reverence given to a recurring San Francisco quake? Perhaps the reason is because the New Madrid quakes occurred at a time in history when there were no large cities in the epicentral areas and correspondingly the damage to life and property was small. If they were to reoccur today, it would be an entirely different story. The 1811-12 quakes were only one of a series in the region. Fuller (1912) cites geological evidence showing that earthquakes of similar intensities occurred prior to 1811 and will probably occur again.

In the light of the times, the recorded damage to the fledgling transportation system was disastrous. The major means of transportation to the earthquake area was by the Mississippi River. Also, whatever roads existed in the early 18th century were in poor condition even for horse-drawn carriages. If the earthquakes were to reoccur today, there is no doubt that they would effect extensive damage to our modern transportation system.

The first of the three shocks occurred about 2 a.m. on the morning of December 16, 1811. The entire 800 population of New Madrid was suddenly awakened by the sounds of the earthquake, the movement of their furniture, and the crashing of falling chimneys. They fled their homes in the cold, wintry night and were prevented from returning because of constantly recurring shocks, which continued for more than a year. Of the original population, only two families returned. Eventually, during the three shocks, the streets of New Madrid were inundated as the collapse of the riverbanks moved the course of the river through the town. Not only was the town inundated, but much of the farmland was rendered unfit for cultivation. The town did not recover its population for about 20 years, when a new city was established on higher ground.

Right after the quake the river itself became very hazardous to navigate. Along the river, forests which were originally dry sank as much as 20 feet, with the result that the tree branches became part of the fixed river debris. The tree branches became nearly impassible barriers (Penick, 1976). Whole islands disappeared because of the shocks, eliminating some of the landmarks needed for safe navigation.

Figure 4 shows the epicentral region, (shaded area) a territory devastated by pronounced earthquake phenomena such as domes and sunken land, fissures, sinks and blows, large landslides, etc., an area of about 50,000 square miles. However, the felt area was as large as two million square miles.

It is fortunate that written records were kept of the earthquake in newspaper accounts of the time, and by some people with a scientific mind who constructed crude pendulums which recorded aftershocks for approximately two years. The earliest collation of the written information was not done until 1912 when Myron L. Fuller of the U.S. Geological Survey published an accounting of the New Madrid Earthquake after visiting the area on horseback several times and studying the geological evidence

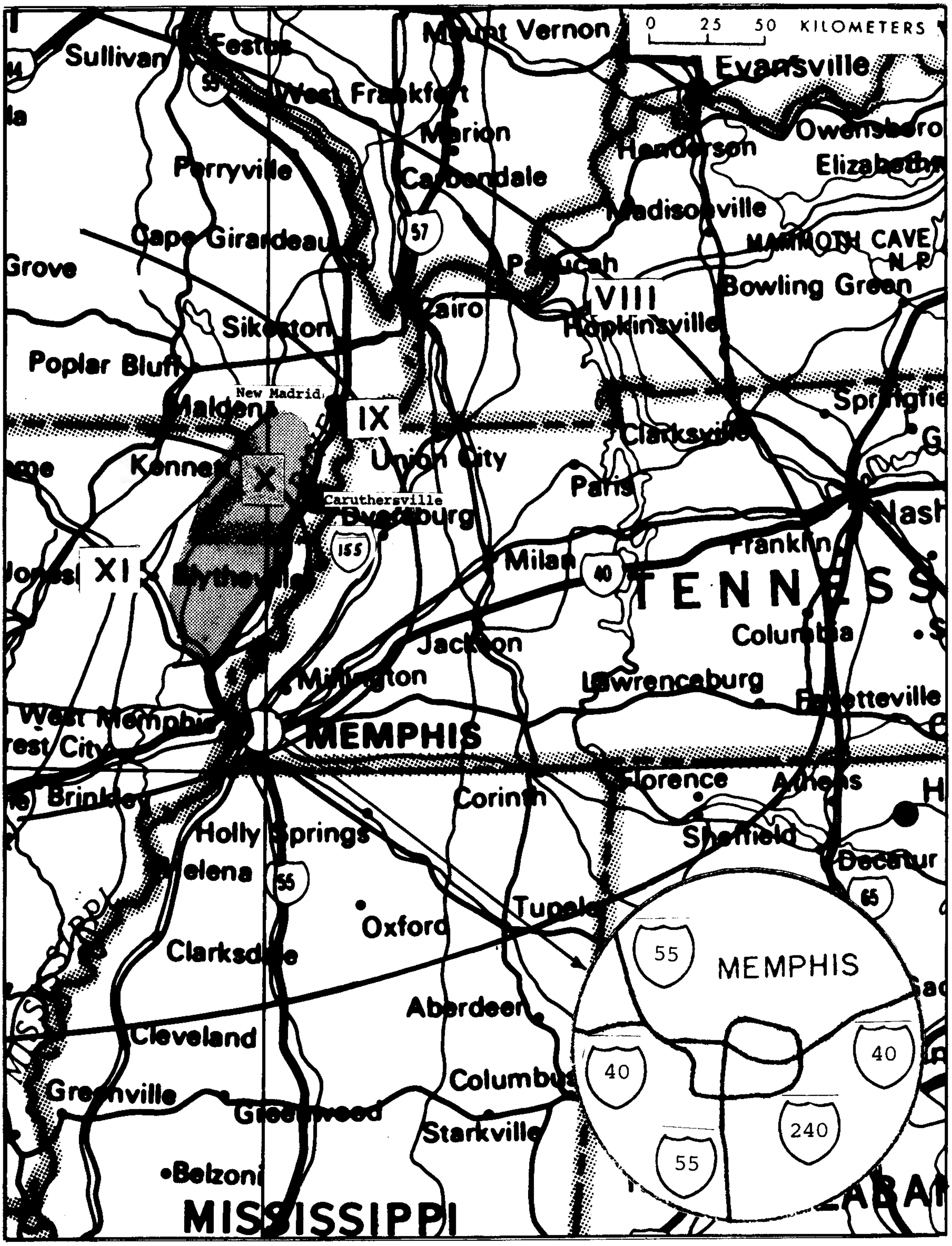


Figure 4. Epicentral area and generalized isoseismal M.M. contours for the New Madrid 1811-12 earthquakes. (Epicentral area (shaded) after Penick, Isoseismal contours after Nuttli)

for effects of the quake. In 1973, Otto W. Nuttli, Department of Earth and Atmospheric Sciences, St. Louis University, published a generalized isoseismal map of the December 16 shock after studying published accounts of the effect of the earthquake upon the landform and upon people, Figure 5. Because of the scarcity of the information in the sparsely inhabited area west of the epicenter, the isoseismal curves could not be completed to the west; however, enough information is presented in Figure 5 that can be applied to a modern transportation system. The greatest intensity was not at New Madrid, but at Little Prairie, Missouri, with an intensity of X-XII. As recently as 1976, James Penick, Jr., an historian, also wrote a book about the earthquake based upon extensive research from newspaper and other accounts.

Accounts of damage to the 1811 transportation system are practically meaningless without isoseismal information. For example, the earliest episode of road damage in an earthquake is described by Fuller, "In Arkansas a delegate to Congress from Missouri Territory, the roads between New Madrid where court was held and the settlements of Arkansas, 200 miles distant, were rendered impassible by the earthquake. This made a circuit of 300 miles necessary, seriously interfering with the accessibility to the judicia." Since isoseismal information is based upon a record of damage, one wonders how values of intensity XII can be arrived at based on such a meager damage report. The answer is that damage to the transportation system per se is not the only criteria for an intensity XII. Referring to Table 4, there is listed the following:

> Disturbances in ground great and varied, numerous shearing cracks
> Landslides, slumping of riverbanks, etc.
> Fault slips in firm rock
> Water channels, surface and underground, disturbed and modified greatly
> Deflected rivers
> Waves seen on ground surfaces from people reports

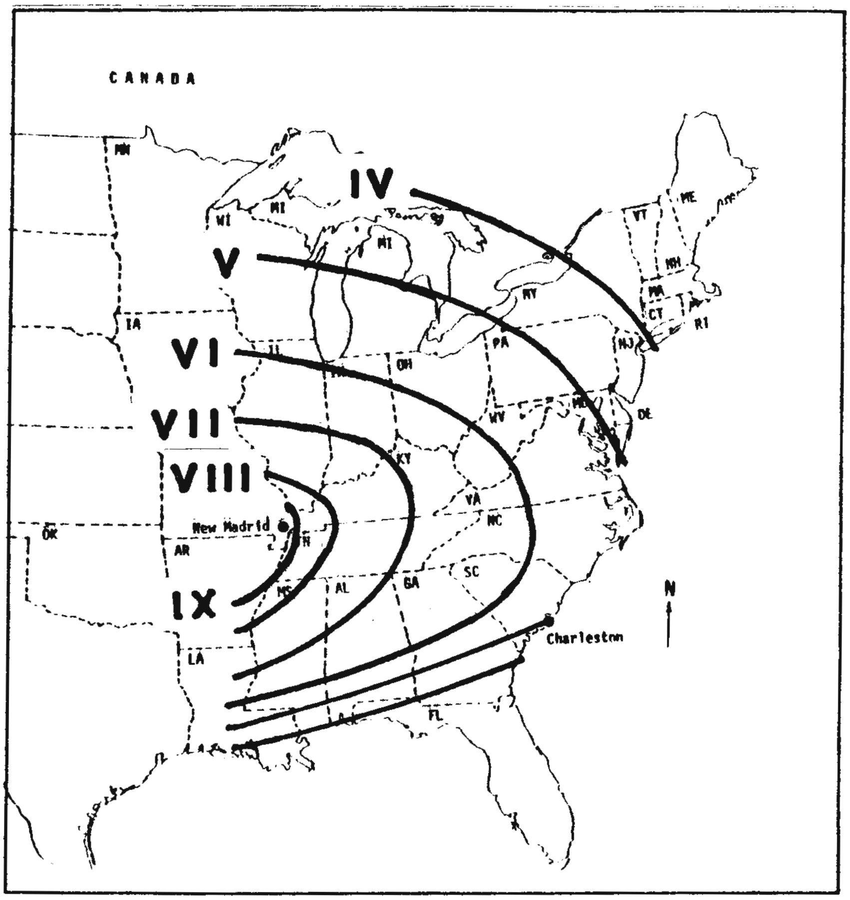


Figure 5. Generalized isoseismal contours for New Madrid earthquake. (After Nuttli)

all of which did occur in this earthquake as evidenced in the available literature. Had there been a modern transportation system in the areas of intensity XII, then *practically all works of construction would have been damaged greatly or destroyed.**

Figure 4 shows the generalized isoseismal contours of intensity VIII through XI overprinted on a current highway map of the region. Note that U.S. Highway 55 goes right through the epicentral area with many bridge interchanges. U.S. Highway 155 joins U.S. Highway 55 at Caruthersville, an area of intensity X. (Later we shall look at what kind of damage has occurred in recent earthquakes with the same intensity.) At Memphis, U.S. Highways 40 and 55 intersect the beltway U.S. 240 in an intensity IX region. In the event of a repeat earthquake of the New Madrid type and intensity, U.S. Highways 40, 55, 155, and 240 are expected to be out of service following the quake because of bridge failures and severe highway cracking.

Figure 6 shows the generalized isoseismal contours of intensity VIII through IX overprinted on a current Class 1 railroad map. No railroads existed in this country in 1812. It was not until 1815 that Stephenson first patented the steam locomotive. However, when Fuller visited the New Madrid area before 1912, several railroad lines did exist, and were mentioned in his report referring to sand blows:

> "...The most northern point at which blows were observed was along the railroad between New Madrid and Campbell...No distinct blows were observed on the railroad from Sikeston to Dexter a few miles

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* U.S. Earthquakes (1973) lists the maximum intensity as XII, although this high a value is not reported by Nuttli.

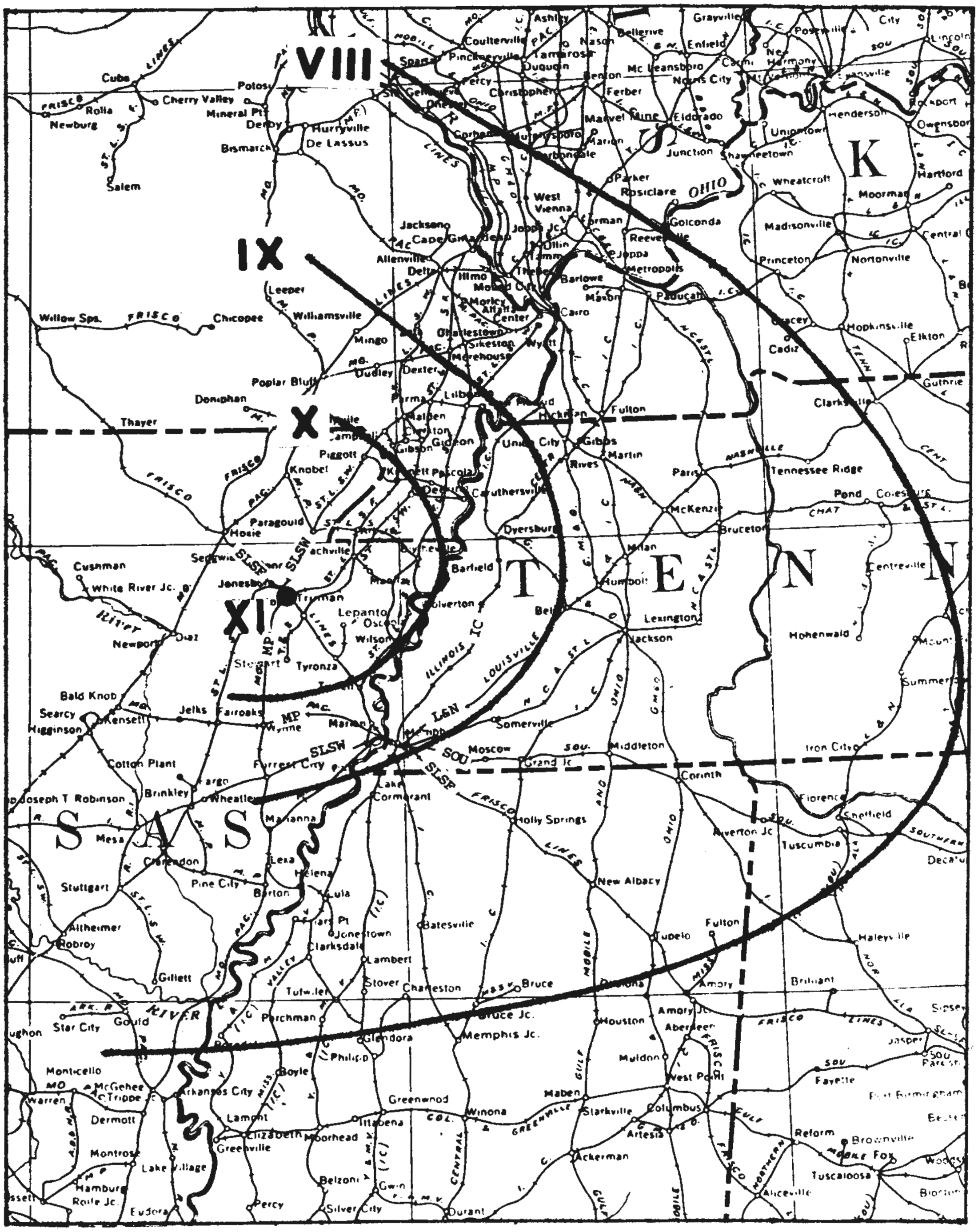

Figure 6. Generalized isoseismal contours for New Madrid earthquake overprinted on a base railroad map.

> north...On the railroad from Hayti to Kennett fairly strong blows are seen at Pascola and again in weaker development between Lake Nicormy and Kennett...From Blytheville northwest along the railroad to Paragould blows are constantly in evidence...On the railroad running westward from Blytheville to Jonesboro blows are seen at short intervals for the whole distance, especially between Blytheville and Lake City...On the railroad running south from Jonesboro toward Memphis strongly developed blows are seen about Big Bay and Culberhouse..."

Figure 6 shows the extensive network of railroads that might suffer damage during a New Madrid type earthquake. The SLSF (St. Louis, San Francisco), MP (Missouri, Pacific), SLSW (St. Louis, Southwestern) railroads go right through the epicentral area and would be extensively damaged. Memphis with an expected intensity of IX serves as a transfer point between the SOU (Southern Pacific), SLSF, MP, L&N (Louisville and Nashville), IC (Illinois Central), and SLSW lines.

Some stoppage of railroad traffic will occur along these lines, especially where the lines are within intensity IX areas. The Modified Mercalli scale does not recognize railroad damage with intensity IX; however, damage to railroads has occurred at lower intensities. For example, on August 13, 1978, a Southern Pacific Transportation Company freight-train derailment occurred west of Goleta, California due to a "kink" in the tracks, apparently the result of roadbed-fill failure in an intensity VII earthquake. On June 7, 1975, at Rio Dell, California, the Scotia Bluffs fell across the Northwestern Pacific Railroad tracks, knocking out the tracks and tearing away the southern end of the trestle. Here the intensity was also VII. Hence the knowledge of actual damage with known isoseismal contours for earthquakes serves as a basis for establishing the criteria for possible damage in all earthquake areas where damage to a transportation system starts. Intensity VIII-IX is a *compromise between information of damage that has occurred at a lower intensity and the expected damage identified on the Modified Mercalli scale at a higher intensity.**

3. The San Fernando Earthquake - February 9, 1971. Intensity XI.

Earthquakes in the eastern part of the continental United States are much less attenuated with distance than their counterparts in the western part of the country. The felt area of the New Madrid quake was 2 million square miles; that of the San Fernando quake was 80,000 sq. miles, even though the maximum intensities were approximately the same. Figure 7 shows the isoseismal information compiled from U.S. Earthquakes with a modern map as background. The contour VIII-XI is only approximately 30 kilometers long; and since isoseismal information is subjective all the damage to the transportation system should be within the area bounded by that contour -- which is the case. Figure 8, taken from reference (19) is a map showing locations of damaged bridges on Routes 5, 14, 210, and 405.

The most severe damage occurred to overpass structures at three major interchanges; 5/14, 5/210, and 5/405. Almost all of the remaining structures in the general vicinity of the interchanges, approximately 50 structures, were damaged to some extent, many requiring extensive repair. Numerous roads and city streets in the Sylmar-San Fernando area were made dangerous or impassable by ruptures.

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* A statement by Richter (1958, p. 136) is noted in this regard, "Each effect is named at that level of intensity at which it first appears frequently and characteristically. Each effect may be found less strongly, or in fewer instances, at the next lower grade of intensity; more strongly or more often at the next higher grade."

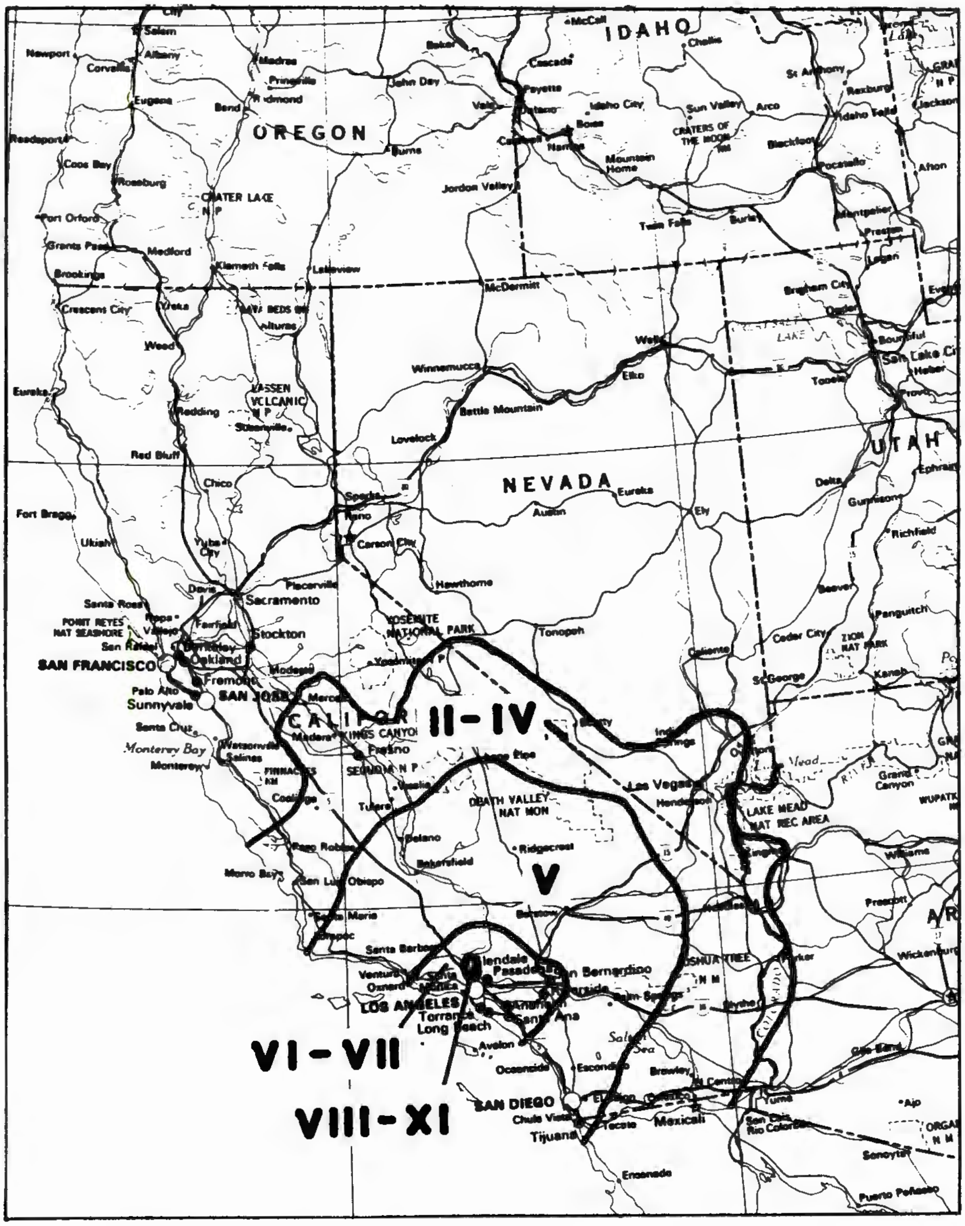

Figure 7. Isoseismal contours for the San Fernando earthquake overprinted on a base highway map. (After U.S. Earthquakes)

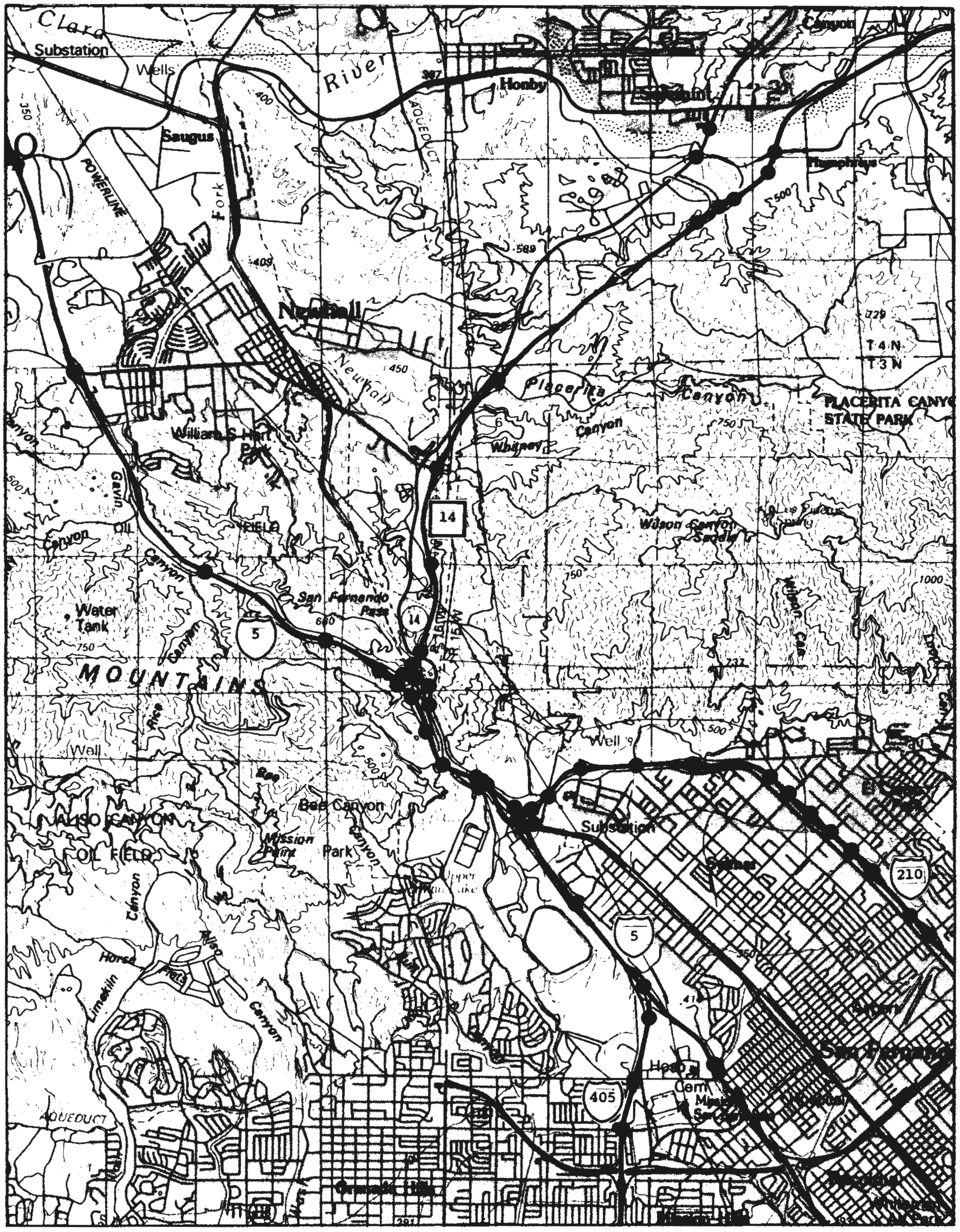

Figure 8. Location of bridges damaged in San Fernando earthquake. (After Elliot)

Railroad traffic also was disrupted owing to displacement and distortion of rails and to a collapsed overpass which fell onto the track. In front of the San Fernando Valley Juvenile Hall facilities, railroad tracks were twisted and broken and displaced as much as 1.2 meters.

