Historic Surface Faulting in Continental United States and Adjacent Parts of Mexico

(A Factor in Nuclear Facility Siting and Design)

by M.G. Bonilla[1]

TID-24124
REACTOR TECHNOLOGY
(TID-4500)

Version 1.3

1967

A contribution of the National Center for Earthquake Research, U.S. Geological Survey, prepared on behalf of the U.S. Atomic Energy Commission

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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Version History

Version History for:

Bonilla, M.G., 1967, Historic Surface Faulting in Continental United States and Adjacent parts of Mexico: U.S. Atomic Energy Commission report TID-24124.

Version 1.3 - July 14, 1999

Corrected typographical errors and references to page numbers. Added credits to Version 1.1 history

Version 1.2 - July 13, 1999

Replaced small-print Table 1 with three larger-print pages each of which contains one third of the table. Replaced black USGS identifier with green one

Version 1.1 - July 9, 1999

Doc Bonilla used OCR on original typewriter pages to digitize text. Mike Diggles scanned original inkwork-on-Mylar illustrations to digitize figures. Richard Koch digitized the table on a large scanner. Diggles made new page layout using proportional PostScript fonts and created Adobe Acrobat Portable Document Format (PDF) file for inclusion on the Web (http://caldera.wr.usgs.gov/iaspei/BONILLA.pdf) and as a reprint in the *International Handbook of Earthquake and Engineering Seismology* of the International Association of Seismology and Physics of the Earth's Interior to be published by Academic Press (Harcourt, Inc.)

Version 1.0 - 1967

First release by the Division of Reactor Development and Technology of the U.S. Atomic Energy Commission.

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PREFACE

The Division of Reactor Development and Technology of the U.S. Atomic Energy Commission supports a program of applied and long-range research oriented toward assuring that reactors and other nuclear facilities are sited in safe environments, and that they are designed to avoid undue risk to public health and safety. The projected increasing need for nuclear power in seismically active west-coastal areas of the United States necessitates an increased knowledge of the occurrence and effects of earthquakes.

At present, quantitative data are sparse on the seismic responses of earth materials in the complex geologic environments in which most earthquakes occur. Such data are needed to provide a basis for judging the suitability of sites and also to provide a technical basis for developing satisfactory designs for reactor containment and component systems. Sudden, permanent displacement of the ground surface by faulting is one of the major seismic responses to be considered. Surface faulting is known to have occurred during historic earthquakes at many places in the world and, on geologic evidence, is inferred to have occurred during many prehistoric earthquakes. However, the data on historic faulting are scattered widely throughout the literature, and in some cases are open to question.

This report, by M.G. Bonilla, presents the results of part of a program of research in earthquake geology and seismology sponsored by the Division of Reactor Development and Technology. The report summarizes and evaluates what is known about the amounts and kinds of historic surface faulting that have occurred in several geologic-seismologic environments in the United States and adjacent parts of Mexico. These basic data will be of direct value to those engaged in siting, designing, and constructing nuclear facilities by indicating the values of fault displacements that should be considered in seismic regions. The data are anticipated to be valuable also in the current development, by the Atomic Energy Commission, of guidelines and criteria for siting and design of nuclear power plants.

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INTRODUCTION

This report summarizes geometric aspects of approximately 35 instances of historic faulting of the ground surface in the continental United States and adjacent parts of Mexico. This information is of immediate importance in the selection and evaluation of sites for vital structures such as nuclear power plants. The data are presented in a table and graphs which show the quantitative relations between various aspects of the faulting. Certain items in the table that are uncertain, poorly known, or not in the published literature are briefly described in the text.

Most of the information was obtained from published reports but some is from unpublished material, field work, and study of aerial photographs. I have examined, in more or less detail, the important historic faults in California, Nevada, and on Montague Island, Alaska, but not the faults in other areas.

Several colleagues helped me in the field and office. E.H. Pampeyan participated in part of the field examination of the Fort Sage, Mohawk Valley, Owens Valley, White Wolf, and Imperial Valley faulting. George Plafker participated in the field examination of the Pleasant Valley, Cedar Mountain, Excelsior Mountain, Rainbow Mountain, Fairview Peak, and Dixie Valley faulting, and was the principal investigator of the Patton Bay and Hanning Bay faulting on Montague Island. D.H. Radbruch did historical research and field work in connection with the 1868 Hayward faulting. A tabulation of branch and secondary faulting that occurred along the San Andreas fault in 1906, prepared by Julius Schlocker for another project, has been of much value in this study.

The meanings of selected geologic terms used in this report are given below in alphabetical order. The meanings apply to the use of the terms in this report, but do not necessarily apply to all possible uses of the terms.

Dextral-normal,--Fault displacement consisting of nearly equal components of dextral strike-slip and normal slip.

Dextral strike-slip.--Strike-slip displacement in which the block across the fault from an observer has moved to the right.

Displacement.--Relative movement of the two sides of a fault, measured in any specified direction.

Fault.--A fracture or fracture zone along which there has been tectonic displacement of the two sides relative to one another parallel to the fracture. The displacement may range from a few inches to many miles,

Fault creep.--Apparently continuous displacement along a fault at a low but varying rate, usually not accompanied by felt earthquakes. As used in this report, fault creep is not necessarily tectonic in origin,

Fault scarp.--A cliff or steep slope formed by fault displacement of the ground surface.

Graben.--A fault block, generally long and narrow, that has been depressed relative to the adjacent blocks by movement along the bounding faults. The same form of the word is used for both the singular and plural.

Landslide.--The downward and outward movement of slope- forming materials composed of rock, soils, artificial fills, or combinations of these materials (Varnes, 1958, p. 20); the topographic feature and the deposit resulting from such movement.

Normal fault.--A fault in which the block above the fault has moved downward relative to the block below the fault; also includes vertical faults with vertical slip.

Reverse fault.--A fault in which the block above the fault has moved upward relative to the block below the fault.

Sinistral strike-slip.--Strike-slip displacement in which the block across the fault from an observer has moved to the left.

Slip.--The actual relative displacement of formerly adjacent points on opposite sides of a fault, measured in the fault surface.

Strike.---The direction or bearing of a horizontal line in the plane of an inclined or vertical stratum, joint, fault, or other structural plane.

Strike-slip.--The component of the slip parallel with the strike of the fault; the horizontal component of slip.

Strike-slip fault.--A fault in which the slip is approximately in the direction of the strike of the fault. The historic displacements on strike-slip faults discussed in this report have, in places along those faults, included a vertical component which has generally been less than one-quarter of the horizontal component.

Tectonic.--Of, pertaining to, or designating the rock structure and external forms resulting from deep-seated crustal and subcrustal forces in the earth,

BASIC DATA

General

The basic data concerning historic fault displacements in the area of study are presented in table 1. Some of the items in the table which require explanation of their meaning and of their source are discussed below.

The episodes of faulting are numbered and listed in column 1 of the table in chronological order. Type of displacement is that which occurred during the historic faulting and is generally (though not necessarily) the characteristic movement for that fault as indicated by the geologic record. In general, the maximum horizontal and vertical movements given in the table have not been at the same point on the fault. The abbreviations used for the type of displacement are explained at the end of the table.

The vertical displacements for normal faults given in columns 4, 5, and 6 of table 1 are the scarp heights except where otherwise specified, because the scarp height is generally more critical for engineering purposes than the vertical component of fault displacement, and because many published reports give only scarp heights. Scarp heights of normal faults are commonly greater than the vertical component of fault displacement, chiefly because gravity graben form along the fault (Gilbert, 1890, p. 354; Slemmons, 1957, p. 367-375). This is shown in Figure 1 which is a diagrammatic cross section of a typical graben formed by gravity settling of part of the hanging wall of a normal fault. The vertical component of fault displacement, equal to the vertical distance from A to B, is less than the scarp height AC. In order to avoid having to accommodate the full scarp height, an engineering structure across the main fault would have to bridge the graben. Because the width CD of the graben is generally more than 10 feet and can be as much as 300 feet (Wltkind, 1964, p. 45) structures may bear on the graben and have to accommodate the full scarp height. In addition to the effects of graben formation described above, scarp heights may be increased by minor landsliding and other erosional processes that cause a gradual uphill retreat of the brow (A) of the scarp. Scarp heights are not given in the table for specific points where erosional processes are known to have substantially increased them as, for example, in parts of the Fairview Peak scarps formed in 1954 (Slemmons, 1957, p. 373-375).

Fault (name or location), date, and type of displacement (See notes at end of table)	Magnitude (Richter) of associated earthquake	Length of surface rupture (miles)	Displacement (feet), main fault (max.)	Displacements (feet) at indicated distances (miles) from center of main fault zone: Branch faulting	Displacements (feet) at indicated distances (miles) from center of main fault zone: Secondary faulting	Distances (max.) from center of main zone to outer limits of: Main zone	Distances (max.) from center of main zone to outer limits of: Branch faulting	Distances (max.) from center of main zone to outer limits of: Secondary faulting	Remarks	Principal References
1	2	3	4	5	6	7	8	9	10	11
1 New Madrid, Missouri; 1811-1812; N(?)			6 (?) V						Fault whose scarp bounds Reelfoot Lake shows vertical separation of 40 ft. in Eocene beds 160 ft. below the surface. Uplift as well as subsidence occurred in this earthquake. See text.	Fuller, 1912; Fisk, 1944; U.S. Army Corps of Engineers, 1950.
2 Hayward, Calif.; 1836; D(?)		38(?)								Louderback, 1947
3 San Andreas, Calif.; 1838; D(?)		35(?)								Louderback, 1947
4 San Andreas, Calif.; 1857; D		200±	Large							Lawson and others, 1908; Wood 1955; Allen and others, 1965; Brown and Vedder, 1967
5 Hayward, Calif.; 1868; D		30±	3D; 1V	Displacement unknown	1.5V @ 1.4		0.8± mi.	1.8 miles	Given length includes a 23-mile southern segment and a probable segment 0.3 mile long, 7 miles to the north. See text for branch and secondary faults.	Lawson and others, 1908; Radbruch, 1965
6 Owens Valley, Calif.; 1872; DN	8.3 (est.)	60+	23N; 20D		18V @ 1.6+; 4N @ 8; 2.5N @ 8; 15V @ 1½	0.5 miles		8 miles	Displacements given for secondary faults at 8 miles are scarp heights; net displacements were 1½ and 1 ft. See text.	Whitney, 1888; Hobbs, 1910; Bateman, 1961; Bonilla, unpub. data.
7 Mohawk Valley, Calif.; 1875; N(?)									May have been landsliding rather than faulting. See text.	Turner, 1891, 1896, 1897; Gianella, 1957
8 Sonora, Mexico; 1887; N		35+	26N			500± ft.			Possible secondary faulting at maximum distance of 13 miles from main fault but contemporaneity is doubtful.	Aguilera, 1920; Goodfellow, 1888; Richter, 1958
9 San Jacinto, Calif.; 1899; D(?)		2								Danes, 1907; Allen and others, 1965
10 Yakutat Bay, Alaska; 1899; N(?) & D(?)	8.5-8.6	Unknown	29-42N (?) See text	See Remarks	See Remarks and text		See Remarks and text	See Remarks and text	Maximum uplift 47 ft. Inferred principal faults under water. Uplift, warping, and possible faulting in area at least 30 miles by 15 miles and probably much greater. Secondary(?) faulting produced scarps as much as 8 ft. high, 21 miles from the inferred principal faults.	Tarr and Martin, 1912; Richter, 1958
11 Gold King, Nev.; 1903(?); N(?)		3+							Possibly 12 miles long. Fault marked by open crack 3 to 5 ft. wide. No data available on vertical or horizontal components of displacement. Movement also occurred on this fault in 1954.	Slemmons and others, 1959
12 San Andreas, Calif.; 1906; D	8.3	270	20D; 3V	4D & 2.5V @ 0.6	2V @ 1.5; 0.5D @ 1.3; 4S @ 0.3; 1V @ 0.2. See text.	200 ft.	0.6 mi.	1.5 miles	Small cracks in bedrock as much as 10 miles from fault. A tunnel perpendicular to the fault was offset, and deformed along nearly a mile of its length; at 4,000 ft. from the fault the displacement was 14 inches.	Lawson and others, 1908
13 Shelter Cove (San Andreas?) Calif.; 1906; D, DN(?)		2+	(?)D; 4(?)V	Displacement unknown	Displacement unknown				Dextral strike-slip movement indicated by appearance of trace. May be the San Andreas fault itself or a branch or secondary fault 1.5 to 25 miles east of the San Andreas.	Lawson and others, 1908; Curray and Nason, 1967
14 Pleasant Valley, Nev.; 1915; N	7.6	20 to 40	15N	None?	3V @ 2.5. See text	500 ft.		2.5 mi.	Northern 5 miles of fault is en echelon to principal segment, partly overlaps it, and is 2½ miles perpendicularly from it.	Jones, 1915; Page, 1935

