Evaluation of Potential Surface Faulting and Other Tectonic Deformation

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FOREWORD

This draft technical report, "Evaluation of Potential Surface Faulting and Other Tectonic Deformation" was developed within the Subcommittee for Evaluation of Site Hazards of the Interagency Committee on Seismic Safety in Construction (ICSSC). The membership of the Subcommittee during the preparation of this report was:

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* Chairman

The Subcommittee has recommended that this draft report be submitted to all concerned agencies with the request that they test its implementation through use in planning, design, contract administration, and quality control, either on a trial or real basis during 1982 and 1983. Following the trial implementation, the Subcommittee plans to review the draft report, revise it as necessary, and then recommend its adoption by the Interagency Committee as a manual of standard practice for evaluating surface faulting and other tectonic deformation for Federal buildings. Comment on this draft is welcomed. Comment should be forwarded to the author or to:

Dr. Walter W. Hays
Chairman, ICSSC Subcommittee #7
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CONTENTS

SECTION PAGE

FIGURES

TABLES

1 INTRODUCTION

1.1 PURPOSE AND SCOPE.

This report summarizes and provides references to much of what is known about tectonic deformation associated with earthquakes and describes current approaches and procedures for evaluating the hazards of surface faulting and other earthquake-related tectonic deformation. Emphasis is placed on surface faulting because it is the more significant hazard for most construction. Figure 1 shows the currently-known distribution of young surface faulting in the United States.

The deformation discussed here is the permanent deformation of the ground arising from the sudden displacement of buried rock masses that generates an earthquake. Such deformation includes both faulting that ruptures the surface of the earth and permanent distributed deformation of the rocks surrounding the earthquake-generating fault.

Surface faulting also results from slow movement of large sedimentary deposits (for example, the "growth faults" of the Gulf Coast), from withdrawal of subsurface fluids, or from movement of salt, gypsum, or anhydrite deposits. Such faulting can damage structures (Allen, 1969; Verbeek, 1979; Yerkes and Castle, 1970), but, because it is aseismic or produces only very small earthquakes, it is not treated in this report, nor is faulting associated with volcanic activity.

Permanent deformation of the ground also results from failure phenomena within surficial sediments in response to earthquake shaking. Examples include landslides, earth flows, lateral spreads and settlements. Such distortions are regarded as secondary effects because they are induced by earthquake shaking, and are not discussed here.

1.2 TECTONIC DEFORMATION AS A HAZARD.

An earthquake is the vibration of the ground produced by sudden displacement of rock masses. Most earthquakes, apart from those associated with volcanic processes, landslides and collapse of caverns, result from the movement of one rock mass past another along a buried fault in response to tectonic forces. Ground shaking is one surface manifestation of fault movement at depth. Another is tectonic deformation of the earth's surface. Both are primary earthquake effects. Of the two, ground shaking typically leads to far more loss of life and damage to structures. Nonetheless, tectonic deformation poses a very serious earthquake hazard in many places.

It is useful to distinguish between two types of tectonic deformation, namely surface faulting and distributed deformation. Large displacement on a buried but shallow fault deforms the earth's surface. The deformation is distributed in the sense that it occurs over a broad region above or near the rupture. A characteristic of the deformation is that it varies little between neighboring points. An example of distributed deformation is regional uplift and subsidence accompanying earthquakes caused by reverse or thrust faulting. Surface faulting, on the other hand, is localized deformation, affecting only those structures that are located within or athwart the zone of ground breakage.

As illustrated in a following section of this report, surface faulting is an obvious hazard to structures built across active faults. It can be particularly severe for structures partially embedded in the ground and for buried pipelines and tunnels. Displacement as large as several meters may occur within a zone less than a meter wide.

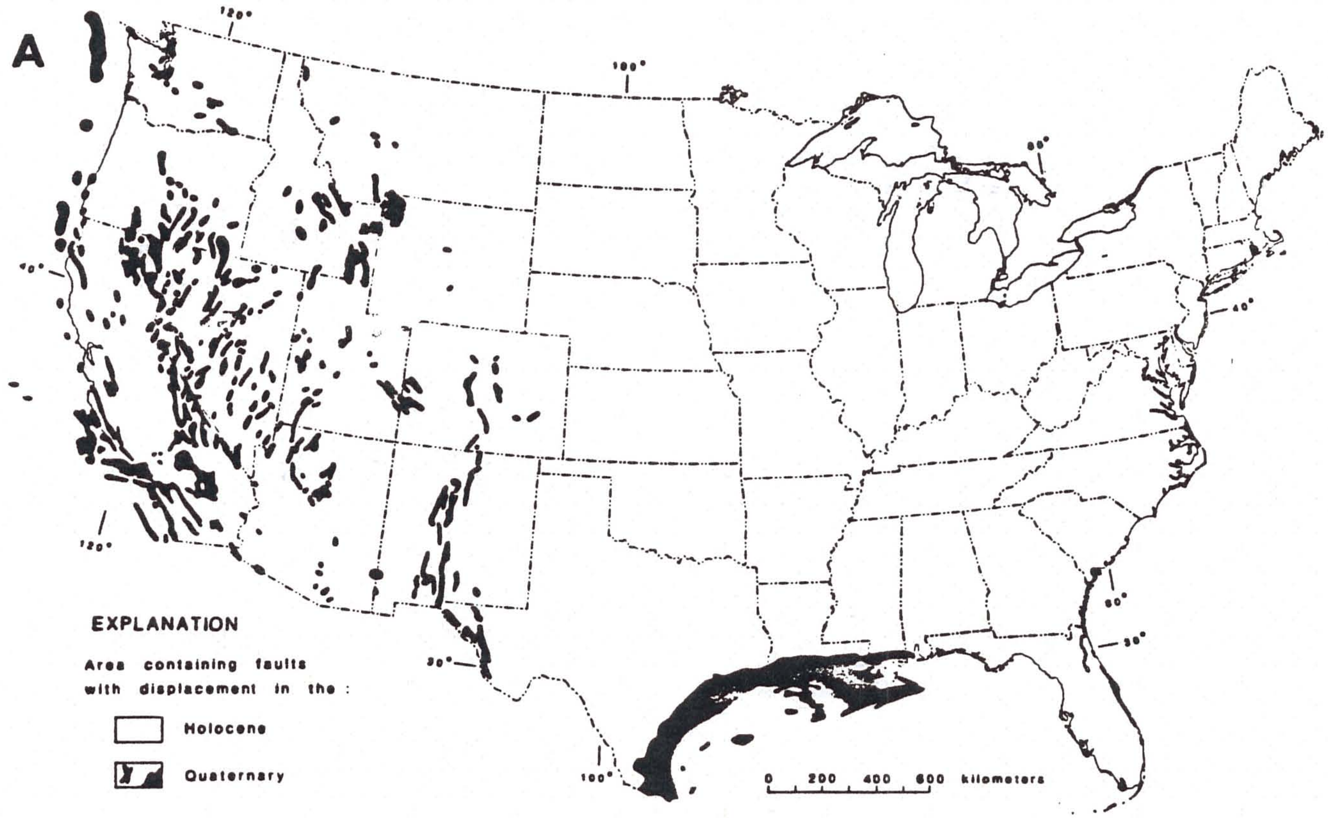

Figure 1. Maps of United States showing areas containing faults with surface displacement in Holocene and Quaternary time. A, Conterminous United States. B, Alaska and Hawaii. In addition to faulting associated with damaging earthquakes, the maps include faulting resulting from slow movement of large sedimentary or mineral deposits (e. g. Gulf Coast, Paradox Basin) or associated with volcanic activity (e.g. Hawaii). In general, future surface faulting is most likely in the areas of Holocene faulting, less likely in areas of Quaternary faulting, and least likely in the remaining area. Based on Howard and others (1978), Russ (1979), and Verbeek (1979).

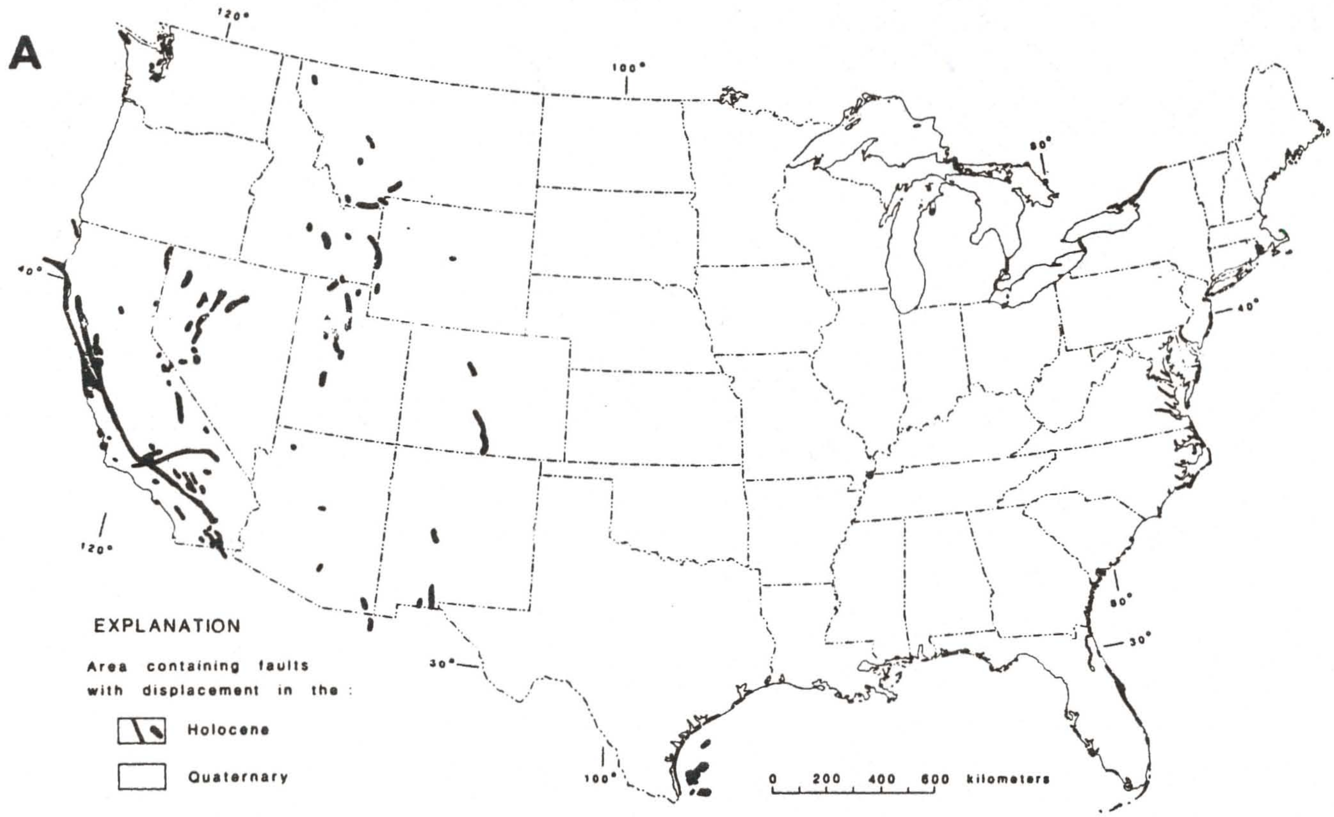

Figure 1 (cont.)

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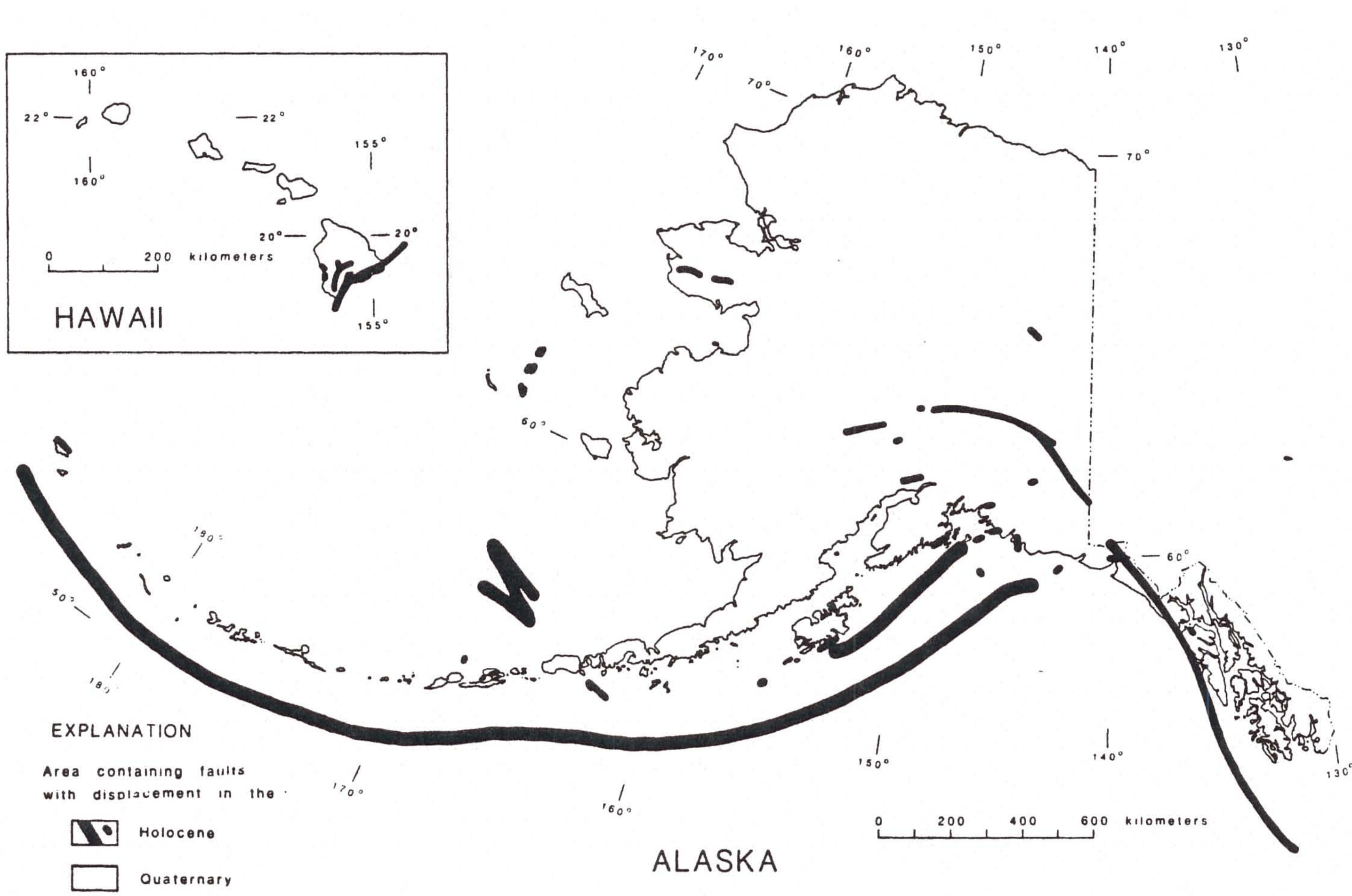

