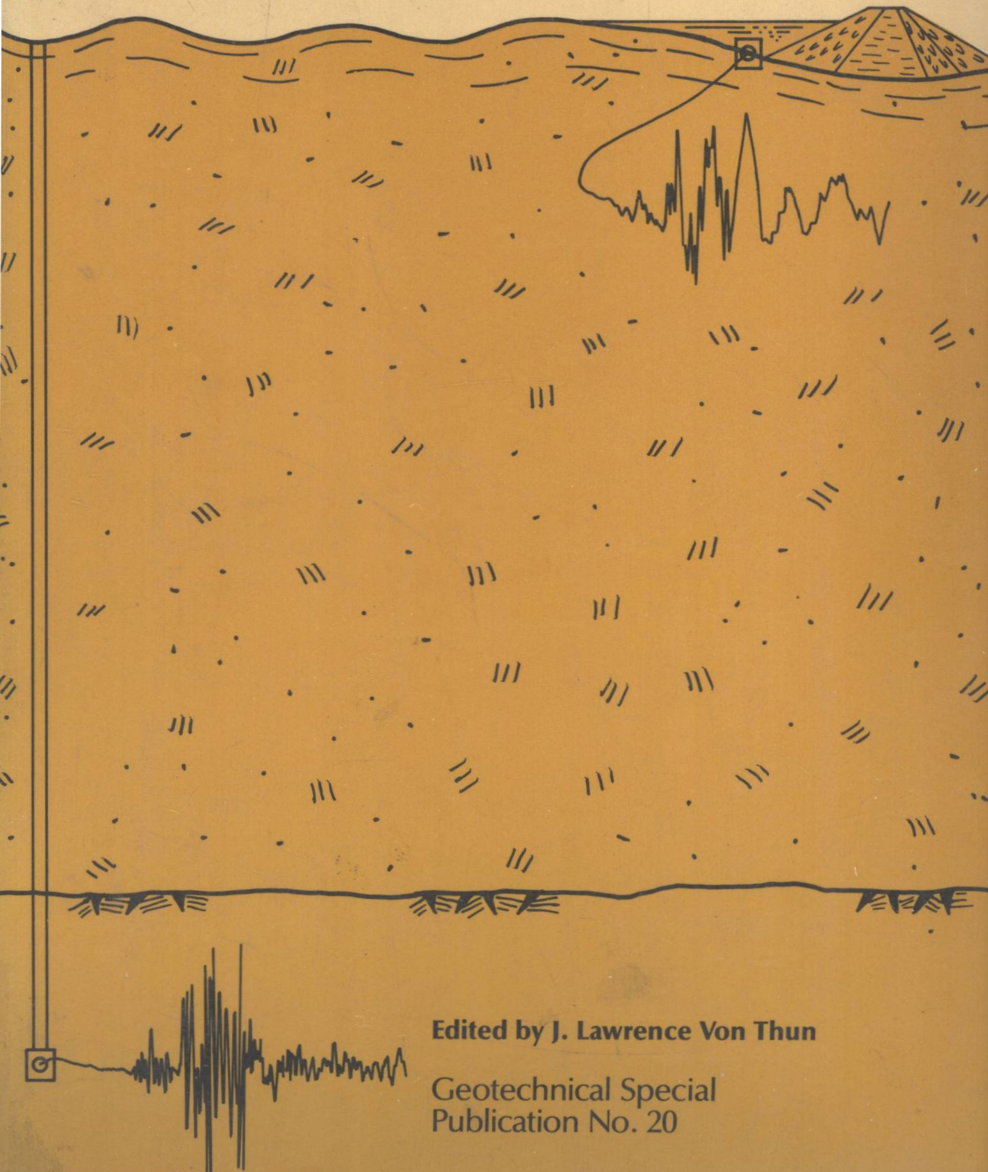
EARTHQUAKE ENGINEERING AND SOIL DYNAMICS II—

RECENT ADVANCES IN GROUND-MOTION EVALUATION



Edited by J. Lawrence Von Thun

Geotechnical Special
Publication No. 20

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RECENT ADVANCES IN GROUND-MOTION EVALUATION

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sponsored by the Geotechnical Engineering Division
of the American Society of Civil Engineers

in cooperation with the
Association of Engineering Geologists
Earthquake Engineering Research Institute
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ABSTRACT

Ground-motion determination for analysis and design of engineering structures is a shared, interdisciplinary task involving geologists, seismologists, geophysicists, geotechnical engineers, and earthquake engineers. Considerations in developing ground motions representing all of these disciplines are presented beginning with a current assessment of geologic and seismic hazard on an overall or regional scale and continuing with discussions on: local site effects measurement of strong ground motion, seismologic characterization of ground motion; determination of laboratory and in-situ properties to enhance analysis of ground-motion transmission; practical development of ground motion for structural analysis; and ending with an analysis of the effects of strong ground motion and large deformation.

