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The Wasatch fault zone, Utah—segmentation and history of Holocene earthquakes

MICHAEL N. MACHETTE, STEPHEN F. PERSONIUS and ALAN R. NELSON

U. S. Geological Survey, Denver, Colorado, U.S.A.

DAVID P. SCHWARTZ

U.S. Geological Survey, Menlo Park, California, U.S.A.

and

WILLIAM R. LUND

Utah Geological and Mineral Survey, Salt Lake City, Utah, U.S.A.

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Abstract—The Wasatch fault zone (WFZ) forms the eastern boundary of the Basin and Range province and is the longest continuous, active normal fault (343 km) in the United States. It underlies an urban corridor of 1.6 million people (80% of Utah's population) representing the largest earthquake risk in the interior of the western United States.

We have used paleoseismological data to identify 10 discrete segments of the WFZ. Five are active, medial segments with Holocene slip rates of 1–2 mm a^{-1}, recurrence intervals of 2000–4000 years and average lengths of about 50 km. Five are less active, distal segments with mostly pre-Holocene surface ruptures, late Quaternary slip rates of <0.5 mm a^{-1}, recurrence intervals of ≥10,000 years and average lengths of about 20 km. Surface-faulting events on each of the medial segments of the WFZ formed 2–4-m-high scarps repeatedly during the Holocene; latest Pleistocene (14–15 ka) deposits commonly have scarps as much as 15–20 m in height. Segments identified from paleoseismological studies of other major late Quaternary normal faults in the northern Basin and Range province are 20–25 km long, or about half of that proposed for the medial segments of the WFZ.

Paleoseismological records for the past 6000 years indicate that a major surface-rupturing earthquake has occurred along one of the medial segments about every 395 ± 60 years. However, between about 400 and 1500 years ago, the WFZ experienced six major surface-rupturing events, an average of one event every 220 years, or about twice as often as expected from the 6000-year record. This pattern of temporal clustering is similar to that of the central Nevada–eastern California Seismic Belt in the western part of the Basin and Range province, where 11 earthquakes of **M** > 6.5 have occurred since 1860. Although the time scale of the clustering is different—130 years vs 1100 years—we consider the central Nevada–eastern California Seismic Belt to be a historic analog for movement on the WFZ during the past 1500 years.

We have found no evidence that surface-rupturing events occurred on the WFZ during the past 400 years, a time period which is twice the average intracluster recurrence interval and equal to the average Holocene recurrence interval. In particular, the Brigham City segment (the northernmost medial segment) has not ruptured in the past 3600 years—a period that is about three times longer than this segment's average recurrence interval during the early and middle Holocene. Although the WFZ's seismological record is one of relative quiescence, a comparison with other historic surface-rupturing earthquakes in the region suggests that earthquakes having moment magnitudes of 7.1–7.4 (or surface-wave magnitudes of 7.5–7.7)—each associated with tens of kilometers of surface rupture and several meters of normal dip slip—have occurred about every four centuries during the Holocene and should be expected in the future.

INTRODUCTION

SEVERAL problems are central to understanding the processes and timing of earthquakes associated with surface-faulting events in extensional terrains: (1) the identification of long (>50-km) faults; (2) the determination of the occurrence and nature of characteristic earthquake events; and (3) the determination of the length and variability of recurrence intervals for large magnitude earthquakes, which could be potentially devastating to the region. We have gained greater insight into these problems through paleoseismological investigations involving detailed geologic mapping and exploratory trenching across the Wasatch fault zone (WFZ) in Utah.

Regional setting

The WFZ is one of the longest and most active extensional fault zones in the western United States. Its late Quaternary trace extends for 343 km from Malad City, Idaho, to Fayette, Utah, and is marked by large (30–50-m-high) scarps on glacial, lacustrine, colluvial and alluvial deposits of middle to late Pleistocene age and smaller (3–10-m-high) scarps on Holocene deposits. The WFZ is the main component of a prominent struc-

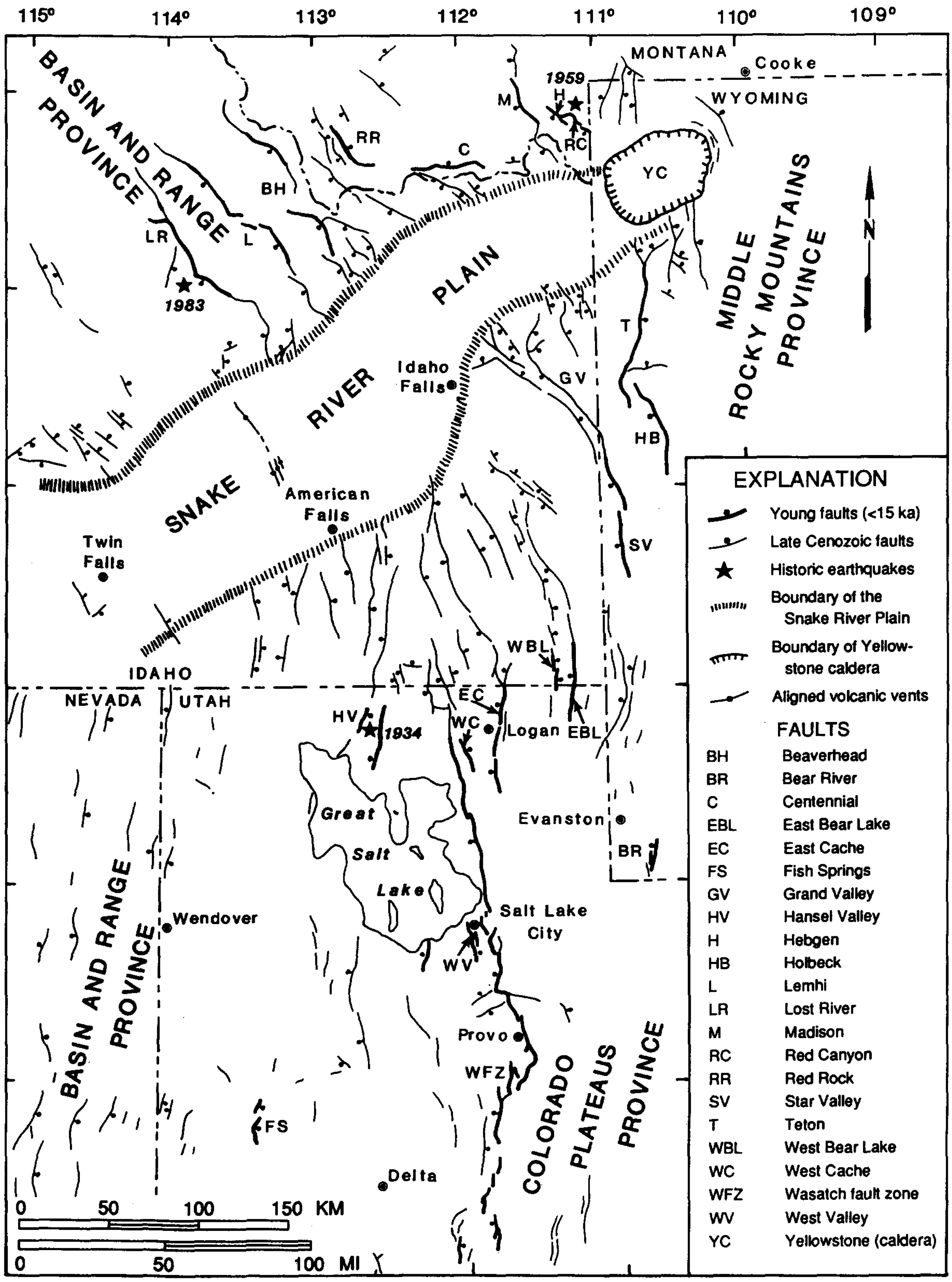

Fig. 1. Index map showing selected major late Cenozoic faults in the northeastern part of the Basin and Range province and the northern part of the Intermountain Seismic Belt. Faults having young movement (<15 ka) are shown by bold lines. (Compiled from maps of Howard *et al.* 1977, Nakata *et al.* 1982, Anders *et al.* 1989, Machette *et al.* in press, Smith *et al.* in press.)

