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OBSERVATIONAL SEISMOLOGY AND THE EVALUATION OF EARTHQUAKE HAZARDS AND RISK IN THE WASATCH FRONT AREA, UTAH

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Submitted to

Hays, W.W., and Gori, P.L., eds.

ASSESSMENT OF REGIONAL EARTHQUAKE HAZARDS AND RISK ALONG THE WASATCH FRONT, UTAH

U.S. Geological Survey Professional Paper

October 1987

Revised June 1988

ABSTRACT

This paper presents and considers in a systematic way up-to-date information from observational seismology that is basic to evaluating earthquake hazards and risk in the Wasatch Front area. We present fundamental information relating to (1) the earthquake data base, (2) the seismotectonic framework, (3) seismic source zones and seismicity parameters, (4) ground-shaking hazard, and (5) current seismicity and the Wasatch fault.

Important features of the seismotectonic framework of the Wasatch Front include (1) a threshold magnitude for surface faulting of M_L 6.0 to 6.5, (2) a maximum magnitude of M_S 7.5 to 7.7, (3) the absence of any large surface-faulting earthquakes and the notable paucity of smaller earthquakes on the Wasatch fault during historical time, and (4) the problematic correlation of background seismicity with mapped Cenozoic faulting. In light of this framework, we consider seismic hazards in the Wasatch Front region to arise from two fundamental sources: first, the occurrence of infrequent large (M_S 6.3±0.2 to 7.5±0.2) surface-faulting earthquakes on identifiable faults having evidence of late Quaternary displacement and, second, small- to moderate-size (up to M_L 6.5) earthquakes that are not constrained in location to mapped faults and may occur anywhere throughout the region. The small to moderate earthquakes dominate the historical earthquake record, and at most localities are the largest contributor to probabilistic ground-shaking hazard for exposure periods of 50 years or less. Recurrence modeling using independent main shocks from the 23.5-year instrumental catalog from July 1962 through 1985 predicts an average recurrence interval of 24^{+16}_{-10} years for potentially damaging earthquakes of magnitude 5.5 or greater in the Wasatch Front area. Eight such shocks occurred from 1850 through 1987, which gives an observed average recurrence interval of 17 years.

INTRODUCTION

The record of earthquake activity since 1850, together with geological observations dating from more than a century ago, firmly establishes the danger of earthquakes in Utah's Wasatch Front area. The purpose of this paper is to present and consider in a systematic way information from observational seismology that is basic to evaluating earthquake hazards and risk in the Wasatch Front area.

We follow usage urged by the Earthquake Engineering Research Institute and distinguish a seismic hazard from seismic risk in the following way. A seismic hazard is "any physical phenomenon...associated with an earthquake that may produce adverse effects on human activities," whereas seismic risk is the "probability that social or economic consequences of earthquakes will equal or exceed specified values at [one or more sites] during a specified exposure time" (EERI Committee on Seismic Risk, 1984). The most notable seismic hazards are the geological processes of ground shaking, ground failure, surface faulting, tectonic deformation, and inundation.

Insofar as the evaluation of earthquake hazards involves recognition of the location, frequency, and severity of those hazards, observational seismology is generally relied upon to characterize the space, time, and size distribution of earthquakes giving rise to those hazards. This might involve little more than a qualitative consideration of the available earthquake record and the spatial pattern of earthquake occurrence. On the other hand, more rigorous evaluations of seismic hazard and risk rely on observational seismology to specify quantitative models of earthquake behavior and mechanics so that either the level of a hazard (e.g., a non-exceedance value of ground motion) or the level of risk can be computed at one or more sites for some exposure time. Either a deterministic or a probabilistic approach may be used. In the former case, each independent variable has a single value and a model predicts a specific value for the dependent variable. For example, the maximum ground shaking expectable at a site might be estimated from the comparative effects of nearby earthquake source zones, each of which is assigned a maximum-size event and minimum distance to the site—with a corresponding upper limit of predicted ground motion. In the case of a probabilistic approach, uncertainties arising from natural variations or incomplete knowledge are taken into account, and probability theory is used for the analysis (e.g., see Youngs and others, this volume; Algermissen and others, this volume).

A flowchart shown in figure 1 outlines the basic elements of a modern seismic hazard analysis (e.g., Savy and others, 1986; Electric Power Research Institute, 1987)—using as an example the objective of estimating the hazard of ground motion. (Seismological input to a risk analysis would be similar.) The sequence of necessary procedures is shown by steps 1 through 5 in the left-hand column; interrelated aspects of observational seismology are shown in the right-hand column. We use the figure as a useful guide for our presentation as we give an overview of fundamental information from observational seismology in the Wasatch Front area contributing to steps 1 to 4. Sequentially we consider (a) the earthquake data base, (b) the seismotectonic framework, and (c) seismic source zones and seismicity parameters. We then discuss a selected aspect of ground-shaking hazard—referring the reader to Youngs and others (this volume) for an example of the fully completed process of step 5 in which probabilistic estimates of ground motion are made. In the final section we address the question. What does observational seismology tell us about the behavior of the Wasatch fault?

FIGURE 1.--NEAR HERE

ACKNOWLEDGMENTS

The data in this manuscript implicitly reflect substantial efforts by numerous individuals associated with the University of Utah Seismograph Stations. We thank D. Veneziano of the Massachusetts Institute of Technology for providing data on independent main shocks for the recurrence modeling, and for assistance with the probabilistic hazard methodology. We also thank J.A. Barlow, L.B. Burnett, P.A. Onstott, K.J. Quigley and J.E. Shemeta for assistance in the manuscript preparation. Critical reviews were provided by R.L. Wheeler and C.J. Langer of the U.S. Geological Survey. The research arises from ongoing support by the U.S. Geological Survey, Department of the Interior, currently under award numbers 14-08-0001-G1349 and 14-08-0001-A0265, and from support by the state of Utah.

EARTHQUAKE DATA BASE

The catalog of documented earthquakes in the Utah region (step 1, fig. 1), as elsewhere in the western United States, is a mixed one relying initially upon reports and newspaper accounts of felt earthquakes, and later upon seismographic recordings during several stages of evolving instrumental coverage (Arabasz and others, 1979, 1980; see fig. 2). (Our usage of "Utah region" is defined in fig. 2.) The historical earthquake record effectively dates from 1850 with the publication of the first newspaper in the region, shortly after settlement by Mormon pioneers beginning in 1847. Instrumental earthquake locations in the region, based on regional seismographic recordings in the western United States, date from about 1938 with the exception of the 1934 M_S6.6 Hansel Valley earthquake and its larger aftershocks.

FIGURE 2.--NEAR HERE

The most prominent sources of earthquake data for the Utah region are (1) compilations made by the University of Utah Seismograph Stations (UUSS) (Arabasz and others, 1979; Richins and others, 1981, 1984; Brown and others, 1986; also, unpublished current data) and (2) data files of the National Geophysical Data Center, National Oceanic and Atmospheric Administration (NOAA). Other earthquake summaries include: (1) a recent compilation for the state of Utah by Stover and others (1986)[1], (2) a data file compiled by Askew and Algermissen (1983) for the Basin and Range province, (3) a western U. S. data file produced by Eddington and others (1987) for a study of Basin and Range geodynamics, and (4) a continental-scale data file produced by Engdahl and Rinehart (1986) for the "Decade of North American Geology" publication series.

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[1]This compilation omits significant earthquakes in Utah that occurred on November 10, 1884, July 21, 1959, and August 30, 1962 (table 1; Coffman and others, 1982).

Ideally, the establishment of a master "consensus" catalog would involve the coordinated and formalized efforts of numerous individuals with relevant data and expertise, as was recently done for the entire central and eastern United States (Electric Power Research Institute, 1987). The required efforts relate to establishing catalog completeness, uniform estimates of earthquake size, preferred epicentral locations and origin times, and to documenting uncertainties. Similarly rigorous and formal scrutiny of a data base for the Utah region remains to be made. In this paper, we rely upon the University of Utah's data base, which represents the primary source of instrumental earthquake data since mid-1962 for the Utah region and which includes a comprehensive listing of historical seismicity for which only minor variance should be found with other catalogs. For 1962 to 1986, the UUSS catalog contains an order of magnitude more earthquakes than the NOAA data file for the Utah region (e.g., 6,994 versus 342 earthquakes for the Wasatch Front area alone).

Although seismographs were first installed on the University of Utah campus in 1907, contributions to the instrumental location of regional earthquakes postdate 1939 when photographic records from modern seismographs began to be routinely forwarded from Salt Lake City to the U.S. Coast and Geodetic Survey. Systematic computerized locations based on local seismographic coverage in the Utah region by the University of Utah date from mid-1962. From mid-1962 to late 1974, a skeletal statewide network of several widely-spaced stations was in operation (fig. 2, upper right). Instrumental earthquake data for the 1962-1974 period were systematically re-analyzed and revised in a major study by the UUSS (Arabasz and others, 1979). Since late 1974, the University of Utah has operated a modern telemetered network of high-gain short-period seismographic stations in the Intermountain region. About two-thirds of the current network's 85 stations lie within the Utah region (fig. 2, lower right). The seismographic data are centrally recorded at the University of Utah in Salt Lake City. From 1974 through 1980 data were recorded in analog form; since January 1, 1981, recordings have been in digital form.

The UUSS catalog for the Utah region currently contains 9,561 earthquakes for the period from 1850 through 1986. These include 413 (chiefly non-instrumental) earthquake locations from 1850 through June 1962, and 9,148 (instrumental) locations from July 1, 1962 to

December 31, 1986. Magnitudes given in the UUSS catalog are estimates of local Richter magnitude (M_L) based on systematic procedures described, for example, in Brown and others (1986). Such estimates may differ significantly from values of magnitude in the NOAA catalog, which are typically body-wave magnitude (m_b) and known to be commonly as much as one magnitude unit larger than M_L for small ($m_b \leq 4.0$) earthquakes (Dewey, 1987). We refer the reader to special publications of the UUSS (e.g., Arabasz and others, 1979; Brown and others, 1986) for other details of the UUSS data base.

SEISMOTECTONIC FRAMEWORK

The characterization of the seismotectonic framework of any seismically active region (step 2, fig. 1) basically involves an understanding of its geological and geophysical makeup, its earthquake-generating faults, and the operative deformational processes that lead to earthquake occurrence. Previous studies which have developed such a framework for the Wasatch Front area and its surrounding region include those by Smith and Sbar (1974), Smith (1978), Arabasz and others (1980), Zoback (1983), Smith and Bruhn (1984) and Arabasz and Julander (1986). We will not attempt a complete review of previous studies here. Our intent in this section is (1) to summarize some essential characteristics of the seismotectonic framework of the Wasatch Front area and (2) to emphasize new information acquired from observational seismology by researchers at the University of Utah. Information from network and portable-array seismology (element 8, fig. 1) includes precise earthquake locations, earthquake focal mechanisms and source properties, strain-rate tensors from seismic-moment release, and models of crustal structure.

General Setting and Characteristics

The Wasatch Front area, synonymous herein with the rectangular area outlined in figure 3, is located along the eastern boundary of the Basin and Range province. This boundary coincides with a prominent west-facing topographic escarpment that follows the 370-km-long Wasatch normal-fault zone. The Wasatch Front area is traversed by the Intermountain seismic belt (ISB), a coherent belt of intraplate earthquake activity extending more than 1,300 km from southern Nevada and northern Arizona to northwestern Montana (Smith and Sbar, 1974; Smith, 1978; Stickney and Bartholomew, 1987). In general, the ISB is characterized by late Quaternary normal faulting, diffuse shallow seismicity (focal depths < 15-20 km), and episodic scarp-forming earthquakes (M~6.5-7.5), all associated with intraplate deformation within the western North American plate.

FIGURE 3.--NEAR HERE

Since 1850, at least 16 independent earthquakes (aftershocks excluded) of magnitude 6.0 or greater have occurred within the ISB (fig. 3). Three of these historical earthquakes were associated with documented surface faulting. Normal fault scarps with maximum surface displacements of 0.5 m, 5.5±0.3 m, and 2.7 m, respectively, were produced by the M_S6.6 Hansel Valley, Utah, earthquake of March 1934 (Shenon, 1936), the M_S7.5 Hebgen Lake, Montana, earthquake of August 1959 (Bonilla and others, 1984), and the M_S7.3 Borah Peak, Idaho, earthquake of October 1983 (Crone and others, 1987).

The ISB within the Utah region is notably characterized by: (1) a general predominance of normal faulting, reflecting an extensional stress regime—although young strike-slip deformation has recently been recognized from seismological and geological studies in central Utah (Arabasz and Julander, 1986; Anderson and Barnhard, 1984); (2) moderate background seismicity, which is lower by a factor of 4 to 6 than that along the western North American plate boundary (Arabasz and Smith , 1981); (3) diffuse seismicity having weak correlation with major active faults, and with focal depths almost exclusively shallower than 15-20 km; (4) relatively long (~1,000 yrs or more), and perhaps temporally variable, average recurrence intervals for surface faulting on individual fault segments (Schwartz and Coppersmith, 1984; Wallace, 1987; Machette and others, this volume); (5) slip rates of late Quaternary faulting of about 1 mm/yr or less, one to two orders of magnitude lower than those on major plate-boundary faults (Schwartz, 1987); and (6) the historical absence of any surface-faulting earthquake larger than the M_S6.6 Hansel Valley earthquake of 1934—despite the presence of abundant late Quaternary and Holocene fault scarps.

Figure 4 illustrates in cartoon form some important aspects of the seismotectonic framework of the Wasatch Front area. (Letters in parentheses here are keyed to the figure.) There is an eastward increase in total crustal thickness (a) from about 36 to 44 km across the transitional boundary between the eastern Basin and Range and the Middle Rocky Mountain-Colorado Plateau provinces (Loeb and Pechmann, 1986; Loeb, 1986). Total lithospheric thickness similarly increases from about 65 km beneath the Basin and Range to more than 80 km beneath the Colorado Plateau (Smith and others, 1987). A wedge of material (b) with P-wave velocity of ~7.5 km/sec, formerly thought to be upwarped mantle, has been mapped by Pechmann and Loeb (Pechmann and others, 1984; Loeb, 1986) as lying above the 7.9 km/sec Moho—based on analysis of travel times from local earthquakes and blasts recorded by the University of Utah's regional seismic network. The importance of low-angle detachments (c) and listric-fault geometries (d) in upper-crustal structure beneath the eastern Basin and Range appears well established from COCORP seismic reflection profiling (Allmendinger and others, 1983, 1987) and from interpretation of industry seismic reflection data at the University of Utah (Smith and Bruhn, 1984; see also Smith and others, 1987, for a summary of multiple studies).

FIGURE 4.--NEAR HERE

The brittle-ductile transition (e) marking the base of the seismogenic layer has been modeled rheologically by Smith and Bruhn (1984) to be transitional, perhaps as shallow as ~8 km but probably about 10 to 15 km deep beneath the Wasatch Front area. Large surface faulting earthquakes in the Wasatch Front area are expected to nucleate (f) at that depth on penetrative planar faults of moderate dip (Smith and Richins, 1984; Doser, 1985a) somehow connected to surface fault scarps (g). As discussed later, most of the small to moderate-size background seismicity in the area is not directly associated with the first-order faults. Source properties for small to moderate earthquakes in the Utah region appear to be comparable to those for other seismic zones in the western U.S., but the moment-magnitude relationship may differ (Doser and Smith, 1982; Peinado, 1986). Variability in slip, rupture velocity, and fault orientation during large normal-faulting earthquakes can be expected to produce locally complex ground motions (Benz and Smith, 1987). Segmentation (h) of first-order faults such as the Wasatch fault (Swan and others, 1980; Schwartz and Coppersmith, 1984; Machette and others, this volume) places important constraints on rupture length, maximum earthquake size, and rupture dynamics.

The Wasatch Front area is characterized by roughly east-west extensional deformation (i), as indicated by earthquake focal mechanisms and slickenside data (Smith and Lindh, 1978; Arabasz and others, 1980; Zoback and Zoback, 1980; Zoback, 1983). Twenty-four single-event focal mechanisms recently determined by Bjarnason and Pechmann (1988), representing the best focal mechanism data to date for the Wasatch Front area, have an average tension-axis azimuth of 96°±12° s.d. Extension calculated by Eddington and others (1987) from moment tensors of historical earthquakes (see also Doser and Smith, 1982) implies an average strain rate of about 2 x 10^{-16}/sec for the Wasatch Front area and a total extension rate of 1 to 2 mm/yr across the study area.

The stress tensor in the upper crust (j) implied by earthquake focal mechanisms and other stress-indicator data (e.g., Zoback, 1983) has a vertical maximum principal stress axis and intermediate and minimum principal stress axes lying in the horizontal plane, with the latter oriented in an east-west (±20°) direction. Zoback (1984) has argued that both horizontal principal stresses are approximately equal in magnitude along the Wasatch Front, implying the potential for slip on normal faults of varying strike. Earthquake focal mechanisms, however, display strong clustering of tension axes in an east-west direction (Arabasz and Julander, 1986; Bjarnason and Pechmann, 1988). Focal mechanisms for earthquakes in the Wasatch Front region south of about 40°N show a mixture of normal, oblique-normal, and strike-slip faulting, in contrast to those north of 40°N which show predominantly normal faulting. This observation suggests that in the southern Wasatch Front region the maximum and intermediate principal stresses may be of similar magnitude (Bjarnason and Pechmann, 1988).

Late Quaternary Faulting

In the absence of a definitive map of known and suspected active faults throughout the Wasatch Front area, efforts were made to compile a base map of late Quaternary faulting for comparison with instrumental seismicity. The resulting map shown in figure 5, which relies chiefly on published sources, includes the traces of fault displacements of Holocene (less than

10,000 yrs B.P.) and late Pleistocene (10,000 to about 500,000 yrs B.P.) age.

FIGURE 5.--NEAR HERE

The following sources were used to compile the digitized base map of figure 5: The trace of the Wasatch fault is based chiefly on detailed mapping done by Cluff and others (1970, 1973, 1974) and was taken, in part, from subsequent compilations by Davis (1983a,b; 1985). Depiction of the West Valley fault zone near Salt Lake City is from Keaton and others (1986). Faulting to the east of the Wasatch fault in Utah is from detailed maps of Sullivan and others (1986) and Foley and others (1986); that in Wyoming, from Gibbons and Dickey (1983). The trace of the East Great Salt Lake fault, lying within the bounds of the Great Salt Lake, was taken from Cook and others (1980) and Viveiros (1986). West of 112°W, we relied heavily on maps of fault scarps in unconsolidated sediments published by Bucknam (1977) and Bucknam and Anderson (1979). Some additional faults in the "Western Desert" region of Utah included in the compilation of Anderson and Miller (1979) were added for completeness. Finally, faulting to the north of 42°N in Idaho, other than the northern extension of the Wasatch fault, was taken from Witkind (1975).

There is some inhomogeneity in figure 5 in that some of the fault traces to the west of the Wasatch fault within the Basin and Range province reflect only the extent of mapped fault scarps in unconsolidated deposits and not necessarily the entire length of a seismogenic range-front fault. Fluctuation of ancient Lake Bonneville, especially between about 25,000 yrs and 13,000 yrs ago (Currey and others, 1984), could have obliterated evidence of late Quaternary surface faulting in many places.