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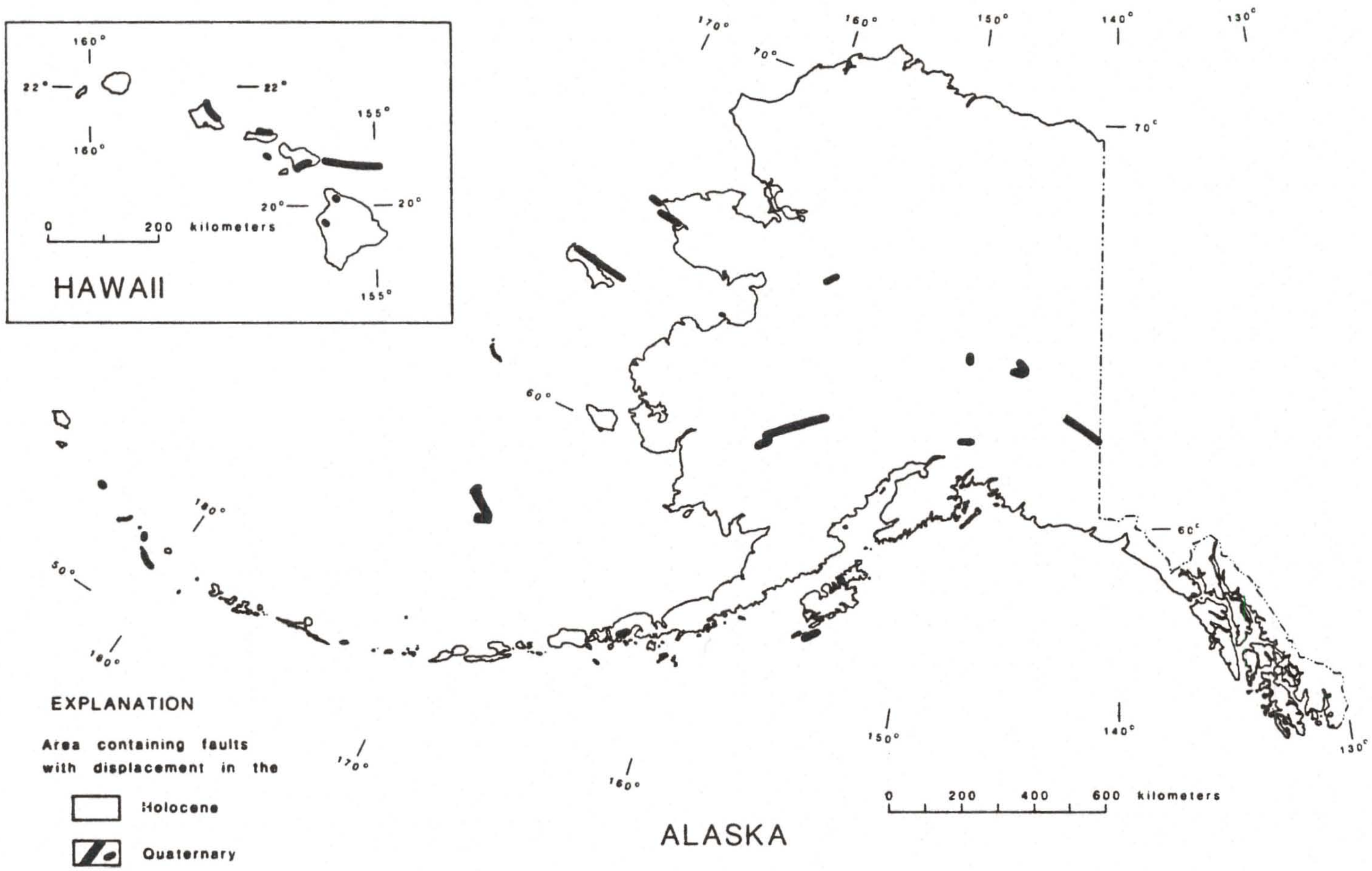

Figure 1 (cont.)

The surface faulting hazard can be mitigated by the careful siting of structures to avoid potentially dangerous faults and by designing structures to accommodate a particular amount of fault displacement without destruction or loss of function. As discussed in Section 3, several techniques have been developed to identify active faults, that is, faults that have slipped in recent geologic time and are likely to slip in the future. The use of such techniques permits the possibility of avoiding active faults for structures of limited dimensions. Avoidance of active faults is a key strategy in the safe siting of nuclear power plants and large dams throughout the United States, and in reducing earthquake risk from surface faulting in California (Blair and Spangle, 1979, pp. 62-68). For extended structures, such as lifeline facilities, avoidance of faults may be impossible. In such cases, however, the facility or structure possibly can be designed to accommodate or minimize the effect of faulting.

Regional tectonic deformation constitutes a hazard to shoreline facilities and extensive hydraulic systems where broad-scale changes in land elevation occur relative to water level. Such changes, either uplift or subsidence, can affect many thousands of square kilometers of the earth's surface, damaging harbor facilities, canals, and other structures.

In addition to regional uplift and subsidence, local vertical or horizontal deformation commonly occurs close to surface faults and can distort or tilt structures.

Selective siting of structures is a less effective strategy in reducing risks associated with widespread earthquake hazards such as regional changes in elevation, than it is for localized hazards such as surface faulting. Although some types of structures and facilities may be excluded from areas subject to inundation from subsidence of shorelines, others such as harbor facilities must be located in a hazardous zone because of their function. Accordingly, engineering design is a key strategy in mitigating risks associated with distributed tectonic deformation.

2 EFFECTS OF TECTONIC DEFORMATION AT THE GROUND SURFACE

This section describes the manifestations of tectonic deformation at or near the ground surface and gives examples of its effect on structures. This background knowledge is necessary in planning and conducting investigations and in anticipating the possible impact of tectonic deformation on existing or proposed structures.

2.1 FAULTING AND LOCAL DEFORMATION.

Effects in the vicinity of the fault consist of shearing, which can occur either suddenly or slowly, and horizontal or vertical warping.

2.1.1 Map Patterns of Faults.

The map pattern of surface faulting commonly consists of a main fault and subsidiary faults. These map patterns are shown schematically in figure 2. The main fault can appear at the surface as a single break or as en echelon, parallel, branching, or interlacing fractures. Subsidiary faults consist of branch faults, which extend a substantial distance from the main fault zone, and secondary faults, which at the surface are entirely separate from the main fault (Bonilla, 1970). Some historic surface faulting, usually with comparatively small surface displacements, has however consisted of widely distributed ruptures with no dominant main fault.

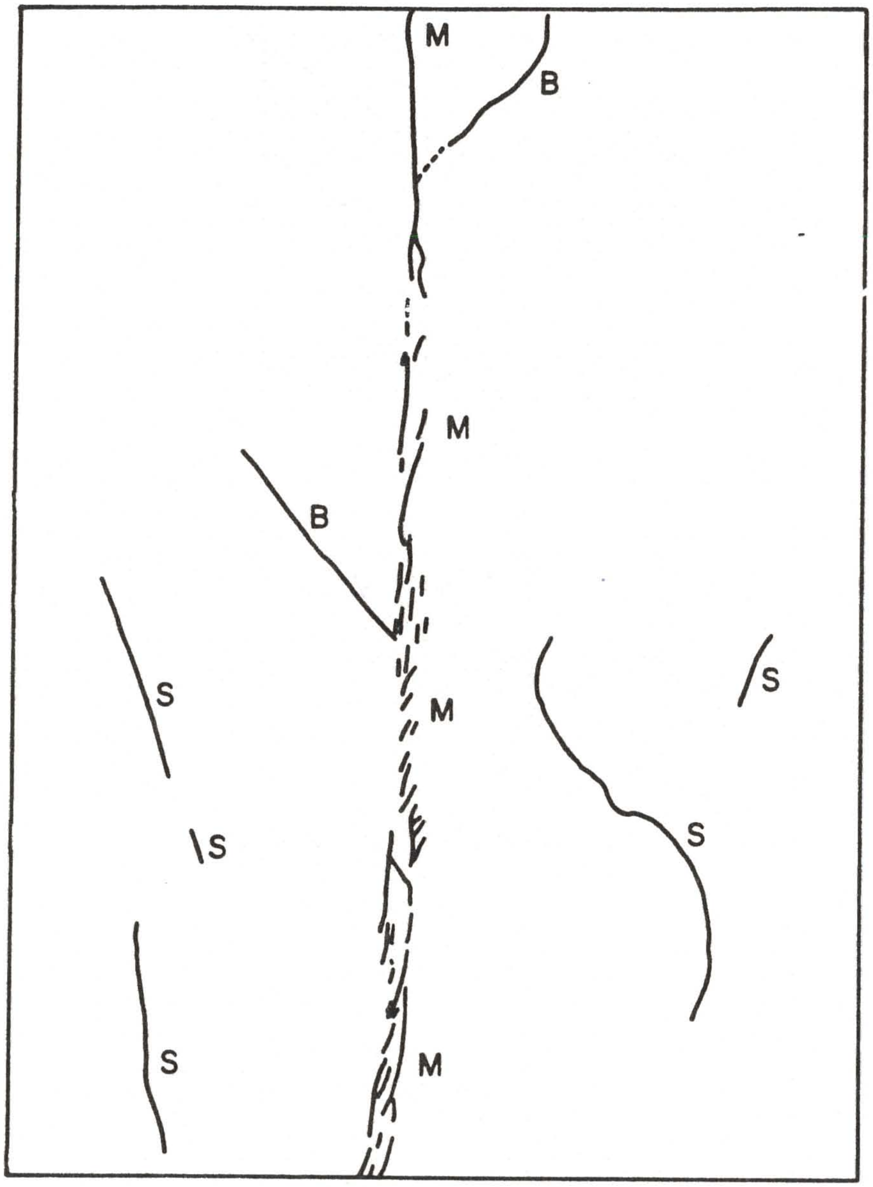

Figure 2. Map Patterns of Surface Faulting. This schematic diagram is based on actual rupture patterns in historic events of strike-slip, normal-slip, and reverse-slip type. Letters M, B, and S designate main, branch, and secondary faults.

2.1.2 Types of Faults.

Faults are classified into several types according to the relative displacement of the sides of the fault. The three principal types are normal-slip, reverse-slip, and strike-slip. These are illustrated in figure 3 and defined in the glossary. Strike-slip faults can be of either right-slip or left-slip type. Faults commonly display a combination of strike slip and dip slip; these are called oblique-slip faults. Faulting that is primarily strike slip may locally have a vertical component which, in historic events, has ranged from less than 10 percent to more than 60 percent of the maximum strike-slip component.

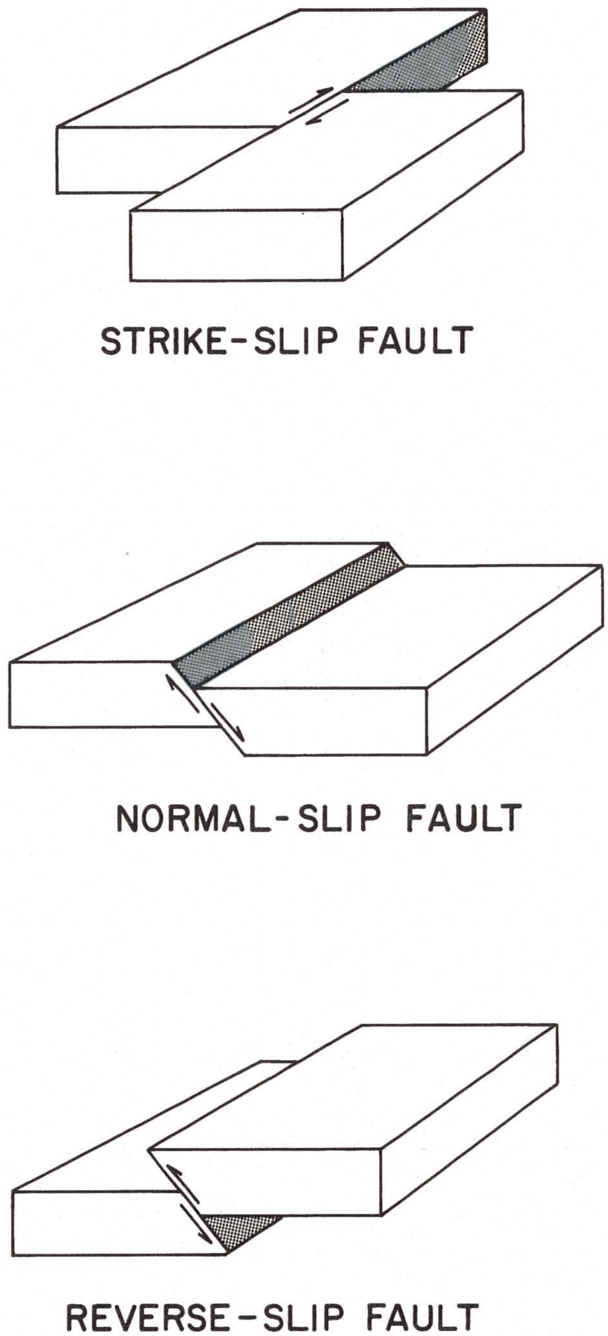

Figure 3. Simplified diagram illustrating the principal types of faults. Strike-slip faults can have displacement to right or left as viewed across the fault; right slip is illustrated. Actual ruptures have finite width and usually include subsidiary breaks on one or both walls.

2.1.3 Dimensions of Faults.

Surface ruptures have shown a wide range in length, displacement, and width for all types of faults. Lengths of historic ruptures on land have ranged up to about 400 km. Displacements have ranged from a few millimeters to more than ten meters. The width of the zone along the main fault within which faulting has occurred has ranged from a few centimeters to hundreds of meters. More refined generalizations are difficult because few events have been accurately mapped, and variations in width are great even in a single event. Strike-slip faults tend to have narrower rupture zones than the other types, but en echelon or parallel strands of this type can be widely spaced. The statistical data on all types of historic surface faulting, which are strongly influenced by a few well-studied events, suggest that 90 percent of the branch faulting will be 5 km or less from the main fault, and 90 percent of the secondary faulting will be 15 km or less from the main fault. Branch faults have extended as much as 10 km from the main fault, and secondary faulting has occurred 30 km or more from the main fault.

2.1.4 Variation in Displacement Along Fault.

The amount of surface displacement has varied greatly in short distances along historic ruptures. The normal-slip faulting that occurred in Nevada in 1915 is a typical example (fig. 4). Two peaks in displacement are prominent, and the displacement decreased to zero at the ends of individual en-echelon segments. This wide variation in surface displacement is typical for faulting of all types. The maximum displacement may be near one end of the fault and two or more high points in displacement may be prominent. The few good data that are available suggest that the ratio between average displacement (area under the displacement curve divided by length of the rupture) and maximum displacement is about 1:3 for most events (Bonilla, unpublished data).

2.1.5 Variation in Faulting between Events at Same Site.

Only a small amount of data exists for comparison of fault position, width, and displacement in successive events at the same place. The topographic expression of faults suggests that successive ruptures are confined to narrow zones on some parts of a fault but occur over wider zones in other parts of the fault. Support for this generalization comes from the Imperial fault in California where the zones of ruptures in 1979 were either wide or narrow at the same places as the 1940 ruptures were wide or narrow, and the successive ruptures were within a few meters of each other (Sharp, 1982). A few other historic ruptures have been described as being exactly on earlier ruptures but some have been 8 m to more than 60 m from earlier historic ruptures. Several historic ruptures have locally followed one preexisting fault while leaving unaffected another fault no more than a few meters away (Bonilla, 1979).