tural transition zone that separates the greatly extended terrain of the Basin and Range province from the uplifted Colorado Plateaus and Middle Rocky Mountains provinces (Fig. 1). Concentrated seismicity along this zone (the Intermountain Seismic Belt, Smith & Sbar 1974) is largely coincident with a belt of young faulting (<15 ka) that forms a right-stepping en échelon pattern from the northern part of the WFZ to the Yellowstone area; from there, it trends westward across southwestern Montana into central Idaho and includes the two largest historic earthquakes in the region (Fig. 1). This V-shaped pattern of recent tectonism flares out from the Snake River Plain and the tip of the V is centered on the Yellowstone calderas, which are the present location of the Yellowstone hotspot (see Scott *et al.* 1985, Smith *et al.* 1985, Pierce & Scott 1986, Smith 1988, Anders *et al.* 1989, Pierce & Morgan 1990, Smith *et al.* in press). The Yellowstone hotspot forms a regional thermal anomaly (Quaternary volcanism, mantle upwelling and high heat flow), which has migrated to the northeast along the Snake River Plain during the past 15 Ma at an average rate of 3–4 cm a^{-1} (see discussions in Pierce & Scott 1986, Pierce & Morgan 1990). Although these authors discuss various hypotheses about the relation between the Yellowstone hotspot and its effect on late Cenozoic tectonism, all agree that the track of the Yellowstone hotspot has greatly influenced the region's temporal and spatial pattern of faulting in the past, and may do so in the future.

Previous studies

Although the WFZ has been the subject of scientific interest since the pioneering work of G. K. Gilbert a century ago (Gilbert 1890, Machette 1988a), the first comprehensive study was undertaken in the 1970s by Cluff *et al.* (1970, 1973, 1974) using low-sun-angle aerial photographs to map the surface trace of the WFZ. As an extension of their reconnaissance mapping, geologists at Woodward-Clyde Consultants made detailed investigations at four trench sites along the WFZ during the period 1978–1982. Their work culminated in two major synthesis reports that applied new concepts to the paleoseismological history of the WFZ. In the first report, Swan *et al.* (1980) proposed segmentation of the WFZ and speculated on the number of possible segments; they suggested at least six on the basis of modern microseismicity to as many as 10 on the basis of geometric variations along the fault zone and the commonly observed rupture length of 30–40 km for historic normal faults. In the second report, Schwartz & Coppersmith (1984) proposed that the WFZ is composed of six major segments that were chosen on the basis of a combination of geomorphic, topographic, geophysical, paleoseismic and geodetic data.

The concept of fault segmentation embodies the idea that major slip events (long surface ruptures having several meters of offset that are associated with large-magnitude earthquakes) on normal fault zones are largely confined to discrete parts that represent only a fraction of the fault's total length and whose boundaries are related to geometric and structural controls along the fault zone. However, the term *segment* was not explicitly defined in either of these reports; recently, the term has been used in various contexts that range from "a portion" (e.g. a geometric segment) to "a structural entity" (e.g. a structural segment). dePolo *et al.* (1991) discussed this nomenclature problem and suggested that the term "earthquake segment" be used for those parts of a fault or faults that "rupture as a unit during an earthquake". In this paper, we use the term *segment* in the same way, although our determination of segments of the WFZ is based on paleoseismology rather than contemporary seismology. The segments defined herein indicate the extent of surface rupturing that we would expect during large-magnitude earthquakes that nucleate on the WFZ.

Recent studies

Our investigations of the WFZ during the 1980s were conducted under the U.S. Geological Survey's (USGS) National Earthquake Hazards Reduction Program, which focuses on analysis of seismic risk in populated regions with earthquake hazards. The first phase was to make 1:50,000-scale surficial geologic maps of the Wasatch Front region (Personius 1988, 1990, Machette 1989, in press, Nelson & Personius 1990, in press, Personius & Scott 1990, in press) as a basis for derivative studies (potential shaking, liquefaction, hazard assessments, special study zones, etc.). The results of initial mapping of the WFZ led Machette *et al.* (1986) to modify some of Schwartz & Coppersmith's (1984) proposed segment boundaries, suggested several new boundaries and subdivided four of the original segments. These modifications were based on recent fault movements as determined by analysis of fault-scarp morphology and from the relations between young surficial deposits and fault scarps. In 1986, the USGS and the Utah Geological and Mineral Survey initiated a second phase with a co-operative program of exploratory trenching to test segmentation models by determining (1) the recency of faulting along several of the newly proposed segments, (2) the timing and recurrence intervals of older faulting events and (3) the timing of movement on adjacent fault segments (i.e. presence or lack of synchronous movement). Trenching studies have been completed at sites near Brigham City, at East Ogden, Dry Creek (south of Salt Lake City), at the mouths of American Fork and Rock Canyons, and near Mapleton (see Machette *et al.* in press, fig. 1 and appendix). In addition, co-operative studies with geologists at the Bureau of Reclamation, University of Colorado, and Utah State University have augmented our own findings. This recent flurry of co-operative investigations has more than tripled the number of trenches available in 1980, increased our data on the timing of faulting events by a factor of five, and significantly tightened the error limits on previously documented faulting events.

This paper is our attempt to reach a consensus on a segmentation model and the movement history for the WFZ based on our collective studies. However, as work continues on the WFZ and as new sites are explored, we anticipate further refinements in our segmentation model and timing history.

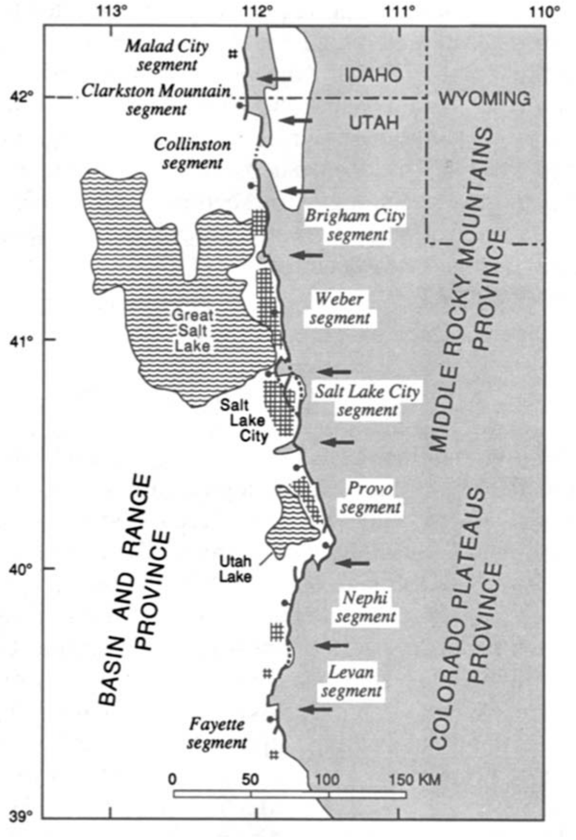

Fig. 2. Location of segments of Wasatch fault zone. Solid arrows indicate segment boundaries. Major towns shown by cross-hachure symbol.