The Wasatch fault is by far the best-studied fault depicted in figure 5. We refer the reader to other papers in this volume for summaries of up-to-date paleoseismological information on its segmentation, slip rate, and the timing and size of prehistoric earthquakes. A major active fault to which little attention has heretofore been paid is one beneath the Great Salt Lake that Cook and others (1980) named the "East Great Salt Lake fault zone" and whose slip rate and earthquake potential have recently been investigated by one of us (Pechmann, 1987; Pechmann and others, 1987). This fault zone can be clearly seen in seismic reflection profiles across the lake (Mikulich and Smith, 1974; Smith and Bruhn, 1984; Bortz and others, 1985; Viveiros, 1986). Reflection data and well data indicate that the sedimentary basin underlying the lake deepens eastward and is bounded on the east by the East Great Salt Lake fault. The deepest part of the basin contains more than 10,000 feet (3,048 m) of post-Miocene sedimentary rocks (Mikulich and Smith, 1974; Bortz and others, 1985; Viveiros, 1986), indicating major subsidence during the past 24 million years.

The East Great Salt Lake fault cuts sediments identified as Quaternary on the basis of well data (Mikulich and Smith, 1974; Viveiros, 1986) and must be considered active. Seismic reflection data (Mikulich and Smith, 1974; Viveiros 1986) indicate that the East Great Salt Lake fault appears to offset sediments to within at least 0.015-0.025 sec two-way travel time beneath the lake bottom, corresponding to an approximate depth of less than 10-20 m , which implies that slip has occurred in the recent geologic past. Viveiros (1986, p. 72) estimated fault slip rates on the East Great Salt Lake fault of 0.96 mm/yr during the Pliocene and 1.48 mm/yr during the Quaternary from the thicknesses of sedimentary deposits—dependent upon an interpreted geometry of faulting. Pechmann and others (1987) interpret average Quaternary slip rates of 0.4 to 0.7 mm/yr, taking subsurface fault dip into account and assuming that rates of sedimentation adjacent to the fault are controlled by subsidence on the fault. These slip rates are about half the recent slip rates along central segments of the Wasatch fault (Schwartz and Coppersmith, 1984).

The 1959 Hebgen Lake and 1983 Borah Peak Earthquakes

The only historical earthquake in the Utah region known to have produced surface faulting occurred on March 12, 1934, in Hansel Valley just north of the Great Salt Lake (figs. 3, 5). This earthquake was assigned a magnitude of 6.6 by Gutenberg and Richter (1954), and is the largest earthquake to have occurred in the Utah region since 1850. Because earthquakes with surface displacements much larger than the 0.5 m of the 1934 earthquake are expected to occur in Utah in the future, based on geologic evidence, information from large surface faulting earthquakes elsewhere in the Intermountain seismic belt and in the Basin and Range province is important for evaluating their likely magnitudes and other characteristics.

In the Intermountain seismic belt, there have been two large, historical normal faulting earthquakes over magnitude 7.0, both of which produced surface rupture: the October 28, 1983, M_S7.3 (USGS determination) Borah Peak earthquake in central Idaho, and the August 18, 1959, (GMT), M_S7.5 Hebgen Lake earthquake in southern Montana (fig. 3). These two earthquakes are generally considered to be good models for future large earthquakes on the Wasatch fault and other major faults in Utah (Smith and Richins, 1984; Doser, 1985a). The surface wave magnitude (M_S) of 7.5 for the Hebgen Lake event is from Abe (1981), and is probably more accurate than a previous estimate of 7.1, attributed by Murphy and Brazee (1964) to Pasadena. The Hebgen Lake earthquake was accompanied by 35 km of surface faulting along the Red Canyon and Hebgen faults with vertical displacements of up to 5.5±0.3 m (Bonilla and others, 1984; Witkind, 1964) and an average displacement of 2.1 m (Hall and Sablock, 1985). The Borah Peak earthquake produced 36 km of surface faulting along the Lost River and Arentson Gulch faults with vertical displacements of up to 2.7 m and an average displacement of 0.8 m (Crone and Machette, 1984; Crone and others, 1987). Both earthquakes nucleated at depths of about 15-16 km and ruptured upward along faults dipping at 45°-60° (Doser, 1985a, b; Doser and Smith, 1985).

The most reliable and physically meaningful measurement of earthquake size is the seismic moment, M_o, (Aki, 1966) given by

$$M_o = \mu S d$$

where μ is the shear modulus, S is the area of the rupture surface, and d is the average displacement along the rupture surface. From the seismic moment, a moment magnitude, M_W (Kanamori, 1977; Hanks and Kanamori, 1979) can be calculated from the definition

$$M_w = (2/3)\log M_o - 10.7$$

M_w should be comparable to M_s for earthquakes of $5.0 \leq M_w \leq 7.5$ (Hanks and Kanamori, 1979). The Hebgen Lake earthquake had a seismic moment of 1.0×10^{27} dyne-cm (Doser, 1985b), which converts to a moment magnitude of 7.3. The Borah Peak earthquake had a moment of 2.1×10^{26} (Doser and Smith, 1985) to 3.1×10^{26} (Ekstrom and Dziewonski, 1985), which gives a moment magnitude of 6.8 to 7.0.

Threshold of Surface Faulting

Various authors (e.g. Arabasz, 1984; Arabasz and Julander, 1986; Doser, 1985a) have suggested that the threshold magnitude for surface faulting in Utah is approximately 6.0-6.5. This conclusion appears to be well founded based on the historical record of earthquakes in the Intermountain seismic belt and in the Basin and Range province. Bucknam and others (1980) note that all 7 historical earthquakes of $M_L > 6.3$ in the Great Basin have produced surface faulting, including the 1934 M_S 6.6 Hansel Valley, Utah, event. In their tabulation of 11 earthquakes with historical surface faulting in the Basin and Range Province, all 5 events with $M_L < 6.8$ had maximum displacements of less than 1 meter. The tabulation includes one California normal-faulting earthquake of M_L 5.6 in 1950 that had 0.2 m maximum displacement and a Nevada earthquake of M_L 6.3 in 1934 that had 0.1 m maximum displacement. In the Intermountain seismic belt, Doser (1985a) points out that neither the 1975 M_L 6.0 Pocatello Valley earthquake nor the 1975 M_L 6.1 Yellowstone Park earthquake (fig. 3) had identifiable surface faulting, although both earthquakes were accompanied by an apparently coseismic subsidence of up to 12-13 cm (Bucknam, 1976; Pitt and others, 1979). On the basis of the historical record, we adopt M_L 6.3±0.2 as a reasonable estimate for the threshold of surface faulting in the Utah region. The implication of this threshold is that one can argue that earthquakes up to this size could occur anywhere in the Wasatch Front region within the main seismic belt, even where there is no geologic evidence for Quaternary surface faulting. We elaborate in a later section.

Seismicity

Figure 6 shows the distribution of all historical main shocks of estimated Richter magnitude 4.0 or greater (or maximum Modified Mercalli intensity V or greater) in the Utah region. The historical sample includes at least fifteen independent main shocks that have had an estimated Richter magnitude of 5.5 or greater (or a Modified Mercalli intensity of VII or greater). These earthquakes are listed in table 1 and their epicenters are shown as solid circles in figure 6. At the scale of figure 6, apparent correlations of historical seismicity with specific faults must be considered with care. For example, many of the epicenters located along the Wasatch fault are non-instrumental and correspond to locations where felt effects were strongest for a particular shock, typically an established city or town. Hence, the coincidence of historical epicenters with the Wasatch fault reflects the locations of settlements along the Wasatch Front, and is not necessarily indicative of earthquake activity on the Wasatch fault itself. It is arguable whether the earthquakes of about magnitude 5-1/2 in 1910 near Salt Lake City and in 1914 near Ogden occurred directly on the Wasatch fault (Arabasz and others, 1980). Thus, as many as two—or perhaps no—earthquakes of magnitude 5 or greater have occurred on the Wasatch fault in historical time. The average interevent time since 1884 of the moderate-to-large main shocks listed in table 1 is 6 to 7 years. There was, however, one unusually long 25-year interval between 1934 and 1959 without an earthquake of magnitude 5.5 or greater.

FIGURE 6.--NEAR HERE

TABLE 1.--NEAR HERE

Figure 7 shows the pattern of instrumental seismicity for the Utah region determined from monitoring by the University of Utah since mid-1962 (element 7, fig. 1). The epicentral distribution of small- to moderate-size background earthquakes is generally similar to that in figure 6. The sample of figure 7 includes 9,148 earthquakes of all sizes up to magnitude 6.0, and 2,152 earthquakes of magnitude 2.0 or greater. Table 2 lists independent main shocks in the sample of magnitude 4.0 and greater. Focusing attention on the Wasatch Front study area, figures 8 and 9 show the patterns of instrumental seismicity respectively for October 1974 through June 1978 (2,480 events) and July 1978 through December 1986 (3,936 events). The first sample is the same as that described in detail by Arabasz and others (1980) for the initial 3.75 years of detailed monitoring by the University of Utah's telemetered seismic network. The second sample allows an updated comparison for the subsequent 8.5-year period. The earthquake samples of figures 8 and 9 are probably complete above about magnitude 2.0 (discussed later). The extent of seismographic coverage, relevant to inferences of epicentral precision, is shown in figure 2.

FIGURE 7.--NEAR HERE

TABLE 2.--NEAR HERE

FIGURE 8.--NEAR HERE

FIGURE 9.--NEAR HERE

The patterns of seismicity shown in figures 8 and 9 are remarkably similar, and comparison with that for the period 1962-1974 (Arabasz and others, 1980, fig. 4) indicates general stability in the pattern of seismicity throughout the period of instrumental monitoring. One notable difference in the seismicity before and after 1974 is the aftershock activity that followed the 1975 M_L 6.0 Pocatello Valley earthquake on the Idaho-Utah border (upper left, figs. 8 and 9). The pattern of most recent seismicity in the Wasatch Front area illustrated in figure 9 includes several notable features, described from north to south:

(1) At the northern extremity of figure 9, earthquake clusters are part of a northeast-trending belt of seismicity that continues to the Jackson-Yellowstone Park region. This includes episodic swarm seismicity in the Soda Springs, Idaho, area (approx. 42°30'N, 111°30'W). A swarm begining as early as December 1981 peaked with an M_L 4.7 earthquake in October 1982 (Richins and others, 1983), and seismicity continues in that area.

(2) Earthquake activity in the Idaho-Utah border area west of the Wasatch fault has been prominent ever since the 1975 M_L 6.0 Pocatello Valley earthquake (Arabasz and others, 1981).

Small- to moderate-size earthquakes extending southward from the state border form an inverted "Y" pattern, which began to form several months after the March 1975 main shock and in which seismicity persists to the present. At the southwest extremity of the "Y" pattern, scattered small earthquakes beneath the northern part of the Great Salt Lake have previously appeared to be part of a broad northeast-trending belt. The sample of figure 9, however, suggests a northwest-trending pattern of epicenters in the vicinity of the East Great Salt Lake fault.

(3) Densely-clustered earthquakes occurring roughly 10 to 40 km east of the Wasatch fault define a linear belt extending southward from about 41°50'N to at least 41°N—and perhaps as far south as 40°N. Earthquakes in the northern part of this belt lie east of the west-dipping East Cache and Wasatch faults and occur within a volumetric zone beneath the Bear River Range, whose western boundary is formed by the East Cache fault. To the south of 41°N, earthquake clusters within this belt to the east of the Wasatch fault follow a zone of northerly-trending valleys within the so-called Wasatch Hinterland (Sullivan and others, 1986).

(4) Clusters of seismicity appear close to or just west of the trace of the Wasatch fault variously near Honeyville at about 41°40'N, in the vicinity of Salt Lake City at about 40°45'N, at the northern end of Utah Valley at about 40°20'N, in the vicinity of Goshen Valley at about 40°00'N, and in a broadly scattered zone at the southern end of the Wasatch fault. We return to these observations when we consider the Wasatch fault in finer detail in a later section.

(5) In the lower right part of figure 9, a prominent feature of the seismicity of east-central Utah is a pattern of persistent shallow seismicity forming an inverted U-shape that corresponds with underground coal mining along the eastern side of the Wasatch Plateau (between about 39°15'N and 39°35'N) and along the arcuate Book Cliffs escarpment (east of about 39°45'N, 111°00'W). The seismicity is well known to be mining-related and appears to correlate with mining areas where annual rates of extraction exceed 500,000 tons (see summary by Arabasz and Julander, 1986). Results of a recent study of mining-related seismicity in the eastern Wasatch Plateau are reported by Williams and Arabasz (1988).

Earthquake Focal Depths

The purpose of this section is to examine the seismic network data in the Wasatch Front region for focal-depth information. It is an unfortunate fact that computed focal depths of most earthquakes located with the regional seismic network are unreliable due to the large station spacings of 15-35 km in the immediate Wasatch Front area and 35-100 km elsewhere (fig. 2). As a partial solution to this problem, temporary arrays of portable seismographs are routinely deployed by the University of Utah in selected target areas (element 8, fig. 1) and have provided some of the best data for correlating seismicity with structure (e.g., Arabasz and Julander, 1986). It remains useful, nonetheless, to evaluate the regional network data for focal-depth information.

It is commonly assumed that the presence of a recording station within one focal depth of an earthquake's epicenter provides good depth control. To test this assumption, K. J. Quigley (Univ. of Utah, unpub. rept., 1986) performed numerical experiments on synthetic P-wave arrival-time data for the Wasatch Front seismic network to determine statistical criteria for focal-depth reliability. Based on his results, 485 earthquakes out of 6,416 from the 1974-1986 UUSS catalog for the Wasatch Front area were judged to have reliable focal depths, using the following criteria: (1) distance to the nearest station less than or equal to the focal depth or 5 km, whichever is larger, and (2) standard vertical hypocentral error (ERZ) of 2 km or less, as calculated by the location program HYPOELLIPSE (1974-1980) or HYPOINVERSE (1981-1986). Quigley's results verify theoretical expectations that there is a 68% probability that the computed focal depth for such events is within 1.0 ERZ of the true focal depth, and a 98% probability that it is within 2.4 ERZ.

Figure 10 shows the best-resolved foci in map and cross-section view. It should be noted that the selection criterion of having a close station may filter out shallow events in some areas, but deeper events will be less affected. In general, the east-west cross sections do not appear to be particularly informative in terms of significant variations in the east-west distribution of maximum focal depths or spatial association with the Wasatch fault. The north-south cross section, however, suggests that there may be variations in maximum earthquake depth along the Wasatch Front. For example, there are no earthquakes deeper than 17 km in the central part of the cross section, whereas there are earthquakes deeper than 17 km and as deep as 25 km at the northern and southern ends. We caution, however, that the apparent variation in maximum focal depth may be an artifact of the relatively small number of events in the central and southern parts of the section. The larger any sample, the more likely it is to observe extreme values. The focal depth above which 90 percent of the earthquakes lie is as follows: 16 km between 39°N and 40°N latitude, 13 km between 40°N and 41°N latitude, 15 km between 41°N and 42°N latitude, and 11 km from 42°N to 42.5°N latitude (where the sampling is dominated by aftershocks of the M_L 6.0 Pocatello Valley earthquake of 1975). These results suggest the possibility of variations in maximum focal depth on the order of 2 to 5 km.

Maximum earthquake focal depths bear directly on crustal rheology, the depth of nucleation of large earthquakes, and maximum fault-rupture dimensions. Accordingly, the north-south variations of maximum focal-depth suggested in figure 10 should be investigated further. Figure 10 emphasizes the sparseness of three-dimensional information available from the thousands of earthquakes located by the permanent regional network. A consequence is that only limited information is available to address the association of seismicity with subsurface structure, as we discuss next.

FIGURE 10.--NEAR HERE

Problematic Correlation of Seismicity with Geologic Structure

Fundamental problems in correlating diffuse seismicity with mapped Cenozoic faulting and subsurface geologic structure in the Utah region have been discussed at length by Arabasz (1984) and by Arabasz and Julander (1986). Discussion is repeated here because of its continued relevance. Problems include: (1) uncertain subsurface structure, which typically is more complex along the main seismic belt than apparent from the surface geology; (2) observations of discordance between surface fault patterns and seismic fault slip at depth (Arabasz and others, 1981; Zoback, 1983); (3) a paucity of historic surface faulting; and (4) inadequate focal-depth resolution from regional seismic monitoring.

Crustal structure along the eastern Great Basin is known to involve vertically stacked plates separated by low-angle detachments resulting from relict pre-Neogene thrustbelt structure and/or Neogene extension (Allmendinger and others, 1983; Smith and Bruhn, 1984; Smith and others, 1987). Smith and Bruhn (1984) present a summary of seismic-reflection data that indicate the widespread presence of low-angle and downward-flattening faults in the subsurface and an intimate relationship between pre-Neogene thrustbelt structure and young normal faults along the eastern Basin and Range margin. Seismological evidence to date indicates that, at least for small to moderate earthquakes, seismic slip in this region predominates on faults with moderate (≥ 30°) to high-angle dip (Zoback, 1983; Arabasz and Julander, 1986; Bjarnason and Pechmann, 1987).

Given the relatively high magnitude threshold of surface faulting, and observations of discordance between surface fault patterns and seismic slip at depth, one can argue that—with the sole exception of the 1934 Hansel Valley earthquake—no other of Utah's 15 historical earthquakes of M_L 5.5 or greater (table 1) can be confidently associated with a mapped surface fault. Within the domain of Utah's main seismic belt, future seismicity below the threshold of surface faulting (M_L 6.3±0.2) thus cannot be confidently precluded by knowledge of the surface geology alone. Where subsurface structure is complex, moderate size earthquakes may occur on blind subsurface structures that have no direct surface expression.

On the basis of special earthquake studies in the southern Wasatch Front area, neighboring parts of central Utah, and southeastern Idaho, the following working hypothesis was offered by Arabasz (1984; see also Arabasz and Julander, 1986) to explain observations of diffuse background seismicity. Background seismicity, it was suggested, is fundamentally controlled by variable mechanical behavior and internal structure of individual horizontal plates within the seismogenic upper crust. Diffuse epicentral patterns may then result from the superposition of seismicity occurring within individual plates, and also perhaps from favorable conditions for block-interior rather than block-boundary microseismic slip. Figure 11 schematically shows some aspects of the working hypothesis.

FIGURE 11.--NEAR HERE

SEISMIC SOURCE ZONES AND SEISMICITY PARAMETERS

General Remarks

Two key steps in any analysis of earthquake hazards or risks are (1) the identification and geometric depiction of seismic source zones within which earthquakes are likely to originate (step 3, fig. 1), and (2) the estimation of seismicity parameters for these source zones (step 4, fig. 1). The important seismicity parameters are the maximum magnitude, the expected earthquake distribution as a function of size, and the rate of activity. Both earthquake catalog data and geologic data on active faults can be used to identify and characterize seismic source zones.