NOAA's extensive 1973 report contains a table listing every bridge that sustained damage and gives a brief description of the damage. Interchange 5/14 was under construction at the time of the earthquake. A two-span frame of this high nine-span ramp came off the hinge seats and collapsed. The collapsed sections were of prestressed box girder construction. The ends of the section were supported by the remaining sections of the bridge by means of hinge joints. Elastomeric bearing pads were used at the joints, and three 1-1/2 inch diameter mild steel bolts connected the bridge sections in the longitudinal direction. The spans were not tied in the vertical direction to each other.[*]

The 5/210 interchange was also in the construction phase, being almost 95% completed. The highest level ramp, the Separation and Overhead structure, experienced a total collapse and fell on the Northwest Connector Overcrossing and on several of the spans of the San Fernando Road Overhead.[**] The central, simply-supported steel girder spans of the San Fernando Road Overhead fell onto the Southern Pacific railroad, putting the railroad out of operation for at least a day until the fallen

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[*] Since the quake, studies by the University of California have demonstrated that with properly designed hinge restrainers for both longitudinal and vertical resistance, this type of overcrossing would survive the seismic vibrations (Tseng and Penzien).

[**] Two men were killed when their truck was crushed by this collapsing freeway overpass. Also one death occurred when a person fell from another freeway structure. (Olson, p.261)

spans could be removed. The route 5/210 interchange is in an area of consolidated coarse granular sediments of the Saugus Formation overlain by alluvium of fairly low density, a factor which would have contributed to extensive bridge damage. All of the bridges at this interchange suffered collapse or damage, except one.

At interchange 5/405 the Southbound Truck Ramp bridge collapsed onto the San Diego freeway.

According to Elliott, about 25% of the bridges in the epicentral area sustained severe damage or total collapse, 50% were moderately damaged, and the remaining 25% suffered relatively minor damage. Reports to District 7 of the California Division of Highways states the following road conditions resulting from the quake:

> "1. The Golden State Freeway, the only direct north-south route from the San Joaquin Valley into the Los Angeles area, was impassable in many locations.
> 2. Route 14 was closed due to the heavy damage suffered at the interchange between Routes 5 and 14.
> 3. The San Diego Freeway was impassable just south of the Golden State Freeway.
> 4. Route 210 Freeway east of Route 5 was closed.
> 5. Route 2, the Angeles Crest Highway, was closed by landslides approximately 5 miles north of Foothill Boulevard.
> 6. Telephone communications were out in most of these areas.
>
> A detour system was established by noon of February 9. By 7 p.m. one lane southbound Route 5 was opened and at 9:30 p.m., one lane northbound was opened for passenger vehicles and light trucks...On February 11, two lanes were open in each direction for Route 5 traffic excluding heavy trucks... Within 3 days after the quake the Southern Pacific tracks were cleared and shortly thereafter trains resumed operations...detours to all legal loads were not open until February 19...In a total of 10 days of design and 45 days of construction a $3 million 6-lane freeway approximately 2.5 miles long, mostly on new alignment was placed in operation on April 15."

With sufficient redundancy in the transportation system (freeways, county roads, etc.) the ability of the transportation system to serve its intended function may not be critically impaired. In moderate earthquakes this situation is possible. The author knows of one psycho-therapist who left her home in Glendale the morning of February 9, after experiencing a severe tremor, and drove to San Fernando without realizing there had been a damaging earthquake until she drove up to the psychiatric unit of the Olive View Hospital and learned that the second floor had fallen to ground level.

Although there were about a dozen airports within a 30-mile radius of the epicenter the only structural damage was glass breakage at several of the airports. All airport control towers remained on the air. The most critical earthquake-induced problem was the loss of commercial electric power, which prevented the pumping of aircraft fuel stored underground. Most power was restored in 8 to 10 hours. The operational capacity of an airport can be seriously hampered by loss of communications, navigation aids, or lights.

Damage to the transportation system hampered the fire department in its work of extinguishing fires and rescue operations. The following excerpts from Olson's report indicates the degree of difficulty:

> "At least 17 fire departments (as far away as Orange County responded to incidents attributed to the earthquake. These included 116 fires... They experienced difficulty responding to calls due to damage to roads and highway obstructions. The Los Angeles County department reported numerous instances where damage included broken water mains flooding the streets often obscuring holes, making driving hazardous, and requiring extra care on the part of the driver...Landslides and bridge failure blocked all thoroughfares except one between the San Fernando Valley and the New Hall area.

> Two fire department helicopters were sent up on patrol, followed shortly thereafter by two more when pilots were available. From the air, the Veterans Administration Hospital collapse was observed...Following the discovery of the Veterans Administration Hospital emergency, the first reporting engine company was delayed until 7:40 a.m. because of the heavy congestion in the passable streets.
>
> At approximately 9:00 a.m. the first county fire department representative on the scene found the Los Angeles City department heavily committed to rescue operations. In addition to requesting county engine companies, nine camp crews comprising a total of 89 men were dispatched to the scene. The closest crews, located about 1 1/2 miles north of the hospital, were trapped in their own area by slides and men had to be flown in by helicopter. Immediately thereafter one county helicopter was sent to Harbor General Hospital where it picked up nine doctors and medical supplies for transport to the Veterans Hospital.
>
> By approximately 10:15 a.m. the county was able to assume charge of operations, with the fire chief requesting additional bulldozers, compressors and jack hammers, dump trucks, and six more camp crews..."

4. The Charleston Earthquake - August 31, 1886. Intensity X.

This earthquake was the most destructive earthquake in the history of the southeastern United States, and took place at night at 21:51 hours. The shaking destroyed much of Charleston, S. C. and killed approximately 60 people. The earthquake started with a barely perceptible tremor, then by swift degrees became more violent, with no break in the increasingly heavy jar. Everyone in the city of Charleston and its surrounding communities feared instant death. The people fled to the streets for safety only to be killed by the falling walls. Because few houses escaped damage and many were totally destroyed, the amount of debris in the streets was very great, making travel through the streets very difficult because they were so narrow.

They are still narrow in the old sections of the city which will make it difficult to perform rescue operations should another earthquake occur.

Right after the 1886 quake, aid from the outside was impossible, as the railroads (the major source of transportation) were badly damaged and the telegraph lines were down. News of the disaster did not get through to the rest of the country until the following day. As soon as the railroads were repaired, many people fled the city.

Several people immediately started putting together accounts of the quake. One year later Clarence E. Dutton summarized these accounts in the ninth annual report of the U.S. Geological Survey. Dutton's article gives a detailed description of the damage to the railroad system from which he inferred two separate epicenters and also published an isoseismal map within the epicentral tracts. Unfortunately no intensity values were assigned on these maps. Dutton, however, did publish a general isoseismal map for the felt area (about 2 million square miles) based on the Rossi-Forel scale. The earthquake was felt over the entire eastern half of the United States from Canada to the southern tip of Florida. Figure 9 shows a comparison of areas observed to have intensities VII or greater for four U.S. earthquakes, and aptly demonstrates the low intensity attenuation for eastern earthquakes as compared to western earthquakes. Almost a century after Dutton filed his report, Bollinger reexamined the intensity data for this earthquake and reinterpreted it in terms of the Modified Mercalli scale. Figure 10 shows the isoseismal contours plotted on a base highway map.

The epicentral area, intensity X, is enclosed by an oval contour passing through Charleston, Jedburg, and Adams Run. The epicenter was near Summerville, a small town that had a population of about 2,000 at the time of the quake. Within this area were three railroads, the South Carolina Railroad

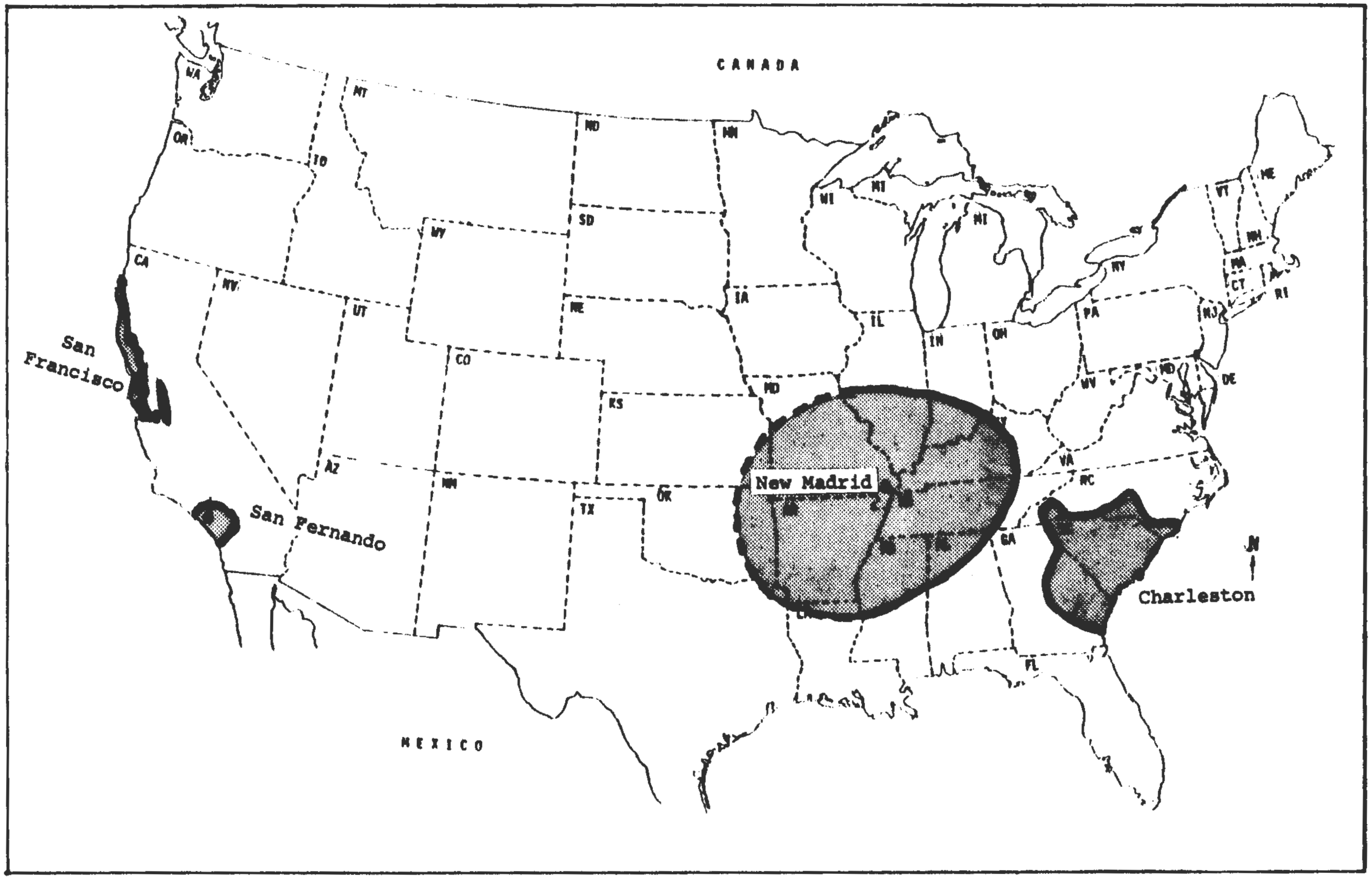

Figure 9. Comparison of areas for M.M. Intensity VII+ isoseismal contours for earthquakes. (From Bollinger)

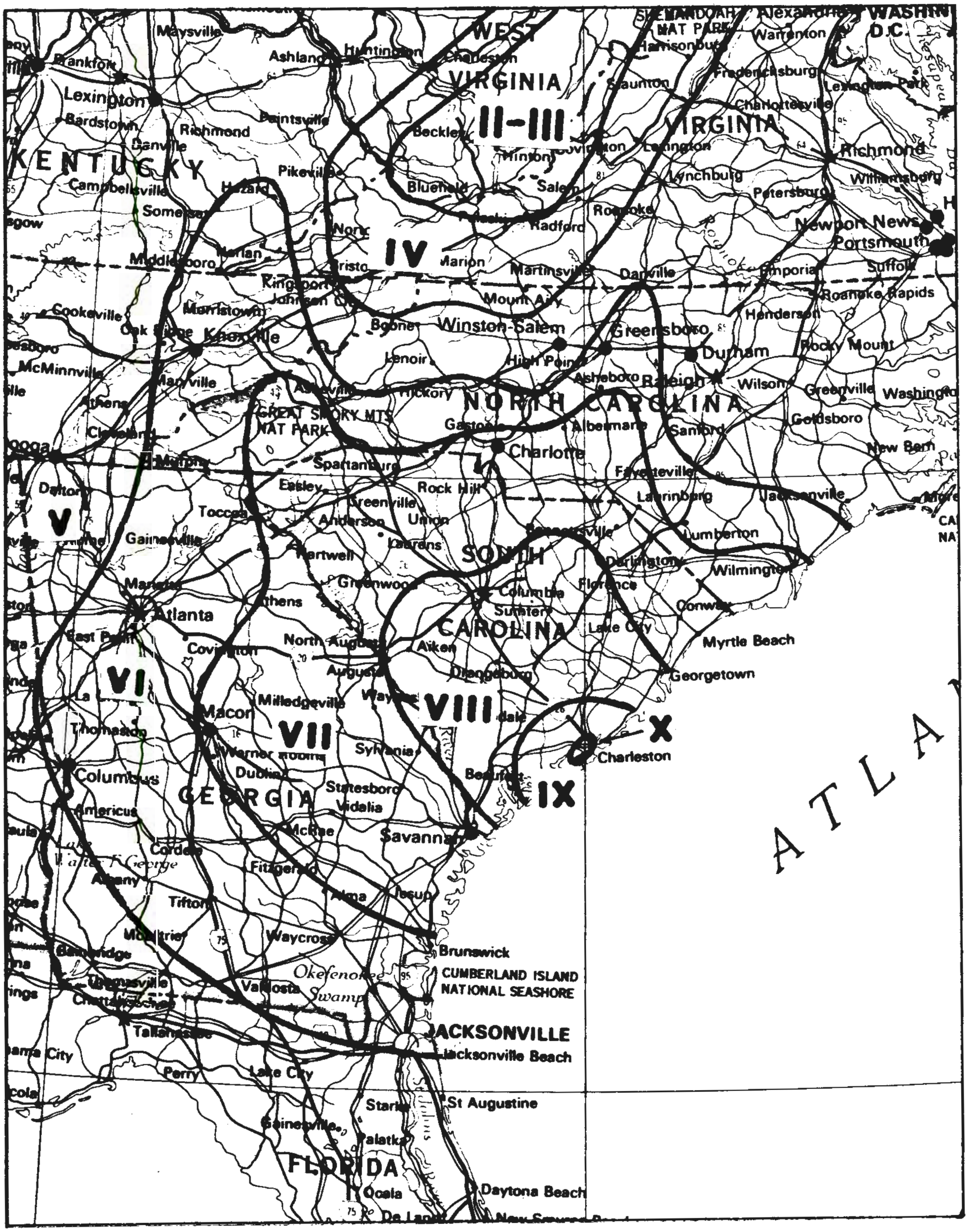

Figure 10. Isoseismal M.M. contours for the Charleston, 1880 earthquake. (After Bollinger)

(now the Southern railroad), the North-Eastern Railroad (now the Atlantic Coast Line), and Charleston & Savannah Railroad (also now the Atlantic Coast Line). Today the Savannah and Atlanta Railroad also crosses the epicentral area with a stopover at Charleston. Damage to the three original railroad tracks began about 9 miles northwest of Charleston and were extensive. More than 62 miles of these tracks were affected with such damage as lateral and vertical displacement, formation of S-shaped curves, and the longitudinal movement of hundreds of meters of track. Bollinger's reinterpretation of seismic data shows all the damaged sections of track within the intensity X contour. On the South Carolina Railroad an outgoing train from Charleston met with a disaster. The fireman, while leaning out the cab, was thrown to the ground by the sudden lurch of the first great shock and was seriously injured. As the train moved onward it came to the sharp kink in the tracks and overturned.* On the South Carolina Railroad the distortions of the track and its dislocations attained their maximum between the 10-mile and 11-mile posts. Many hundreds of feet of track had been shoved bodily southeastward. The buckling always took place when this lateral shoving encountered a rigid obstacle, usually a long rigid trestle. At the northwestern end of the trestle the accumulation of rails resulted in a sharp kink. Near the 11-mile post the track was parted longitudinally, leaving gaps of 7 inches between the ends of the rails. The trackway also sank here about 18 inches through a length of about sixty feet. Several stretches of track are described by Dutton. The epicenter was at about the 16-mile point of the railroad. Beyond this point there were several S curves and kinks in the railroad. A complete listing of the effects along the South Carolina Railroad is summarized in a table by Bollinger.

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* In Japan, alarm seismographs in substations now are set to cut the power to electric trains and thereby set the emergency brakes on the trains. (Nishiki, 1969)

On the Northeastern Railroad, besides discussing damage to the tracks, Dutton mentions the damage to the railroad trestles. At the 11-mile post a trestle 40 feet long was supported on four bents. The girders above were notched two inches deep on their lower faces to receive the tops of the bents. The shock lifted the girders far enough to release the bents from their notches, and two of them fell prostrate, one to the north, the other to the south. At 12 miles the north end of the trestle was shifted 8 feet 4 inches to the west and also against the south end of the trestle. It was necessary to cut out 22 inches off the girders before the alignment could be restored because the ground had also shifted so much. At the 16 mile point the ground was thrown into ridges or permanent waves and the rails were bent in a vertical plane to conform to the fixed undulations.

Dutton used the damage along the Charleston and Savannah Railroad to establish the possible existence of a second epicenter. The reinterpretation by Bollinger does not bear this out. Instead both epicenters are united into an epicentral contour X given by Bollinger. At the Ashley River the Charleston and Savannah Railway suffered serious disturbance. The approach to the drawbridge was by embankments and trestles on both sides of the river. The drawbridge portion was jammed by the earthquake, the immediate cause being the sliding or creeping of both river banks toward the center of the stream carrying the trestle with them. West of the river the joints of the rails were torn open. The Rantowles bridge was moved 37 inches south of its original position. The banks on both sides of the river flowed toward the center of the river. Further kinks also showed up on this railroad.

Today a modern network of highways leads into Charleston. The same conclusions concerning the highways near New Madrid can be repeated for those entering and leaving Charleston. Note that contour VIII comprises about half of the state of South Carolina.* (See Figure 10)

The Charleston Earthquake was the first earthquake in the history of the United States that centralized near a large city. Bollinger has estimated its magnitude between 6.8 to 7.1.

5. The San Francisco Earthquake - April 18, 1906. Intensity XI.

The second earthquake in U.S. history to have been centered near a large city, the San Francisco Earthquake, was listed by Richter as having a magnitude of 8.3. However, in a recent book by Verney (1979) the quake was downgraded to 7.9. Its felt area was about 375,000 square miles, but its destructive intensity extended for over 400 miles. Its importance in earthquake literature comes not because of its size, but because it occurred in an area of heavy population density. It was the first time in U.S. history that high rise buildings were damaged severely, and it represented the first time that an earthquake could be tied in with strike slip action along the San Andreas fault. Figure 11 shows California's active fault system (DeNevi, 1977).

The earthquake occurred at 5:12 a.m. while most people were asleep, which may have been the reason the loss of life due to the shock (approximately 150 persons) was low. The total loss of life of 700+ people was due to the fire following the earthquake. The earthquake was in two phases of 45 seconds and 25 seconds, respectively, separated by a complete stoppage of vibration for 10 seconds. The water mains broke leaving the firefighters no alternative but to use dynamite to create fire breaks before the fire burned out in three days.

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* "The absence of large-magnitude earthquakes in eastern North America since the Charleston, S.C., earthquake of 1886 has resulted in complacency, or perhaps unawareness on the part of the general populace of the existence of any earthquake threat to them." (Nuttli, 1973)

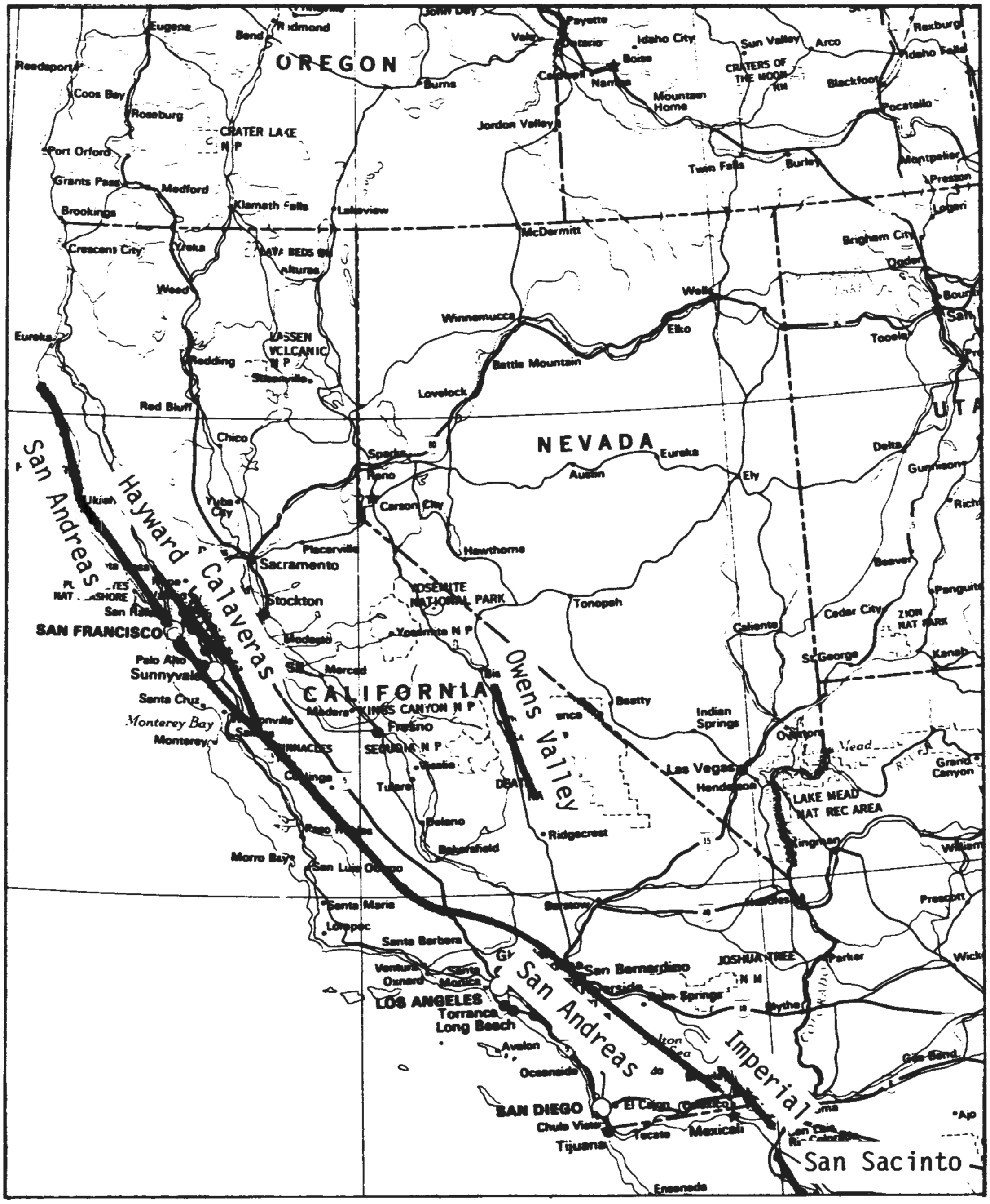

Figure 11. Location of long faults in California. (After DeNevi)

Roads crossing the faultline were rendered impassable; however, transportation was not entirely cut off. Unlike Charleston, news of this earthquake was immediately telegraphed to the rest of the country and the army set up relief trains filled with food, supplies, and water. The first train reached San Francisco the night of April 18.

Lawson's extensive 451-page report of the State Earthquake Investigation Commission (1908) contains many plates showing damage to bridges and tracks, but the damage to the transportation system is scattered throughout the report. Instead the report by ASCE and the San Francisco Association joint committee (1907) does separate the information via its subcommittee reports. The following is extracted:

> COMMITTEE ON LIGHTING AND STREET-RAILWAY TRANSPORTATION
>
> The injury caused to the street-car tracks was relatively slight and only on ground that had been filled...The slots of cable roads were found closed only in the burned district, and the evidence points to its being due mainly to expansion caused by the excessive heat. The fact that the Geary Street Line, which is a cable road, operated for several hours after the earthquake, is very pertinent. The cable roads, however, were put entirely out of use by the fire and the falling debris.
>
> Many of the trolley lines outside of the burned district could have been operated at any time, except for the fire hazard from the tangle of other wires. The street-railroad power-houses were but little injured except by the falling of a brick stack and the collapse of a roof...
>
> Immediately after the earthquake all gas was shut off to the city lines, but sufficient gas was in the mains to cause numerous explosions as the fire progressed... The damage to mains was principally due to explosions.
>
> COMMITTEE ON RAILWAY STRUCTURES
>
> Within the area of destructive effect...the following companies were operating: Southern Pacific; Atchinson,

Topeka, and Santa Fe; California Northwestern; and North Shore*...

The structures peculiar to railroads which were affected, are embankments, trestles, bridges, tunnels, and water and oil tanks...Embankments...These settled more or less where they crossed marshes or were underlaid by soft strata...On the marsh between Benicia and Suisun, on the Southern Pacific, the settlement was 11 ft.; at another point, 5 ft. These were nearly vertical...On the North Shore, about 2 miles north of Point Reyes,... two embankments, 2,200 ft. and 900 ft. long, respectively, sank until the water at high tide washed over the rails... Settlements of this character were common on all railroads operating about the Bay of San Francisco and its tributaries.