Very little quantitative data is at hand on amount of displacement in successive events at the same site. A trench across a normal fault in Idaho indicates a prehistoric event with a displacement of 5 to 6 m followed by another with a displacement of more than 3 m (Malde, 1971). Evidence from a trench across the Pleasant Valley, Nevada, normal-slip fault suggests that the 1915 faulting and several prehistoric events all had displacements of less than 1 m at the trench site (Bonilla and others, 1980), although the 1915 displacements were substantially larger on other parts of the fault. Probably the best set of comparative data for two successive events is from the strike-slip Imperial fault in California. The 1979 rupture coincided with the north half of the 1940 rupture. At points where displacements were measured for both events, nearly all the 1979 displacements were smaller by 7 to 50 percent, but in two places the 1979 displacements were apparently 47 to more than 200 percent larger than the 1940 displacements. These comparisons can only be considered approximate because afterslip was important following the 1979 event and probably following the 1940 event also (Sharp, 1982; Sharp and others, 1982).

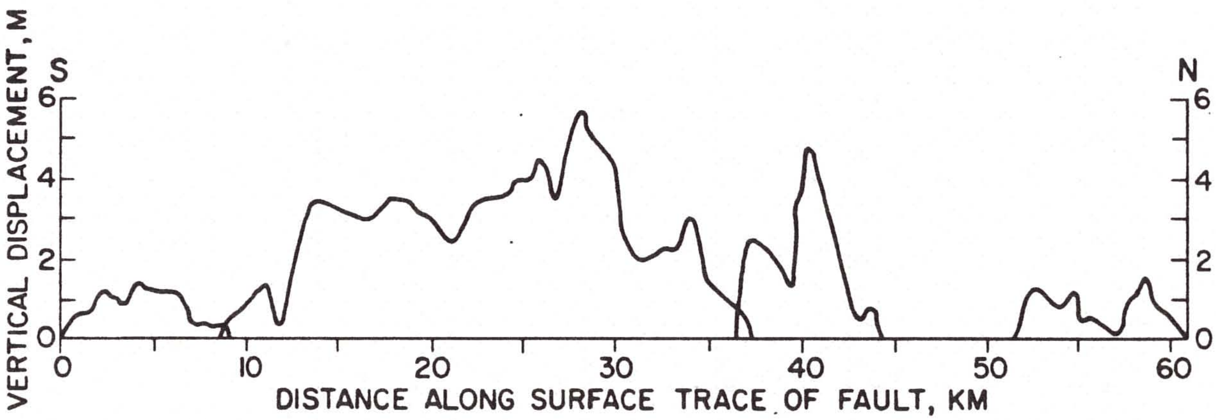

Figure 4. Variation in surface displacement in 1915 along the Pleasant Valley, Nevada, fault zone. Measurements were made at the fault scarp. Vertical exaggeration 2,200. From Wallace, in press.

2.1.6 Fault Creep.

Some fault displacement occurs at such a slow rate that instruments are necessary to detect the progress of the movement; however the long-term effect of creep is sometimes obvious in structures. Segments of some faults show creep displacement at rates of about 30 mm per year (Burford and Harsh, 1980), characteristically not accompanied by earthquakes large enough to be felt. Creep following sudden fault slip is called afterslip.

Afterslip has been detected following at least 15 historic fault-events and may be a common process. Moderately good data are available for about half of the 15 events, and based on this small sample some provisional generalizations can be made. 1) Typically, the rate of afterslip is high at first and decreases logarithmically with time, but minor variations commonly are superimposed on this general pattern (Wallace and Roth, 1967, fig. 25; Smith and Wyss, 1968; Burford, 1972; Bucknam and others, 1978). 2) The largest reported afterslip (as a percentage of initially measured slip) has been associated with parts of faults that have a history of tectonic creep, such as the Parkfield-Cholame reach of the San Andreas fault where afterslip at one place during an interval 10 hours to 13 days after the main shock of June 27, 1966, was 142 percent of the displacement initially measured at the same place (Allen and Smith, 1966; Wallace and Roth, 1967, p. 32, fig. 25). Similarly on a part of the Imperial fault, California, where tectonic creep had occurred prior to 1979, afterslip 1 to 50 days after the October 15, 1979, earthquake was 74 percent of the displacement initially measured at the same place (Sharp, 1979 and personal communication, 1981). 3) Faults with no known history of tectonic creep can also have substantial afterslip along them. Afterslip on the Motagua fault near Zacapa, Guatemala, 4 to 79 days after the earthquake of February 4, 1976, was 27 percent of the displacement measured there 4 days after the earthquake (Bucknam and others, 1978). The available evidence indicates that creep was not occurring on the fault prior to the 1976 earthquake (R. C. Bucknam, 1981, personal communication). 4) Parts of a fault can have a high or moderate rate of afterslip while other parts have a low rate. 5) Evidence from four events suggests that the largest afterslip is usually not at the place where the largest total surface displacement occurred. In the area of maximum displacement in the 1968 earthquake on the Coyote Creek fault, California, afterslip 11 to 302 days after the earthquake was only about 1 percent of the maximum surface displacement measured just after the earthquake but on another part of the fault with smaller displacement, afterslip 17 to 295 days after the earthquake was 62 percent of the displacement originally measured there (Burford, 1972). In the area of greatest surface displacement in the 1971 earthquake on the San Fernando fault, California, afterslip (vertical component) 4 to 330 days after the earthquake was about 1 percent of the initially measured vertical component, whereas in one area where displacements were small, afterslip (vertical component) 52 to 371 days after the earthquake was about 8 percent of the initially measured vertical-component (Sylvester and Pollard, 1975; Sharp, 1975, points x and y). Similarly the largest afterslip following the 1976 Guatemala and 1979 Imperial Valley, California earthquakes was not at the points of maximum recorded displacement for these events (Bucknam and others, 1978, p. 171; Sharp and others, 1982).

2.1.7 Local Deformation.

Surface faulting is generally accompanied by horizontal or vertical distortion within a few meters to a few hundreds of meters of the fault. The distortion can result from drag (bending), rebound, or concealed closely-spaced fractures. An example of drag is provided by a fault in California where the relation of vertical drag to vertical component of fault slip measured at two places was 100 percent and 200 percent respectively, distributed over a band about 50 m wide on each side of the fault (Clark and others, 1972). Several other examples are provided by the California faulting of 1906. Fences were distorted for distances of 12 to 540 m from the fault, the distortion being greatest at the fault and decreasing away from it. Because of the position of the fences, distortion could usually be measured on one side of the fault only, but if one doubles the measurements to estimate the distortion on both sides of the fault, the relation of horizontal distortion to horizontal fault slip ranged from 20 percent to 170 percent (Lawson and others, 1908, p. 94-113). The relation of vertical warping to vertical component of slip on the Patton Bay, Alaska, reverse fault at one place was about 200 percent, extending 245 m from the fault (Plafker, 1967, p. G7), and vertical warping of nearly 3 m occurred within 200 m of one part of the Hebgen Lake, Montana, fault where the faulting consisted of a zone of many small ruptures each of which had a displacement of less than one meter (Myers and Hamilton, 1964, p. 83). In all of these examples, the local deformation was greatest at the fault and decreased with increasing distance from the fault.

2.1.8 Effects of Faulting and Local Deformation on Structures.

Many kinds of structures have been damaged by faulting or local deformation. These have included houses, apartments, commercial buildings, nursing homes, roads, railroads, tunnels, bridges, canals, embankment dams, storm drains, water wells, and water, gas, and sewer lines; some examples are illustrated in figures 5 to 12. The damage has ranged from severe to minor, and has resulted from shearing, extension, compression, or local horizontal or vertical warping. Fault damage is described in many reports, including those by Lawson and others, 1908; Ambraseys, 1960; Duke, 1960; California Department of Water Resources, 1967; Subcommittee on Water and Sewerage Systems, 1973; Niccum and others, 1976; Hradilek, 1977; Youd and others, 1978; Sylvester, 1979; and Gordon and Lewis, 1980. The effects on structures depend on the type of structure and on the type, amount and distribution of the tectonic deformation and its angle of intersection with the structure (Sherard and others, 1974; Newmark and Hall, 1975; Kennedy and others, 1977; Hall and Newmark, 1977; Taylor and Cluff, 1977; Swiger, 1978; O'Rourke and Trautman, 1980). The type and intensity of earthquake vibrations also are affected by type of faulting (Bouchon, 1980a, 1980b; Bureau, 1978).

Figure 5. Canal displaced 4 m by strike-slip faulting in 1940, Imperial Valley, California. Photo courtesy of Imperial Irrigation District.

Figure 6. Damage to apartment house caused by about 2 m of reverse oblique-slip faulting during the Ms 6.6 1971 San Fernando, California, earthquake. The apartment had to be torn down. Photo by J. Schlocker.

Figure 7. Damage to sidewalk, curb and pavement caused by 1.5 m of reverse-slip faulting, San Fernando, California, 1971. The nursing home on left was severely damaged by the faulting and had to be torn down. Photo by R. E. Wallace.

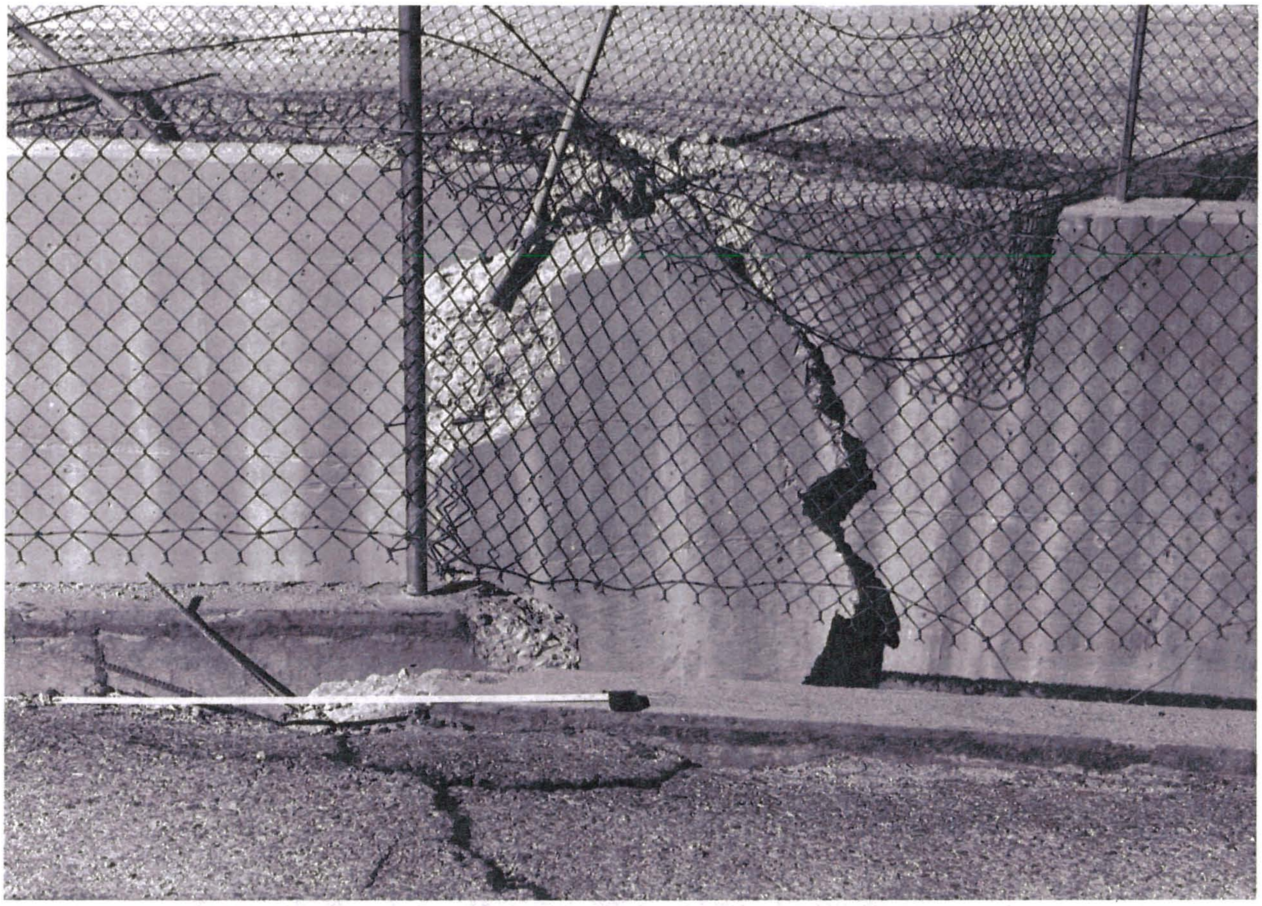

Figure 8. Compressional damage to reinforced concrete drainage channel caused by reverse-slip faulting in the 1971 San Fernando, California earthquake. East wall of channel (foreground) was broken and overlapped 0.9 m. Part of west wall (background) was broken and moved toward channel. This damage occurred about 75 m from the main fault trace. The channel and its damage are described by the Subcommittee on Water and Sewerage Systems (1973, p. 163-167). Photo by V.A. Frizzell.

Figure 9. Compressional damage to one of a pair of water supply pipelines caused by reverse-slip faulting in Western Australia associated with an Ms 6.9 earthquake in 1968. Both pipes were telescoped 1.3 m, and reinforced concrete pipe supports were damaged on each side of the surface ruptures. For a distance of 400 m on one side of the fault and 1.2 km on the other side the pipe was shifted with respect to its supports. From Gordon and Lewis (1980, p. 22-23, fig. 9), courtesy of Geological Survey of Western Australia.

Figure 10. Damage to aqueduct by right-slip displacement on the San Andreas fault in 1906. The pipe, 76 cm in diameter, which crosses the fault from left to right, has been sheared and shortened. From Schussler (1906, photo 6), courtesy of San Francisco Water Department.

Figure 11. Aqueduct, which crosses the fault from right to left, was pulled apart about 1 m by right-slip displacement on the San Andreas fault, 1906. From Schussler (1906, fig. 7), courtesy of San Francisco Water Department.

Figure 12. Damage to brick-lined tunnel by about 2 m of right slip on the San Andreas fault, 1906. The tunnel was repaired and restored to use. From Schussler (1906, photo 33), courtesy of San Francisco Water Department.

2.2 REGIONAL DEFORMATION

Whether faulting reaches the earth's surface or not, it is usually accompanied by regional deformation. The regional deformation can be both horizontal and vertical (see for example Plafker, 1969), but substantial vertical regional deformation, which is the more important from an engineering viewpoint, is generally restricted to faulting that has a large dip-slip component. Only vertical deformation is discussed here.

2.2.1 Dimensions of Regional Deformation.

Measurement of regional deformation is difficult because the deformation is distributed over a large area, the reference points are commonly few and irregularly scattered, and compaction of sediments may occur locally; nevertheless the data show that areas with dimensions as large as hundreds of kilometers can be involved. Figure 13 and the other examples in Table 1 indicate the dimensions of the phenomenon.

