RECOMMENDED SETBACKS FROM ACTIVE NORMAL FAULTS

by
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ABSTRACT

The geometry of near-surface ground breakage was analyzed from 40 trenches across Quaternary normal faults to help define reasonable setback distances. From each of the trench logs (28 on the Wasatch Fault, 11 on other Great Basin faults) eight parameters characteristic of surface rupture style were measured. Parameters included: 1) position of the main fault in relation to scarp morphology, 2) dip of the main fault, 3) number of faults on the upthrown block, 4) width of the upthrown block fault zone, 5) number of faults in the downthrown block, 6) width of the downthrown deformation zone, 7) ratio of antithetic to main fault displacement, and 8) degree and type of tilt or drag. A typical rupture event on the Wasatch Fault resulted in a 2-3 m displacement along a main fault lying near the scarp mid-point (48% ± 11% of distance from base to crest) with a dip of $78^{o} \pm 10^{o}$, often fronted by a gouge zone 0.3-0.6 m wide. A single minor fault typically occurs on the upthrown block within a meter of the main fault, in contrast to an average of four faults on the downthrown block over a width of 12-14 m. Tilt or drag occurs in 50% of the cases, averaging 9^{o} over a distance of 5 m from main fault.

The typical rupture and ensuing scarp degradation scenario define a zone of hazardous geologic processes to be avoided in siting structures. On smoothly sloping, previously unfaulted terrain, setbacks from the inferred fault trace of 40 feet on the upthrown side and 50 feet on the downthrown side are recommended as minimums. For pre-existing fault scarp areas, setbacks of 20 feet from the 30% slope break at the scarp crest, and 30 feet from the 30% slope break at the scarp base are recommended. In many areas, the standard building setback from lot boundaries (20-50 feet) would be an appropriate setback from the non-buildable area (>30% slopes) of the fault scarp face. Data further suggest that building within graben should only be allowed after a detailed site investigation, wherein building recommendations are based on extensive trenching studies.

INTRODUCTION

Current research into earthquake hazards reduction is resulting in large- to medium-scale (1:24,000-1:50,000) maps which carefully delineate the surface traces of active faults. For normal faults, the most detailed study has been that of the Wasatch Front, Utah; the entire fault system (the 400 km-long Wasatch Fault and the 60 km-long East Cache Fault) is being mapped at 1:50,000 scale (Scott and Shroba, 1985; Machette, in prep.; Nelson and Personius, in prep.; Personius, in prep.; McCalpin, in prep.). The next step is implementation of hazard-reducing measures, including: 1) specifying the extent of the hazardous zone surrounding the active fault trace, and 2) defining the limitations to particular land uses which result from a high potential for surface rupture. Previous regulations addressing those problems, particularly the Alquist-Priolo Special Studies Zone Act of 1975 in California (Hart, 1974), have concentrated on strike-slip faults.

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However, the pattern and style of normal fault surface rupture is distinctly different than that of strike-slip faults (Bonilla, 1982). Therefore, this paper seeks to summarize what is known of the deformation style of active normal faults, and how that style directly influences land uses within the fault zone. Because building setbacks are commonly used to control placement of structures, definition of safe setback distances is the major recommentation of this study.

The data base for faulting style comes from two sources. First, published works on historic normal surface-rupturing earthquakes yield data on areal patterns of ground breakage and on scarp formation. Second, trenches excavated across historic and pre-historic fault scarps reveal the deformation style of particular faults. Because this study was initiated to make recommendations for the Wasatch Fault, 28 logs of trenches, artificial cuts, and natural exposures of the Wasatch Fault were examined (Fig. 1, Appendix A). In addition, 11 other trench logs were measured from the

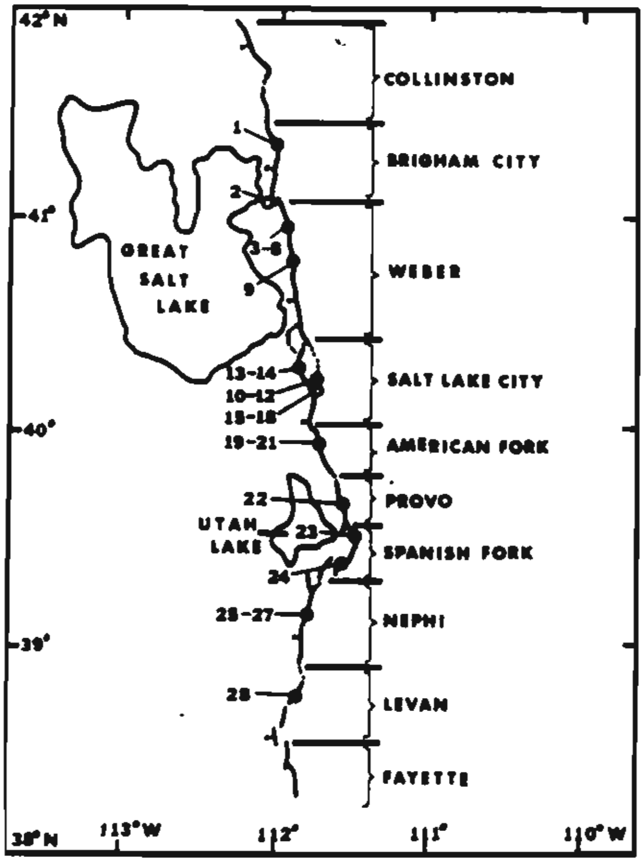


Fig. 1. Map of the Wasatch Fault Zone, Utah (heavy line, center, bar-and-ball on downthrown side) showing the 10 segments and trenches used in this study (open circles). Trench numbers are keyed to Appendix A. Segment data from Anderson, in press.

East Cache Fault, Utah (1), the Lost River Range Fault, Idaho (3), the Pleasant Valley Fault, Nevada (1), the Sierra Nevada Fault at Lone Pine, California (1), and the Sangre de Cristo Fault, Colorado (5)(Appendix A).

DEFORMATION PATTERNS

Surface rupture can be described in large-scale or small-scale patterns. In the following discussion, large-scale patterns include the overall areal distribution of surface breaks over the entire length of the fault. Small-scale patterns include the geometry of fault scarps at individual locations along the fault, the number and spacing of subsidiary fractures, and localized tilting or drag. A brief review will be made of historic rupture patterns in the Basin-Range Province, and their implication for the Wasatch Fault.

Large-scale Patterns

Previous compilations (e.g. Bonilla, 1970; 1982) have defined areal terms such as the main fault and subsidiary faults (secondary and branch faults; Fig. 2). Historic normal-fault ruptures in the Basin-Range Province