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PREFACE

This publication contains the papers prepared for presentation, review, and discussion at the ASCE Geotechnical Division Specialty Conference held in Park City, Utah, from June 27 through June 30, 1988. The conference, titled Earthquake Engineering and Soil Dynamics II—Recent Advances in Ground Motion Evaluation, focused on all aspects of earthquake ground-motion specification for design and analysis of engineering structures. The topics spanned from regional geologic consideration, through transmission of motions from bedrock to the ground surface, to idealization of ground motions for design.

The publication contains five invited state-of-the-art papers covering five different aspects of ground-motion determination and 23 papers submitted by engineers, geophysicists, and seismologists through a call for papers.

It is the practice of the Geotechnical Engineering Division that each paper published in a Conference Proceedings undergo a peer review before being accepted. The standards for the peer review are essentially the same as those for papers being reviewed for possible publication in the ASCE *Journal of Geotechnical Engineering*. Each paper must receive two positive reviews to be accepted, and must be revised to conform to the mandatory revisions of the reviewers. But, because there is a tight schedule from receipt of papers through review and on to publication, there is not time for more than one cycle of editing and revising for Conference papers. All papers published in this volume are eligible for discussion in the ASCE Journal of Geotechnical Engineering and for ASCE awards.

One of the primary goals of the conference and of this publication was to bring together the various considerations of seismologists, geophysicists, and engineers in portraying ground motions. Hopefully, through this effort, engineers will be able to improve their understanding of earthquake source and ground-motion transmission processes, and seismologists and geophysicists will be able to better understand the engineer's methods and needs in developing representative ground motions for design and analysis.

J. Lawrence Von Thun
Editor

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*State-of-the-Art Report

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GEOLOGIC CHARACTERIZATION OF SEISMIC SOURCES: MOVING INTO THE 1990s

DAVID P. SCHWARTZ*

INTRODUCTION

As a geologist who spends much of his field time in 3- to 4-m-deep trenches excavated across major active faults like the San Andreas and Wasatch, questions of when?, where?, and how large? are never far from mind. The ability to answer these, whether estimating the time of the next earthquake, a maximum earthquake magnitude, the amount of potential surface displacement on an active fault, or the probability of exceeding a particular level of ground motion, rests on our ability to correctly characterize a seismic source. Seismic source characterization is the quantification of the size(s) of earthquakes that a fault can produce and the distribution of these earthquakes in space and time. As such, source characterization provides the basis for evaluating the long-term seismic potential at particular sites of interest.

In the late 1960s and early 1970s, largely in response to expansion of nuclear power plant siting and the issuance of a code of federal regulations by the Nuclear Regulatory Commission referred to as Appendix A, 10CFR100, the need to characterize the earthquake potential of individual faults for seismic design took on greater importance. Appendix A established deterministic procedures for assessing the seismic hazard at nuclear power plant sites. Bonilla and Buchanan (1970), using data from historical surface-faulting earthquakes, developed a set of statistical correlations relating earthquake magnitude to surface rupture length and to surface displacement. These relationships, which have been refined and updated (Slemmons, 1977; Bonilla *et al.*, 1984), along with the relationship between fault area and magnitude (Wyss, 1979), and seismic moment and moment magnitude (Hanks and Kanamori, 1979), have served as the basis for selecting maximum earthquakes in a wide variety of design situations (Schwartz *et al.*, 1984). A related concept that developed at about the same time and that has also seen widespread use is the idea that a seismic source can produce two types of earthquakes, a "maximum credible" event or simply a "maximum" earthquake, which is the largest conceivable, and a "maximum probable" event, which is smaller and more frequent.

It is clear that the correlations between earthquake magnitude and fault parameters can provide reasonable estimates of the magnitude or surface displacement associated with future earthquakes on a fault when appropriate input values are used. However, in applying these correlations to actual siting situations, there is often much uncertainty, and there has frequently been great controversy. Perhaps no better example can be found than the diversity of conclusions regarding the seismic design parameters for the proposed Auburn Dam on the American River east of Sacramento, California. Reports on these were issued by the U.S. Bureau of Reclamation, the U.S. Geological Survey, Woodward-Clyde Consultants, and five additional independent consultants to the Bureau of Reclamation. Estimates of the magnitude of the maximum earthquake on a fault in the vicinity of the dam ranged from 6.0 to 7.0; the closest approach of the source of the maximum earthquake ranged from less than 0.8 km to 8 km; estimates of the focal depth of the maximum event varied from 5 km to 10 km; the amount of the surface displacement expected during the maximum event varied from 25 cm to 3 m; and estimates of the recurrence interval of the maximum earthquake ranged from 10,000 to 85,000 years. Characteristics of expectable faulting within the dam foundation similarly had a wide range of estimated values: the maximum earthquake was 5.0 to 7.0; displacement per event was less than 2.5 cm to 1 m; and the recurrence interval of an event in the foundation was 260,000 to about 1 million years. This variability reflects, to a large degree, the differences in perception among the various consultants or groups regarding both the physical basis for quantifying

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a particular fault parameter and the general understanding of fault behavior.