Table 1. Examples of Regional Deformation

Event	M_s*	Type of Faulting	Regional Deformation	Reference
Montana, 1959	7.1	Normal-slip	Subsidence ≥0.3 m extending 30 km parallel to fault, 9 km perpendicular to fault	Fraser and others, 1964, fig. 50
Chile, 1960	8.5	Reverse-slip, low angle	Uplift (max. 5.7 m) in area >850 km by perhaps 100 km. Subsidence (max. 2.3 m) in area >800 km by 75-110 km	Plafker, 1972
Alaska, 1964	8.4	Reverse-slip, low angle	Uplift (max. 11.3 m) in area 950 km by >150 km. Subsidence (max. 2.3 m) in area 950 km by 150-250 km	Plafker, 1972
New Zealand, 1968	7.1	Reverse-slip	Uplift ≥0.4 m in area about 33 km by about 20 km	Lensen and Otway, 1971, fig. 2
California, 1971	6.6	Reverse-slip	Uplift ≥0.5 m extending >13 km parallel to fault and about 5 km perpendicular to fault	Savage and others, 1975

*Surface wave magnitude

2.2.2 Effects of Regional Deformation on Structures and Facilities.

Vertical tectonic deformation has adversely affected various kinds of structures and facilities. In the 1960 Chile and 1964 Alaska events, piers, docks, breakwaters, highways, railroads, airstrips, houses, and other buildings were tectonically lowered relative to sea level resulting in permanent or intermittent inundation (Sievers C. and others, 1963; Kachadoorian, 1965; Kachadoorian and Plafker, 1967; McCulloch and Bonilla, 1970). The affected structures were relocated, modified, or abandoned. Tectonic uplift has caused shallowing of harbors and waterways, restricting their use, but subsidence has improved navigation in some places (Sievers C. and others, 1963; Plafker and others, 1969).

Indirect effects of regional deformation include the generation of tsunami, seiches, and surges of water in reservoirs. These are known to result from vertical tectonic displacements (Myers and Hamilton, 1964; McCulloch, 1966); some waves and rapid rise of water level may result from sudden regional horizontal displacements (Plafker, 1969, p. I-39-I-40).

Accelerated erosion of embankments and shorelines has been another indirect effect of tectonic subsidence.

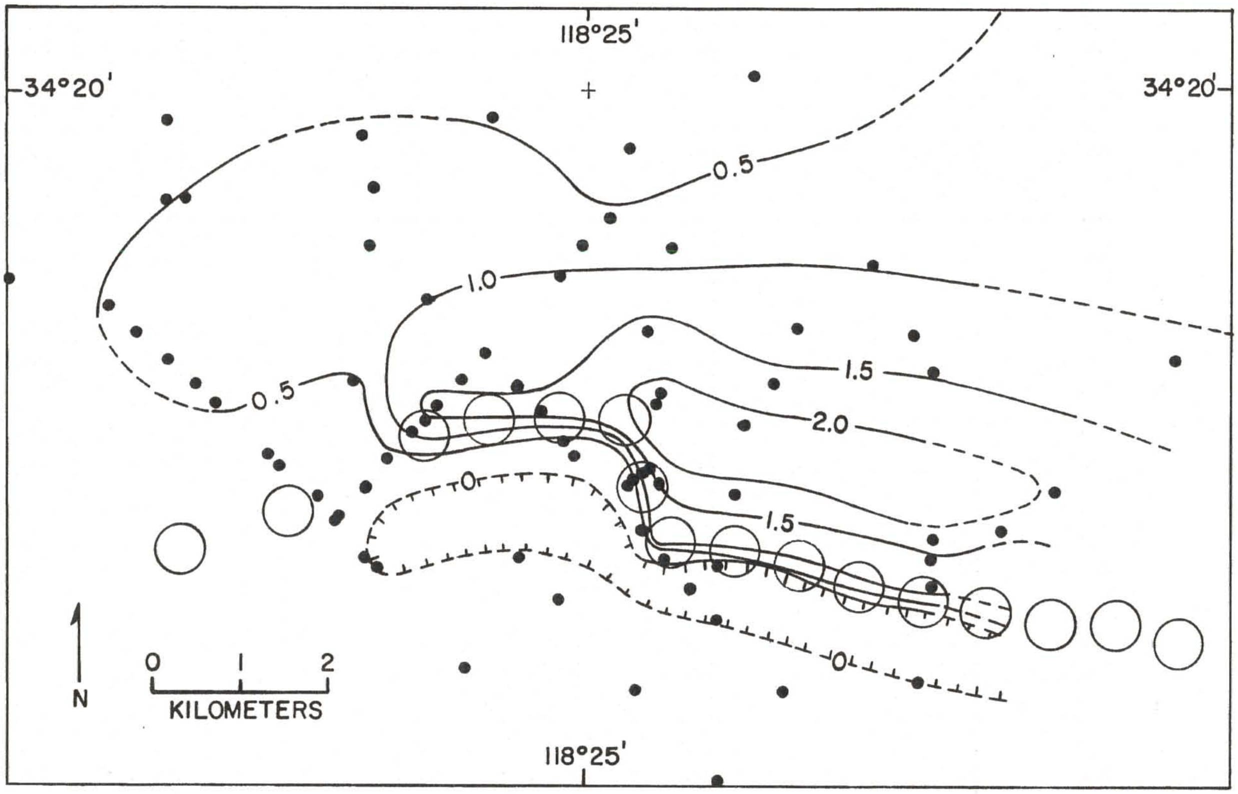

Figure 13. Map showing part of the regional deformation associated with the 1971 San Fernando, California, earthquake of Ms 6.6. Contours show changes in surface elevation (m) relative to a local benchmark; open circles show approximate position of principal surface fault traces; solid dots show control points for elevation changes. After Savage, Burford, and Kenoshita (1975, fig. 2).

3 INVESTIGATIONS FOR EVALUATION OF POTENTIAL TECTONIC DEFORMATION

3.1 GENERAL.

Investigations for evaluation of potential tectonic deformation should seek to answer several questions: 1) whether the site is subject to tectonic deformation, 2) what type of deformation can occur, 3) where will it occur, 4) what will its dimensions be, and 5) whether the deformation is likely to occur during the useful life of the structure. Most historic surface faulting and other tectonic deformation has occurred where such deformation had occurred in the geologically recent past and has been of a nature similar to previous events in the same area. Thus the basis for answers to the questions posed above is an understanding of the tectonic and seismologic setting and recent geologic history of the site and surrounding region. Guidelines or regulations for the investigations required to bring about such an understanding have been prepared by various agencies and are listed in Table 2. Other references that are pertinent to investigations are given in sections that follow.

Table 2. Current guidelines and criteria for assessment of faults

Agency	Facility	Fault Terminology	Activity Criteria	Remarks	Reference
Nuclear Regulatory Commission	Nuclear power plants	Capable fault	1, Movement at least once in past 35,000 yr, or 2, Recurring movement in past 500,000 yr, or 3, Macroseismicity, or 4, Structural relation to another capable fault.	Specific guidance on assessment.	U.S. Atomic Energy Commission, 1973; U.S. Nuclear Regulatory Commission, 1975a, 1978a, 1978b
Corps of Engineers	Dams	Capable fault	1, 3, and 4 as above. Macroseismicity is magnitude 3.5 or greater	General guidance on assessment. Refers to 1974 state-of-the-art paper	U.S. Department of the Army, 1977.
Department of Transportation	LNG (liquefied natural gas facilities)	Surface faulting	Storage facility cannot be located at a site, unless specifically approved, if a) surface faulting can be predicted but displacement not exceeding 30 inches cannot be assured, or b) future surface displacement cannot be predicted but cumulative displacement of a Quaternary fault within one mile of the tank exceeds 60 inches.	General guidance on assessment	U.S. Department of Transportation, 1980.
Veterans Administration	Hospitals	Active fault	Movement in past 10,000 yr.	General guidance on assessment. Interim requirements	U.S. Veterans Administration, 1973.
Environmental Protection Agency	Hazardous waste facilities	Holocene fault	Displacement in Holocene time	Specific guidance on assessment	U.S. Environmental Protection Agency, 1981
State of California	Structures for human occupancy	Active fault	Surface displacement in Holocene time	Specific guidance on assessment.	Alquist-Priolo Special Studies Zones Act of 1972 (Hart, 1980)

The investigations should begin with a review of pertinent existing data concerning the region. These include historical accounts of earthquakes and surface faulting, geological and seismological reports and maps, and geodetic data. In examining geologic maps for evidence of young faulting one must keep in mind the purposes for which the mapping was done. Mapping done in the search for metallic mineral deposits, for example, is not likely to show late Quaternary deposits and landforms which are important in evaluating faults, nor the locations of historic faulting. Proper use of maps showing seismicity similarly requires an understanding of the completeness, time span, and lower magnitude cutoff of the earthquake data set, and the accuracy of the epicentral locations. Dewey (1979) discusses the inaccuracies in routinely determined epicenters, the erroneous conclusions that can be drawn from them, and ways of improving the location accuracy. Dewey (1979, p. 116) also indicates the accuracy that can be expected by redetermining the epicenters and hypocenters. Valuable information can be obtained on the locations and types of active faults from relatively short-time monitoring of microearthquakes. Lee and Stewart (1981) thoroughly cover the principles and applications of microearthquake networks, including listings of permanent networks and examples of reconnaissance microearthquake surveys made on land and offshore. If no earthquakes are found in the area of interest however, one must keep in mind that a lack of epicenters on a fault does not necessarily indicate that the fault is inactive, as demonstrated by the seismically quiet reach of the San Andreas fault which had a large surface displacement in 1857. The review of existing data should include contacting organizations and individuals that may have unpublished information.

The review of existing data will provide a general understanding of the regional tectonic setting and regional seismicity, which are essential to evaluating the potential for both surface faulting and distributed deformation. Most projects, however, will require investigations that also develop new data or refine existing data. The importance of the project, the consequences of its failure, and the regional setting will affect the choice of and thoroughness of the investigations. Important projects may require most of the investigations outlined below, and perhaps other, less-frequently used ones. Analysis and evaluation of offshore geophysical data may be needed for coastal sites. Further discussions of investigations can be found in Allen (1975), Cluff and others (1972), and Sherard and others (1974). Those planning and conducting the investigations should keep in mind the manifestations of faulting and distributed deformation outlined in section 2, and the questions listed at the beginning of this section (3.1) which the investigation should attempt to answer.

3.2 FAULTING AND LOCAL DEFORMATION

3.2.1 General.

The objectives of the investigation are to locate faults in the vicinity of the site, and to obtain information on their ages, types and rates of activity, and dimensions. The investigation generally will proceed from a broad regional examination to detailed investigations of the site and of critical places off the site. A regional approach is necessary because an understanding of the general tectonic setting is needed to correctly interpret conditions at the site, because important features may be obscure at the site but well expressed elsewhere, because the full length of the active fault provides one parameter used in estimating fault displacement (section 4.2) and earthquake potential, and because subsidiary faulting can occur 30 km or more from the main fault (Florensov and Solonenko, 1963; Bonilla and others, 1976). For most faults, study of a region within a radius of 100 to 300 km of the site is sufficient, but long strike-slip or subduction zone faults may require a larger area of study (Slemmons, 1977, p. 106-110; Sherard and others, 1974).

For most projects where surface faulting is in question detailed site studies should include trenching (section 3.2.5.2), and determination of ages of geologic and other entities in relation to faulting. The age of latest faulting is commonly used as the principal criterion for deciding whether a fault is sufficiently active to pose a threat to a project (Table 2). Dating techniques useful in fault investigations are reviewed by P. J. Murphy and others (1979). The dating of fault scarps is discussed by Wallace (1977), Bucknam and Anderson (1979), Nash (1980), Dodge and Grose (1980), and Mayer (1982). Because some of the dating techniques are being improved and new ones are being developed, the use of up-to-date methods is necessary.

Detailed geological examinations should continue into the construction phase. Very important information can be revealed in excavations made during construction, and the excavations often provide better information than the pre-construction investigations. The geologist making the examinations should have the authority, with the approval of the engineer in charge, to temporarily halt construction until possibly critical features which could be destroyed or concealed are adequately studied.

Many criteria may be used for the recognition of faults. The more common ones are listed in table 3, which is slightly modified from American Nuclear Society (1980). The items in table 3, of course, do not apply to every site, and some of them can result from non-tectonic causes. The following examples of features and relationships that may incorrectly suggest the existence of a fault are from the American Nuclear Society (1980):

1. Scarps and failure surfaces associated with large landslides.
2. Scarps, ground cracking, and failure surfaces associated with seismically induced ground failure.
3. Ground cracking, scarps, and failure surfaces associated with non-tectonic subsidence.
4. Ground water level and gradient anomalies resulting from facies changes or other formation variations not associated with tectonic displacement.
5. Anomalous relations between sedimentary facies not associated with tectonic deformation.
6. Deformation, including shearing, brecciation, and crushing of rock and other materials resulting solely from disturbances such as folding, intrusion, consolidation (compaction), and collapse.
7. Lineaments of non-tectonic origin such as terrace backscarps, differential erosion controlled by bedding or jointing, and aeolian features.
8. Reflection or refraction seismic discontinuities associated with lateral lithologic or stratigraphic changes.
9. Surficial features related to glaciation including glacially induced movement on pre-existing fault planes.

With regard to item 6 above, one must keep in mind that sudden displacements on bedding planes have accompanied at least two earthquakes with surface faulting, in New Zealand in 1968 (Lensen and Otway, 1971) and in California in 1971 (Barrows, 1975, pl. 4; Sharp, 1975, p. 192).