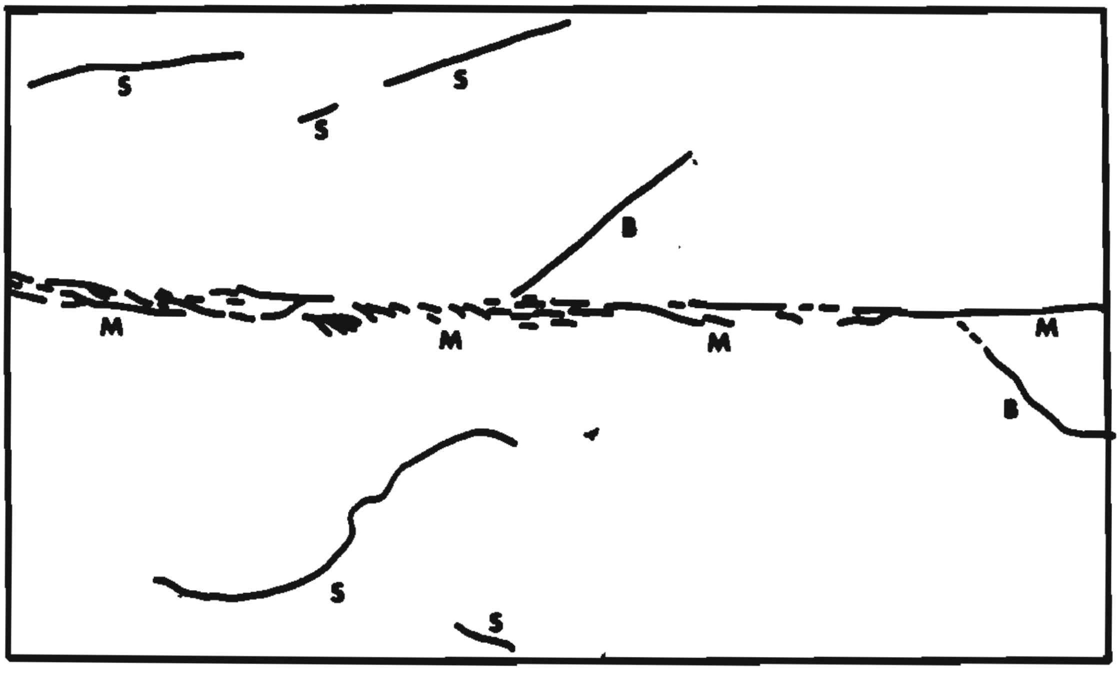


Fig. 2. Map patterns of surface faulting, after Bonilla (1982, Fig. 2). The diagram is based on actual rupture patterns in historic events of strike-slip, normal, and reverse offset. Letters M, B, and S designate main, branch, and secondary faults.

have broken dominantly along main and secondary faults (Hebgen Lake, 1959; Dixie Valley, 1954; Fairview Peak, 1954; Rainbow Mountain, 1954; Pleasant Valley, 1915; Owens Valley, 1872), with branch faults more rare (Hebgen Lake, 1959; Fairview Peak, 1954; Bonilla, 1970, Table 3.1). Secondary faulting length varied widely, ranging from 6% to 95% of main fault rupture length (Bonilla, 1970, Fig. 3.5). Mapping in progress for the Wasatch Fault shows that secondary faults are common (Scott and Shroba, 1985; Personius, in prep., Machette, in prep.), but branch faults (like the East Bench fault of the Salt Lake segment) are scarce. Can the Wasatch Fault be relied upon to rupture only pre-existing breaks during the next major faulting event? Bonilla (1970, p. 68), in reviewing historic normal fault ruptures, states that almost all major displacements followed pre-existing faults for all or nearly all of their extent. In addition, at least one-third of all subsidiary faulting occurred on easily-recognizable pre-existing faults. The well-documented Borah Peak, Idaho earthquake scarp of 1983 (Crone and Machette, 1985) followed pre-existing scarps for much of its length. However, examples are also cited by Myers and Hamilton (1964, p. 85) of Hebgen Lake, Montana, faulting (1959) possibly advancing into unfaulted rock. Bonilla (1970, p. 68) further cites examples of historic faulting criscrossing previous scarps and diverging from pre-existing faults by 60-300 m. On the Wasatch Fault no historic surface-faulting has occurred, but most fault scarps display evidence of multiple Holocene offsets. With the limited data set available (28 trenches over a 400 km fault length), the conservative inference would be that future surface rupture could occur on any previously-established main, secondary, or branch fault. In any individual event, ruptures would probably be confined to the fault segment containing the earthquake epicenter, with possible spillover of ruptures to the adjoining segments. The original six segments of the Wasatch Fault (Schwartz and Coppersmith, 1984) have recently been expanded to 10 segments by Machette and others (in Anderson, in press) and Machette (in press).

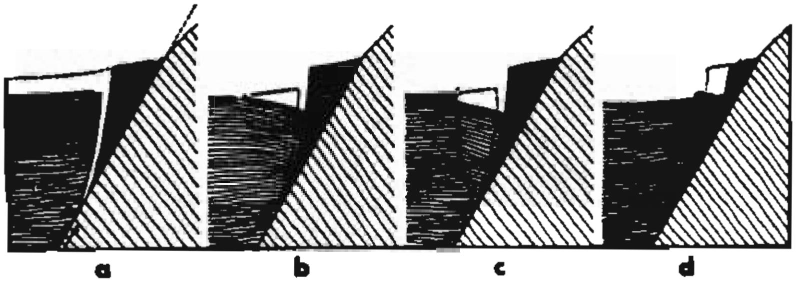


Fig. 3. Illustration of Gilbert's theory for the formation of complex normal fault scarps. a. tension fissure, b. surface tilt, c. graben, and d. step-fault. Diagonal lines indicate bedrock, horizontal lines show unconsolidated deposits. From Gilbert (1890, p. 355).

Small-scale Patterns

The majority of this paper concerns small-scale patterns of surface rupture and how these patterns influence building setbacks. Gilbert (1890) was the first to recognize the several surface variations of normal fault rupture in his study of the Wasatch and other Basin-Range faults (Fig. 3). The fault may create a single, translational break with no rotation resulting in a simple scarp (as defined by Slemmons, 1957). Conversely, steepening of the fault plane as it approaches the surface often leads to opening of tension fissures. Subsequent collapse during shaking may form tilted blocks, graben, or step faults (b, c, and d respectively, Fig. 3), creating complex scarps as defined by McCalpin (1983, p. 39). The percentage of total fault length subjected to each kind of deformation has not been published for an historic event, but McCalpin (1983, Appendix B) reports that, for 90 randomly-spaced profiles across a 120 km length of the Sangre de Cristo Fault, Colorado, 59% of scarps are simple, 17% are complex-graben, 10% are complex-tilted, and 14% are complex-stepfaulted. The asymmetry of surface breakage contrasts with that of the more nearly vertical strike-slip faults, in which rupture (and setbacks) are usually symmetrical about the main fault trace.

In order to construct a physical process model on which to base reasonable setbacks, 40 trench logs were carefully examined to define the typical style of surface breakage. Eight parameters were measured on each log, and the means, medians, modes, and standard deviations were calculated, both for the Wasatch Fault (28 trenches) and other faults (11 trenches). Summary statistics are given in Table 1; all data are listed in Appendix A. In the following sections each parameter will be described; their relevance to building setbacks is discussed in a later section.