Our current understanding of the seismotectonic framework of the Wasatch Front region, as summarized above, leads to the position that seismic hazards arise from two fundamental classes of earthquakes: (1) infrequent, large ($M_S \geq 6.3\pm0.2$) surface-faulting earthquakes on identifiable faults having evidence of late Quaternary displacement, and (2) small-to moderate-size (up to M_L 6.5) earthquakes, below the threshold of surface faulting, that are not constrained in location to mapped faults and may occur randomly in space throughout broadly defined regions. This position is a consequence of detailed studies that show clear evidence for large, prehistoric earthquakes on faults in the region (e.g., Swan and others, 1980; Schwartz and others, 1984; Machette and others, this volume), the diffuse scatter of small-to moderate-size earthquakes illustrated in figures 7, 8, and 9, and the problematic correlation of seismicity and geologic structure discussed above. It therefore seems reasonable to distinguish two different types of seismic source zones: (1) fault-specific sources for which the evidence is primarily geological, and (2) areal source zones that are based upon the historical and instrumental earthquake record and have a maximum magnitude of 6.5. These two types of source zones have been used in several studies of seismic hazard in the Wasatch Front region, including the elaborate probabilistic analysis of ground shaking hazard by Youngs and others (this volume), a study of the "Wasatch Hinterland" by Sullivan and others (1986), and a study by Arabasz and others (1987) of the region surrounding the sites that Utah proposed for the Superconducting Supercollider, which are located southwest of the Great Salt Lake along the western boundary of the Wasatch Front region.

In this section, we treat the entire Wasatch Front study area as one areal source zone and use the instrumental earthquake record to model the recurrence of earthquakes within the area of up to magnitude 6.5. Although the available data suggest that seismicity rates may vary somewhat within this region, there are not enough earthquakes in the record to reliably estimate seismicity parameters for subsets of this region. Furthermore, the 25-year record of instrumental seismicity is simply too short to allow the extrapolation into the future of spatial variations of seismicity rate within the Wasatch Front area. We first present results from recurrence modeling for the Wasatch Front area, then briefly discuss the fault-specific sources in this region and the maximum earthquake size that can be expected to occur on them.

Recurrence Modeling

Earthquake catalog data provide the only means to determine the rate of occurrence and size distribution of earthquakes smaller than the threshold of surface faulting. A standard way to characterize seismicity in any seismically active region is with the Gutenberg-Richter exponential frequency-magnitude relationship given by

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

where N is the average number of independent events per year of magnitude M or greater and a and b are constants appropriate for the particular region. The a-value is a measure of the overall rate of earthquake activity. The b-value is a measure of the relative proportion of small events to large events, with higher b-values indicating relatively more small events. If we define A as the average number of events per year of $M \geq 3.0$, i.e., $A = 10^{a - 3.0b}$, then the above equation can be rewritten as

$$N = A\ 10^{-b(M - 3.0)}$$

In order to obtain meaningful estimates for the seismicity parameters a (or A) and b from earthquake catalog data, it is first necessary to remove from the catalog dependent events such as aftershocks, foreshocks, and secondary events in swarm sequences. Shimizu (1987) identified dependent and independent events in the University of Utah catalog for the time period July 1962 through December 1985 by applying the local clustering method of Veneziano and Van Dyck (1985, 1986). This method uses statistical tests to identify earthquake clusters, which Veneziano and Van Dyck define as space-time windows in which the rate of earthquake ativity is significantly greater than the estimated local background rate. One or more of the earthquakes within each cluster are then classified as main shocks, and the rest are classified as dependent events. This procedure is repeated until no additional events are identified as dependent. The primary advantage of the local clustering method compared to other methods of identifying dependent events is that it allows for variations in the spatial and temporal extent of clusters of dependent events associated with different mainshocks of the same magnitude.

Shimizu's listing of independent events of $M_L \geq 2.0$ in the catalog for this time period was supplied to us on computer tape by D. Veneziano. This listing contained 571 main shocks within the study area. The epicenters of these events are plotted in figure 12. For purposes of the recurrence modeling, we eliminated the 126 events in the study area south of 39°50'N and east of 111°15'W (dashed box, fig. 12), where the seismicity is predominantly mining-related. This left 445 independent main shocks of $2.0 \leq M_L \leq 6.0$ in the remaining 85,000 km^2 of the study area. These main shocks form the basic data set for our recurrence modeling of the Wasatch Front area.

FIGURE 12.--NEAR HERE

Figure 13 is a cumulative recurrence plot (log N versus M) for the 445 independent main shocks (dots). Note that the observed number of $M_L \geq 2.0$ events per year is equal to or greater than the number expected from a linear extrapolation of the data for the larger magnitude cutoffs. In fact, the recurrence curve formed by connecting the dots in figure 13 even appears to have a steeper slope for $M_L \leq 3.0$. This observation suggests that the University of Utah catalog contains a reasonably complete listing of main shocks of $M_L \geq 2.0$ in the Wasatch Front region after July 1962. However, the precise threshold magnitude of completeness for the catalog varies with time and with location within the region, dependent on station coverage (fig. 2).

FIGURE 13.--NEAR HERE

The apparent change in slope of the recurrence curve near magnitude 3 may be an artifact of the way that magnitudes are assigned in the University of Utah catalog. The catalog magnitudes for most earthquakes in the Wasatch Front region over magnitude 3 are true local magnitudes calculated from peak amplitudes measured on seismograms from low-gain Wood-Anderson-type instruments. The magnitudes listed for most of the smaller earthquakes are coda magnitudes calculated from signal durations measured on records from various types of higher-gain instruments (for details, see Arabasz and others, 1979; Richins and others, 1981; Richins and others, 1984; and Brown and others, 1986). The coda magnitude scales were calibrated against Wood-Anderson M_L measurements, and should therefore give compatible results. Nevertheless, it is possible that there are some small, systematic differences between the two types of estimates. Research on refined methods of magnitude determination using digital waveform data is currently underway at the University of Utah.

The heavy line in figure 13 shows a straight-line fit to the recurrence data (dots) above M_L 3.0, determined by the maximum likelihood technique of Weichert (1980) using an assumed maximum magnitude of 7.5. The best-fit line has a slope of $b = 0.71 \pm 0.09$. The lighter lines are drawn with the lower-bound and upper-bound slopes of 0.62 and 0.80, respectively. Note that all three lines are constrained to pass through the data point for the minimum magnitude of 3.0. The lighter lines appear to bound the range of possible slopes quite well if a magnitude cutoff of 3.0 is used. However, the b-value is unfortunately very sensitive to the cutoff magnitude. Cutoff magnitudes of 2.0 and 2.5 give b-values of 0.82±0.04 and 0.88±0.07, respectively. We chose the cutoff magnitude of 3.0 because of the possible problems with the smaller magnitudes discussed above and because the lines calculated using this cutoff provide a better fit to the data for the larger earthquakes, which are the ones of primary concern for seismic hazards.

The recurrence relationship given by our preferred maximum likelihood fit to the data shown in figure 13 is

$$N = (2.51)10^{-(0.71\pm0.09)(M_L - 3.0)}$$

or, alternatively,

$$\log N = 2.53 - 0.71\ M_L$$

Table 3 lists average recurrence intervals for earthquakes in the Wasatch Front region calculated from the first of these equations. The preferred estimate is for the b-value of 0.71. The values in the right-hand column are lower and upper limits calculated using the limiting b-values of 0.62 and 0.80, respectively.

TABLE 3.--NEAR HERE

As a check on table 3, consider the number of earthquakes of estimated magnitude 5.5 or greater in the Wasatch Front region from 1850 to 1987. There have been eight such earthquakes (table 1, fig. 6), which gives an average recurrence interval of 17 years. This falls within the lower end of our estimated range of recurrence intervals for $M_L \geq 5.5$ earthquakes, which is 14 to 40 years. If, following Arabasz and others (1980), we assume that the catalog is complete at the $M_L \geq 5.5$ level only since 1878, the average recurrence interval shortens to 14 years. The interevent times for the eight $M_L \geq 5.5$ earthquakes range from 0.6 to 28.5 years, with a mean of 12.9 years.

The recurrence intervals calculated for earthquakes greater than magnitude 6 represent an extrapolation beyond the limits of the data shown in figure 13. Nevertheless, it is interesting to compare our predicted recurrence interval for $M_L \geq 7.0$ events with estimates of the recurrence interval for $M_L \geq 7.0$ events on the Wasatch fault, given that the Wasatch fault is the dominant source of magnitude 7.0 and greater earthquakes in the region. The average recurrence interval for $M_L \geq 7.0$ earthquakes on the Wasatch fault has been estimated to be 400 to 666 years by Schwartz and Coppersmith (1984), 330±90 years by Youngs and others (this volume), and 250-280 years by Machette and others (this volume). These estimates are consistent with our predicted average recurrence interval of 120 to 630 years (with a preferred value of 280 years) for $M_L \geq 7.0$ events in the Wasatch Front region as a whole.

Arabasz and others (1980) modeled earthquake recurrence for the Wasatch Front region using independent main shocks in the University of Utah catalog of MM intensity V or greater (approximately $M_L \geq 4$) from 1850 through 1978. They obtained the equation

$$\log N = 2.98 - 0.72M_L$$

Their b-value of $\bar{0}.72$ is essentially the same as our b-value of 0.71±0.09. However, their a-value of 2.98 is larger than our value of 2.53. This difference corresponds to a difference in seismicity rates of a factor of 2.8. Two possible explanations for this disparity are (1) the seismicity from 1962 through 1985 was low compared to the seismicity from 1850 through 1961, or (2) the magnitudes of the pre-1962 events were overestimated by about 0.6 magnitude units by Arabasz and others (1980).

It should be pointed out that our preferred b-value of 0.71 is lower than the b-values obtained in most previous studies of earthquake recurrence along the Wasatch Front that made major or exclusive use of the post-1962 instrumental University of Utah catalog. Arabasz and others (1980) determined a b-value of 0.95±0.15 using all magnitude 2.3 and greater earthquakes in the catalog from July 1962 through June 1978 within a subarea of the Wasatch Front region between 111°15'W and 112°15'W. Youngs and others (this volume) obtained b-values ranging from 0.75±0.03 to 0.83±0.03 (depending on the criteria used to remove dependent events), using catalog data from 1850 through March 1986 above the uniform detection thresholds that they estimated. The north-south extent of the study area of Youngs and others is from 39°N to 42°30'N, nearly the same as that of our study area, but their area has a narrower east-west extent. Finally, Shimizu (1987) obtained a b-value of 1.1 using independent main shocks from July 1962 through December 1985 for a region extending from 39°N to 42.5°N and 108°45'W to 114°15'W (excluding mining-related seismicity in east-central Utah), which he calls the "Central-Northern Utah" region.

The higher b-value obtained by Arabasz and others (1980) for the post-1962 instrumental catalog can be attributed to the fact that they did not remove dependent events from the catalog before calculating their b-value. The differences between the b-values of 0.75 to 0.83 determined by Youngs and others (this volume) and our value of 0.71 appear to result primarily from differences in the methods employed to remove dependent events. The higher b-value of 1.1 obtained by Shimizu (1987) cannot be explained in this way, since we used his listing of independent events for our recurrence modeling. The higher b-value obtained by Shimizu results from his use of a minimum magnitude of 2.5 in his recurrence analysis, and, to a lesser extent, his use of the maximum likelihood method of Utsu (1965) to fit a straight line to the data. In the method of Utsu (1965), the b-value is calculated from the equation

$$b = \log_{10} e \,/\, (\overline{M} - M_0)$$

where $\overline{M}$ is the mean magnitude of all events with magnitude greater than or equal to M_0. Utsu's method tends to give higher b-values than the more elaborate method of Weichert (1980), which was used both by us and by Youngs and others (this volume). Application of Utsu's method to the data in figure 13 for $M_L \geq 2.5$ gives a b-value of 0.97, which is in reasonable agreement with Shimizu's value considering that his calculation included data from a larger area.

Fault-Specific Sources

Although the 1934 M_S6.6 Hansel Valley earthquake is the largest historical earthquake to have occurred in the Wasatch Front region, there is good geologic evidence that larger earthquakes can be expected to occur on the Wasatch fault and other active faults in the region. All of the faults with evidence for late Quaternary (< 500,000 years) movement shown on the map in figure 5 are considered to be potential source of earthquakes larger than M_L 6.3±0.2, the likely threshold for surface faulting. Maximum earthquake magnitudes for these fault-specific sources can be assessed from estimates of the rupture length, area, and displacement for the maximum size event. Average recurrence intervals for surface-faulting events can, at least in some cases, be determined from geomorphic observations or from the stratigraphy of deposits near the fault trace exposed by trenching (see Allen, 1986, and Schwartz and Coppersmith, 1986, for reviews of these techniques). A detailed description of all the fault-specific sources shown in figure 6 is beyond the scope of this paper. We refer the reader to the paper by Youngs and others (this volume) for a thorough summary of available information on the major faults in the Wasatch Front region and a determination of seismicity parameters for these faults. Here, we present information on four fault-specific sources that we use below in some probabilistic hazard calculations, consider the maximum probable earthquake for the whole Wasatch Front area, and briefly discuss the issue of frequency-magnitude relationships for individual faults.

Table 4 presents basic information for the four most prominent fault-specific sources near Salt Lake City: the Wasatch fault, West Valley fault zone, East Great Salt Lake fault, and North Oquirrh Mountains fault (figure 5). The faulting parameters for the Wasatch fault are taken from segmentation model B of Youngs and others (this volume). This model has ten segments, and is very similar to the segmentation model proposed by Machette and others (1986). The maximum magnitude listed for each segment is a mean estimate calculated from the set of possible values and their assigned weights listed in table 1 of Youngs and others. The recurrence intervals for maximum earthquakes are mean estimates taken directly from table 3 of Youngs and others. For the West Valley fault zone the maximum magnitude of 6.5 is also a mean value calculated from table 1 of Youngs and others. The average recurrence interval of 2,000 years is inferred from the observation of 6 to 7 discrete faulting events on the fault zone within the last 13,000 years (S.J. Olig, written communication, 1987). The segmentation of the East Great Salt Lake fault is very uncertain, but it appears to be divided into at least two segments, each about 50 km long (fig. 5; Pechmann and others, 1987). The maximum magnitude of 7.2 assigned to each segment is based on a simple analogy with the Weber and Salt Lake City segments of the Wasatch fault, which are of comparable length. The average recurrence interval for maximum earthquakes on each segment of the East Great Salt Lake fault is judged to be about 4,000 years, based on the fact that the observed slip rates are about half of those measured for the central segments of the Wasatch fault, which have recurrence intervals of about 2,000 years (Pechmann and others, 1987). For the North Oquirrh Mountains fault, the maximum magnitude of 7.0 is from table 1 of Youngs and others (this volume). The average recurrence interval of about 10,000 years or more is inferred from the observation that the most recent surface-faulting event on this fault occurred between 8,000 and 13,500 years ago (Youngs and others, this volume), together with generic arguments made by Arabasz and others (1987). For all of the faults in table 4, the annual probability of the maximum earthquake is taken to be the inverse of the average time interval between maximum earthquakes, since in most cases the elapsed time since the last large earthquake is poorly known.

TABLE 4.--NEAR HERE

Estimates of the maximum earthquake size on any particular fault are subject to uncertainties inherent in both the prediction of future rupture characteristics and in the conversion of these rupture characteristics to magnitude estimates. For this reason, it is useful to consider from a historical point of view the maximum earthquake size that is likely to occur anywhere within the Wasatch Front region.

The 1959 M_S7.5 Hebgen Lake earthquake is considered by some to represent the maximum earthquake for the Intermountain seismic belt (e.g. Doser, 1985a). However, it is worth noting that earthquakes larger than this have occurred in the western Basin and Range Province. Slemmons (1980) lists 13 historic surface faulting earthquakes in the western Great

Basin. These include two events of magnitude greater than 7.5: the March 26, 1872 Owens Valley, California earthquake of estimated magnitude 8.0, and the October 3, 1915 Pleasant Valley, Nevada earthquake of magnitude 7.75. Slemmons (1980) lists a rupture length of 110 km for the Owens Valley event with a maximum displacement of 6.44 m, and a rupture length of 62 km with a maximum displacement of 5.6 m for the Pleasant Valley event. Thus, both of these earthquakes have a maximum displacement comparable to that of the Hebgen Lake event, but significantly longer rupture lengths. The magnitude of 7.75 for the Pleasant Valley event is from Gutenberg and Richter (1954), and is nearly identical to the surface wave magnitude of 7.7 calculated by Abe (1981). The magnitude of the Owens Valley event is more controversial, owing to the lack of seismographic instruments at the time. Magnitude estimates for this earthquake based on felt reports range from 8.3 (Oakeshott and others, 1972) to 7.2 (Evernden, 1975). From the surface faulting, Beanland and Clark (1987) estimate a moment magnitude of 7.5 to 7.7.

The slip that occurred during the 1872 Owens Valley earthquake had a large strike-slip component to it (Richter, 1958; Oakeshott and others, 1972) and may even have been dominantly strike-slip (Beanland and Clark, 1987). Faults in the Wasatch Front region show predominantly normal slip, although there is abundant evidence of strike-slip faulting in south-central Utah (Anderson and Barnhard, 1984; this volume). Thus, the Pleasant Valley and Hebgen Lake earthquakes may be better models for the maximum credible Wasatch Front earthquake than the Owens Valley earthquake. The characteristics of the Pleasant Valley and Hebgen Lake earthquakes suggest that future Wasatch Front earthquakes could have surface wave magnitudes of up to 7.5-7.7, rupture lengths of up to 35-65 km, and maximum vertical displacements of up to about 6 m.

One interesting question concerning fault-specific sources is to what extent they act as sources for small-to moderate-size earthquakes, excluding foreshocks and aftershocks of large events. The Gutenberg-Richter exponential frequency-magnitude relationship usually fits the size distribution of earthquakes over large regions quite well. However, in general, this relationship does not apply to individual faults (Wesnousky and others, 1983; Singh and others, 1983; Youngs and Coppersmith, 1985). Youngs and others (this volume) modeled the magnitude distribution of independent earthquakes on individual faults in the Wasatch Front region in two different ways: (1) using a standard exponential magnitude distribution, and (2) using the "characteristic" magnitude distribution proposed by Youngs and Coppersmith (1975). In both cases, only earthquakes of $M_L \geq 6.0$ were included in their analysis. The characteristic distribution is a modification of the exponential distribution that incorporates a decrease in b-value at magnitudes approaching the maximum magnitude for the fault. Thus, the characteristic magnitude distribution includes relatively more larger earthquakes. A third possible model to consider is the "maximum magnitude" model, which holds that each fault or fault segment produces only maximum-size earthquakes, together with their associated aftershocks and possible foreshocks (Wesnousky and others, 1983; Wesnousky, 1986). In tectonic regions where the repeat time for large earthquakes is relatively short, the available data favor either the characteristic or the maximum magnitude model. In the Wasatch Front region, major faults such as the Wasatch fault have not been important sources of small to moderate background earthquakes over the 25-year record of instrumental seismicity. This observation tends to favor the characteristic and maximum magnitude earthquake models, but the period of observation is too short relative to the repeat times for large earthquakes to allow any definite conclusions to be drawn.