Table 1, Part 1 of 3. Historic surface faulting in continental United States and adjacent parts of Mexico (see Notes at bottom of Table 1, part 3 of 3

Fault (name or location), date, and type of displacement (See notes at end of table)	Magnitude (Richter) of associated earthquake	Length of surface rupture (miles)	Displacement (feet), main fault (max.)	Displacements (feet) at indicated distances (miles) from center of main fault zone		Distances (max.) from center of main zone to outer limits of:			Remarks	Principal References
				Branch faulting	Secondary faulting	Main zone	Branch faulting	Secondary faulting		
1	2	3	4	5	6	7	8	9	10	11
15 Cedar Mountain, Nev.; 1932; DN	7.3	38	2.8D; 4V	See Remarks	See Remarks				Discontinuous traces scattered over a belt 4 to 9 miles wide and 38 miles long.	Gianella and Callaghan, 1934
16 Excelsior Mountains, Nev.; 1934; N	6.5	0.9	0.4N; slight S	None	None					Callaghan and Gianella, 1935
17 Hansel Valley, Utah; 1934; N		5+	1.7N							Neumann, 1936; Ryall and others, 1966
18 San Jacinto, Mexico; 1934; D(?)	7.1								Faulting inferred from aerial photos taken in 1935.	Kovach and others, 1962; Biehler and others, 1964
19 Imperial (El Centro), Calif.; 1940; D	7.1	40+	19D; 4V	.08D & 0.17V @ 0.5. See text.	None	300 ft.	0.5 mi.			Ulrich, 1941; Richter, 1958
20 Vacherie, Louisiana; 1943; N		1	0.7N	None	None				This is on flank of a salt dome and near an oil test well that had been abandoned because it encountered salt water at 2,000 lbs. pressure at depth of 8,800 ft. Evidence at surface of an earlier fracture; drilling indicates a vertical separation of 3½ ft. at depth. Lies along the Red River fault zone. See text.	Fisk, 1944; U.S. Army Corps of Engineers, 1950
21 Manix, Calif.; 1947; S	6.4	1	0.25S	None	None				Surface faulting may be secondary to concealed right-lateral rupture.	Richter, 1958
22 N. of Bakersfield, Calif.; 1949; N(?)	No quake	2							May be related to subsidence	Hill, 1954
23 Fort Sage, Calif.; 1950; N	5.6	5.5	0.6-2N See text	None	0.25V @ 0.25	0.1 mile		0.25 mi.	The given distance from the center of the main zone to its outer limits is one-half the perpendicular distance between overlapping en echelon segments.	Gianella, 1957
24 Superstition Hills, Calif.; 1951; D	5.6	2±							Strike-slip indicated by en echelon fractures but amount of displacement unknown.	Dibblee, 1954; Allen and others, 1965
25 White Wolf, Calif.; 1952; SR&N	7.7	33 (discontinuous)	2.5S; 4VR; 4VN	1S @ 1.1 See text	0.3N @ 8 See text	0.5 mile	1.7 mi.	8 miles	Ten feet of shortening measured across main fault zone at one locality. Shaking or regional readjustment of strain produced 0.5 ft. vertical faulting for 400 ft. along Garlock fault, 20 miles from White Wolf fault.	Buwalda and St. Amand, 1955; Dibblee, 1955; Kupfer and others, 1955; Richter, 1958, p. 83-84.
26 Rainbow Mountain, Nev.; 1954, July; N	6.6	11	1N	None	0.15V @ 0.3	0.2 mile		0.3 mi.		Tocher, 1956
27 Rainbow Mountain, Nev.; 1954, August; N	6.8	19	2.5N	None	?V @ 0.3			0.3 mi.	Partly overlaps the July 1954 Rainbow Mountain ruptures and increased the displacement on some of them.	Tocher, 1956
28 Fairview Peak, Nev.; 1954, Dec.; DN	7.1	36	14D; 12N	?V @ 1.6 See text	3N @ 2; 1.5D @ 2.5; 1.7D @ 0.6; 1.5N @ 3±; 0.5N @ 4±. See text	0.5 mile	1.6 mi.	4± miles	Produced scarps 16 to 23 ft. high. Movement occurred along part of this zone of faulting in 1903 (Gold King fault). Max. oblique slip 16 ft.	Slemmons, 1957; Romney, 1957

Table 1, Part 2 of 3

Fault (name or location), date, and type of displacement (See notes at end of table)	Magnitude (Richter) of associated earthquake	Length of surface rupture (miles)	Displacement (feet), main fault (max.)	Displacements (feet) at indicated distances (miles) from center of main fault zone		Distances (max.) from center of main zone to outer limits of:			Remarks	Principal References
				Branch faulting	Secondary faulting	Main zone	Branch faulting	Secondary faulting		
1	2	3	4	5	6	7	8	9	10	11
29 Dixie Valley, Nev.; 1954, Dec.; N	6.8	38	7+ N (15' scarp)	None?	2N @ 1.4; 0.5N @ 2.4; 0.2N @ 1.5; 0.2N @ 2. See text	3000 ft.		2.5 mi.	Rupturing could have occurred during Fairview Peak shock (M. 7.1) which occurred 4 minutes earlier and whose epicenter was about 30 miles from the midpoint of, and about 13 miles south of the end of, the Dixie Valley faulting. The epicenter of the magnitude 6.8 shock was near the Dixie Valley faulting.	same
30 San Miguel, Mexico; 1956; DN	6.8	12+	3N; 2.6D	None	0.75N @ 0.4	450 ft.		0.5 mi.		Shor and Roberts, 1958
31 Fairweather, Alaska; 1958; D	8.0	115+	21.5D; 6V	None	5N @ 0.4			0.6 mi.	Vertical displacement recorded along 0.25 mi. of the fault. Vertical displacement was 3.5 ft. where horizontal displacement was 21.5 ft., indicating oblique slip of 21.8 ft.	Tocher, 1960a
32 Hebgen Lake, Montana; 1959; N	7.1	15±	20N	3N @ 3 See text	2.75N @ 4.5±; 1N @ 4±; 1N @ 7.5±; 1V @ 8.5±; 0.7V @ 8±; 3N @ 8. See text	500 ft.	3 mi.	8.5 mi.		Myers and Hamilton, 1964; Witkind, 1964
33 Patton Bay, Alaska; 1964; R	8.4	39+	20-23 VR; 1.4S(?); 26± dip slip	None	None	1500 ft.			In addition to faulting of 8 ft. at one place, distortion of 1 part vertical in 56 parts horizontal occurred within 800 ft. of the fault. Magnitude given is for main shock, whose epicenter was more than 75 miles from the surface faulting. Four aftershocks within 50 miles of the faulting had magnitudes ranging from 6.2 to 6.6. Simultaneous faulting occurred 6 miles away (see Hanning Bay fault).	Plafker, 1965; Plafker, 1967b
34 Hanning Bay, Alaska; 1964; R		4	16VR	None	None	650 ft.			For magnitude see Patton Bay fault, which occurred simultaneously 6 miles away.	same
35 Imperial, Calif.; 1966, March; D	3.6	6	0.05D	None	None					Brune and Allen, 1967a, 1967b
36 San Andreas, Parkfield, Calif.; 1966, June; D	5.5	23	0.58D; 0.16V	0.08D @ 0.85	None	10 ft.	0.85		Displacement given includes tectonic creep that occurred within 50 days following main shock. Initial strike-slip displacement unknown at this locality; at another locality strike-slip displacement totaled about 1.8 inches 10 hours after the shock and 4.7 inches 37 days later.	Brown and Vedder, 1967
37 Buena Vista Hills, Calif.; continuing fault creep; R	No quake								Fault creep has been occurring on this reverse fault, without felt earthquakes, for more than 30 years. Total dip-slip displacement 1.6 ft. between 1933 and 1958. See text for other localities where creep has occurred.	Koch, 1933; Wilt, 1958

Table 1, Part 3 of 3

[Notes: Abbreviations for type of displacement: D, Dextral strike-slip; S, Sinistral strike-slip; N, Normal (includes vertical faults); HS, Heave, shortening; HL, Heave, lengthening; DN, Dextral normal; SR, Sinistral reverse; R, Reverse (both high-angle and low-angle); V, Vertical (either normal or reverse); VN, Vertical displacement on normal fault; VR, Vertical displacement on reverse fault; Query (?) indicates uncertainty as to type, quantity, or identification. Blank spaces in table indicate no reliable data available.]