Table 3. Features and Relationships Commonly Used in Recognition of Faults (Modified from American Nuclear Society, 1980)

---

1. Geologic
    - Displaced rock against rock
    - Displaced soil against rock
    - Displaced soil against soil
    - Missing formations or other expected entities
    - Repeated formations or other entities
    - Non-stratigraphic and non-intrusive truncation of formations
    - Anomalous relations between sedimentary or metamorphic facies
    - Abrupt termination of geologic structure
    - Expressions of drag
    - Monoclinal flexures
    - Slickensides
    - Gouge, fault breccia, or angular fault rubble
    - Linear distribution of chemical alteration or mineralization, including occurrences of caliche or tufa
    - Alignments of volcanic vents
    - Alignments of mud boils
    - Decreased spacing of joint sets
2. Topographic and geomorphologic
    - Offset streams and drainage patterns
    - Beheaded stream channels
    - Scarps
    - Monoclinal or other deformation of land surface
    - Tilting of land surface
    - Sag structures and sag ponds
    - Linear troughs or ridges
    - Shutterridges
    - Triangular facets on ridges and spurs
    - Gravity grabens below scarps
    - Uplift, subsidence or tilting of shorelines
    - Tilting or offsets of shoreline remnants, including uplifted or submerged shorelines
    - Anomalous stream gradients
    - Anomalous pediment or terrace relationships
    - Linear alignment of landslides
    - Lineaments visible on aerial photographs or other remote sensing imagery
3. Hydrologic
    - Ground water anomalies including anomalies in ground water levels, gradients, temperatures, and chemistry
    - Vegetation pattern anomalies
    - Alignments of springs, seeps, or sinks
    - Hot springs and fumaroles
    - Geysers
4. Geophysical (other than earthquake seismology)
    - Anomalies in seismic reflection data

Disruptions in reflection data
Abrupt divergences in dip
Vertical shifts of reflection patterns
Drag patterns
Diffraction patterns
Reflected refraction events on reflection records
Anomalies in seismic refraction data
Shifts in intercept times
Diffraction effects
Abrupt changes in velocity
Abrupt changes in character of first arrivals
Gravity anomalies
Steep gravity gradients
Interruptions of regional gradients
Magnetic anomalies
Steep linear gradients
Displacements of linear trends
Radioactivity anomalies
Steep linear gradients
Displacement of linear gradients
Linear alignment of highs or lows
Other geophysical anomalies
Abrupt changes in resistivity or other electrical properties

5. Seismologic
   - Long-term distribution of historical earthquake locations
   - Fault surfaces defined by linear or near-planar distribution of epicenters or hypocenters
   - Fault-plane solutions
   - Other instrumental earthquake data
6. Horizontal and vertical deformation, as detected by
   - Triangulation
   - Trilateration
   - Other techniques including creep measurements
7. Other categories
   - Displaced cultural features
   - Disturbed vegetation

The investigation should attempt to estimate the rate of activity of faults rather than just classifying them as active or inactive. If this can be done, it permits comparison between different faults and, with other information, may allow estimates to be made of recurrence intervals and the sizes of earthquakes and displacements that may occur (Molnar, 1979; Anderson, 1979). The faults may be classified as shown in table 4, which is based on reports by Matsuda (1975) and Slemmons (1977, p. 65-68) and used by American Nuclear Society (1980).

Table 4. Classification of Fault Activity

Class	Description	Long term rate of slip, s (mm/yr)
AAA	Extremely High	$s > 100$
AA	Very High	$10 < s < 100$
A	High	$1 < s < 10$
B	Moderate	$0.1 < s < 1$
C	Low	$0.01 < s < 0.1$
D	Extremely Low	$s < 0.01$

The long-term average rate of slip is determined geologically. It is based on the total displacement of a geologic unit divided by the age of the unit; the unit can range in size and makeup from tectonic plates to geomorphic features.

Short-term slip rate can be determined geodetically if data of appropriate time span and location are available.

Short-term slip rate can also be determined seismologically. As shown on figure 14, this is done by use of seismic moments of earthquakes that have occurred on the fault. The seismic moments are determined by analysis of seismograms. As shown in the upper right of the figure seismic moment Mo is equal to the shear modulus (or modulus of rigidity) μ times average slip $\bar{u}$ times area A of the fault segment that has slipped. As shown in the lower part of the diagram the seismic slips for each earthquake are combined into an equivalent average slip $\bar{U}$ for the whole fault. This is done by adding up the individual moments and solving for the combined average slip, shown in the lower right. This slip divided by the number of years of record gives the slip rate. The slip rate determined in this way is of course strongly influenced by the level of seismicity during the period of study, and may not reflect the long-term slip rate.

3.2.2 Use of Remote Sensing Imagery.

Imagery produced by remote sensing techniques can provide a general view of surface features and relationships that an observer on the ground cannot obtain. Depending on scale and resolving power, imagery can reveal structures with dimensions ranging from many kilometers to less than one meter. A search can be rapidly and efficiently made for many of the features listed in table 3, groups 1, 2, 3, and 7. The selection and interpretation of various kinds of imagery have been treated in several publications (Colwell, 1960; Glass and Slemmons, 1978; McEldowney and Pascucci, 1979; Reeves and others, 1975; Sabins, 1978; Slemmons, 1977, Siegal and Gillespie, 1980), and only some of the more important points are included here.

3.2.2.1 Aerial Photographs.

The most useful and readily available remote imagery is aerial photography. It is available from various government agencies and some private companies at 1:16,000 to 1:60,000 scales in black-and-white with stereoscopic coverage. Old, pre-urbanization photography is available for many areas. Private companies can provide special black-and-white or color photography at larger or smaller scales by contract. For study of faults, photography taken when the sun is at a low angle to the ground surface and at a high angle to the geologic structure is very effective in revealing small scarps and other features. Solar position diagrams such as those in figure 15 from Clark (1971) provide a basis for selecting the optimum dates and time of day for low sun-angle photography and aerial reconnaissance.

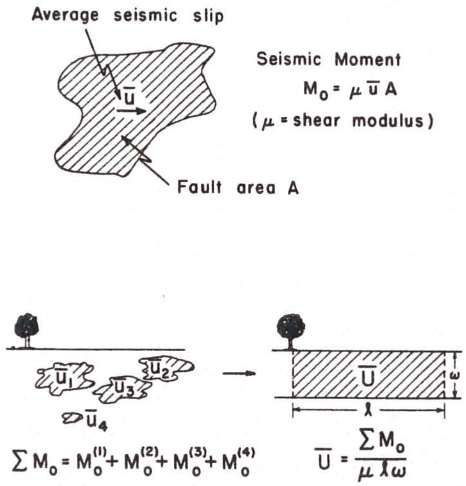

Figure 14. Diagrammatic sections showing method of determining cumulative slip from seismic moments of earthquakes on a fault. Diagrammatic sections are in the plane of the fault. Most terms are defined in the diagram and an explanation is given in the text. From Thatcher, Hileman, and Hanks (1975).

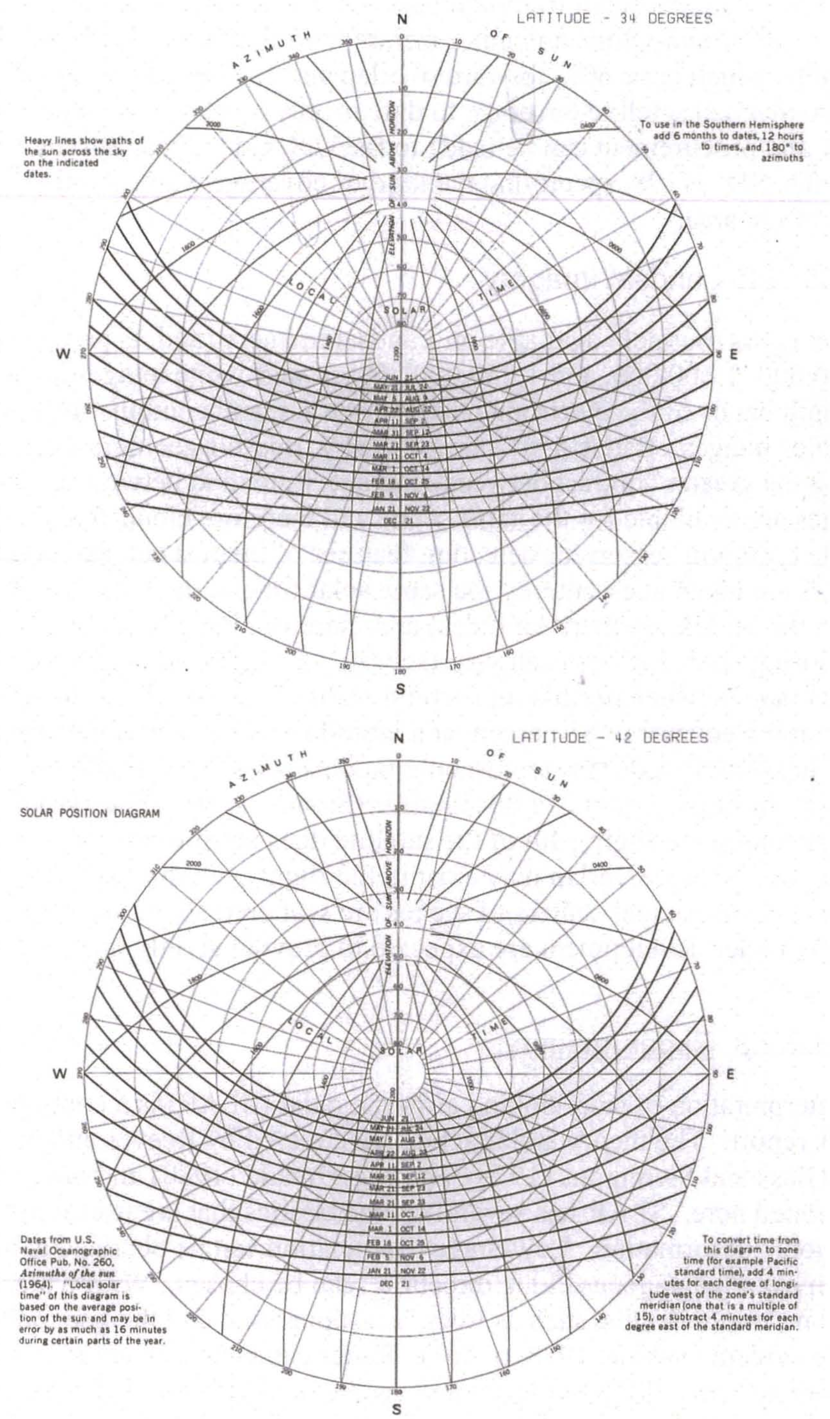

Figure 15. Examples of solar position diagrams. Diagrams are upper hemisphere stereographic projections, with heavy lines showing paths of the sun on the indicated dates. Radial lines give azimuth of sun, concentric lines give altitude of the sun, and great circles labeled 0600, 0800, etc. indicate local solar time. Upper diagram, latitude 34°N; lower diagram, latitude 42°N. Although changes in solar position with latitude are not linear, comparison of the two charts shows the amount of change and permits useful interpolations for other latitudes. From Clark, 1971.

Various kinds of photographs taken from manned satellites are available. These include oblique and vertical color, black-and-white, and color infrared. Probably the most useful are some of the Skylab photographs which have 60% forward overlap and can be viewed stereoscopically. Unfortunately the manned satellite coverage to date is only available for limited areas. Inquiry as to availability and procurement can be made to the U.S. Geological Survey EROS Data Center, Sioux Falls, SD 57198, specifying the kind of coverage wanted and the latitude and longitude limits of the area.

3.2.2.2 Landsat Imagery.

Worldwide coverage is routinely available on Landsat imagery (and its predecessor, ERTS) at scales of 1:1,000,000, 1:500,000, and 1:250,000. Black-and-white images are available for several wavelength bands of the electromagnetic spectrum, and combinations of them which produce false-color images. Bands 5 or 7 are generally used for geologic interpretation, with band 7 providing the greater contrast between land and water and between types of vegetation. Sequential images are available for the same scene and therefore cloud-free cover can usually be obtained, and the optimum season for detecting features of interest can be chosen. The sequential images are taken at essentially the same solar time of day on each pass of the satellite (mid-morning in the middle northern latitudes) and therefore images at low sun elevations are produced only during short periods each year (see fig. 15). Landsat images provide limited stereoscopic coverage between north-south orbital paths. The theoretical image sidelap ranges from 14 percent at the equator to 85 percent at a latitude of 80°. Vertical exaggeration (ratio of vertical scale to horizontal scale) in stereoscopic models is less than for aerial photographs and ranges from 1.2 at the equator to 0.2 at 80° latitude (Sabins, 1978). The 10 percent overlap in successive images along the flight path of the satellite does not provide stereoscopic viewing, but some accidental stereoscopic overlap may exist in the flight-path direction for images produced at different times because actual centers of scenes are scattered about the intended centers. Systems currently under development are expected to provide greatly improved imagery in the near future.

3.2.2.3 Radar Imagery.

Selection and interpretation of side-looking airborne radar (SLAR) is a complex subject beyond the scope of this report. The theory and practice are covered by Reeves and others (1975), Sabins (1978), Glass and Slemmons (1978), and MacDonald (1980) and only the salient practical points are mentioned here. SLAR has several characteristics that are useful in evaluation of faulting and tectonic deformation. Low-angle illumination can be obtained at any season or time of day, and the most advantageous "look direction" can be chosen. With typical ground resolution of 10 m, minor details, such as trees, are suppressed and the general topographic features become evident (Sabins, 1978, p. 207). Radar can penetrate clouds which can be a hindrance to other systems. Regional coverage can be obtained in strips hundreds of kilometers long and several tens of kilometers wide; however the cost per unit area is very high compared to Landsat imagery. Although most existing imagery is monoscopic, stereoscopic imagery can be obtained (Sabins, 1978, p. 207; MacDonald, 1980).

3.2.2.4 Thermal Infrared Imagery.

Thermal infrared imagery records the pattern of heat radiated from the surface. The imagery permits recognition of high moisture content in surface soil and rock and, therefore, the recognition of fault zones that have concentrations of moisture along them. A limited differentiation of rock types is also possible. Interpretation is complicated by low resolution of the imagery, and by clouds and surface winds that modify the pattern. Geometric distortion produced by the scanner must be electronically corrected. Imagery recorded in daylight is strongly affected by solar heating and shadow effects, and nighttime recording is usually required for geologic purposes. Reeves and others (1975, p. 1205) characterize thermal infrared as a "special purpose technique that should be applied to specific problems of restricted extent." Case histories of use of thermal infrared imagery are summarized in Sabins (1978) and McEldowney and Pascucci (1979).

3.2.3 Aerial Reconnaissance.

Aerial reconnaissance by the geologist, of the site and the region around it, can be cost-effective. A large area, some of which may be hard to get to on the ground, can be examined in a short time and fault features can be identified, photographed, and noted for further study. Small, low-speed high-wing planes or helicopters are best suited for this purpose.

3.2.4. Ground Reconnaissance.

Geological reconnaissance on the ground is a logical next step. This should be done of the site area and of possibly critical places identified by photo-interpretation and aerial reconnaissance. The main objectives are to look for geomorphic, stratigraphic, or other evidence of faulting (table 3) and its age.

In conducting the ground reconnaissance one should keep in mind that recognition of active faults is difficult in some places. A reverse-slip fault rupture (3 m displacement) that accompanied the M_s 6.9 earthquake of 1968 near Meckering, Australia, broke the surface in an area where no fault was recognized prior to the surface faulting. The ground was nearly flat, and no preexisting scarps are known although outcrops of fresh rock are more common on the upthrown than the downthrown side of parts of the fault (Gordon and Lewis, 1980). Although the rupture occurred in a broad belt of moderate seismicity, no surface faulting had occurred anywhere in Australia during historic time prior to this event, and the faulting was a complete surprise. Most of the surface trace of the strike-slip Imperial fault in southern California, where as much as 5.8 m of surface displacement accompanied a M_s 7.2 earthquake in 1940, is hard to recognize today, primarily because of agricultural activity. On the California side of the Mexican border scarps or other geomorphic evidence for the fault are no longer visible, nor was the fault recognized prior to the surface faulting in 1940. Small graben at the bases of scarps generally indicate an active normal fault (Slemmons, 1957), but landslides exhibit similar features (Varnes, 1978; Rib and Liang, 1978).

During the reconnaissance the type and feasibility of further investigations can be considered, and the accessibility, both physical and with regard to permission from landowners, can be learned.