During the past ten years the integration of geological, seismological, and geophysical information has led to a much better, though still far from complete, understanding of the relationships between faults and earthquakes in space and time. Geological studies, especially trenching and geomorphic analysis, mapping of coseismic surface faulting and secondary deformation from historical earthquakes, and investigations of fault zone structure in both unconsolidated sediments and bedrock have led to some of the most exciting and important contributions to the understanding of earthquake behavior (Hanks, 1985; Allen, 1986; Schwartz, 1987; Crone, 1987). Such investigations are now referred to as paleoseismology (Wallace, 1981), seismic geology, and earthquake geology. They have demonstrated that individual past large-magnitude earthquakes can be recognized in the geologic record and that the timing between events can be measured. Additionally, they have yielded information on fault slip rate, the amount of displacement during individual events, and the elapsed time since the most recent event. These data can be used in a number of different ways and have led to the development of new approaches to quantifying seismic hazard.

The objective of the present paper is to discuss leading-edge directions in paleoseismology and seismic geology, particularly as they relate to characterizing seismic sources. The paper builds on earlier articles that discuss some of these trends (Schwartz and Coppersmith, 1986; Schwartz, 1987). There are several areas that appear to be especially important as we move into the 1990s. These are: fault segmentation, which provides a physical framework for evaluating both the size and potential location of future earthquakes on a fault zone; earthquake recurrence models, which provide information on the frequency of different size earthquakes on a fault; and long-term earthquake potential, an area in which significant advances have been made through development of earthquake hazard models that use probabilistic methodology to incorporate the uncertainties in seismic source characterization and the evolving understanding of the earthquake process.

The Geologic Data Base

Figure 1 is a schematic diagram showing the types of geologic data that can be obtained for individual faults, and the applications of each to the evaluation of seismic hazard.

Slip Rate

Slip rate is the net tectonic displacement on a fault during a measurable period of time (Figure 2). In recent years a great deal of emphasis has been placed on obtaining slip-rate data, and published rates are available for many faults. For example, Clark *et al.* (1984) have produced a major compilation of 160 slip rates for 81 faults in California. An important aspect of the compilation is the rating of individual slip rates based on reliability of both the measured displacement and the age estimate of the displaced datum. Slip rates are an expression of the long-term, or average, activity of a fault. In a general way, they can be used as an index to compare the relative activity of faults. Slip rates are not necessarily a direct expression of earthquake potential. While faults with high slip rates generally generate large-magnitude earthquakes, those with low rates may do the same, but with longer periods of time between events. Slip rates reflect the rate of strain energy release on a fault, which can be expressed as seismic moment. Because of this they are now being used to estimate earthquake recurrence on individual faults, especially in probabilistic seismic hazard analyses.

Recurrence Intervals

A recurrence interval is the time period between successive geologically recognizable earthquakes. The excavation of trenches across faults has proven to be a tremendously successful technique for exposing stratigraphic and structural evidence of past individual earthquakes in the geologic record (Figure 3). The recognition of geomorphic features such as tectonic terraces and individual

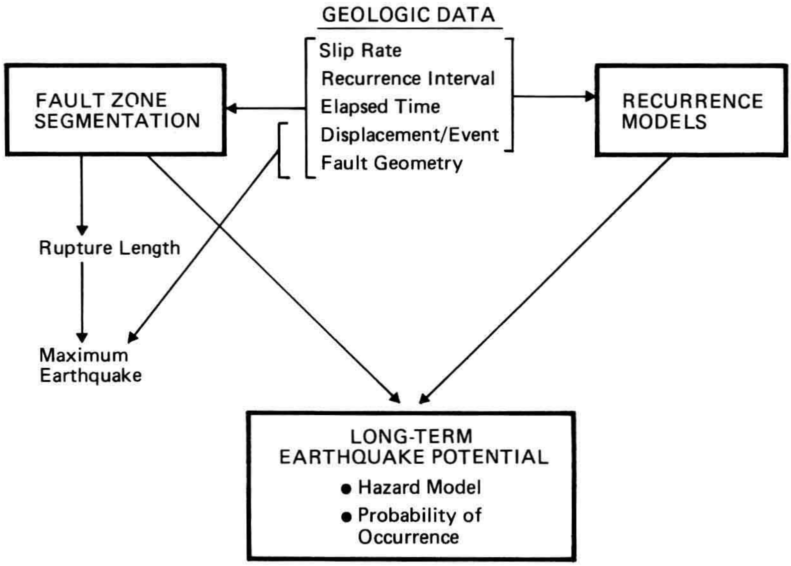


FIGURE 1. Relationship between geologic data and aspects of fault behavior and seismic hazard evaluation.

stream offsets, morphometric analysis of fault scarps, and evidence of past liquefaction also provide direct information on the number of past events for many faults. Where datable material is found, the actual intervals between successive events can be determined, although in many cases only average recurrence intervals can be estimated. Data on recurrence intervals can be combined with information on displacement during each event to develop fault-specific recurrence models.