GROUND SHAKING HAZARD

The final step in the seismic hazard analysis outlined in figure 1 is the estimation of ground motion for engineering applications. Predictions of ground motions from future earthquakes can be arrived at in many different ways and presented in a variety of different forms. One especially popular approach to the problem is the probabilistic methodology for estimation of peak ground motions first outlined by Cornell (1968). Algermissen and others (1982) use this basic methodology to derive maps of probabilistic ground motion estimates for the contiguous United States, including Utah. Youngs and others (this volume) use a similar methodology to carry out a detailed probabilistic analysis of ground shaking hazard for the Wasatch Front region. In this section, we use Cornell's method to perform some simple probabilistic calculations of maximum ground acceleration for a representative site in the Salt Lake Valley, halfway between the Wasatch and West Valley faults. Our intent here is not to duplicate the extensive work of Youngs and others (this volume), but rather to illustrate the relative contributions of various seismic sources to the ground shaking hazard. In particular, we investigate the relative importance to seismic hazard of small to moderate ($M \leq 6.5$) earthquakes, which dominate the historical earthquake record.

The site that we chose for our calculation is the intersection of interstate highways 15 and 80 in the city of South Salt Lake at approximately 40°43.1'N, 111°54.2'W (diamond, fig. 5). Our calculation incorporated two fundamental types of earthquake sources, as discussed above: (1) small to moderate ($3.0 \leq M_L \leq 6.5$) earthquakes within a circular source area of radius 100 km centered on the site, and (2) the fault-specific sources listed in table 4, which have maximum magnitudes of 6.5-7.3. Although we have not included all of the possible earthquake sources in the Wasatch Front region in our calculations, we believe that we have included all of the major contributors to ground shaking hazard in the Salt Lake Valley. Earthquakes within the circular source area are assumed to be independent in size and location, have a spatially uniform probability of occurrence, and have an exponential magnitude distribution. We used the seismicity parameters estimated in the recurrence modeling section above to characterize this source area. For the fault-specific sources, only the contribution of the maximum earthquake to the hazard was included in the computation. For these maximum earthquakes, the contribution to the annual probability of exceedance of a given peak acceleration value is the product of two factors: (1) the annual probability of occurrence of the earthquake, and (2) the probability that the given peak acceleration level will be exceeded if an earthquake of the specified magnitude and distance occurs.

Peak horizontal acceleration as a function of magnitude and distance was calculated using the constrained relationship of Campbell (this volume). Campbell actually presents a range of median acceleration estimates to reflect uncertainties in how stress regime, fault type, anelastic attenuation, and local site conditions could affect ground motion in Utah. We performed our calculations using both his upper-bound curves and his lower-bound curves, which differ in their predictions of peak horizontal accelerations by about a factor of two. In both cases, the natural log of the peak acceleration was assumed to be normally distributed about the predicted median value with a standard deviation of 0.3, the standard error given by Campbell.

Some assumption about the depths of the earthquakes was necessary since Campbell defines source-to-site distance as the shortest three-dimensional distance between the site and the zone of seismogenic rupture. For the earthquakes in his data set, Campbell identified this zone from the aftershock distribution, when possible. We assumed that the zone of seismogenic rupture penetrates to within 4 km of the surface for all earthquakes included in the computation, based on the observation that the tops of the aftershock zones for the 1962 Cache Valley earthquake (Smith and Sbar, 1974), the 1975 Pocatello Valley earthquake (Arabasz and others, 1981) and the 1983 Borah Peak earthquake (Richins and others, 1987) were all at 3-4 km depth. However, the assumed minimum depth is important only for earthquakes very near the site. The site is located about 4 km east of the surface trace of the West Valley fault and 4 km west of the surface trace of the Wasatch fault. Because the West Valley fault dips to the east and the Wasatch fault dips to the west, both faults probably extend directly beneath the site. Assuming fault dips of 45° to 70°, the distance to the seismogenic rupture for a surface-faulting event on either fault would be about 3-4 km, which is consistent with the assumption we made about seismogenic depth.

Figure 14 presents four graphs of the probability of exceedance per year versus peak horizontal ground acceleration at our representative Salt Lake Valley site. The four graphs illustrate the contributions to the ground-shaking hazard from (1) background earthquakes, (2) earthquakes on the Wasatch fault, (3) earthquakes on the other three faults listed in table 4, and (4) all of these sources together. The solid curves bordering the shaded regions on each graph were calculated using Campbell's lower- and upper-bound peak acceleration relationships. The shaded regions between these curves indicate the range of annual probabilities for any given peak horizontal acceleration. On the graph for the background seismicity, the two dashed curves were calculated with the preferred b-value of 0.71 whereas the upper and lower solid curves were calculated with the lower- and upper-limit b-values of 0.62 and 0.80, respectively.

FIGURE 14.--NEAR HERE

Assuming that earthquake occurrence is a Poisson process, peak acceleration values having a 90% probability of nonexceedance in 50 years have an annual probability of 0.0021 or a return period of 475 years (upper horizontal lines, fig. 14). On the graph that includes all of the sources, the acceleration value corresponding to this return period lies between 0.17 and 0.40 g, as indicated on the plot. For comparison, the value obtained by Algermissen and others (1982) is 0.20-0.28 g and the value obtained by Youngs and others (this volume) is 0.3 g. Peak acceleration values having a 90% probability of nonexceedance in 250 years have an annual probability of 0.00042 or a return period of 2,373 years (lower horizontal lines, fig. 14). The acceleration value corresponding to this return period is 0.49 to 1.05 g on figure 14. For comparison, the value obtained by Algermissen and others (1982) is 0.60-0.70 g and the value obtained by Youngs and others (this volume) is 0.7 g. Thus, the results of Algermissen and others (1982) and Youngs and others (this volume) fall within the range of probabilistic acceleration values that we calculate for both the 475-year and the 2,373-year return periods.

Figure 14 implies that the background source is the largest contributor to the ground shaking hazard at the site for return periods shorter than 500 years and accelerations less than 0.1 to 0.2 g, depending on the ground motion model used. The Wasatch fault is the largest contributor to the hazard at longer return periods and higher accelerations. However, other faults, particularly the West Valley faults, are also quite important. We note that our calculation assumes that earthquakes on the West Valley fault are independent earthquakes, even though there is some possibility that they represent subsidiary fault movements associated with earthquakes on the Wasatch fault (S.J. Olig, personal communication, 1987). At locations farther away from the West Valley and Wasatch faults, the contribution of these faults to the ground shaking hazard will be less than is indicated by figure 14. At locations closer than 4 km from the Wasatch fault or near segments with shorter recurrence intervals than the Salt Lake City segment (table 4), the contribution of the Wasatch fault to the ground-shaking hazard will be slightly greater than is indicated by figure 14. The hazard curves for the background source, on the other hand, are applicable throughout most of the interior of the Wasatch Front region. Thus, from figure 14 we can infer that at most localities, the background source will be the largest contributor to ground-shaking hazard for return periods of 475 years or less (exposure periods of 50 years or less).

CURRENT SEISMICITY AND THE WASATCH FAULT

In this final section we wish to consider the question, separate from the systematics of a hazard or risk analysis, What does observational seismology tell us about the behavior of the Wasatch fault? We then summarize our perspective on evaluating earthquake hazards and risk in the Wasatch Front area from the viewpoint of observational seismology.

Let us first consider instrumental earthquake locations. Figure 15 shows a detailed plot of instrumental seismicity that might, on the basis of epicentral locations alone, be associated with the Wasatch fault zone. The data include 1,538 earthquake locations from the UUSS catalog for the period July 1962 through December 1986. The largest earthquake included is the M_L 5.2 Magna earthquake of September 1962, located in the northwest corner of box B-B'. Earthquakes were sampled from 30-km-wide zones extending 10 km east of the surface trace of the Wasatch fault, to allow for epicentral errors, and 20 km west of the fault, to allow both for epicentral errors and reasonable down-dip projection of the fault. Figure 16 shows complementary cross-section views for those foci included in figure 15 that meet the rigorous criteria for focal-depth reliability specified for figure 10. Epicentral precision of ± 5 km would be conservative for the data of figure 15, but errors as large as ± 10 km cannot be ruled out for a very minor fraction of the sample. Insofar as the vast majority of the data postdate 1974 when modern network recording began, most of the epicenters probably have a precision of ± 2-3 km (Brown and others, 1986; Arabasz and Julander, 1986).

FIGURE 15.--NEAR HERE

FIGURE 16.--NEAR HERE

The cross sections of figure 16 suggest that very few of the well-located foci sampled from the vicinity of the Wasatch fault could be interpreted to lie on the fault—if one believes that the fault is a planar penetrative structure of moderate dip. Although the subsurface geometry of the Wasatch fault is not generally well known, Zoback (1987) interprets a planar, relatively steeply-dipping (50°-55°W) subsurface geometry for the Wasatch fault near Nephi.

Smith and Bruhn (1984) interpret a subsurface fault dip of ~34° for the Wasatch fault near Levan.

The best available data for addressing the question of whether small earthquakes might be occurring on a listric Wasatch fault are those from portable-array studies reported by Arabasz and Julander (1986). At the southern end of the Wasatch fault, both in the northern and southern parts of box D-D', they show that earthquake foci and corresponding focal mechanisms are incompatible with seismic slip on either a listric or simple planar projection of the Wasatch fault. Rather, the background seismicity appears to be occurring on secondary structures of moderate (> 30°) to high-angle dip. Elsewhere along the Wasatch fault, existing data for earthquakes down-dip of the fault are either inadequate or ambiguous (e.g., Pechmann and Thorbjarnardottir, 1984) for interpreting subsurface association with a listric projection of the fault.

Comparison of figure 15 with figures 8 and 9 indicates a remarkable paucity of microseismicity along the Wasatch fault within the broadly active earthquake belt of the Wasatch Front. Some specific features of small-earthquake occurrence in the vicinity of the fault are targets of ongoing investigation, such as epicentral clustering along the fault trace at the northern end of the Brigham City segment, and clustering to the west of the Collinston and Salt Lake City segments. The episodic nature of the earthquake activity, however, handicaps the studies.

Figure 17 shows the space-time distribution of the earthquake sample included in figure 15. Such data might appear attractive for relating seismicity to segmentation of the Wasatch fault, but caution is clearly appropriate given the problematic relationship between the seismicity and the fault.

FIGURE 17.--NEAR HERE

The following general observations can be made from figure 17: Seismicity north of Brigham City provides a clear contrast with that between Brigham City and Bountiful. Ironically, the northernmost segments of the Wasatch fault show no evidence of latest Quaternary movement (Machette and others, this volume). There is a clear onset of the northern seismicity at about 1975, which corresponds both to the timing of the 1975 M_L 6.0 Pocatello Valley earthquake and the approximate beginning of operation of the UUSS telemetered seismic network. The case for seismic quiescence before the 1975 earthquake is made by Arabasz and Smith (1981). Activation of regional seismicity west of the Wasatch fault after the Pocatello Valley earthquake (discussed earlier) would be consistent with the interpretation that most of the northern seismicity in figure 17 is not on the Wasatch fault itself—although the episodic clustering of earthquakes near Honeyville at the boundary between the Brigham City and Collinston segments (fig. 15) is indeed suggestive of at least partial association.

Seismicity near the northern end of the Salt Lake City segment (northern end of box B-B'), both west and east of the Wasatch fault, has long been recognized—as has quiescence to the south. Other apparent features of the space-time diagrams of figure 17 are the post-1974 appearance of scattered earthquakes along the latitudes of the American Fork and Provo segments of the Wasatch fault, and temporally persistent seismicity near Santaquin and along the southernmost Wasatch fault. There is minimal microseismicity along a 30-km-long section of the Wasatch fault north of Levan. This includes at least the southern half of the Nephi segment, which has perhaps the youngest (< 300-500 years) surface rupture on the Wasatch fault (Schwartz and Coppersmith, 1984). Depending on the structural association of earthquakes west of the Wasatch fault along much of its course, the Wasatch fault itself could conceivably be aseismic throughout most of the space-time diagram of figure 17 (see Arabasz and others, 1980). Thus, figure 17 may not simply provide a side view of seismicity on the Wasatch fault. To what extent seismicity in the vicinity of the fault might be reflecting segmented behavior of the fault remains to be investigated further (see Wheeler and Krystinik, this volume).

As argued by Arabasz and Smith (1981), apparent seismicity gaps along the Wasatch fault are not necessarily indicative of a late (i.e., pre-earthquake) stage of a seismic cycle. Temporal decreases in seismicity ambiguously characterize both the early post-aftershock stage and the late pre-main-shock stage of a seismic cycle (e.g., Ellsworth and others, 1981).

Veneziano and others (1987) have recently analyzed the UUSS earthquake catalog between 1962 and 1985 for the identification of independent main events and for the hierarchical clustering of secondary events. One result of the statistical analysis was documentation that between roughly 40°N and 41.5°N—along an area encompassing most of the Wasatch fault—dependent events are systematically suppressed, compared with earthquake behavior in neighboring areas. The significance of this suppressed earthquake clustering is the subject of current study.

The Wasatch Front area is a classic example of a seismically active region in which the historical and instrumental earthquake record provides an inadequate guide to assessing earthquake potential. The absence of any surface-faulting earthquakes on the Wasatch fault in historical time, the problematic correlation of background seismicity with mapped Cenozoic faulting, and the notable paucity of contemporary earthquakes with the Wasatch fault all combine to enhance the importance of paleoseismological information. The potential for large surface-faulting earthquakes effectively must be considered independently of observed seismicity. The occurrence of the 1983 M_S 7.3 Borah Peak, Idaho, surface-faulting earthquake in an area of low historical seismicity (Richins and others, 1987; Dewey, 1987)—but in an area of clearly recognizable late Quaternary faulting—is a case in point.

Our closing perspective is that observational seismology contributes essential information— much of it still to be refined—for accurate estimations of earthquake hazards and risk in the Wasatch Front area. Background seismicity currently predominates on second-order faults in the Wasatch Front area and is the largest contributor to the probabilistic ground-shaking hazard for exposure periods of 50 years or less. From a seismotectonic point of view, background seismicity poses a major challenge in terms of understanding its association with geological structure and its information content about deformation on individual segments of the Wasatch fault. Beyond providing essential input to analyses of hazards and risk for engineering applications and decision-making, observational seismology remains a critical tool for probing the deformational state of segments of the Wasatch fault and for monitoring changes in their behavior.

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TABLE 1.—Largest earthquakes in the Utah region—1850 through December 1986[1] (modified from Arabasz and others, 1979)

Local Date	Lat(°N)	Long(°W)	Location	Intensity (MM)	Magnitude (M_L)	Moment[3] ($\times10^{24}$ dyne-cm)
1884 Nov 10	*42.0*	*111.3*	*Bear Lake Valley*	*8*	*(6)*	
1887 Dec 05	37.1	112.5	Kanab	7	(5½)	
1900 Aug 01	*40.0*	*112.1*	*Eureka*	*7*	*(5½)*	
1901 Nov 13	38.8	112.1	Richfield	9	(6½+)	
1902 Nov 17	37.4	113.5	Pine Valley	8	(6)	
1909 Oct 05	*41.8*	*112.7*	*Hansel Valley*	*8*	*(6)*	
1910 May 22	*40.8*	*111.9*	*Salt Lake City*	*7*	*(5½)*	
1914 May 13	*41.2*	*112.0*	*Ogden*	*7*	*(5½)*	
1921 Sep 29	38.7	112.2	Elsinore	8	(6)	
1921 Oct 01	38.7	112.2	Elsinore	8	(6)	
1934 Mar 12	*41.7*	*112.8*	*Hansel Valley*	*9*	*6.6*[2]	*77.0*
1959 Jul 21	37.0	112.5	Utah-Arizona border	6	5.5+	
1962 Aug 30	*42.04*	*111.74*	*Cache Valley*	*7*	*5.7*	*7.0*
1966 Aug 16	37.46	114.15	Nevada-Utah border	6	5.6	1.1
1975 Mar 27	*42.06*	*112.52*	*Pocatello Valley*	*8*	*6.0*	*18.6*

[1]Table includes earthquakes of either maximum Modified Mercalli intensity VII or greater, or of Richter magnitude 5.5 or greater. Aftershocks excluded. Magnitudes in parentheses are estimated from intensity. Sample area: 36.75°N - 42.50°N, 108.75°W - 114.25°W (fig. 6). Italics denote earthquakes within the Wasatch Front study area: 38.92°N - 42.50°N, 110.42°W - 113.17° W (fig. 3).

[2]Richter (1935, p. 24) estimated an M_L value of 7.0. The value of 6.6 comes from Gutenberg and Richter (1954) and appears to be a surface-wave magnitude.

[3]Doser and Smith (1982).

TABLE 2.—Independent main shocks of magnitude (M_L) 4.0 or greater in the Utah region—July 1962 - December 1986[1]

Local Date	Lat (N)	Long (W)	Magnitude (M_L)	Location
1962 Aug 30	*42.04*	*111.74*	*5.7*	*Cache Valley (Logan)—damage*
1962 Sep 05	*40.72*	*112.09*	*5.2*	*Magna—damage*
1963 Jul 07	*39.53*	*111.91*	*4.4*	*Juab Valley (Levan/Nephi)—damage*
1963 Jul 09	*40.03*	*111.19*	*4.0*	*Soldier Summit area*
1963 Sep 30	38.10	111.22	4.3	Capitol Reef Area
1964 Oct 18	*41.73*	*111.73*	*4.1*	*Cache Valley*
1966 Mar 17	*41.66*	*111.56*	*4.6*	*Logan*
1966 May 20	37.98	111.85	4.1	Aquarius Plateau area
1966 Aug 16	37.46	114.15	5.6	Nevada-Utah border
1966 Oct 21	38.20	113.16	4.2	Escalante Valley
1967 Feb 14	40.11	109.05	4.0	Utah-Colorado border
1967 Feb 16	41.27	113.33	4.0	Newfoundland Mts. area
1967 Oct 04	38.54	112.16	5.2	Marysvale—damage
1970 Mar 29	41.66	113.84	4.7	Grouse Creek area
1970 Apr 21	40.06	109.01	4.0	Colorado-Utah border
1971 Dec 03	42.50	110.34	4.1	SW Wyoming
1972 Jan 03	38.65	112.17	4.4	Elsinore—damage
1972 Jun 01	38.67	112.07	4.0	SW Sevier County
1972 Oct 01	*40.51*	*111.35*	*4.3*	*Heber City—damage*
1973 Apr 13	*42.04*	*112.63*	*4.2*	*Pocatello Valley*
1975 Mar 27	*42.06*	*112.52*	*6.0*	*Pocatello Valley—damage*
1976 Nov 04	*41.81*	*112.70*	*4.0*	*Hansel Valley*[2]
1977 Sep 30	*40.46*	*110.48*	*4.5*	*NW Duchesne County—damage*
1978 Nov 29	*42.10*	*112.49*	*4.6*	*Pocatello Valley*
1979 Mar 19	40.04	108.86	4.1	Colorado-Utah border
1980 May 24	*39.94*	*111.96*	*4.4*	*Goshen Valley*
1981 Apr 04	37.59	113.30	4.6	Kanarraville
1982 May 24	38.71	112.04	4.0	Sevier Valley (Annabella)
1983 Oct 08	*40.75*	*111.99*	*4.3*	*N. Salt Lake Valley*
1986 Mar 24	*39.24*	*112.01*	*4.4*	*Japanese Valley*
1986 Aug 22	37.45	110.53	4.0	SE Utah (near Bullfrog Basin)

[1] Italics denote earthquakes within the Wasatch Front study area (see Table 1 for boundaries of the Utah region and Wasatch Front area).

[2] Identified by Shimizu (1987) as a dependent event related to the March 1975 Pocatello Valley earthquake. Included here for the sake of argument.