SEGMENTATION OF THE WASATCH FAULT ZONE

The central two-thirds (Brigham City to Nephi segments) of the WFZ has ruptured two or more times in the past 6000 years (Fig. 2). The most recent movement on the four other distal segments is considered to be pre-Holocene because we have not found fault scarps on uppermost Quaternary deposits along these segments. The distal portions have short segments, low slip rates (<0.5 mm a^{-1}), and long recurrence intervals ($>10,000$ years) whereas the medial segments along the central portion of the WFZ are characterized by long segments, high slip rates (1–2 mm a^{-1}) and recurrence intervals of about 2000 years. Obviously, the WFZ is a fundamental province-scale fault zone that serves to decouple the greatly extended terrain of the Basin and Range province from the more intact provinces to the east (Fig. 1).

Segmentation models

The six segments originally proposed by Schwartz & Coppersmith (1984) are retained in our current model with some changes in position and nomenclature. Although they ended their northernmost (Collinston) segment at the Bear River, they followed the belief of Cluff *et al.* (1970) that older movement on the WFZ continued farther to the north into southern Idaho (Fig. 2). The southern end of their Collinston segment has been relocated 5 km north of Brigham City by Personius (1988) and its northern end has been extended about 11 km past the Bear River (Machette *et al.* 1987, in press). Machette *et al.* (1987) also extended the Wasatch fault zone north along the Malad Range to Malad City, Idaho. Although no detailed paleoseismic studies have been conducted on this portion of the WFZ, the northern 41 km has been subdivided tentatively into the Clarkston Mountain and Malad City segments (Fig. 2), which are separated by a 6-km-wide salient. The original Ogden segment of Schwartz & Coppersmith (1984), which extended from north of Brigham City to northern Salt Lake City, is now divided into the 40-km-long Brigham City segment and the 61-km-long Weber segment. The Salt Lake City segment remains virtually unchanged from Schwartz & Coppersmith's proposed location and boundaries.

The Provo segment, which borders the eastern margin of Utah Valley (Machette 1989, in press) was named by Schwartz & Coppersmith (1984), but Machette *et al.* (1986) subdivided this part of the WFZ into three shorter segments (American Fork, Provo—restricted sense, and Spanish Fork) on the basis of apparent recency of movement as determined from scarp morphology and detailed mapping of the fault zone. However, trenching at three new sites has lead us to conclude that the entire length (70 km) of the range-bounding WFZ in Utah Valley is a single segment (Provo). This conclusion is based on similarities in the timing of the most recent (500–650 years ago) and penultimate (2.6–3.0 ka) events determined from trenching at the American Fork Canyon (Machette 1988b, Forman *et al.* 1989) and Mapleton sites (Schwartz *et al.* 1988, Lund *et al.* in press). The most recent movement along the central part of the segment had been poorly constrained at about 1100 years ago (Machette *et al.* 1987), but recent trenching at the Rock Canyon site constrains it to between 600 and 2700 years B.P., which is compatible with events at the American Fork and Mapleton sites (Lund *et al.* in press).

The Nephi segment (Fig. 2) is the southernmost segment of the WFZ that shows demonstrable evidence of repeated Holocene movement and is one of the most recently active segments. A 15-km-long gap in latest Quaternary faulting separates the Nephi segment from the Levan and Fayette segments, which comprise the southern part of the WFZ. Machette's studies of fault-scarp morphology suggest that scarps along the Levan segment are distinctly younger than those along the Fayette segment, and thus comprise two discrete fault segments. The Fayette scarps are probably early Holocene(?) or latest Pleisocene in age, whereas the Levan scarps are latest Holocene in age. The southern part of the WFZ is characterized by low slip rates (<0.5 mm a^{-1}) and recurrence intervals that are >6000 years (Levan segment) to $\leq 10,000$ years (Fayette segment).

Segment lengths

The total length of the WFZ is about 383 km as measured along its surface trace, which is our preferred method of reporting fault lengths, and about 343 km from end-to-end (Table 1). However, the net length of surface trace does not include overlapping portions or gaps in the cumulative lengths. Individual segments are as short as 11–17 km on the distal parts to as long as 60 km on the Weber segment and about 70 km on the Provo segment. The average length along surface trace for all 10 segments of the WFZ is about 37 ± 19 km. The five medial segments average about 52 ± 13 km in length along their surface trace. The five distal segments (three on the north and two on the south) average about 21 ± 8 km in length, with the inboard segments (Levan and Collinston) each being of intermediate length (30 km). In general, the distribution of both segment lengths and slip rates on the WFZ forms a broad envelope with maximum values in the central part and decreasing values at the ends, as reflected by the altitude of the crest of the Wasatch and associated ranges along the fault zone (see Schwartz & Coppersmith 1984, fig. 10). In general, these relations indicate a strong positive correlation between topographic relief along the WFZ (a proxy for structural offset), slip rates and segment lengths, and an inverse correlation between topography and recurrence intervals of major surface-faulting events.

Segment boundaries

Many normal fault zones present continuous structural pathways for surface rupturing that are one hundred to several hundred kilometres long. Typically, individual surface-faulting events can rupture as much as 50 km of ground—only a fraction of the total length of fault zones. Studies of both historic and prehistoric faulting show that rupturing tends to occur in discrete sections (or segments) of fault zones that are separated by boundaries.

If boundaries between segments of long fault zones are persistent barriers to lateral propagation of earthquake ruptures, then they should coincide with structural anomalies along the fault. These anomalies may be coincident with abrupt changes in structural relief along strike (Wheeler 1989) or with areas of increased fault complexity (King 1986, Bruhn *et al.* 1987). Changes in structural relief may be expressed as: (1) subsurface

Table 1. Lengths of Wasatch fault zone segments and positions of boundaries (lengths are rounded to closest 0.5 km)