FIGURE 2. Example of slip rate calculation for a normal fault. The displaced datum is a 13,500-year-old terrace surface displaced by the Wasatch fault. The stippled band is the projection of the surface across the fault zone. The fault scarp at this location is 28.5 m high but the cumulative net vertical tectonic displacement (CNVTD), which is the displacement used for the slip rate, is 11.5–13.5 m. This yields a slip rate of 0.85–1.0 mm/yr. for the past 13,500 years. Similar types of measurement can be made for strike-slip and reverse faults. Vertical scale = horizontal scale. (Modified from Swan *et al.*, 1980).

Elapsed Time

Elapsed time is the amount of time that has passed between the present and the most recent large earthquake on a fault. Many faults have experienced repeated late Pleistocene and Holocene surface-faulting earthquakes but have not ruptured historically. With trenching and geomorphic analysis it is possible to identify and estimate the timing of the most recent event. Information on elapsed time is desirable because, when combined with data on recurrence intervals, it provides the basis for calculating conditional probabilities of the occurrence of future events on a fault. Differences in the timing of the most recent surface rupture along the length of a fault zone are also extremely useful in identifying segments that may behave independently.

Displacement Per Event

Displacement per event is the amount of slip that occurs at the surface during an individual earthquake. Geologic studies are providing this information for past earthquakes and assume that the measured displacement occurred coseismically; that is, most occurred simultaneously with seismic rupture, although an unknown percentage could be associated with post-seismic adjustment called afterslip. Displacements may be obtained, for example, from measurements of displaced stratigraphic horizons, the thickness of colluvial wedges observed in trenches, stream offsets, the heights of tectonic terraces on the upthrown side of faults, and inflections in fault scarp profiles. Displacement reflects the energy associated with an earthquake and displacement data can be used as input for calculating maximum earthquakes. Because the amount of coseismic slip generally varies in some systematic way along the length of a surface rupture, care must be taken to evaluate the degree to which a particular displacement value reflects a minimum, maximum, or average displacement for that event. Displacement per event data for repeated earthquakes at a point on a fault, coupled with the timing of the events, provide a basis for formulating recurrence models.

Fault Geometry

The geometry of a fault is defined by its surface orientation, its dip, and its down-dip extent. For many faults, and particularly dip-slip faults, changes in the strike of the fault at the surface, especially when coupled with major changes in lithology, may aid in assessing the location of fault segment boundaries. For strike-slip faults dips are generally vertical or very high angle, but for dip-slip faults the dip at depth may vary considerably from the surface dip. Some normal faults may decrease in dip with depth (become listric), whereas seismogenic thrust or reverse faults often steepen with depth. Seismic reflection data and seismicity data such as focal mechanisms can provide constraints on dip. The thickness of the seismogenic or brittle crust in a region determined from the depth distribution of seismicity also places constraints on the down-dip extent of the part of a fault that exhibits brittle behavior. Fault dip and down-dip seismogenic extent define fault width. Fault length and fault width are the key parameters for quantifying the fault area that is used to estimate magnitude and seismic moment.

Dating Past Earthquakes

Though individual past earthquakes can be recognized in the geologic record, the actual dating of an event can be difficult. This is especially true throughout large parts of the western United States, especially in the Great Basin, where charcoal and other datable organic material are not commonly found in faulted deposits. To overcome this, important advances have been made in the dating of Quaternary deposits (Pierce, 1986). One very recent technique is morphologic dating of fault scarps by modeling fault-scarp degradation with diffusion-equation model mathematics (Hanks *et al.*, 1984; Nash, 1980, 1984; Hanks and Wallace, 1985). At present, this approach appears reliable for distinguishing between early, middle, and late Holocene single-event scarps. Factors such as scarp height, microclimate, vegetation, material properties, and scarp orientation may control rates of scarp degradation (Mayer, 1984; Pierce and Colman, 1986). As they are more systematically