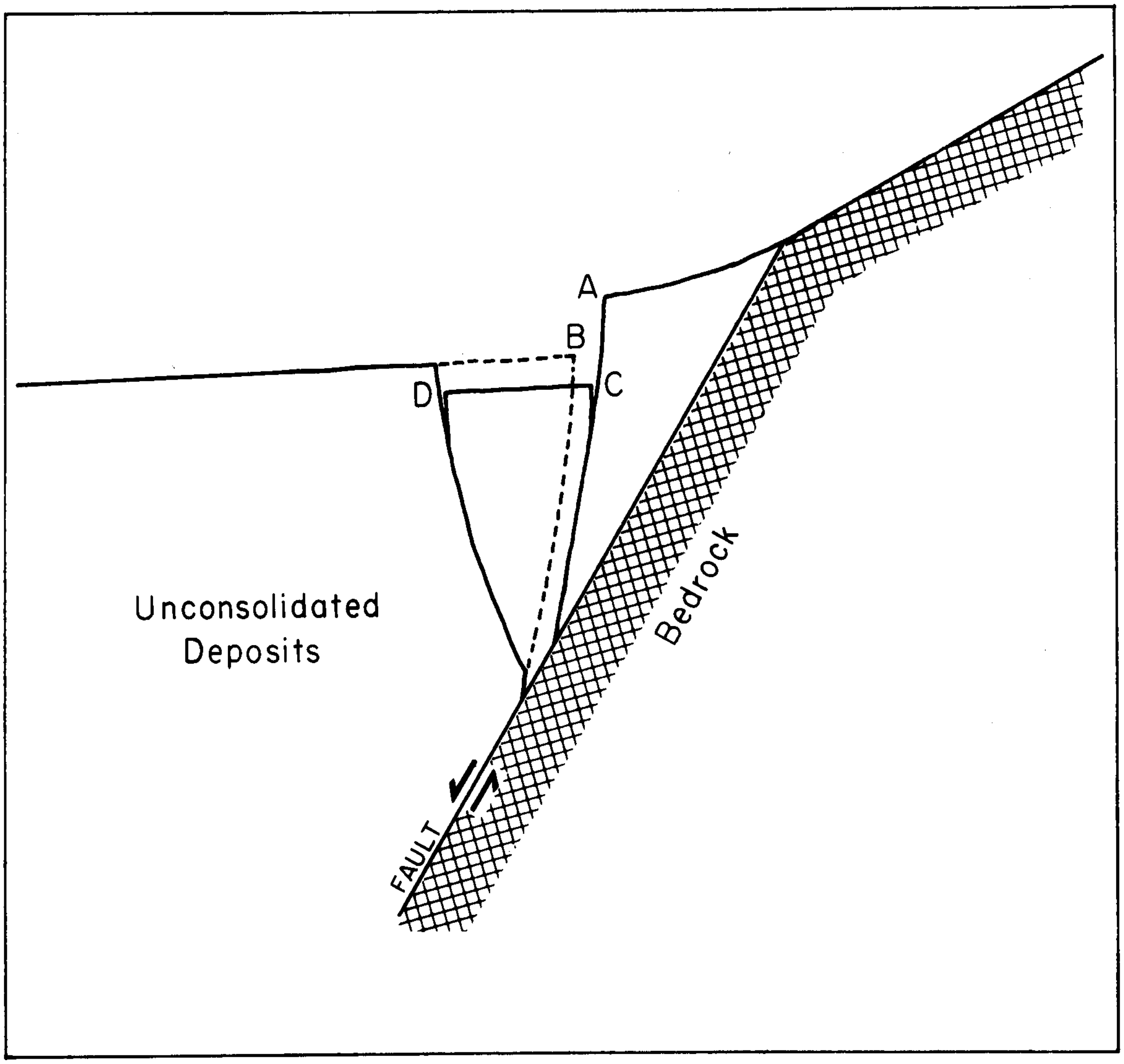

Figure 1. Cross section of a gravity graben associated with a normal fault

[Arrows show relative movement of fault]

Fault ruptures can generally be divided into three categories or zones (fig. 2): one includes the main fault, another includes the branch faults, and the third includes the secondary faults. Zone I contains the main fault and closely associated faults which, at a map scale of 1/250,000, form a band of varied width. For the purposes of this study the surface fault with the greatest displacement, length, and continuity is regarded as the main fault; some of these, such as the Patton Bay fault of 1964, may actually be subsidiary to a concealed principal earthquake-generating fault. Branch faults which constitute zone II diverge from and extend well beyond the main zone of faults. The branch faults generally show the same type of displacement as the main fault and either join it at the surface or can reasonably be inferred to do so in the subsurface. The secondary faults which constitute zone III are completely separate spatially from the main fault, as shown on figure 2, but nevertheless most of them also have the same type of displacement as the main fault.

The distances given in columns 5 through 9 of the table were measured at right angles to the trend of the main fault from its approximate centerline. The distances given in columns 5 and 6 are to points where the displacement was actually measured or estimated by the investigator; the corresponding distances in columns 8 and 9 are generally greater as they were measured to the most distant parts of the branch or secondary ruptures.

The concept of zones cannot be applied to some episodes of historic faulting. An example is the Cedar Mountain, Nevada faulting of 1932 in which the surface ruptures were widely scattered and no single continuous fault predominated over the others. Another example is the Yakutat Bay, Alaska, faulting of 1899 in which the observed minor faults were irregularly distributed and, although several large faults have been postulated, the main fault has not yet been identified.

Specific faults

Some of the faults listed in the table are noteworthy because of the number or extent of the secondary faults, or because they occurred in areas where faulting is not usually expected, or for other reasons. The unusual aspects of these faults are briefly discussed below as a supplement to table 1. For a more complete description the references cited in the text or in column 11 of table 1 should be consulted.

The distribution and displacement of branch and secondary faults are emphasized here because of their potential importance in engineering works and because such faults have generally received little attention in the published literature.

<u>New Madrid, Missouri, 1811-1812.</u> Faulting at the surface has not been unequivocally established for this great earthquake but the available evidence strongly suggests that it did occur. Historic accounts mention the formation of both barriers and waterfalls across the Mississippi River near New Madrid; one of the waterfalls was estimated to be 6 feet high (Fuller, 1912, p. 58, 59, and 62). Reelfoot Lake, which formed in the earthquake, is bounded on its southwest and west sides by a fault of which one side was uplifted while the other side subsided (Fuller, 1912, p. 75; Fisk, 1944, p. 25 and fig. 33; U.S. Army Corps of Engineers, 1950, p. 6-11). This fault extends below the surficial sediments, and borings show a vertical separation of 40 feet in Eocene beds 160 feet below the surface (U.S. Army Corps of Engineers, 1950, fig. 4). Other areas that sank during the earthquake may be bounded by faults also but I have no definite information about them.

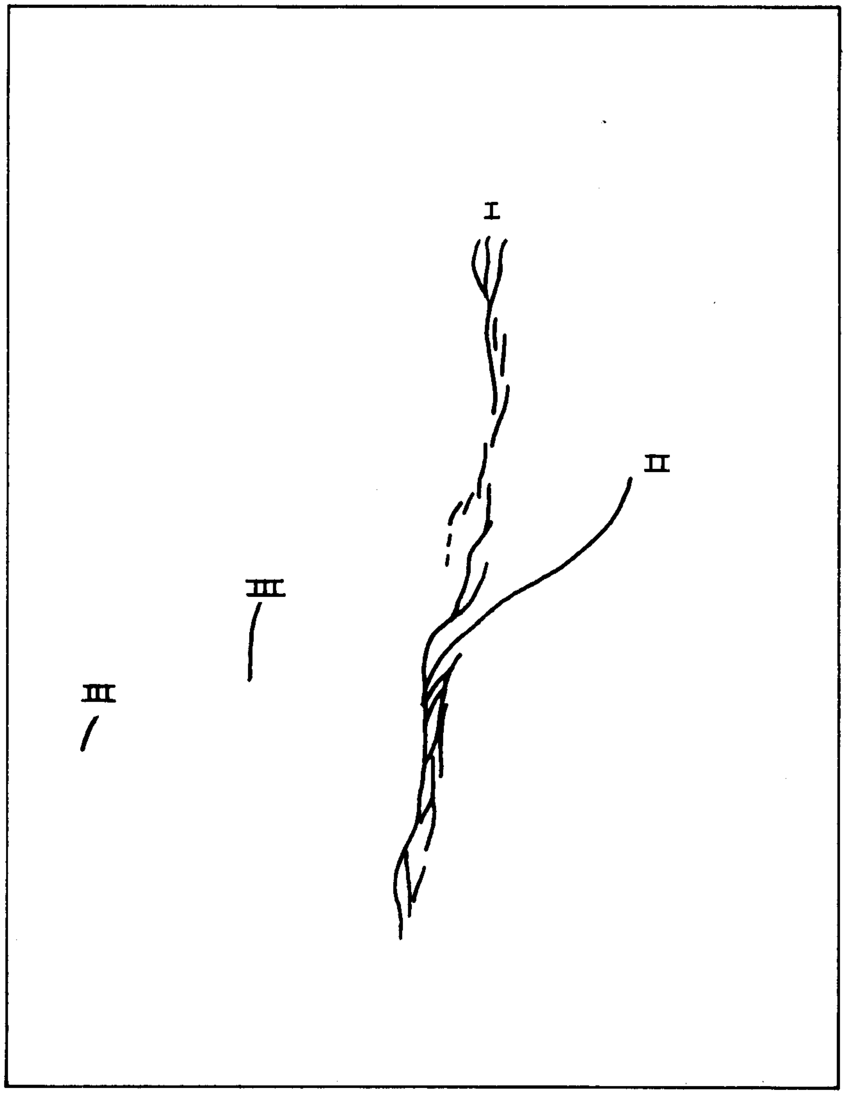

Figure 2. Diagram showing (I) main fault zone; (II) branch fault; and (III) secondary faults

Faults which are expressed in the present topography are found in several parts of the lower Mississippi Valley (Fisk, 1944; U.S. Army Corps of Engineers, 1950; Veatch, A.C., 1906), and faulting of a Pleistocene terrace in the nearby southern part of Illinois has been reported by Ross (1963). This is a seismic region which experienced other great earthquakes prior to 1811 (Fuller, 1912, p. 12-13) and which has had many small to moderate earthquakes since then (Heinrich, 1941; U.S. Army Corps of Engineers, 1950, p. A9-A17; Wollard, 1958; Heyl and Brock, 1961, p. D-4).

Hayward fault, 1868. A secondary fault formed near the southern end of the main 1868 fault trace and extended south of the end of the main trace, This secondary fault was about 4 miles long and was nearly parallel to the main fault, lying 1.4 miles to the east of the projection of the main fault at its south end and 1.8 miles to the east at its north end. Contemporary accounts describe it as a crack 10 or 12 inches wide accompanied by a vertical movement ranging from 10 to 18 inches (Lawson and others, 1908, p. 435 and 444; Radbruch, 1965).

A probable 1868 branch fault in the city of Hayward was at least 1.5 miles long (Lawson and others, 1908, p. 441- 442; Radbruch, 1965). The amount of 1868 displacement on this branch fault is unknown and the fault's exact location is uncertain but the available information indicates that its northern end was about 0.15 mile, and its southern end at least 0.8 mile, from the main fault trace.

Owens Valley, California, 1872. The vertical displacement of 18 feet at a distance of 1.6 miles (see column 6 of table) from the main fault occurred on a secondary fault that extends north from Red Mountain, which is about 9 miles south of Big Pine. The secondary fault is subparallel to the main fault, lies 0.5 to at least 1.6 miles to the west, and its scarp ranges from 8 to 18 feet high. The scarp is reported to have formed in 1872 (Knopf and Kirk, 1918, p. 77 and p. 80), This statement Is supported by the fresh appearance of the scarp, although its full height may not have developed then.

The secondary faults 8 miles from the main fault are near Swansea, which is about 10 miles southeast of Lone Pine. The faulting produced two long narrow graben that are 0.75 mile apart along their common northwest strike. The northwestern graben is 55 to 80 feet wide, about 0.4 mile long, and is bounded by scarps as much as 4 feet high. The southeastern graben is 35 to 55 feet wide, more than 0.25 mile long and the highest bounding scarp is about 2.5 feet high (Bonilla, unpub. data). The net vertical displacement across each graben is only 1 to 1.5 feet, but the larger scarp heights have been used in table 1 for the reasons given on page 6. The northwestern graben formed in 1872 according to W.D. Johnson (Hobbs, 1910, p. 375-376), who first described and photographed it. The southwestern graben is so similar to the northwestern graben in form, dimensions and freshness (for example, open fractures in the graben still serve as sinks for surface runoff) that they almost certainly formed at the same time.

