PART I

GUIDANCE FOR THE LOCATION STANDARDS

Chapter 2

Locating Hazardous Waste Facilities in Seismically Active Areas

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1.0 INTRODUCTION

This chapter of the Guidance Manual for the Location Standards provides guidance to EPA permit writers and owners or operators of new hazardous waste management facilities concerning the seismic location standard in 40 CFR 264.18(a) and the corresponding Part B (RCRA permit) information requirements in 40 CFR 122.25(a)(11).

Beyond this introduction, the second section of this chapter describes the seismic location standard and provides a summary of the technical basis for the standard. Section 3.0 defines geological terms used in the standard and this Manual. Section 4.0 provides a detailed discussion of the Part 122 information requirements and the methods and tools of geologic investigations. The references are in Section 5.0. Three appendices follow, providing background information on earthquakes, faulting, and Holocene deposits.

2.0 REGULATORY BACKGROUND

2.1 The Seismic Location Standard

The potential threat that a hazardous waste management facility presents to human health and the environment is increased by locating the facility in seismically active areas. Damage and loss of life in earthquakes occur as a result of ground shaking (ground motion), secondary effects of the shaking such as liquefaction, and permanent surface displacement along faults (surface faulting). The siesmic location standard addresses one of these hazards, surface fault displacement, and the associated ground deformation in the vicinity of the displacement. Specifically, the seismic location standard prohibits hazardous waste management facilities from locating within 61 meters (200 feet) of a fault that has had displacement in Holocene time (approximately the last 11,000 years). Such a fault is referred to as a "Holocene fault" within this document.

Surface fault displacement and deformation do not represent a significant risk to hazardous waste facilities in the entire United States. Even though large earthquakes have occurred in the East[1], a surface fault has not been conclusively identified as being associated with these earthquakes. Because displacement and deformation along Holocene faults, the very processes that the

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[1] As used in this manual, "in the East" means east of the eastern front of the Rocky Mountains.

seismic standard is intended to protect against, do not present a significant risk to hazardous waste facilities in the East, the seismic location standard impacts only those new facilities that are proposed to be located in certain areas west of the eastern front of the Rocky Mountains. Appendix VI to P. -t 264 lists those political jurisdictions where EPA has determined that applicants must demonstrate compliance with the seismic location standard.

For reasons specified in the _____ Federal Register (__FR __) EPA amended the January 12th version of Appendix VI. The preceding discussion is consistent with that amendment. The amended version of Appendix VI is given in Table 1 and mapped in Figure 1.

Sections 122.25(a)(11)(i) and (ii) of Part 122 contain the information requirements for Part B of the RCRA permit application relative to the seismic location standard (see 46 FR 2889). Part 122 requires permit applicants whose facilities are located in areas listed in Appendix VI to demonstrate either that Holocene faults are not present within a 3,000-foot radius of the facility or that Holocene faults are not present within 200 feet of the facility. However, if Holocene faults are determined to be present within a 3,000-foot radius of the facility, the applicant must also demonstrate that Holocene faults are not present within 200 feet of the facility. Part 122 also specifies investigative methods that may be used to make the above described demonstrations.

TABLE 1

POLITICAL JURISDICTIONS* IN WHICH COMPLIANCE WITH §264.18(A) MUST BE DEMONSTRATED (APPENDIX VI TO PART 264)

Alaska

Aleutian Islands
Anchorage
Bethel
Bristol Bay
Cordova-Valdez
Fairbanks-Fort Yukon
Juneau.
Kenai-Cook Inlet
Ketchikan-Prince of Wales
Kodiak
Lynn Canal-Icy Straits
Palmer-Wasilla-Talkeena
Seward
Sitka
Wade Hampton
Wrangell-Petersburg
Yukon-Kuskokwim

Arizona

Cochise
Graham
Greenlee
Yuma

California

All

Colorado

Archuleta
Conejos
Hinsdale

Colorado (Concluded)

Mineral
Rio Grande
Saguache

Hawaii

Hawaii

Idaho

Bannock
Bear Lake
Bingham
Bonneville
Caribou
Cassia
Clark
Franklin
Fremont
Jefferson
Madison
Oneida
Power
Teton

Montana

Beaverhead
Broadwater
Cascade
Deer Lodge
Flathead
Gallatin
Granite

*These include counties, city-county consolidations, and independent cities. In the case of Alaska, the political jurisdictions are election districts, and, in the case of Hawaii, the political jurisdiction listed is the island of Hawaii.

TABLE 1 (Concluded)

Montana (Concluded)

Jefferson
Lake
Lewis and Clark
Madison
Meagher
Missoula
Park
Powell
Sanders
Silver Bow
Stillwater
Sweet Grass
Teton
Wheatland

Nevada

All

New Mexico

Bernalillo
Catron
Grant
Hidalgo
Los Alamos
Rio Arriba
Sandoval
Santa Fe
Sierra
Socorro
Taos
Torrance
Valencia

Utah

Beaver
Box Elder
Cache
Carbon
Davis
Duchesne
Emery
Garfield
Iron

Utah (Concluded)

Juab
Millard
Morgan
Piute
Rich
Salt Lake
Sanpete
Sevier
Summit
Tooele
Utah
Wasatch
Washington
Wayne
Weber

Washington

Chelan
Clallam
Clark
Cowlitz
Douglas
Ferry
Grant
Grays Harbor
Jefferson
King
Kitsap
Kittitas
Lewis
Mason
Okanogan
Pacific
Pierce
San Juan Islands
Skagit
Skamania
Snohomish
Thurston
Wahkiakum
Whatcom
Yakima

