ACTIVE FAULTS, PALEOSEISMOLOGY, AND EARTHQUAKE HAZARDS

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Abstract

Active faults are those that may have displacement within a future period of concern to humans. Studies of prehistoric earthquakes and displacements on faults--paleoseismology--show that average recurrence intervals on most active faults in the United States are generally longer than 1000 years. Only on the San Andreas fault, its major branches, or similar faults are average recurrence intervals as short as 10-200 years. Probabilistic expressions of the likelihood of future behavior of active faults are needed.

Active Faults

Active faults are those faults that may have displacement within a future period of concern to humans. Most, but not all, are seismogenic. Both the fault displacement and earthquakes generated create hazards.

Present methods of estimating future hazards of faults are deficient. The designation of a fault merely as "active" provides, at best, an inadequate indication of the attendant hazard. Restriction of the definition of "active faults" to those having had displacement within a defined past period of time, such as 10,000 or 35,000 years, provides little assessment of the hazard, and the adoption of different restricted definitions by different agencies has caused confusion. An accurate expression of the probability of occurrence of future displacement, of earthquakes generated, and of the size of such events is needed in evaluating the hazards of active faults.

Estimates of the probability of future displacements on faults have been based on past behavior of a given fault or related faults, or have been inferred from the behavior of a tectonic province. The historic record was used almost exclusively until recent years, but, used alone, it was inadequate. Paleoseismology is becoming a very important basis for estimating the long-term or average behavior of faults and for characterizing provinces. In addition to estimations of future displacements based on paleoseismology, specific earthquake predictions based, for example, on changes in strain, may become feasible, and more accurate prediction of short-term future behavior of faults may become possible.

The rate of past activity can be usefully expressed as: (a) average recurrence intervals for either displacement events or earthquakes of a given size on a single fault, (b) average number (or fractions) of events per year; (c) number of earthquakes or displacement events on sets of faults or fault segments averaged over unit areas for defined periods of time to characterize regions. Average rates of displacements, without an indication of the size of individual displacement events, also carry an implication, albeit incomplete, of the degree of activity, but rate of displacement alone cannot define the size of events to be expected.

Paleoseismology

The historic record of seismicity, which is especially useful in regions of high seismicity, has proven inadequate for assessing future seismicity in regions where major earthquakes occur at intervals considerably longer than the historic record. Even in regions of high seismicity, segments of faults that have generated large earthquakes in the past may be currently very quiet, and this lack of current earthquakes can give a falsely low measure of the hazard.

The study of prehistoric earthquakes--paleoseismology--is emerging as a critical consideration in evaluating earthquake hazards. Techniques of paleoseismology are principally geologic and include analysis of such features as: (a) microstratigraphic relations along faults as seen in natural or artificial exposures, (b) fault scarps and other fault topography, (c) offset drainage and changes in profiles of channels, (d) regional geologic relations which reveal long-term rates of displacement, (e) seismically induced sedimentary structures, and (f) marine, lacustrine, and river terraces related to uplift and faulting. A variety of techniques that can provide dates in late geologic time include: ^{14}C, K/Ar, and other isotopic ratios and tree-ring, volcanic-ash, soil, amino-acid, and paleomagnetic techniques.

Exploration of faults and exposure of them by trenching have become common engineering-geologic practices. Some exploration sites have been selected especially to examine paleoseismic history. The best sites for this purpose have many distinct stratigraphic units that can record displacement events on faults and dateable material to provide a time scale of the events. Among the most productive sites thus far analyzed are those on the San Andreas fault at Pallett Creek, California, on the Garlock fault at Fremont Valley, California, and on the Javon Canyon fault, western Transverse Range, California. For nine events in about 1400 years of record at Pallett Creek, Sieh (1978, 1980) determined an average recurrence interval of about 145 years and a range of 100-230 years. On the Garlock fault, Burke (1979) found evidence for nine to possibly seventeen events in about 15,000 years, or an average recurrence interval in the range of 900 to 1800 years. On the Javon Canyon fault, A. M. Sarna-Wojcicki, K. R. Lajoie and R. F. Yerkes (written commun., 1980) recognized five events in 3500 years. Sites developed on the Wasatch fault in Utah have also been informative. Swan and others (1980) found evidence at Kaysville, Utah, that the average recurrence interval for large-displacement events on the Wasatch fault is between 500 and 1000 years.

Such characteristics of fault scarps as their slope angle and sharpness of crest provide a useful reconnaissance means of dating faulting events. Wallace (1977a, 1977b and 1978) has used this technique to analyze

20 sets of young faults in Nevada. Bucknam and Anderson (1979) and Bucknam (1980) refined the method by showing that a correlation between scarp slope and height exists for scarps of a given age in western Utah. Grose and Dodge (1979) in studying the Black Rock fault in western Nevada, developed corrections for slope angles of scarps as a function of different lithologies.