Trestles...Trestles over marshes suffered more or less from the movement of the soft material into which the piles were driven...On the North Shore Railroad, a trestle of framed bents on piles, 600 ft. long and 70 ft. high, was thrown down, and portions of the trestle over Lagunitas Creek, about a mile from Point Reyes, was thrown entirely off the piles, the piles themselves being moved down stream. These trestles were on soft ground and near the fault-line.

Bridges...Draw bridges across the little creeks and inlets around San Francisco Bay, being generally on soft ground, were affected by a slight movement of their piers, in many cases resulting in the bridge binding so that it could not be opened until some repairs were made... A steel drawbridge over Petaluma Creek, was open at the time of the earthquake, and was thrown off its center 2 ft. to the east and 1 ft. to the north. It was a 220-ft. span, and on four iron cylinders, filled with concrete, on pile foundations.

Fixed spans, with a few exceptions, were not affected seriously. Where affected it was by a movement of the piers or abutments relative to each other...The Southern Pacific Bridge across the Pajaro River, at Watsonville, consisting of four 80 ft. wooden spans on pile piers, had the second pier from the east end moved (up stream)

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* The Northwestern and North Shore railroads are not reported on a modern map; instead the Northwestern Pacific comes into San Francisco from the north.

> about 3 ft...The bridge across the Pajaro River, near Chittenden, on the Southern Pacific, was badly damaged. The line of fault crosses this bridge near the west end. The bridge consists of three 120-ft. riveted spans with 50-ft. girders at each end.
>
> *Tunnels*...The tunnel at Wright's Station on the South Pacific Coast Railway (Southern Pacific Company), was on the line of the fault, and suffered considerable damage. The tunnel is 6,225 ft. long. The line of fault crosses the tunnel about 400 ft. from the north portal; the movement at this point was 5 ft. practically at right angles to the axis of the tunnel...The damage, however, being confined entirely to broken timbers and cave-ins from the roof...minor shocks that occurred during the day shook down enough material to block it completely at four points.
>
> *Overturned Cars*...On the North Shore (3 ft. guage), a passenger train consisting of three cars and an engine, standing at Point Reyes, was thrown over on its side... On the Southern Pacific, a freight train which was running at the time toward San Francisco, a few miles south of Chittenden, was derailed...In the mountain region adjoining the line of fault there were a great many slides of earth and loose rock. When these occurred in railroad cuts there was some little delay of traffic, but the actual damage was small.

The Committee on Highway Structures reported that the earthquake did very little damage to highway bridges. The discussion which follows the report lists only two instances of highway bridges being damaged. For example, the highway bridge across a creek tributary to Tomales Bay, near Point Reyes Station on the North Shore Railway was less than 2 miles from the fault line. This bridge originally had 8 panels of total length about 120 ft. The earthquake settled the north abutment 2 to 3 ft. and moved it southward, so that in repair an apron had to be built from the approach to the bridge roadway. The bridge at Watsonville was distorted in like manner due to the shifting of the bank deposits.

It should be remembered in this context that the railroads were the main avenue of transportation in 1906 and that the highway bridges were mainly built to accommodate horse drawn wagon traffic. A comparison with today's modern arterial system would be unrealistic. For example, consider what happened at San Fernando with an earthquake less than 1/10 the energy release of the San Francisco quake.

Figure 12 shows the M.M. contours overprinted on a modern map of California. This information was extracted from an R.F. contour map in Lawson's report (supplemental map volume) and Table 5. This figure will help in understanding what follows.

In 1973, the Office of Emergency Preparedness published a report about estimated earthquake losses in the San Francisco Bay Area for an 8.3 magnitude or a 7.1 magnitude earthquake activating either the San Andreas or the Hayward faults. (Figure 13a)

The experience of the 1906 earthquake was used as a basis for estimating damage to the railroad system. For an earthquake activating the San Andreas fault, embankments will fail where the system crosses marsh land or earth underlain by soft strata. (Figure 13b) Damage to trestle bridges would be small; most of the damage would be confined to trestles on soft ground. Draw bridges might be vulnerable to damage if they were open at the time of the quake. For fixed span bridges there would be some movement of their piers or abutments. Tunnels would suffer little damage. The bridge of the Southern Pacific main coastal line to Los Angeles, crossing the San Andreas fault at Pajaro River near Watsonville is expected to fail. (Figure 13c) The previous bridge at this site failed in the 1906 quake. Also on structurally poor ground, the damage would be similar to that of the Alaska Railroad.*

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* To be discussed on page 53.

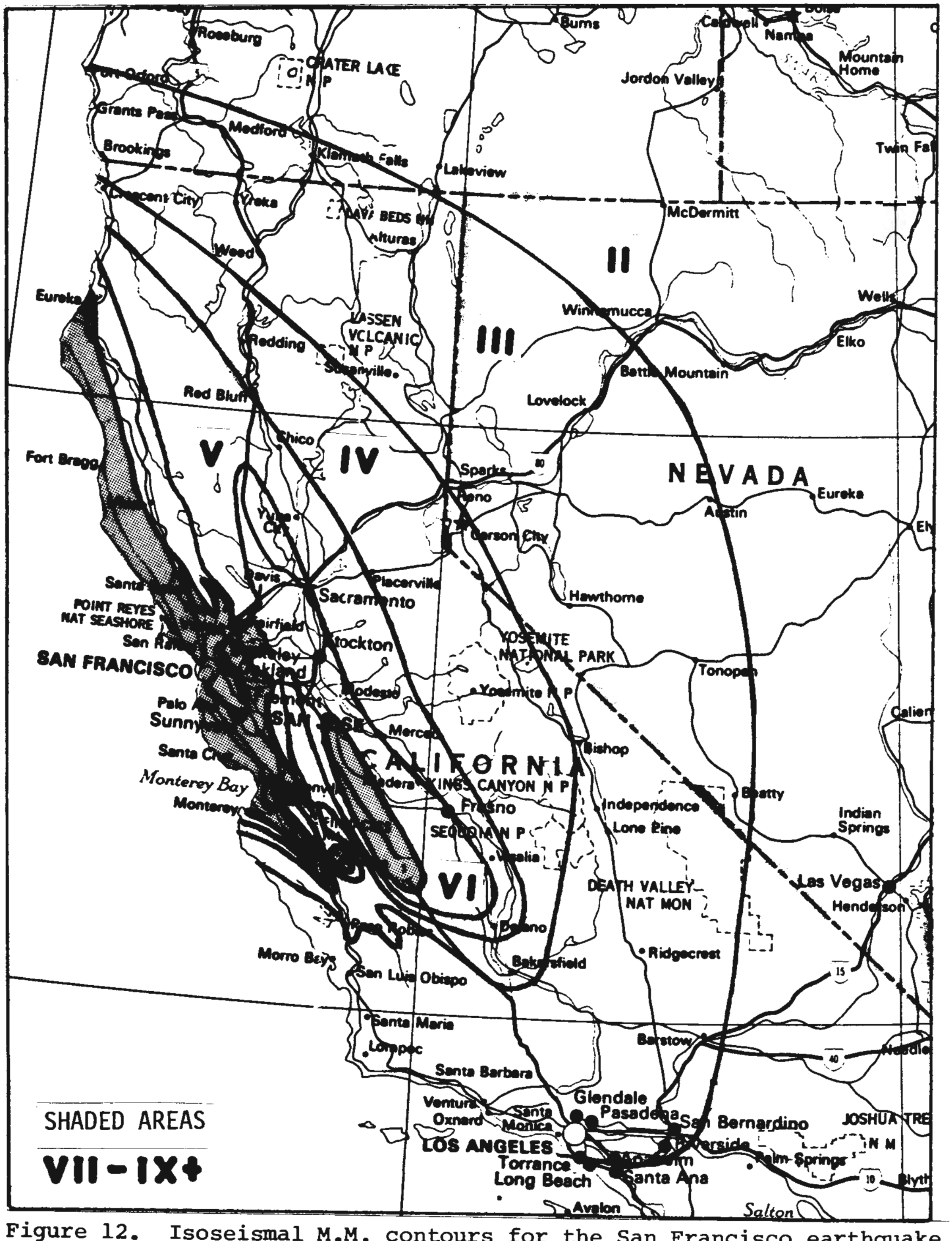

Figure 12. Isoseismal M.M. contours for the San Francisco earthquake of 1906. Curves translated into M.M. values from R.F. values by Lawson.

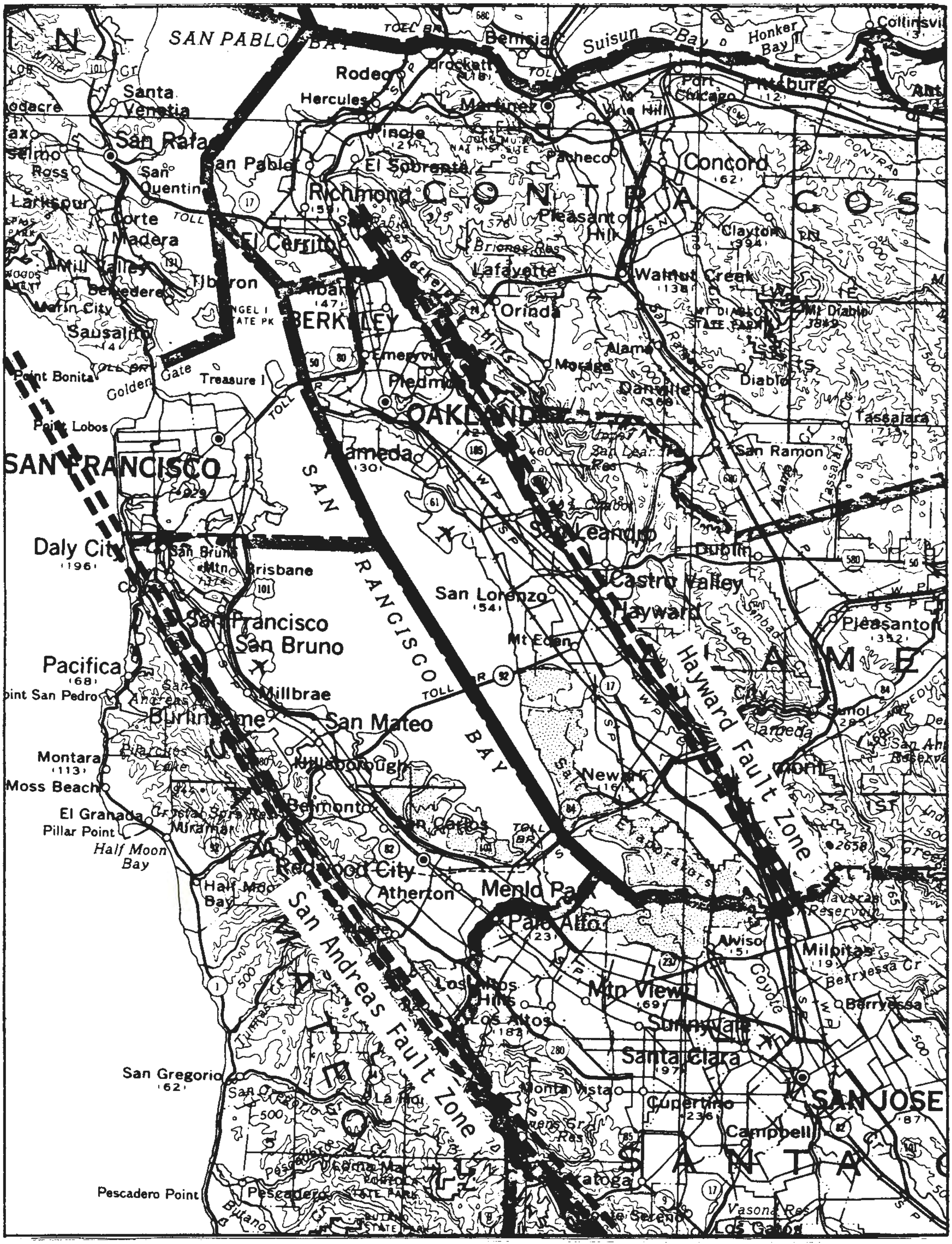

Figure 13a. Map of San Francisco Bay area showing approximate location of San Andreas and Hayward faults. (After Algermission & Steinbrugge)

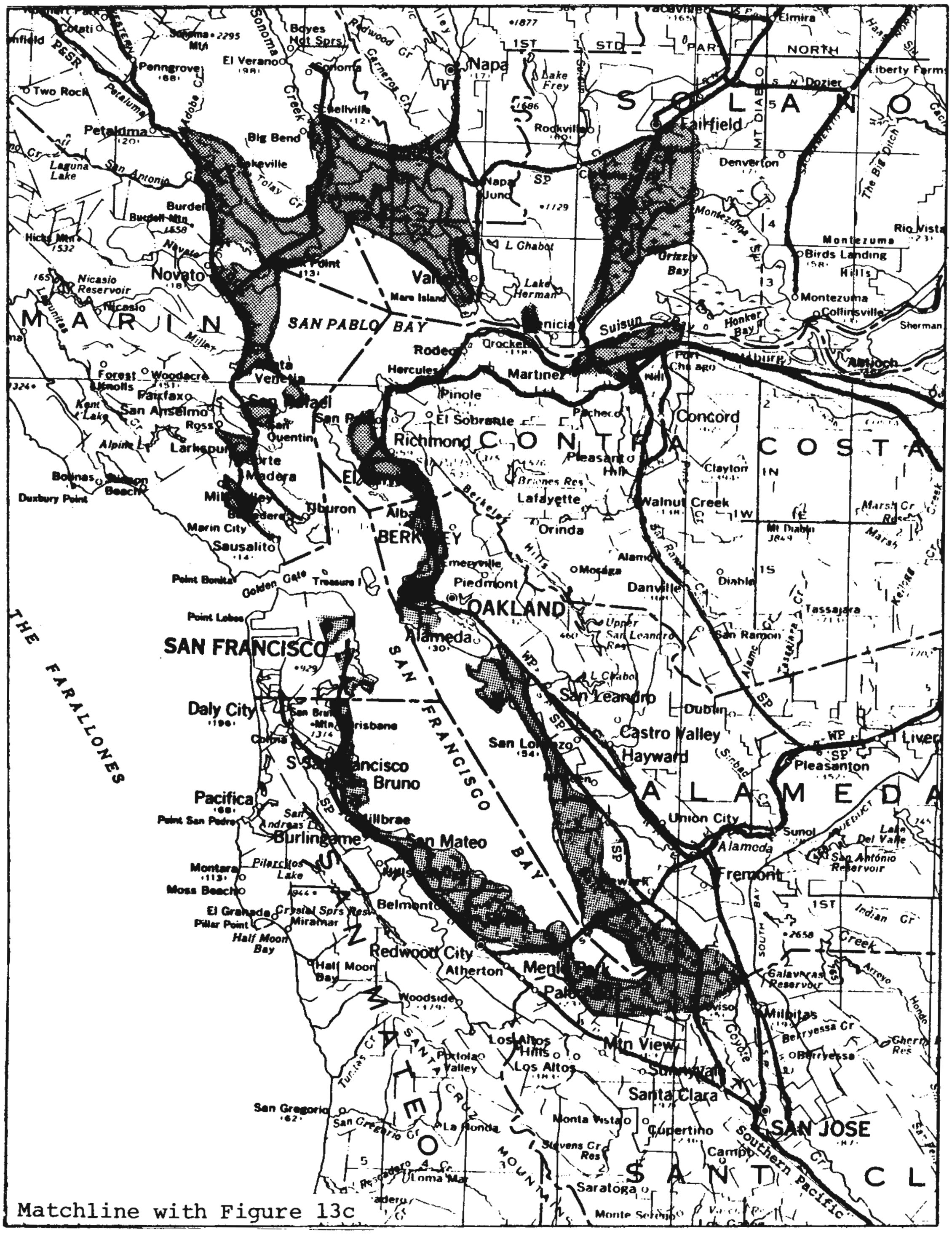

Figure 13b. Railroad network in the San Francisco area. Approximate location of marshlands (shaded area). (After Algermission & Steinbrugge)

Matchline with Figure 13b

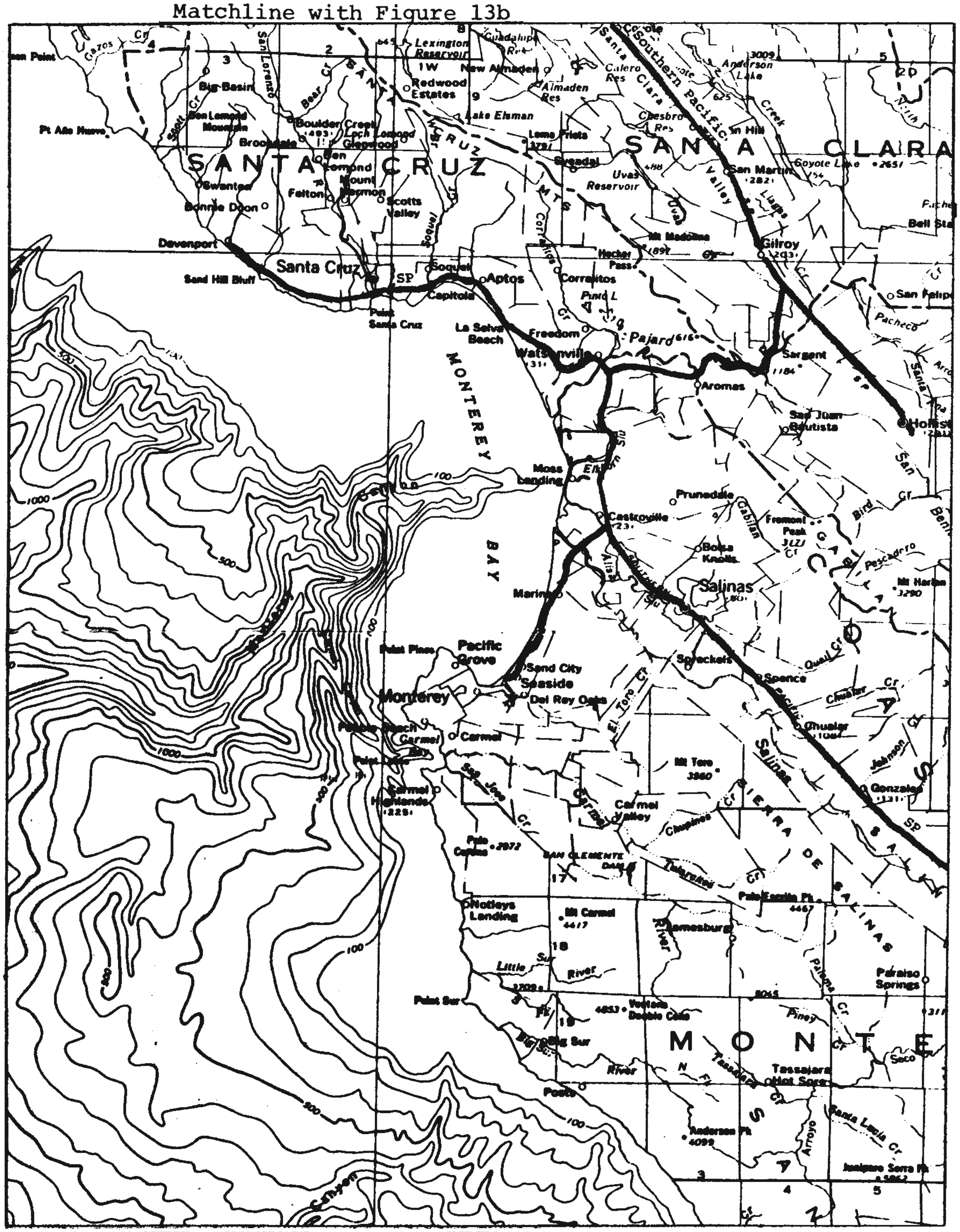

Figure 13c. Extension of railroad system south of San Francisco Bay area.

The railroad would be out of service for an indefinite period following an 8.3 magnitude earthquake, but for a 7.0 or 6.0 quake damage would be confined to the rail lines on the west side of the Bay.

If the Hayward fault is activated during an 8.3 or 7.0 earthquake the rail lines are expected to be offset where they cross the Hayward fault. Damage to bridges and trestles is expected to be more extensive than would be caused if the San Andreas fault were activated. This is also the belief concerning landsliding. For an 8.3 magnitude earthquake all east-west routes are expected to be closed for an indefinite period; for a 7.0 shock the east-west routes would be closed for a week while the coastal routes would be operating.

The following excerpts explain the expected damage to the highway system: (Figure 13d)

> "(Reference 1)...Principal damage...may be placed in one of three categories: (1) earth failure due to landslide or to structurally poor gound movements, (2) overpass damage, and (3) damage to bridges which cross the Bay.
>
> Should the postulated earthquake occur during the wet season of the year, landslides will be extensive in the high intensity areas...serious slides will be those in the hill areas where their physical volume will preclude quick bulldozer removal...or rapid construction of a bypass...Southern Marin County is particularly vulnerable. In addition to the damage to the main arterials, large residential hillside regions in the study areas can reasonably be expected to be isolated for days, with the same landslides destroying the utilities going to the isolated areas...
>
> ...at approaches to bridges and overcrossings, the pavements on the well placed deep fills may settle in terms of inches as compared to the surface of the bridge deck...these problems will slow up traffic or stop it until repairs are made...
>
> ...problems which are much more serious from a long term standpoint relate to the potential stability of certain major engineered fills. For one example, the

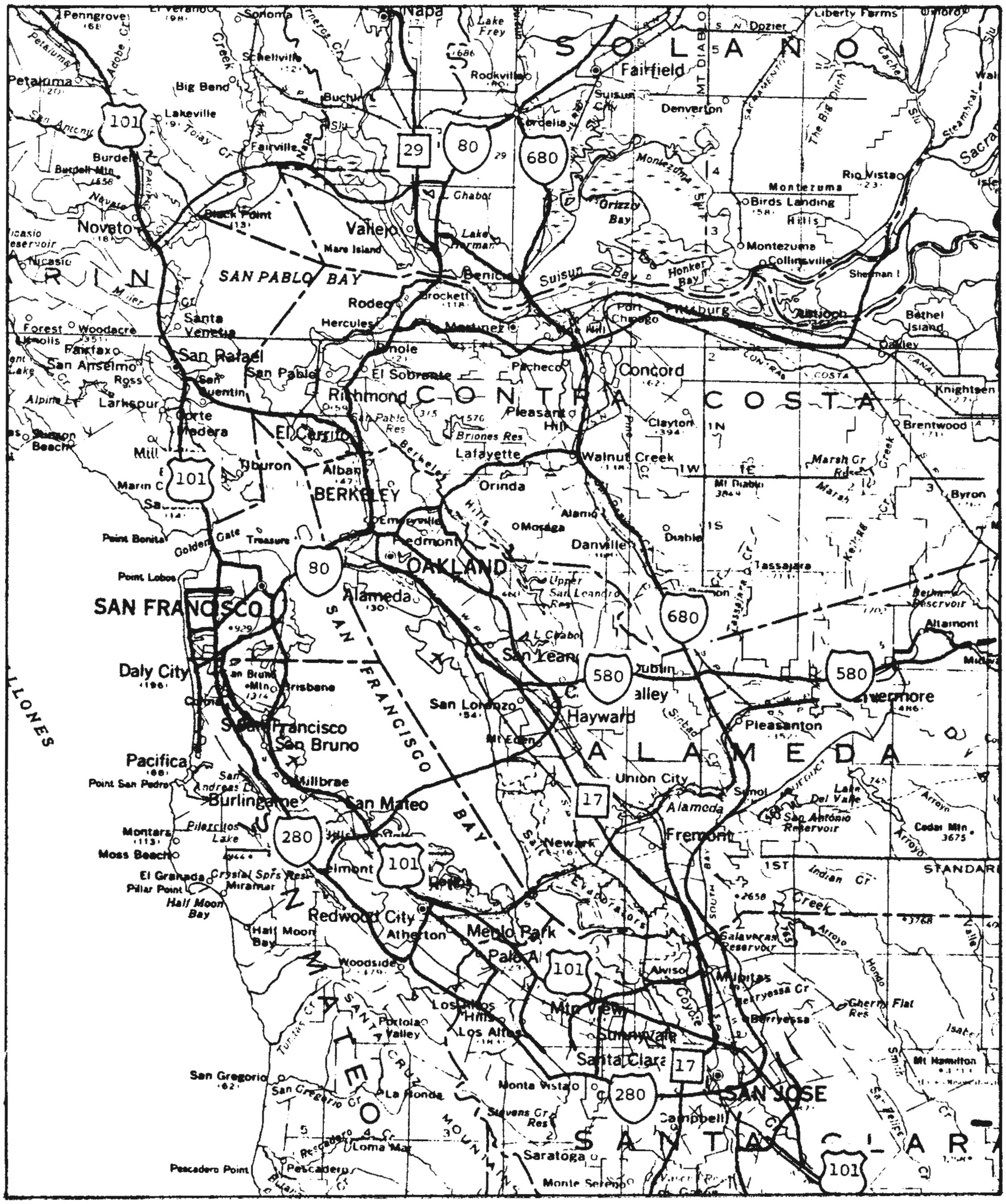

Figure 13d. Principle highways in the San Francisco Bay area.

> miles of US 101 south of Candlestick Point in San Francisco to San Bruno may be cited; major land slips or movements are distinctly possible in heavy ground motion, and major stretches of this freeway can be under water or badly damaged due to soil movements. Additionally, the hydraulic fills used to construct miles of freeways along the east shore of the Bay in Alameda County may liquefy during heavy shaking, with long sections becoming totally impassable.
>
> ...The bridges which cross the Bay pose special problems... no high intensity earthquake experience exists to back up the theoretical bases for their designs...
>
> Easier to evaluate are the approach problems for the specific bridges, and these turn out to be as critical as those of the bridge for the first few weeks. The earth fills in the east approaches of the Bay Bridge appear to be subject to extensive slippage and differential settlements from strong ground motion, and the failure of these approach fills would effectively put the bridge out of operation for many days...for planning purposes the Bay Bridge is vulnerable in major earthquakes.
>
> Similar problems exist for the San Mateo Bridge and Dumbarton Bridge...
>
> The Golden Gate Bridge approaches on the north side are vulnerable to major landslides, particularly in the wet season, and virtually a complete halt to bridge traffic is possible from landslides..."