Position of the Main Fault

It is important for anticipating future ruptures to know exactly where under a fault scarp the actual fault trace lies. Modeling of fault scarp evolution (e.g. Nash, 1980; Hanks and others, 1984) assumes that the scarp is symmetrical and the main fault lies exactly at the scarp center, under the steepest slope segment. Actual field data, however, show that scarps are rarely symmetrical (Nash, 1986) and that the main fault may be found at various positions under the scarp. For trench logs studied, the horizontal position where the main fault would intersect the ground surface was measured from the scarp base. If scarp evolution models are valid, this position should be 50% of the horizontal distance from the scarp base to scarp crest. Data show that the actual position is 48±11% on the Wasatch Fault, and 45% ± 14% on all trenches studied (Table 1). The data are normally distributed (Fig. 4a) and statistics indicate that on the Wasatch Fault the zone on scarp from 37% to 59% of horizontal distance from the

TABLE 1 SUMMARY STATISTICS OF FAULT-GEOMETRY PARAMETERS (definitions given in Appendix A. Explanation)

	MAIN FAULT		UPTHROWN BLOCK		DOWNTHROWN BLOCK			
	Position of Fault	Apparent Dip	No. of Faults	Width of Deformed Zone	No. of Faults	Width of Zone	% of Antithetic	tilt
WASATCH DATA								
Number	15	29	29	29	29	29	15	29
Mean	48%	78°	2.8	1.4 m	4.6	14.9 m	14%	9.5°/5.5 m
Std. Deviation	11%	10°	2.0	1.6 m	7.0	26.3 m	13%	16°/13 m
Modal Class	35-40%	70-75%	2	0-1 m	1	0-1 m	NC	0-5°
Median	49%	76.5°	2	0.6 m	2	3.0 m	NC	2°
ENTIRE DATA SET								
Number	23	40	40	40	40	40	19	40
Mean	45%	77°	3.3	1.8 m	4.1	12.7 m	18%	9.4°/4.8 m
Std. Deviation	14%	10°	3.0	2.4 m	6.7	23.2 m	19%	15.5°/11.6 m
Modal Class	40-45%	70-75°	2	0-1 m	1	0-1 m	NC	0-5°
Median	45%	79°	2	0.7 m	2	3.0 m	NC	2.5°

NC not calculated due to small data set.

scarp base to crest should encompass most (67%) of main surface ruptures (Fig. 5).

Apparent Dip of the Main Fault

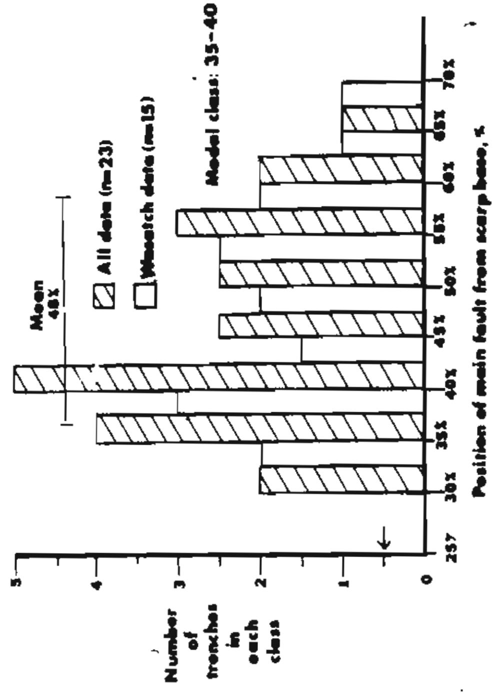
For designing subsurface structures such as buried utilities, the dip of the main fault plane must be known along with its position under the fault scarp. Apparent dips for the Wasatch Fault (78 ± 10°) and for other faults (79 ± 8°) are strikingly similar. In several instances, fault planes steepened within 1.5-3.0 m of the ground surface by 12°-20° (Appendix A). Fig. 4b shows that the distribution for all trenches is very similar to that for Wasatch trenches.

Number of Faults on the Upthrown Block

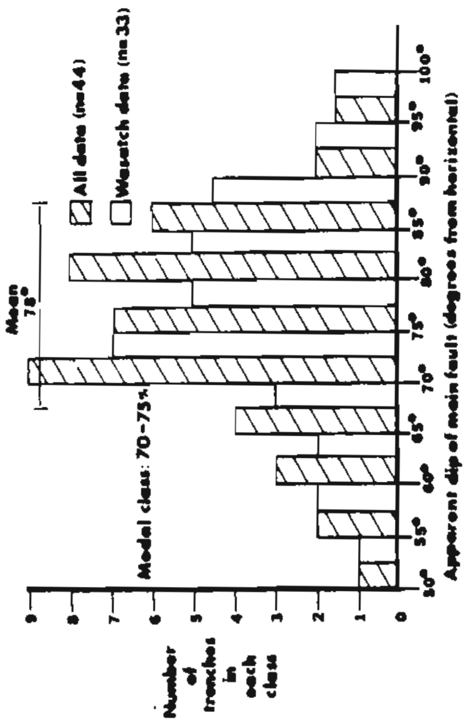
Although complex faulting is usually restricted to the downthrown block, many trenches expose subsidiary faults within roughly 2 m of the main fault within the upthrown block. In the compilation of trench data, the main fault is counted with upthrown block faults (1's in Appendix A). If the main fault consists of a gouge zone, the fault number is 2 (App. A) and the gouge zone width is given in the next column. Separate fractures within the upthrown block occur on 9 of the 29 faults studies (31%); however, this number may be an underestimate, because many trenches do not extend very far above the main fault into the upthrown block. Displacements on such minor faults normally amount only to several to tens of centimeters. The frequency distribution is not normal, being dominated by 1's and 2's (Fig. 4c). The modal frequency class is 2 faults, which usually represents a single main fault and accompanying gouge zone.

Width of Deformation Zone on the Upthrown Block

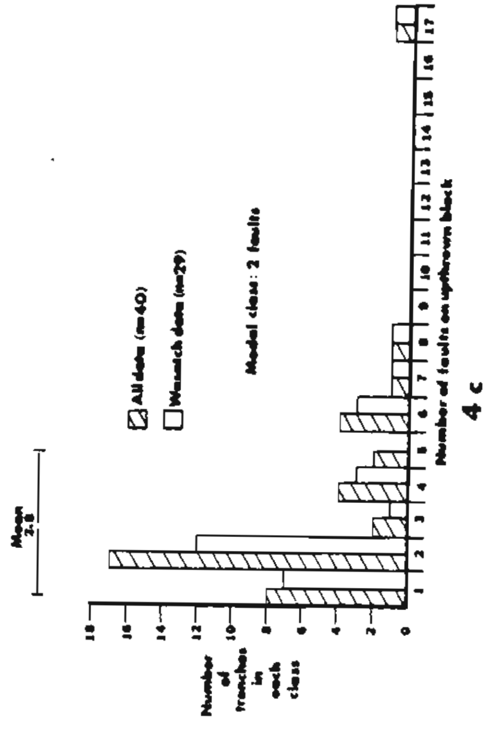
The secondary faults described above occupy a zone with an average horizontal width of 1.4 m on the Wasatch Fault and 2.6 m on other faults (Table 1). Many trenches have a single main fault (width of zone=0) so the frequency distribution is not normal (Fig.4d). However, several trenches


Number of trenches in each class
0
1
2
3
4
5
Mean 48%
All data (n=23)
Wasatch data (n=15)
Modal class: 35-40%
25%
30%
35%
40%
45%
50%
55%
60%
65%
70%
Position of main fault from scarp base, %

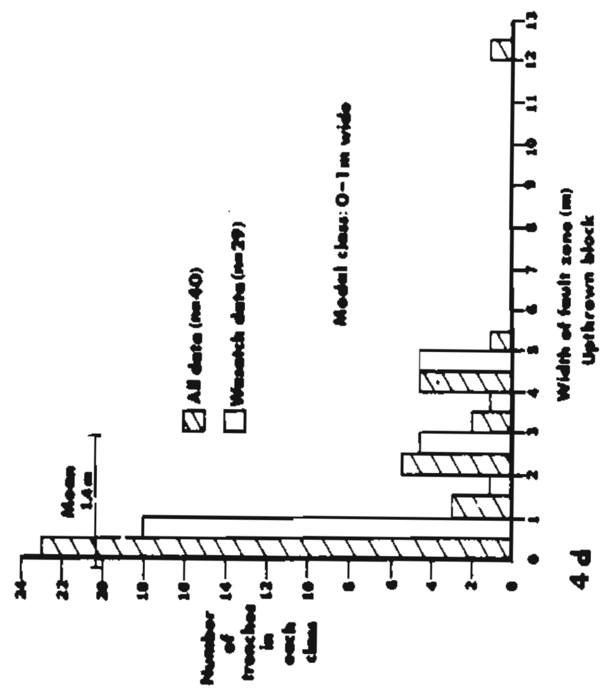
4a


Number of trenches in each class
0
1
2
3
4
5
6
7
8
9
Mean 78°
All data (n=44)
Wasatch data (n=33)
Modal class: 70-75%
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
Apparent dip of main fault (degrees from horizontal)