Fault segment	Length (km) Surface trace	Length (km) Straight line	Comments
Malad City	17.0	16.5	Last movement >14 ka. Does not include 6-km Woodruff spur to south
Clarkston Mountain	19.0	17.0	Last movement >14 ka. Extends from Woodruff spur to Malad River. Has 7-km left-step and 2-km overlap with Collinston segment
Collinston	30.0	29.5	Last movement >14 ka. North end at Short Divide; position of fault adjacent to Bear River uncertain
Brigham City	40.0	35.5	Repeated Holocene movement. Has 1-km left step and 1.5-km overlap with Weber segment at south end
Weber	61.0	56.0	Repeated Holocene movement. South end on north-central flank of Salt Lake salient. Steps 2.7-km west to Warm Springs fault
Salt Lake City	46.0	39.0	Repeated Holocene movement. Has three left-stepping surface traces: Warm Springs (10 km), East Bench (13 km) and main Wasatch (23 km; Cottonwood section). South end steps 7.5 km east across Traverse Range on Fort Canyon fault
Provo	69.5	59.0	Repeated Holocene movement. Extends from Traverse Range to Payson Canyon. Has overlap and right step to Nephi segment
Nephi	42.5	37.5	Repeated Holocene movement. Extends from Payson to Nephi, steps 8.5-km to Juab Valley. Separated from Levan segment by 15-km gap
Levan	30.0	25.5	One Holocene movement. Includes two major gaps (6-km net) within segment. Steps 3.5 km east and 5 km south to Fayette segment
Fayette	11.0	10.5	No Holocene movement. Has 4-km-long western strand and 9-km-long range-bounding eastern strand
Entire WFZ	383.0	343.0	Total length of all segments from end to end
All segments	366.0	326.0	Net length of all segments of the WFZ, excluding gaps
Average segment	36.6 ± 19.0	32.6 ± 16.2	Length of all segments divided by 10
Holocene segments	259.0	227.0	Sum of lengths of segments with repeated Holocene movement
Average Holocene segment	51.8 ± 12.8	45.4 ± 11.1	Length of Holocene segments divided by 5
Older segments	107.0	99.0	Sum of lengths of segments without repeated Holocene movement
Average older segment	21.4 ± 8.4	19.8 ± 6.8	Length of older segments divided by 5

bedrock ridges between deep structural basins (i.e. gravity saddles, Zoback 1983); (2) depressed structural levels in the footwall; (3) bedrock blocks (e.g. salients) stranded at intermediate structural levels between parallel strands of the fault zone; or (4) a combination of these features. Our studies show that structural boundaries along the WFZ probably have terminated or arrested the propagation of earthquake ruptures repeatedly in the Holocene (see next section).

Most persistent segment boundaries on the WFZ are associated with major bedrock blocks (salients or spurs) that extend into the basin at intermediate structural levels (Fig. 3). These salients commonly are bounded by Quaternary faults that are less active than the range-bounding faults. The bedrock spurs south of Malad City, and north of Ogden (Pleasant View, Fig. 3b) and Salt Lake City (Fig. 3c) and the Traverse Range (Fig. 3d) are salients. The Traverse Range is detached from the Wasatch Mountains along the Fort Canyon fault, which is the westward extension of the S-dipping low-angle Deer Creek fault (Bruhn *et al.* 1987). Salients can persist for millions of years as barriers to laterally propagating ruptures along a fault zone. Some persistent barriers, however, may not fully arrest the propagation of rupturing. For example, Ostenaa (1990) argues that the Provo–Nephi boundary (Fig. 3e) may be a "leaky" barrier (terminology of Crone & Haller 1991); that is, one which allows partial or sympathetic rupture of an adjacent segment as occurred in the 1983 rupture of the Warm Springs and Thousand Springs segments of the Lost River fault zone (Crone *et al.* 1987).

Several of the segment boundaries along the WFZ are associated with major en échelon (lateral) steps. These steps typically cross bedrock-cored ranges, such as at Dry Mountain (Fig. 3e, Payson salient) and between the Levan and Fayette segments (Fig. 3g), and can be considered as a variety of salient bounded by active faults on both sides. Most steps that are not associated with salients are non-persistent barriers; e.g. dePolo *et al.* (1991) and Zhang *et al.* (1991) showed that during the 1954 Fairview Peak, Nevada, earthquake surface faulting extended across several en échelon steps and, thus, failed to arrest or stop the lateral propagation of ruptures.

Cross faults or other intersecting faults also occur at persistent boundaries. This type of boundary involves oblique intersection of two or more fault traces. The cross faults typically extend into bedrock (e.g. the northern part of the Brigham City segment) (Fig. 3a). The boundary between the Collinston and Clarkston Mountain segments is formed by an E–W cross fault that links two en échelon segments. These types of fault intersections are not usually associated with reduced structural relief in either the ranges or basin and, thus, may be largely non-persistent.

Several other morphological features are present along fault segments that do not appear to be unique criteria for differentiating segment boundaries. The most common of these are geometric changes in fault zones, such as changes in fault strike, branching faults (bifurcations), some en échelon steps, and gaps in faulting.

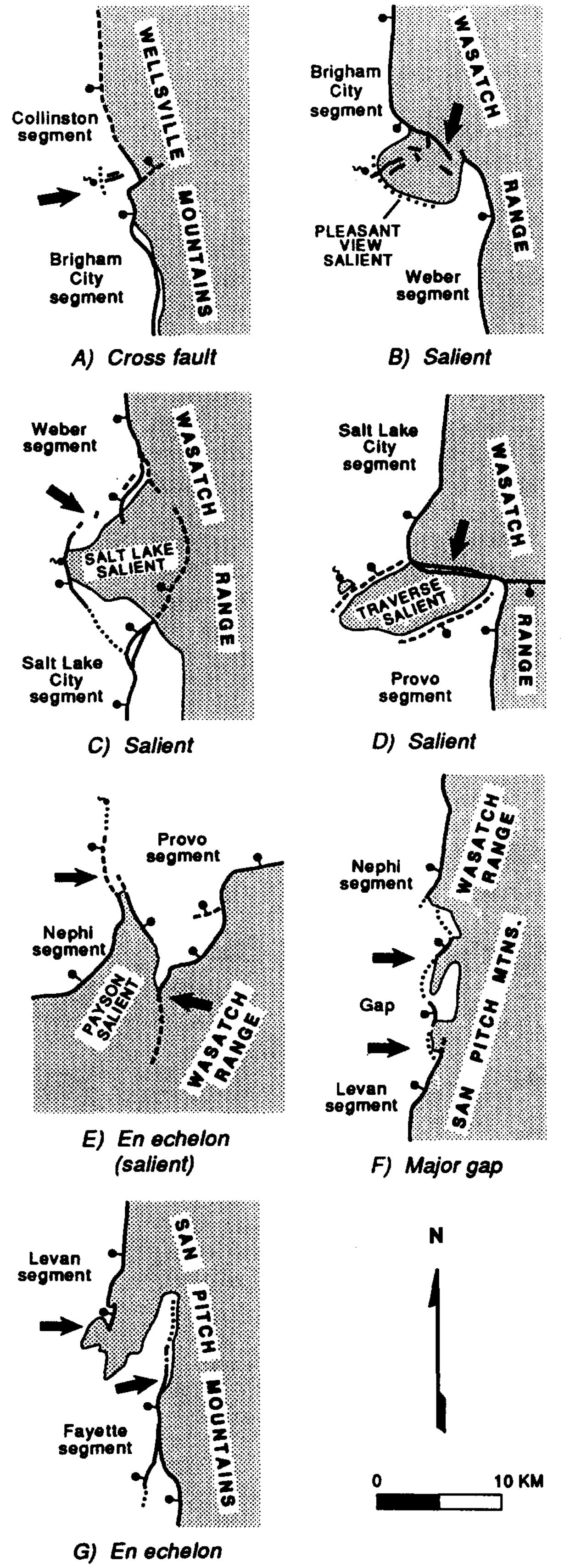

Fig. 3. Examples of map patterns at segment boundaries along the Wasatch fault zone in northern Utah. Bedrock shown by stipple pattern. Figures are listed from north (A) to south (G).