3.2.5 Detailed Studies.

After review of existing data, study of imagery, and aerial and ground reconnaissance, detailed studies are needed for most projects. These studies are done at the site and at places off the site where critical information may be obtainable. The principal objectives of the detailed studies are to determine the location, width, and recent displacement history of faults. The studies will probably include geologic mapping and trench investigations, and may include drilling and geophysical surveys.

3.2.5.1 Geologic mapping.

The amount and scale of geologic mapping required varies greatly from site to site. Some important controlling factors are whether or not a fault is known to exist; the structural complexity of the area; the kinds, ages, and degree of exposure of the geologic units; and the importance of the facility. Mapping should be done to the extent that it, in conjunction with other methods of investigation, permits determination and depiction of the presence or absence of faults, and the location, width, age, amount, and type of the younger fault displacements that may have occurred. Geologic mapping may of course be required for other purposes also, such as foundation studies or the evaluation of potential for ground failure.

3.2.5.2 Trenching.

Of all subsurface methods, trenching provides the most complete and accurate information on near-surface faulting. It is, however, costly in time and money, and both the decision to trench and the locations of trenches should be carefully considered. If trenching is to be done, generally more than one trench should be planned because faulting can be very obscure in one place and very clear in another place nearby; furthermore the width of rupture and amount of displacement can vary markedly in short distances. The investigator should keep in mind that not all discontinuities are the result of faulting (section 3.2.1.).

Collapse of trench walls results in about 100 deaths and more than 1000 disabling injuries each year in the United States (Thompson and Tanenbaum, 1977). Before any trench 1.5 m or more deep is entered for inspection or mapping, it shall be properly shored in accordance with U.S. Occupational Health and Safety Administration (1974) standards, other equivalent standards, or in accordance with competent engineering analysis of site conditions. Although the standards may permit sloping of the walls in lieu of shoring, this hinders and complicates the examination and mapping process, and vertical-walled shored trenches are preferable.

Other comments and suggestions based on trenching experience follow. The details of fault topography should be suitably recorded and photographed before the area is disturbed by trenching. Important surface features should be marked by stakes or other means so they can be related to structures found in the trench. If trenching is done by bulldozer or other large earthmoving equipment, care should be taken not to destroy critical evidence regarding age of movement on the fault. Trenches excavated to depths of about 4 m and widths of about 1 m are recommended as a general minimum for exploratory trenches. Trenches of these dimensions can be excavated by widely-available backhoes, they destroy little of the evidence of faulting, in most places they expose materials of some antiquity, and they permit convenient photography of the walls. Lengths of trenches will vary with local conditions, but should be long enough to detect tilting or drag, normal irregularities in contacts, variations in facies or thickness of units and intersect possible subsidiary faults. A minimum length of 30 m is suggested for most locations. The shoring used should be of a type that can be easily shifted if necessary because experience has shown that narrow critical features in fault zones can be concealed behind the shoring. The trench wall(s) should be cleaned by picking, scraping, brushing, or other suitable technique before detailed examination and mapping. Careful mapping of the trench results in close inspection and often reveals structural relations that are not otherwise apparent. Reports by Taylor and Cluff (1973), Bonilla (1973), Bonilla and others (1978), Harpster and others (1979), and Hatheway and Leighton (1979) are among several that discuss the techniques, advantages, and shortcomings of trenching as an investigative method.

3.2.5.3 Drilling.

Drilling is generally of only moderate value for detailed fault investigation. Even closely spaced holes may not lead to definite conclusions regarding faulting owing primarily to normal changes in facies or thickness, irregular contacts, small fault displacements, and the possibility that vertical holes will miss steeply-dipping faults. Drilling can be effectively used to extrapolate information vertically or horizontally beyond the area reached by trenching, and it may reveal differences in ground water across a fault. Results of drilling done for foundation or other purposes should of course be utilized in the fault studies. Borehole geophysics can increase the usefulness of drilling.

3.2.5.4 Geophysical studies.

Several geophysical techniques are applicable to the evaluation of faults. Table 3 lists some of the geophysical anomalies that may be detected, and a discussion of the techniques together with references are contained in Dobrin (1976), Murphy (1978), and V. J. Murphy and others (1979). The applicability of specific geophysical techniques in detailed studies may be limited by low resolution or by ambiguities in interpretation; thus some geophysical techniques are best suited to regional or subregional rather than detailed studies. Offshore geophysical investigations may be essential in the evaluation of coastal sites.

3.3 REGIONAL DEFORMATION

3.3.1 General.

Evaluation of the potential for regional deformation is a difficult task, and firm conclusions may be unattainable. The evaluation is based on the tectonic setting of the region and on what has occurred in the region in the past. The investigation must seek answers to 1) whether the area is subject to sudden regional deformation, 2) whether such deformation is likely in the lifetime of the facility, 3) what will be the type and dimensions of the deformation. The types of data to be sought are historical, geological, geophysical, and geodetic. Because the process involves large regions, the investigation must also be regional in scope.

3.3.2 Tectonic Setting.

Substantial regional vertical deformation is associated with faulting that has a dip-slip component and therefore the presence or absence of such faults needs to be established. This is done by analysis of the regional and local tectonic setting, using existing or new geological and geophysical (including seismological) investigations.

3.3.3 Evidence of Regional Deformation.

If faults with a dip-slip component exist in the region, evidence for regional vertical displacement should be sought. Historical records of earthquakes should of course be examined for descriptions of earthquake-related deformation. Geodetic data may indicate regional uplift, subsidence, or tilting related to past earthquakes or occurring gradually at the present time. Geologic evidence includes submergent or emergent coastlines; uplifted, submerged, tilted, or warped marine, lacustrine, or fluvial terraces; submerged forests, and other evidence of change in level. Testimony to the value of such data is the fact that most of the area of uplift and subsidence in the 1964 Alaskan earthquake displays evidence of long-term pre-1964 Holocene movements of corresponding type. However, in some areas vertical displacement in 1964 was opposite to that which had progressed for several centuries before 1964 (Plafker, 1969, p. 55-63), and a similar reversal was noted locally in the 1960 Chile earthquake (Weischet, 1963, p. 1240-1243). All of the data gathered should be put in quantitative terms to the extent possible.

The question of whether recognized regional deformation was sudden or gradual may not have a definite answer if no historic records of coseismic deformation exist. For example, it is generally very difficult or impossible to tell from geologic evidence whether a given marine terrace was uplifted suddenly or slowly. Pertinent geologic, geomorphic and paleontologic evidence should nevertheless be sought, and the tectonic setting may permit a reasonable inference. Active subduction-type plate boundaries, for example, probably will produce sudden vertical displacements such as occur in Alaska and Chile, but transform plate boundaries characteristically do not.

Whether regional deformation will occur in the lifetime of a facility is a difficult question to answer in quantitative terms. Background for answering the question can come from a variety of sources. For example, a group of marine terraces on Middleton Island, Alaska, indicates that events such as the 1964 Alaska earthquake have occurred at intervals ranging from about 500 years to about 1,350 years (Plafker and Rubin, 1978). Recurrence times of inland dip-slip events can also be estimated from geomorphic or subsurface studies. Geodetic information may indicate the rate at which elastic strain is accumulating. The existence of a seismic gap may suggest that an earthquake will occur in the near future (Kelleher and others, 1973; McCann and others, 1979; several papers in Simpson and Richards, 1981).

4 ESTIMATING FUTURE FAULTING AND LOCAL DEFORMATION

4.1 GENERAL.

Estimates of future faulting and local deformation may be necessary if a structure, such as a pipeline, is to be placed across an active fault, or to evaluate whether an existing structure can tolerate displacement, or to estimate the sizes of future earthquakes that a fault may produce. For these applications it is desirable to provide a best estimate of the probability, type, location, and dimensions of the faulting that may occur. Estimates of the amount and location of future local deformation are particularly difficult and practically restricted to judgments based on what has been learned in the site investigations (section 3), and on the ratios between slip and distortion that have been observed in historic faulting (section 2.1.7).

4.2 PROBABILITY.

The probability of the appearance of surface faulting is difficult to confidently state in either qualitative or quantitative terms. Detailed site investigation can reveal evidence of repeated faulting, and sometimes enough age control is found to estimate recurrence intervals of faulting (Sieh, 1978; Swan and others, 1980; Wallace, 1981; Sieh, 1981). Factors that affect the occurrence of faulting at the ground surface include earthquake size and focal depth. The empirical data base does not yet permit a precise statement of the probability of surface faulting for an earthquake of given size and focal depth but one can state that in much of the western United States, shallow-focus (focal depths less than 15 or 20 km) earthquakes of magnitude 6 or larger are likely to have surface faulting associated with them. Otsuka (1964) presented an analytical rather than empirical solution to this problem. He used a theoretical relation between earthquake magnitude and source radius, assumed that the earthquakes occurred uniformly through the whole thickness of the seismogenic zone, and that surface faulting appears when the depth to the center of the source is less than the radius of the source. Otsuka then used the geometric relation between the source radius and the thickness of the seismogenic zone to estimate the probability of surface faulting for earthquakes of given magnitude. His results seem to be in accord with some of the Japanese empirical data (Otsuka, 1964).

Elaborate analyses of the probability of surface faulting have been made in connection with a nuclear test reactor in California (U.S. Nuclear Regulatory Commission, 1980). One of the analyses calculated the probability per year of surface faulting with displacement equal to or greater than a specified value. Among the factors included in some of the analyses were: probability distribution of time between offsets, time since last offset, slip rates on the fault, characteristic offset on the fault, earthquake magnitude-frequency relations, source radius for given earthquake magnitude, total length and width (downdip) of the fault, upper cutoff for earthquake magnitude on the fault, and empirical relations between earthquake magnitude and surface rupture length and displacement. Expert reviews of these analyses, included in the safety evaluation (U.S. Nuclear Regulatory Commission, 1980), point out various shortcomings in the assumptions, analyses, and models used.

The factors mentioned above, as well as others, permit the calculation of numerical probabilities of faulting. However, the conceptual models should be critically examined by independent experts to determine whether they are realistic, appropriate, and complete. Any numerical probabilities that are derived should be used only with a full understanding of the sensitivity of the results to the various necessary assumptions and approximations.

The statement of a panel of the National Research Council (1980) regarding siting of critical facilities seems to also apply to faulting: "At present, because of the many uncertainties in the existing geologic and geophysical data base for most parts of the nation, extreme caution must be exercised when using the results of most computer-produced earthquake risk analyses that are becoming available. The Panel believes that at this time statistical probabilistic analyses should be used for insight rather than for numerical results."

4.3 TYPE OF FAULTING

What has happened on the fault in the geologic and historic past is the best indication of the type of faulting (fig. 3) that will happen in the future. That is, reverse-slip faults will have reverse-slip displacements, strike-slip faults will have strike-slip displacements and normal-slip faults will have normal-slip displacements. At least one apparent exception to this generalization has been reported, however. The 1977 strike-slip faulting in Iran (maximum displacement 0.2 m, Ms 5.8) occurred on the part of the Kuh Banan fault that has had high-angle reverse displacement in Quaternary time (Berberian and others, 1979). About 40 km away however the same fault does show older strike-slip features (Huckriede and others, 1962). Some faults are hybrids, having components of both dip-slip and strike-slip that result in oblique-slip displacements. On some hybrid faults, oblique-slip displacements occur only locally; on others they are the characteristic type of displacement. A vertical component commonly accompanies strike-slip faulting; the maximum vertical component has averaged about one-third of the maximum strike-slip for historic strike-slip events, but has ranged from less than 10 percent to more than 60 percent.

A structure which crosses a strike-slip fault obliquely will be subjected to either compressional or tensional stresses, depending on the sense of strike slip and whether the structure crosses the fault from left to right (compression on a right-slip fault) or from right to left (extension on a right-slip fault) as viewed along the fault. Examples of this effect are shown in figures 10 and 11.

Geologic, seismologic (focal mechanism solutions), historic, geodetic, and in-situ stress data can be used to determine or infer characteristic types of displacement on a fault.

Displacements on subsidiary faults may or may not be the same as on the main fault. Strike-slip subsidiary faulting was associated with the reverse-slip California faulting of 1952. Normal-slip faulting commonly occurs on the upthrown block of reverse-slip faults, and has been associated with strike-slip faults also.

4.4 LOCATION AND WIDTH

The location of existing faults, determined as outlined in section 3, is the best indication of where faulting will occur. Most historic ruptures have occurred within a few meters of prominent faults or earlier historic ruptures, although some have locally been several tens of meters distant. The widths of historic main ruptures and the distance of subsidiary faults from the corresponding main faults is summarized in section 2.1.3. This provides guidance as to the area subject to faulting but, because of the great variation in width of rupture zones along faults and the fact that new faulting is quite rare (Bonilla, 1979), the best guide to future faulting is the location and width of existing faults determined by the detailed field studies that include trenching.

4.5 SIZE OF DISPLACEMENTS

Some currently used methods of estimating the size of future fault displacements at the surface are outlined in the following sections. The probabilities of stated amounts of displacement should be given if practical; if so the underlying assumptions and the sensitivity of the result to those assumptions must also be stated.

4.5.1 Displacement in Past Earthquakes.

If any historic surface ruptures have occurred on the fault, they can be used as a guide to future displacements.

Under favorable conditions the sizes of prehistoric events can be estimated. This requires identification of a single event, or the cumulative displacement in several events can be taken as an upper limit. Single rupture events can be identified on normal-slip faults in areas of low precipitation, mostly on the basis of age of scarps. The age is usually inferred from scarp morphology supplemented by the relation of the scarp to dated topographic features, soils, age of trees, and any other applicable technique (Dodge and Grose, 1980; Wallace, 1978; Wallace, 1981; Mayer, 1982). For normal-slip faults in areas of low rainfall, both the length of fault and the displacement can be estimated from surface evidence, but strike-slip and reverse-slip faults are hard to treat in this way. In strike-slip faulting there are few reference points at the ground surface except stream channels or rare terrace steps, and reverse faulting tends to be masked by landslides.

Occasionally evidence is found in trenches which permits an estimate of prehistoric displacements. Such estimates have been made for normal-slip, reverse-slip, and strike-slip faults although the estimates have been somewhat ambiguous, and have usually been stated as ranges of possible displacements (Malde, 1971; Bonilla, 1973; Sieh, 1978; Swan and others, 1980).

4.5.2 Displacement Related to Earthquake Magnitude.

If the magnitude of the earthquake expected from a fault has been estimated, empirical data that relate magnitude to maximum surface displacement can be used. Some of the measured displacements used in these correlations may include a component of afterslip (see section 2.1.6) but generally this is quite small. Such correlations have been made by various investigators, including Bonilla and Buchanan (1970) and Slemmons (1977). Figure 16 shows a least squares regression of maximum fault displacement (D) at the surface on the main fault as a function of surface-wave magnitude (M_s), with consideration of measurement errors in both variables, done by R. K. Mark using a modification of the methods of York (1966). The regression equation is $\log D = -6.35 + 0.93 M_s$, in which D is in meters*. Standard deviations for the two numerical constants in the equation are 0.87 and 0.12, respectively. Very few data exist for magnitudes less than about 6, and they were not used in the regression. The scatter in the data points in Figure 16 shows the range of displacement that can be expected for a given magnitude. Uncertainties in estimates of the expected magnitude of the earthquake must be added to the uncertainties in the magnitude-displacement relation.