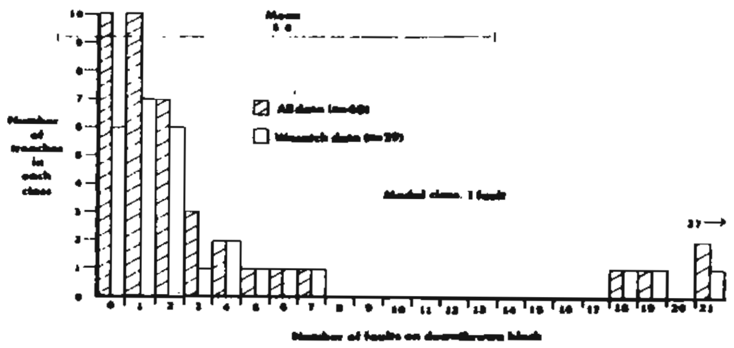
4 b


Number of trenches in each class
0
2
4
6
8
10
12
14
16
18
Mean 2.8
All data (n=40)
Wasatch data (n=29)
Modal class: 2 faults
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Number of faults on upthrown block

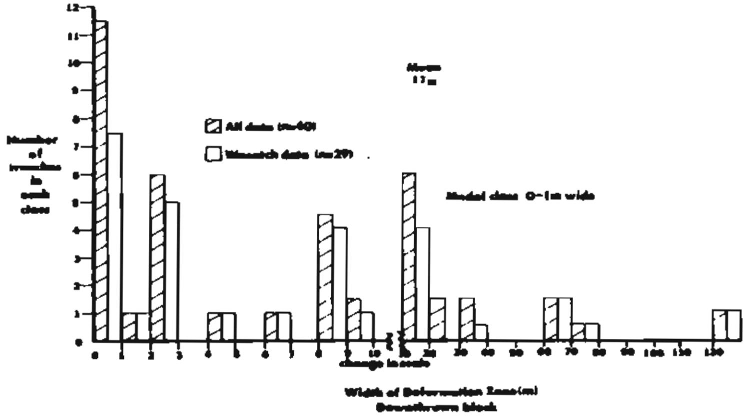
4 c


Number of trenches in each class
0
2
4
6
8
10
12
14
16
18
20
22
24
Mean 1.4m
All data (n=40)
Wasatch data (n=29)
Modal class: 0-1m wide
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Width of fault zone (m)
Upthrown block

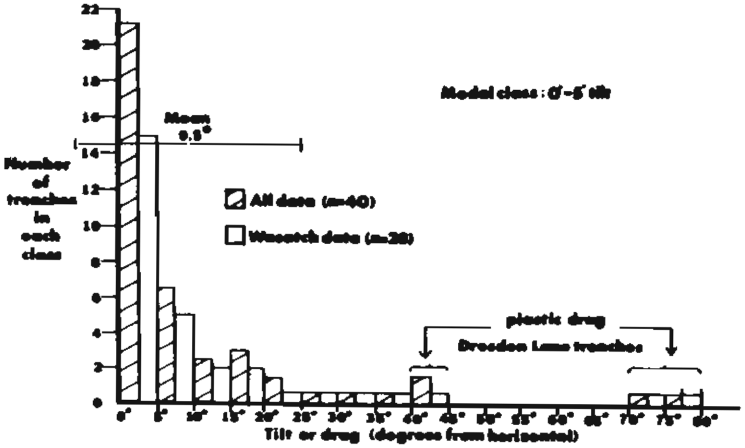
4 d



4 e



4 f



4 g

Fig. 4. Frequency histograms for fault geometry parameters from 40 trenches.
a. Position of main fault in relation to scarp width, b. Apparent dip of main fault,
c. Number of faults, upthrown block,
d. Width of fault zone, upthrown block,
e. Number of faults, downthrown block,
f. Width of deformation zone, downthrown block, g. Tilt or drag. Raw data are given in Appendix A. Width of thin bar under mean represents one standard deviation on each side of the mean.

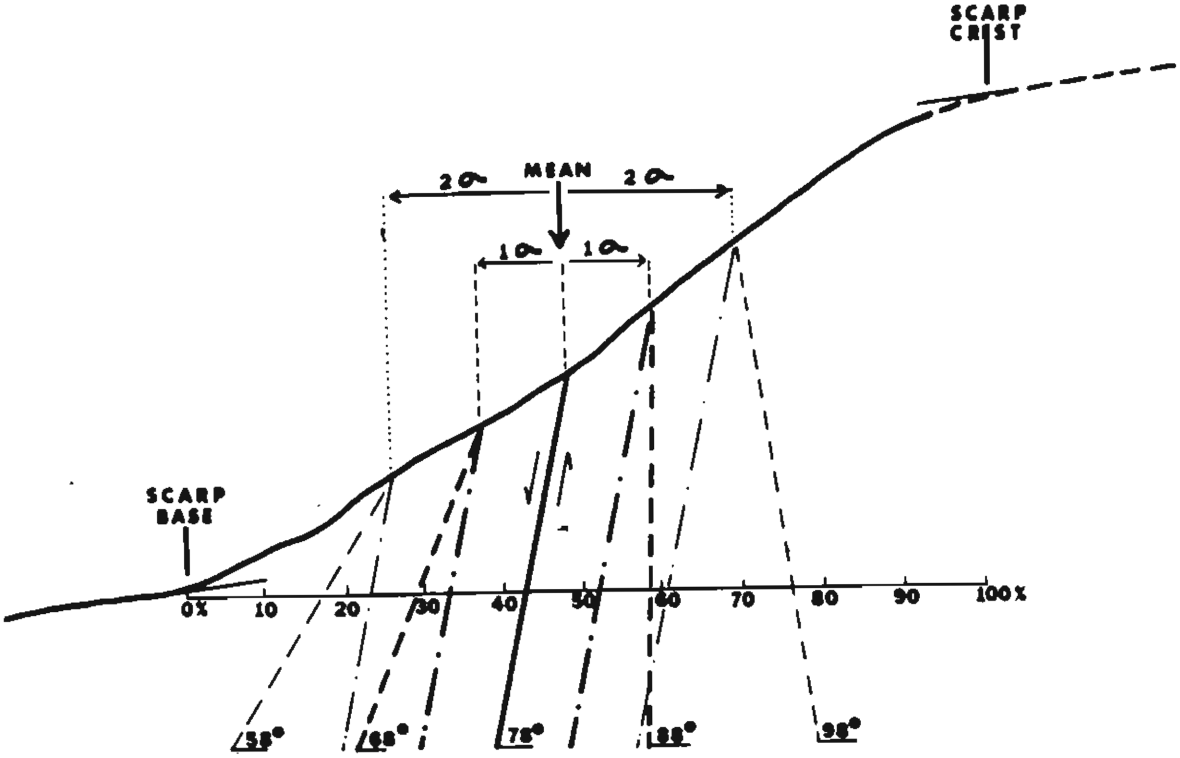


Fig. 5. Statistical representation of fault position and dip under a scarp. Heavy solid line, mean position and dip. Heavy dashed lines, 1σ variation in position and dip; light dashed lines, 2σ variation in position and dip. Values from Table 1.

have zones of faults that extend 4-5 m in above the main fault into the upthrown block. These faults may have sufficient displacement to be a danger to buildings, but (as discussed later) their location is also coincident with ravelling of the upthrown block due to free-face erosion following a surface faulting event.