Abrupt bends in fault traces, such as the 110° bend on the Provo segment at Spanish Fork Canyon, rarely form segment boundaries or persistent barriers to rupturing. Crone & Haller (1991) found that concave bends in the down-dip directions of late Quaternary faults north of the Snake River Plain (Fig. 1) typically do not form segment boundaries, whereas convex bends may be persistent boundaries. Bruhn *et al.* (1987) suggest that bifurcations in fault zones may be areas of increased fault roughness and thus points of rupture nucleation or termination. Bruhn *et al.* (1987, table 1) identified five potential barriers to rupturing along the Salt Lake City segment of the WFZ by analyzing paleoslip directions, stress tensors, and fault-zone rupture characteristics. They suggest that non-conservative barriers at the ends of the segments (the Salt Lake Salient and the Transverse Mountains, Figs. 3c & d, respectively) and at the bifurcation zone between the southern part of the Salt Lake segment (Cottonwood section, Table 1) and the East Bench fault (Table 1) may control the propagation of ruptures during a large earthquake. Although this hypothesis cannot be tested because of a lack of good trenching sites, Personius & Scott (1990, in press) argue that the bifurcation zone is probably a less resistant barrier that has directed rupturing from the Cottonwood section away from the range front and onto the East Bench fault, thereby leaving the range-bounding fault inactive along the northern part of the segment. A similar bifurcation zone at the Springville fault on the Provo segment (Table 1) appears to be a non-persistent barrier to rupture propagation (Machette in press).

Most of the gaps in surface rupturing along the WFZ are the result of en échelon steps that are several kilometers wide. However, a 15-km-long gap in recent faulting south of Nephi (Fig. 3f) marks the boundary between the Nephi and Levan segments (Machette *et al.* in press). This boundary appears to be a barrier that has persisted for tens of thousands of years. Holocene and uppermost Pleistocene alluvium (<15 ka) is not faulted in the gap, whereas upper and middle(?) Pleistocene alluvium has been offset tens of meters. The older scarps in the gap attest to the presence of a through-going WFZ that now is inactive. Long gaps such as this may persist for hundreds of thousands of years, but do not appear to result in anomalous structural relief along the fault zone.

Patterns of en échelon steps, bifurcations and gaps are examples of the types of geometric boundaries along fault zones that rarely are associated with persistent rupture barriers. In this context, some geometrically defined segments (such as the three proposed by Machette *et al.* 1986 for the Utah Valley part of the WFZ) are not persistent rupture entities but, rather, may be building blocks for long ruptures associated with large-magnitude earthquakes.

TIMING AND RECURRENCE OF HOLOCENE MOVEMENT ON THE WASATCH FAULT ZONE

Since the late 1970s, extensive efforts have been made to date individual earthquake events along the WFZ through trenching of productive sites. As of 1987, more than 45 trenches and natural exposures had been logged and described on six segments of the WFZ (Machette *et al.* 1987, table 1); since then, several additional sites have been investigated. Most of the trench sites have provided some control on the time of most recent faulting and set limits on recurrence intervals and slip rates. Since beginning our co-operative effort in 1985, we have obtained about 50 radiocarbon dates using both conventional and accelerator-mass-spectrometry methods on charcoal and soil organic matter and 17 experimental thermoluminescence age estimates. These ages (see appendix in Machette *et al.* in press) have been used to construct a chronology of Holocene surface-faulting and recurrence intervals for the WFZ. More importantly, we have used this chronology as the primary tool for defining segments along the zone.

Recurrence intervals

Our calculations of the average recurrence interval for segments having repeated Holocene movement are shown in Table 2. The *average* recurrence interval (*RI*) on any single segment is about 1980 ± 310 years. However, there is so much variation between and within segments that this value has little meaning. The *composite* recurrence interval (*CRI*), which is defined as the average time between two faulting events anywhere on the central part of the WFZ is 395 ± 60 years. Schwartz & Coppersmith (1984) reported a maximum recurrence interval (*CRI*) of 615–666 years, but preferred a value of 444 years, which is within the error limits of our new value. Even though the two methods of calculation were somewhat different, both investigations reached basically the same conclusion—i.e. a major surface-rupturing earthquake has struck the Wasatch Front once every four centuries (on average) during the past 6000 years.

Figure 4 shows our chronology of faulting along the medial segments of the WFZ. The recurrence intervals on these segments may vary from as little as 500 years (for the past two events on the Weber segment) to as much as 4000 years (on the Salt Lake City segment). At least one segment (Provo) has had two recurrence intervals of similar duration. Of particular interest is the lack of movement along the Brigham City segment during the past 3600 years. Two faulting events occurred at about 3.6 and 4.7 ka on the Brigham City segment, and a third between 4.7 and 6–8 ka (see Machette *et al.* 1987, in press)—an average of one event every 1500–2200 years. However, the two most-recent faulting events yield a recurrence interval of only 1100 years (Fig. 4). Of the medial segments, only the Brigham City has been inactive longer than its average recurrence interval. Thus, although the seismological record for the WFZ is one of relative quiescence, the paleoseismological record suggests that a major earthquake associated with tens of kilometers of surface rupture and several meters of normal dip-slip should be expected in the future.

Table 2. Timing, number of major surface-faulting earthquakes, and recurrence intervals for Holocene movement of the Wasatch fault zone

Fault segment	Trench site	(A) Oldest event (t)* or datum (d)† (years ago)	(B) Estimated time of MRE (years ago)	(C) Time interval (A − B, years)	(D) Number of events (E) and intervals (I): E	I
Brigham City	Brigham City	4700 ± 500t	3600 ± 500	1100 ± 1000	2	1
Weber	East Ogden	3750 ± 250t	500 ± 300	3250 ± 550	4	3
Salt Lake City	Dry Creek	5250 ± 250t	1500 ± 300	3750 ± 550	2	1
Provo	American Fork	5300 ± 300t	500 ± 200	4800 ± 500	3	2
Nephi	North Creek	5500 ± 200d	≥400	4900 ± 200	3	2
Levan	Deep Creek	7300d	1000	N/A	1	0
Totals (based on segments 1–5)				17,800 ± 2800	15	10
Calculated recurrence intervals for WFZ segments that have repeated Holocene movement‡				Value and error limit (years)		
Average recurrence interval (*RI*)				1980 ± 310		
Average composite recurrence interval (*CRI*; *RI*/5)				395 ± 60		

Note: All values for age and time intervals (columns A–C) are rounded to the nearest 100 years. Ages based on calendar-corrected radiocarbon dates and thermoluminescence analyses. The average recurrence interval is determined by dividing the sum of time intervals (column C) by the sum of intervals between faulting events (column D). Time interval (column C) for Nephi segment includes time between the oldest (undated) event at site and the age of the datum; thus, value in column (C) is a maximum. MRE, most recent faulting event; N/A, not applicable.

*t—time of oldest well-dated faulting event (rounded to nearest 50 years).

†d—age of datum from dating, stratigraphic, or tectonic considerations (rounded to nearest 50 years).