A group of graben 5 miles south-southeast of Lone Pine lies about 1.5 miles east of the main fault. These graben can be clearly seen on aerial photographs and the largest is about 1,500 feet long and has a maximum width of about 250 feet. A sketch of the 1872 faults in the field notebook of G.K. Gilbert dated 1883, in the U.S. National Archives, shows graben in this vicinity with displacements of 3 to 15 feet.

The graben near Swansea and southeast of Lone Pine could conceivably be of landslide origin but a tectonic origin is much more probable. Graben of similar dimensions formed by landsliding in Anchorage, Alaska, during the 1964 earthquake (Hansen, 1965, p. A38-A66) but they differed from the Owens Valley graben in being strongly arcuate in plan and in being close to steep bluffs; moreover, one of the graben southeast of Lone Pine trends nearly at right angles to the slope of the ground, an orientation which strongly suggests a tectonic origin.

Mohawk Valley, California, 1875. Whether surface faulting or merely landsliding occurred during this earthquake is uncertain. Fissures as much as two feet wide are said to have formed in Mohawk Valley during an earthquake about 1876 (Turner, 1891, p. 396), and Gianella (1957, p. 177) infers this to have been the earthquake of January 24, 1875. E.H. Pampeyan and I examined a locality which is probably the one described by Turner, The locality is at lat 39°45'N., long 120°33'0"W., on the south bank of the Middle Fork of the Feather River. The rock there has numerous short fissures as much as 8 inches wide generally trending upslope; the hummocky ground uphill from the fissures is bounded by a steep arcuate scarp that is probably the head of a landslide. Thus the rock containing the fissures may be in the toe area of a landslide and the fissures produced in 1875 may have been of landslide origin rather than of tectonic origin.

Yakutat Bay, Alaska, 1899. The faults associated with this earthquake, and affecting an area greater than 15 by 35 miles, have been inferred largely from differential vertical displacements of the opposing shores of bays and narrow fjords, although some minor surface faults were directly observed. A fault (fault C, fig. 3) was postulated along the axis of Disenchantment Bay by Tarr and Martin (1912, p1. 14) to account for the 29-foot difference between the maximum uplift of 47 feet 4 inches on the northwest shore of the Bay and an uplift of 18 feet 6 inches on Haenke Island, 2 1/4 miles away.

Tarr and Martin postulated a westward-trending fault (G, fig. 3 this report) principally to account for the variation in the amount of uplift of the northwest shores of Yakutat and Disenchantment Bays, ranging from no uplift (possibly even a slight subsidence at point shown with question mark) at the southwest through 9 feet 4 inches and 42 feet at successive points to the northeast. The 42 feet of vertical displacement could have been distributed on two adjacent faults (collectively equivalent to fault G) that stepped the shoreline up from zero through 9 feet 4 inches to 42 feet. Recent geologic mapping (Plafker, 1967a) has suggested a concealed fault (shown by a dotted line on fig. 3) in the general location of fault G with the same trend and sense of displacement. Glaciers, steep topography, and vigorous streams may conceal evidence of the 1899 faulting.

Other faults (A, B, D, E, F, and H, fig. 3) were postulated by Tarr and Martin to account for smaller differences in vertical movement than those across faults C and G; two of these (A and E) are along faults that juxtapose different geologic units (Tarr and Martin, 1912, pl. 22; Plafker, 1967a). Faults F and H were doubtfully inferred from small changes in level of the shores of some islands (not shown on fig. 3). All of the changes along fault H and most along fault F were subsidences, but four measured points along F showed uplifts of 2 to 3 feet. The subsidences could have resulted from landslides or compaction in the unconsolidated sediments in which the changes occurred; landsliding does sometimes produce small areas of uplift. On the basis of the limited data available, I am inclined to agree with Tarr and Martin (1912, p. 35), who state that the evidence for faulting along lines F and H is not convincing.

The differential vertical movements across the faults postulated by Tarr and Martin could have been accommodated by warping, but a fault interpretation is more plausible. A warping of 1 foot vertically in 440 feet horizontally would account for the differences across fault C; even greater warping (1 in 370) occurred in 1899 without faulting on the northwest shore of the bay between the adjacent points marked 47’4” and 33’ll” on figure 3. The 42-foot difference across fault G

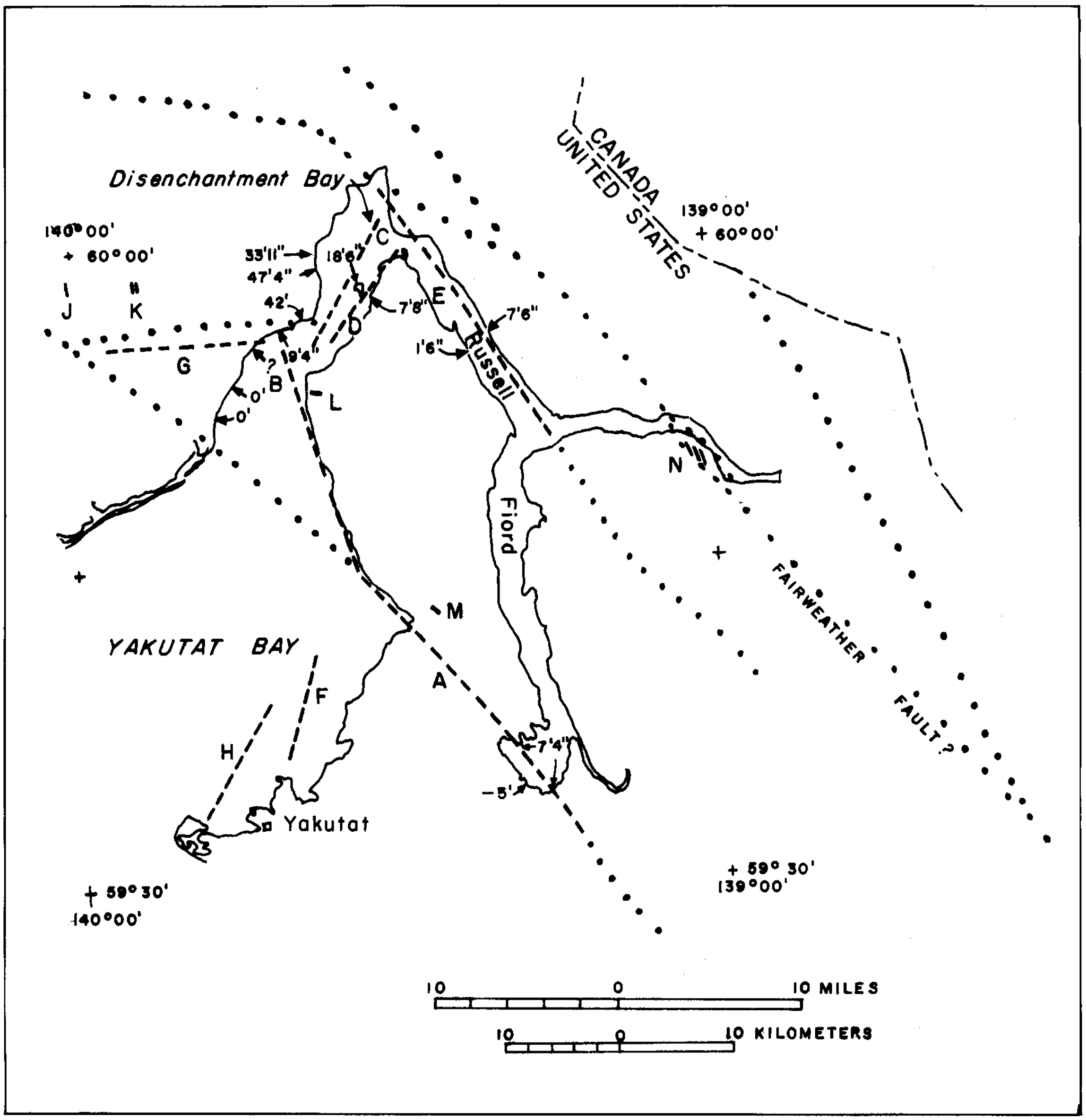

Figure 3. Faulting in and near Yakutat Bay, Alaska

[Heavy dashed lines, faults of 1899 inferred (A through H) and observed (J through W) by Tarr and Martin (1912); dotted lines, faults shown on "Geologic map of the Gulf of Alaska Tertiary province, Alaska" (Plafker, 1967a). A few of the elevation changes measured by Tarr and Martin are indicated in feet and inches.]

would require flexure of 1 in 152 but this was exceeded in the 1964 Alaskan earthquake by warping of 1 in 56 adjacent to the Patton Bay fault on Montague Island (Plafker, 1967b, Pl. 1, sec. A-A'). Nevertheless, as stated by Tarr and Martin (1912, p. 40-41), faulting seems more reasonable than warping to account for the differential displacements because a) the zones of deformation extend in many directions, b) the zones are narrow and the intervening areas are broad, c) minor faulting was seen in the area (see below), and d) profound faulting is indicated by the severe earthquakes.

Faults which Tarr and Martin (1912, p. 37-40) considered minor were seen by them at several points (J,K,L,M, and N, fig, 3) and will be described below. The most prominent were at point N, on The Nunatak (a northwest-trending ridge). There northeast and southwest-facing scarps and graben formed in a zone about 2,000 feet wide and more than a mile long. The highest scarp was 8 feet high, and the net apparent vertical displacement of the ground surface across the zone was about 18 feet, up on the southwest; part of this seemingly resulted from a left-lateral (sinistral) strike-slip component of movement as no evidence of large vertical displacement was found on the adjacent shore (Martin, 1907; Tarr and Martin, 1912, p. 37-40). If the movement at The Nunatak was left-lateral, it is noteworthy because The Nunatak is in or adjacent to the right-lateral (dextral) Fairweather fault or one of its branches (Plafker, 1967a). In the 1958 earthquake the Fairweather fault had more than 21 feet of dextral strike-slip movement about 100 miles south of The Nunatak, and also produced small scarps on The Nunatak itself (Tocher, 1960a).

A fault south of Floral Pass (J, fig. 3) was mentioned by Tarr and Martin but they did not indicate the trend or displacement of the fault nor show it on their maps. Its location was inferred from their geographic description and is approximately correct, but the trend shown on figure 3 was arbitrarily drawn parallel to the nearest observed fault (K),

The faults at K are on a nunatak in Lucia Glacier. The displacements were not reported but the position and trend of the faults are shown on plate 14 of Tarr and Martin (1912),

The faults at point L are 1,900 feet above sea level, on a ridge east of Point Latouche. The location of the faults is shown on Tarr and Martin's 1906 map (p1. 23) but not on their 1912 map (p1. 14). Tarr and Martin (1912, p. 40) state that the strike of the faults is N.85°W. and that several have a throw (vertical displacement) of 3 feet.