TABLE 3.—Average recurrence intervals for earthquakes in the Wasatch Front region[1]

Magnitude Range	Average Recurrence Interval (years) Preferred Estimate	Range of Estimates
$M_L \geq 3.0$	0.40	
$M_L \geq 3.5$	0.90	0.81 - 1.0
$M_L \geq 4.0$	2.0	1.7 - 2.5
$M_L \geq 4.5$	4.6	3.4 - 6.3
$M_L \geq 5.0$	10	7 - 16
$M_L \geq 5.5$	24	14 - 40
$M_L \geq 6.0$	54	29 - 100
$M_L \geq 6.5$	120	60 - 250
$M_L \geq 7.0$	280	120 - 630
$3.0 \leq M_L \leq 3.5$	0.71	.66 - .78
$3.5 \leq M_L \leq 4.0$	1.6	1.6 - 1.7
$4.0 \leq M_L \leq 4.5$	3.7	3.3 - 4.2
$4.5 \leq M_L \leq 5.0$	8.3	6.6 - 10
$5.0 \leq M_L \leq 5.5$	19	14 - 26
$5.5 \leq M_L \leq 6.0$	42	28 - 66
$6.0 \leq M_L \leq 6.5$	96	57 - 170
$6.5 \leq M_L \leq 7.0$	220	120 - 420
$7.0 \leq M_L \leq 7.5$	490	240 - 1000

[1] 38°55'N–42°30'N, 110°25'W-113°10'W, excluding mining-related seismicity in the southeast corner of the area. Area equals 85,000 km^2.

TABLE 4.—Information for selected fault-specific sources

Fault Source	Approx. Length (km)	Maximum Magnitude (M_S)	Minimum Distance to Site (km)[1]	Interval for Max. Earthquake (years)	Annual Probability of Max. Earthquake
1. Wasatch fault (Youngs and others, 1987; Machette and others, 1986)					
Collinston segment	60	7.3	110	8,800	1.1×10^{-4}
Brigham City segment	40	7.1	70	7,250	1.4×10^{-4}
Weber segment	57	7.2	15	1,350	7.4×10^{-4}
Salt Lake City segment	45	7.2	0	2,550	3.9×10^{-4}
American Fork segment	18	6.8	25	1,900	5.3×10^{-4}
Provo segment	19	6.8	40	1,900	5.3×10^{-4}
Spanish Fork segment	32	7.0	60	2,050	4.9×10^{-4}
Nephi segment	40	7.1	80	1,750	5.7×10^{-4}
Levan segment	35	7.1	120	7,100	1.4×10^{-4}
Fayette segment	14	6.6	155	10,000	1.0×10^{-4}
2. West Valley fault zone (Young and others, 1987; S.J. Olig, written communication, 1987)	18	6.5	0	2,000	5.0×10^{-4}
3. East Great Salt Lake fault (Pechmann and others, 1987; Viveiros, 1986)					
Promontory segment	50	7.2	70	4,000	2.5×10^{-4}
Antelope Island segment	50	7.2	20	4,000	2.5×10^{-4}
4. N. Oquirrh Mts. fault (Youngs and others, 1987; T. Barnhard, personal communication, 1987)	35	7.0	30	10,000	1.0×10^{-4}

[1]The site used for the calculation of the hazard curves is the intersection of I-15 and I-80 in South Salt Lake, at approximately 40°43.1'N, 111°54.2'W (diamond, fig. 5).

FIGURE CAPTIONS

FIGURE 1. Flowchart outlining steps in a formalized earthquake hazard analysis (left column) and interrelated aspects of observational seismology (right column).

FIGURE 2. Maps of the Utah region showing distribution of seismograph stations (triangles) at four different times between 1955 and 1985. The "Utah region," corresponding to a specific domain of the University of Utah's earthquake catalog, extends from latitude 36°45'N to 42°30'N, and from longitude 108°45'W to 114°15'W.

FIGURE 3. Map showing setting of the Wasatch Front study area with respect to the Intermountain seismic belt (hachured zone) and the epicenters of historical earthquakes of magnitude 6.0 and greater (large dots) (adapted and updated from Arabasz and Smith, 1981). Year and magnitude labeled for each earthquake.

FIGURE 4. Schematic block-diagram (vertical exaggeration ~1.0-1.5) illustrating selected aspects of the seismotectonic framework of the Wasatch Front area. Heavy lines with arrows (directions of displacement) represent fault traces. Bold lower-case letters indicate elements discussed in the text, including (a) the base of the crust defined by the Moho, (b) lower-crustal material, (c) low-angle detachments, (d) listric fault geometry, (e) the brittle-ductile transition, (f) the nucleation zone of a large earthquake, (g) surface fault scarps, (h) fault segment boundary, (i) the direction of crustal extension, and (j) the orientation of principal stresses (σ_1, σ_2, σ_3) with compression positive.

FIGURE 5. Index map of the Wasatch Front study area showing traces of late Quaternary faulting (see text for sources). Large arrows delimit the extent of the Wasatch fault zone. Other faults labeled for general orientation include: BL, Bear Lake; BR, Bear River Range; CL, Clear Lake; CM, Crawford Mts.; DM, Drum Mts.; EC, East Cache; ECN, East Canyon; EGSL, East Great Salt Lake; HV, Hansel Valley; JV, Joes Valley; LD, Little Diamond Creek; ME, Mercur; MO, Morgan; NO, Northern Oquirrh; OV, Ogden Valley; PR, Pavant Range; PV, Puddle Valley; RV, Round Valley; SC, Sulphur Creek; SH, Sheeprock Mts.; ST, Stansbury Mts.; STW, Strawberry Valley; SV, Scipio Valley; TH, Topliff Hill; WV, West Valley. The diamond near Salt Lake City marks the site for which we performed a probabilistic calculation of ground shaking hazard (see fig. 14).

FIGURE 6. Epicenter map of the Utah region showing all independent main shocks of M_L 4.0 or greater (or Intensity V or greater), 1850-1986, and Quaternary faults. Earthquakes of estimated M_L 5.5 or greater are indicated by solid circles labeled with date. Data from University of Utah Seismograph Stations.

FIGURE 7. Epicenter map of all earthquakes located by the University of Utah Seismograph Stations in the Utah region, 1962-1986.

FIGURE 8. Epicenter map of all earthquakes located by the University of Utah Seismograph Stations in the Wasatch Front area, 1974-1978. Base map as in figure 5.

FIGURE 9. Epicenter map of all earthquakes located by the University of Utah Seismograph Stations in the Wasatch Front area, 1978-1986. Base map as in figure 5.

FIGURE 10. Epicenter map (right) and corresponding vertical sections (left) of earthquakes in the Wasatch Front area located with reliable focal depths, October 1974 through December 1986. Sample includes only earthquakes located with a standard vertical hypocentral error of 2 km or less and with the distance to the nearest recording station less than or equal to the focal depth or 5 km, whichever is larger. Each vertical section includes foci whose epicenters lie within 15' latitude of the line of section.

FIGURE 11. Schematic geologic cross-section of the upper crust illustrating complex association of seismicity with geological structure in the Intermountain seismic belt (from Arabasz, 1984, and Arabasz and Julander, 1986). Starbursts indicate foci of moderate-to-large earthquakes; small circles, microseismicity; lines in subsurface, faults. Arrows indicate sense of slip on faults; two-directional arrows, extensional backsliding on pre-existing low-angle faults possibly formed as thrust faults. Base of seismogenic layer is approximately at 10-15 km depth. Letters identify aspects (not exhaustive) of observations and a working hypothesis relating seismicity to structure: (a) local predominance of seismicity within a lower plate; (b) nucleation of a large normal-faulting earthquake near the base of the seismogenic layer, hypothetically on an old thrust ramp, and with linkage or an established rupture pathway to a major surface fault; (c) occurrence of a moderate-size earthquake within a lower plate, without linkage to a shallow structure; (d) occurrence of a moderate-size earthquake and aftershocks on a secondary fault where an underlying detachment restricts deformation to the upper plate; (e) diffuse block-interior microseismicity predominating within an upper plate--perhaps responding to extension enhanced by

gravitational backsliding on an underlying detachment; and (f) diffuse block-interior microseismicity within a lower plate where frequency of occurrence is markedly lower than in the overlying plate.

FIGURE 12. Epicenters of independent main shocks in the Wasatch Front area from July 1962 through December 1985, plotted on the map of late Quaternary faulting shown in figure 5. Dashed box at lower right indicates area of mining-induced seismicity that was excluded from the recurrence analysis.

FIGURE 13. Recurrence data for independent main shocks in the Wasatch Front area from July 1962 through December 1985. The dots show the cumulative number of earthquakes per year greater than or equal to the local magnitude, M_L, given on the horizontal axis. The dots are spaced 0.1 magnitude unit apart. The heavy line through the dots for $M_L \geq 3.0$ indicates the preferred maximum likelihood fit with a slope, b, of 0.71, calculated using the method of Weichert (1980). The lighter lines indicate the lower- and upper-bound slopes of 0.62 and 0.80. The area used for the recurrence modeling is 85,000 km^2 (area shown in fig. 12 minus the dashed box).

FIGURE 14. Graphs showing the probability of exceedance per year for peak horizontal ground accelerations on soil at the intersection of I-15 and I-80 in South Salt Lake at approximately 40°43.1'N, 111°54.2'W (diamond, fig. 5). The shaded zones represent the range of values calculated using the range of median attenuation curves for peak horizontal acceleration presented by Campbell (1987). The results of separate calculations for the background seismicity, the Wasatch fault, other faults (the West Valley, East Great Salt

Lake, and North Oquirrh Mountains faults), and all of these sources together are shown. On the graph for the background seismicity, the dashed curves bound the range of values obtained using the preferred b- value of 0.71. The lower solid curve was calculated using the upper-bound b-value of 0.80 and Campbell's lower-bound acceleration estimates, whereas the upper solid curve was calculated using the lower-bound b-value of 0.62 and Campbell's upper-bound acceleration estimates. The vertical axes at the right show the average return period in years (the inverse of the annual probability).

FIGURE 15. Strip map showing the Wasatch fault, segment boundaries and names (according to Machette and others, this volume, right-hand side; and Schwartz and Coppersmith, 1984, left-hand side), and all earthquakes located by the University of Utah Seismograph Stations during the period July 1962 through December 1986. Circle sizes indicate relative magnitudes of events.

FIGURE 16. Composite figure of cross sections keyed to the boxes in figure 15. WF marks the surface trace of the Wasatch fault, arbitrarily depicted by a plane dipping 45° to the west. Only foci meeting criteria for reliable focal depths, as in figure 10, are included.

FIGURE 17. Composite figure of space-time diagrams of earthquake occurrence keyed to figure 15. Circle sizes indicate relative magnitudes of events. Shown for reference are the locations of selected cities and towns along the Wasatch fault (above) and the boundaries and names of segments of the Wasatch fault delineated by Machette and others (this volume) (below).

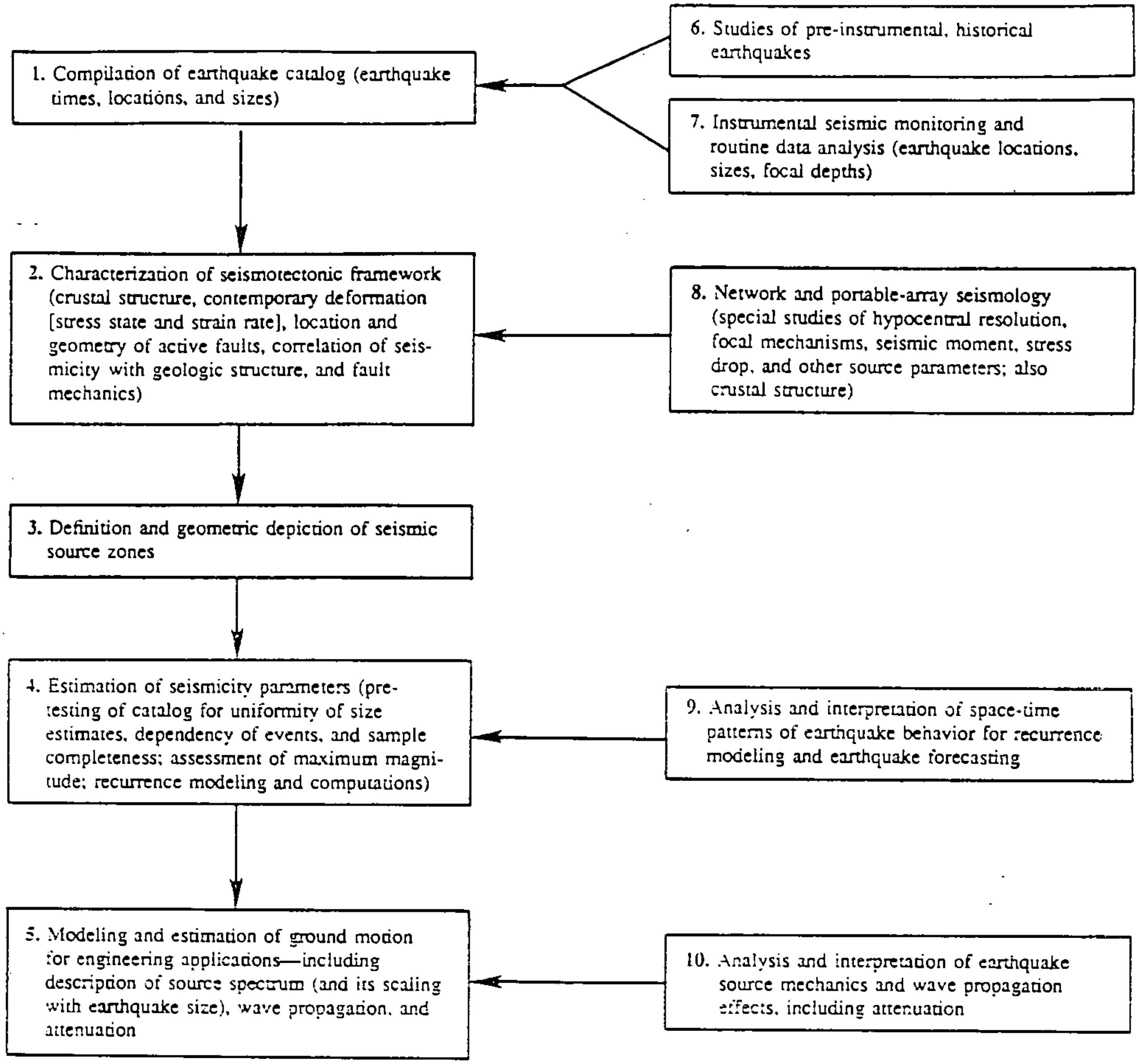

1. Compilation of earthquake catalog (earthquake times, locations, and sizes)
6. Studies of pre-instrumental, historical earthquakes
7. Instrumental seismic monitoring and routine data analysis (earthquake locations, sizes, focal depths)
2. Characterization of seismotectonic framework (crustal structure, contemporary deformation [stress state and strain rate], location and geometry of active faults, correlation of seismicity with geologic structure, and fault mechanics)
8. Network and portable-array seismology (special studies of hypocentral resolution, focal mechanisms, seismic moment, stress drop, and other source parameters; also crustal structure)
3. Definition and geometric depiction of seismic source zones
4. Estimation of seismicity parameters (pretesting of catalog for uniformity of size estimates, dependency of events, and sample completeness; assessment of maximum magnitude; recurrence modeling and computations)
9. Analysis and interpretation of space-time patterns of earthquake behavior for recurrence modeling and earthquake forecasting
5. Modeling and estimation of ground motion for engineering applications—including description of source spectrum (and its scaling with earthquake size), wave propagation, and attenuation
10. Analysis and interpretation of earthquake source mechanics and wave propagation effects, including attenuation

Figure 1.

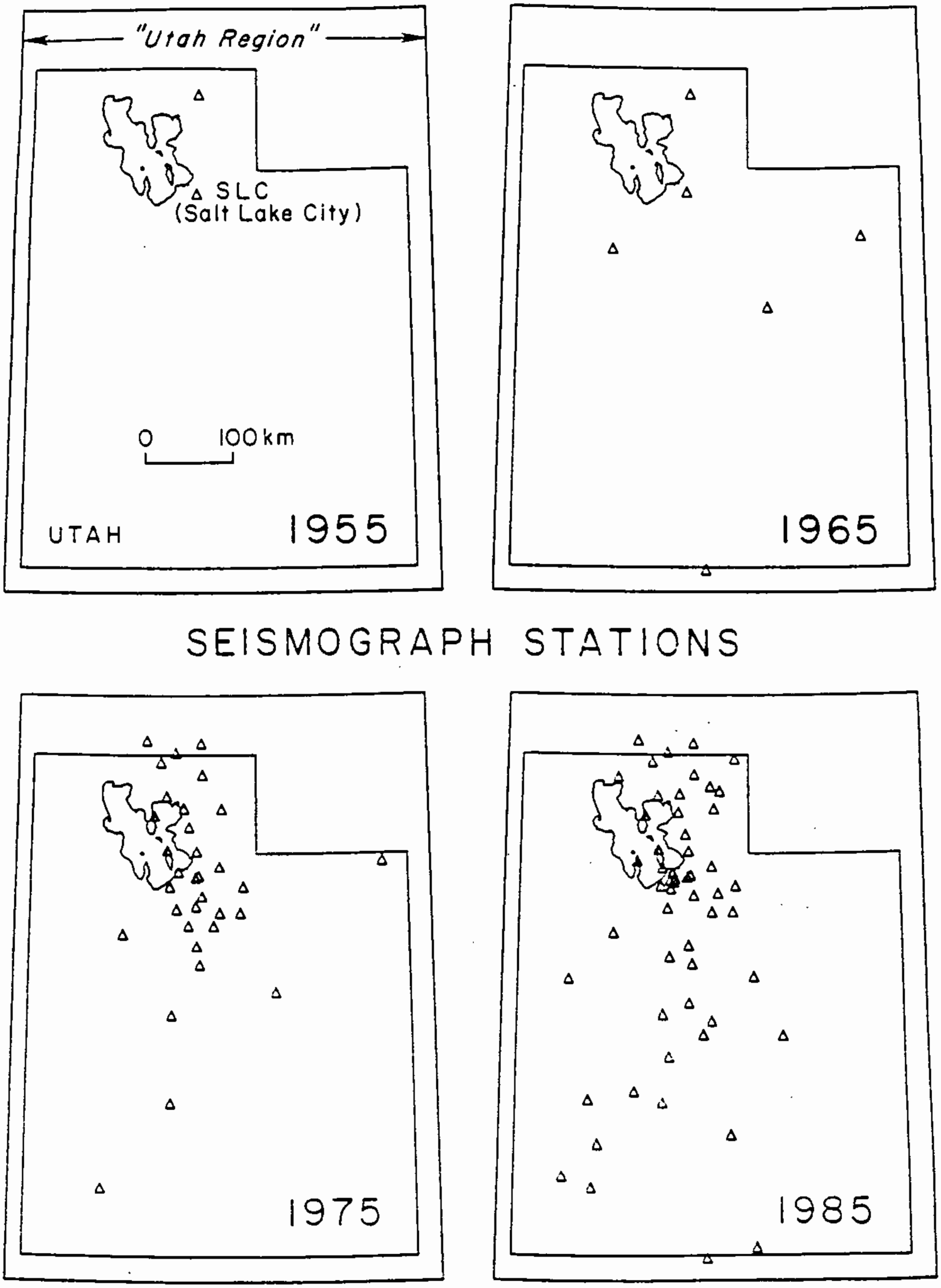

"Utah Region"
SLC
(Salt Lake City)
0
100km
UTAH
1955
1965
SEISMOGRAPH STATIONS
1975
1985

Figure 2.