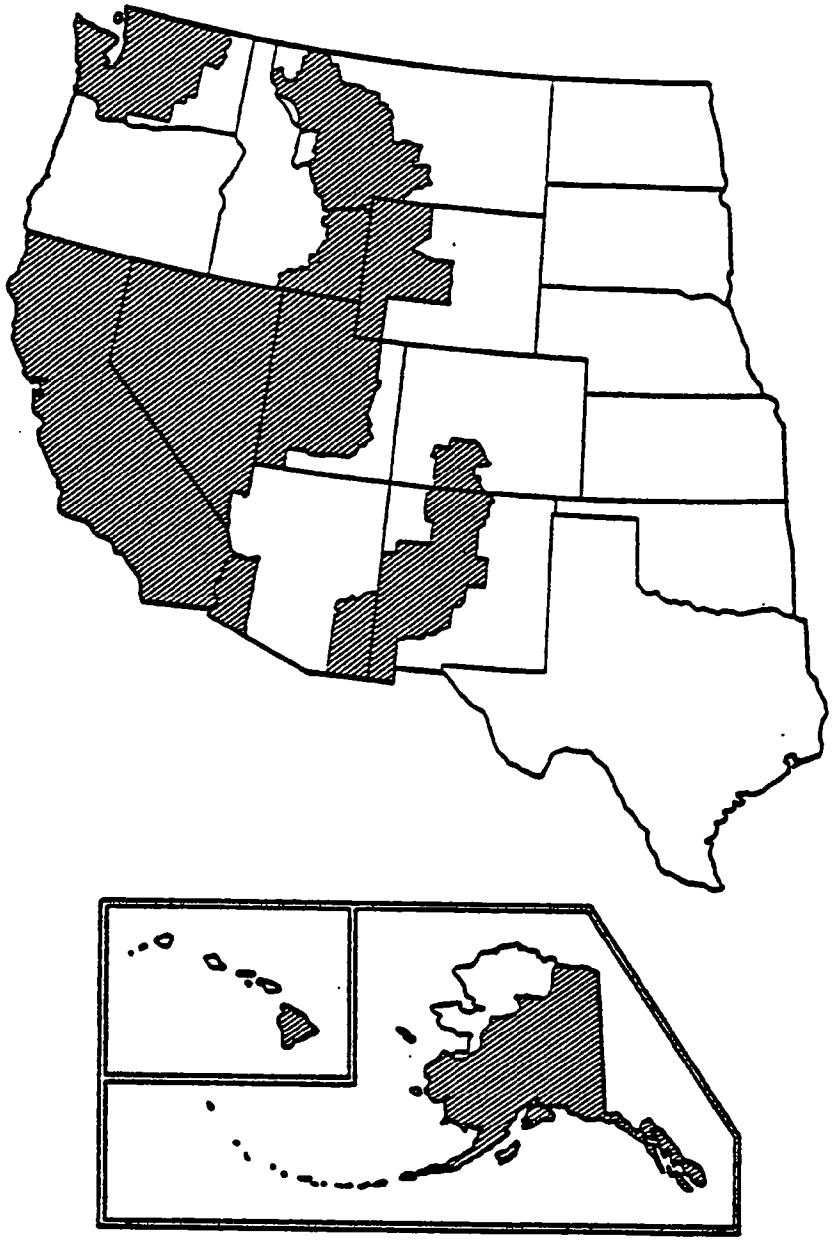

FIGURE 1

AREAS OF THE UNITED STATES LISTED
IN APPENDIX VI

As indicated in the preamble to the January 12 rules, EPA did not promulgate location standards addressing ground motion and ground failure because the Agency lacked sufficient data and information relating ground motion and ground failure risks to hazardous waste facility siting and design. These issues are discussed in greater depth on page 2811 of the January 12th Federal Register (Vol. 46, No. 7) (U.S. Environmental Protection Agency, 1981).

2.2 Summary of Technical Rationale[1]

It is generally considered economically infeasible and, in some cases, impossible to design a critical structure[2] to resist significant fault displacement. For this reason many regulatory agencies prohibit the construction of certain structures adjacent to faults that have the potential for surface faulting during the life of the structures (Slemmons, 1977).

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[1] EPA prepares Background Documents which contain technical support for regulations promulgated under the authority of RCRA. The Background Document General Facility Standards for Location of Facilities (December 30, 1980; MS. 1941. 34) should be read for an in-depth discussion of the Agency's technical rationale with respect to the seismic location standard.

[2] Examples of critical structures are dams, reservoirs, nuclear reactors, tall building, schools, prisons, and structures containing large quantities of potentially explosive or toxic materials (California Seismic Safety Committee, 1979).

Hazardous waste management facilities encompass treatment, storage or disposal of hazardous waste in containers, tanks, surface impoundments, waste piles, landfills, incinerators, and structures or mediums for thermal, chemical, physical, and biological treatment. These facilities contain structures similar to those that have been damaged during past historical earthquakes and episodes of surface faulting (U.S. Geological Survey, 1971; Murphy, 1973; and Earthquake Engineering Research Institute, 1979). Therefore, in order to protect human health and the environment, there is a need to regulate the location of hazardous waste management facilities in areas subject to fault displacement.

The basic premise applied to identifying and locating faults that may be significant to man-made structures is that the type, amount, and location of fault displacement in the future will be similar to that which has occurred in the recent geologic past. This premise has been substantiated by the results of studies that demonstrate that surface fault rupture typically is confined to a relatively narrow zone along a pre-existing fault trace (Cluff, 1968; Rogers, 1973; Slemmons, 1969; Swan, Schwartz, and Cluff, 1980; and Wallace, 1968).

The evaluation of a given site with regard to the potential hazard of surface fault rupture is based extensively on the concepts of recency and recurrence of faulting along existing faults. In a

general way, the more recent the faulting, the greater the probability for future faulting (Ziony, Wentworth, and Buchanan, 1973). In other words, faults that have had displacment in Holocene time are more likely to displace in the near future than faults whose last displacement occurred during the Eocene (58 to 36 million years before the present) and earlier.

In almost all known instances of historical faulting, surface displacements have occurred along a pre-existing fault that had previous displacement in Holocene time and could have been recognized by geologists prior to the faulting as a potential source of future activity (Cluff, Slemmons, and Waggoner, 1970). The geologic and historic record of fault activity shows that is is very likely that the displacement along a given fault will occur on or near the most recently active fault trace (Sherard, Cluff, and Allen, 1974; Wallace, 1968). For an engineering project or structure located across or in the vicinity of a fault, the primary consideration is the potential for recurrent movement on that fault within a time period that is significant to that project or structure. EPA has determined that faults that have had displacement during Holocene time are likely to experience recurrent movement at a frequency that is significant to hazardous waste facilities.

Non-compliance with the seismic location standard could result in the placement of a facility across a Holocene fault. These faults

have a high probability of displacement within the life of the facility, and therefore, such displacement could result in loss of life, damage to the environment, or both.

3.0 DEFINITIONS

Branch fault - A fault or fault trace that diverges from a main fault (see Figure 2).

Displacement* - The relative movement of any two sides of a fault measured in any direction.

Fault* - A fracture along which rocks on one side have been displaced with respect to those on the other side.

Fault trace - The line formed by the intersection of a fault and the ground surface or near-surface materials. The representation of a fault as depicted on a map.

Fault zone - A zone of related faults, which are commonly braided and parallel but may be branching and divergent.

Holocene* - The most recent epoch of the Quaternary period, extending from the end of the Pleistocene to the present. A geological epoch that represents about the last 11,000 years. In some parts of the United States the upper limits of the Holocene may range from 10,000 to 15,000 years ago. This definition also includes recent historic time of about the last 200 years.

Main fault - The fault with the greatest displacement, length, and continuity. Sometimes referred to as first, original, primary, or principal fault trace (see Figure 2).

Secondary fault - A fault that is completely separate spatially from the main fault. The displacement is generally of the same type as the main fault, but the amount of displacement is less (see Figure 2).

Surface faulting - Displacement or deformation at or near the ground surface caused by movement along a fault.

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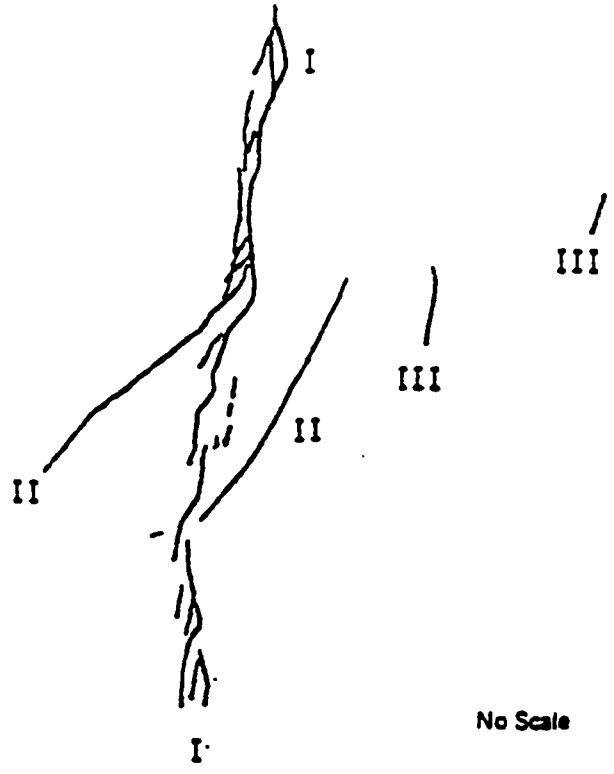
*These terms are also defined in the seismic location standard in Section 264.18(a).