For an earthquake on the San Andreas fault:

> "...one-fourth of the freeway structures in the counties of Marin, San Francisco, San Mateo, and Santa Clara will be impassible or virtually so in the event of an 8.3 magnitude shock. Surface faulting will disrupt freeways in the Daly City-San Bruno-Pacifica region, and Pacifica and other coastal cities will be isolated... U.S. 101 between Candlestick Point and San Bruno will be out of service due to land failure. The Golden Gate Bridge, Bay Bridge, and San Mateo Bridge will be out of operation for indefinite periods due to direct damage to the bridge structures and/or approach problems...The highways and roadways not requiring overpasses, etc., are expected to remain sufficiently intact to provide adequate transportation facilities,

> although time delays will be great in some areas. Assuming wet weather, 75% of southern Marin County will be isolated due to landslides and ground failures to freeways, highways, and city streets...
>
> For planning purposes, a 7.0 magnitude shock will cause failure of 5% of the overpasses. Bay bridges are expected to survive, but the approach damage will restrict the effective capacity to 50% for all bridges."

For an earthquake on the Hayward fault:

> "...residential areas east of the Warren and MacArthur Freeways will be isolated...trucked supplies from eastern areas to the San Francisco and Peninsula cities will be subject to substantial delivery delays due to the disruption of normal transportation routes.
>
> ...50% of the freeway structures within 10 miles of either side of the fault will be out of service immediately after the earthquake. The Eastshore Freeway (Interstate 80) will be out of service for an indefinite period of time in Oakland, Emeryville, and Berkeley due to ground failure...
>
> The Caldecott Tunnels on State Route 24 will remain serviceable, but the highway will be out due to landslides on the assumption of wet season conditions. US 50 near Castro Valley will be out due to landslides. Most other routes will also be out. Effectively, then, the communities of Martinez, Concord, Walnut Creek, Pleasanton, and others east of the Berkeley Hills will be isolated from Oakland, Berkeley, etc., for a day or two.
>
> For planning purposes, the Richmond-San Rafael Bridge, the Bay Bridge, and the San Mateo Bridge will be out of service for an indefinite period of time in the event of an 8.3 magnitude shock.
>
> Transportation routes to and from the city of Alameda will be essentially closed down for 24 hours, and then partially restored. The tubes under the estuary will be considered to be out of service for an indefinite period of time.
>
> A magnitude 7.0 shock will cause similar damage along the Warren and MacArthur Freeways since it makes little difference if an elevated structure is offset by 3 feet of faulting or by 6 feet of faulting -- damage is serious in either case..."

A general comment:

> "...most of the confusion is expected to be over in several days."

6. Alaska (Prince William Sound) Earthquake - March 27, 1964. Intensity XI.

The most catastropic earthquake in the United States on an existing transportation system, this earthquake severely hampered or wrecked all forms of transportation in the south central part of Alaska. Verney has upgraded its magnitude classification to 9.3 from a former classification of 8.3. Figure 14 shows the location of the epicenter, and some isoseismal contours. The contours shown were taken from the National Academy of Sciences report on the quake, reference (21), and is based on aerial reconnaissance flights made immediately after the earthquake over the higher intensity areas, on 450+ reports received from questionnaire forms sent to locations in Alaska and Canada, and reports by organizations and the new media. Although there was a wealth of data from centers of population, data from the outlying, sparsely settled regions made drawing the contours a difficult task.

The transportation system in Alaska is one example where redundancy in either the railway system or the highway system was practically nil. That is to say all routes were main line routes. The effects of this earthquake are described in detail to illustrate the extent of damage that can occur in a very large earthquake. The felt area was 700,000 square miles with vertical displacements occurring over an area of 170,000 - 200,000 square miles.

A. Alaska Railroad

The Alaska Railroad had a southern terminal in the deep-water, all-weather port of Seward. From there the main line ran north approximately 64 miles to Portage where it was

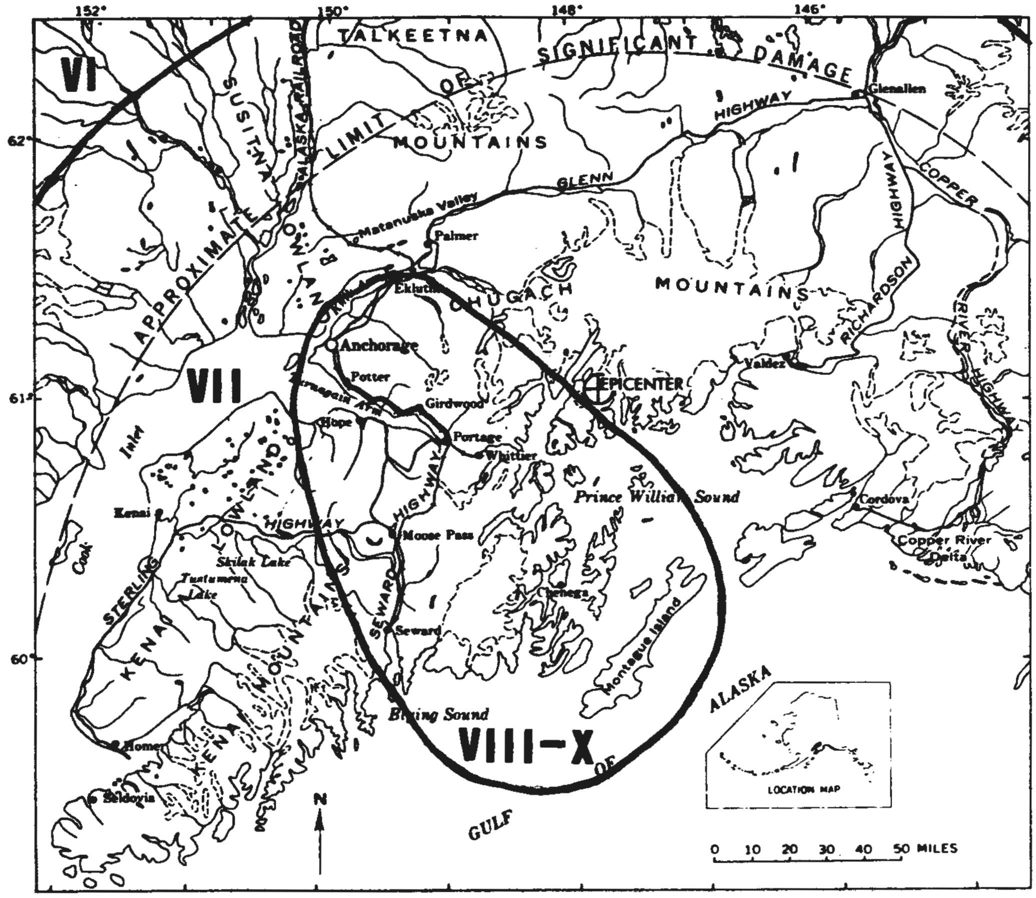

Figure 14. Isoseismal M.M. contours, Alaska earthquake. (after Hudson and Cloud)

joined by a 12-mile spur line to a second deep-water, all-weather port at Whittier. (No highway existed between Portage and Whittier.) The main line continued from Portage in a northwest direction for 50 miles to Anchorage, then continued on for 32 miles in a northeast direction to Mantanuska near Palmer, where it was joined by a 22-mile spur to Eska. The main line turned west at Mantanuska and swung north in a long curve through the mountainous terrain near Mt. McKinley Park. It then swung in another northeasterly curve to Fairbanks. The total length of main line was 471 miles. D. S. McCullough and M.G. Bonilla have reported in detail the effects of the earthquake on the Alaska railroad and give a table stating the damage incurred by each railroad bridge in the system. Much of the damage to the rail line occurred in areas underlain by soft sediments. Where the railroad was built on bedrock, there was much shaking but little damage. Restrictions for possible railroad locations necessitated that part of the rail line be built on the floors of glaciated valleys, marshes, and active flood plains.

Many of the railroad bridges that were affected in the area of the strong earth motion were open wood trestles supported on wood piling with wood bulkheads. Much of the bridge damage resulted from the movement of foundation materials towards the center of the crossing and high accelerations generated within the bridge structure by amplification of the ground motion. Bridge decks were bowed laterally. Some bridge decks were jackknifed and kinks were formed in the rail lines because of compression in the rails due to the decreasing distance between stream banks. Bents were shifted towards the streams. The stringers acted as struts pushing into the bulkheads or punching through them.

Steel railroad bridges were damaged in a different way than wood trestle bridges. The Twentymile River Bridge at mile

64.7, where the Twentymile River joins the eastern end of Turnagain Arm, was built of seven 70.08 foot steel deck trusses supported on concrete piers and abutments. Compression at the deck level jammed all the trusses together and drove the end trusses into the abutments, breaking away the back walls and shearing the anchor bolts on three piers and the abutments. This bridge did not fall down as did the highway bridge which was running parallel to it. Figure 15 shows the two bridges side by side.* The Ship Creek bridge at mile 114.3 has two 35 foot steel beam span approaches and a central 123 foot through truss carried on pile supported concrete abutments and piers. The main damage to this bridge was in its bearings. In the fixed bearings the anchor bolts were pulled out of the concrete at the abutments as the piers shifted streamward, while in the adjacent expansion bearings nested rollers were driven to their extreme position. This bridge was closed to traffic until new bearing surfaces were constructed on the pier tops.

Figures 17 and 18 indicate the degree of damage to railroad bridges as severe, moderate, or slight. McCullogh and Bonilla assigned the degree of damage on the basis of the amount of repair needed to salvage the bridge. Essentially, severe means the entire bridge or part of it needed replacement, moderate means that major repairs were required, and slight means that only minor repairs were anticipated to put the bridge back into operating service.

---

* In several earthquakes where railroad and highway bridges are in the same area the railroad bridges have remained standing while the highway bridges have collapsed. (Figure 16) This could be due to the rails tying the bridge segments together as restrainers, or could be due to the difference in weight distribution of the bridges. Heavy concrete highway slabs could cause highway bridges to act as inverted pendulums during an earthquake.

Figure 15. Photo taken about one month after the 1964 earthquake. Highway and railroad bridges across Twentymile River, 48 miles southeast of Anchorage, Alaska. Railroad cars were left on the bridge to help stabilize the structure during high tides. (Photo courtesy of U.S.D.A. Forest Service)

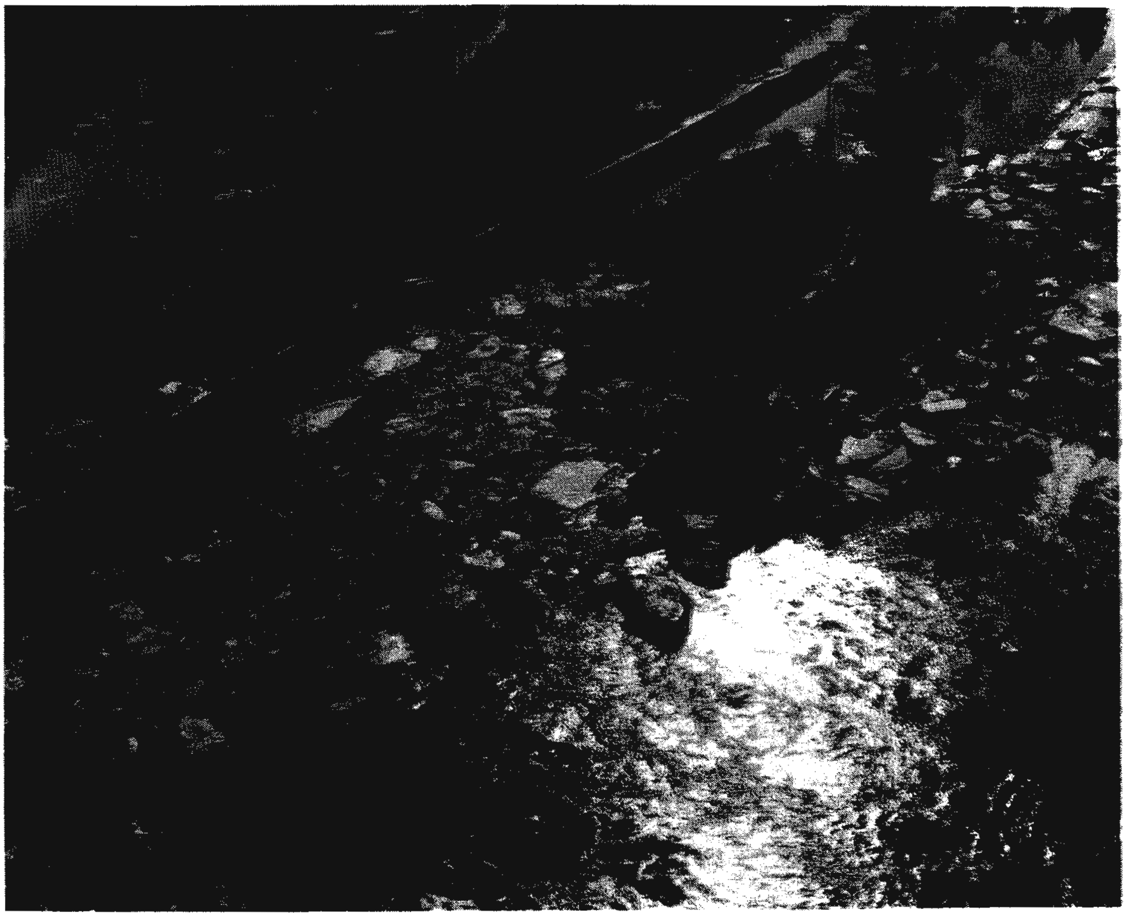

Figure 16. Damage to bridges across Portage Creek after 1964 Good Friday earthquake. Bridges located 50 miles southeast of Anchorage, Alaska. (Photo courtest of U.S.D.A. Forest Service)

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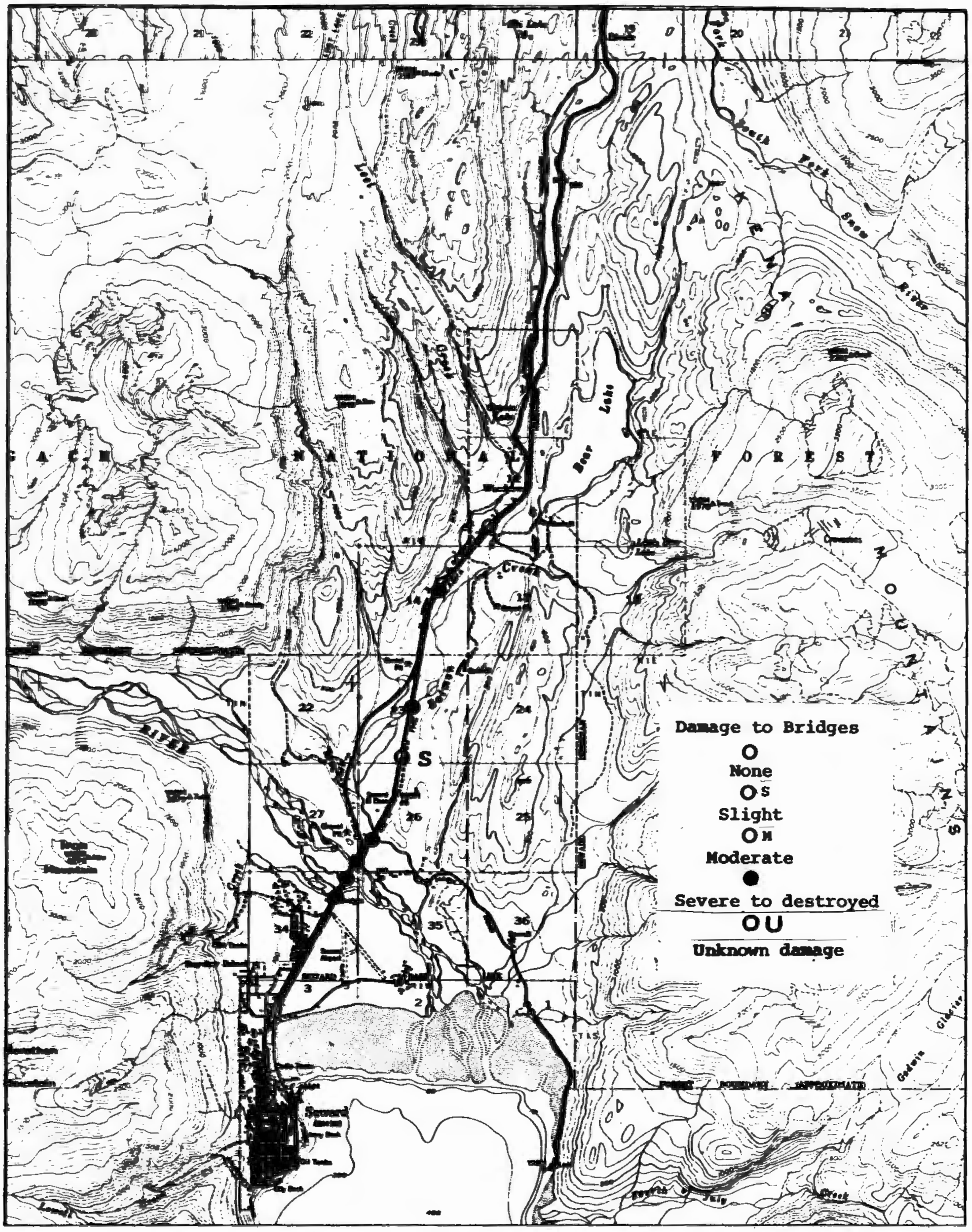

Figure 17. Route of Alaska railroad from Seward to Whittier and effects of the earthquake upon railroad bridges. (After McCullogh & Bonilla)

Matchline pg. 61

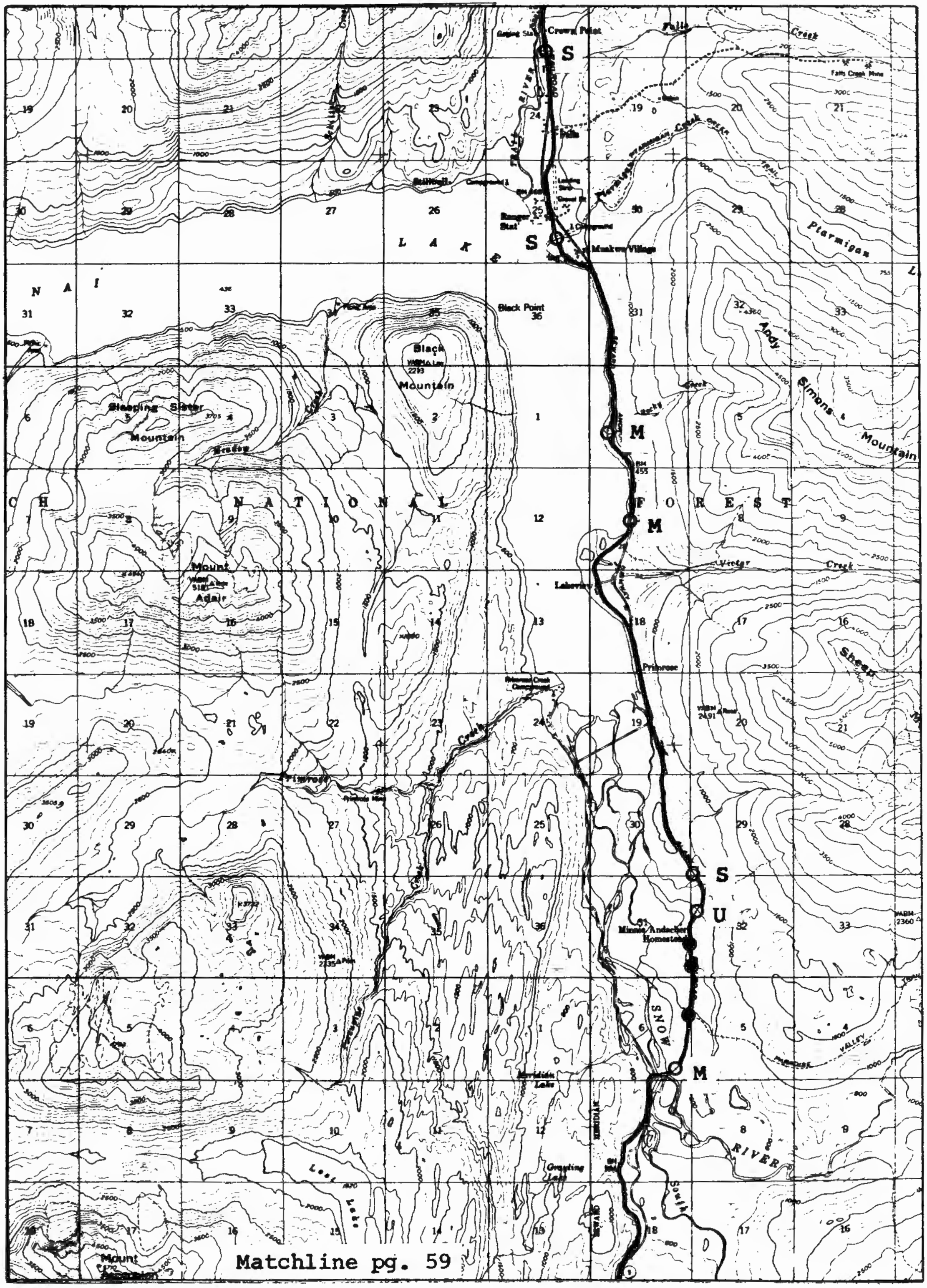

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Figure 17 cont.

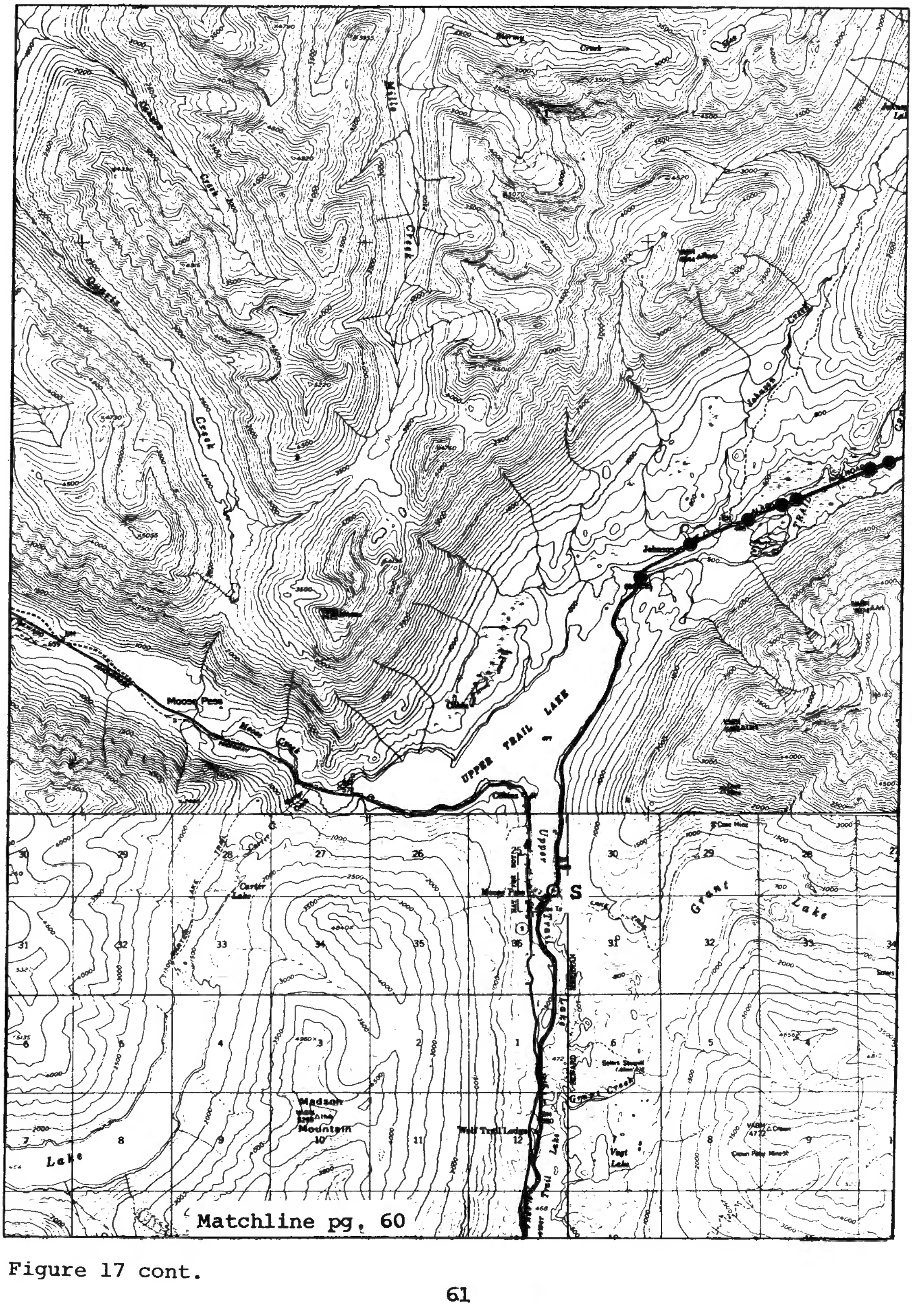

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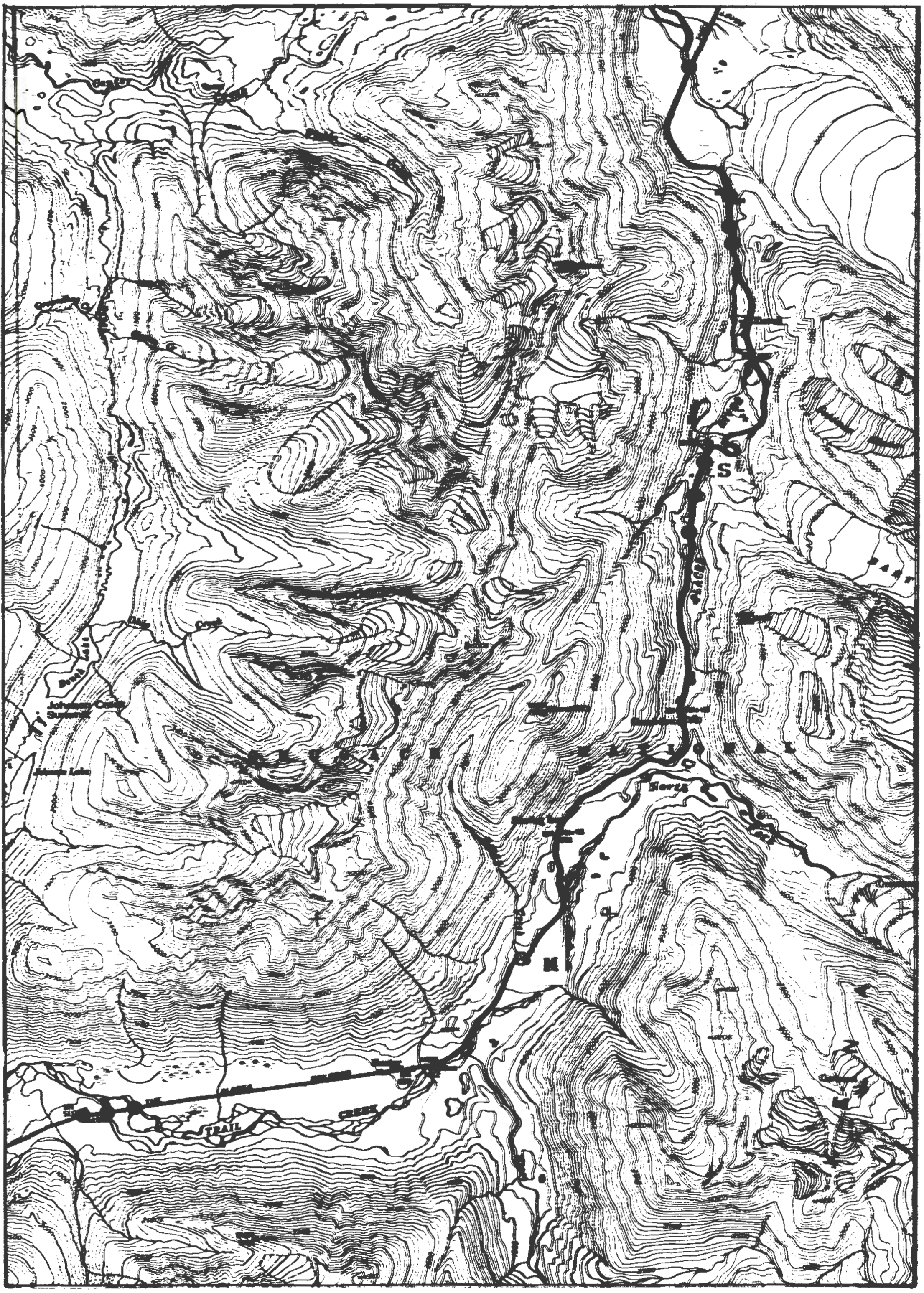
Figure 17 cont.