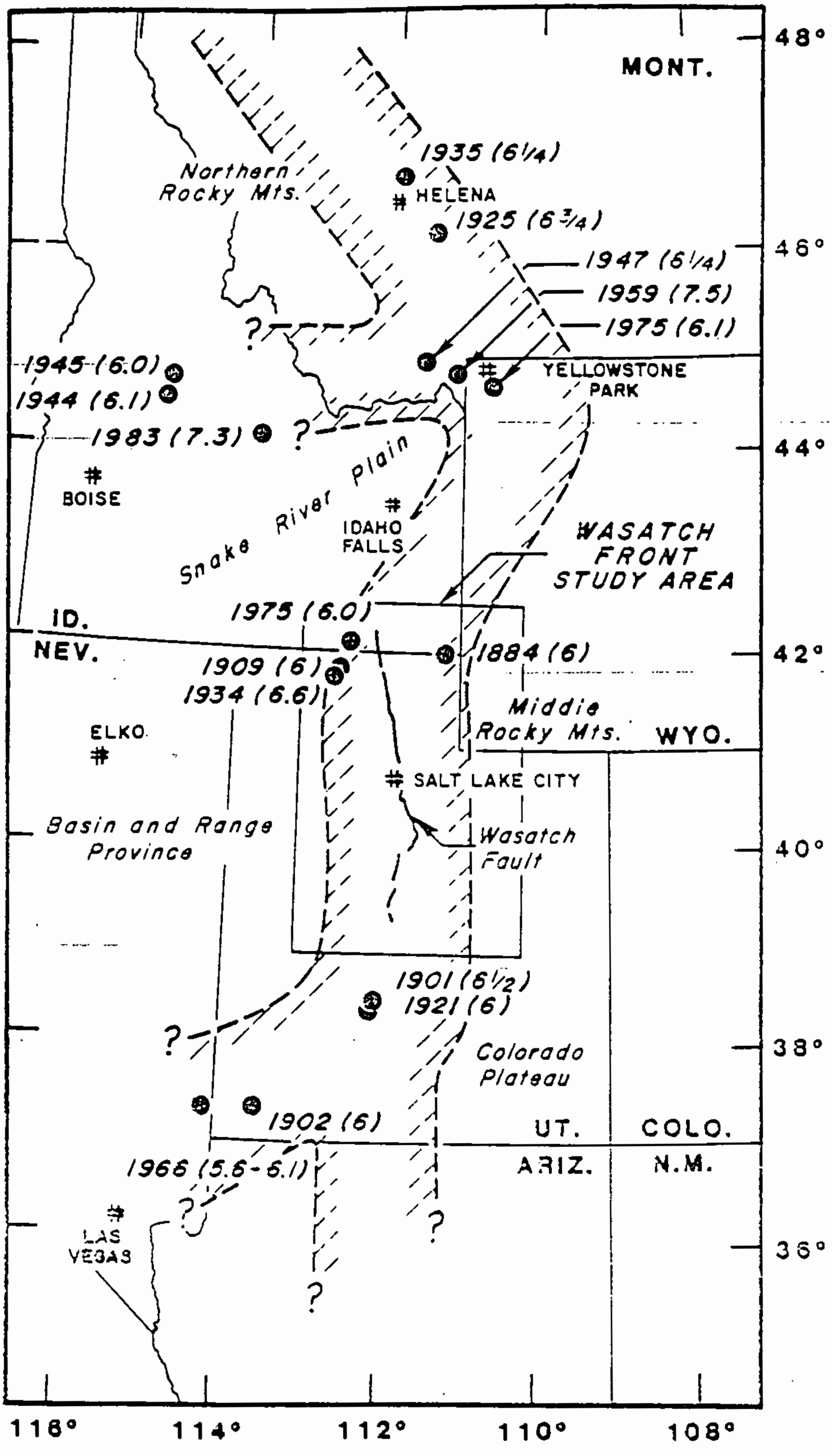
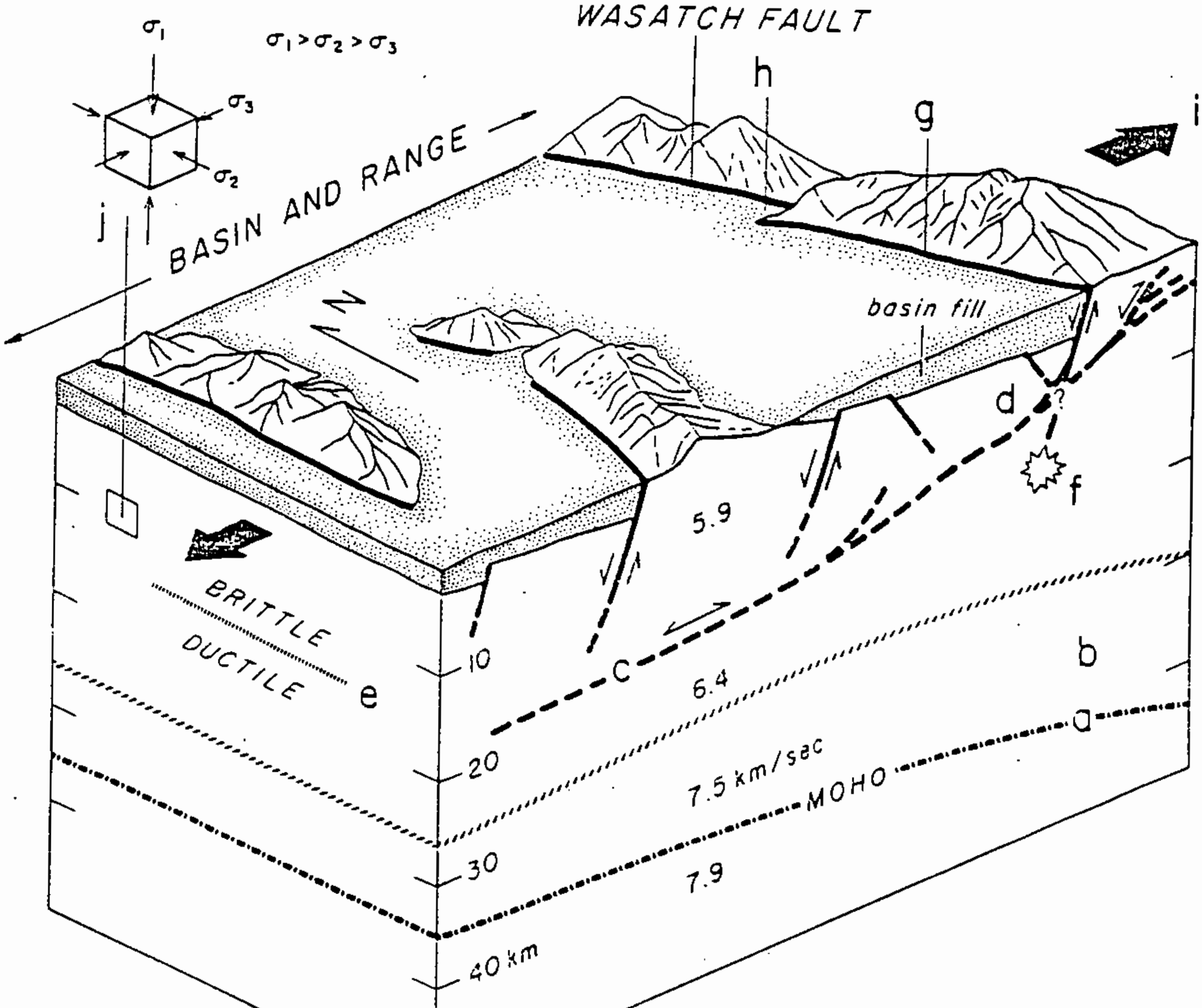
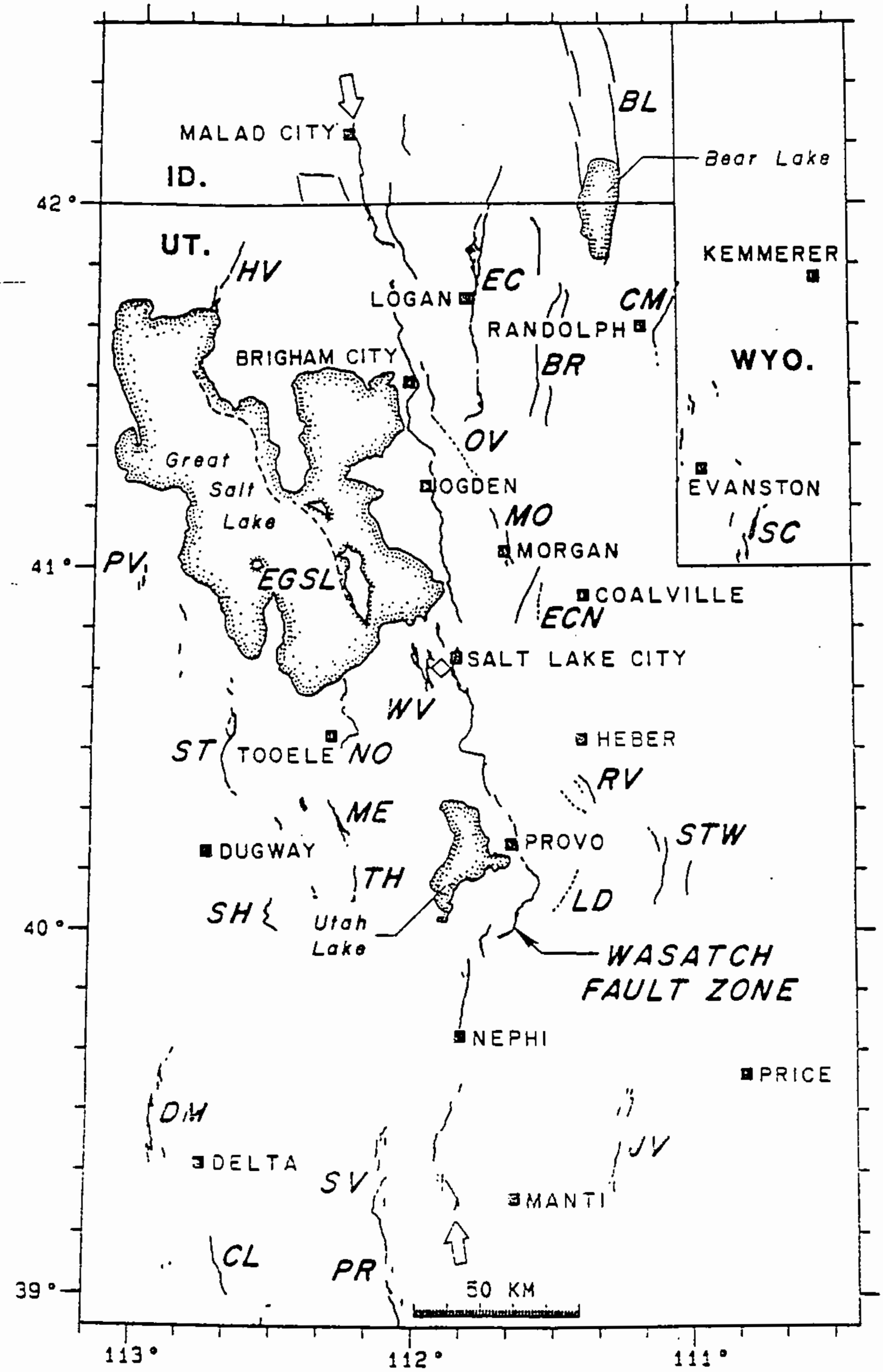

48°
MONT.
1935 (6¼)
Northern
Rocky Mts.
HELENA
1925 (6¾)
46°
1947 (6¼)
1959 (7.5)
1975 (6.1)
1945 (6.0)
1944 (6.1)
YELLOWSTONE
PARK
1983 (7.3)
44°
BOISE
Snake River Plain
IDAHO
FALLS
WASATCH
FRONT
STUDY AREA
1975 (6.0)
ID.
NEV.
1884 (6)
42°
1909 (6)
1934 (6.6)
ELKO
Middle
Rocky Mts.
WYO.
SALT LAKE CITY
Basin and Range
Province
Wasatch
Fault
40°
1901 (6½)
1921 (6)
38°
Colorado
Plateau
1902 (6)
UT.
COLO.
1966 (5.6-6.1)
ARIZ.
N.M.
LAS
VEGAS
36°
116°
114°
112°
110°
108°

Figure 3.



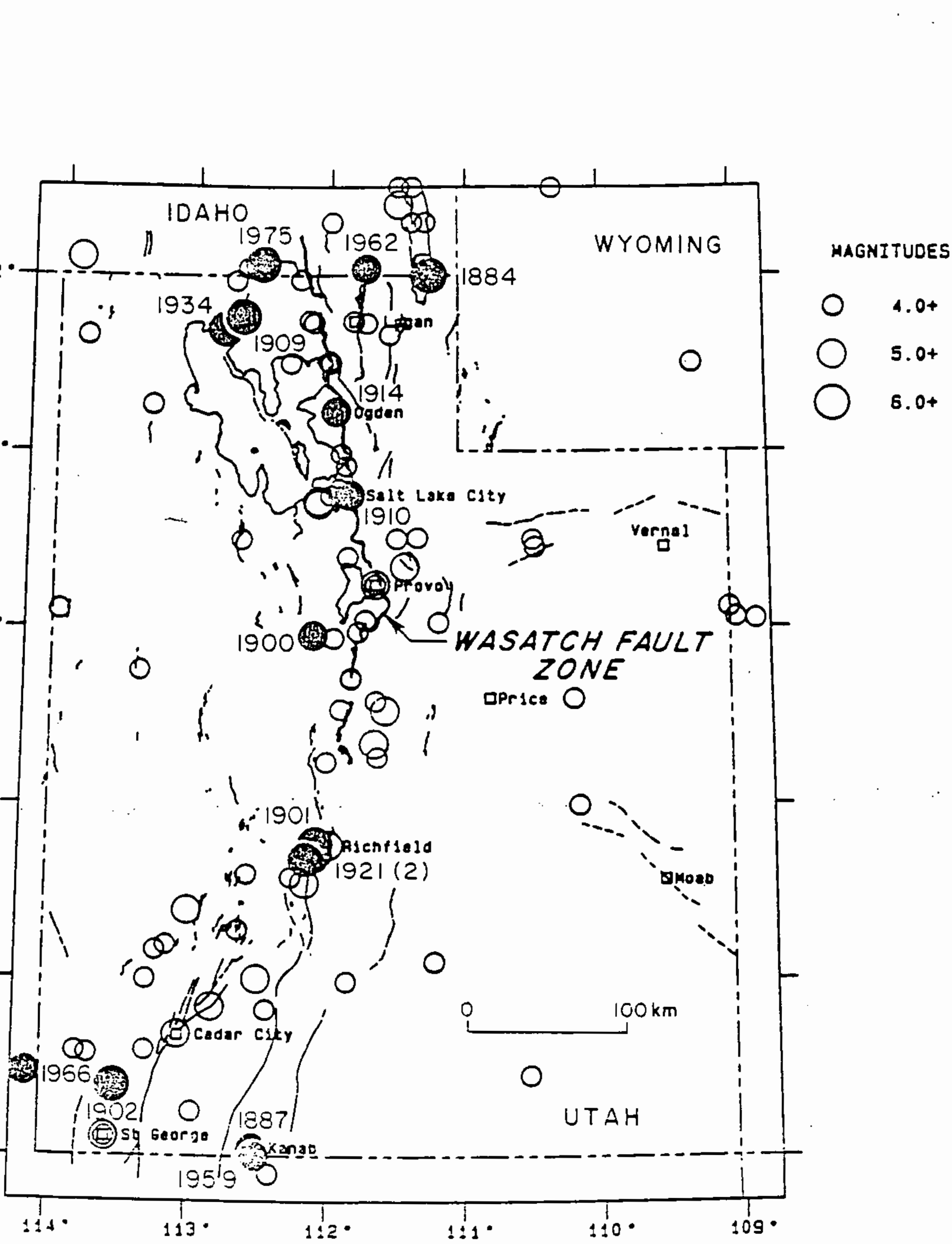
WASATCH FAULT
σ1 > σ2 > σ3
σ1
σ3
σ2
BASIN AND RANGE
h
g
i
j
N
basin fill
d
f
5.9
BRITTLE
DUCTILE
e
10
c
6.4
b
a
20
7.5 km/sec
MOHO
30
7.9
40 km

Figure 4.



MALAD CITY
ID.
UT.
42°
BL
Bear Lake
KEMMERER
HV
EC
LOGAN
CM
RANDOLPH
BRIGHAM CITY
WYO.
BR
OV
Great
Salt
Lake
OGDEN
EVANSTON
MO
SC
MORGAN
41°
PV
EGSL
COALVILLE
ECN
SALT LAKE CITY
WV
HEBER
ST
TOOELE
NO
RV
ME
DUGWAY
PROVO
STW
TH
SH
LD
40°
Utah
Lake
WASATCH
FAULT ZONE
NEPHI
PRICE
DM
JV
DELTA
SV
MANTI
CL
PR
39°
50 KM
113°
112°
111°

Figure 5.



IDAHO
WYOMING
UTAH
MAGNITUDES
4.0+
5.0+
6.0+
1975
1962
1884
1934
1909
1914
1910
1900
1901
1921 (2)
1966
1902
1887
1959
Logan
Ogden
Salt Lake City
Vernal
Provo
WASATCH FAULT ZONE
Price
Richfield
Moab
Cedar City
St George
Kanab
0
100km
42°
41°
40°
39°
38°
37°
114°
113°
112°
111°
110°
109°

Figure 6.