SOURCE: Bonilla, 1967

I - Main

II - Branch

III - Secondary

FIGURE 2

TYPES OF SURFACE FAULTING.

4.0 DEMONSTRATING COMPLIANCE WITH THE SEISMIC LOCATION STANDARD

Compliance with the seismic location standard may be demonstrated using either published geologic data or data obtained from field investigations carried out by the permit applicant. The information submitted to EPA must demonstrate either that Holocene faults are not present within a 3,000-foot radius of the facility or that Holocene faults are not present within 200 feet of the facility. However, if Holocene faults are determined to be present within a 3,000-foot radius of the facility, the applicant must also demonstrate that Holocene faults are not present within 200 feet of the facility.

Part 122 [40 CFR 122.25(a)(11)] specifies that the 3,000-foot demonstration must be based on information obtained from published geologic studies, aerial reconnaissance within a five-mile radius of the facility, analysis of aerial photographs for an area within a 3,000-foot radius of the facility, and if necessary to make the demonstration, a reconnaissance based on walking portions of the area within 3,000 feet of the facility. The 200-foot demonstration must be based on data from a comprehensive geologic analysis of the site and, if necessary to make the demonstration, a subsurface exploration (See 46 FR 2889).

General guidance can be given as to when it would be more efficient to conduct a 200-foot study rather than a 3,000-foot

study. In the following instances it is generally advisable to do a 200-foot study:

(1) If reliable data indicate that active faults are located near the site

(2) If the age of surface materials at the site demonstrates that the site (and the area within a 200-foot radius of those portions of the facility where hazardous waste will be treated, stored, or disposed of) is underlain by unfaulted materials older than Holocene age.

Because EPA's intent in the Part 122 language is not always clear, the Agency hopes that the bulleted information produced here will help in that regard.

- The sequential listing of investigative methods in Section 122.25(a)(11)(i)(A) is not meant to imply that the permit applicant must obtain data using each method listed. Rather, only those investigative methods that will provide needed information should be used. The Agency certainly does not want the applicant to repeat geological studies that have already been performed in the area. To this end, it is always advisable to review and analyze all geological information that is available for the area before proceeding to conduct new geologic studies.

- If an aerial reconnaissance or analysis of aerial photographs will not yield pertinent information because the geology of an area is obscured by development or forestation, then such areas should not be studied using those methods.

- The last sentence under Section 122.25(a)(11)(i)(B), "Such investigation shall document with supporting maps and other analysis, the location of any faults found," is also meant to apply to investigations carried out under 122.25(a)(11)(i)(A).

- In Section 122.25(a)(11)(i)(B), the 200-foot study is based on data from a "comprehensive geologic analysis of the site". EPA intended for this comprehensive geologic analysis to include, at a minimum, a review of available geological information for a distance of 3,000 feet from the facility and a ground geological reconnaissance for the same

distance. If this information or any additional information that the applicant provides is not sufficient to conclude that it is extremely unlikely that Holocene faults exist within 200 feet of the facility, some type of subsurface exploration will have to be conducted.

Because of the potential complexity of the required demonstration, Regional Offices that are responsible for political jurisdictions listed in Appendix VI to Part 264 and owners and operators of new facilities that are proposed to be located in these jurisdictions should consider seeking the help of a geologic consultant experienced in identifying and evaluating fault activity.

In summary, Part B of the RCRA permit application should contain documentation, by a qualified geologist, that portions of the facility where treatment, storage, or disposal of hazardous waste will be conducted will not be located within 200 feet of a Holocene fault. The documentation should be appropriate for the site and the tectonic environment and should be of such quality as to be acceptable to geologists experienced in identifying and evaluating fault activity.

The remainder of this section contains a discussion of the methods and tools for conducting geological investigations and the information that should be included in Part B of the RCRA permit application.

4.1 Methods and Tools of Geologic Investigations

The methods and tools for conducting both the 3,000-foot and 200-foot geologic investigations include a review of published data, aerial reconnaissance, interpretation of aerial photographs, ground reconnaissance, and subsurface investigations. These tools are used to iden[illegible] faults and lineations (linear features that suggest the presence of a fault) that may be associated with Holocene fault displacement and to determine if such faults have had displacement in Holocene time.

4.1.1 Review of Existing Data

The review of existing data is directed toward obtaining geologic and seismic information about the areas surrounding the facility. Any available information on the area's geology, degree and recency of fault activity, and earthquakes for which recorded information exists should be reviewed to determine if any Holocene faults have been identified and to further identify any structural trends that may be related to faulting. Also, concentrations of earthquake activity, and historical accounts of major earthquakes and surface effects in the project area, may indicate the presence and location of faults.

Published information on the location of faults near the site and the recency of their activity may exist. Because fault-related studies of a particular site will not exist in many cases, geological information will usually have to be reviewed for a larger area.

The purpose of reviewing existing data is to determine what is currently known about the geology of the area surrounding the facility. After this knowledge has been gained, one can determine if some type of field investigation (e.g., aerial reconnaissance, ground reconnaissance, borings) must be conducted to demonstrate compliance with the seismic location standard.

Before new field studies are conducted, it is advisable for the permit applicant to inform the appropriate permitting official of his plans for the study. Potential problems may surface at this stage and can be worked out before time and money are spent on field studies that may be inadequate.

The United States Geological Survey (USGS) and the geological surveys of the individual states are good sources of information concerning geology, faults, and historic earthquakes. The USGS operates nine Public Inquiries Offices, listed in Table 2, to provide Federal and state agencies and the general public with convenient access to information about Survey activities and products. Over-the-counter and mail order sales include topographic, geologic, and hydrologic maps and book reports relating to the geographic area of each office. Offices provide question-answering, interpretive, and referral services. Other sources include local offices of the Soil Conservation Service of the U.S. Department of Agriculture, local colleges and universities, county and city building departments

TABLE 2

PUBLIC INQUIRIES OFFICES OF THE
U.S. GEOLOGICAL SURVEY

108 Skyline Building
508 Second Avenue
Anchorage, Alaska 99501
(907) 277-0577
FTS 399-0150 (Seattle number - ask for Anchorage number)

7638 Federal Building
300 North Los Angeles Street
Los Angeles, California 90012
(213) 688-2850
FTS 798-2850

504 Customhouse
555 Battery Street
San Francisco, California 94111
(415) 556-5627
FTS 556-5627

1012 Federal Building
1961 Stout Street
Denver, Colorado 80202
(303) 837-4169
FTS 327-4169

1028 General Services
Administration Building
19th and F Streets, N.W.
Washington, D.C. 20244
(202) 343-8073
FTS 343-8073

1045 Federal Building
1100 Commerce Street
Dallas, Texas 75202
(214) 749-3230
FTS 749-3230

8102 Federal Building
125 South State Street
Salt Lake City, Utah 84138
(801) 524-5652
FTS 749-5652

302 National Center
Room 16402
12201 Sunrise Valley Drive
Reston, Virginia 22092
(703) 860-6167
FTS 928-6167

678 U.S. Courthouse
West 920 Riverside Avenue
Spokane, Washington 99201
(509) 456-2524
FTS 439-2524

or public works departments, and consulting geologists. The references used during the study and the sources of data should be cited in Part B of the RCRA permit application to support information obtained that demonstrates compliance with the seismic location standard.