Faults striking N.50°W. and N.65°W. developed on the southwest slopes of Mount Tebenkof (M, fig. 3). Tarr and Martin did not give the displacement or show the faults on their maps. The location shown on figure 3 is inferred from their description and a map (Tarr and Martin, 1912, p1. 22) showing their route of travel.

The method generally used in this report to measure distances from the main fault to secondary faults is difficult to apply to the 1899 faulting because of the uncertain identification of the main fault. If fault C is taken as the main fault then secondary faulting occurred 21 miles away on The Nunatak (N, fig. 3) and near the south end of fault A. An alternative hypothesis, expressed by St. Amand (1957, p. 1358), is that the principal movement was on the Fairweather fault and that most of the faults inferred and observed by Tarr and Martin were secondary phenomena. Under this hypothesis the Fairweather fault would be the main fault; fault M is about 16 miles and fault A about 18 miles from the nearest point on the Fairweather fault. Because of these unsolved problems the subsidiary faulting in this earthquake is not listed in table 1 nor included in some of the graphs.

<u>San Andreas fault, California, 1906.</u> Although many secondary ruptures occurred in this earthquake, only those few for which measurements or estimates were made are listed in the table and discussed below.

A branch rupture occurred in the town of Inverness approximately 0.6 mile west of the main trace which, in that vicinity, was in Tomales Bay. The branch fault extended for about half a mile, transversely crossing parts of two valleys and a flat ridge or mesa between the valleys.

Vertical displacement was 2.5 feet and horizontal displacement about 4 feet. The published report (Gilbert, in Lawson and others, 1908, p. 69) states that the horizontal displacement was 2.5 feet but this figure referred to the vertical rather than the horizontal displacement. The notebook of G.K. Gilbert in the U.S. National Archives under the date December 21, 1906 states “The apparent throw is 2 l/2’. The horizontal throw is at least 4’, as shown by a fence, but is too diffused for close measurement.” This movement ruptured the wall of a barn in one of the valleys and produced an irregular ridge on the mesa (Lawson and others, 1908, pl. 45-B and 47-A) which was still visible in 1963.

About 1.5 miles west of the main fault, on the west side of Mt. Wittenburg a secondary fault with a vertical displacement of 1 or 2 feet could be traced for about 1,000 feet (Lawson and others, 1908, p. 75). The topography there is steep and Gilbert noted landslides, but his notebook specifically states that the rupture was not related to landslides. Another crack crossed a spur of Mt. Wittenburg at nearly right angles and from the ridging of the earth along it, Gilbert (Lawson and others, 1908, p. 75) inferred that it had horizontal movement.

A fault with a right-lateral displacement of 2 to 6 inches was observed about one mile west of Tomales Bay and about 1.3 miles from the main fault. It was traced for more than 800 feet (Lawson and others, 1908, p. 75) and Gilbert’s notebook states that it was nearly parallel to the valley in which it occurred; the relation to the topography, coupled with strike-slip movement, effectively rules out landsliding as an origin. About 50 miles south of San Francisco a left-lateral rupture displaced a road, fence, and orchard, and destroyed the house on the Morrell ranch. Many questions regarding the faulting in that vicinity were left unanswered as the investigators were hampered by inadequate maps, thick vegetation, steep topography, and landslides. The report on the earthquake (Lawson and others, 1908, p. 110, 277, fig. 57, pls. 64B, 65A) did not specify the location of the Morrell rupture nor its relation to the main fault. The location of the Morrell house was learned recently from G.A, Waring (oral communication to E.E. Brabb, 1963 or 1964), who investigated the area in 1906, permitting a better interpretation of the data in the 1908 report. Joining the nearest known points on the main fault indicates that the Morrell site is not on the main line of faulting but at least 1,600 feet from it. The 1908 report states (pl. 64B and p. 278) that the Morrell rupture was directly over a railroad tunnel which was not displaced, implying a shallow and possibly landslide origin for it, whereas in fact the house was more than 3,000 feet from the tunnel (shown on topographic maps) and even though the rupture were deep-seated, it could easily have died out in that horizontal distance. Also opposed to a landslide origin is the absence of a second rupture corresponding to the other side of a hypothetical landslide.

North of the town of Bolinas a fault about 1,200 feet west of the main trace crossed Pine Gulch Creek almost perpendicularly. Its angular relation to the creek and its length (about 1,100 feet) are evidence for an origin by faulting rather than by landsliding or other superficial effects of the earthquake vibrations. Although Gilbert (Lawson and others, 1908, p. 67, fig. 28, p1. 39A) did not measure the displacement, in the published photograph one can see about one foot of vertical movement and from the echelon fracture pattern infer at least as much right-lateral movement.

<u>Pleasant Valley, Nevada, 1915.</u> Several secondary ruptures have been reported for this earthquake but little is known of them as they were not investigated in 1915. A prominent rupture in the Sou Hills, attributed to the 1915 faulting by Muller and others (1951), begins 3.5 miles southwest of the south end of the main fault at a perpendicular distance of about 2.5 miles from the projected position of the main fault. It had a vertical displacement of about 3 feet. Other secondary faults southwest and northeast of the main fault are mentioned in the literature

(Muller and others 1951; Ferguson and others, 1952; Page, 1935) but their locations are not precisely given in the reports.

Imperial, California, 1940. Near the north end of the main fault a branch fault extended eastward at least 0.5 mile. Unpublished field notes of J.P. Buwalda, in the files of the California Institute of Technology in Pasadena, record small right-lateral strike-slip and vertical movements on the branch fault.

Vacherie, Louisiana. This fault movement was accompanied by a small earthquake felt locally. The nearest seismograph, which was 50 miles away and designed to record distant large shocks, did not record the earthquake. The initial displacement was 3 inches; it increased to about 8 inches in the next 24 hours (U.S. Army Corps of Engineers, 1950, p. A34-A37; Fisk, 1944, p. 33).

The origin of this faulting remains in doubt. The area is on the flank of a salt dome and is also in the Red River fault zone (Fisk, 1944, p. 33). A well being drilled nearby encountered a strong flow of water under 2,000 pounds of pressure at a depth of 8,800 feet short]y before the surface faulting occurred, suggesting a possible cause-and-effect relation, but prior movement had also occurred on this fault as drilling revealed 3.5 feet of vertical separation of upper Pleistocene sediments at a depth of *55* feet (Fisk, 1944, p1. 17).

Fort Sage, California, 1950. The maximum fault scarp produced in this earthquake was only 8 inches high, but monoclinal warping of the alluvium indicates that the displacement in the underlying rock may have been as much as 2 feet (Gianella, 1957, p. 175). The magnitude given in table 1 is from Richter (1958, p. 516).

White Wolf, California, 1952. A branch fault extended 1.7 miles from the center of the main zone of faulting into the footwall block. The branch fault displayed consistent left-lateral movement, and at a point 1.1 miles from the main zone the displacement was estimated to be 1 foot (Buwalda and St. Amand, 1955, p. 46, p1. 2).

A fracture described by Buwalda and St. Amand (1955, p. 53) about 8 miles north of the main fault on the southwest slope of Breckenridge Mountain was probably tectonic. It was about 0.5 mile long, 4 inches wide, downthrown 4 to 5 inches on the downhill side, and crossed ridges and valleys. A line of older scarps with approximately the same trend extends for several miles northwest of the fracture. This line of scarps lies along the Dougherty fault of Dibblee and Chesterman (1953, p. 46-47, pl. 1); according to their map, the southeast end of the Dougherty fault is about 1 mile from the 1952 fracture. I have not examined this area in the field.

A horizontal shortening of 10 feet across the main fault was measured between the portals of two railroad tunnels (Kupfer and others, 1955, p. 72). Shortening of this large amount was not detected elsewhere; geodetic measurements indicate a shortening of only 2 or 3 feet on a regional scale (Whitten, 1955), and geologic observations suggest a similar figure. The large local shortening has not been satisfactorily explained.

Fairview Peak, Nevada, 1954. The branch and secondary faults listed in the table and the place names mentioned below are shown on the map accompanying the reports of Slemmons (1957) and Steinbrugge and Moran (1957). The first two secondary ruptures listed in the table are, respectively, north and south of Highway 50 on the West Gate fault and east of the main zone of faulting. The third rupture is in the center of Bell Flat, about 11 miles south of the highway. The fourth and fifth ruptures are northwest of Mt. Anna, 17 miles south of Highway 50. These ruptures are beyond the end of the main fault zone and the distances from the zone were obtained by projecting the zone along its strike, toward Eagleville.

The one branch fault listed in the table (column 8) is the southerly branch of the Gold King segment of the main fault, which extends 1.6 miles to the west. The displacement on the branch fault was vertical but of unknown amount.

Dixie Valley, Nevada, 1954. The map accompanying the reports of Slemmons (1957) and Steinbrugge and Moran (1957) show the faults and place names for this event also. Four secondary ruptures are listed in table 1; the first pair occurred on faults east-northeast of IXL Canyon 26 miles north of Highway 50 and the second pair on faults east of Elevenmile Canyon, 9 miles north of the highway. The main fault zone was projected along strike in order to estimate the perpendicular distances of the southerly pair of secondary faults from the zone. One of the northerly pair extended 2.5 miles from the main zone.

Hebgen Lake, Montana, 1959. The Red Canyon and Hebgen faults, the principal faults on which surface movement occurred in this earthquake, are subparallel and about 3 miles apart where they overlap for about 3 miles. In the region of overlap, displacements range from 9 to 15 feet on the Red Canyon fault and from 1 to 5 feet on the Hebgen fault so that locally the latter can be considered a branch of the former and is listed as such in the table.

Of particular interest are four secondary ruptures 7.5 to 8.5 miles from the main faults. They will be described in the order in which they are listed in the table.

At the Basin Ranger Station, about 7.5 miles from the Red Canyon fault, several new scarps, showing displacements as large as 1 foot, formed along prequake scarps (Myers and Hamilton, 1964, p. 59-60, p1. 2).

At the Madison Fork Ranch, 8.5 miles from the Red Canyon fault, several prequake scarps showed new movements ranging from a few inches to 1 foot. A lodge built across the projection of one of the scarps was being slowly deformed prior to the earthquake (Myers and Hamilton, 1964, p. 60), which strongly suggests that tectonic creep was active across this normal fault. In addition to discrete faulting in 1959, the ground was locally warped in this vicinity, affecting a stream, ditch, and the local runoff pattern.

A series of scarps as much as 8 and 9 inches high formed along a preexisting fault and monocline that cross the South Fork of the Madison River about 8 miles from the Red Canyon fault (Myers and Hamilton, 1964, p. 61-62, fig. 35, p1. 2). The origin of the new scarps is uncertain; Myers and Hamilton (1964, p. 62) suggest that they resulted from a combination of earthquake vibrations and folding of the sediments rather than direct fault displacement.

Part of the Madison Range fault, 7 to 8.5 miles from the Hebgen fault, moved in this earthquake. The maximum displacement, 3 feet, occurred at a point 8 miles from the Hebgen fault (Myers and Hamilton, 1964, p. 78, p1. 2).