Utah Earthquakes
July 1, 1962 - December 31, 1986

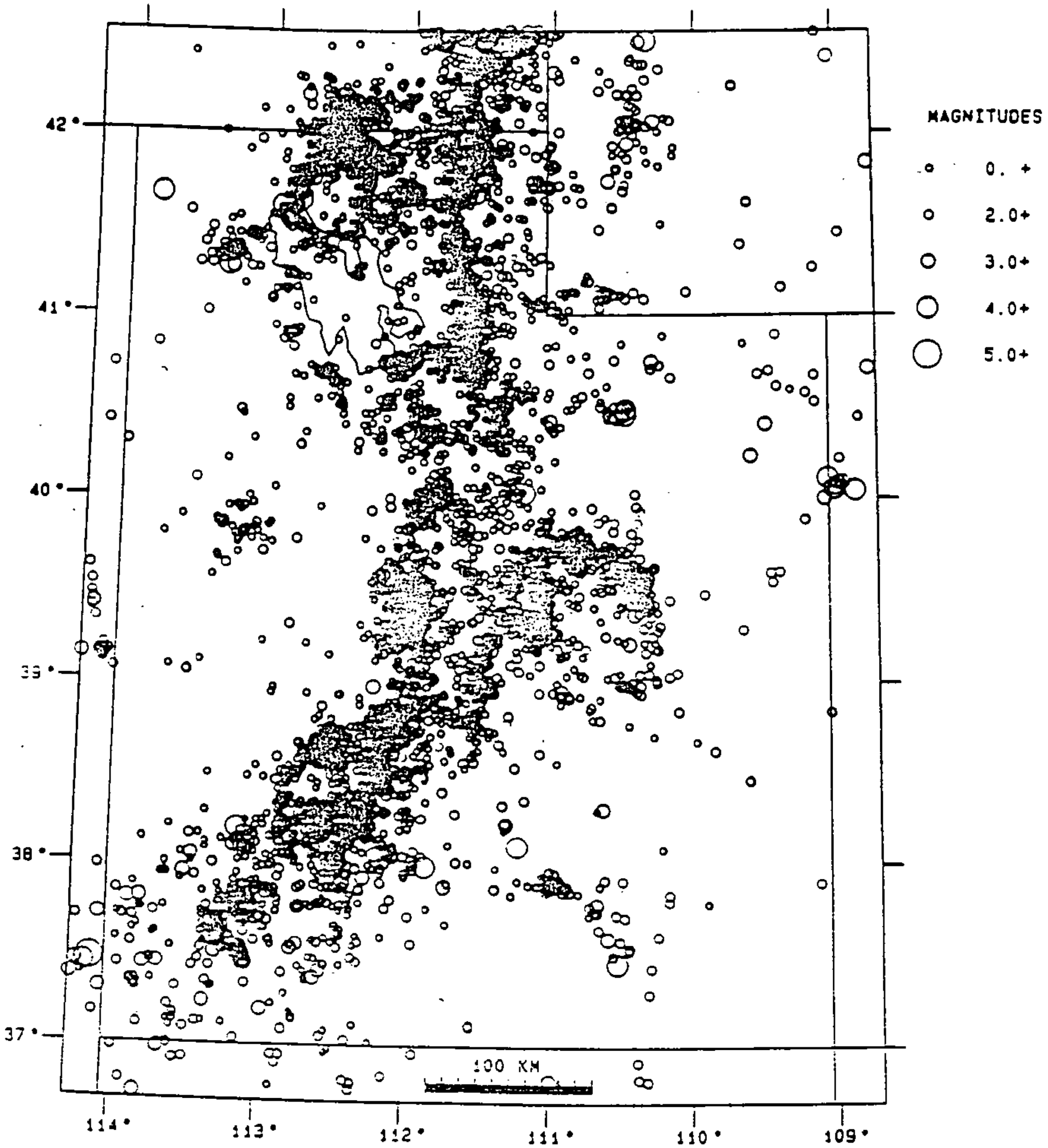
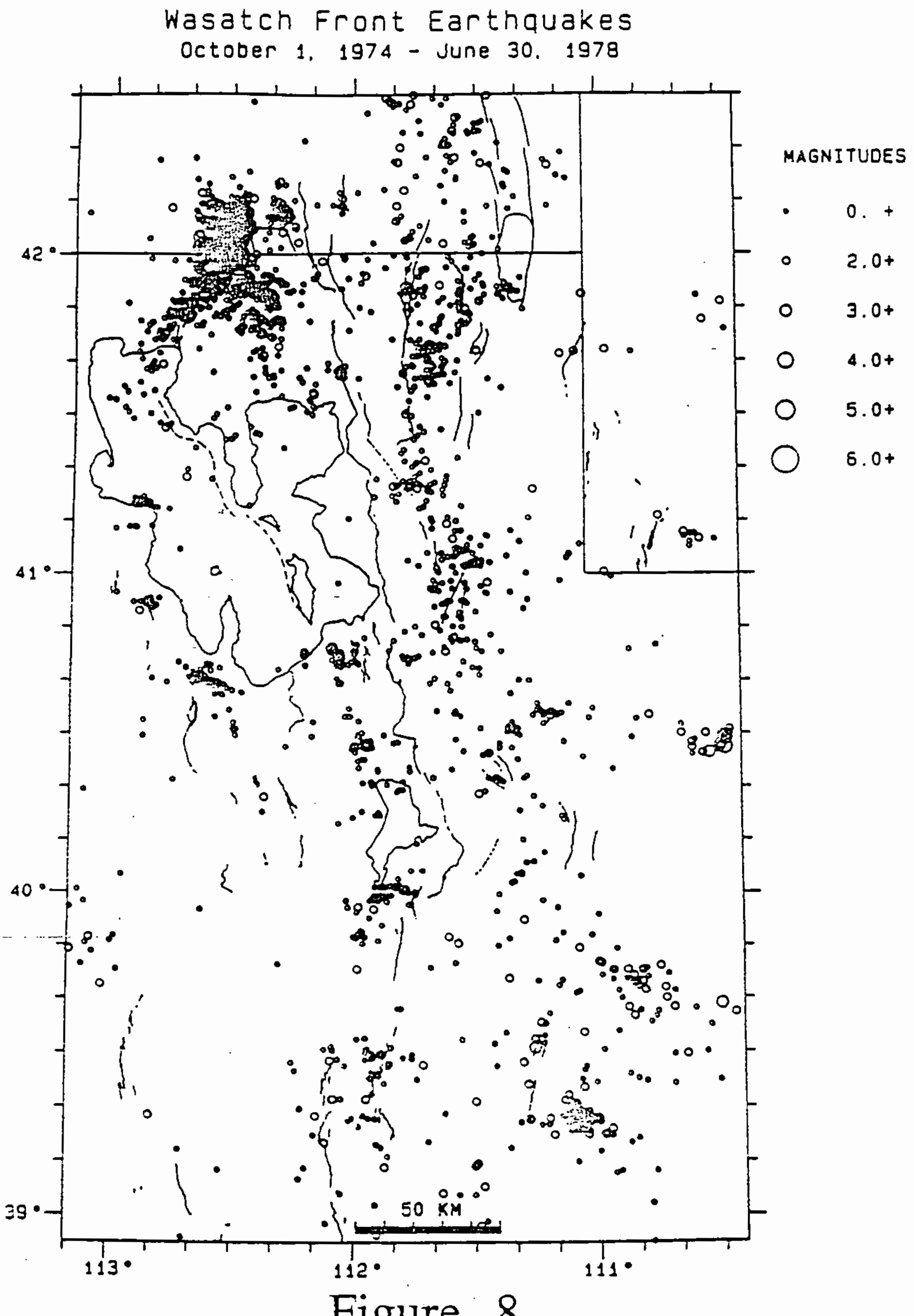


Figure 7.



Wasatch Front Earthquakes
October 1, 1974 - June 30, 1978
MAGNITUDES
0. +
2.0+
3.0+
4.0+
5.0+
6.0+
42°
41°
40°
39°
50 KM
113°
112°
111°

Figure 8.

Wasatch Front Earthquakes
July 1, 1978 - December 31, 1986

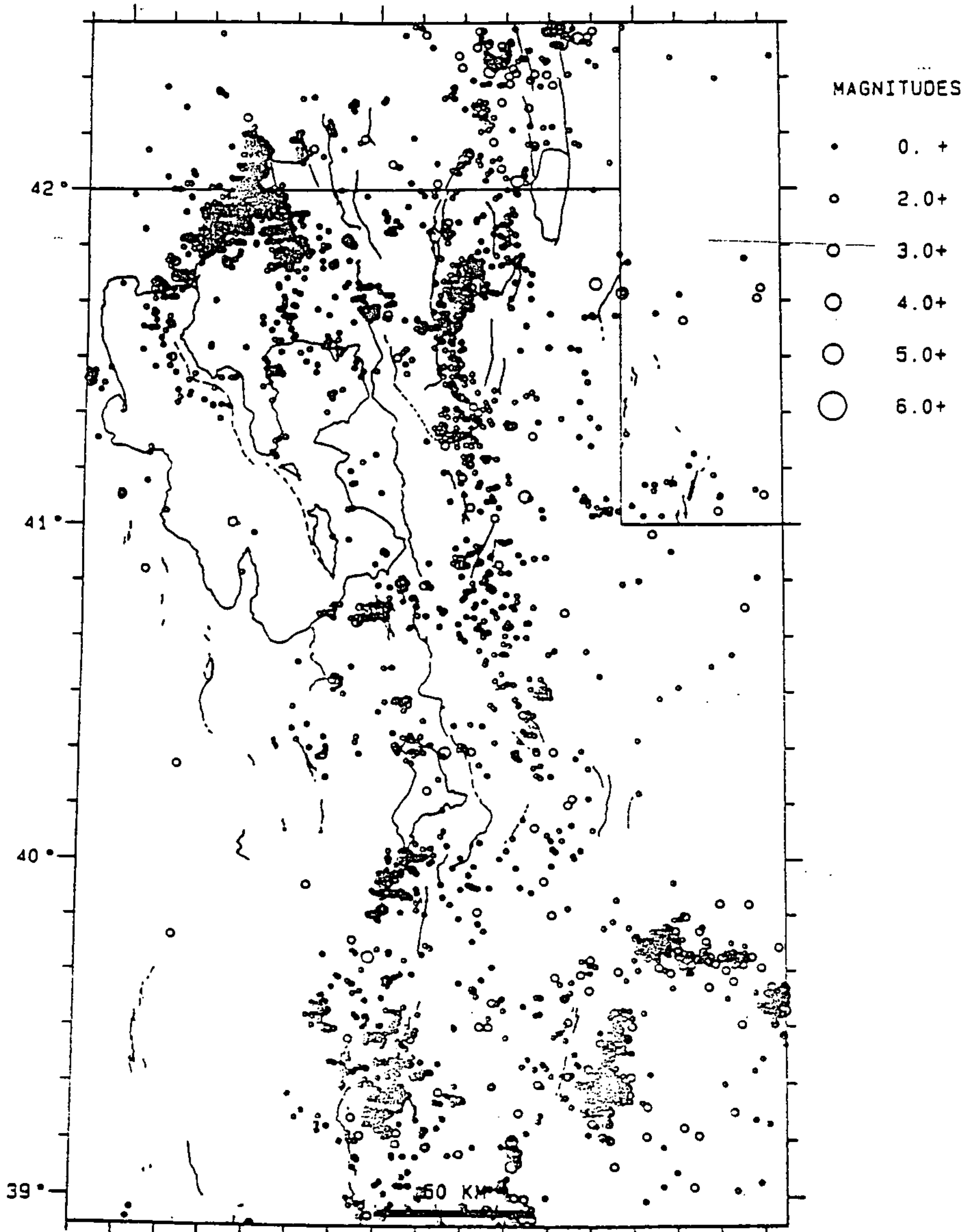
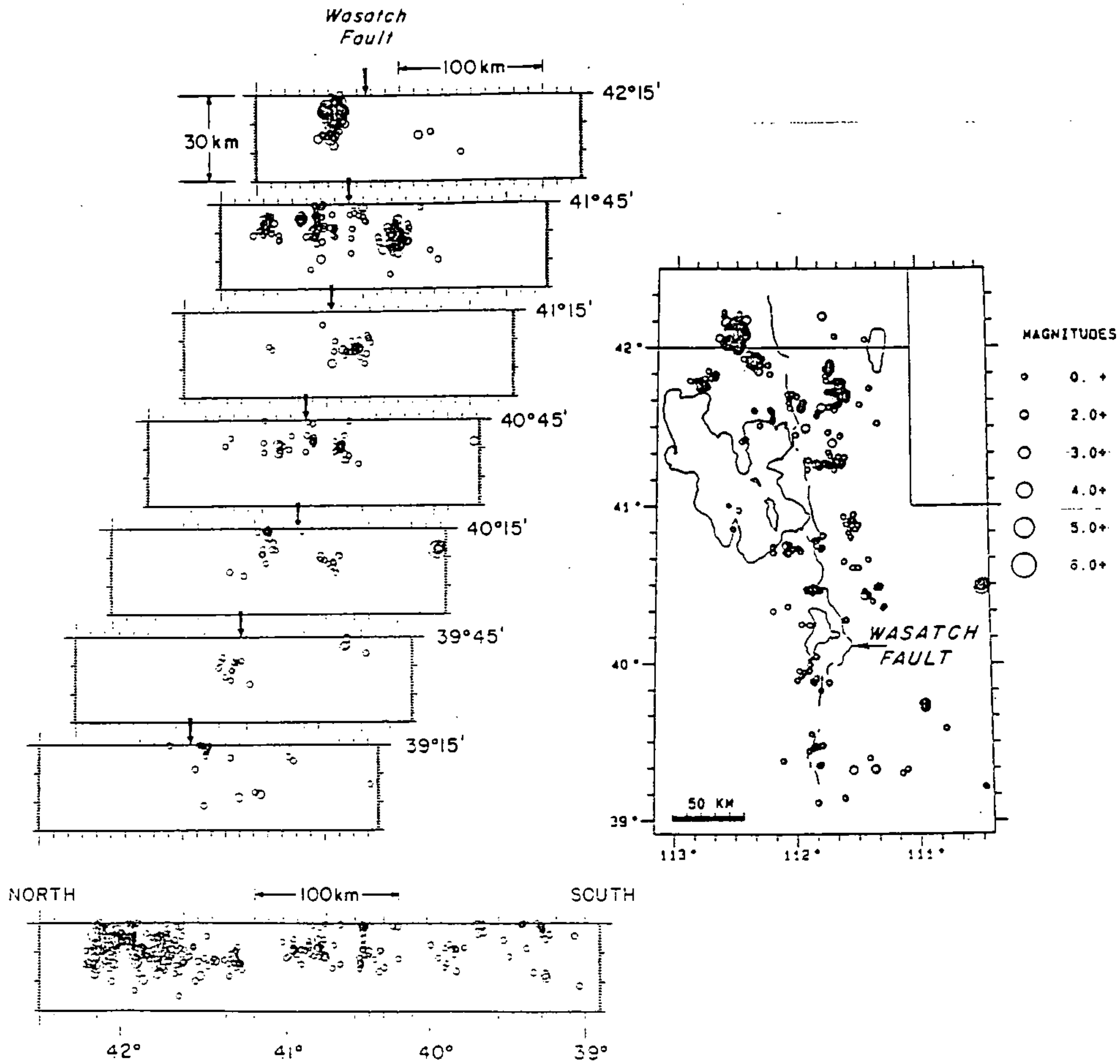
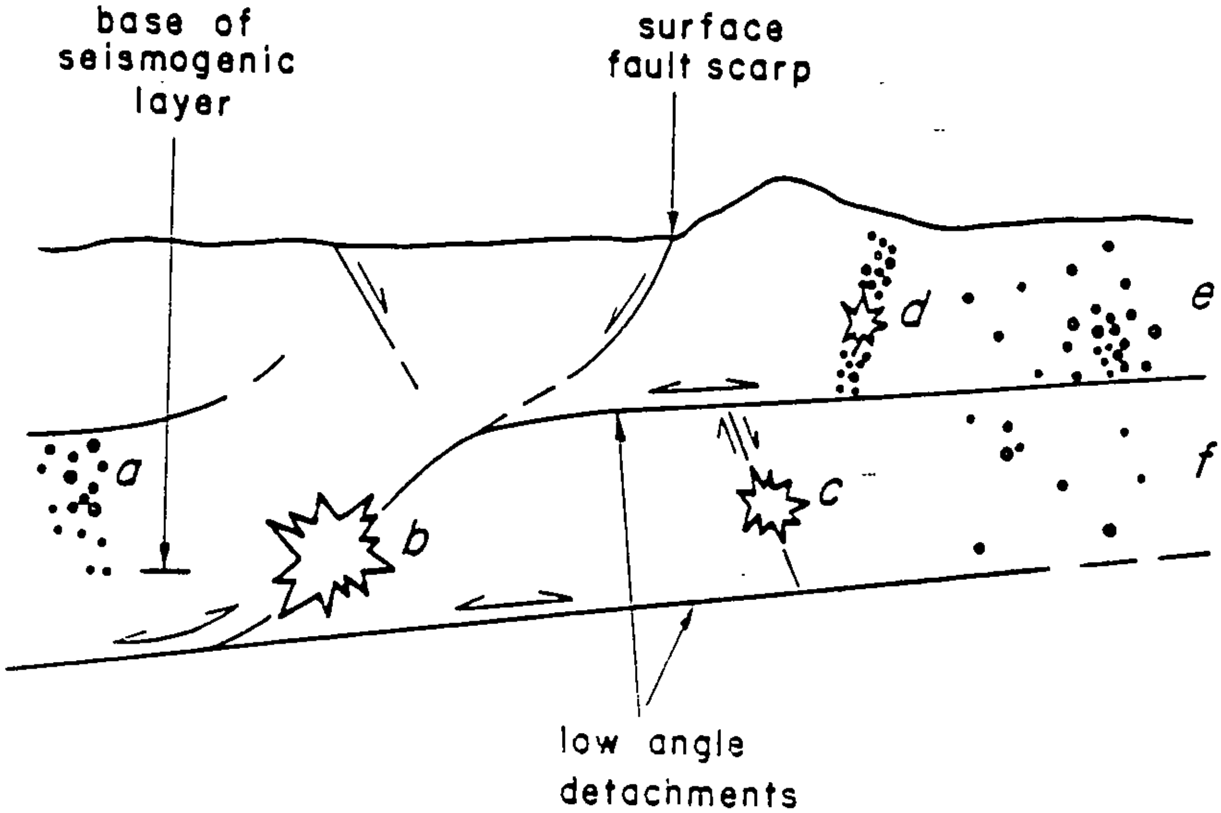


Figure 9.