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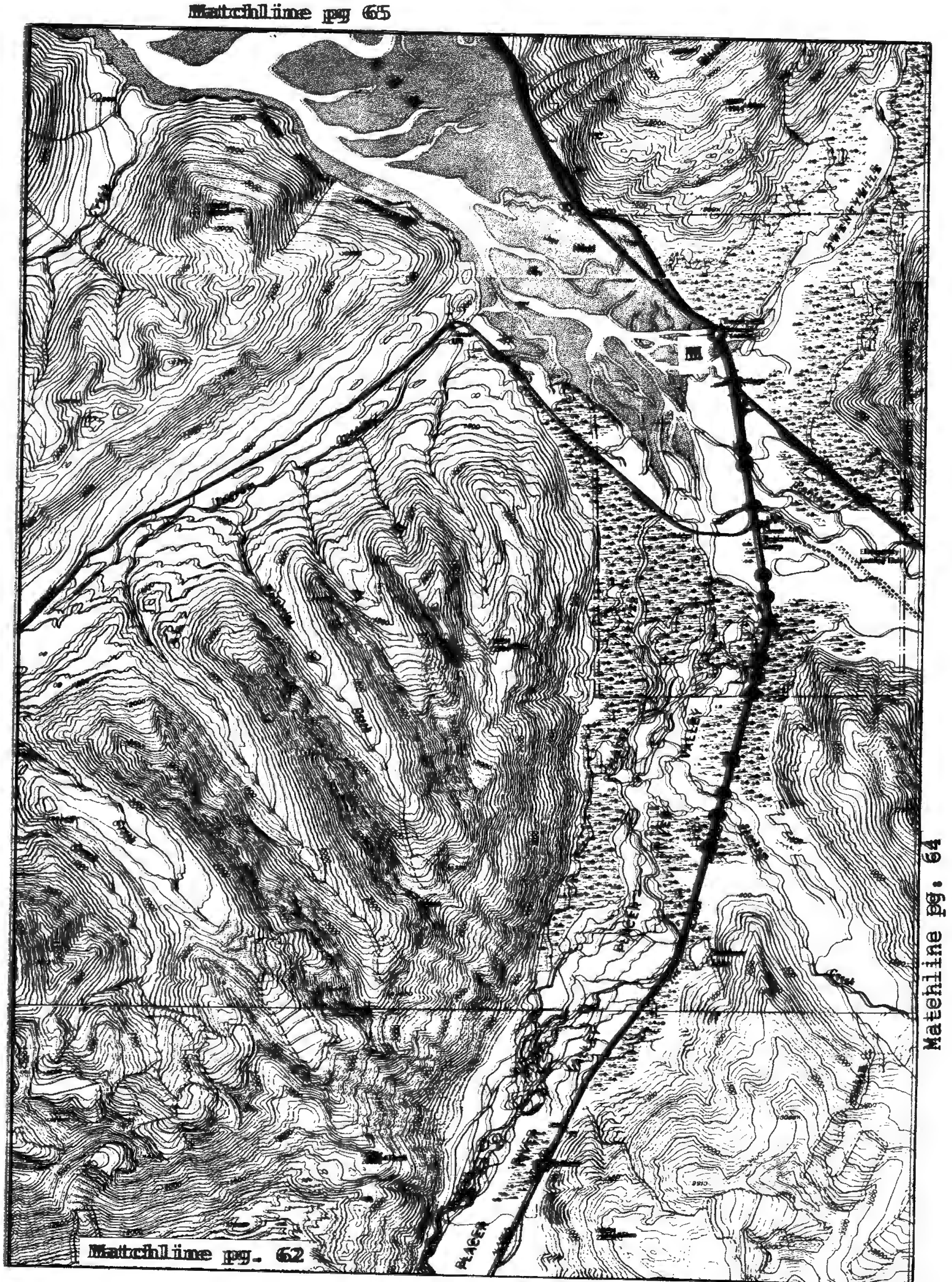

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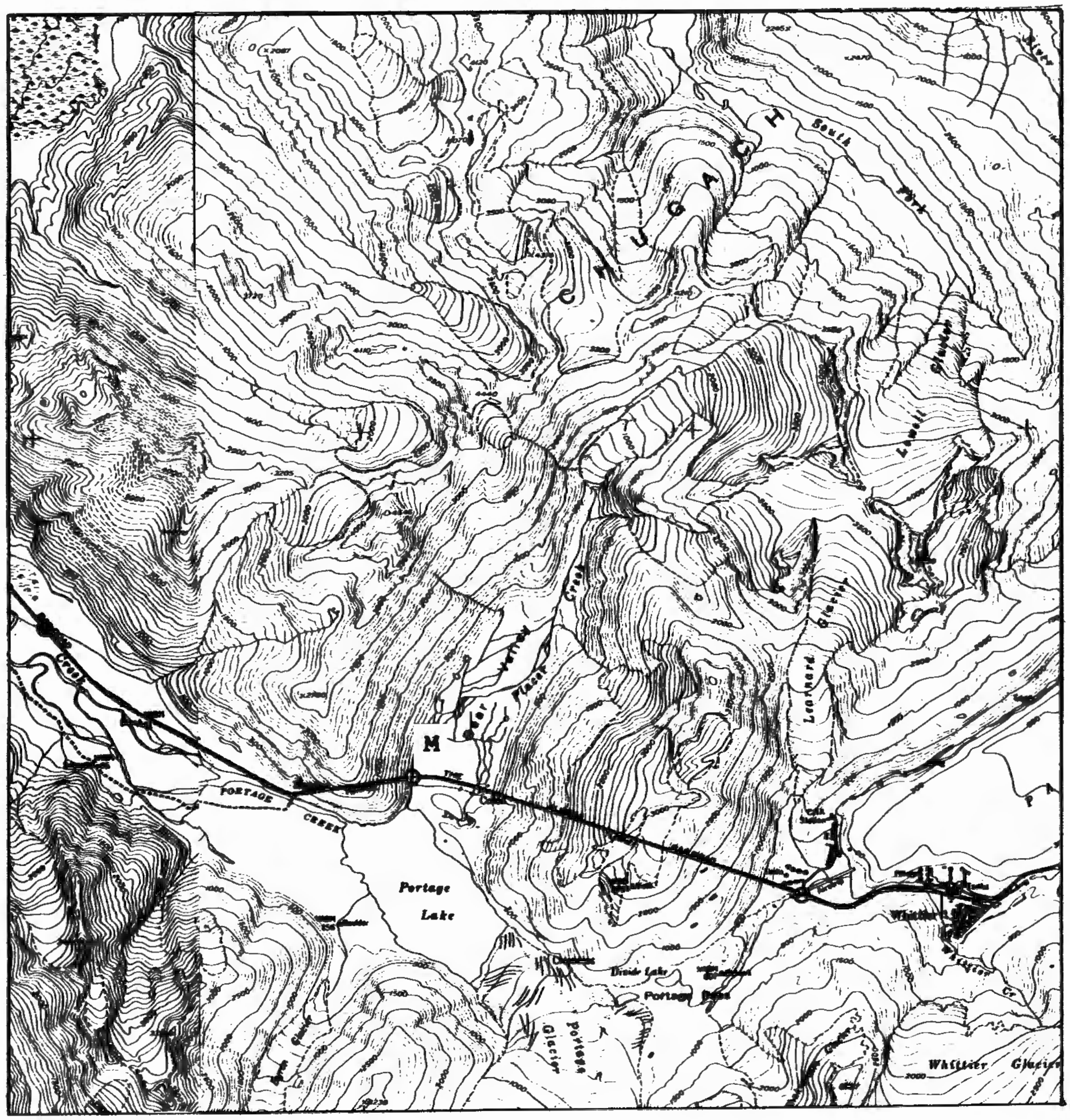

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Figure 17 cont.

Matchline pg. 66

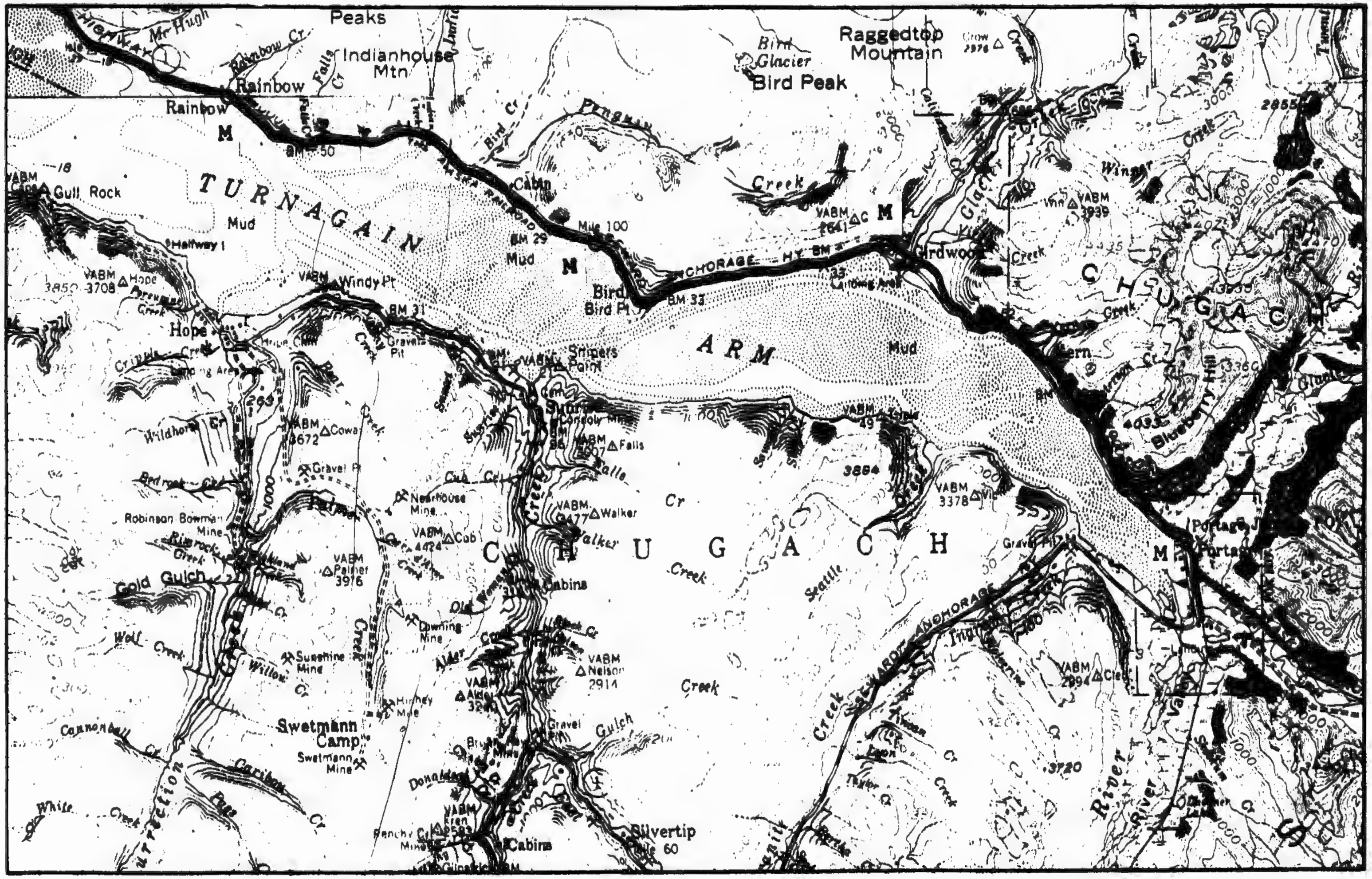

Figure 18. Continuation of Route of Alaska railroad from Portage to Moose Creek and Nancy. (After McCullogh & Bonilla)

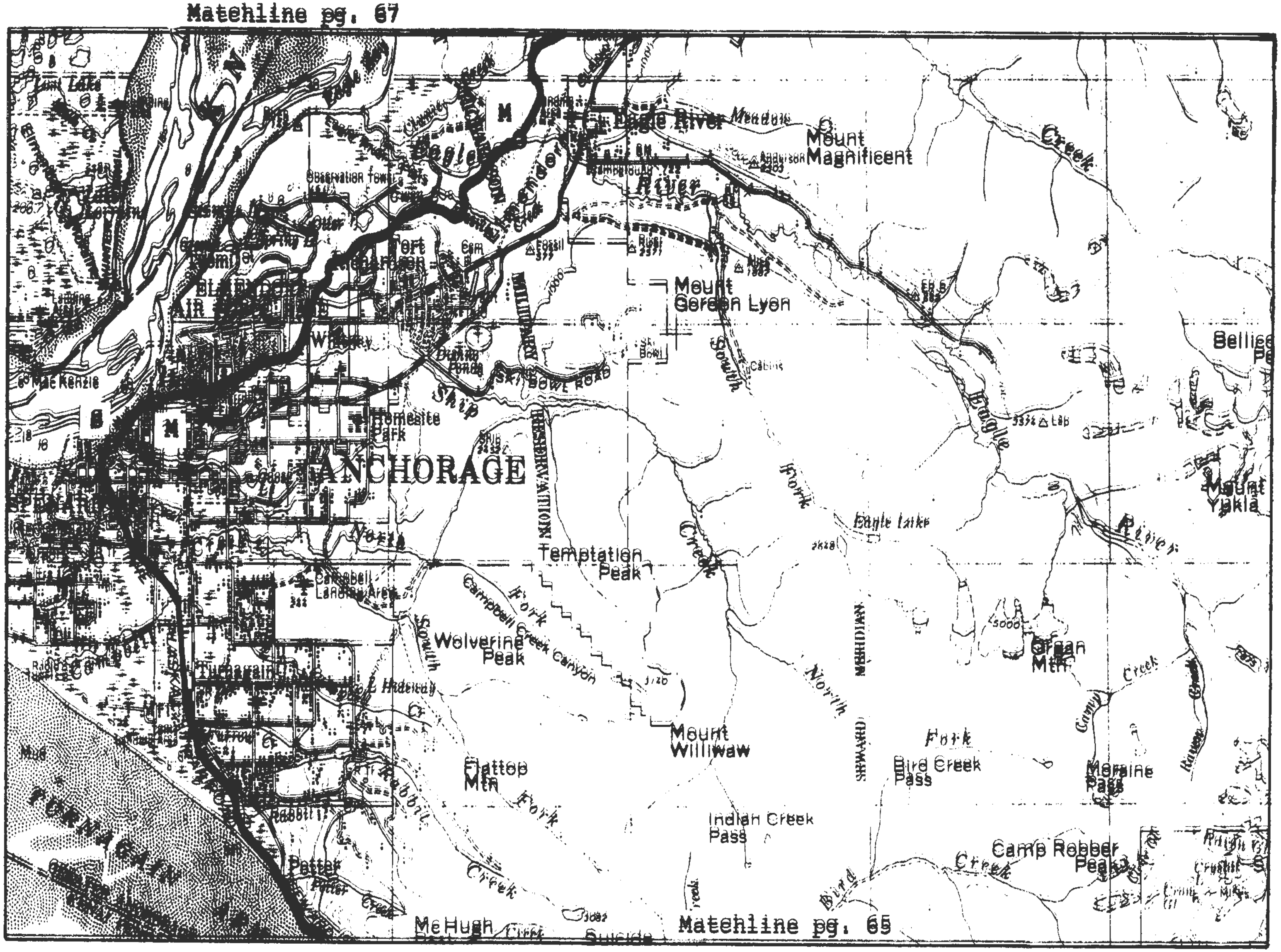

Figure 18 cont.

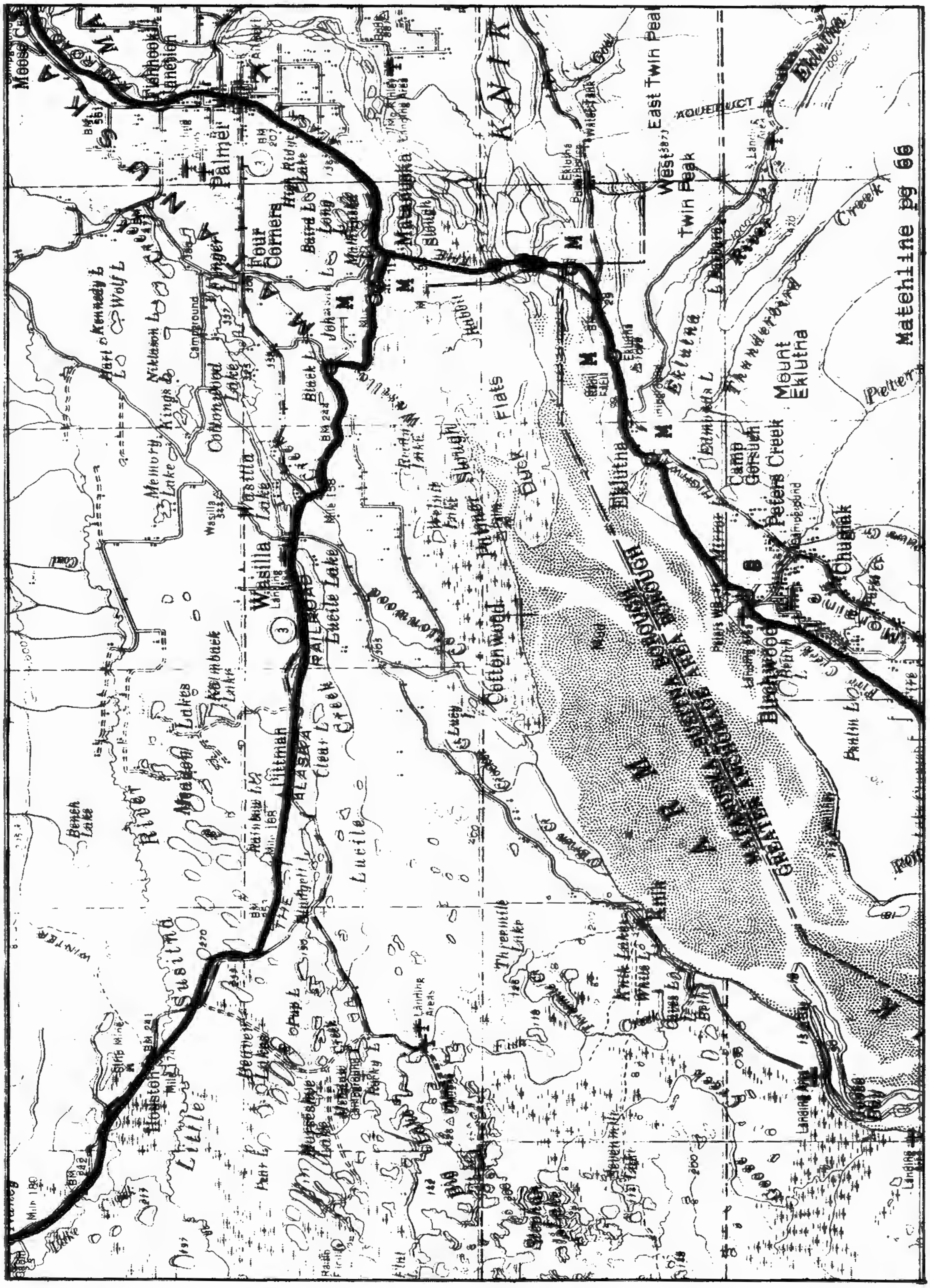

Figure 18 cont.

At Potter Hill a major slide occurred carrying disintegrating blocks of earth, track, and ties as much as 140 feet horizontally. Along Turnagain Arm, waves eroded the railroad embankment which had been lowered due to tectonic subsidence. In Anchorage several shop and office buildings of the Alaska Railroad were damaged.

In summary, more than 100 miles of roadbed settled or was displaced and broken by ground cracks in areas underlain by unconsolidated settlements. Approximately 70 bridges and numerous culverts were damaged or destroyed. Landslides carried away or overran several miles of roadbed and tectonic subsidence lowered the land as much as 5 1/2 feet and made about 35 miles along the shore of Turnagain Arm susceptable to flooding at high tide.

The Alaska railroad was the principle means of transshipping sea cargo from the ports of Seward to Anchorage and Fairbanks. Before the earthquake Seward was considered to be the major port for sea traffic because of its ice free condition. After the earthquake icebreakers were able to reach Anchorage all year around and Seward became a secondary port compared to Anchorage or Whittier. The Alaska Railroad suffered economically.

At the time of the earthquake (Friday), communication between points of the railroad was cut off. On Saturday helicopters and airplanes were used to survey the railroad and determine the amount of damage. Using emergency power, communications were established from Anchorage to mile 92 via a microwave system. By Sunday night communications were operational to Portage and by March 30, communications were carried all the way to Seward. On April 6, the first freight train moved north from Anchorage to Fairbanks by means of temporary repairs to the railroad system. (reference 28 p. D4). Service was also soon restored from Anchorage to Whittier. Services to Seward awaited a major reconstruction of the port facilities which had been destroyed by the earthquake.

B. Alaska Highway System

All the major highways and most secondary roads were impaired. 141 of 204 bridges were damaged, 92 of which were severely damaged or destroyed. 186 miles of roadway were damaged, 83 miles of which were so severely damaged that replacement or relocation was required.

The earthquake caused damage to the roadway and bridges by seismic shaking, compaction of fills, lateral displacement of the roadway and bridges, inundation by sea waves, and avalanches. R. Kachadoorian has tabulated the damage to bridge approaches and bridges along the highway system in a U.S.G.S. report (reference 25). Figures 19 through 24 are taken from his report, and locates those bridges having severe, moderate, or slight damage. Another summary of bridge damage is given by G. A. Ross, H. B. Seed, and R. R. Migliaccio in discussing the performance of highway bridge foundations in Alaska. Although highway damage was first thought to be confined to bridges, the useability of the roadway system itself was impaired because sinking of the land mass put some portions of the highway under water at high tide.

On the Anchorage-Seward Highway (Figure 19) after the earthquake there was no useable land communication route between Anchorage and Seward and between Anchorage and the Kenai Peninsula towards Seldovia and Homer. High tides threatened the highway and railway roadbed between Potter and Ingram Creek, and flooded the highway from Portage to Ingram Creek. About 24 highway bridge crossings required construction of temporary bridges to carry traffic, while 30 other bridges required light to heavy repairs. It was estimated that the temporary bridges would be needed for about five years before permanent reconstruction could be accomplished.