Fault creep

Fault creep has been recognized at several localities since the original discovery of the process at the Buena Vista Hills (no. 37 of table). The fault creep at Vineyard on the San Andreas fault was found in 1956 and has been measured for several years (Tocher, 1960b). More recently, creep has been recognized on the Hayward fault and described in six papers in the Bulletin of the Seismological Society of America for April 1966. Fault creep has recently been identified at the following additional places: on the Calaveras fault in Hollister, California (Thomas Rogers, oral communication, 1967); north of San Juan Bautista, California, on the San Andreas fault (R.D. Nason, oral communication, 1967); and possibly on the San Andreas fault in the San Francisco Peninsula (Phillip V. Burkland, oral communication, 1967),on the Imperial fault, California (Brune and Allen, 1967b, p. 507-508), and on the Pleasanton and Calaveras faults, Alameda County, California (Gibson and Wollenberg, in press). Creep also seems to have occurred at least locally prior to the Hebgen Lake, Montana, faulting (see p. 19). Fault creep has been preceded or followed by known historic surface fault rupture at all the localities mentioned above except Buena Vista Hills, Vineyard, Hollister, and Alameda County.

Fault creep has occurred at various locations in Texas, where movements on faults have damaged roads, buildings, pipelines and other structures (Bryan, 1933, p. 439; Sheets, 1947, p. 216; Bell and Brill, 1938; Weaver and Sheets, 1962; Wiggins, 1954, p. 308). Some of these movements are undoubtedly related to withdrawal of fluids or secondary effects related to the presence of salt domes, but some probably are tectonic (Weaver and Sheets, 1962, p. 254; Russell, 1957, p. 69).

RELATIONS AMONG PARTICULAR ASPECTS OF THE FAULTING

Some of the data in the table have been plotted on graphs to illustrate relations among various fault parameters. Figures 4-10 all use the same system of symbols, which are explained on figure 6. The numbers alongside the symbols represent the particular episode of faulting, which can be identified by referring to table 1.

Figures 4 and 5 show the relation between the maximum displacement on the main fault at the ground surface and the magnitude of the associated earthquake. As expected, the displacement generally increases as the magnitude increases but with considerable scatter of individual points. A line of best fit (A, fig, 4) for all the points has been obtained by the method of least squares, yielding the equation

$$\log D = 0.57M - 3.39 \qquad \text{(A)}$$

in which D is the maximum displacement in feet and M is the Richter magnitude. The line of best fit for strike-slip faults alone (not shown on graphs) is almost the same as the line for all faults together, and the line for normal faults has a somewhat higher slope than the line for all faults. Inasmuch as only a small number of points are presently available for each of the various types of faults and the best-fit lines are not greatly different, it seems best to combine all types.

A line (B, fig. 4) that includes the largest displacements for all the faults has been drawn parallel to the line of best fit. Its equation is

$$\log D = 0.57M - 2.67 \qquad \text{(B)}$$

Another line (C, fig. 4) corresponding to line B has been drawn on the other side of line A, making the separation between lines A and C the same as between A and B. The equation for line C is

$$\log D \quad 0.57M - 4.11 \qquad (C)$$

Line C bounds all but one of the smallest displacements. The excluded point (numbered 21) represents the Manix California faulting of 1947. Richter has suggested that the surface faulting at Manix was secondary to a concealed main rupture (Richter, 1958, p. 517-518; Allen and others, 1965, p. 768), A larger displacement would shift point 21 closer to, and perhaps to the other side of, line C.

Lines A, B, and C on figures 4 and 5 and the corresponding equations A, B, and C can be used to estimate fault displacement at the ground surface that may accompany an earthquake of a given magnitude occurring in the area studied. Whether line A, B, or C is used depends upon the degree of risk that can be tolerated. For high magnitudes, line B indicates displacements substantially larger than any that have been recorded to date and therefore the line is dashed for magnitudes greater than 7.5. With this exception, the lines permit realistic estimates of fault displacement.

Figure 6 shows the distance from the main fault to the outer edge of the various zones as related to magnitude. The correlation between distance and magnitude is weak and the points are so scattered that a line of best fit was not drawn.

The graph and the table show that the widths of the three zones of faulting differ among the four types of faults in this sample, the strike-slip zones being the narrowest. Roman numerals on figure 6 indicate, for each of the four types of faults, the greatest distance to the outer edge of the main zone (I), the zone of branch faults (II), and the zone of secondary faults (III). The maximum distance from the centerline of the main zone to the outer edge of the main zone of strike-slip faults is less than 0.06 mile, whereas for the other types it is between 0.5 and 0.6 mile. The maximum distance to the edge of the zone of branch faults is less than 0.9 mile for strike-slip faults but 1.6 to 3 miles for the other types. The maximum distance to the edge of the zone of secondary faults is 1.5 miles for strike-slip faults*[*] but 8 to 8.5 miles for the other three types in the sample. Because of the uncertainties regarding the Yakutat Bay faulting of 1899 (see discussion elsewhere in this report) it is not included on the graph, but it may have produced wider zones than given above.

[*] Secondary faulting that occurred 1.8 miles from the Hayward fault is not shown on figure 6 because the magnitude of the earthquake is not known.

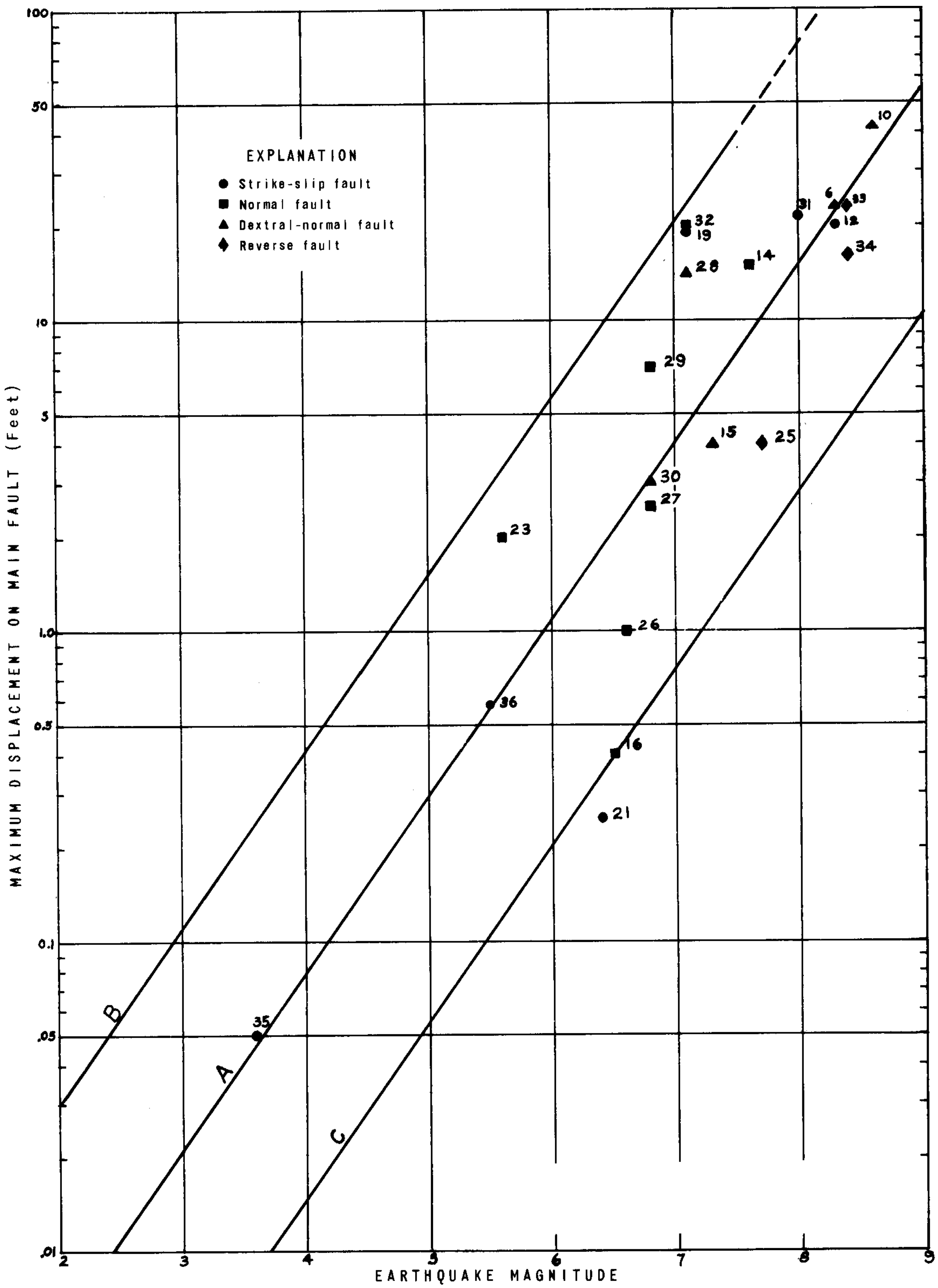

Figure 4. Maximum displacement on main fault as related to earthquake magnitude (logarithmic plot)

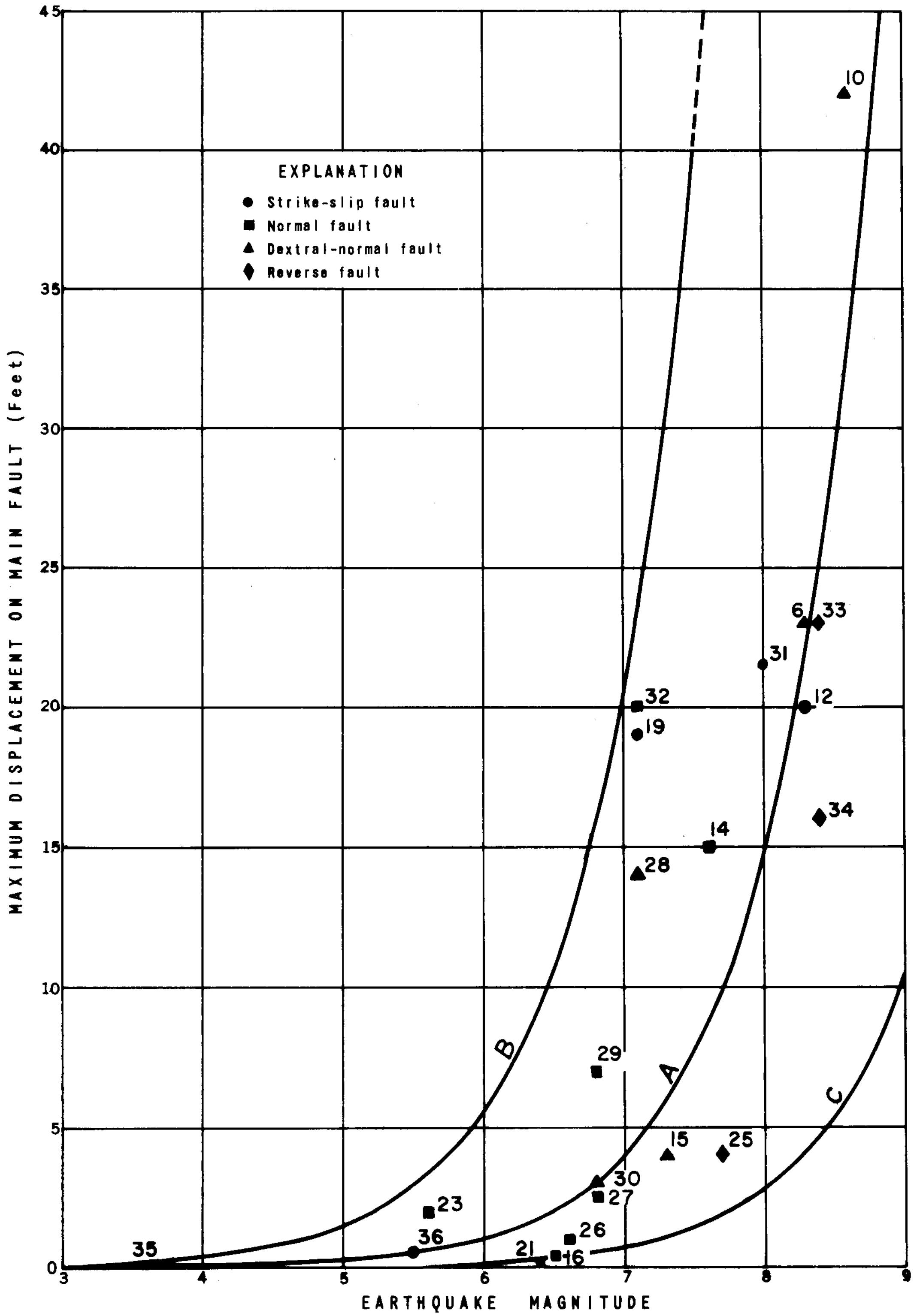

Figure 5. Maximum displacement on main fault as related to earthquake magnitude (arithmetic plot)