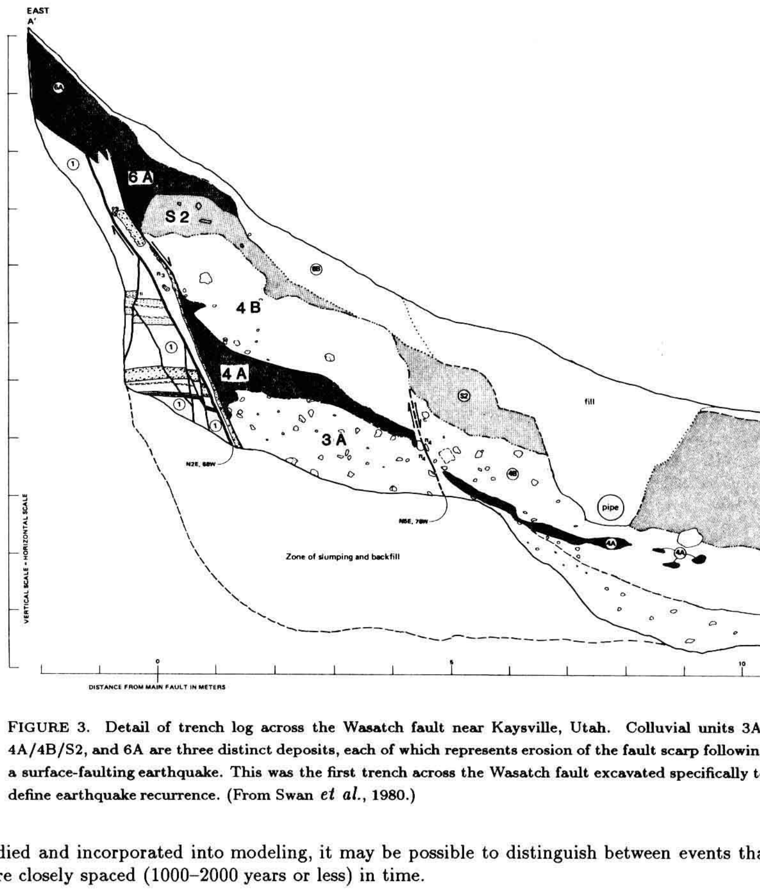


FIGURE 3. Detail of trench log across the Wasatch fault near Kaysville, Utah. Colluvial units 3A, 4A/4B/S2, and 6A are three distinct deposits, each of which represents erosion of the fault scarp following a surface-faulting earthquake. This was the first trench across the Wasatch fault excavated specifically to define earthquake recurrence. (From Swan *et al.*, 1980.)

studied and incorporated into modeling, it may be possible to distinguish between events that are more closely spaced (1000–2000 years or less) in time.

An important advance in radiocarbon dating has been the development of accelerator mass spectrometry (Donahue *et al.*, 1983; Kutschera, 1983). This technique can provide dates on samples as small as 2 to 5 mg and should lead to the dating of many deposits that contain charcoal in amounts too small for conventional β-counting. New and revised dendrologically-corrected calibration curves for converting radiocarbon ages to calendar years have been published for periods back to about 10,000 years (Stuiver and Pearson, 1986; Pearson and Stuiver, 1986; Kromer *et al.*, 1986). These dendro corrections must be made when using radiocarbon dates to calculate recurrence intervals and slip rates. Also, very precise radiocarbon dates with a precision of less than 20 years, as compared to the standard 50 to 100 years, can now be obtained using large amounts of sample, long counting times, and special counters.

Estimates of the age of faulted surfaces are also benefiting from increased understanding of soil development and soil chemistry. Soils tend to become better developed with increasing age and area-specific soil chronosequences are being widely recognized (Birkeland, 1985). Harden (1982) described a soil profile development index that quantifies relative strength of soil profile development using changes in soil chemistry, texture, and soil-horizon thickness. These provide a basis for estimating soil ages within a chronosequence where some absolute age control is available (Harden and Taylor, 1983). Similarly, the degree of development of pedogenic calcium carbonate (Machette, 1985; McFadden and Tinsley, 1985) seems to be a promising index for estimating the age of geomorphic surfaces; it has been used to estimate the timing of events on the La Jencia fault in New Mexico (Machette, 1986).

Another dating technique with promise is thermoluminescence (TL) (Wintle and Huntley, 1982; Forman, 1987). Thermoluminescent properties of minerals like quartz and feldspar result from the effects of ionizing radiation. TL can be measured when these minerals are heated in the laboratory. Exposure to sunlight has the same effect as heating, and zeroes the thermoluminescence. It is this zeroing and the subsequent buildup of TL starting at the time of burial of mineral grains that provide the basis for dating sediments. This technique may be especially useful for dating deposits that contain sparse organic material such as loess that can be deposited in graben or on alluvial fan surfaces, or possibly scarp-derived colluvial deposits.

Fault Zone Segmentation

Fault segmentation is emerging as an important field of earthquake research. It is based on the common observation that fault zones, especially long ones, do not rupture along their entire length during a single earthquake. Studies are suggesting that the location of rupture is not random, that there are physical controls in the fault zone that define the extent of rupture and divide a fault into segments, and that segments can persist through many seismic cycles. The recognition and identification of rupture segments have the potential to provide new insights into characterizing seismic sources and understanding controls of rupture initiation and termination. Inherent in the concept of segmentation is the idea of persistent barriers (Aki, 1979, 1984) that control rupture propagation.

Geological, seismological, and geophysical observations from recent and ongoing paleoseismic studies and historical earthquakes are discussed below. These examples present the basic concepts of segmentation and also discuss the complexities, variability, and uncertainties in fault behavior that must be taken into account in segmentation modeling.