Number of Faults on the Downthrown Block

The number of faults within the complexly faulted downthrown block is typically higher than that on the upthrown block on the Wasatch Fault(5 vs 3), but is nearly the same for other faults,(3.4 vs 2.6). However, the frequency distribution is not normal, with many faults having but a single antithetic or step fault while others have up to 21 small faults, usually within complex graben (Fig. 4e). Longer trenches tend to have the most faults, suggesting the low numbers in Appendix A might have been higher if some trenches had been longer.

Width of Deformation Zone on the Downthrown Block

The deformation zone was measured horizontally from the main fault to the farthest extent of either faulting or tilting on the downthrown block.

Where no deformation occurred on that block, a "0" was entered in the calculation of statistics. Wasatch trenches contained a zone averaging 17 m wide, with a large standard deviation of 27 m. The distribution is not normal, with values ranging from 1 to > 120 m (the length of the longest trench)(Fig.4f). The values are not typical of the fault zone as a whole, because trenches are often preferentially sited in graben zones to take advantage of trapped fine-grained sediments and organic material suitable for dating.

Antithetic Fault Displacement as a Percentage of Main Fault Displacement

The antithetic faults observed in trenches tend to fall into two groups: 1) small displacement faults with no surface expression with 1-5% of the main fault displacement, and 2) larger displacement faults bounding well-expressed graben with 15-35% of the main fault displacement. The mean for Wasatch trenches (14%) and large standard deviation (13%) reflect this bimodality.

Degree, Style, and Extent of Tilt

As described in Fig.3, the downthrown block may be "bent" or tilted backwards during failure into the tension fissure. More rarely, blocks topple forward along longitudinal step faults. Graben that settle unevenly will contain strata with an upslope or downslope tilt. Normal drag (strata dragged down on upthrown block, up on downthrown block) suggests that in some environments (subaqueous or groundwater-saturated) normal faults can create plastic deformation (e.g. Dresden Lane trenches in Appendix A). The mean tilt for 29 Wasatch trenches was 9.5%, with a standard deviation of 16°. This non-normal distribution results from the lack of measureable tilt at 52% of the Wasatch trenches, yet a scattering of tilts up to 78° (Fig. 4g).

Summary

The objective of trench data collection was to describe a "typical" Wasatch fault geometry in statistically valid terms. This effort is hindered by the wide range of measurements found in a relatively small sample size. In addition, only two of the eight variables measured (Position of Main Fault, Dip of Main Fault) are normally distributed. For these variables, the mean and standard deviation are taken to represent "typical" geometries. For the other seven variables, the modal frequency class or median value may more realistically estimate the probability of future occurrence than the mean.

IMPLICATIONS FOR LAND-USE CONTROLS

Current Standards for Study Zones and Setbacks in Utah

Previous recommendations for the Wasatch Fault suggested that the zone of potential deformation extended 200 ft (61 m) from the main fault into the upthrown block, and 1500 ft (457 m) into the downthrown block (Sharp, 1976). Since that time several municipalities have adopted standards for defining either: 1) the limits of the potential deformation zone (for requiring geologic investigations) or 2) minimum setbacks from fault traces. In the first area, Mapleton City (Utah County) has defined two fault hazard zones, ranging from 4062 ft (1.2 km) to 10,300 ft (3.1 km) in combined width, in which site investigations are required (Kaliser, 1984). Provo City (Utah County) has delineated four levels of hazard zones which include earthquake hazards (Payton and Truesdell, 1985). Work in progress in Utah County to implement recent fault trace mapping (Machette, in prep.) identifies the zone of potential hazard to extend 1/4 mile (402 m) horizontally from any mapped fault trace (Robison and others, this volume). Mapped fault traces as defined therein include known, inferred, and concealed faults (solid, dashed, and dotted map lines, respectively; R.M. Robison, Utah County, personal communication). Ogden City (Weber County) defines an earthquake hazard study zone to extend 1/8 mile (201 m) horizontally from any mapped fault with measurable Holocene displacement (M.V. Lowe, Weber County, personal communication).

Particular land use limitations are also set forth in regulations. In Mapleton City, within the Critical Environmental (CE-1) Zone, "No portion of a dwelling or other structure intended for human occupancy shall be located over any identified fault trace or zone of deformation" (Mapleton City, 1985). The zone of deformation is defined as "any area where the stratification has been folded, faulted or tilted by tectonic activity or downslope movement". However, "The minimum setback distance from any fault trace or zone of deformation, or from the base or crest of any potentially unstable slope, shall be as established by the City Engineer following the receipt of a recommendation on the subject from the geotechnical engineer as a part of the technical reports" (Mapleton City, 1985). In Ogden City, a minimum 50 ft (15 m) setback from any fault was established in 1984. It is assumed that the fault trace lies at the base of the fault scarp (M.V. Lowe, Weber County, personal communication), something which is not borne out by the results of this study. Provo City uses a 50 ft setback from mapped fault traces (Payton and Truesdell, 1985).

Salt Lake County and City have neither established special studies zones nor required setbacks from fault traces, but instead rely on consultant's recommendations (C.V. Nelson, Salt Lake fCounty, personal communication). In at least three cases, setbacks from faults mapped and exposed in trenches have been recommended. Dames and Moore (1977) recommended different setbacks for faults with large vs small scarps. For large scarps, the setback on the upthrown block was based on an uphill 2:1 projection from the scarp base. On the downthrown block a setback of 50 ft (15 m) from the fault trace (presumed to be at the center of the scarp) was suggested. For the small antithetic fault at the site, a 25 ft (8 m) setback on both sides of the trace was recommended. In a similar tectonic setting, Dames and Moore (1983) suggested 20 ft (6 m) setbacks from primary faults. On the East Bench Fault in Salt Lake City, Dames and Moore (1986) recommended a 20 ft (6 m) uphill setback, again based on a 2:1 upslope projection from the scarp base plus an aditional 3.3 m "safety factor". A more general graphical method for establishing setback distances on the upthrown sides of normal faults has been devised by J.R. Keaton (personal communication, 1986).

For those faults which underlie topographic scarps, the slope limitation on buildable areas becomes pertinent. In Utah, Salt Lake and Weber Counties, any natural slope in excess of 30% grade (roughly 17°) is classified as a "non-buildable area" and cannot be disturbed. Because the large, relatively planar midslope sections of almost all Wasatch Fault scarps slope at greater than 30%, the scarp face itself cannot be built upon anyway, regardless of the hazard due to surface rupture.

Repetition of Faulting Styles

The procedure of estimating future faulting style based on past faulting style at a given location rests on the premise that faulting is repeatible. Bonilla (1982, p. 15-16) reviewed the existing data on this question and concluded that both for strike-slip and normal faults, repeatibility of displacement on main fault traces does occur. For smaller fractures and tilts, the data base was too sparse to support conclusions; however, the 1983 Borah Peak provided key data. Mapping of the Doublespring Pass trench showed that almost every pre-historic fault within the graben zone was similarly displaced in the 1983 event (Schwartz and Crone, 1985). However, logs of at least two trenches in the data set (Hobble Creek, Little Cottonwood-2) show small faults which moved in early events but which were not rejuvenated in later events. Despite this, the uniformitarian and conservative approach should presume that future rupture events at a location should closely mimic past events.