Sims (1975) has developed techniques to determine recurrence intervals from deformational structures in young lacustrine sediments. The structures observed are intricately deformed thin beds that suggest deformation in units weakened by liquefaction. Sand boils or sand craterlets, also liquefaction phenomena, are used by Sieh (1978) as a key to prehistoric earthquakes at Pallett Creek, California.

Earthquake Hazard Evaluation Based on Paleoseismicity

Data in Table 1 demonstrate that most faults thus far studied in the United States are characterized by average recurrence intervals at a particular location along a fault of 1000 years or more, or expressed as chances per year, one-thousandth or less. Only the San Andreas fault, its major branches such as the San Jacinto, and similar major faults are characterized by recurrence intervals appreciably lower, e.g., in the 10- to 200-year range. Recurrence intervals of between 500 and 1000 years interpreted on the Wasatch fault at Kaysville (Swan and others, 1980) suggests that the Wasatch may be more active than others of the Basin and Range province, even though historically it has been notably free of both displacement events and large earthquakes.

For regional evaluations of earthquake hazards derived from paleoseismologic studies of faults, normalization by area is required. Larger faults, or sets of faults, are capable of producing large earthquakes on any of a number of segments or units. For example, Swan and others (1980) point out that inasmuch as each of 6 to 10 segments of the entire Wasatch fault could produce earthquakes at the rate of the segment at Kaysville, the average recurrence interval for the entire fault can be expressed as between 50 and 400 years. Wallace (1970) performed a similar analysis for the San Andreas fault. In the Great Basin province a reconnaissance of young fault scarps (Wallace, 1977a, 1978) indicates that generalized rates of faulting in the range 5 x 10^{-5} to 5 x 10^{-6} events (surface faulting events that could accompany a M=7 or larger earthquake) per year per 1000 km^2 are characteristic of western Nevada, eastern California, and west-central Utah in Holocene time (12,000± years). In contrast, an area of approximately 100,000 km^2 in western Utah and eastern Nevada may have had no such events in late Quaternary time (past 500,000 years). In western Utah, Bucknam and others (1979) have recognized six subprovinces, some having Holocene faulting, and others no Holocene faulting; the Wastach frontal zone is characterized by the greatest concentration of prominent scarps active in late Quaternary time.

Paleoseismology can be helpful in refining the patterns of expected seismic shaking derived from historic records alone. For example, in a test area in Nevada paleoseismicity suggests a uniform seismic flux over four counties instead of the wide range of coefficient Aa values (3-7) shown on the ACT-3 map (Applied Technology Council, 1978). Using paleoseismic data from Salt Lake Valley, Utah, Bucknam and others (1979) estimate that accelerations with a 10 percent chance of being exceeded in 50 years may be two or three times as large as those estimated on the map by Algermissen and Perkins (1976) which was based principally on historic records.

An important step to be taken in estimating the hazards of faults is the development of probabilistic models of the likelihood of future displacement. Cluff and others (1980) have taken a step in this direction in analyzing the Wasatch fault zone. They use a model, commonly assumed by geologists and seismologists, in which strain release is constant over long periods and the intervals between large earthquakes can be represented by averages. Given these assumptions, it follows that the longer the time since the last large surface displacement or earthquake, the shorter the time until the next. Uniformity of strain release and of recurrence interval over long periods of time may not be an entirely correct model, however, because long-term clustering of events in time seems to be real. Given clustering, probabilistic models suggest the conclusion that the longer the time since the last large event, the longer the time until the next, and vice versa (Kagan and Knopoff, 1979, Mandelbrot, 1977). The degree and styles of long-term clustering are as yet poorly known.

Paleoseismology is just emerging as a distinct discipline. Despite many unresolved questions, the long-term record available only from paleoseismology already has provided valuable insight into the faulting process and assists in the evaluation of earthquake hazards.

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Table 1

Average Recurrence Intervals and Rates of Slip on Some Active Faults, and Selected Paleoseismic Data, United States