Examples of Segmentation

Wasatch Fault Zone, Utah. The Wasatch is a 370-km-long normal-slip fault that has not had a historical surface-faulting earthquake but has produced large-magnitude scarp-forming earthquakes throughout the Holocene. Based on historical surface ruptures on normal faults in the Great Basin, which have ranged in length from about 25 to 65 km, only a part of the Wasatch fault zone will be expected to rupture in a future earthquake, and with a length comparable to the Great Basin historical events. A segmentation model for the Wasatch fault zone (Schwartz and Coppersmith, 1984; Bruhn *et al.*, 1987; Machette *et al.*, 1987; Wheeler and Krystinik, 1987) is shown on Figure 4. Each Wasatch segment has been defined using a variety of observations including surface fault geometry and structure, differences in slip rate, timing of the most recent earthquake and prior events, gravity data, and geodetic data. From north to south, the length and orientation of the segments are: (1) Collinston segment, 25 km, N20°W; (2) Brigham City segment, 40 km, N10°W; (3) Weber segment, 50 km, N10°W; (4) Salt Lake City segment, 35 km, convex east N20°E to N30°W; (5) American Fork segment, 22 km, N25°W; (6) Provo segment, 30 km, N25°W to N25°E; (7) Nephi segment, 35 km, N11°E; and (8) Levan segment, 35 km, convex west.

The proposed segment boundaries may represent structurally complex transition zones ranging from a few to more than ten kilometers across. To varying degrees, boundaries selected on the basis of paleoseismic and geomorphic observations are coincident with changes in the surface trend of the fault zone; major salients in the range front; intersecting east-west or northeast structural trends observed in the bedrock geology of the Wasatch Range; gaps in Holocene surface faulting; cross faults and transverse structural trends interpreted from gravity data (Zoback, 1983); and geodetic changes (Snay *et al.*, 1984). Smith and Bruhn (1984) showed a strong spatial correlation between segment boundaries and the margins of major thrust faults of Late Jurassic to Early Tertiary age.

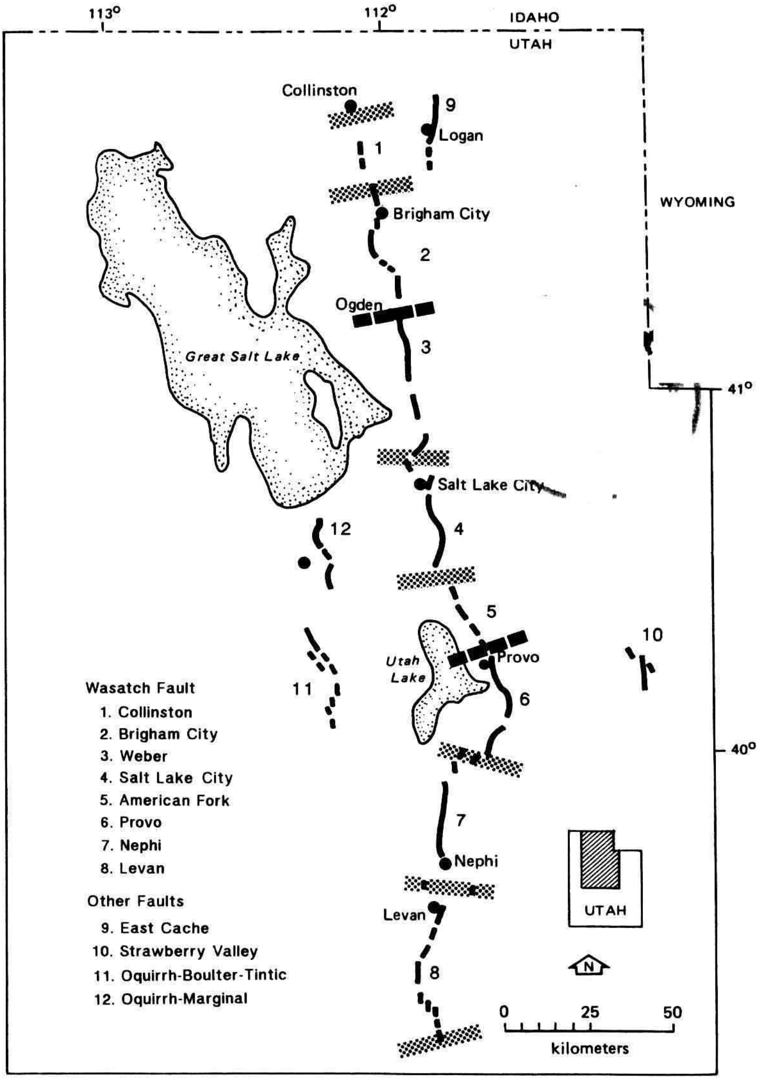
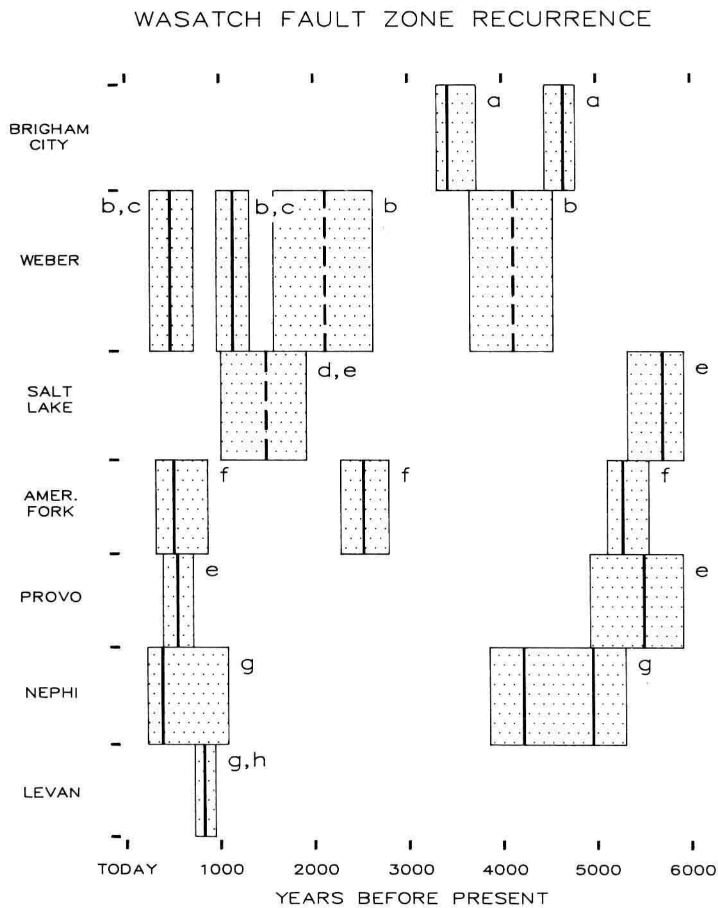