Limitations to Structures

Little work has been done in documenting the threshold of surface-faulting displacement which initiates building damage. Youd (1980), based on observations in California, Japan, and South America, suggests the following correlation between extensional and vertical ground displacement and building damage: 1) less than 0.1 m (4 inches), little damage, repairable; 2) 0.1-0.3 m (4 inches-1 ft), severe damage, repairable; 3) 0.3-0.6 m (1-2 ft), destroyed, non-repairable; and 4) more than 0.6 (2 ft), collapse, non-repairable. Because the 0.3 m limit seems to separate repairable and non-repairable damage, the width of the zone encompassing >0.3 m displacements at each trench site is of interest. In most cases, the width of this zone is less than the combined width of the deformation zones of the upthrown and downthrown block (columns 4 and 6, Appendix A), because >0.3 m displacements do not occur at the extremity of upthrown block fractures. For 31 measured trenches, the mean width of the zone is 11 m. No structures intended for human occupancy should be sited in zones potentially subject to 0.3 m or greater displacements. In most of the graben logged in studied trenches the more abundant displacements are usually less than 0.3 m, but 0.3 m offsets may occur either within graben or on the major antithetic fault. Therefore, human-occupied structures should not be sited in graben without careful subsurface documentation on the location and past displacement styles of small faults in the graben.

Youd (1980) also documents instances in which buildings survived tilts of up to 60° without superstructure damage. The potential tilt within the downthrown block (excluding plastic drag in subaqueous events) has a median value of roughly 2°. Such small tilts can be mitigated by jacking and releveling structures, if foundation failure has not occurred. Therefore, tilt within graben zones is not a particularly limiting factor for small structures provided that foundations are strengthened to withstand small differential displacements without failure.

Initial Fault Geometry

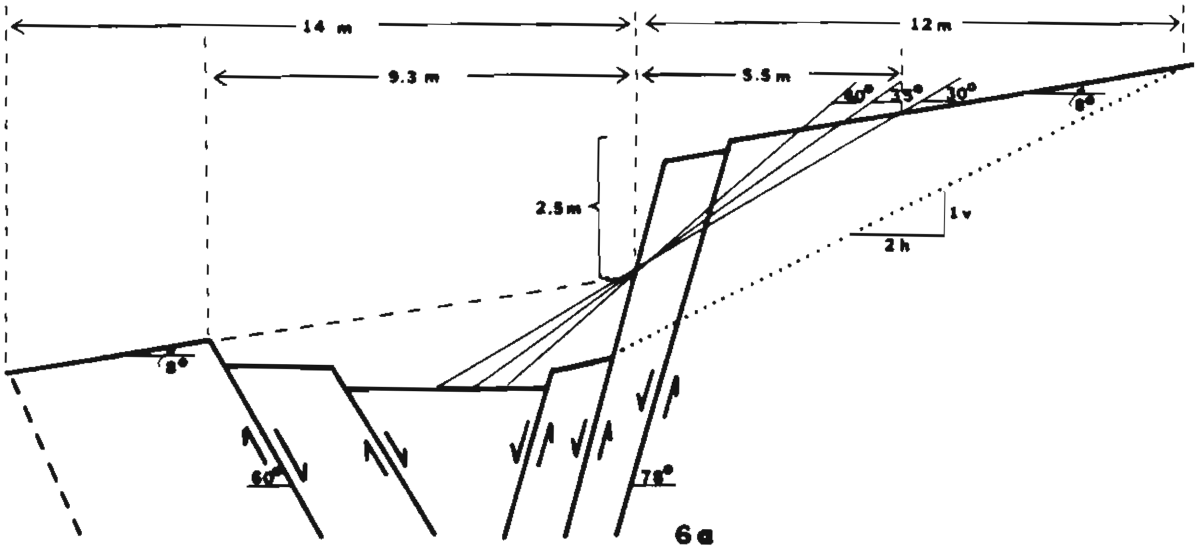
The initial surface-rupture geometry can be estimated by applying the statistical parameter values from Table 1. Previous workers (Schwartz and Coppersmith, 1984) have shown that in the past surface displacements per event have ranged from 1.6-3.4 m on the Wasatch Fault. Superimposing an event of "typical" displacement and geometry onto an arbitrarily-selected topography (Fig. 6) allows us to predict what the probable consequences of future surface rupture will be.

Post-Rupture Erosion and Deposition

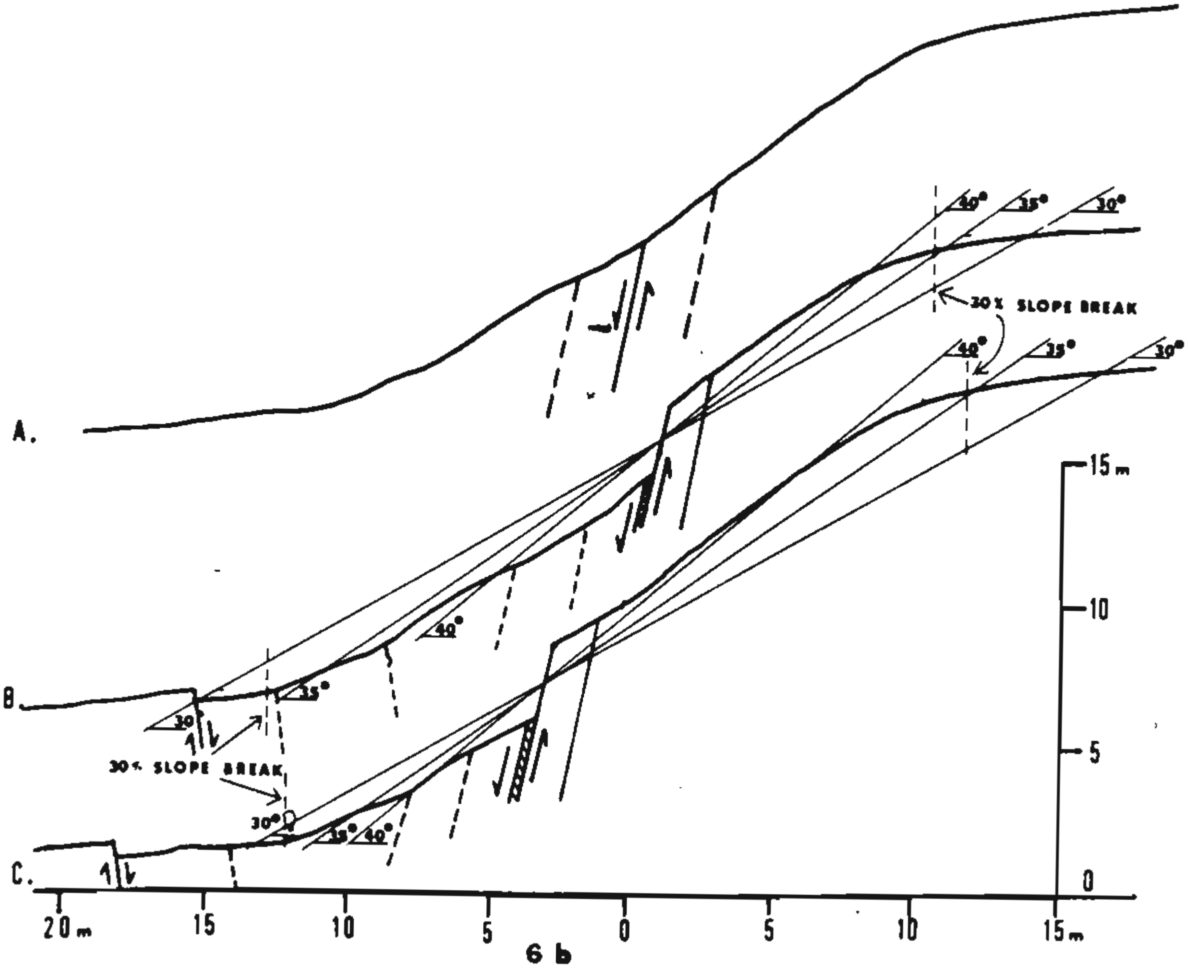
After formation of the 2-4 m high free face, weathering processes lead to erosion of the scarp crest and deposition at the scarp toe. Numerous workers (Wallace, 1977; Nash, 1980) have shown that ravelling of the free face by gravity processes back to the angle of repose is a geologically rapid event. Personal observations of the 1983 Borah Peak scarp free face (now buried an average of 50%) and the 1959 Hebgen Lake free face (now buried an average of 90%) attest to the speed of modification. To model the areal impact of ravelling, we must assume a stable angle for typical Wasatch Front surficial deposits. Bouldery, matrix-rich Holocene alluvial fan gravels seem to be stable at slopes between 30° and 40°. Therefore, on Fig. 6 upslope and downslope projections from the center of the free face should approximate the limits of scarp modification.