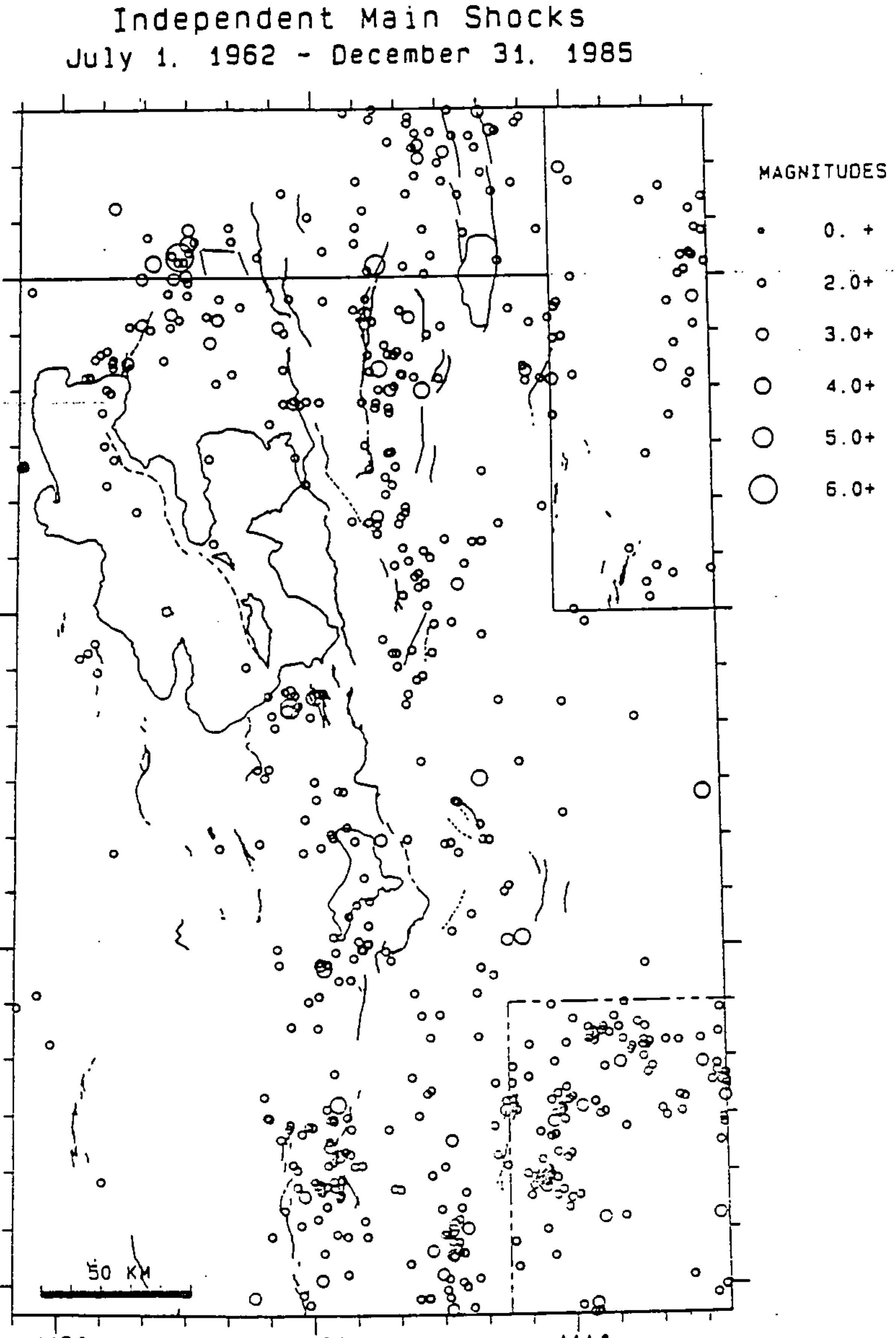
Wasatch Fault
100 km
30 km
42°15'
41°45'
41°15'
40°45'
40°15'
39°45'
39°15'
NORTH
100 km
SOUTH
42°
41°
40°
39°
MAGNITUDES
0. +
2.0+
3.0+
4.0+
5.0+
6.0+
WASATCH FAULT
50 KM
113°
112°
111°

Figure 10.



base of
seismogenic
layer
surface
fault scarp
a
b
c
d
e
f
low angle
detachments

Figure 11.



Independent Main Shocks
July 1. 1962 - December 31. 1985
MAGNITUDES
0. +
2.0+
3.0+
4.0+
5.0+
6.0+
42°
41°
40°
39°
50 KM
113°
112°
111°

Figure 12.

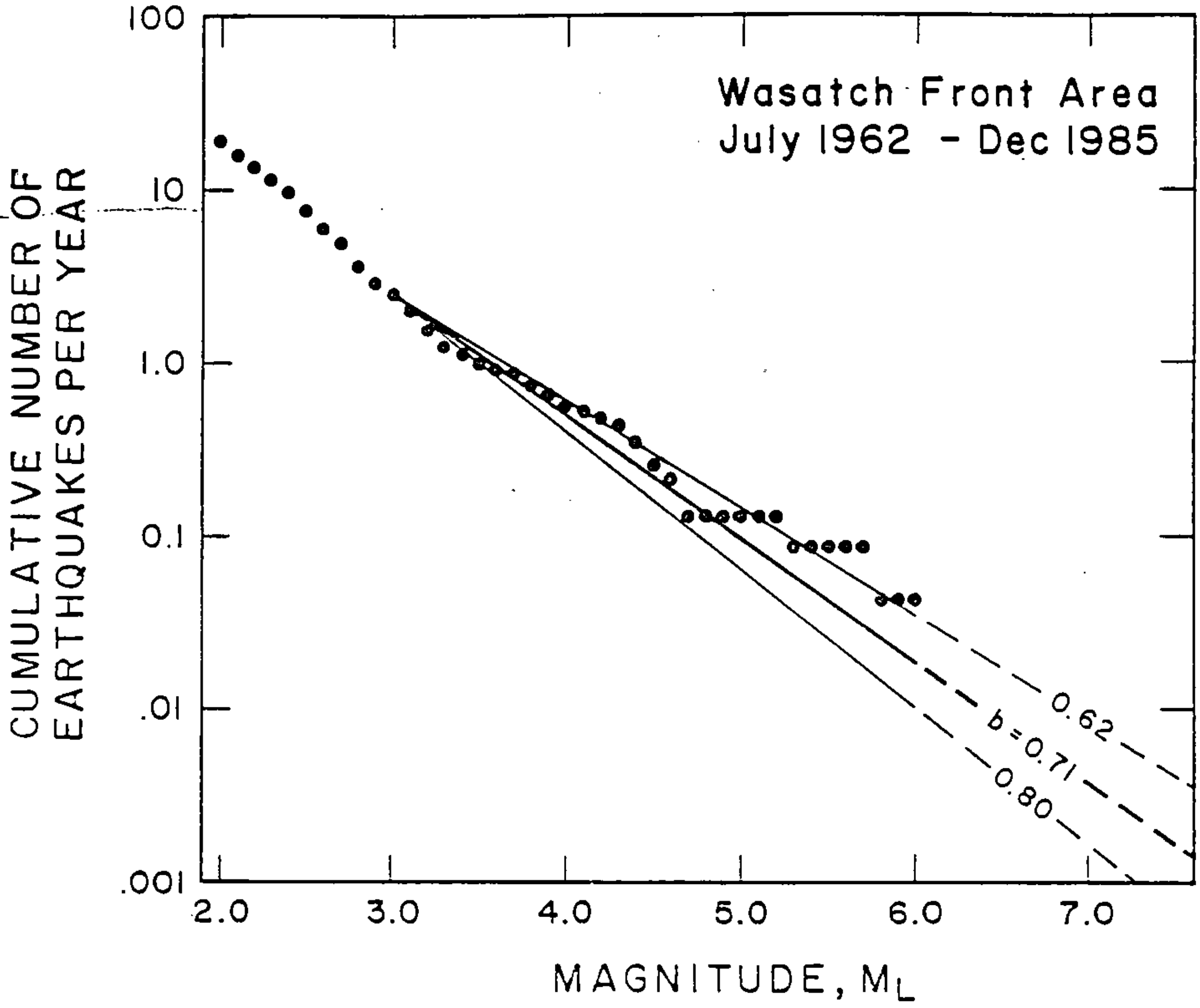

Wasatch Front Area
July 1962 - Dec 1985
CUMULATIVE NUMBER OF EARTHQUAKES PER YEAR
100
10
1.0
0.1
.01
.001
2.0
3.0
4.0
5.0
6.0
7.0
MAGNITUDE, M_L
0.62
b = 0.71
0.80

Figure 13.

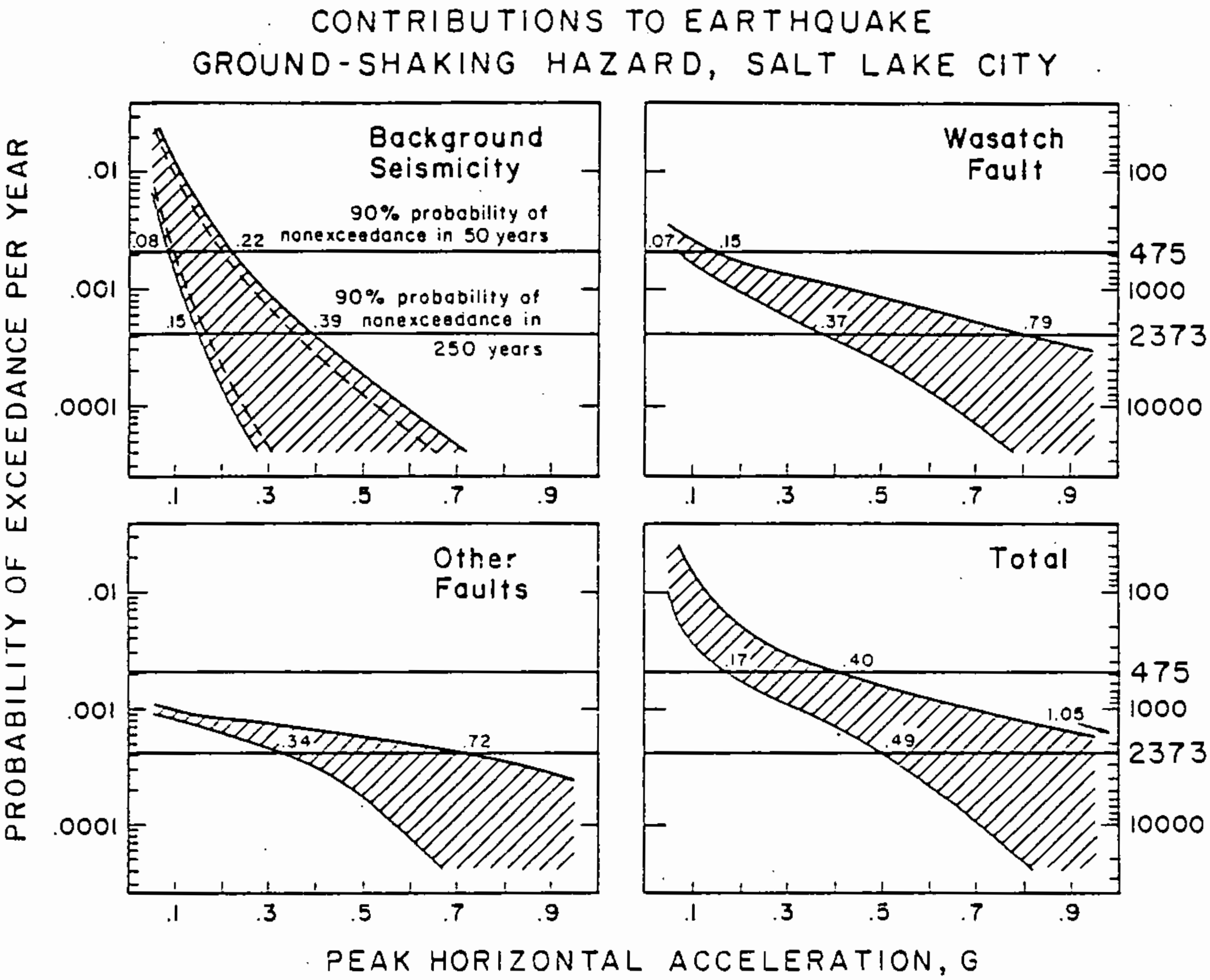
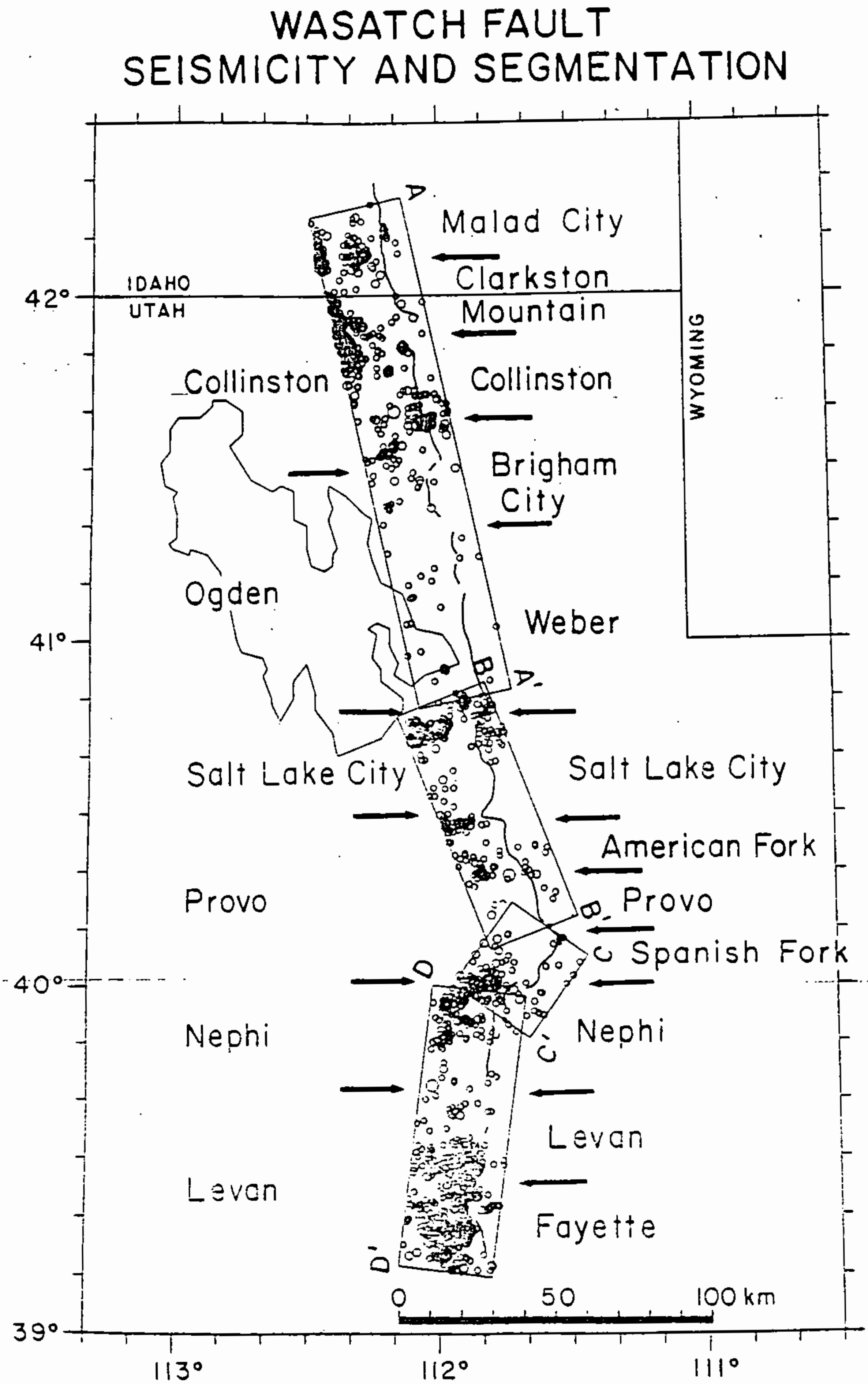

CONTRIBUTIONS TO EARTHQUAKE
GROUND-SHAKING HAZARD, SALT LAKE CITY
PROBABILITY OF EXCEEDANCE PER YEAR
RETURN PERIOD, YEARS
Background Seismicity
90% probability of nonexceedance in 50 years
90% probability of nonexceedance in 250 years
Wasatch Fault
Other Faults
Total
.01
.001
.0001
100
475
1000
2373
10000
.08
.22
.15
.39
.07
.15
.37
.79
.34
.72
.17
.40
.49
1.05
.1
.3
.5
.7
.9
PEAK HORIZONTAL ACCELERATION, G

Figure 14.



WASATCH FAULT
SEISMICITY AND SEGMENTATION
IDAHO
UTAH
WYOMING
Malad City
Clarkston Mountain
Collinston
Collinston
Brigham City
Ogden
Weber
Salt Lake City
Salt Lake City
American Fork
Provo
Provo
Spanish Fork
Nephi
Nephi
Levan
Levan
Fayette
A
A'
B
B'
C
C'
D
D'
42°
41°
40°
39°
113°
112°
111°
0
50
100 km

Figure 15.

DOE/EIS-0136-R-118

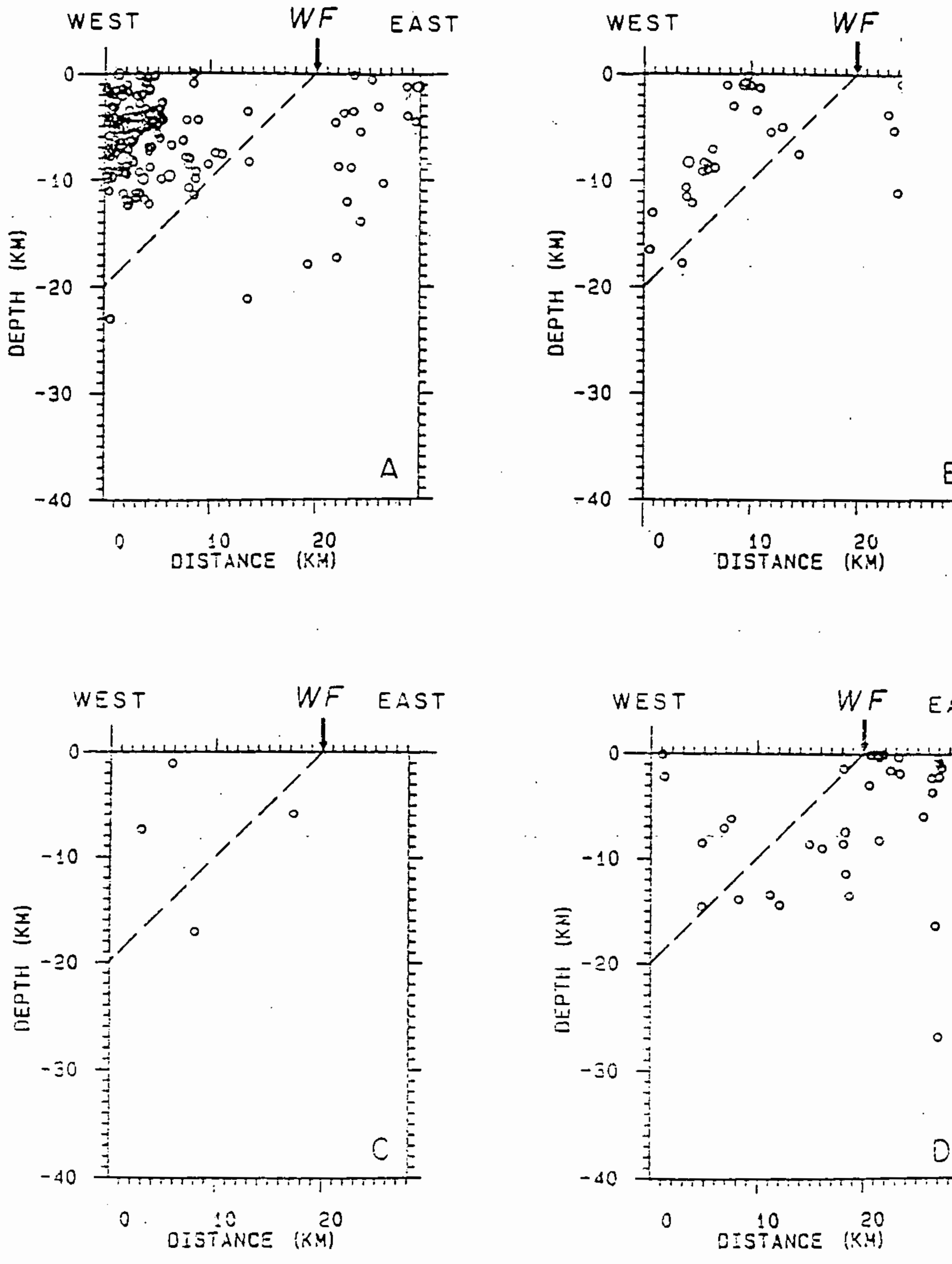


Figure 16.