4.1.2 Analysis of Aerial Photographs

Studies of aerial photographs and other remote-sensing images are an essential part of fault investigations. However, aerial photographs may be of limited use in forested areas or in areas that were developed before the photographs were taken. In many cases, features of faults can be observed on aerial photographs that could not be readily identified during land-based studies. The traces of some faults can be easily and immediately identified. At the other extreme, the surface features of some faults seen on the aerial photographs may be so small and relatively insignificant that they can only be recognized as suspicious features by a geologist with considerable experience in studying faults and in aerial phtographic interpretation. There is a large element of experience and judgment in the interpretation of aerial photographs, particularly in the interpretation of Holocene fault activity.

Until the past few years, ordinary black-and-white photographs have been used for aerial photography. Much of the world has been photographed at scales of 1:30,000 to 1:60,000. These photographs

are especially good for preliminary regional investigations and should be obtained if possible, because a large area is covered by few photographs. For more detailed studies, scales of 1:12,000 to 1:20,000 are preferable. For stereoscopic viewing, which is absolutely necessary, 60 percent overlap and 30 percent sidelap ar standard practice. The ability to interpret the photographs is somewhat dependent on the quality of the photography, but it is, t a larger degree, dependent on the quality of the printing.

Aerial photographs not taken specifically for fault studies a usually taken during midday. Starting in 1967, a research prograr was carried out jointly by the University of Nevada Department of Geology-Geography and Woodward-Lundgren & Associates; in this prog um new photographic techniques were developed for the specific purpos of studying active faults. A recent procedure of low-sun-angle aerial photography utilizes photographs taken at different times c the day, and sometimes in different seasons of the year, depending on the fault trend and the azimuth of the sunlight (Cluff and Brograr 1974). The purpose of the photography is to enhance shadows from subdued ground-surface irregularities. The optimum light conditic is obtained when the sun is shining nearly perpendicular to the tr id of the fault, in the direction from the uphill side of the fault scarp toward the downhill side, at an angle slightly lower than th average slope of the scarp (usually 10° to 25°). The most

universally useful scale is about 1:12,000, with scales of 1:6,000 and 1:3,000 good for detailed analyses. While it is desirable to repeat the photography in both the early morning and late afternoon, experience has shown that photographs taken either in the early morning or late afternoon pick up most of the detail that can be obtained by flying at both times (Cluff and Brogan, 1974). Other types of images that are helpful include infrared and color images, photographs from satellites, and high-altitude aircraft photographs.

In summary, the following points may be made:

- The most useful type of photograph is the black-and-white, low-sun-angle, vertical aerial photograph.
- When photographs are taken for the purpose of a fault study, color photographs are superior to black-and-white photographs taken at midday, but not to low-sun-angle black-and-white aerial photographs.
- The infrared photograph occasionally gives a better indication of differences in ground-water level or vegetation contrasts on the opposite sides of a fault, but low-sun-angle photographs appear to be better for evaluating fault activity.
- Satellite and high-altitude aircraft images can be useful for identifying structures that need careful evaluation using low-sun-angle photography or field studies.

Documentation of analysis of aerial photographs should include sources of photographs, photograph numbers, data photographs were taken, type of photographs, and either copies of photographs or plastic overlays on which analysis is made. Aerial photographs can generally be obtained from local aerial photographic companies, the

Agricultural Stabilization and Conservation Service, Soil Conservation Service, or U.S. Geological Survey.

4.1.3 Aerial Reconnaissance

Aerial reconnaissance can be used to identify geomorphic fault features that are not readily identifiable on the ground. Of course, use of this method is limited by the degree that the subject area is forested or developed. Faults may appear visually as lineations or linear alignments of features resulting from various physical conditions created by faulting, such as disruption of the normal ground surface along the traces of previous fault breaks; different soils, rock types, and vegetation on opposite sides of the fault; and displaced topographic features. These features include scarps, offset drainage channels, saddles, sag ponds, ponded alluvium, closed depressions, and shutter ridges or parallel ridges. The geomorphic features of fault zones are discussed in Appendix B of this document and are well described by Slemmons (1977).

Aerial reconnaissance is best done in a high-winged aircraft when the visibility is good. Early morning or late afternoon flights are generally better than midday flights because shadows enhance subdued ground-surface irregularities along fault zones. The flight lines should consist of two different orientations: one perpendicular to the geologic structures and the other one parallel to the geologic structures. In most cases it is best to have two

observers, one on each side of the aircraft, in order to take advantage of the difference in lighting conditions. The observers should have previous experience in identifying fault-related features from aircraft. Documentation of aerial reconnaissance should include the name of the flying service, the date of the flight, the type of aircraft, observations outlined on a topographic map, and 35mm slides of flight observations.

4.1.4 Ground Geologic Reconnaissance

A ground geologic reconnaissance is made to observe geological and geomorphic features that may be associated with faults, especially Holocene faults. If a fault has been active recently, geomorphic evidence will be expressed at a few locations along its length. Therefore, more confidence in conclusions drawn from a ground reconnaissance can be obtained by extending the reconnaissance beyond the site (i.e., out to 3,000 feet from the facility), examining locations of known faults in the area for type of faulting and evidence of activity, examining lineations or suspicious features identified during the aerial reconnaissance or on aerial photographs, and describing any stratigraphic evidence that would demonstrate a lack of Holocene fault activity in the vicinity of the site. Ground reconnaissance should be documented by showing observations on a topographic map or photo overlay and by providing 35mm slides of observations and an original geologic map.

4.1.5 Subsurface Exploration

The purpose of subsurface exploration is to demonstrate (1) the presence or absence of faults within 200 feet of portions of the facility where treatment, storage, or disposal of hazardous waste will be conducted and (2) to determine whether any of these faults have had displacement in Holocene time or at some older time period. Subsurface exploration may consist of:

- Trenching and other extensive excavations to permit detailed and direct subsurface observations
- Borings and test pits to permit collection of data at specific locations and depths
- Geophysical investigations of subsurface conditions

Geophysical methods are indirect methods to measure variations and anomalies in subsurface strata. These variations and anomalies may or may not be faults. Therefore, they require specific knowledge of subsurface conditions for reliable interpretation. Geophysical methods alone do not prove the absence of a fault nor the recency of fault activity.

The purpose of a geophysical investigation is to detect and locate subsurface geological structures or masses. During the investigation, measurements of variations in subsurface properties are obtained. These data are analyzed to surmise the causes of the variations. Geophysical methods used for fault studies may include seismic refraction, seismic reflection, magnetism, resistivity, or

gravity. These methods are described in standard textbooks on applied geophysics.

Exploratory excavations are the most positive and detailed method to establish the location and activity of faults on a given site. The exploratory excavation is commonly made by a backhoe, a dozer, or some other means of exposing the subsurface materials. Selection of the excavation equipment depends upon accessbility, depth of excavation, difficulty of excavation, cost, length of time the excavation is to remain open, and the environmental impact of the excavation.

The purpose of the excavation is to expose the subsurface materials to a depth sufficient to enable geologists to make a detailed inspection and evaluation of the excavation walls to determine if there are any fault features. In order to ensure that the maximum amount of information is obtained from each excavation, the following procedures are necessary:

- The excavation should be perpendicular to the trend of known faults, lineations, or suspicious features since faults generally occur parallel to other faults. Thus, maximum coverage can be obtained by perpendicular trenches.