‡Three significant figures are used to compute average values of recurrence from the totals in columns (C) and (D). Values are rounded to nearest 5 years.

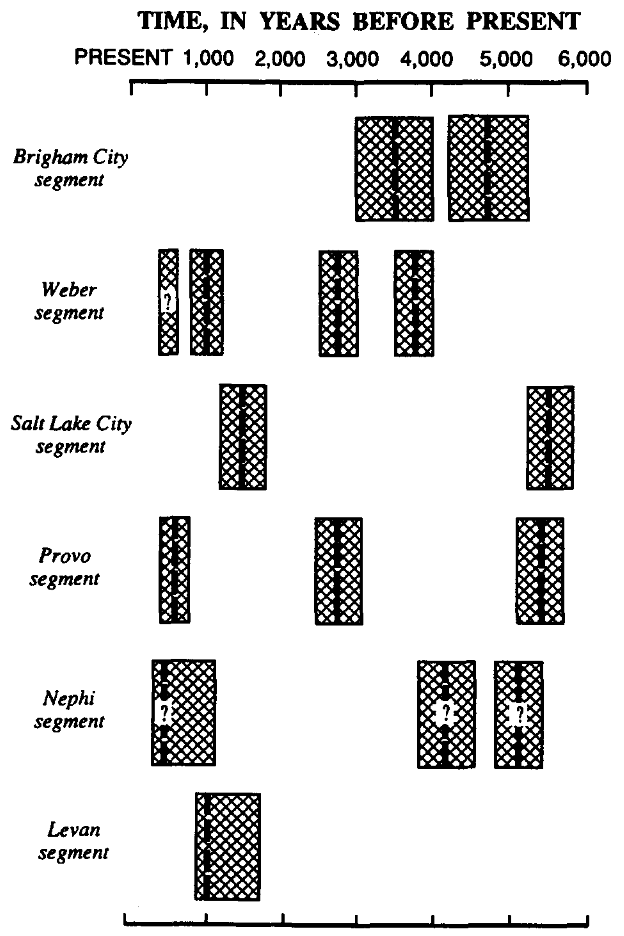

Fig. 4. Timing of movement on segments of the Wasatch fault zone during the past 6000 years. Heavy-dashed line indicates our best estimates for time of faulting; cross-hachure pattern indicates likely time limits as determined from radiocarbon and thermoluminescence age estimates. (See Machette *et al.* in press, for catalog and discussion of dates used in determining times of fault movement.)

Holocene faulting patterns

Several interesting patterns evolve from the chronology depicted in Fig. 4. One pattern is the apparent random distribution of faulting events during the 1500–6000-year time interval. This apparent random pattern could be interpreted as one of northward-sweeping waves of fault activity. There could be three waves of activity, the first affecting the northern half of the WFZ from about 5500 to 3000 years ago. The second wave sweeps from south to north cross the WFZ from the Nephi segments (4200 years ago) to the Weber segment (1000 years ago), and the third wave (the most recent cluster of activity; 400–1000 years ago) extends from the Nephi through Weber segments in a more random fashion. Noticeably missing is movement on the Brigham City segment in the last two waves, which might be explained by proximity to the intersection of the V-shaped belt of tectonism and the WFZ. In addition, the Salt Lake City segment appears to have been inactive during the last (third) wave, perhaps owing to its characteristically large displacement per event (4.5 m at Dry Creek), and its inherently long recurrence interval (about 4000 years, Fig. 4) (Schwartz & Lund 1987). If this wave pattern is real, it might be associated with loading of adjacent segments owing to a small but regionally significant component of left-lateral slip, as indicated by the WNW orientation of least principal stresses in the eastern Basin and Range province (Zoback & Zoback 1980). The least principal stress orientation for the WFZ appears to be approximately E–W as indicated by slip indicators on bedrock fault scarps and from focal mechanisms of small earthquakes in the region (Zoback 1983). However, as previously noted in the discussion of the Borah Peak earthquake, some

Table 3. Historic surface-rupturing earthquakes in the vicinity of the Wasatch fault zone

Name (date of earthquake	Magnitude (number of events	Fault(s) (segment)	Rupture length (km) Total	>25 cm NVD	NVD (m) (and net slip, m) Max.	Aver.	Total slip (m) (and source)
Hansel Valley (12 March 34)	M6.6 (single?)	Hansel Valley	11.5	6e	0.5	0.2e	n.d.
Hebgen Lake (18 August 59)	M_S7.5	Red Canyon	23	21e	6.7	2.4	6.8 (SD)
	M_W7.3	Hebgen	14.5	11e	6.1	1.6	1.0 (SD)
	(double)	Both faults	35 ± 5	26–32		(2.1)	10 (net GD)
Borah Peak (28 October 83)	M_S7.3 M_W6.8–7.0 (single)	Lost River (Thousand Springs)	36 ± 3	26 ± 2e	2.7 (2.9)	0.8 (1.0)	1.5–2.2 (GD) 1.5 (SD)

Symbols: NVD, net vertical displacement; e, estimated value; n.d., not determined. Magnitudes: **M**, unspecified Richter; $\mathbf{M_S}$, surface-wave; $\mathbf{M_W}$, moment. Slip determinations: GD, geodetic data; SD, computed from seismic data. Data from following sources: Hansel Valley, Utah—Shenon 1936, Slemmons 1977, Doser 1989; Hebgen Lake, Montana—Witkind *et al.* 1962. Witkind 1964, U.S. Geological Survey 1964, Doser 1985, Doser & Smith 1985. Hall & Sablock 1985, Smith *et al.* in press; Borah Peak, Idaho—Doser & Smith 1985, Crone *et al.* 1987, Smith *et al.* in press.

faults that have a significant component of oblique-slip in the subsurface might not produce geomorphic or structural evidence of oblique-slip at the surface (Crone *et al.* 1987).

A second pattern is more striking. There is strong evidence for a recent period of temporal clustering of large earthquakes; i.e. a strong grouping of surface-rupturing earthquakes on the WFZ over a geologically short time interval. If the most recent event on the Salt Lake City segment occurred about 1500 years ago (Fig. 4), then between 400 and 1500 years ago movement occurred on five of the six segments of the WFZ that have been active in the Holocene. The recent clustering (six faulting events during an interval of 1100 years) indicates that one major surface-rupturing event occurred every 220 years. In contrast, we estimate that a surface-rupturing earthquake occurred once every 395 ± 60 years during the past 6000 years along the WFZ between Brigham City and Nephi (Table 2). In addition, we have no evidence for a major surface-rupturing earthquake on the WFZ during the past 400 years, which is the youngest time we allow for the Weber segment and our best estimate for the most recent event on the Nephi segment. These relations point strongly to a process of temporal clustering of large-magnitude earthquakes on the WFZ, but the process seems to be intermittent through time. This pattern of temporal clustering is similar to that of the central Nevada–eastern California Seismic Belt in the western part of the Basin and Range province, where 11 earthquakes of **M** > 6.5 have occurred since 1860 (dePolo *et al.* 1991). Although the time scale of the clustering is different—130 years vs 1100 years—we consider the central Nevada–eastern California Seismic Belt to be a historic analog for movement on the WFZ during the past 1500 years.