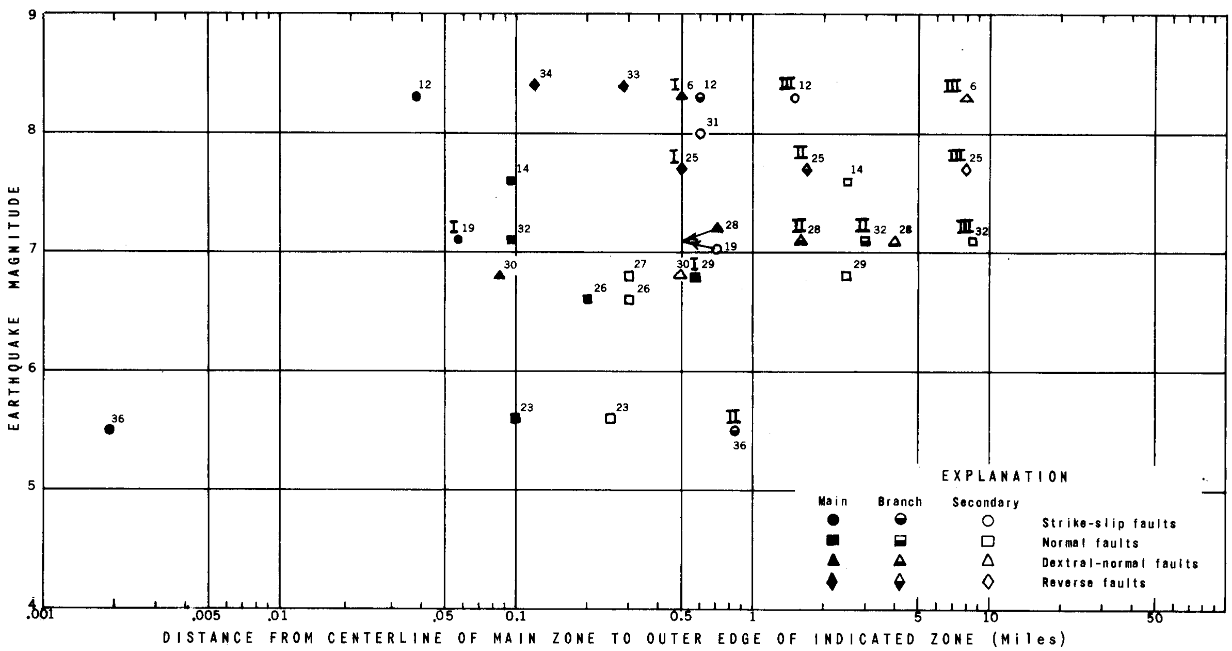

Figure 6. Distance to outer edge of zone as related to earthquake magnitude

Figure 7 shows the displacement, in feet, of secondary and branch faults as related to increasing distance from the main fault, The not-uncommon occurrence of displacements of a few feet at distances ranging from 2 to 8.5 miles from the main fault is noteworthy. Curves were sketched joining all points for particular earthquakes, but the points are either so few or so scattered that the curves can be drawn several ways and are not shown on the graph, The sketched curves did, however, suggest that the displacements on branch and secondary faults decrease more rapidly for strike-slip faults than for the other types.

Figure 8 also shows the relation between distance from the main fault and displacement on secondary and branch faults, but the displacement is plotted as a percentage of the maximum displacement on the main fault rather than in feet. As with the previous graph, curves were sketched for individual earthquakes but are not shown because the points are too few or too scattered. In general, the curves are steep near the main fault but flatten with increasing distance from the main fault. A line which contains all but three of the data points below it has been sketched on the graph. This bounding curve crosses the 20-percent line at a distance of 3 or 4 miles from the main fault and decreases slowly beyond that, but the curve could be drawn in other ways also.

The three data points outside the bounding curve may be incorrect as to amount of displacement associated with the particular earthquakes. The upper pair, which are from the 1872 Owens Valley faulting, were not measured until many years after the earthquake so that it is not known whether part of the displacement may have occurred in prior earthquakes. The other data point, from the 1868 Hayward faulting, is based on the accounts of residents. The fault was not investigated by scientists until 38 years later.

Figure 9 shows the relation between earthquake magnitude and length of surface rupture on the main fault. A line that bounds all of the data points has been drawn on the graph. The position of this line is strongly influenced by two small earthquakes accompanied by surface faulting (no. 35 and no. 36) that occurred in 1966.

With present-day techniques and detailed field examinations, surface faulting will probably be found to accompany many future low-magnitude earthquakes, providing more points near the bounding line on the graph.

Figure 10 shows in a logarithmic plot the relation between maximum displacement on the main fault and length of surface rupture on the main fault. The general increase of displacement with length of rupture is apparent. The line of best fit, obtained by the method of least squares, has the equation

$$\log D = 0.86 \log L - 0.46$$

where D is maximum displacement in feet and L is length of surface rupture in miles. This graph can be used as an aid in roughly estimating the maximum displacement that may occur on a fault of known length.

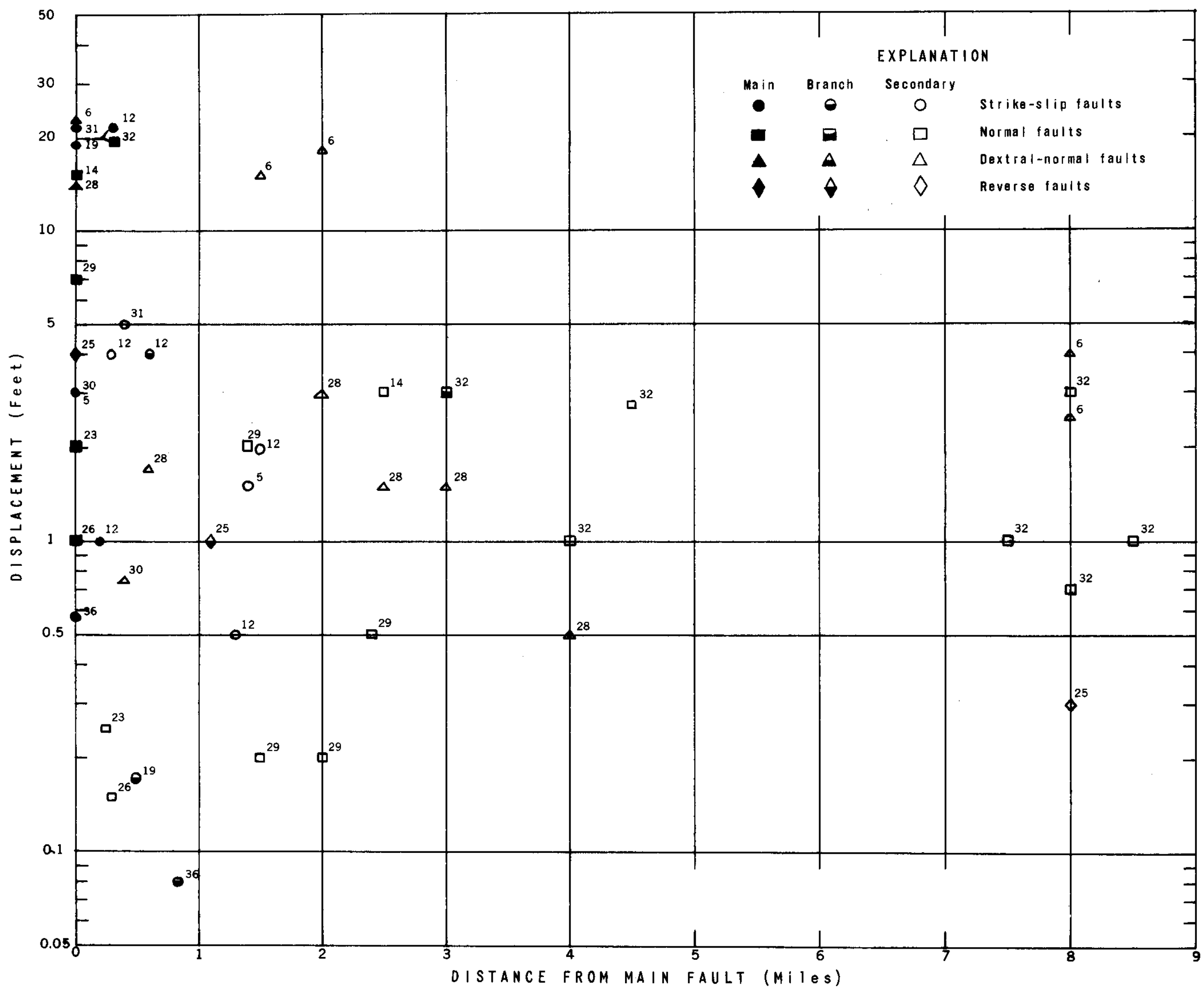

Figure 7. Displacement on branch and secondary faults as related to distance from main fault