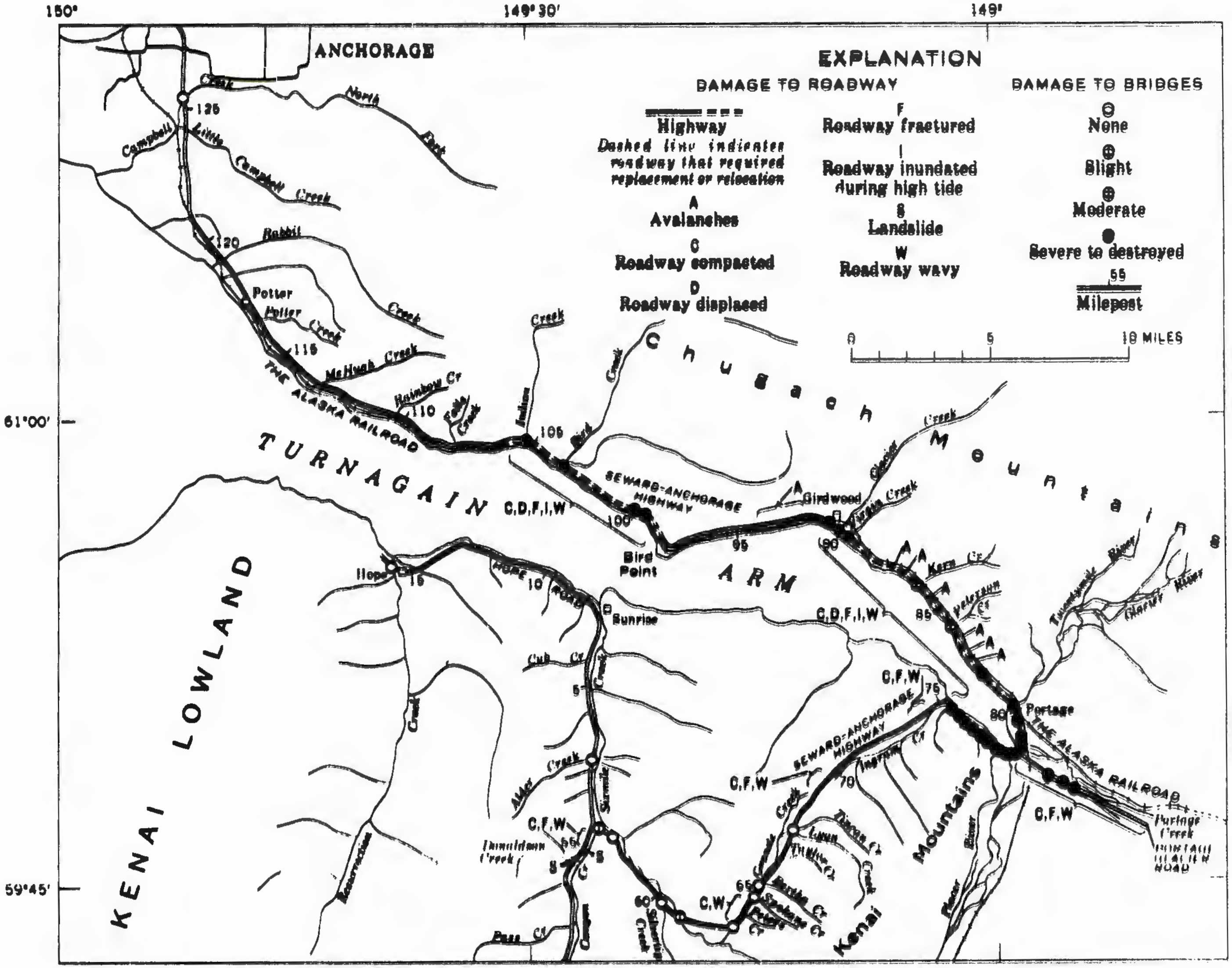

Figure 19. Damage to bridges on Seward-Anchorage Highway, Hope Road, and Portage Glacier Road. (After Kachadoorian)

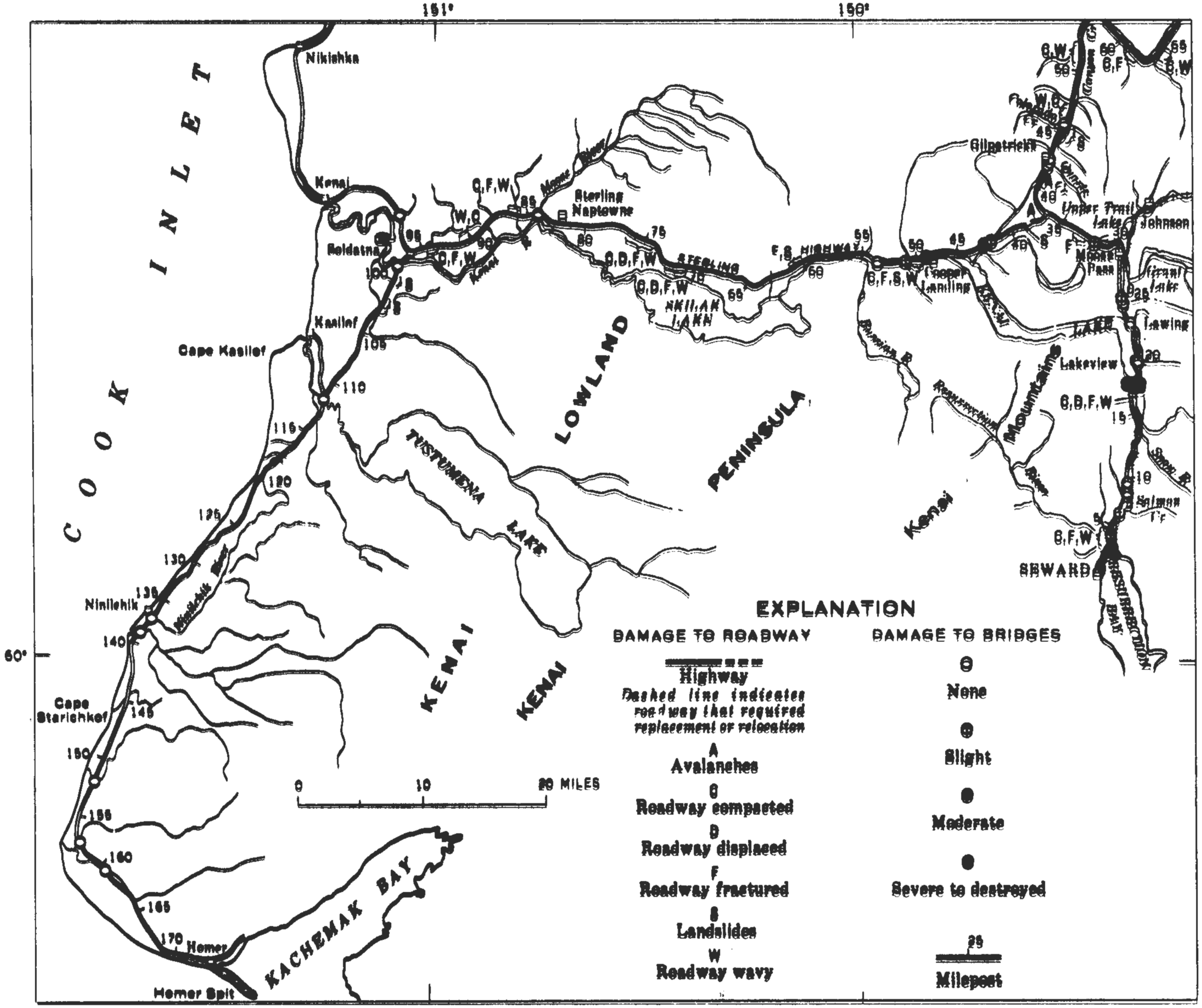

Figure 20. Damage to bridges on Sterling and Seward-Anchorage Highways. (From Kachadoorian)

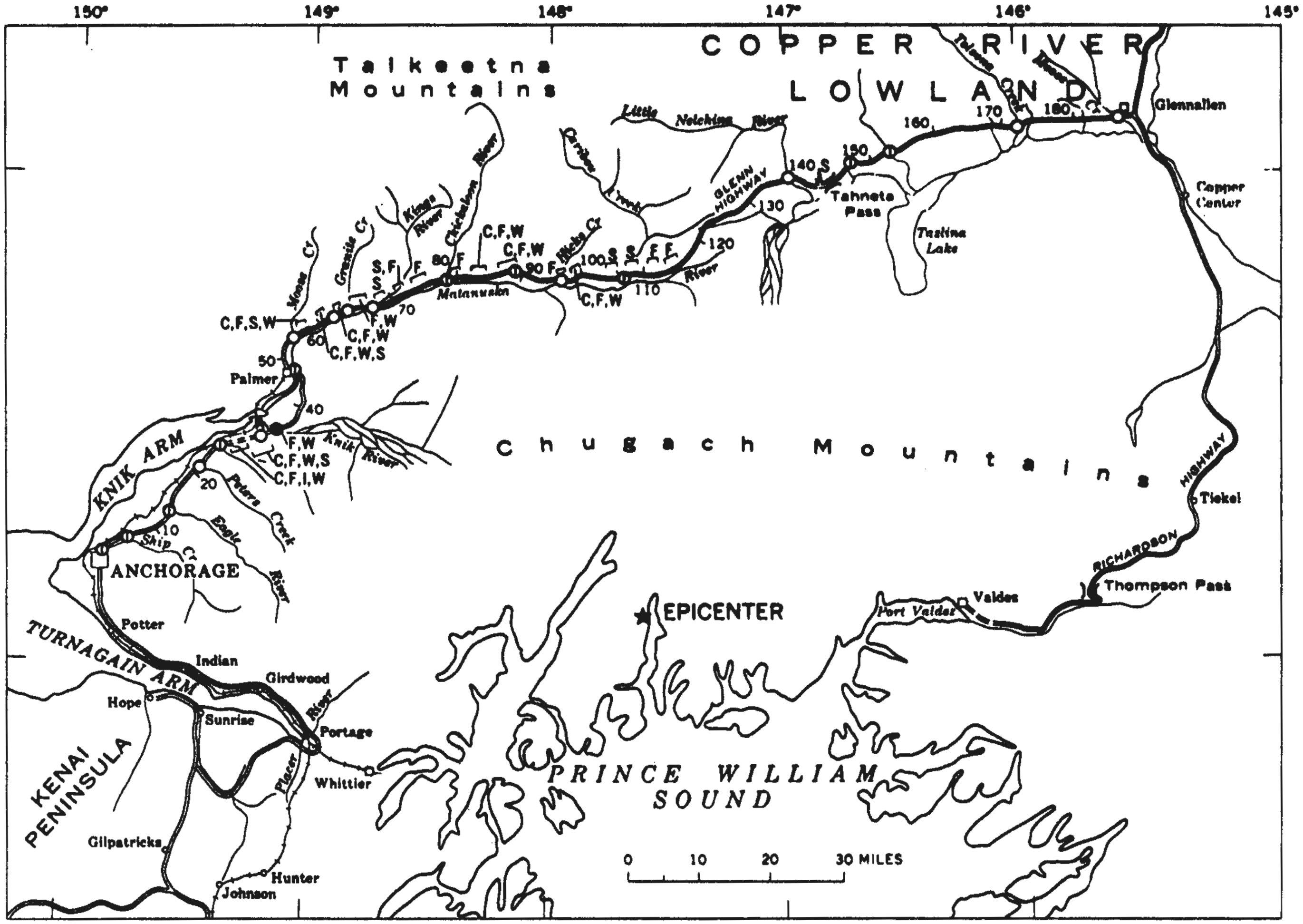

Figure 21. Damage to bridges on Glen Highway. (From Kachadoorian)

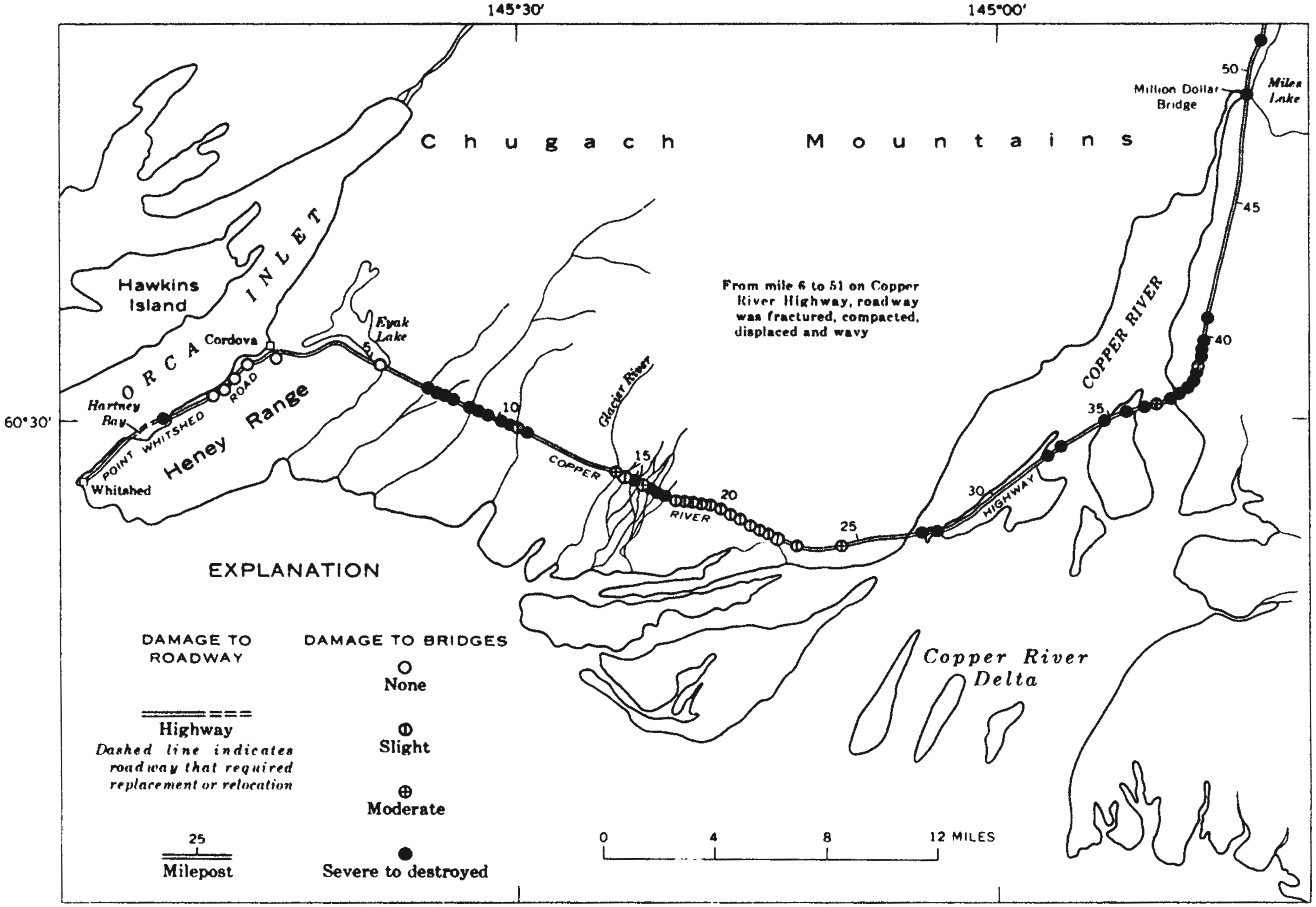

Figure 22. Damage to bridges on Copper River Highway and Point Whitshed Road. (From Kachadoorian)

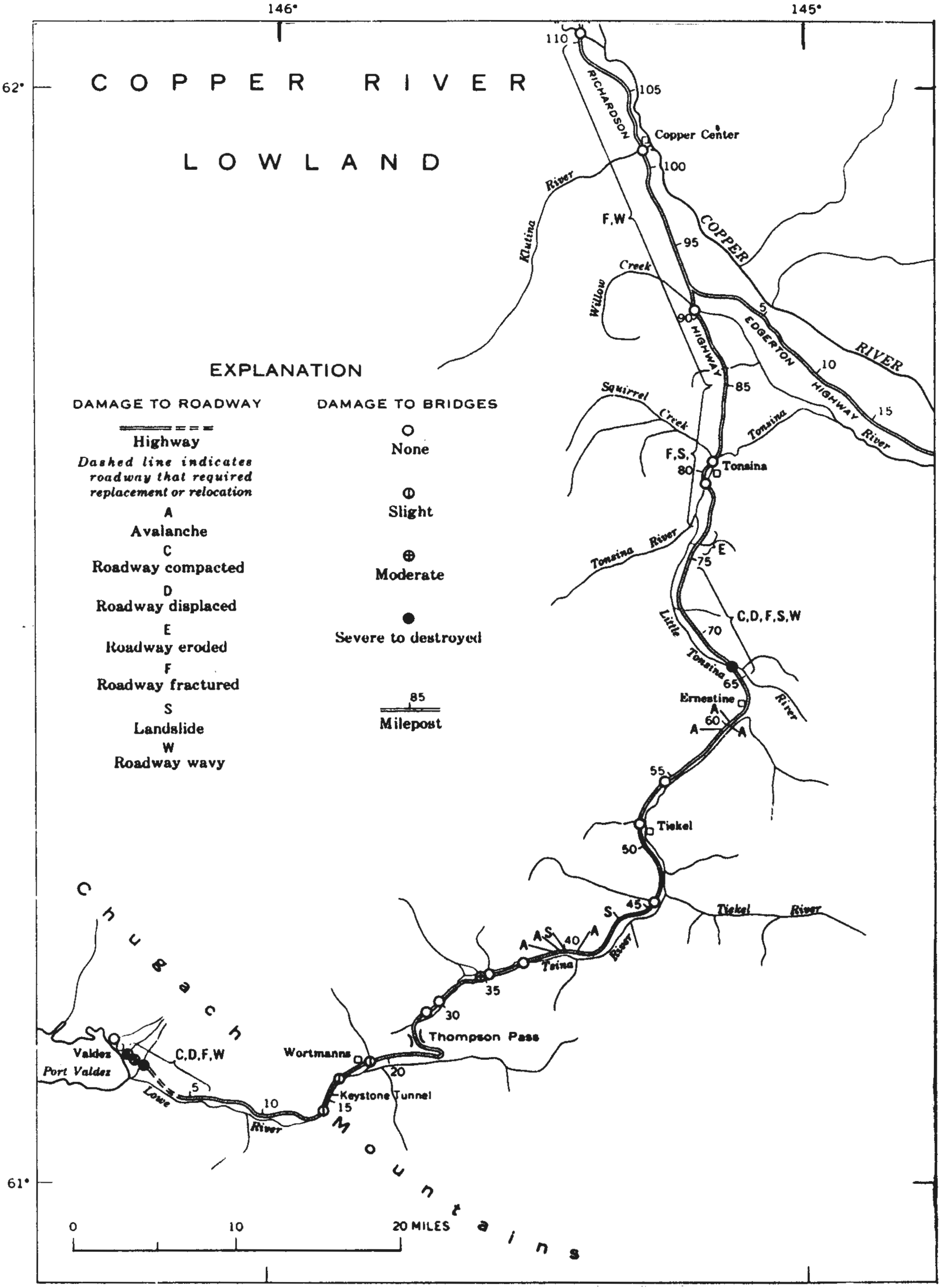

Figure 23. Damage to bridges on the Edgerton and Richardson Highways. (From Kachadoorian)

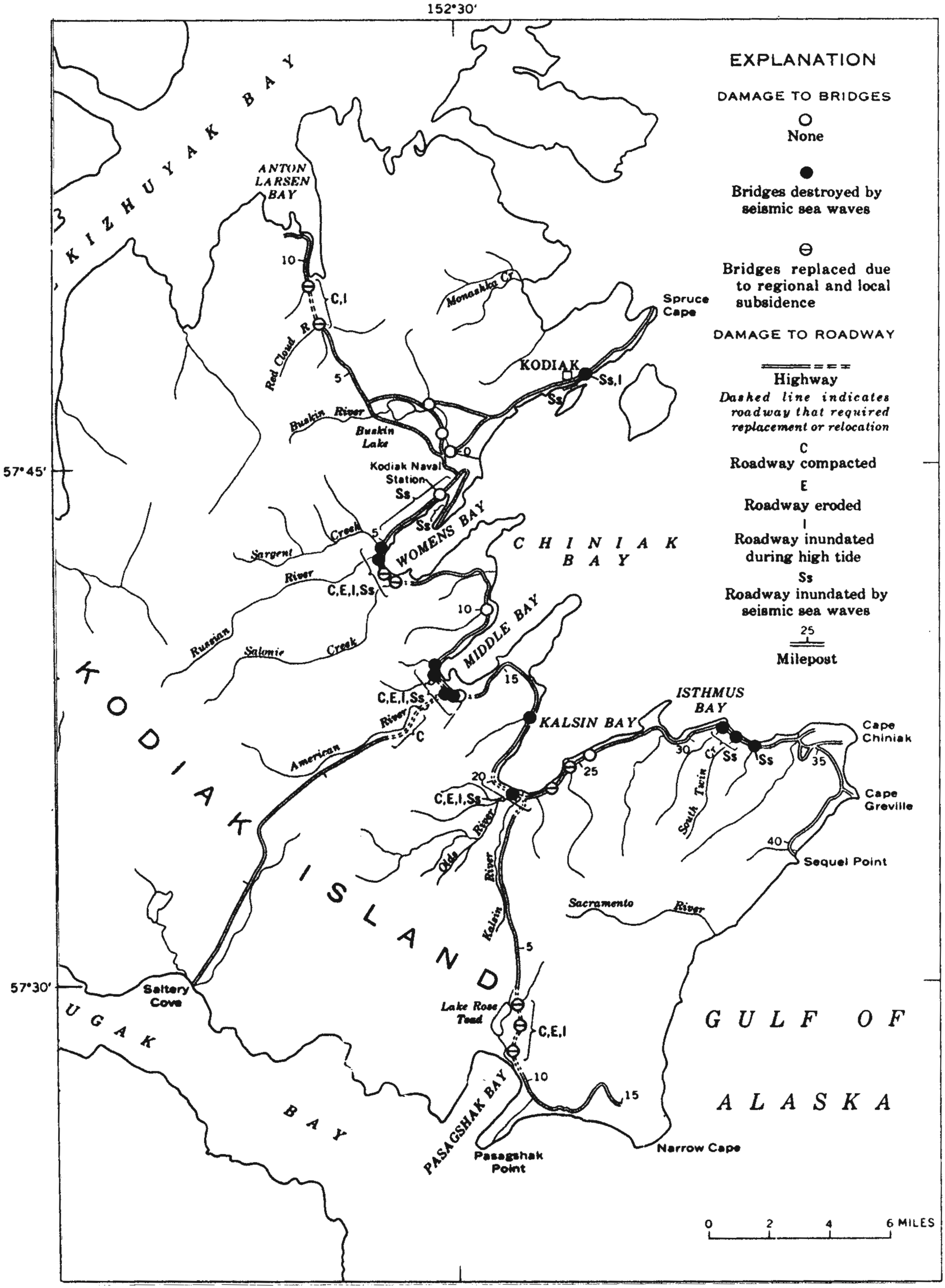

Figure 24. Damage to bridges on Kodiak Island Highways. (From Kachadoorian)

On the Sterling Highway (Figure 20) from Seward Highway to Homer - the primary bridge damage was the collapse of the bridge at Cooper Landing over the Kenai River. A temporary Bailey bridge was needed to restore traffic. On the Glen Highway - from Anchorage to the north (Figure 21) - very little damage to bridges was reported except at the Knik River Bridge located about 45 miles from Anchorage. Several piers were shifted out of line. On the 12 mile section of the Copper River Highway (Figure 22) between Cordova and the municipal airport, five of the twelve bridges needed reconstruction. Considerable damage was done to the bridges on the section of highway from the municipal airport to the Million Dollar Bridge (Figure 22). Several long spans of reconstructed railroad bridges were dropped into the river. Kachadoorian states that all the structures in this area were severely damaged and would require replacement. On the Richardson Highway (Figure 23) the bridges over Valdez glacial stream number 3 and the Little Tonsina River were severely damaged.

On Kodiak Island (Figure 24) there is a state road on the secondary system from Kodiak to Chiniak Point. Where this road crossed the heads of the various bays, the earth fills and bridge structures were carried away by the tide.

There was considerable damage to the streets of Anchorage due to the formation of deep fissures and because of subsidence up to 10 feet.

The Million Dollar Bridge - a landmark which had withstood the ravishes of glacial ice, cyclonic winds, and numerous earthquakes for 50 years - was severely damaged with one of its four spans falling into the river.

The area of major damage was confined to south central Alaska except for a single damaged bridge at Klawock in the southeastern Alaska panhandle.

The types of bridge damage in the Anchorage district included sheared or bent anchorage bolts, concrete piers broken at ground line, roadway slabs torn loose from stringers, broken sole plate welds, displaced piers, split piles, broken abutment backwalls, settlement of fills behind abutments, and tilted rockers. At Turnagain Arm on the Anchorage-Seward highway all bridges sustained shortening, closure of expansion devices, crowding of abutments up to 6 feet, and settlement of approach fills as much as 3 feet. The heavy concrete spans were either displaced horizontally or dropped to the ground. For concrete slabs on steel stringers resting on concrete piers anchor bolts were sheared, rockers were tilted, and sole plates were torn loose, but these bridges still remained in service.

One can generally state that where the bridges were located on or very near bedrock, little or no damage was experienced compared to the damage for bridges built on sedementary deposits.

As far as the transportation system was concerned, immediately after the earthquake the first need was to give aid to people stranded on the highways or surging onto the roads in panic from the damaged communities. Highway maintenance camps found themselves caring for stranded, homeless, hungry, and thirsty people. The 27-mile camp above Valdez sheltered more than 300 people. Camp Silvertip on the Seward highway also housed stranded motorists. The Alaska State Civil Defense headquarters in Anchorage established a warning network by radio. They also set out warning flares and markers at the most severely damaged sections of the roadway, and placed barricades where roads were impassable.

The next objective was to restore traffic service to communities which were isolated. Temporary Bailey bridges were installed and temporary road repairs were accomplished with the use of local material and available equipment. Forces of the

Alaskan Command assisted the highway department in clearing slides, erecting temporary Bailey bridges and evacuating the homeless. Light traffic was restored between Seward and the rest of the Kenai Peninsula within two weeks after the earthquake. By early summer 1964, all damaged routes were passable with the exception of the Copper River highway between the Copper River and the Million Dollar Bridge. Permanent reconstruction was started one year later. In the meantime it was possible to observe the latent effects from frozen ground conditions when the surrounding soil had thawed and the drifted snow had melted. Breaks in foundation piling were not apparent as long as the pilings remained in frozen soil.

C. Airports in Alaska

The one system of transportation that was immediately operational after the earthquake was the vital air transportation system in Alaska, and thanks to the ingenuity of its personnel, this system did not fail to perform its function. Damage occurred to nearly every airport, both civilian and military, in south central Alaska, yet airborne planes were brought down safely while planes on the ground were made ready for takeoff and reconnaissance. Very few planes on the ground were damaged by the quake.