COMPARISONS WITH THE WASATCH FAULT ZONE

The empirical relations between historic earthquakes and normal faulting (Slemmons 1977, Bonilla *et al.* 1984) and recent studies of prehistoric faulting in the region are our best analogs for the expected nature of future surface rupturing during large-magnitude earthquakes on the WFZ.

Historic earthquakes and surface faulting

Large-magnitude (**M** ≥ 7) earthquakes have occurred in two regions of the western interior of the United States in historic times: (1) an elongate NE-trending zone known as the central Nevada–eastern California Seismic Belt (Wallace & Whitney 1984, dePolo *et al.* 1991), which has been the locus of most of the historic surface faulting in the Basin and Range province; and (2) the northern part of the Intermountain Seismic Belt (ISB), which is characterized by abundant Holocene and late Pleistocene faulting, but only three historic earthquakes that were accompanied by surface rupturing. As originally defined by Smith & Sbar (1974), the ISB is the active seismic zone between the Colorado Plateau, middle Rocky Mountains and northern Rocky Mountains provinces to the east, and the extended terrain of the Basin and Range province to the west (Fig. 2). Arabasz *et al.* (1987) show the ISB as an arcuate belt of pronounced seismicity that extends from southern Nevada and northern Arizona to northwestern Montana and Idaho. The three **M** > 6.5 earthquakes associated with demonstrable surface rupturing in the northern ISB (Table 3) are: the 1959 $\mathbf{M_S}$7.5 Hebgen Lake earthquake in southwestern Montana (Doser 1985), the 1983 $\mathbf{M_S}$7.3 Borah Peak earthquake in central Idaho (Doser & Smith 1985, Smith *et al.* in press) and the 1934 **M**6.6 Hansel Valley earthquake in northern Utah (Doser 1989).

Faulting events in the central Nevada–eastern California Seismic Belt have included both normal dip-slip and oblique-slip (dePolo *et al.* 1991), whereas the faulting events in the ISB have been primarily dip-slip. Therefore, the following discussion focuses on ISB earthquakes and their relation to the WFZ.

The Hebgen Lake earthquake was a complex normal-faulting event that probably occurred along reactivated older (Laramide) faults (Witkind 1964). Doser's analysis of seismic data from the Hebgen Lake earthquake indicates a composite of two subevents 5 s apart on one or more S-dipping fault planes. Surface rupturing occurred on two faults during this earthquake: an average of 2.4 m of surface offset along 23 km of the Red Canyon fault, and an average of 1.6 m of surface offset along 14.5 km of the Hebgen fault (U.S. Geological Survey 1964, Witkind *et al.* 1964). Because the two traces overlap, the net rupture length for this earthquake is between about 29 and 38 km; Witkind (1964) reported a total rupture length of 35 km (Table 3). However, the occurrence of small-displacement ruptures in heavily forested terrain leads us to suspect that the rupture length for the Hebgen Lake earthquake was probably underestimated by at least several kilometers. In addition, about 1 m of sympathetic movement occurred along 3 km of the Madison fault, 15 km west of Hebgen Lake (U.S. Geological Survey 1964). A maximum of 6.1 m of surface offset occurred during the Hebgen Lake earthquake (Witkind *et al.* 1962), with the bulk of the movement expressed as subsidence in the adjacent Yellowstone basin. In a more recent study, Hall & Sablock (1985) reported an average surface displacement of 2.1 m for the whole fault zone. Savage & Hastie (1966) estimated a maximum of 10 m of slip at depth from modeling of the geodetic data. In summary, it appears that the Hebgen earthquake, the largest recorded in the ISB, produced an average of several meters of surface rupturing along the two faults having a total length of 35 ± 5 km, and as much as 10 m of net slip at depth. The estimated seismic moment ($\mathbf{M_0}$) (Aki 1966) for the main 1959 faulting event is 1.0×10^{27} N m, which equates to an estimated moment magnitude ($\mathbf{M_W}$) of 7.3 (cited in Arabasz *et al.* 1987) using the empirical relations developed by Hanks & Kanamori (1979).

In October of 1983, the ISB was struck by the $\mathbf{M_S}$7.3 Borah Peak, Idaho, earthquake. The earthquake was associated with 36.4 ± 3.1 km of surface rupturing that was concentrated along the Thousand Springs segment of the Lost River fault zone (Crone *et al.* 1987). Additional, subsidiary ruptures extended north on a basinward splay into the Warm Springs Valley and along the adjacent range-bounding Warm Springs segment of the Lost River fault zone. Of the total surface-rupture length reported for the earthquake, only 26 km (72%) had a continuous offset of ≥25 cm (Crone *et al.* 1987, fig. 4). An average of 0.8 m of vertical offset (1.0 m net slip) occurred along the Thousand Springs segment (Table 3). Geodetic data suggests about 1.56 m of offset at the surface and as much as 2.2 m of net slip along the fault at depth (Stein & Barrientos 1985), whereas body-wave modeling indicates about 1.5 m of slip (Doser & Smith 1985). Measurement of slickenlines and grooved surfaces on the exposed fault plane indicated an average of 17% left-lateral slip, whereas the preferred focal plane solution suggested about 30% left-lateral slip (Crone *et al.* 1987). The estimated $\mathbf{M_0}$ for the 1983 faulting event is 2.1×10^{26}–3.1×10^{26} N m, which equates to an estimated $\mathbf{M_W}$6.8–7.0 (cited in Arabasz *et al.* 1987).

The smallest of the three historic surface-rupturing earthquakes in the ISB—the M6.6 1934 Hansen Valley, Utah, earthquake—produced about 11.5 km of surface faulting (Slemmons 1977). This faulting occurred mainly within the basin floor of the valley (Shenon 1936) and was not associated with a major range-bounding fault. The fault's recurrence interval and slip rates appear to be an order of magnitude less than that of the WFZ (McCalpin *et al.* 1987, Doser 1989). The maximum displacement was 52 cm (Slemmons 1977), but the average was probably ≤20 cm; it appears that this earthquake was only slightly above the threshold magnitude for normal surface faulting, which is probably $\mathbf{M_L}$6.3 ± 0.2 (Arabasz *et al.* 1987) or $\mathbf{M_S}$6.0–6.25 (Doser 1989) for this portion of the Basin and Range province.

Prehistoric surface faulting in the region

One way to estimate the magnitude of prehistoric earthquakes on the WFZ is to compare its paleoseismologic parameters (length and offset) with historic surface-rupturing faults in the region using the empirical relations derived by Slemmons (1977) or Bonilla *et al.* (1984). However, all but three of the historic surface ruptures in the interior of the western United States are associated with the central Nevada Seismic Belt, and the majority of these Nevada earthquakes have large components of oblique-slip and significant lengths of small vertical displacement (<25 cm) that have produced scarps which are easily obliterated. Because the relations between length and offset along surface ruptures and earthquake magnitude are different for normal dip-slip vs strike-slip faulting (see Slemmons 1977, Bonilla *et al.* 1984), a more reasonable comparison might be made with the historic surface faulting that occurred closer to the WFZ and within the ISB. In addition, comparisons between the WFZ's paleoseismic data and segmented latest Pleistocene and Holocene faults in the northern part of the ISB can provide valuable insight into the nature and style of segmentation of normal faults in the region.