- The excavation should be at least 10 to 20 feet deep. It is necessary to excavate the trench below the depth influenced by man-made activities and soil processes and to locate materials that will show fault offset. Generally, at these depths, the strata are older and will show any fault offset. These strata also aid in determining the recency of fault activity.

- The excavation must be constructed with worker safety in mind; it must comply with local, state, and Federal

requirements for safety and permits. For instance, it may be required that the excavation be shored or walls layed back.

- The trench should be inspected and logged (see Figure 3) by individuals experienced in logging fault features in test trenches. Since some of the significant fault features are difficult to recognize, experience is invaluable.

- Sufficient time should be allowed to inspect and log the excavation. Once the excavation is backfilled, the excavation log is the only evidence available. Therefore, it is very important that the log reflect the actual conditions observed in the excavation. The graphic log should show scale, the length and depth of the trench, the contacts between various subsurface materials, representative strike and dip of bedding or joints, faults and shears, lithology, and continuous unfaulted material within the lenth of the trench. See Figure 3, Taylor and Cluff (1973), and Slemmons (1977) for examples of trench logs.

- The excavation, or series of excavations, should extend to a distance on either side of the fault and the proposed structure to identify and parallel fault planes. Generally more than one excavation should be made across a fault or suspected fault to conclusively determine its location and relative activity. The number of trenches will depend on size of the facility (small-large), tectonic environment (active-inactive), style of faulting (strike-slip, normal, or reverse), type of surface materials (Rock-Holocene materials), and results of initial trenching (simple-complex). One trench might be sufficient for a small site with a simple, narrow, well-defined fault in the subsurface; well-recognized surface features; and continuous Holocene deposits. At least two trenches should be used at large sites; sites with no evidence of subsurface faulting, but surface lineations or Holocene faults within 300 feet; a wide or complex fault pattern; a fault that changes width, direction, or pattern; or thrust or normal type faults. Three, four, or more trenches may be needed to adequately locate a fault zone across a site, show that the site is unfaulted, and show that any faults that cross the site have not had Holocene displacement.

The logging of exploratory excavations and the observations of "active" faults in test trenches is discussed by Taylor and Cluff (1973).

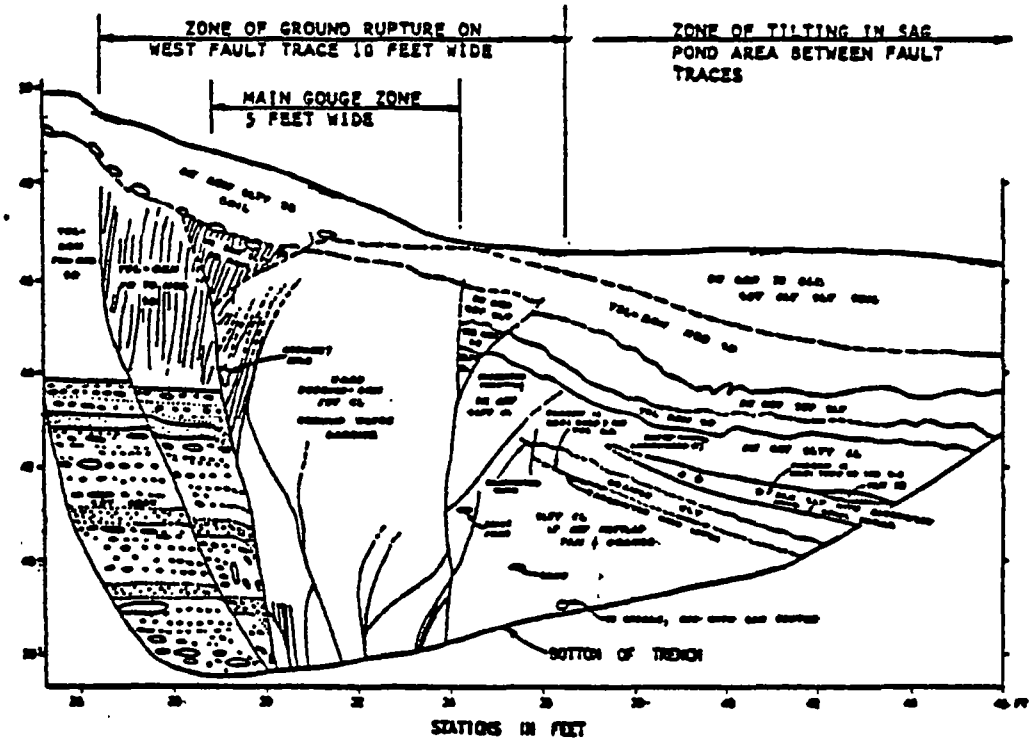


FIGURE 3

LOG OF AN EXPLORATORY EXCAVATION
ACROSS THE ACTIVE HAYWARD FAULT

Exploratory trenches have been used with increased frequency for fault investigations. These trenches provide a better view of the nature of the fault than can be obtained from a study of the ground surface. The trenches allow examination of surface soils above a fault and can provide an opportunity to assess the relative movement.

4.2 Information in Part B of the RCRA Permit

The results of the geologic study should be presented in a report signed by the geologist(s) responsible for the study, and the contents should be of a quality acceptable to a geologist experienced in identifying and evaluating faults. Contents of the report should include, but not be limited to, the following:

- Location and map of study area
- Sources of available data
- List of key scientists/engineers conducting study
- Description of geologic setting and site conditions
- Investigative methods and approaches
- Aerial photographs or remote sensing images interpreted (type, scale, source, index number)
- Logs of subsurface exploration (showing details, not diagrammatic), if appropriate
- Geologic site map with exploration locations (1" = 200 feet, for example), if appropriate
- Regional geology map (1" = 2000 feet, for example)
- Results, conclusions, and basis of findings
- References cited

- Signature of geologist(s) responsible for conducting the study.

Each step of the study will need to be documented for the permit writer. The above contents provide an outline of that documentation.

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APPENDIX A - GENERAL DISCUSSION OF EARTHQUAKES AND FAULTING

CAUSES OF EARTHQUAKES

There is no one cause of all earthquakes. A minor cause of earthquakes is volcanic activity. Some deeper earthquakes may perhaps be related to sudden changes in rock properties due to motion deep within the Earth's mantle. However, most destructive. shallow-focus earthquakes appear to be associated with a sudden rupturing (faulting) of the Earth's crust[1]. The resulting earthquakes are caused by the sudden release of accumulative strain energy. The rupture, or break, is called a fault and is generally accompanied by displacement of blocks either vertically or horizontally or both on opposite sides of the fracture.

The seismic waves that are generated when the fault ruptures arise from the movement of the rocks in the vicinity of the fault.

SIZE OF EARTHQUAKES

Two measures of earthquakes size, intensity and magnitude, have been found to be useful. Unfortunately, these terms are often confused and sometimes even used synonymously. Magnitude attaches a single number that is independent of the distance from the earthquake center and independent of geological and soil conditions to an earthquake. For a measure of the variation of ground motion from

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[1]The crust is a rock layer of varying thickness, ranging from 30 miles under the continents to 3 miles under the oceans, which is found world-wide and is composed of mainly basaltic and granitic rocks.

point to point, an intensity scale is used. The intensity value is assigned by an experienced observer using a descriptive scale. Both measures are too simple to describe the full complexity of an earthquake and should be used judiciously.

Intensity Scales

Intensity is a rating of the severity of the ground motion at a specific location. The scale of measurement is based upon the sensations of persons, the behavior of natural objects, and the physical damage to natural and man-made objects. Intensity scales came into being long before magnitude scales because intensity does not require instrumental observation. Over the years, different intensity scales have been devised. The scale must reflect the geologic setting of a particular region. The most widely accepted intensity scale in the United States is the Modified Mercalli Intensity Scale. It goes from I to XII on a twelve-point scale.