4.5.3 Displacement Related to Rupture Length.

If the expected length of surface rupture has been estimated from the geologic record or by other means, empirical data relating maximum surface displacement to surface rupture length can be used. Plots of this relation show a great deal of scatter whether the various types of faults are considered separately or collectively. The correlations that follow were done by R.K. Mark using a modification of the methods of York (1966). At least two types of correlations can be made between these variables. The more commonly used one is a log-log relation such as in figure 17 where the regression equation is $\log D = -1.42 + 1.07 \log L$, in which maximum displacement D is in meters and rupture length L is in kilometers*. Standard deviations for the two numerical constants in the equation are 0.27 and 0.14, respectively. A direct linear correlation of surface displacement and surface rupture length can also be made (Fig. 18). The regression equation is $D = -0.40 + 0.059L$, in which D is in meters and L is in kilometers. Standard deviations for the two numerical constants in the equation are 0.08 and 0.006, respectively. The linear correlation yields results that are less than 5 percent larger than the log-log correlation for rupture lengths greater than about 30 km. For lengths less than 30 km, use of the linear correlation is not recommended because the results differ considerably from the log-log relation and the regression line does not pass through the origin of the graph. As can be seen from the data points on figures 17 and 18 the curves are not well constrained for rupture lengths less than about 10 km, and such points were not used in the correlations. The scatter in the data points indicates the range in surface displacement that can be expected for a given surface rupture length. Uncertainties in estimates of expected surface rupture length must be added to the uncertainties in the rupture length-displacement relations.

4.5.4 Slip Rate Multiplied by Time Since Last Displacement.

A method of roughly estimating potential displacement on a fault is based on the long-term slip rate, which is determined geologically. The time of the last displacement must be determined, either from historic records or from geologic evidence. The potential slip is equal to the long term rate multiplied by the elapsed time since the last displacement minus any tectonic creep in the interval.

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* [Note added in version 1.1: Better equations are in Bonilla, M.G., Mark, R.K., and Lienkaemper, J.J., 1984, Statistical relations among earthquake magnitude, surface rupture length, and surface fault displacement: U.S. Geological Survey Open-File Report 84-256, 37 p.]

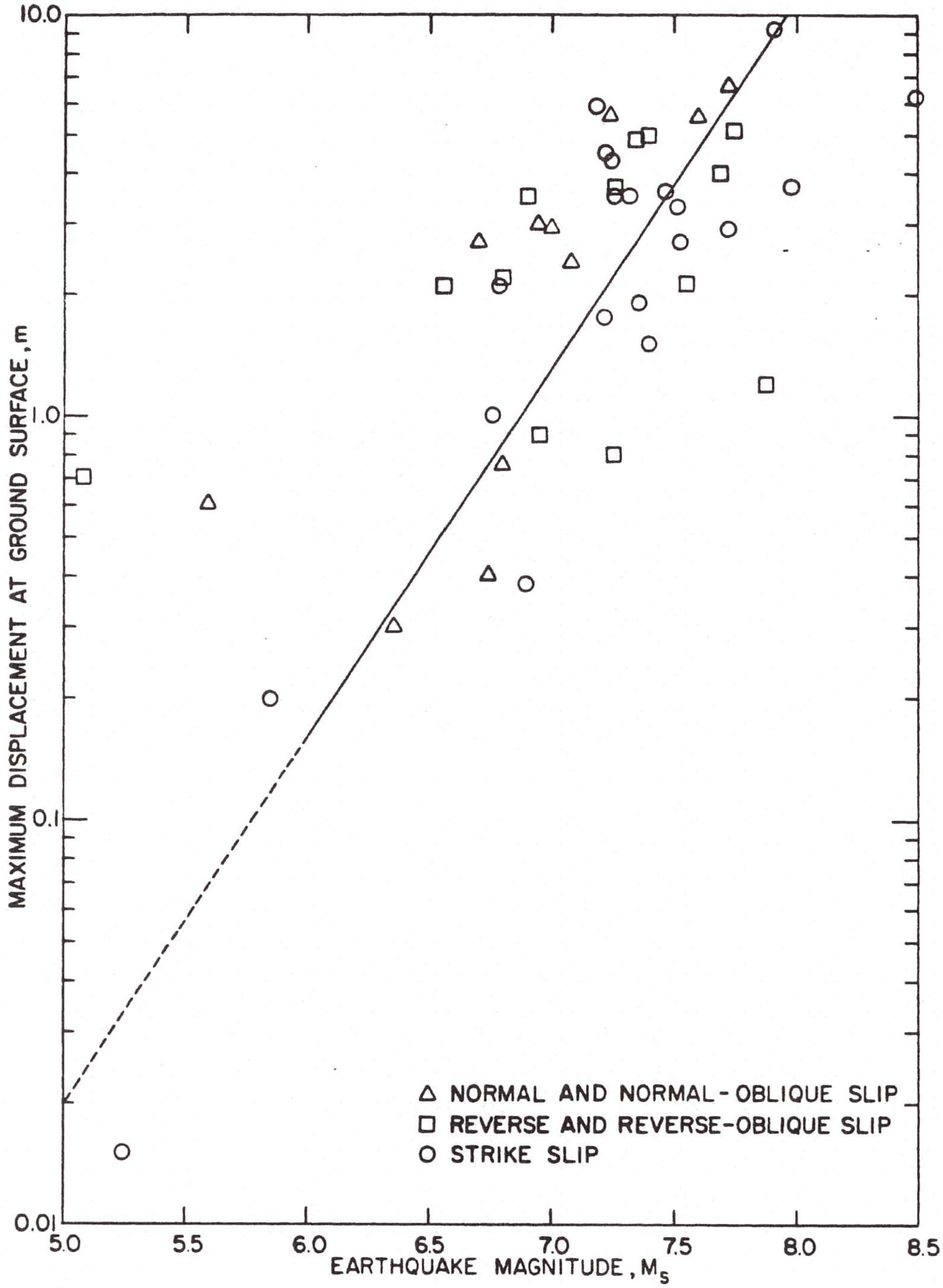

Figure 16. Relation between earthquake magnitude (M_s) and maximum fault displacement (net slip) at the ground surface. The least squares regression line reflects consideration of measurement errors in both variables. The regression line is based on events of Ms 6 or larger. From unpublished data of M.G. Bonilla, R.K. Mark, and J.J. Lienkaemper. (Note added in version 1.1: Better equations are in Bonilla, M.G., Mark, R.K., and Lienkaemper, J.J., 1984, Statistical relations among earthquake magnitude, surface rupture length, and surface fault displacement: U.S. Geological Survey Open-File Report 84-256, 37).

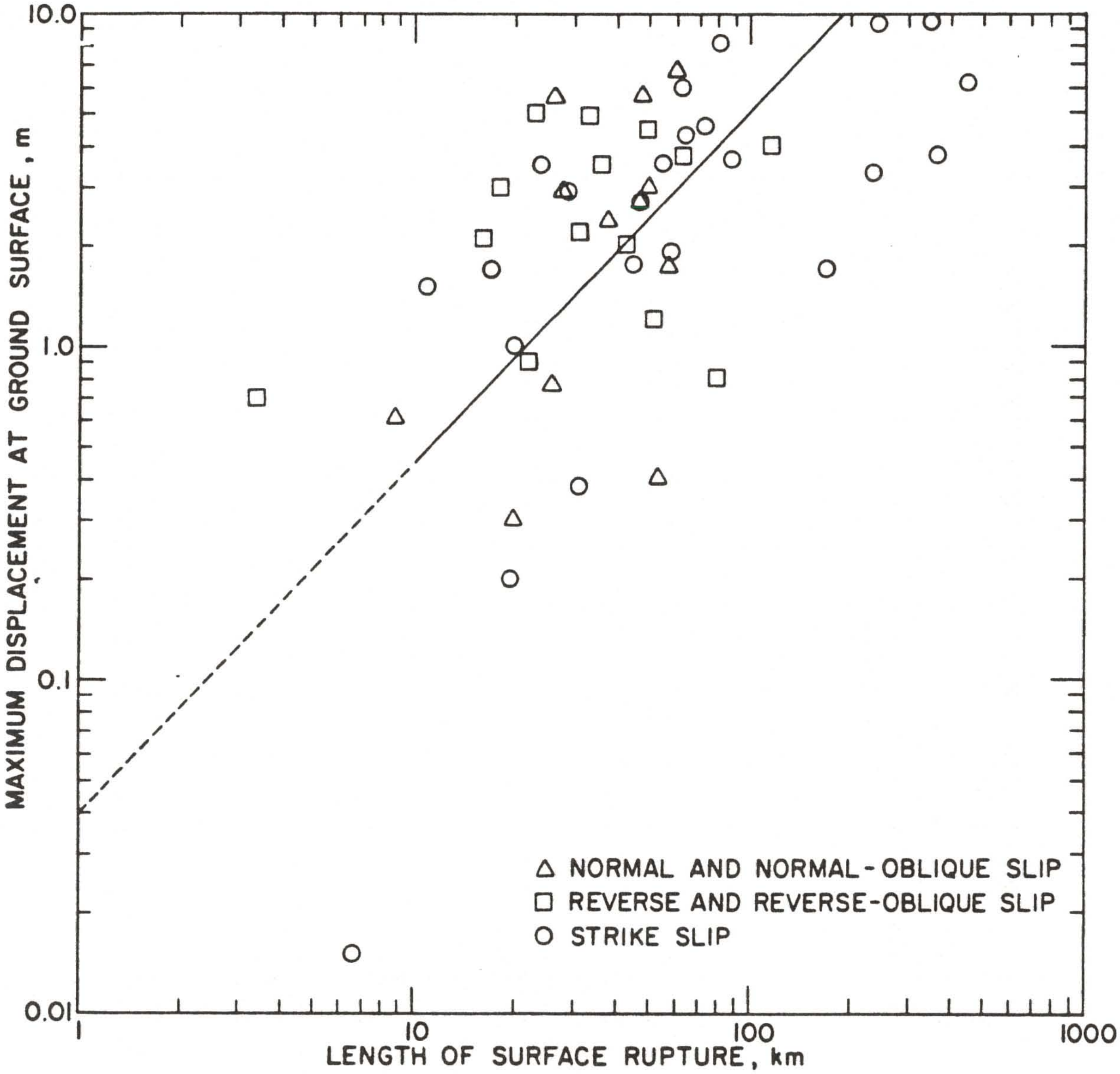

Figure 17. Logarithm of maximum surface displacement (net slip) as a function of logarithm of length of surface rupture. The least squares regression line reflects consideration of measurement errors in both variables. The regression line is based on rupture lengths of 10 km or more. From unpublished data of M.G. Bonilla, R.K. Mark, and J.J. Lienkaemper. (Note added in version 1.1: Better equations are in Bonilla, M.G., Mark, R. K., and Lienkaemper, J.J., 1984, Statistical relations among earthquake magnitude, surface rupture length, and surface fault displacement: U.S. Geological Survey Open-File Report 84-256, 37).

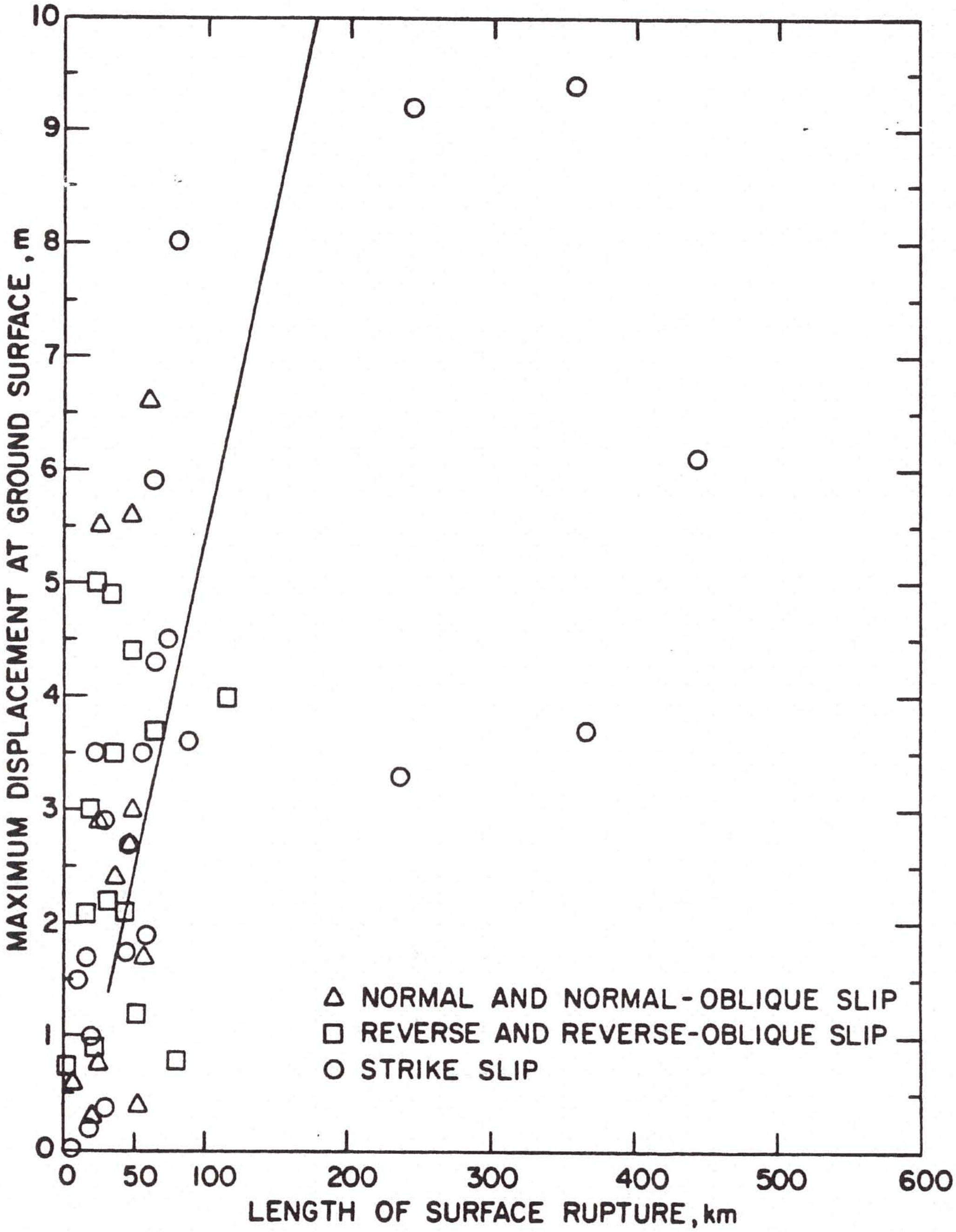

Figure 18. Maximum surface displacement as a function of length of surface rupture. The least squares regression line reflects consideration of measurement errors in both variables; it is based on rupture lengths of 10 km or more. From unpublished data of M.G. Bonilla, R.K. Mark, and J.J. Lienkaemper. (Note added in version 1.1: Better equations are in Bonilla, M.G., Mark, R.K., and Lienkaemper, J.J., 1984, Statistical relations among earthquake magnitude, surface rupture length, and surface fault displacement: U.S. Geological Survey Open-File Report 84-256, 37).