As previously mentioned, the northern part of the ISB is largely coincident with a belt of young faults (<15 ka) that form a right-stepping en échelon pattern from the northern part of the WFZ northeastward through the Cache, Bear Lake and Star Valleys, and from Jackson Hole to the Yellowstone area (Fig. 1); from Yellowstone, it trends westward and includes the 1959 movement on the Hebgen and Red Canyon faults, and young movement on the Centennial fault. The ISB extends across southwestern Montana and central Idaho as a corridor of NNW-striking, young range-bounding fault zones that typically have their highest slip rates, most recent movement, and maximum throw along the medial part of the fault zones (see Crone & Haller 1991).

The regional studies of late Quaternary surface faulting along the belt of young tectonism suggest a common range of segment lengths for range-bounding faults (Table 4) believed to be associated with large-magnitude (M ≥ 7) earthquakes. Figure 5 summarizes the lengths of segments found in two classes of faults: (1) those along

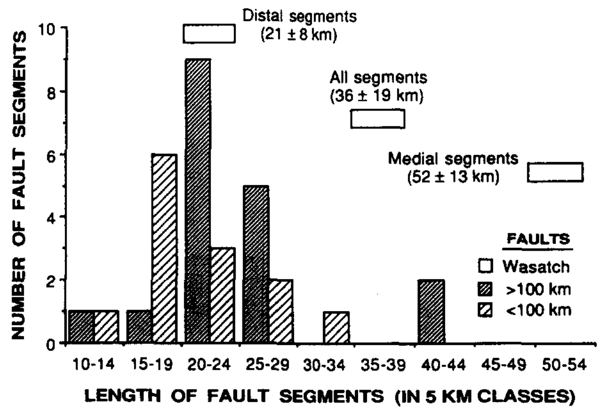

Fig. 5. Histogram of proposed segment lengths for late Quaternary fault zones that have been active in the past 15 ka in the northern Basin and Range province and northern part of the Intermountain Seismic Belt. Average length of segments: 24.6 ± 7.6 km on fault zones >100 km long; 19.8 ± 6.4 km on fault zones <100 km long. Lengths of various types of Wasatch fault zone segments are shown for comparison.

major range fronts that are typically >100 km long (the Beaverhead, Lemhi, Lost River and Wasatch fault zones) (Fig. 1) and (2) those along lesser range fronts that are typically <100 km long (the East Bear Lake, East Cache, Red Rock, Star Valley and Teton faults) (Fig. 1). The proposed segments on the longer faults range from 18 to 43 km in length and average about 25 ± 8 km, whereas the shorter faults have segments that range from 11 to 32 km in length and average about 21 ± 6 km (Table 4).

Some of the differences between the length of segments along historic and prehistoric faults probably can be explained by differences in slip-rate, slip-orientation and scale of mapping. For example, careful mapping of modern surface ruptures, such as those that formed during the 1983 Borah Peak earthquake (Crone *et al.* 1987, fig. 4), shows that as much as one-quarter of the length (9 km) may be of small (<25 cm) displacement (Table 3). Small ruptures might not be recognized along prehistoric faults solely on the basis of surficial geologic mapping or trench studies; thus, ancient rupture lengths may be underestimated in comparison with historic faults. If small-displacement ruptures overlapped an adjacent fault segment, even careful trenching may fail to detect a second faulting event on the adjacent segment (and vice versa).

Magnitude estimates for prehistoric WFZ earthquakes

Seismological and geological studies of three recent earthquakes suggest that rupture lengths ranging between 11 and 40 km have been associated with historic earthquakes of M_S6.6–7.5 (M_w6.8–7.3) and have primarily normal dip-slip displacement (Table 3). For comparison, studies of late Pleistocene and Holocene normal dip-slip faulting in the same region suggest that segment lengths average between about 20 and 25 km for prehistoric faulting along major uplifted ranges (Table 4). However, the WFZ, which is by far the longest normal fault zone in the western United States, is characterized by segments that are about twice as long (average length 52 ± 13 km) on the central active part and about the same (21 ± 8 km long) on the distal, less active portions (Table 1).

Holocene surface displacement on the medial segments of the WFZ typically has averaged between 2 and 3 m, with a maximum of about 4.5 m. Thus, the length (40–70 km) and surface-displacement (2–3 m) values for the medial segments of the WFZ are as large as those associated with historic faulting in the region. Both the Hebgen Lake and Borah Peak earthquakes occurred at depths of about 15 km (Smith *et al.* in press), which relate to a width of about 20 km on a fault plane that dips 50–60°. If you assume a similar geometry and depth for the WFZ, the seismic moment (M_0, Aki 1966) would have been 5.3×10^{26}–13.9×10^{26} dyne-cm for the prehistoric earthquakes on the WFZ. Using the relation of $M_W = (2/3) \log M_0 - 10.7$ (from Hanks & Kanamori 1979), the seismic moment converts to M_W7.1–7.4. The lesser value reflects 2 m of surface displacement on a 40-km-long segment (i.e. Brigham City or Nephi), whereas the greater value reflects 3 m of surface displacement on a 60–70-km-long segment (i.e. Weber or Provo). Using

Table 4. Length of proposed segments on late Quaternary fault zones, northern part of the Intermountain Seismic Belt

Fault zones >100 km long	Lengths (km, N to S) ($\bar{x}$ = 24.6 ± 7.6 km)*	Segmentation reference
Lost River, Idaho (141 km)	25, 18, 22, 22, 29, 25 ($\bar{x}$ = 23)	Crone & Haller (1991)
Lemhi, Idaho (150 km)	23, 23, 12, 43, 29, 20 ($\bar{x}$ = 25)	Crone & Haller (1991)
Beaverhead, Idaho (151 km)	20, 20, 23, 21, 42, 25 ($\bar{x}$ = 25)	Crone & Haller (1991)
Wasatch, Idaho and Utah (383 km)	17, 19, 30, 40, 61, 46, 69.5, 42.5, 30, 11 ($\bar{x}$ = 36)	This report, Machette *et al.* in press
Fault zones <100 km long	**Lengths (km, N to S) ($\bar{x}$ = 20.7 ± 5.6 km)**	**Segmentation reference**
Red Rock, Montana (27 km)	11, 16 ($\bar{x}$ = 14)	Stickney & Bartholomew 1987, Crone & Haller 1991
Teton, Wyoming (70 km)	24, 20, 20 ($\bar{x}$ = 21)	Susong *et al.* 1987, Byrd *et al.* 1988, Smith *et al.* 1990
Star Valley, Idaho (40 km)	24, 16 ($\bar{x}$ = 20)	Piety *et al.* 1986, Piety 1987
East Cache, Utah (55–62 km)	26, 15, 14–23 ($\bar{x}$ = 18–21)	McCalpin 1989
East Bear Lake, Utah & Idaho (≥78 km)	≥20, 26, 32 ($\bar{x}$ ≥ 26)	McCalpin 1990

*Wasatch fault zone not included in calculation of length.

similar parameters, Arabasz *et al.* (1987) calculated a maximum magnitude of M_S7.5–7.7 for the WFZ. Clearly, the WFZ poses a viable hazard to the urban population of Utah, both in terms of the recurrence and size of large-magnitude earthquakes.

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