Intensity ratings are bound to be subjective, as reported intensities may take on several meanings, depending on who reports them and the type of construction in an area. The reported intensity may be the maximum intensity at the built-up area nearest the epicenter, or it may be what that intensity should have been at the epicenter based on observations at a center of population some distance away. Many circumstances arise that make it difficult to assign intensities. The lack of precision in the intensity index

should be recognized. Basically, intensity refers to the measures of earthquake effects of all types at a specified place. It is not based on true measurement, but it is a rating assigned by an experienced observer using a descriptive scale.

Because intensity is defined by the observed effects on the Earth's surface, such as landslides or broken underground pipes, the intensity of an earthquake on a mid-oceanic ridge might be taken as zero. On the other hand, a smaller shock centered near weak man-made structures on poor ground might yield a high intensity. For a given earthquake, intensity differs between localities depending upon the distance from the source, the severity of the shaking, the duration of the shaking, the geologic foundation, and the quality of design and construction.

Magnitude Scales

Magnitude is based on ground motion as recorded by distant seismographs. The most commonly used method of calculating magnitude in the United States for moderate to large earthquakes is that of C.F. Richter. Other magnitude scales are, however, widely used by seismologists, both in the United States and in other countries, sometimes leading to what appear to be conflicting magnitudes. To briefly illustrate the technique used to calculate a magnitude for an earthquake consider the following case. A particular kind of seismograph (called a Wood-Anderson instrument) at a distance of

about 62 miles (100 kilometers) from the epicenter records the earthquake ground motion. The recording is called a seismogram. Using a ruler with a centimeter scale, the half-width ("amplitude") of the largest wave is measured and coverted to microns (10^4 microns = 1 cm). The logarithm (to base 10) of this number is the Richter magnitude of the earthquake. For example, if the maximum aplitude measured is 1 cm, the Richter magnitude is 4.0. Empirical tables provide the necessary adjustment when the seismograph is at various epicentral distances, when other types of seismographs are used, for various focal depths, and for various types of waves.

EARTHQUAKE-ASSOCIATED DAMAGE

Earthquake damage depends on many variables: earthquake magnitude, epicentral location, depth of focus, duration of shaking, intensity of shaking, near-surface soil and geologic conditions, structural type, and design. Damage related to ground (or soil) conditions depends upon subsurface properties such as material density, shear strength, thickness, and water level.

Earthquake-associated damage is usually manifest in three separate forms: (1) fault displacement, (2) strong ground motion (shaking), and (3) ground (or soil) failure.

FAULTING

Faulting, as the movement or fracturing along faults is called, may have horizontal and vertical components of displacement and may

vary from a fraction of an inch to many feet. In the California earthquake of April 18, 1906, horizontal offsets along the San Andreas fault averaged from 8 to 15 feet and extended from just north of San Juan Batista to north of Point Arena, a distance of more than 200 miles.

Fracturing and shearing associated with faulting are often observed in the field to be of a multiple and en echelon character, with several planes of displacment being formed through geologic time (millions of years); thus the term "fault zone" is a more realistic designation. The exact location and characteristics of a fault zone are of vital concern in estimating the hazard from faulting. Once a fault is formed, it constitutes a plane of weakness that localizes further adjustments.

Some fault zones, such as the San Andreas fault, are more than a mile wide in places, containing many "fault traces" within the broad zone. On might ask, "What is the relative risk of developing or locating structures within such a wide active fault zone?" It depends upon factors such as type of development, intended land use, type of structure, and site location with respect to the active fault traces. The broad fault zones have been formed over long periods of geologic time, and in some future geologic time (millions of years) not only may the present fault traces be reactivated, but new traces may be formed. However, if we consider this problem from the

standpoint of "engineering design time" (on the order of 100 years), the probability of fault movement is much high along the more recently active fault traces that lie within the broad fault zone.

Types of Surface Faulting

Surface faulting can generally be divided into three types (Bonilla, 1967): main fault, branch fault, and secondary fault as shown on Figure 2 (text). The main fault is actually a band of varying width, which includes closely spaced faults that are the location of the major surface displacement and associated faults that decrease rapidly in number and amount of displacement away from the location of major fault displacement. The main fault trace is the surface fault with the greatest displacement, length, and continuity. The main fault trace generally receives the greatest consideration because the amount of fault displacement and the width of the band of faulting are greater than with the other two categories of faulting.

A branch fault generally originates as part of a main fault, but laterally it diverges from and extends well beyond the main zone of faulting. The branch fault generally shows the same type of displacement as the main fault and either joins it at the surface or is inferred to join in the subsurface. While branch faults may form during surface faulting and may be found associated with the main fault at several locations along its length, branch faults do not

exist along a major part of the main fault's length nor do they result in a continuous zone of faulting from the main fault trace out to the branch fault trace.

Secondary faults are completely separated spatially from the main fault trace and from the branch fault trace. Secondary faults occur infrequently and generally consume a very small percentage of the total fault length.

When considering the potential for future surface faulting, it is important to remember that a continuous band of faulting is likely along the main fault trace; branch faults may occur adjacent to the main faulting but only along a small percentage (about 20 percent) of the total fault length and the width of faulting is generally smaller; and secondary faulting is a relatively rare event along a very small percentage of the total fault length (about 5 percent), and the amount and width of faulting is generally much smaller. Even in those cases where the surface faulting consists of a main fault, branch faults, and secondary fauls, this does not represent a continuous zone of faulting, but a zone in which the three types of faulting occur as restricted bands of varying width with considerable unfaulted material in between the bands as shown in Figure 2 (text). The important consideration is not the distinction between the types of faulting (main fault, branch fault, or secondary fault) nor the width in which these categories of faulting may occur, but the actual

width of the fault zone adjacent to a proposed structure and, more specifically, the distance between the structure and any fault.

Width of Surface Faulting and Deformation

Surface fault rupture along a fault trace may be accompanied by displacement along the individual faults and by horizontal or vertical deformation (distortion or warping) of the ground surface extending from some distance on either side of the fault trace. The occurrence and the amount of deformation depend upon the type of faulting, the amount of fault displacement, and the properties (strength, type, and depth) of materials at specific sites along a fault trace.

On the basis of statistical analysis of historical earthquakes, Bonilla (1970), reports that at least half of the historical faulting events in North America include subsidiary faulting (i.e., branch and/or secondary faulting). If one were to take the historical faulting data presented by Bonilla (1970) at face value, it could be inferred that the main zone of faulting could be up to 917 meters (3,000 feet) wide; the zone of branch faulting could be up to 4.8 kilometers (3 miles) wide, and the zone of secondary faulting could be up to 14.5 (9 miles) wide—all measured from the center line of the faulting. However, these data refer to the composite zone in which these different categories of faulting occur and not to a continuous zone of faulting along the entire length of the surface

faulting. Such an interpretation of these data gives an erroneous and overly pessimistic view of the potential width of surface faulting and, therefore, the impact upon adjacent structures. Based on a review of historical earthquakes and reported surface faulting, reconnaissance and interpretation of aerial photographs along faults that have had displacement within historic times, and review and examination of test trenches excavated across faults that have had displacement during historic times, it is concluded that the width of faulting and associated ground deformation generally ranges from several feet to as much as several hundred feet (Taylor and Cluff, 1977).