Setback Distances

Importantly, the horizontal width of the affected zone is highly dependent on the pre-rupture topography. For previously-unfaulted surfaces, the horizontal distance is determined solely by free face height, angle of repose, and the slope of the ground surface. On fig. 6a, an 8° slope (typical of surfaces near the range front) has been faulted by a "typical" Wasatch event, involving: 2.5 m of cumulative net vertical tectonic displacement, main fault dip of 78°, one minor fault on the upthrown block of 1 m from the main fault, four faults in the downthrown block over a distance of 9-14 m, and a maximum 8° tilt within the graben. Assuming stable slope angles of 30°-40° for faulted materials, the extent of upslope ravelling and downslope deposition can be projected from the center of the free face. On the upthrown block, ravelling extends 5.5 m horizontally from the main fault (35° projection). This horizontal distance encompasses 95% of all fractures found on upthrown blocks in trenches studied (Fig. 4d), indicating that, if structures are set back from the ravelling limit, they


14 m
12 m
9.3 m
5.5 m
40°
35°
30°
6°
2.5 m
1 v
2 h
8°
60°
75°

6 a


A.
B.
C.
40°
35°
30°
30% SLOPE BREAK
40°
35°
30°
40°
35°
30
30% SLOPE BREAK
30°
35°
40°
15 m
10
5
0
20 m
15
10
5
0
5
10
15 m

6 b

Fig. 6. a. Effect of a typical faulting event on: a smooth surface with 8° slope; b. a pre-existing scarp (Profile B-B^{1}, Hanson and Schwartz, 1982, Fig 33). Uphill setback is based on a main fault at 59% slope position, downhill setback based on 37% position (see text).

should also be safe from auxiliary fracturing. However, this distance includes no safety factor for larger-than-2.5 m displacements or gentler angles of repose. The 2:1 projection from the scarp base is also shown, which defines a 12 m-wide zone from the main fault. Interestingly, the larger zone is roughly twice as wide as the smaller one (5.5 vs 12 m). Most importantly, the precise location of a fault in previously-unfaulted terrain (e.g., the projection of a fault trace from a fault scarp across a younger, unfaulted surface) or where the scarp has been obliterated by natural or man-made processes, is highly uncertain. Considering this uncertainty, and supposing a "typical" Wasatch main-trace event, the setback on the upthrown block should never be less than 6 m (20 ft) and typically should be about 12 m (40 ft).

On the downthrown block, the potential rupture style is harder to predict. Downslope colluvial deposition will not be the limiting factor here, because faulting and tilting on the downthrown block will certainly extend beyond its limits. Using the average width of the downthrown block deformation zone (14 m, Table 1), it appears that the suggested setback is roughly equal to that of the upthrown block (14.9 m; 49 ft). Therefore, the 50 ft setback required by Ogden City seems reasonable, at least on previously unfaulted terrain.

For successively larger existing scarps, the recurrent faulting will influence a wider area. Fig. 6b shows an actual scarp profile from the Nephi segment of the Wasatch Fault, subjected to a typical 2.5 m displacement. To compute the uphill limit of free-face ravelling, it is assumed the fault breaks at 59% of the distance up the scarp, and ravels at angles of 30°-40°. Ravelling would extend 15.2 m from the scarp midpoint (approximately 3 times as far as on the smooth 8° slope of Fig. 6a). On the downthrown side colluvial deposition from a 37% position fault extends 13 m from the fault, not considerably different than the extent of graben faulting. The complete zone of scarp modification is 29-30 m wide (depending on fault position), as compared to 14.3 m on Fig. 6a.

On both the upthrown and downthrown sides, the limit of scarp modification at 35° roughly equals the 30% (17°) slope break which defines unbuildable areas. This relation holds true regardless of the absolute size of the pre-existing scarp. Therefore, an easily applicable setback for scarp situations would be measured outward from the 30% slope break. On the uphill side of Fig. 6b each 5° variation in repose slope angle corresponds to a (2.5-5 m) (8-16 ft) difference in zone width. Structures should not be sited within 20 ft (6 m) on the 30% break. If the 30% boundary is also a lot line, then most zoning districts require a minimum setback from that line (50 ft in the CE-1 Zone of Mapleton City). Thus, observing reasonable existing lot setbacks (of at least 20 ft) above such fault scarps should prevent structural damage by foundation displacement and undermining. On the downthrown side, the effect of subsidiary graben faulting suggests an even wider setback. For simple scarps with no surface evidence of graben, tilting, or step-faulting, setback should be at least 30 ft from the 30% slope break. Where a graben or tilting is apparent at the surface, the setback from the major antithetic scarp should be computed as for the main scarp. Trenches should be carefully logged to define the displacements on individual faults within the graben in relation to the 0.3 m displacement threshold discussed previously. Some trenches studied show pervasive intra-graben faulting (Kaysville, Little Cottonwood-1, Hobble Creek-1; Appendix A), while others have no internal faults within rather wide graben (Dry Creek-2, North Creek-3, East Cache; Appendix A). Although it is not totally infeasible to construct reinforced structures within some graben, the uncertainty in future displacement pattern and magnitude, coupled with destructive effects on buried utilities, combine to make graben very marginal residential land.

CONCLUSIONS AND RECOMMENDATIONS

Analysis of 40 trench logs across normal faults shows that the position of the fault under the scarp and the fault dip are predictable, but the extent of subsidiary faulting and tilting on the upthrown and downthrown blocks is highly variable along along fault length. Using mean and modal values, a "typical" faulting event geometry on the Wasatch Fault can be calculated. Superimposing such an event as gently sloping, smooth terrain reveals that setbacks of 40 feet on the upthrown side and 50 feet on the downthrown side should be considered minimums. Where large fault scarps exist, erosion and deposition from scarp free faces will typically affect zones 20 feet above the 30% slope break at the scarp crest, and 30 feet below the same break at the scarp base. Where graben exist, no blanket recommendation can be made for structures within the graben but beyond the effects of main scarp deposition. Trenching studies should be performed to determine the extent of and displacement on intra-graben fractures, bearing in mind that displacements of less than 0.1 m could cause slight damage, 0.1-0.3 m severe damage, and 0.3-0.6 m complete destruction and/or collapse.