For example, the northern San Andreas fault has a long-term slip rate of about 3 cm per year (Herd, 1979). It had no surface displacement between April, 1906 and April of 1981, at which time the potential slip was about 3 x 75 or 225 cm. Figure 19 shows the relationship for different rates of slip and time periods. The seismological method of estimating slip rate (section 3.2.1) is not applicable in this connection because that method estimates slip that has already occurred, and is based on a short time span. Potential slip estimated in this way no doubt has a large stochastic variation. The validity of the method itself is uncertain--some investigators believe that, with a constant rate of accumulation of tectonic stress, the time of displacement is predictable but not the amount of displacement (Bufe and others, 1977; Shimazaki and Nakata, 1980). Data supporting both the time-predictable model (Mogi, 1981; Sykes and Quittmeyer, 1981) and the slip-predictable model (Wang, McNally, and Geller, 1982) have been reported. Whether one of the two models or a hybrid model is the most appropriate is not clear at present.

4.6 DISPLACEMENT ON SUBSIDIARY FAULTS

Some of the methods outlined above for estimating displacements on the main fault can be used for subsidiary faults also. If any historic displacements have been recorded, they can be used as a guide. Geologic evidence for individual prehistoric displacements, for slip rate, and for time of last displacement on the subsidiary fault should be sought. Empirical data on rupture length versus displacement can be used. Another method is based on the fact that maximum displacement on subsidiary faults is almost always less than maximum displacements on the main fault. Of about 100 documented subsidiary faults of various types throughout the world, more than 80 percent had displacements that were less than 30 percent of the maximum displacement on the main fault, although one had a displacement larger than on the main fault (Bonilla, unpublished data). Thus one can estimate the maximum displacement on the main fault and assume some percentage of that for the probable displacement on a subsidiary fault. At present (1981) the dependence of this percentage on fault type, geometric relation to the main fault, or other factors is very poorly known. If this method is used, 30 percent is probably an appropriate figure to use for most projects unless local conditions, new concepts, or new data suggest a more appropriate figure. At one damsite, for example, 60 percent was considered appropriate based on local conditions including an analogy with a local historic rupture (Yerkes and others, 1974).

4.7 USE OF ESTIMATED DISPLACEMENTS

In applying the displacement estimates obtained from the procedures outlined above, the differences in the estimates must be kept in mind. Some estimates are maxima, some are averages, and some are based on small samples of a process that has much variation. Existing empirical curves relating displacement to magnitude or rupture length are based on the maximum displacement for each event in the data set, and yield estimates of maximum displacement. Estimates based on a local past earthquake could yield average displacement (for example a well-documented historic event, or many measurements of scarp height for a prehistoric event), probable maximum displacement (only a few measurements for a prehistoric or historic event), or a displacement whose relation to maximum and average are unknown (for example, trench data for a single point on the fault). An estimate of average displacement for the fault is obtained if the product of slip rate and elapsed time are used. In applying estimates of future displacement, consideration must be given not only to the distinction between maximum and average displacement but also to the variation in the data base of the empirical curves and the variation in manifestation of faulting both along the fault and in successive events at the same site (sections 2.1.3, 2.1.4, and 2.1.5). The possibility of afterslip and its effects should be considered in planning repair or continued use of structures damaged by faulting (section 2.1.6).

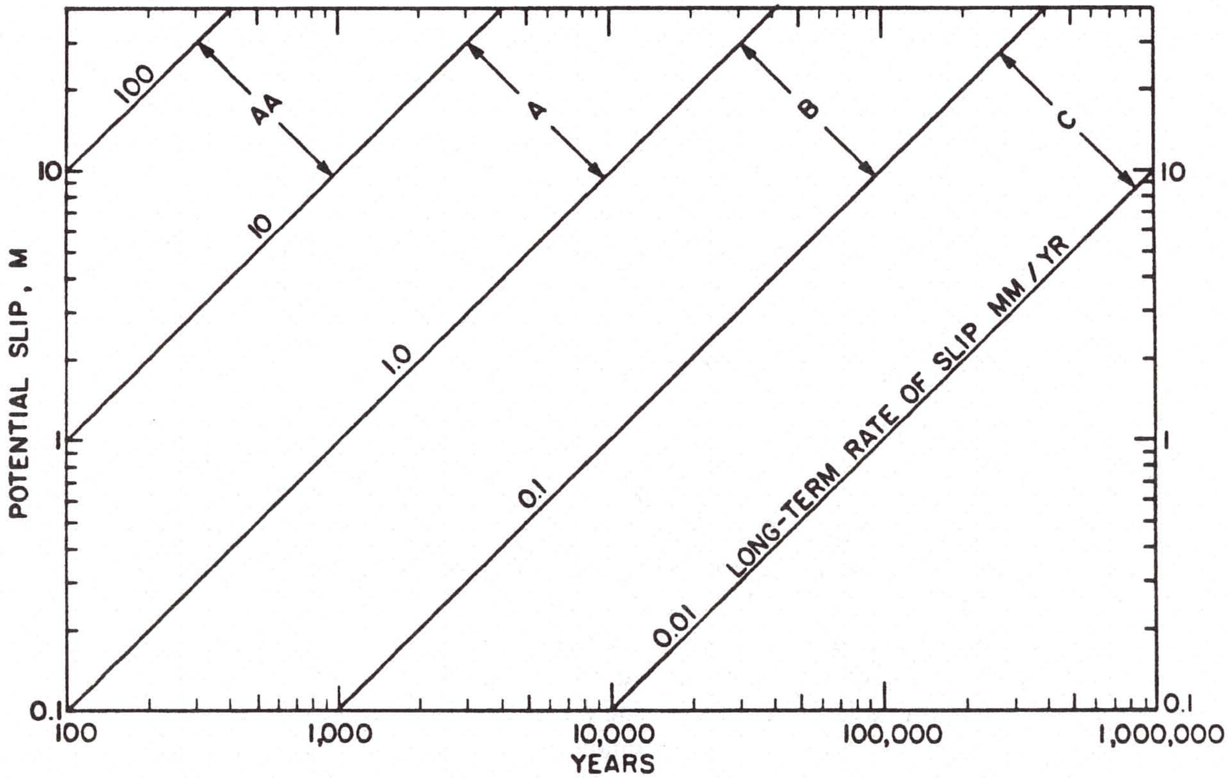

Figure 19. Potential fault displacement as a function of elapsed time since last displacement. Lines for different rates of slip are also boundaries for the different classes of fault activity given in Table 4.

5 ESTIMATING DIMENSIONS OF FUTURE REGIONAL DEFORMATION

5.1 GENERAL.

If, following procedures outlined in section 3.3, the conclusion is reached that the site will be subject to sudden upward or downward regional deformation, the dimensions (areal extent and amount) of the deformation need to be estimated. This section outlines approaches to providing such estimates of the vertical and areal dimensions of future regional deformation.

5.2 HISTORICAL AND GEOLOGICAL METHODS.

As with surface faulting, the dimensions of any historical regional displacement can be considered an indication of what may occur in the future. The vertical component expected on the basis of historic events may be modified for particular projects by consideration of time since last displacement and rate of accumulation of strain, by assuming that the strain accumulates linearly and that the accumulated strain will be released suddenly; however elastic strain rate is usually difficult to determine and partition among known faults. The areal extent of earlier regional deformation events in coastal areas can be approximated by geologic study of emerged and submerged features, as in the Alaskan example discussed in section 3.3.3. The vertical distances between successive terraces may give an indication of the vertical displacement to expect. An example is the set of six terraces on Middleton Island, Alaska, whose average vertical separation is 7.5 m. The uplift of the island in the 1964 earthquake was only about half of the average of the preceding uplifts, but the remaining half could be released in another earthquake in the near future or by aseismic creep (Plafker and Rubin, 1978). As previously mentioned, inferences based on terrace data are uncertain because it is generally difficult or impossible to tell from geologic evidence whether a terrace has been uplifted suddenly or slowly.

5.3 ANALYTICAL METHODS.

If the parameters of future faulting can be estimated, the dimensions of regional deformation can also be estimated. The analysis is based on dislocation theory (Savage, Burford and Kinoshita, 1975; Mansinha and Smylie, 1971) and requires a rather complete estimate of the fault parameters. Estimates must be made of the fault dip, and of the length, width (downdip), depth below the surface, and strike- and dip-slip components of the future rupture. Estimates of some of these can be made following the procedures outlined in section 4 and others will have to be assumed on the basis of whatever relevant geological, geophysical, and geodetic data can be developed. The results should be tabulated to show their sensitivity to various estimates of fault parameters.

5.4 POSTSEISMIC CHANGES.

Small changes in elevation may follow coseismic regional deformation. The possible effects of this process should be considered in planning postseismic reconstruction or replacement of facilities whose function is closely related to water level. This process was of critical concern in rebuilding the railroad car barge slip at Whittier, Alaska, following the 1964 earthquake (C. L. Griffiths, The Alaska Railroad, 1964, personal communication) but at that time no quantitative data were available. An indication of the size of such changes is given by tide gage records in five widely separated communities, all affected by the Alaska earthquake, which showed postseismic recovery (i.e. decrease in coseismic uplift or subsidence) in a ten-year period ranging from 12 cm to 58 cm, or from 6 percent to 34 percent of the coseismic elevation change (table 5).

An analysis of probable long-term (10 to 200 yr) regional postseismic vertical displacement as a function of fault slip is given by Thatcher and Rundle (1979). Their paper also gives references to other models of regional deformation.

Table 5. Postseismic Elevation Changes in the Region Affected by Regional Tectonic Deformation during the 1964 Alaska Earthquake.

From Plafker and Rubin (1978, table 2).

Tide gage	1964 coseismic displacement (cm)	Postseismic Displacement (cm)	Postseismic Recovery (percent)	Years of record
Cordova	+189	-12	6	1964-74
Kodiak	-171	+58	34	do
Seldovia	-119	+14	12	do
Anchorage	-79	+14	18	do
Seward	-110	+15	14	do

6 GAPS IN KNOWLEDGE AND NEEDED RESEARCH

Existing knowledge regarding tectonic deformation has many shortcomings which limit quantitative estimates of future surface manifestations of the process. The more critical gaps are outlined here and a general approach to reducing the gaps is suggested in the last paragraph. One point of weakness is that not enough is known about the relation between surface and subsurface rupture. Theoretical and empirical geophysical methods permit apparently good correlations between earthquake magnitude or seismic moment and subsurface rupture area and average displacement. The relation between subsurface and surface rupture clearly is important in determining fault rupture length and displacement at the surface; however under what conditions and how the subsurface rupture will appear at the surface is very poorly known, except that earthquake size and focal depth are important controlling factors. Existing correlations between magnitude or seismic moment and subsurface rupture are strongly dependent on the distribution of aftershocks, yet the relation between the principal seismogenic rupture and aftershocks seems to vary considerably, and many of the aftershocks used in existing correlations were not accurately located. More data are also needed on the variation in surface displacement along faults and on the factors that control the variation; at present not enough data are at hand to statistically characterize, in a meaningful way, this variation in displacement. Additional data are needed on what proportion of coseismic fault ruptures have afterslip on them and how the afterslip changes with time at various places on the fault, especially in the first hours and days after the earthquake. Very few quantitative data are available on the variation in size, location, width, and type of tectonic deformation in successive events at the same site. More high-quality data are needed on the relations among earthquake magnitude, surface length, and surface displacement in order that the different types of faults can be treated individually rather than collectively and still yield high correlation coefficients. Our ability to distinguish between terraces that have been uplifted suddenly or gradually needs to be improved. At present very few criteria are known, but the distinction can be very important in the siting of structures at or near shorelines. Our ability to recognize and date individual prehistoric fault displacements is rather limited. Finally, few quantitative data exist regarding the speed with which fault ruptures develop at the surface.

Some of the information gaps outlined above can be narrowed through theoretical and experimental methods that lead to a better understanding of the process, but strong reliance on empirical data will probably always be required because of the complexity of both the process and the environment in which it operates. Solution of these problems requires 1) collection of detailed and accurate data related to tectonic deformation associated with future earthquakes of moderate to large size; 2) full utilization of historic, geologic, and geophysical data on previous tectonic deformation; and 3) continuation of theoretical, experimental, and modeling studies to the point where the process of tectonic deformation is thoroughly understood.

7 GLOSSARY

Afterslip. The increase in displacement on a fault by creep following a sudden coseismic slip. The rate generally decreases logarithmically with time after the sudden slip, but can be temporarily accelerated by aftershocks.

Coseismic. Occurring at the same time as an earthquake.

Dip. The angle that a stratum, joint, fault, or other structural plane makes with a horizontal plane.

Dip slip. The component of the slip parallel with the dip of the fault.

Dip-slip fault. A fault in which the slip is predominantly in the direction of the dip of the fault.

En echelon. An overlapping or staggered arrangement, in a zone, of geologic features which are oriented obliquely to the orientation of the zone as a whole (Dennis, 1967).

Entity. Formal and informal rock-stratigraphic units, soil-stratigraphic units and biostratigraphic units, mineral deposits, structural features, geomorphic features, and artificial structures (American Nuclear Society, 1980).

Fault. A fracture or fracture zone along which the two sides have been displaced relative to one another parallel to the fracture. The accumulated displacement may range from a fraction of a meter to many kilometers.

Fault creep. Apparently continuous displacement on a fault at a low but varying rate, usually not accompanied by felt earthquakes.

Fault displacement. The amount of relative movement of the two sides of a fault, measured in any specified direction, or the process of such movement.

Fault sag. A narrow tectonic depression common in strike-slip fault zones. Fault sags are generally closed depressions; those that contain water are called sag ponds.

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

Fracture. A general term for discontinuities in rock; includes faults, joints, and other breaks.

Holocene. Approximately the last 10,000 years; the second epoch of the Quaternary period, extending from the end of the Pleistocene to and including the present.

Hypocenter. The point within the Earth where fault rupture initiates thereby generating earthquake motion.

Graben. A fault block, generally long and narrow, that has been downdropped relative to the adjacent blocks by movement along the bounding faults.

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

Normal-slip fault. A fault in which the block above an inclined fault surface has moved downward relative to the block below the fault surface.

Oblique slip. A combination of strike slip and normal or reverse slip.

Pleistocene. The first epoch of the Quaternary period, extending from approximately 2 million to 10,000 years before the present.

Quaternary. Approximately the last 2 million years; the period of geologic time including the Pleistocene and Holocene.

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

Right slip. Strike-slip displacement in which the block across the fault from an observer has moved to the right; also called dextral strike-slip.

Seismic moment. The product of shear modulus (μ), average slip ($\bar{u}$), and area (A) of the fault that has slipped: $M_o = \mu \bar{u} A$.

Slip. The relative displacement of points on opposite sides of a fault, measured on the fault surface.

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

Strike slip. The component of the slip parallel with the strike of the fault.

Strike-slip fault. A fault in which the slip is predominately in the direction of the strike of the fault.

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

Tectonic creep. Fault creep of tectonic origin.

Thrust fault. A reverse-slip fault with a dip less than 45°.

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