Taylor and Cluff (1978) reviewed fourteen cases of documented deformation associated with the 1906 faulting along the San Andreas fault (a strike-slip fault) near San Francisco, California. From those data it was concluded that the width of the faulting and deformation ranges from 3 meters (10 feet) to 211 meters (690 feet), including 3 cases (21%) having a width greater than 61 meters (200 feet), 3 cases (21%) having a width between 30.5 and 61 meters (100 to 200 feet), and 8 cases (58%) with a width less than 30.5 meters (100 feet). It was also concluded that at distances greater than about 61 meters (200 feet) the deformation is generally insignificant. It is very important to emphasize that the deformations were associated with a fault that had displacements

ranging from 12 to 20 feet horizontally, and the width of faulting and deformation would be less for surface faulting events with displacements of lesser amounts.

A recent study at two sites along the Wasatch fault in Utah (a normal fault with vertical displacement) by Swan, Schwartz, and Cluff (1980) reports that: (1) the fault has had accumulative vertical displacement on the order of 10 to 13.5 meters (33 to 44 feet) during about the last 12,000 to 13,000 years (within Holocene time), (2) the width of faulting is about 68 meters (222 feet), and (3) the width of deformation is about 120 meters (392 feet), i.e., it extends about 52 meters (170 feet) beyond the limits of faulting.

Based on exploratory excavations across Holocene faults, the following general comments are made by Taylor and Cluff (1977):

- "Surface faulting is generally confined to narrow fault-traces in a wider zone of disturbance. The width of the fault-traces can range from a few feet to several tens of feet and is dependent on the type of faulting, amount of faulting, and geometry of the fault plane. Many times the major surface faulting and fault displacement occur along a single fault-trace which is referred to as the main fault-trace."

- "The zone of disturbance can have a width of from a few feet up to more than 50 feet and frequently has a width of several hundred feet. This zone of disturbance includes the individual fault-traces (or main fault-trace) and auxilliary or secondary cracks branching obliquely from or lying parallel to the fault-traces."

- "Surface deformation and distortion of structures is frequently reported within a zone several tens to several hundreds of feet wide adjacent to the surface faulting and within the zone of disturbance."

- "The geologic and historic record of fault activity demonstrates that the location of future surface faulting will most likely occur on or near the most recently active fault-trace."

- "For an engineering project or structure located across or in the vicinity of a fault, the primary consideration is the possibility of recurrent movement on that fault within a time period which is considered significant to that project or structure."

A review of the above data will show that while the width of surface faulting and deformation may in some cases be several thousand feet wide, it generally ranges from a few feet to several hundred feet. However, the major consideration should not be the width of the zone of faulting but the distance from the fault that has had Holocene displacement.

Strong Ground Motion (Shaking)

Damage from strong ground motion (shaking) is caused by the transmission of earthquake vibrations from the ground into the structure. The main variable factors that determine the extent of vibrational damage are: characteristics of ground, design of structure, quality of materials and construction, and intensity and duration of shaking. During moderate to large earthquakes, it is the strong shaking that usually inflicts the most damage to man-made structures.

Damage from Ground Failure

Damage from ground failure may occur in several different forms, such as landsliding, liquefaction, lurching, settlement, and seismically induced flooding.

It is common for earthquake-triggered landslides to occur as renewed movements of old landslide deposits. Areas subject to slope instability could be subject to earthquake-triggered landslides.

Liquefaction occurs when granular, essentially cohesionless soils undergo loss of shear strength due to the buildup of fluid pressures in the soil pore water (caused by cyclic loading during earthquakes). When the loss in strength is low to moderate, partial liquefaction may cause ground settlement and associated ground cracking. However, when liquefaction is complete, the soil can behave as a fluid, and catastrophic failures, including soil flows and landslides, have occurred as a result. Partial liquefaction during strong ground shaking may occur in dense to very dense cohesionless soils; complete liquefaction typically occurs only in loose to medium dense cohesionless soils.

Seismic settlement is also associated with cohesionless soil deposits in poorly placed or uncompacted man-made fill. The strong ground shaking that occurs during earthquakes will densify loose granular soils. When these soils are above the groundwater table, their densification and resulting ground subsidence will occur rapidly. When located below the groundwater table, the pore water pressures that have developed during the shaking must begin to dissipate before a decrease in soil volume can occur and, as a result, settlement occurs at a rate commensurate with the flow of water from the cohesionless soil layer.

Lurching may be generally defined as the development of all types and sizes of irregular ground fractures, cracks, and fissures associated with shaking, settling, and the passage of surface waves during earthquakes. In this general sense, ground cracks that occur as a result of liquefaction, compaction, settlement, or landsliding may be termed "lurch cracks". More specifically, lurching involves the seismically induced lateral movement and spreading of ground toward a "free face," together with the development of associated tension cracks in the ground behind the free face.

APPENDIX B - FAULTING AND GEOMORPHIC FEATURES OF FAULT ZONES

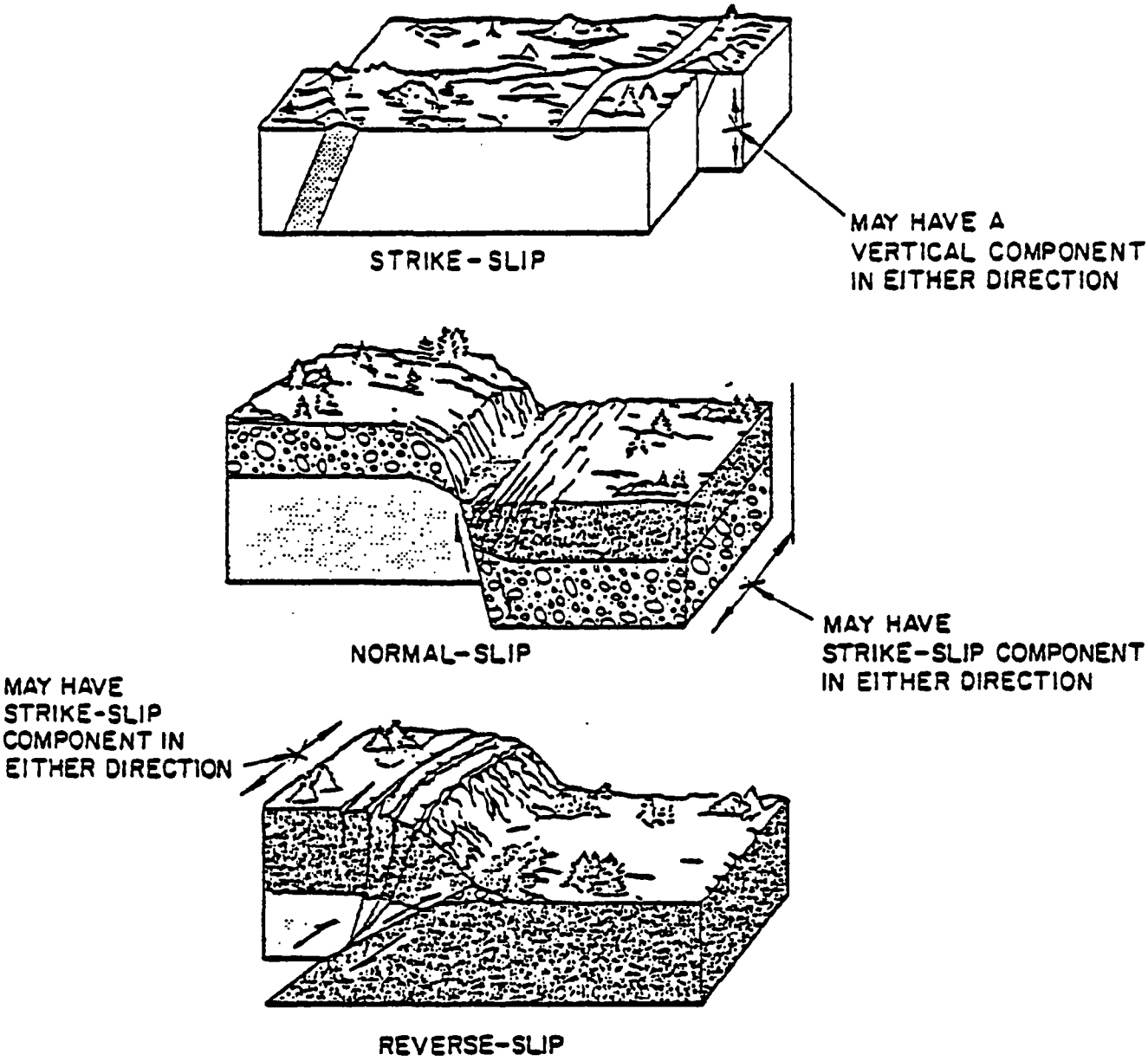
The three main types of faults considered within this discussion are strike-slip, normal-slip, and reverse-slip faults. Each of these three types of faults is characterized by a distinctive type of movement and geometry. A discussion of these fault types follows.