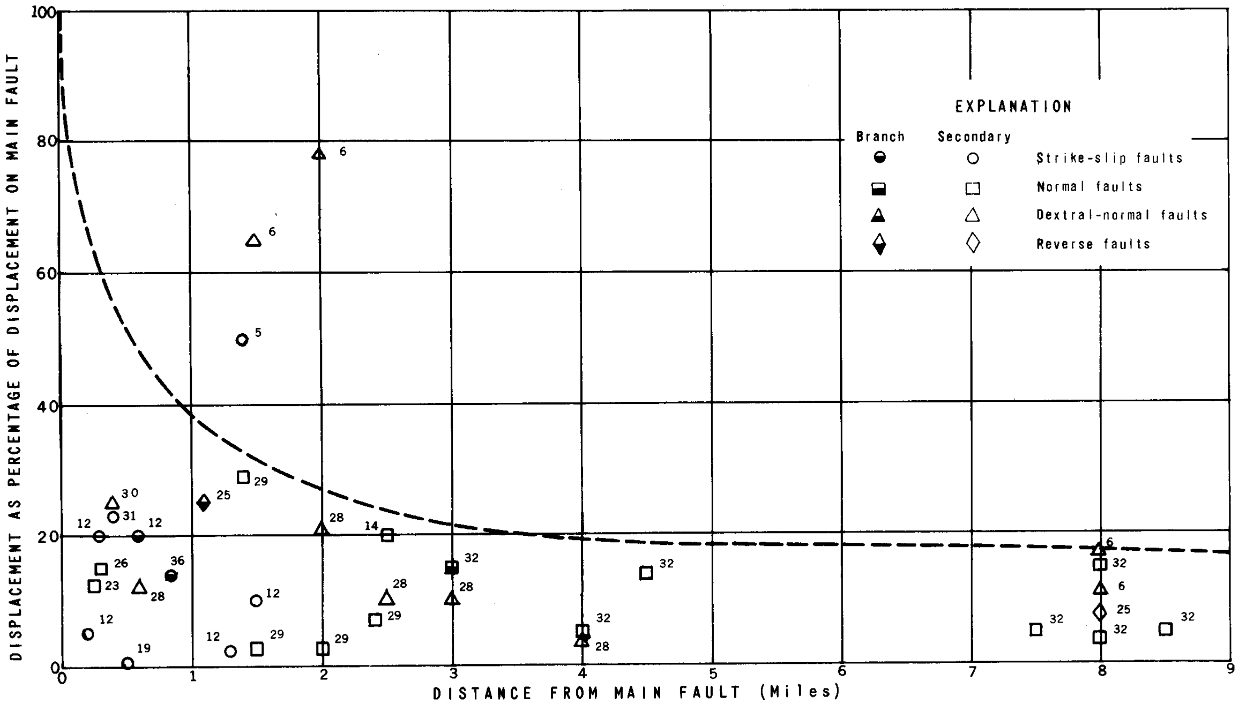

Figure 8. Displacement on branch and secondary faults as related to distance from main fault. Displacement expressed as percentage of displacement on main fault

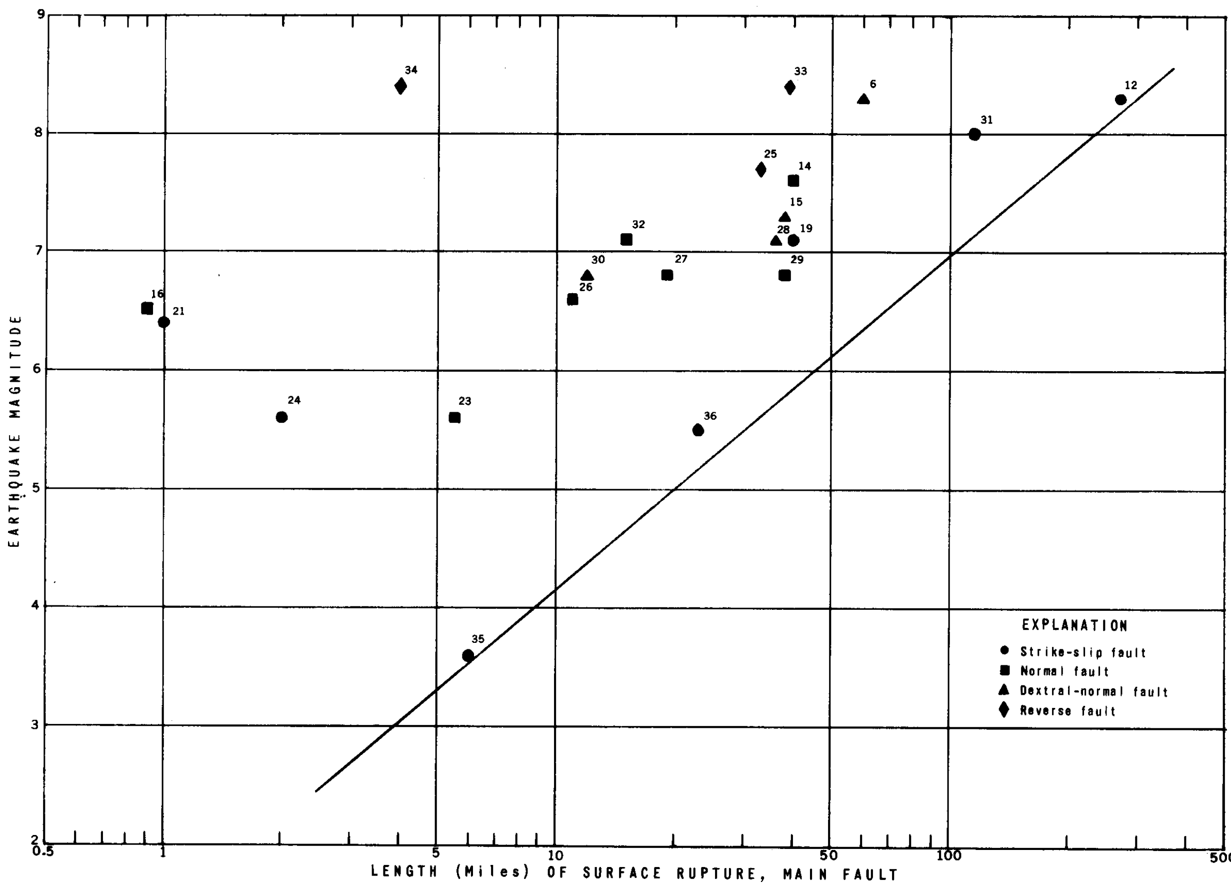

Figure 9. Length of surface rupture on main fault as related to earthquake magnitude

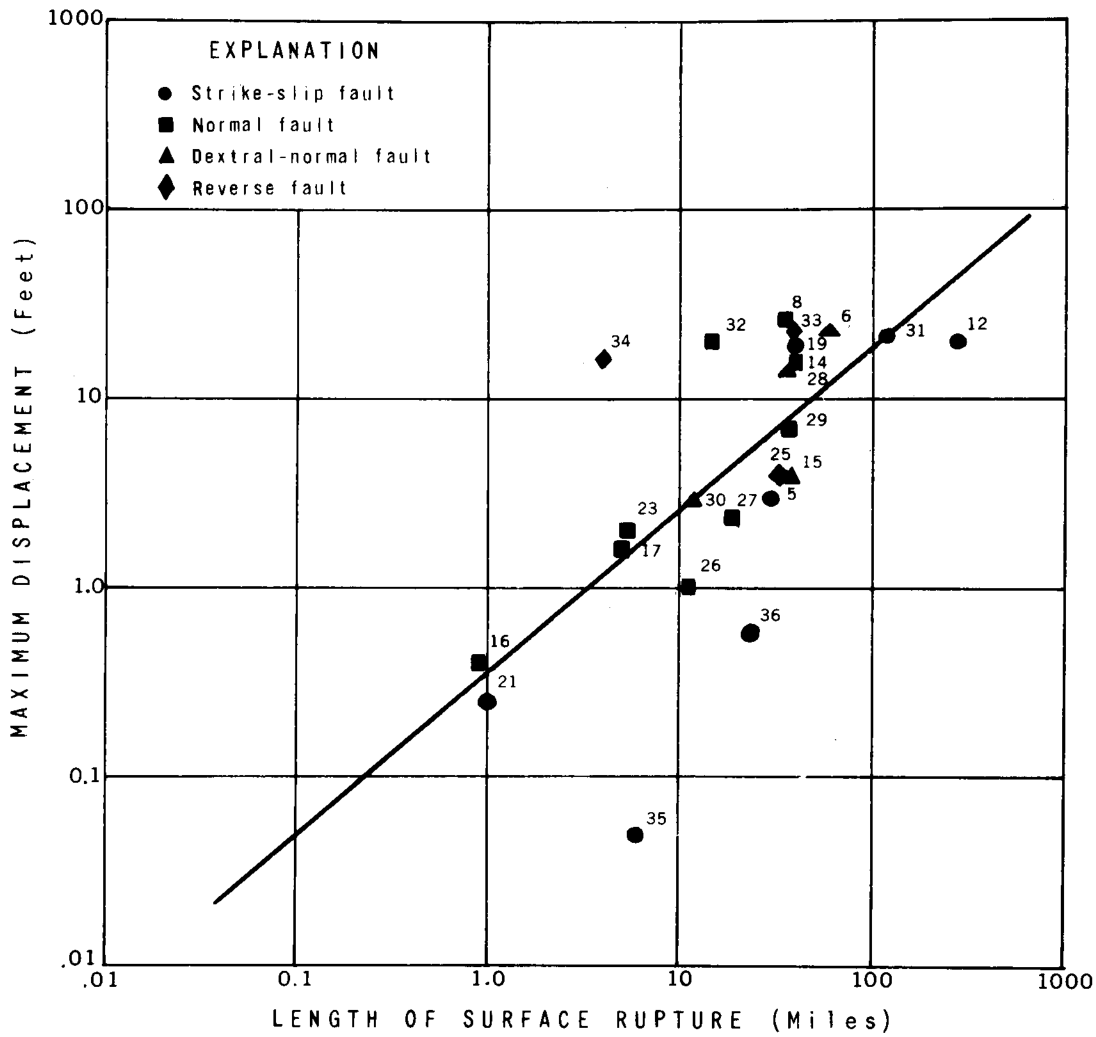

Figure 10. Displacement as related to length of surface rupture on the main fault

CONCLUSIONS

Several tentative conclusions, important in the siting of vital structures such as nuclear reactors, can be reached on the basis of this preliminary study of historic surface faulting:

1. Branch and secondary faulting commonly accompanies the main faulting. About half of the more than 30 main ruptures of undoubted tectonic origin had branch and secondary ruptures associated with them. The proportion is probably greater than half however, because in only one-sixth of the events are we reasonably certain that branch and secondary faulting did not occur.

2. The main fault zone and the zones of branch faults and of secondary faults are narrower for strike-slip faults than they are for normal faults, reverse faults, or dextral-normal faults. The maximum distances (for the particular events studied) from the center of the main fault zone to the outer edges of the three zones are A) for main zone, about 0.06 mile for strike-slip faults and 0.5 to 0.6 mile for the other types; B) for branch faults, 0.85 mile for strike-slip faults and 1.6 to 3 miles

for the other types; C) for secondary faults 1.8 miles for strike-slip faults and 8 to 8.5 miles for the other types. Secondary faulting in the Yakutat Bay earthquake of 1899 may have been as much as 16 to 21 miles from the main fault.

3. A total of seven ruptures, associated with three earthquakes generated by normal, dextral-normal, and reverse faults, occurred 7.5 to 8.5 miles from the main faults. The displacements ranged from 0.3 feet to 4 feet and were equivalent to 3.5 percent to 17 percent of the maximum displacement on the main fault.

4. The displacements on individual branch and secondary faults were less than 30 percent as large as the displacement on the main fault, with three doubtful exceptions that ranged between 50 and 80 percent.

5. With one possible exception, the main faulting occurred along faults that were, or could have been identified beforehand by geologic means. The possible exception is the Sonora, Mexico faulting 1887, for which data are incomplete.

6. One-third of the branch and secondary faulting covered in this study is known to have occurred on preexisting faults that could have been identified by simple geologic investigations; whether the other two-thirds could have been also is not known.

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