At Anchorage International Airport the control tower collapsed, killing one operator. The top floors fell to earth as some of the nonseismically designed column connections failed.* Immediately after the quake radio equipment installed in a flight check aircraft on the ramp of the airport was used to control planes in the traffic pattern above Anchorage.

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* At the time of design the tower was in earthquake zone 2, which did not require a seismic analysis. M.S. Sozen and N.N. Neilsen report that ground motion having only 0.2 g maximum acceleration would have been sufficient to collapse the tower.

International frequencies were installed in the adjacent Lake Hood seaplane base control tower, about 5/8 of a mile away. Later additional frequencies were installed at the Lake Hood tower, which continued to control Anchorage International traffic until a new tower was commissioned in April, 1965.

Fuel tanks and fuel lines ruptured causing a severe fire hazard at the airport. About 100 five-gallon cans of foam were used to prevent ignition of the leaking fuel.

Within the city limits of Anchorage is Merrill Field, which normally provided service for the majority of wheel equipped small aircraft in the Anchorage area. The F.A.A. communication center at Merrill became inoperable because of power outages in the greater Anchorage area, although otherwise the facility was undamaged.

To the northeast of Anchorage lies Elmendorf Air Force Base. Structural damage was sustained by its control tower, however, this airfield remained operational even during the initial shaking and violent swaying of the control tower. The control tower operator still maintained radio contact during that time. After the shaking had subsided, control was transferred to facilities installed in a parked aircraft for a period of two days until a mobile control tower could be flown in from Tinker Air Force Base, Oklahoma. Later communication equipment was installed in an old tower on the roof of a hanger, which continued its operation until a new reinforced concrete tower was commissioned June 28, 1967. Because Elmendorf was the only airfield in the Anchorage area capable of accommodating jet aircraft, both commercial and military aircraft used that airfield until Anchorage International was able to provide partial services.

Bryant Army Airfield at Fort Richardson was the only major airfield in the Anchorage area that was fully operational immediately after the earthquake. Radio equipped taxi units were deployed to establish a communication network between Elmendorf and Fort Richardson. From Fort Richardson the 56th Military Police Company used a radio in a squad car to establish a communication link between the post and the city of Anchorage.

At several major airports, especially near tidal water, runways were partially inundated due to tectonic subsidence. This occurred at Seward, Seldovia, Valdez, Whittier, and Kodiak Naval Station. At Seward the south end of both runways were flooded at high tide. In addition, the control tower was damaged by the tsunami, but communications were established by noon of March 28, operating on a battery system. The tsunami also washed all the gravel surface from the runways and deposited silt and debris. At Seldovia 500 feet of a 2,200 foot runway was submerged at its southern end. The seaplane base at Seldovia, consisting of a float at the end of a dock in the small harbor, was swept away by the tsunami. At Valdez the west end of the runway was extensively fissured, some 48" wide. Temporary repairs were made by filling in the fissures with pit run gravel, and within two days the field was totally operational. The Cordova Municipal Airport was only slightly damaged, with the airstrip needing regrading and resurfacing. At Kodiak Municipal Airfield operations continued despite damage, but the Kodiak seaplane base and all its facilities were destroyed by the tsunami.

Initially air transportation was used to survey damage, establish communications between striken communities, and to furnish the requirements of disaster relief. Aircraft equipped with aerial photographic equipment provided the first concrete information on overall damage. Emergency supplies and specialized personnel to satisfy immediate needs were airlifted to Alaska from all parts of the United States. While the Civil Air Patrol flew rescue missions, the military installations and Civil Defense Headquarters moved to provide a massive transportation airlift of food, potable water, communications equipment, emergency power supplies, technical services, warm clothing, construction equipment, hospital units, and rehabilitation teams. Meanwhile within 16 hours after the earthquake, Fort Richardson was operating field mess halls for the people of Anchorage, serving C-rations, soup and coffee. The assistance provided by the military is well documented by T. L. Gardner and M. J. McMahon.

D. Harbor and Waterfront Facilities.

The major ports damaged by the earthquake were Anchorage, Cordova, Homer, Kodiak, Seldovia, Seward, Whittier, and Valdez. Kodiak, Seldovia, and Cordova were isolated and served only by limited local roads, while the remaining ports were part of the Alaska Highway or Alaska Railroad systems.

Figure 25 shows a plan of the waterfront facilities in Anchorage. The Ocean dock was almost completely destroyed as were the railroad facilities on it. There was considerable heaving and lateral breakage on the approach, and the entire deck was made uneven with large fractures. All the piling canted seaward. Eventually this dock was demolished. The City dock sustained damage to its pile caps. Batter piles were deformed, and the pier was displaced in translation and rotation. Fuel storage tanks on the dock were also damaged to the extent that they leaked gasoline. Piles were sheared at the weld splices. This dock was repaired. The Permanente dock suffered minor damage when a cement bin collapsed on it. The Asphalt and Anderson docks were undamaged, while the only damage to the Alagco dock was caused by a crane tipping over it.

Cordova had a partially protected harbor at Orca Inlet. Damage here occurred due to tectonic uplift and from the tsunami.

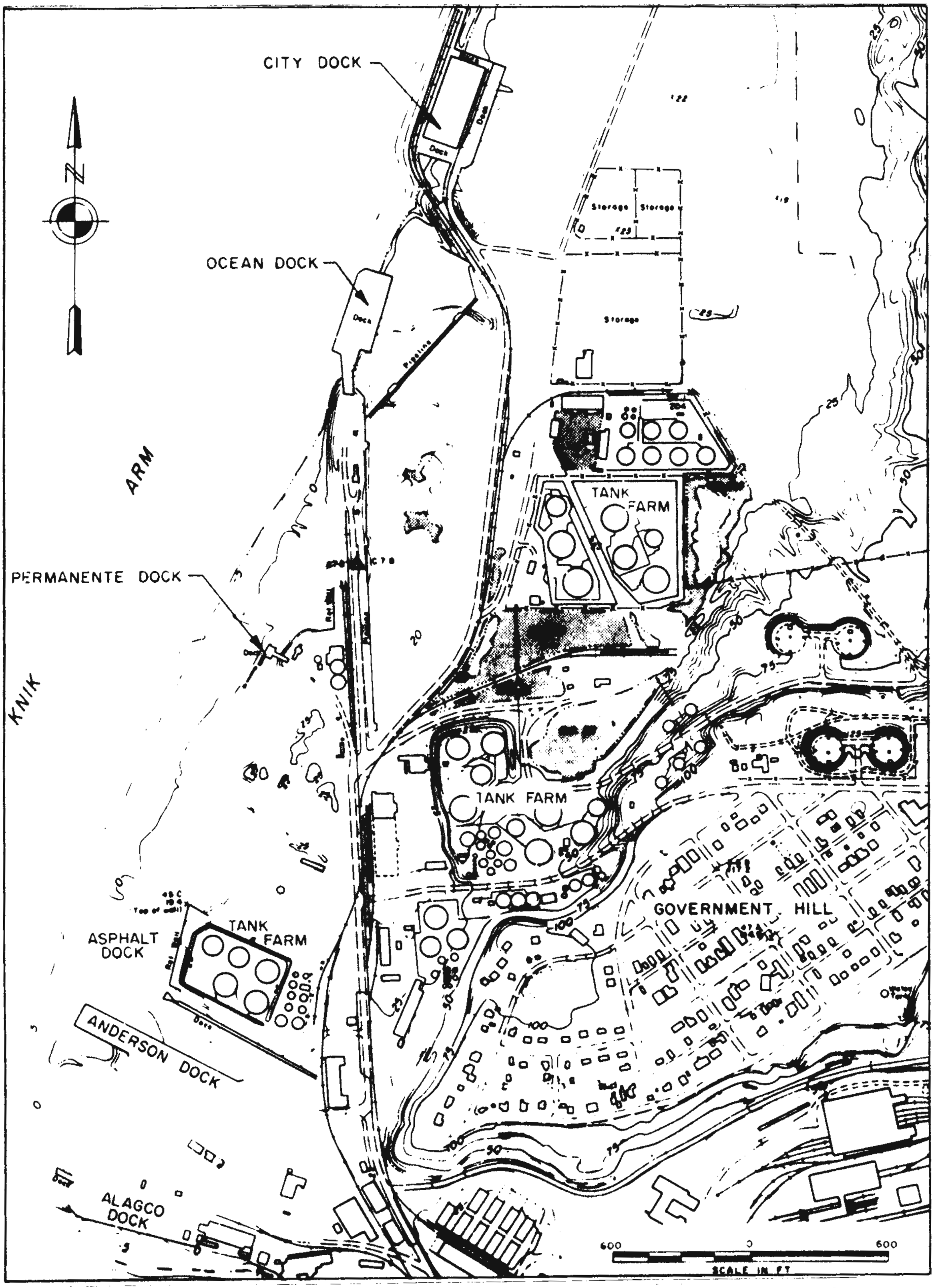

Figure 25. Anchorage waterfront facilities. (From Arno and McKinney)

No slides or fires occurred. When the tsunami arrived, the water rose above the deck of both the City dock and the Ferry dock, pulling pile caps loose from drift pins and allowing many pile caps to be dislocated. The damage was repaired. Deep water vessels have used the port since the time of the earthquake.

At the port of Homer is a long narrow finger of land known as a spit. The tip of the spit supported canneries, motels, restaurants, and the waterfront facilities (a small boat basin and a City dock). There was little damage to the City dock, but the small boat basin was extensively damaged, and the small boats that anchored there before the earthquake moved to other locations until Homer Spit, partly inundated at high tide because of subsidence, was reconstructed. The spit subsided 2-3 feet. Until reconstruction, Homer's economy came to a standstill.

At Kodiak Harbor the mooring facility for the small boat basin and the built-up waterfront housing a City dock were either destroyed or damaged extensively by the tsunami. Even the breakwater armor stones were displaced by the water waves. Damage to Kodiak occurred in three states; (1) earthquake, (2) tsunami, and (3) a windstorm several days later. Three canneries were lost, the workhouse and harbor master building were missing; numerous piers, piles, anchors and lines were lost.

At Seldovia subsidence of 3.5 feet left the dock boardwalk inundated at high tide. The inner harbor facilities were also damaged by the tsunami. The City dock was raised 5 feet in reconstruction, and the small boat basin was repaired and the breakwaters raised to protect the small boats.

Seward's waterfront was highly developed with railroad marshaling yards, several wharfs, petroleum product unloading docks, a cannery dock, and a small boat basin. All Seward's port facilities were destroyed by submarine slides, giant waves, and fire. The port was cut off for some days from all means of communication and transportation except radio and air travel.

Because of unstable soil conditions the port was rebuilt at the mouth of Resurrection River, north of the main town. The original site was made into a park.

The port of Whittier, although close to the epicenter, did not sustain severe damage from the shaking of the ground by the earthquake, but a submarine slide and a tsunami extensively damaged the waterfront facilities. The whole area subsided 3.5 feet. Oil storage tanks were damaged and the oil caught fire. Because most of the military supplies for Alaska had been carried through Whittier, immediate measures were taken to restore the operation of this ice free port.

A large submarine slide destroyed the waterfront facilities at Valdez. Shipping was the main industry. The harbor consisted of two wharves for large steamers, dry storage and petroleum storage facilities, and canneries. Thirty lives were lost, as people at the waterfront were helping unload cargo from a ship. The landslide carried away the docks while waves, as much as 30 feet high, surged into town. Almost every structure in Valdez was damaged. The site of Valdez was abandoned and the town was reconstructed in a less dangerous site, Mineral Creek, where in its new setting Valdez could be better protected from landslides by a series of bedrock hills.

7. Kern County Earthquake - July 21, 1952. Intensity XI.

At 4:52 a.m. the main shock (7.7 magnitude) of a series of shocks occurred in Kern County, California (Figure 26). The shock originated along the White Wolf fault, a relatively short fault at 90° to the San Andreas fault. This earthquake resulted in the partial collapse of several Southern Pacific Railroad tunnels near the town of Calienti. Landslides and rockfalls also blocked the roads to Tehachapi.

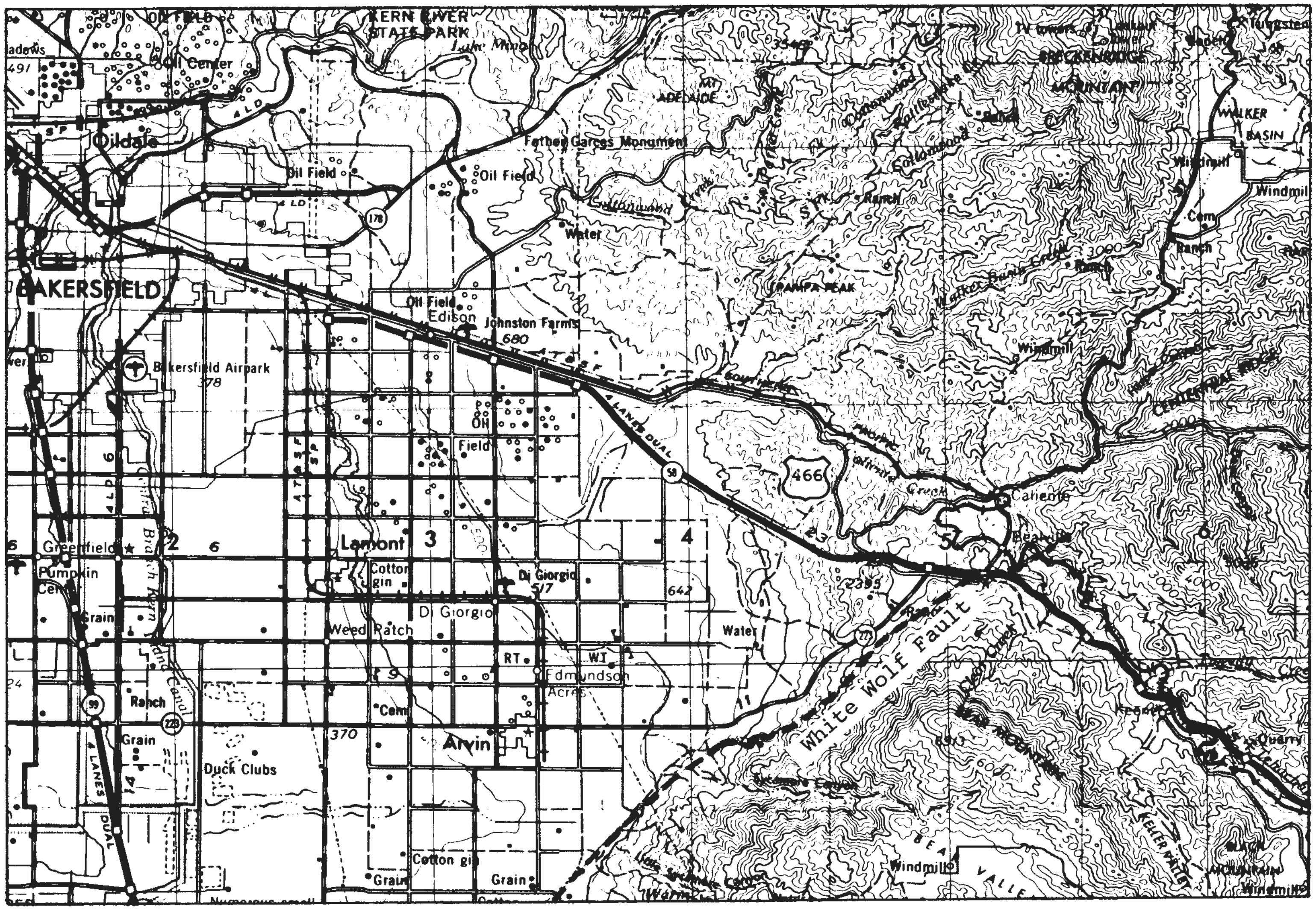

Figure 26. Route of Southern Pacific Railroad in Kern County, California.

The northbound lane of Highway 99 suffered minor slumping about 10 miles south of Bakersfield. Also the paved highway (223) from Arvin northeast to Highway 466 suffered damage chiefly due to slumping, Highway 466 was badly cracked in the vicinity of the Bealville turnoff. (Figure 27) The most spectacular damage was to the railroad tunnels. In tunnel 3 the walls of the tunnel were cracked, broken, and forced inward; constricting the tunnel as though the rock had moved inward into the only space available. The distance between the two walls in one place was reduced to 9.3 ft. from an original 15 ft. The railroad track was compressed into an S curve, the force of compression thrusting one curve of the S under the base of the concrete lining of the tunnel.

The sharpest break occurred in curved tunnel 4, which was within 100 ft. of the fault. The southeast side was lowered 3 1/3 ft. breaking the lining and moving it northward about 2 ft. Rails east of the break were left unsupported for some distance.

Tunnel 5, about 1,200 ft. long, suffered the most damage. The tunnel was caved in at two points; one about 500 ft. from the south portal and the other about 200 ft. from the north portal. Near the south portal the walls were broken inward in several places. (Reference 15)

Tunnel 6 was moved horizontally. (Reference 15)

Because of the severity of damage it was necessary to eventually daylight a portion of tunnel 3 and all of tunnels 4 and 6. Tunnel 5 was bypassed with a temporary track while it was repaired.

The tunnels in the area were lined with steel-reinforced concrete walls from 12 to 24 inches thick. Large slabs of concrete that were held in place by reinforcing after the main shock broke loose in aftershocks. Between Bakersfield and Mohave boulders and large rock masses slumped onto the tracks

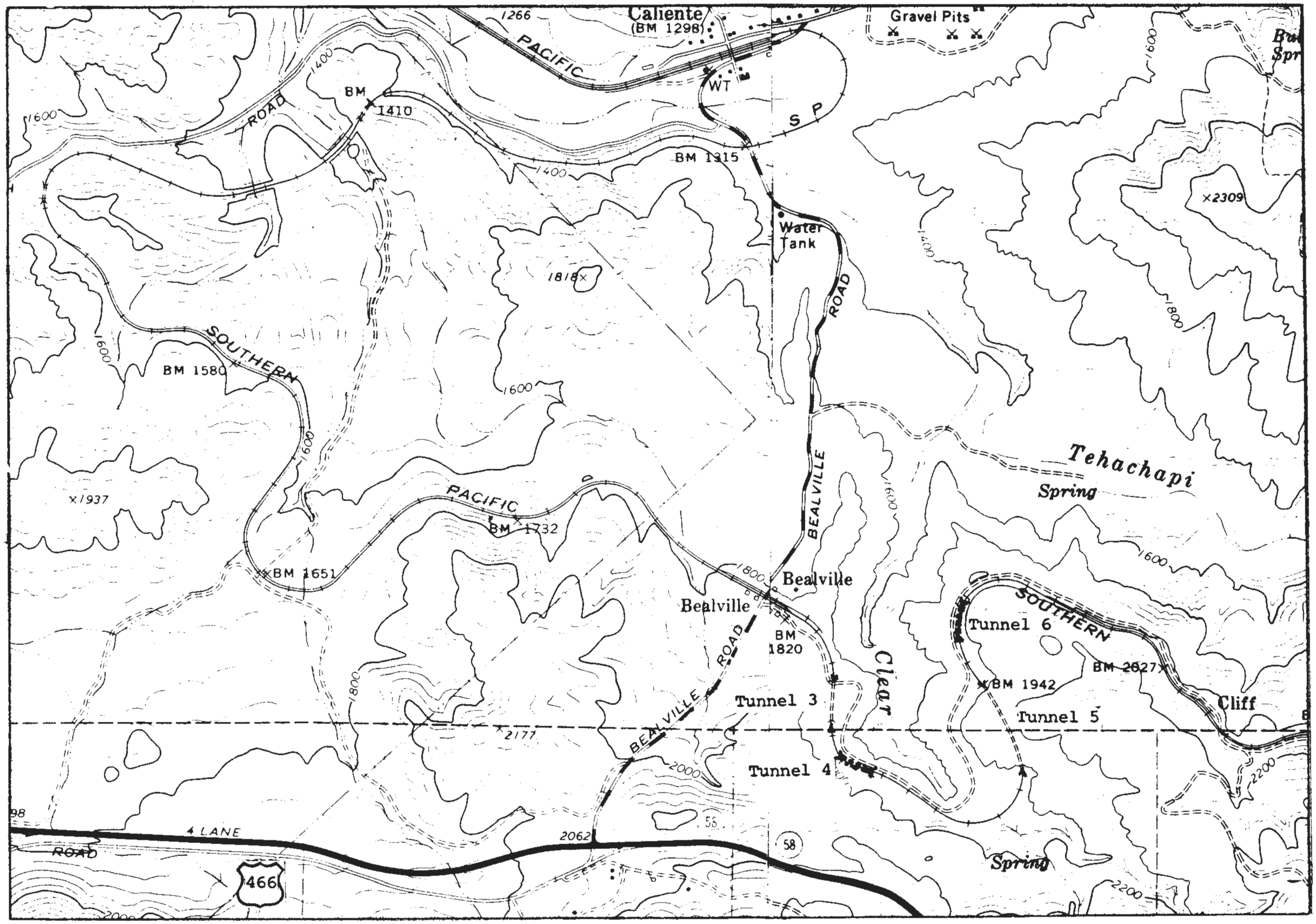

Figure 27. Location of tunnels damaged in Kern County earthquake. (After Jenkins and Oakeshott)

so that most of the track had to be straightened, leveled, and cleared. Traffic on the line was suspended for 25 days.

Figure 28 shows the isoseismal contours for the area (Reference 22). Although one isoseismal VIII-XI surrounds the area near Bakersfield, the XI affects were observed only in a small area at the location of the above mentioned tunnels.

8. Hebgen Lake Earthquake - August 17, 1959. Intensity X.

Slides during earthquakes in mountain areas produce a formidable danger to the highway or railroad system, especially since the network of roads in the system is sparse. If the Hebgen Lake earthquake had occurred in an uninhabited non-mountainous region, this 7.1 magnitude earthquake would have had only mild coverage by the press. Steinbrugge and Cloud's (1962) base isoseismal map, Figure 29, gives the highest intensity of only VI; the higher epicentral ratings which occurred in very small areas are shown in Figure 30. Maximum intensity based on vibrational effects were a weak VIII; however, the nonvibrational spectacular effects such as faulting and the huge landslide bring the epicentral maximum intensity to X. As pointed out by Steinbrugge and Cloud, "Structures stradling the faults or in the range of the landslides were severely damaged or destroyed as a direct result of the earthquake -- this fact the ratings point out. The ratings do not imply that intensities even a few feet away were as high." What made the earthquake a headliner was that it was centered near Yellowstone National Park and it killed 28 people (2 by falling boulders, the other 26 buried in a massive landslide).