FIGURE 4. Segmentation model for the Wasatch fault zone, Utah. Stippled bands define segment boundaries identified by Schwartz and Coppersmith (1984); dashed bands are additional boundaries interpreted by Machette *et al.* (1987).

The timing of events on adjacent parts of a fault zone is the strongest basis for defining segments. Figure 5 is a space-time plot of the distribution of large magnitude earthquakes on the Wasatch fault during the past 6000 years. It is based on published data and in-progress studies. The Collinston segment (not shown on Figure 5) has had no identifiable surface faulting during the past 13,500 years. The Brigham City segment has not produced a surface-faulting earthquake during the past 3400 years. The Weber segment has experienced multiple displacements, including two within the past 1200 years and with the most recent of these about 500 years ago. In contrast, the timing of the most recent event along the Salt Lake City segment occurred between 1100 and 1900 years ago. The behavior of the American Fork and Provo segments is less clear. The preferred timing of the most recent event is extremely close, 500 and 600 years, respectively, and the uncertainties in the age dates overlap; these could very well be the same event. The same is true of the oldest events about 5300 to 5500 years ago. On the other hand, an event at about 2400 years on the American Fork segment has no correlatives north or south. Based on these observations American Fork–Provo could behave as a) a master segment containing a subsegment that occasionally fails independently or b) two truly independent segments having events that are very closely spaced in time. Along the Nephi segment one event has occurred within the past 1100 years and possibly as recently as 300 years ago; two earlier events occurred on this segment between 3800 and 5200 years ago. Along the Levan segment the most recent event occurred about 800 years ago; this has been the only earthquake along this part of the fault during the past 7500 years.

Oued Fodda Fault, Algeria. An excellent example of fault zone segmentation is provided by the Oued Fodda fault, which produced the M_s 7.3 El Asnam, Algeria earthquake of 10 October, 1980. Yielding *et al.* (1981) and King and Yielding (1984) described this earthquake in terms of fault geometry and rupture propagation and termination. Basic features of the surface rupture and segmentation are shown on Figure 6. Thirty kilometers of coseismic surface faulting occurred on a northeast trending thrust fault with secondary normal faulting on the upper plate. This rupture is composed of three distinct segments, referred as A, B, and C. The southern segment contains two smaller segments, A1 and A2. Local and teleseismic data showed that the earthquake occurred at a depth of 10 to 15 km and was a complex rupture event. The main shock nucleated at the southwest end of segment A and propagated 12 km northeast where a second rupture of equal seismic moment occurred and ruptured 12 km further northeast; a smaller third rupture occurred and propagated along segment C. Geologically, coseismic surface displacement during the 1980 earthquake decreases at each segment boundary, the strikes of the segments differ, and there is a gap in the main thrust rupture and an *en echelon* step between the southern and central segments. There are also differences in long-term deformation along each as expressed by the degree of development of folds on the hanging wall of the thrust. A well-developed anticline with an amplitude of more than 200 m occurs along segment B, amplitude of the anticline decreases to less than 100 m along A2, and the amplitude along A1 is less than 30 m before the anticline dies out toward the south end of the segment. The slip distribution from the 1980 earthquake corresponds closely with the observed differences in the amount of long-term deformation. The average net slip in 1980 was greatest on segment B, decreased along A2, and decreased again along A1. Aftershocks show that strike-slip faulting normal to the trend of the surface rupture occurs at the segment boundaries, specifically between A1 and A2, and A and B. In addition, aftershocks indicate differences in dip between segments, with segment A having a steeper dip than segment B. Based on these observations, Yielding *et al.* (1981) and King and Yielding (1984) concluded that the 1980 displacement pattern was similar to past surface ruptures, and that features of fault geometry and barriers that control the nucleation and propagation of rupture on this fault have persisted through geologic time.