Strike-Slip Fault

A strike-slip fault (Figure 4) is one in which displacements are essentially parallel to the strike of the fault; the movement is primarily in a horizontal direction with little vertical displacement. The fault planes on strike-slip faults are most often nearly vertical. Strike-slip faults are of two types: right-lateral and left-lateral. In a right-lateral fault the displacement is such that, in plan view, the side opposite the observer appears displaced to the right. In a left-lateral fault this displacement appears to the left. Strike-slip faults are common in an environment subject to compression of blocks or plates. Depending on their orientations, structures across or in the vicinity of a strike-slip fault can be subject to compression, extension, displacement, or distortion.

Normal-Slip Faults

A normal-slip fault (Figure 4) is one in which one side has moved downward relative to the other side. The movements may involve vertical components only or combinations of vertical and horizontal displacements. The angle of the fault plane in normal-slip faults is



SOURCE: Taylor and Cluff, 1977

FIGURE 4

THREE TYPES OF FAULT DISPLACEMENT

generally 45° to 90°, and these types of faults generally form in a tensional environment characterized by a lengthening of the earth's crust. The zone of faulting is more pronounced and wider on the downthrown (lower) side, although the fault displacement and slope instability appear more dramatic on the upper side about the steep fault scarp.

Reverse-Slip Faults

A reverse-slip fault (Figure 4) is one in which the upper block appears to have moved upward relative to the lower block. As in normal-slip faults, the movement of reverse-slip faults may involve vertical components only or a combination of both vertical and horizontal displacements. The fault plane of reverse-slip faults dips at an angle of 45° and less and generally forms in a compressionable environment characterized by a shortening of the crust.

Of primary importance in the identification, characterization of length and type of movement, and assessment of future rupture patterns in active fault zones is the study of fault-related geomorphic features expressed at the earth's surface (Slemmons, 1977). Each of the three fault types discussed above exhibits characteristic geomorphic features, with strike-slip faults exhibiting the simplest features and reverse-slip faults exhibiting the most complex. The morphology varies from small scale features to

large-scale geomorphic features that form the main topographic expression of the faulting. The following is a brief discussion of the main geomorphic features associated with each of the three fault types.

Landforms associated with strike-slip faults reflect the primarily lateral sliding of opposing blocks past one another, with branch faults and en echelon configurations common and characterizing the fault zone as an area of multiple blocks with complex lateral sliding relations. As opposing blocks slide laterally, some blocks are relatively depressed to form sags or sag ponds, or elongated graben may form between parallel breaks. Other slivers are raised, tilted, or slid diagonally to produce knolls and shutter ridges; elongated horsts may be uplifted between traces. Notches and trenches or troughs along the fault may reflect increased erosion of the crushed or broken rocks, or they may be primary features. The most prominent indicator of vertical movements and probably the most useful in terms of recency of movement is the presence of and freshness of scarps, which are often very long in extent; horizontal shifts are probably best displayed by offsetting of drainage channels and drainage related features. Typically, features associated with strike-slip faults are in alignment with one another and define lineations best observed from the air or in aerial photographs.

Surface expression of faulting associated with normal-slip faults is generally more complex than for strike-slip faults. In general, normal-slip faults have a large component of vertical displacement and develop steep, high scarps. Branch faults are common and tend to transfer displacement to more than one fault, and, in addition, the inclined nature of many of the fault planes provides the possibility of faulting and secondary failures in surficial materials. Subsidiary faulting or disturbances are often restricted to the downthrown block. Slemmons (1977) describes the following five features characteristic of normal faults:

- Simple Fault Scarps - Surface rupturing along a single break which extends to the earth's surface. The scarp in this type of break represents the main fault plane.

- Fault Fissure Scarps or Fissure Trace - Formation of a near vertical fissure at some distance back from the tip of the downthrown block, this fissure branching off the main fault plane. This type of break is more often formed in unconsolidated alluvial materials and the unstable nature of the unconsolidated surfical materials generally results in slumping into the fissure.

- Trench Trace Scarps or Graben Fault-Trace Scarps - These scarps result from the gravitational failure of slump blocks into the fault fissure described above. The slumps may occur on either side of the fault fissure.

- Longitudinal or Step Trace Scarps - These scarps result from one or more slump blocks on the uphill side of the fault fissures, resulting in a staircase arrangement.

- Subsidence Trace Faults or Scarps - This type of scarp normally forms where the fault fissure is filled by semi-plastic flow of materials instead of by slumping.

The geomorphic features of reverse-slip faults are generally more subtle and not as easily distinguished as strike-slip and normal-slip faults. In general, the lower dip angles of the fault plane result in less conspicuous, more irregular fault traces and scarps of complex patterns. Often, numerous branch faults cut to the surface from the main fault, resulting in complexly shattered surface displacements. The fault relations are further complicated and obscured due to the formation of large landslides and gravity slips in the upper block (Figure 4) as a result of the overthrusting. The lower block, in contrast, undergoes little distortion.

APPENDIX C - HOLOCENE DEPOSITS AND ACTIVE FAULTING

The Holocene is generally defined as an epoch of the Quaternary period extending from approximately 11,000 years ago to the present time. Holocene deposits are those formed within this time period, during which climatic and sea level conditions and geomorphic processes have been similar to or are ongoing with those now prevailing. Holocene deposits primarily form in such environments as floodplains; alluvial fans; coastal terraces; deltas in estuaries, reservoirs, or bays; and mudflats or marshland. Deposits can also form in relatively temporary depositional environments, such as in stream channels or on adjacent beaches, as well as in areas characterized by landsliding and landslide deposits.

Depending on such conditions as the physiographic and climatologic regime, the type and degree of weathering, the relative rates of erosion and deposition, and other factors, different areas of the U.S. are characterized by relatively extensive or scanty Holocene deposits. In areas where Holocene deposits are extensive, observation of physiographic features to identify faults and to assess the recency and types of movements is generally adequate. In areas where Holocene deposits are scanty or formed in very localized areas, fault-related features must be identified using older Quaternary or Pre-Quaternary deposits.