Fault	Area	Average Recurrence interval, years [1]	Rate of slip mm/ year	Reference	Notes
	CALIFORNIA				
San Andreas	Wallace Creek	<250-330	>30-40	Sieh, 1980	Average recurrence of 10-m slip events
San Andreas	Pallett Creek	145		Sieh, 1978 Sieh, 1980	Range of recurrence intervals about 100-230 yrs.
San Andreas	Fort Ross	128-508		La Marche and Wallace, 1972	2-3 tilts of redwood tree between 1400 or 1650 and 1906.
Garlock	Fremont Valley	~900-1800		Burke, 1979	9-17 events in 14,700 ± 130 yrs.
Garlock	Koehn Lake		7	Clark and Lajoie, 1974	80 m offset since late Pleistocene 11,360± 160 yrs.
San Jacinto	NE of Anza		≥8-12	Sharp, 1980a, 1980b,	5.7-8.6 km horiz. offset in no more than 0.73 my.
San Jacinto	S. California	<7.4		Sharp, 1980a	Average for entire length of fault
San Jacinto	S. California	100		Sharp, 1980a, 1980b,	Average at one locality
Coyote Creek	W. Imperial Valley		3-5	Clark & others, 1972	1.7 m offset of Lake Cahuilla sediments, age 283-478 yrs. ago
Coyote Creek	W. Imperial Valley	15-200		Clark & others, 1972	Offset of Holocene Lake Cahuilla beds. Original estimate, 160-205 yrs. modified by new data. Sharp, R., pers. commun.
Coyote Creek	W. Imperial Valley		1-2	Sharp, 1980a, 1980b	10.9 m RL offset of buried stream channel, 5000-6800 yrs. old
Javon Creek	W. Transverse Range	700-1750	1-1	Sarna-Wojcicki & others, pers. commun., 1980	5 displacements of marine terrace 3500 yrs. old
Ano Nuevo-	Pt. Ano Nuevo	16,000		Weber & Cotton, 1980	6 offset events, 0.76-1.37 m/event, in marine terrace 105,000 yrs. old.
Frijoles		~6,000		Weber & Cotton, 1979	6 offset soils representing 7 faulting events in 40-50,000 yrs.
Oak Hill	San Fernando	~200		Bonilla, 1973	Previous displacement on fault break of 1971.
Unnamed	Lone Pine	3-7,000		Clark, 1980	Work by L. Lubetkin. 3 1872-type events in 10-22,000 yrs.
	NEVADA				
Genoa	Genoa	2-3,000		Pease, 1979 & pers. commun., 1979	2-3 displacements in last 6,000 yrs.
Unnamed	Carson City	2-6000		Pease, 1979 & pers. commun., 1979	At least 2 displacements in 12,000 yrs.
Pearce	Pleasant Valley	~6,000		Wallace, 1977, 1978 and 1979	1915 scarp plus one large displacement younger than 12,000 ± yrs. and several older than 12,000 ± yrs.
Pearce	Pleasant Valley	<600-1,700		Bonilla, pers. commun., 1980	Recurrence for displacement events of 0.4 m each, offset paleosols.
Unnamed	West Flank Humboldt Range	~12,000		Wallace, 1977, 1978 1979	Single-event younger than Lake Lahonatan shoreline.
Unnamed	Northwest Flank Stillwater Range	>12,000		Wallace, 1978, 1979,	Latest scarp older than Lake Lahontan shoreline
Black Rock Fault	Black Rock Desert	6250-8330 6000-8000		Grose & Dodge, 1979 Dodge and Grose, 1979	3 or 4 displacements in 25,000 yrs. Latest in last 1400 yrs. 4 or 5 displacements in 24,000 yrs.

[1] Some calculations may appear to be inconsistent without qualifications fully developed in original texts.

Table 1

Average Recurrence Intervals and Rates of Slip on Some Active Faults, and Selected Paleoseismic Data, United States

Fault	Area	Average Recurrence interval years [1/]	Rate of slip mm/ year	Reference	Notes
Wasatch	UTAH Big Cottonwood Cr.		0.5-1.0	Scott, 1980	Over past 100,000 yrs.
Wasatch	Kaysville	500-1000		Swan and others, 1980	Minimum of 3 offset events of fan ≈ 6,000 yrs. old. 1.7-3.7 m/event
Wasatch	Hobble Creek	1,500-2,400	1.1	Swan and others, 1980	6-7 offset events in 12,000 yrs., 0.8-2.8 m per event
Wasatch	Wasatch Range	50-400		Swan and others, 1980	Integration 6-10 segments, each of which behaves like those at Kaysville or Hobble Creek.
Unnamed	Fish Springs Range W. Utah	>11,800		Bucknam and Anderson 1979, Bucknam, 1980	Single-event scarp younger than Bonneville shoreline
Unnamed	Drum Mts W. Utah	>11,800		Bucknam and Anderson 1979, Bucknam, 1980	Single-event scarp younger than Bonneville shoreline.
La Jencia	NEW MEXICO Rio Grande Valley	5,000-1,000,000		Machette, 1980	One event in Middle (?) Holocene to latest Pleistocene.
County Dump	Rio Grande Valley	90,000-190,000		Machette, 1978	4 fault events at 20,000, 120,000, 310,000 and 400,000 yrs. ago.
	TENNESSEE New Madrid	600-1000		Russ, 1979	3 large earthquakes in 2,000 yrs. including 1811-12.
	ALASKA Middleton Island	500-1,350	10	Plafker, 1978	6 episodes of uplift recorded by marine terraces in 4,300 yrs.
	Otmeloi Island, Yakatat	420		Plafker, pers. commun., 1980	Beach raised 500± yrs. ago and 1899 earthquake
	IDAHO Arco	>10,000		Pierce, 1980 pers. commun.	
	WASHINGTON Puget Sound	23-276		Sims, 1975	14-21 deformed zones within 1,804 varves.

[1/] Some calculations may appear to be inconsistent without qualifications fully developed in original texts.