The Hebgen Lake area, an attractive tourist site for visitors to Yellowstone National Park, has trailer parks lining Montana State Highway 287 (now Route 499). Where the highway follows the Madison River through a narrow canyon with steep

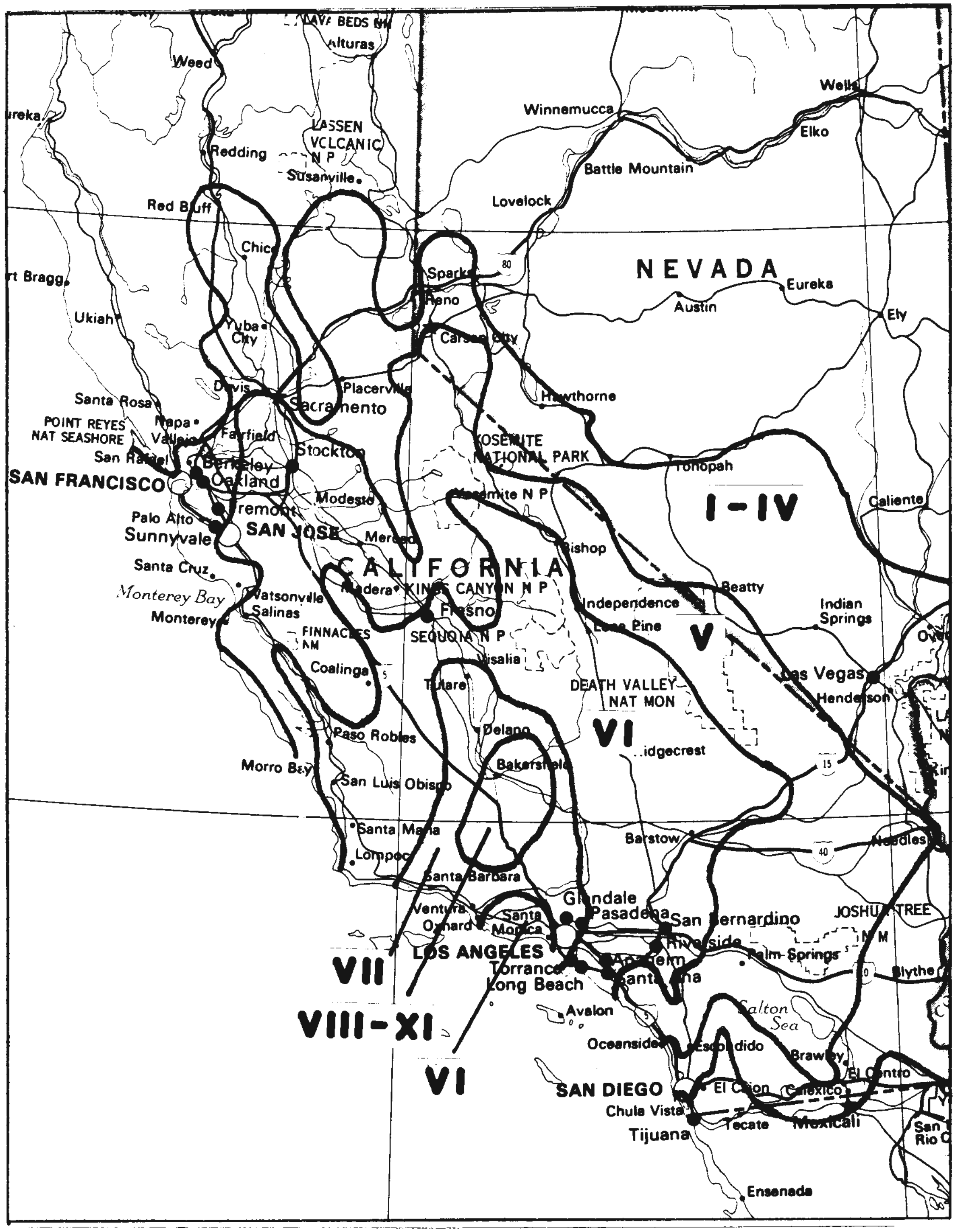

Figure 28. Isoseismal M.M. contours for Kern County earthquake. (After Hodgson, p. 58)

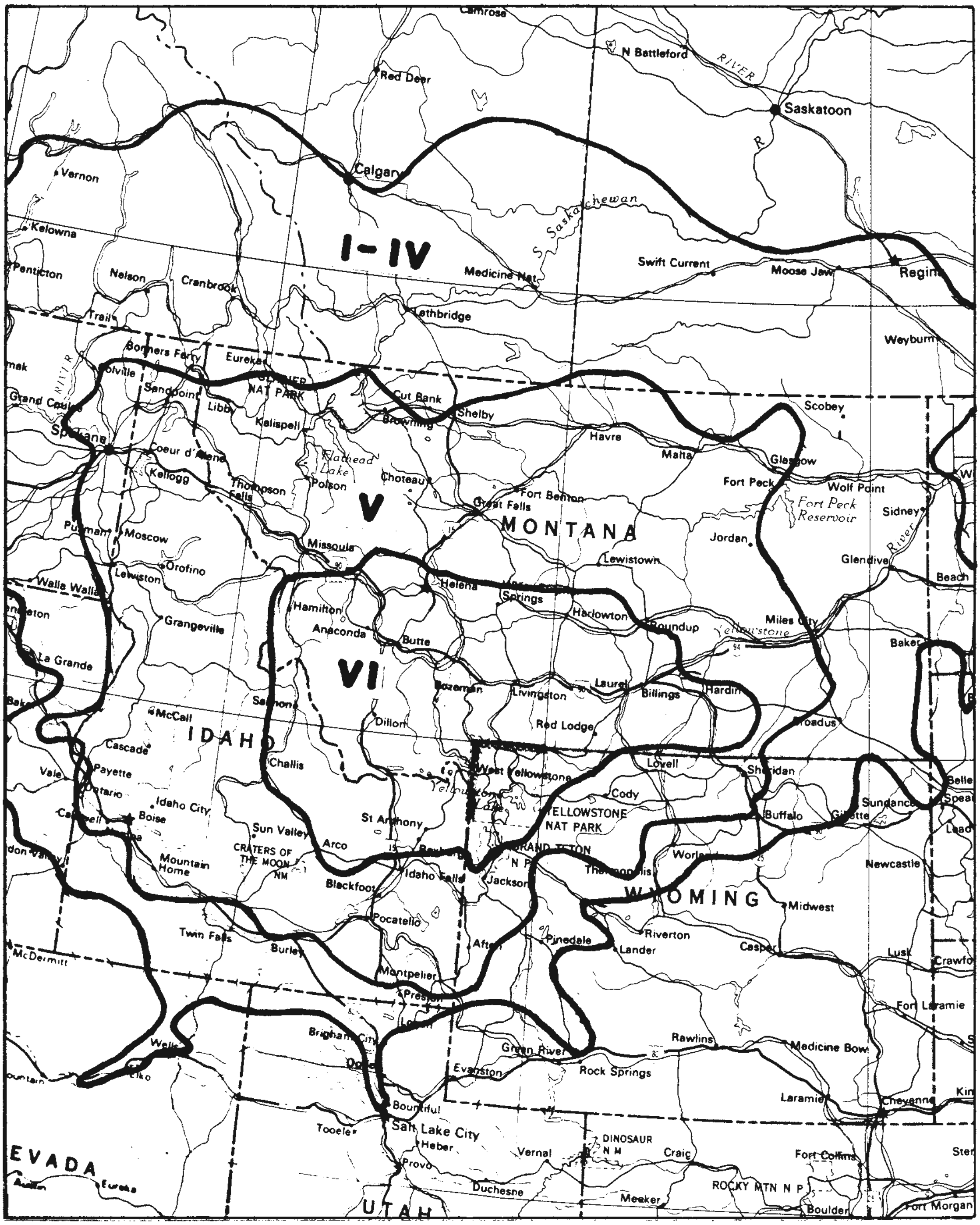

Figure 29. Isoseismal M.M. contours for Hebgen Lake.

(After Steinbrugge and Cloud)

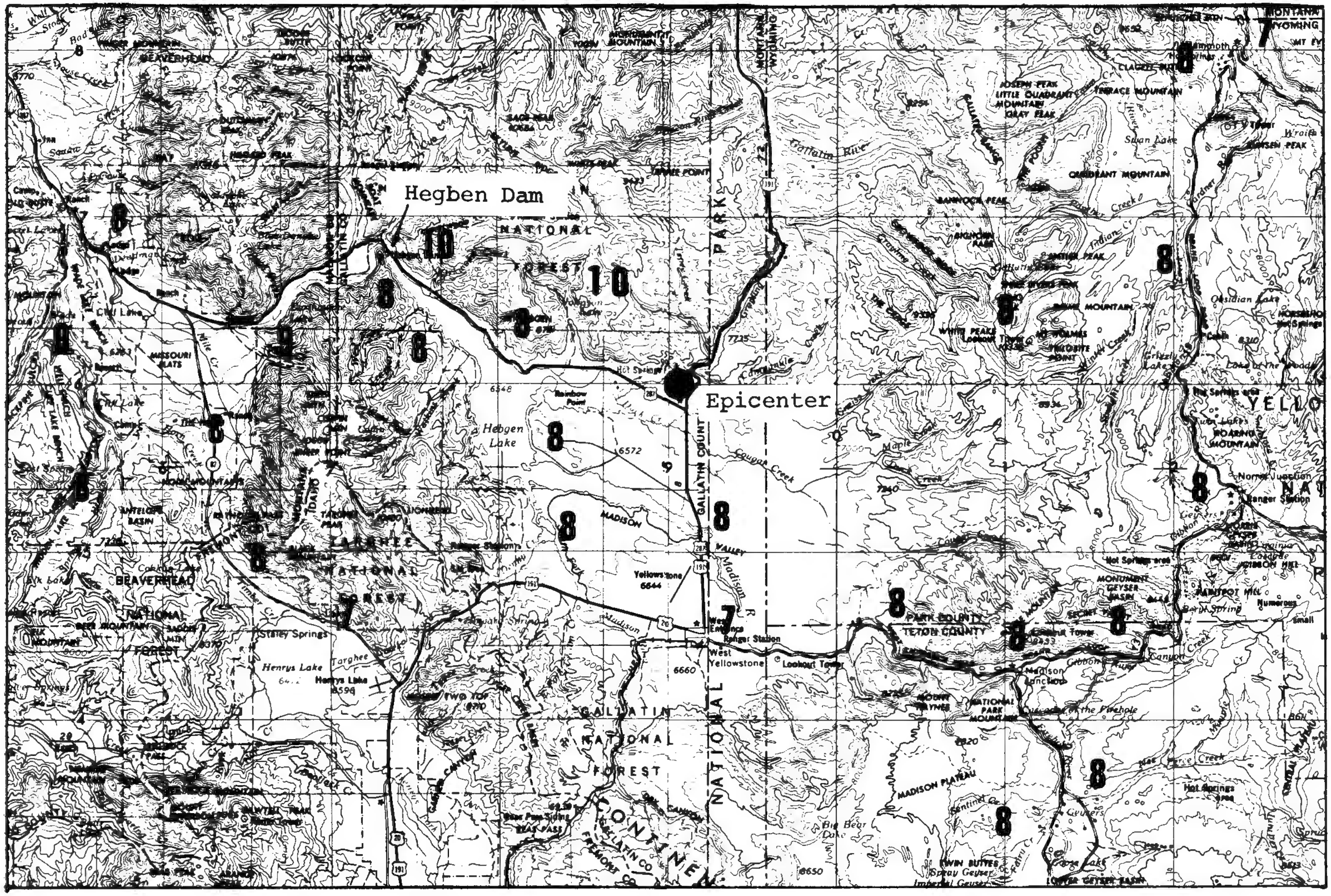

Figure 30. M.M. intensities near epicentral area of Hebgen Lake earthquake. (After Steinbrugge and Cloud)

towering walls, there are a series of campgrounds. The first shock occurred at 11:37 p.m., after most of the tourists were in bed. Irving Witkind in his report by the U.S.G.S. gives a graphic personal description of what it felt like to be in that earthquake:

> "I went to sleep about 9:30 p.m. and was awakened by the frenzied jiggling of the trailer. Things were falling from shelves all over the place. I though that the trailer had somehow come off its jacks, jumped the chocks, and was rolling down the hill. I scrambled out the front door determined to stop the trailer, no matter what, although I had no idea as to how I would go about it. When I got outside, the trailer was in place, but the trees were whipping back and forth and the leaves were rustling as if moved by a strong wind -- but there was no wind. I knew right then that it was an earthquake. I could hear avalanches in the canyons behind me, and could see high clouds of dust billow out of the canyon mouths...I decided to visit the Blarneystone Ranch and see if they needed help. I drove down the hill toward the range. About a quarter of a mile from camp I came upon a large new fault scarp that cut across and displaced my access road."

Highways in the epicentral area were damaged extensively. All roads were broken by fractures, many of which were normal to the roadway. Near their junction U.S. Highway 191 and State Highway 499 were displaced vertically as much as 5 feet by fault scarps. Several tourists tried to evacuate by driving along Highway 191 only to be stopped by the scarps. On Highway 499, a huge landslide blocked the road. Behind the landslide Earthquake Lake started to form and several motorists had to be evacuated by helicopters.

The water in Hebgen Lake oscillated for at least 12 hours after the quake, and state authorities worried that Hebgen Dam would give way, especially since the crest of the dam was submerged several times. The dam remained intact. A part of State Route 499 disappeared into Hebgen Lake during the earthquake along the north shore of the lake. The slide which created the 175 ft. deep Earthquake Lake and acted as a second dam was considered to be vulnerable to the pressure behind it. To keep the water from rising too high the Corps of Engineers constructed a 250 ft. level channel across the top of the slide to act as a spillway. Because of excessive erosion the Engineers deepened the spillway another 50 feet, reducing the danger of failure of the natural dam. In the meantime, emergency one-way roads were created around all other road obstructions in the area.

U.S. Highway 191 was closed from the time of the shock until noon of the next day (reference 37). State Route 499 was cleared for limited travel by evening of the second day; this freed all persons who had been trapped by road damage. Highway damage also occurred in Yellowstone National Park by fallen rock or rock avalanches.

Five reinforced concrete bridges in the epicentral region were reported to have suffered significant damage. All bridges were usable shortly after the earthquake, although major structural repairs were needed. (Steinbrugge and Cloud)

III. Recorded Damage in Additional Earthquakes

The following excerpts are taken from Earthquake History of the United States and United States Earthquakes; and summarizes recorded damage in a variety of earthquakes. These are mentioned in chronological order (see Tables 1 and 2). For the early earthquakes it should be remembered that the existing transportation network at the time of the quake was in its infancy.

1890 April 24. Monterey Bay Region. Intensity VII

> "The railroads were damaged through settling of ground and displacement of a bridge."

1906 May 26. Keweenaw Peninsula, Michigan. Intensity VIII

"At the Atlantic mine, rails were twisted and there was a notable sinking of the earth above the workings."

1906 July 16. Socorro, New Mexico. Intensity VII - VIII

"A train stopped about 10 miles west of Socorro, and was nearly derailed."

1918 April 21. Riverside County, California. Intensity IX

"Roads in the eipcentral area were closed to travel by slides, and one automobile was carried off the road by a slide."

1918 Oct. 11. Northwestern Mona Passage, Puerto Rico Region. Intensity VIII-IX

"Many bridges were damaged and railroad tracks were bent and displaced. Two cable links were broken in Mona Passage."

1925 Feb. 23. Kenai Peninsula, Alaska. Intensity VII

"A bridge and some dwellings were damaged, and a cable was broken between Seward and Valdez."

1925 June 27. Helena, Montana. Intensity VIII

"Railroad trains moved with a sinuous motion. Rockfalls from cliffs delayed trains on the Northern Pacific Railroad, and a great slide of rock blocked the Deer Park entrance of the Lombard Tunnel of the Chicago, Milwaukee, and St. Paul...

Crevices occurred in fills on roads, but not in cuts or where the natural surface had not been disturbed. Approaches to many bridges settled, in some cases as much as a foot."

1932 March 25. South Central Alaska. Intensity VII

"Slides occured on railroads to the north."

1932 June 6. Humboldt County, California. Intensity VIII

"Telephone and telegraph service was interrupted. At Eureka Slough, a railroad drawbridge was put out of commission."

1934 May 14. Kodiak Island, Alaska. Intensity VI

"Landslides blocked roads."

1932 Dec. 30. South of Calexico, California. Intensity VI in U.S.

"In lower California at many points, bridges were damaged by movement both laterally and longitudinally and by settlement of piles. Track was kinked in several locations and settlement was as much as 6 inches (intensity IX).

Inhabitants ran up to the railroad at the time of the shock and sat between the rails, but found it difficult to sit upright, being thrown from side to side by the force of the shock."

1940 May 18. Southeast of El Centro, California. Intensity X

"Railroads -- The fault crossed the railroad at three points. At Grape the track was moved out of line, and just north of Grape about 1,080 ft. of track settled. At Meloland the track was displaced about 18 inches, and at Cocopah there was a shift of 7 ft. Settling of the track occurred at many places, especially where the railroad was close to a river. The Mexican Government Railroad southeast of Pascualitos was damaged and one bridge was seriously damaged. Depots and steel tanks suffered only minor damage.."

1941 June 30. Santa Barbara and Carpinteria. Intensity VIII

"A small slide covered the railroad and reached the highway about 20 miles east of Santa Barbara on Route 101."

1941 Sept. 14. Owens Valley, California. Intensity VI-VII

"Rockslides in the mountains neer Rock Creek raised huge dust clouds and blocked roads and trails."

1942 Oct. 21. Near Borrego Valley, California. Intensity VII

"In Carrizo Gorge, 12 miles north of Jacumba, slides broke bridge timbers and wiring on the SD&AE Railroad."

1947 April 10. East of Barstow, California. Intensity VII

"Highways in the epicentral area were cracked in a number of places and slumped in others...In Afton Canyon, 25 to 30 slides near the railroad made extensive repairs necessary. A trestle settled 2 feet."

1947 June 22. Gilroy, California. Intensity VI

"Hecker Pass was reported closed by slides."

1947 Oct. 15. Fairbanks area, Alaska. Intensity VIII

"Landslides occurred on the Richardson Highway...The Alaska Railroad reported bent rails between Julius, Nevana, and Browne, and changes in roadbed elevation in some areas."

1950 July 29. Imperial Valley, California. Intensity VIII

"In Calipatria a small railroad bridge shifted 6 to 8 inches."

1954 July 6. East of Fallon, Nevada. Intensity IX

"Paved highways in the Fallon-Stillwater area settled, cracked, and buckled in several places. One section south of Fallon settled 18 inches for a distance of 200 feet."

1954 Aug. 23. East of Fallon, Nevada. Intensity IX

"A bridge abutment moved towards the stream damaging a girder."*

1954 Oct. 3. Kenai Peninsula, Alaska. Intensity VIII

"Minor landslides spilled down on the Seward-Anchorage Highway. More than 140 feet of railroad tracks were knocked out of commission north of Potter."

1954 Dec. 16. Dixie Valley, Nevada. Intensity X

"Vertical movement varied between 3 and 6 feet where the fault zone crossed U.S. Highway 50, south of Chalk

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* This was reported in an article by Steinbrugge and Moran (p. 195).

Mountain. The highway was badly cracked. East of Fairview Peak, there were movements of 6 to 20 feet and horizontal displacements of 4 to 12 feet. Several rocks of automobile size fell onto the highway west of Carroll Summit."

1957 March 9. Andreanof Islands. Intensity VIII

"On Adak, two bridges were destroyed...and a 15 foot crack was observed in the road."

1957 March 22. West of Daly City, California. Intensity VII

"State Highway 1, near Mussell Rock, was blocked by landslides; highway pavement was cracked extensively."

1958 July 9. Southeastern Alaska. Intensity XI

"A massive rockslide at the head of Lituya Bay caused water to surge 1,740 feet and generated a gravity wave which swept out of the Bay. At Yakutat, bridges, docks, and oil lines were damaged. Submarine cables of the Alaska Communication System were severed in the Haines-Skagway area."

1958 Dec. 11. Southwest of San Francisco. Intensity VI

"A minor landslide occurred on State Highway 1, west of Daly City."

1959 Sept. 30. Off Coast of Southern California. Intensity VI

"Several large boulders fell and partially blocked U.S. Highway 101."

1962 Aug. 30. Northern Utah. Intensity VII

"At Logan Canyon, falling rock broke a water flume, causing a mudslide which partially blocked the highway."

1973 April 26. Hilo, Hawaii. Intensity VIII

"Damage to buildings, roads, and utilities caused authorities to declare a state of emergency over most of the northeast coastal area of Hawaii Island. Landslides and ground cracking were severe locally; landslides caused damage to roads and structures over a wide area. The main wharf at Hilo sustained damage from subsidence.

Heavy damage occurred along the Laupahoehoe Gulch area where the Belt Highway was closed during most of the day. County roads sustained heavy damage. Police barricaded the entrance to Wainaku Overlook because of everwidening cracks of 20 to 25 cm in the roadway."

1975 June 7. Northern California. Intensity VII (mentioned on p. 26)

"The Scotia Bluffs fell across the Northwestern Pacific Railroad tracks, knocking out the tracks and tearing away the southern end of the trestle.

Section of the bluff on Eel River's east bank fell across the railroad track and trestle, tearing out the track for about 125 yards."

1975 June 30. Yellowstone National Park, Wyoming. Intensity VIII

"The press reported that rock or landslides closed or hindered traffic on many roads in Yellowstone National Park.

Telephone service was out for several hours at Madison, Old Faithful, and West Yellowstone. A resident driving north of Gardiner reported that the road felt "corrugated" for 20-30 seconds."

1975 Nov. 29. Hawaii. Intensity VIII

"Extensive ground cracking heavily damaged roads in Hawaii Volcanoes National Park. On the Crater Rim, road damage was reported in the Waldron Ledge section, Kilauea Military Camp section, Halemaumau section, and Keanakakoi section. Damage was also noted on the Chain of Craters, Ainahou, and Hilina Pali Roads.

Honomu -- Landslides on Coast Road.

Laupahoehoe -- Landslides on Coast Road."

1978 Aug 13. Near Goleta, California. Intensity VII (Mentioned on p. 26)

"A Southern Pacific Transportation Company freight-train derailment occurred west of Goleta near Winchester Canyon Road in an area of cut-and-fill roadbed. The 49 empty and 9 loaded cars travelling at about 50 mph derailed when passing over a "kink" in the tracks, apparently the result of roadbed-fill failure; 30 of the cars were derailed and a section of the track was damaged.

A total of three overpasses crossing U.S. Highway 101, all steel-reinforced concrete structures located in the Goleta area, suffered significant earthquake damage. These overpasses are: the adjacent curving bridges on Ward Memorial Road, the one at Glen Annie Road, and the one at the western end of Hollister Avenue just east of the railroad derailment.

The earthquake caused several rock slides on San Marcos Pass Road, the section of State Highway 154 that runs northwest through Santa Ynez Mountains from U.S. Highway 101 between Goleta and Santa Barbara. Most of the slides occurred on roadcuts where there were steep inclines.

The Ward Memorial Road bridges were temporarily closed."

1979 Oct 15. Imperial Valley, California. Intensity IX

"There were also numerous bridges with cracked abutments and shifted roadbeds due to slumping or faulting.

New River Bridge (on State Highway 86 west of the city)--The abutments at each end of the bridge were cracked and chipped to the extent that the reinforcement bars were exposed at bridge level. Many of the support columns were cracked at the bridge deck connection. The asphalt road had settled about 12.5 cm (5 in) relative to the bridge.

The San Diego and Arizona Eastern Railroad tracks were offset about 23 cm where they crossed the Imperial fault east of El Centro near Meloland."

1980 Jan 27. Livermore, California, Intensity VII

" An earthquake measuring 5.5 on the Richter scale with an epicenter about 12 miles north of Livermore, California, closed off Interstate 580 near that city last week when the approach fill for an overpass subsided 6 to 8 inches."

1980 Nov. 8. Eureka, California. Intensity IX

"The powerful earthquake that struck near Eureka in northern California early last Saturday morning dropped two large viaduct spans and slightly damaged an adjacent structure...Six persons were injured in the viaduct collapse...

The highway spans that fell carried southbound lanes of U.S. Route 101 across a small valley, 7 miles south of Eureka. They are part of twin two-lane viaducts crossing a road and railroad, only about 25 feet high...

> The 406-foot curved structures consisted of four simple spans of about equal length with a hinge over each bent. Superstructures have multiple box girders with an integral deck, all of conventional reinforced concrete cast in place on falsework..."*

IV. Zonal Map for Transportation System

This report has described known earthquake damage to a transportation system as a way of establishing the vulnerability of that system to seismic excitation. Sufficient information has been given to support the author's contention that within intensity VIII-IX contours lies the potential for severe damage in future earthquakes. The usefulness of this information is that it now forms a basis for development of a zonal map identifying those areas specifically hazardous to transportation structures. This zonal map will be materially different from such maps already existing for buildings (references 4,5). For example, buildings are seriously damaged at much lower intensities than transportation structures, such as bridges and roads; therefore, the damage zones will be smaller for the transportation zonal map. This is important from an economic standpoint because transportation structures are so costly to construct, maintain, and retrofit.

To produce the zonal map all areas within the VIII-IX contours of the U.S. earthquake history are needed. Table 1 lists over 45 earthquakes that have reached level VIII-IX intensity; yet in only 17 earthquakes was the author able to find a published isoseismal map. One way to generate the missing isoseismal contours for the remaining earthquakes is by use of Figure 31. Here on a semilog plot a straight line practically represents the variation of intensity with distance from the epicenter. For earthquakes in the central and eastern states, Figure 31 can be used directly. For the western states a

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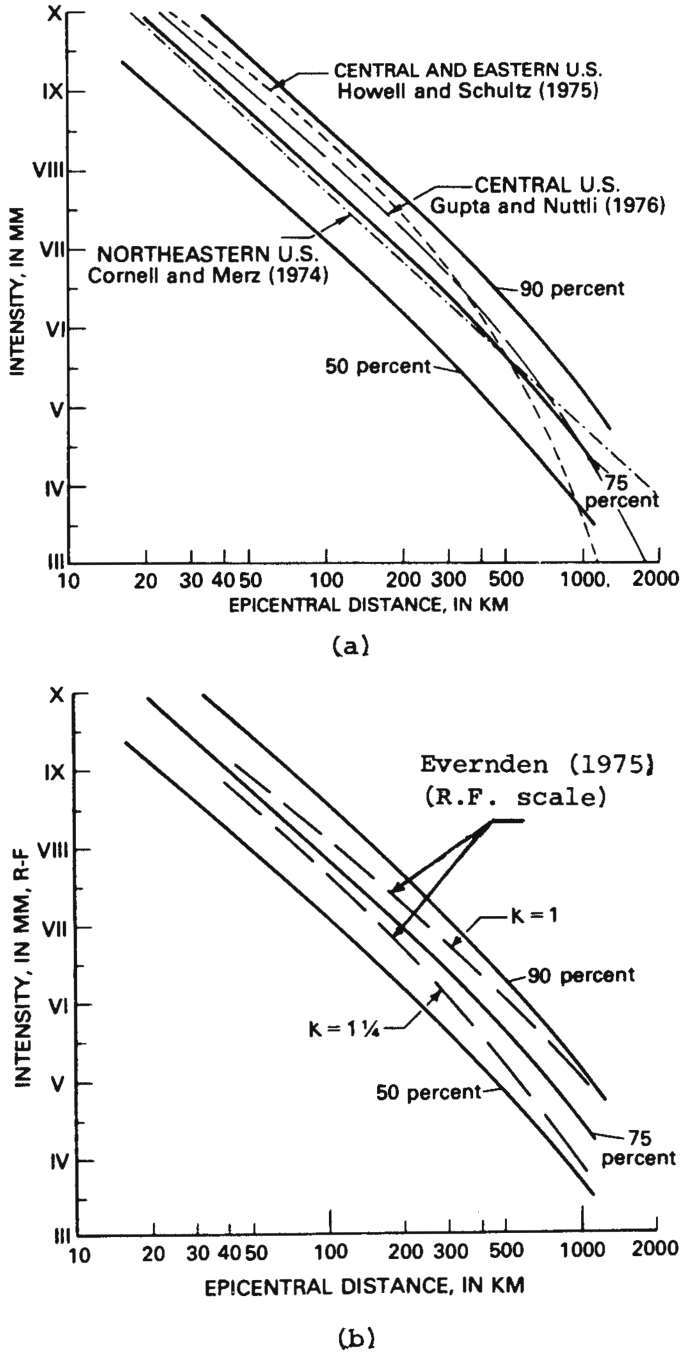
* The Livermore and Eureka earthquakes were reported in the Engineering News Record, 204:17Ja31 and 205:15Nov13 respectively.



(a)

(b)

Figure 31. Attenuation curves with distance from epicenter for various fractiles of intensity. Solid curves are for the 1886 Charleston earthquake. (After Bollinger)

similar variation of intensity can be developed using isoseismal information of past western earthquakes.

The generalized contours will be circular in appearance, a fictitious situation because geomorphic features of the earth affect the shape of the contours and produce a more random appearance; nevertheless, the circular approximation in the central and eastern states is not too crude considering the random location of the epicenters in seismic areas. Along the Pacific Coast one should consider the effects of known faults which have been associated with earthquakes and elongate the contours along the length of the fault. To take care of this situation one can construct lines with different bearings away from the epicenter, and using information from earthquakes of low intensity in the area, construct curves similar to Figure 31 for these lines. Then the curves can be extrapolated to find the isoseismal locations for the highest intensity earthquake ever recorded in the area.

The development of the zonal map is beyond the scope of this report.

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