Lost River Fault Zone, Idaho. Surface faulting associated with the 28 October, 1983, M_s7.3 Borah Peak, Idaho earthquake on the Lost River fault zone provides another excellent example for examining segmentation. The Lost River fault is a normal-slip fault zone that extends for approximately 140 km from Arco to Challis. In 1983 it ruptured along 36 km of its length (Crone and Machette, 1984; Crone *et al.*, 1987). Scott *et al.* (1985) suggested that the zone may be composed of five or six segments characterized by different geomorphic expression, structural relief, and timing of most recent displacement. The segmentation model for the fault zone is shown on Figure 7. The



Sources of data:
a. S. Personius in Machette et al., in prep.
b. A. Nelson in Machette et al., in prep.
c. Swan et al. (1980)
d. Lund and Schwartz (1986)
e. Schwartz et al. (1988)
f. Machette et al. (1987)
g. Schwartz and Coppersmith (1984)
h. M. Jackson, M.A. Thesis, U. Colorado, in prep.

FIGURE 5. Space-time plot of large magnitude, scarp-forming earthquakes on the Wasatch fault zone during the past 6000 years. Solid line is best estimate of timing of event; dashed line is less well-constrained age; stippled box is uncertainty in date.

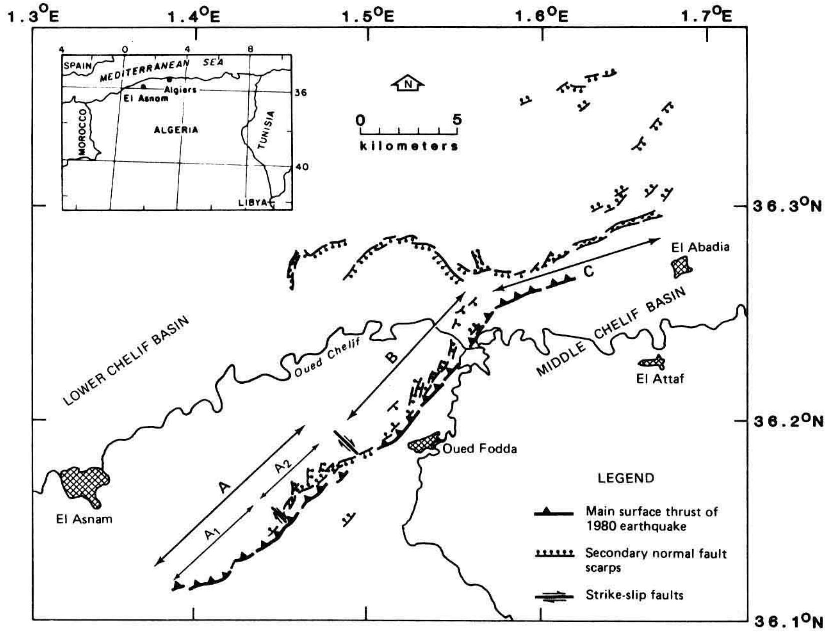


FIGURE 6. Map showing coseismic surface rupture from the 1980 El Asnam, Algeria, earthquake and the segmentation model for the Oued Fodda fault (modified from King and Yielding, 1984). Fault segments A, B, and C are defined by differences in geomorphic expression, seismicity, coseismic slip, geometry, and long-term rates of deformation.

Arco segment has high scarps of Quaternary age but there has been no surface faulting during the past 30,000 years (Malde, 1987). The Pass Creek segment has discontinuous, poorly defined scarps in deposits that are 15,000 to 30,000 years old, but no latest Pleistocene or Holocene faulting. The Mackay segment did not rupture in 1983; however, it has continuous scarps of late Pleistocene and Holocene age. Trenching investigations (Schwartz and Crone, 1988) show this segment produced only one earthquake during the past 12,000 years and this event occurred between 4300 and 6800 years ago. The Thousand Springs segment was the source of the 1983 earthquake. Scarp profiles and trenching show that slip distribution in 1983 faithfully reproduced the slip distribution of the pre-1983 event. Reconstruction and morphometric analysis of the pre-1983 scarp suggests the event occurred about 6000 to 8000 years ago (Hanks and Schwartz, 1987). The Warm Spring segment is north of the Willow Creek Hills. In 1983 it experienced discontinuous surface rupture with displacements averaging 10–20 cm. Radiocarbon dating of inplace burns in and near the base of scarp-derived colluvial wedges observed in trenches, and the degree of soil carbonate development, suggest only one event prior to 1983 occurred on this segment during the past 12,000 years; this paleoearthquake appears to have occurred shortly before 5500–6200 years ago. The North segment has no late Quaternary fault scarps.

In 1983 surface rupture initiated at the south end of the Thousand Springs segment and propagated northwest. At the south end a 25-cm-high scarp that formed in 1983 is coincident with a fault scarp of approximately the same height that defines the pre-1983 event at this location. South