ACKNOWLEDGEMENTS

I would like to thank M.N. Machette, S.F. Personius, A.R. Nelson (U.S. Geological Survey, Denver, CO), J.D. Garr (Ogden, UT), R.M. Robison (Utah County Planning Dept., Provo, UT) and G.E. Christenson and W.R. Lund (Utah Geological and Mineral Survey) for providing unpublished trench logs, and for giving permission to cite their preliminary results. R.M. Robison, M.V. Lowe (Weber County Planning Dept.) and C.V. Nelson (Salt Lake County Planning Dept.) all provided data on current study zone and setback standards, including unpublished consultant's reports. C.J. Sheehan did a fantastic job formatting and proofreading the manuscript.

APPENDIX A. NEAR-SURFACE TECTONIC DEFORMATION DATA FROM TRENCHES ACROSS FAULT SCARPS

		MAIN FAULT[1]		UPTHROWN BLOCK[2]		DOWNTHROWN BLOCK[3]				REFERENCE[13]
NO.	TRENCH Name[4]	Position of Fault[5] (%)	Apparent Dip[6] (°)	No. of Faults[7]	Width of Deformed zone[8] (m)	No. of Faults[9]	Width of zone[10] (m)	% of antithetic[11]	tilt or drag[12] (degrees)	
1	Brigham City	63	84	6	2	2	2	<1	0	a
2	Pole Patch	I[14]	67	1	NA[15]	5	2.7	<1	8(b)5	a
3	East Ogden-1	I	65	2	0.3	I	I	I	0	b
4	East Ogden-2	I	73	4	2.9	1	4.3	16	0	b
5	East Ogden-3	22-44[16]	75-95[16]	2	2.1	1	8.2	NA	0	b
6	East Ogden-4[17]	68	57	1	NA	1	I	26	0	b
7	East Ogden-5	49	72	2	0.7	2	2.4	28	0	b
8	Garner Canyon cut	I	73-86[18]	2	0.5	I	I	I	0	b
9	Kaysville	35	74	2	2.2	19	43-70[19]	10	7(b)70	c
10	Little Cottonwood-1	I	61	7	2.7	18	>65	NA	0	d
11	Little Cottonwood-2	56	70-90[20]	17	4.6	4	2.9	NA	0	d
12	Little Cottonwood-3	I	80	4	1	2	8.2	I	0	d
13	Dresden Lane-N	I	70	2	0.6	6	1-13[21]	<1	75(f)13	e
14	Dresden Lane-S	I	36	2	0.3	≥27	17	<1	40(f)17	e
15	Dry Creek-1	I	65-76[22]	1	NA	3	2.5	NA	35(b)2.5	f
16	Dry Creek-2	I	72	2	0.25	2	15	<1	20-30(b)1	f
17	Dry Creek-3	58	92	2	0.25	0	0	NA	0	f
[illegible]	Dry Creek-4	35	95	2	0.4	0	0	NA	0	f
[illegible]	American Fork-1u[23]	41	88	1	NA	1	1	26	4(b)6.5	g
[illegible]	American Fork-1l	39	84	2	0.2	1	3	<5	7(b)10	g
[illegible]	American Fork-2[24]	45	81	6	4.75	4	8.75	21	0	g
[illegible]	American Fork-3	54	86	1	NA	I	0.7	5	6(b)4	g
[illegible]	Rock Creek exposure	36[25]	79	1	NA	1	0.3	26	13(b)I	h
[illegible]	Hobble Creek-1	I	56	≥6	≥4.3	21	120	I	8(b)17	f
[illegible]	Woodland Hills-2	52	98[26]	4	5	7	3	NA	16(f)I	g
[illegible]	North Creek-1	I	81	2	0.6	2	9.1	NA	0	j
[illegible]	North Creek-2	I	52-77[27]	8	≥4.4	0	0	NA	0	j
[illegible]	North Creek-3	I	73	3	3.4	2	16.5	I	12(b)I	j
[illegible]	Deep Creek exposure	50	79	1	NA	1	30	39	19(b)15	g
	WASATCH DATA									
	Number	15	29	29	29	29	29	15	29	
	Mean[28]	48%	78°	2.8	1.4m	4.6	14.0 m	14%	9.5°/5.5m	
	Std. Deviation[29]	11%	10°	2.0	1.6m	7.0	26.3 m	13%	16°/13m	
	Lost River, ID									
[illegible]	Arco	I	67	5	5.6	NA	NA	NA	0	k
[illegible]	Howe	I	64	6	12.8	3	≥11.2	NA	0	k
[illegible]	Doublesprings Pass	43	74-86[30]	2	0.6	21	33	82	10(f)7	l
[illegible]	Pleasant Valley, NV	64	79	4	2.5	1	2.3	NA	0	m
	Sierra Nevada, CA									
[illegible]	Lone Pine	I	84	2	1	3	6.7	I	0	n
[illegible]	Villa Grove	56	73-87[31]	2	0.5	0	0	NA	22(d)2.5	o
[illegible]	Major Creek	36	74	I	NA	1	≥9	31	17(f)2	o
[illegible]	Baca #1	42	87	2	0.3	I	I	NA	7(d)7.5	o
[illegible]	Baca #2	45	88	3	1.1	2	>11.3	<5	1(b)11	o
[illegible]	Uracca Creek	-10	72	2	1	0	NA	NA	44(d)0.4	o
	East Cache, UT									
[illegible]	Logan	42	75-90[32]	8	3.7	1	28.5	14	0	p
WESTERN U.S. DATA										
	Number	8	14	11	11	11	11	4	11	
	Mean	40%	79°	3.4	2.6 m	2.9	9.3 m	33%	9.2°	
	Std. Deviation	18%	8°	2.1	3.6 m	5.8	11.0 m	30%	13.2°	
ENTIRE DATA SET										
	Number	23	40	40	40	40	40	19	40	
	Mean	45%	77°	3.3	1.3 m	4.1	12.7 m	18%	9.4°/4.8 m	
	Std. Deviation	14%	10°	3.0	2.4 m	6.7	23.2 m	19%	15.5°/11.6 m	

EXPLANATION

[1] the main fault is one with the major amount of displacement

[2] the upthrown block includes the main fault gouge zone as well as the footwall of the normal fault

[3] the downthrown block includes all terrain beyond the main fault gouge zone, including any graben,and the hanging wall of the normal fault. Some trenches (No. 6,20) are cut across large antithetic faults, in which case the downthrown block is actually upslope of the main fault.

[4] informal name, keyed to Fig. 1.

[5] the horizontal position of the main fault trace in relation to the surface fault scarp. Measured as the horizontal distance from the scarp base to the projected surface fault trace, as a percentage of the total horizontal width of the scarp.

[6] the apparent fault dip measured from the trench log. Because most trenches are excavated perpendicular to the fault, this value should closely approximate true dip.

[7] number of faults on the upthrown block. 1 indicates the presence of a single, clean main fault. 2 indicates a main fault gouge zone of varying thickness. Numbers larger than 3 usually indicate small- displacement step faults elsewhere in the upthrown block.

[8] measured horizontally from the main fault into the upthrown block.

[9] number of faults on the downthrown block. 1 indicates a single antithetic fault. 2 or greater indicates extensive faulting and fracturing, with the largest numbers occurring in complex graben.

[10] measured horizontally from the main fault into the graben or downthrown block. Some values are minimums because deformation probably exceeds the downslope limit of the trench.

[11] the displacement on the major antithetic faults expressed as a percentage of the displacement on the main fault.

[12] amount of tilt (in degrees) associated with drag on the upthrown block (d), or forward (f) or backward (b) rotation of the downthrown block or graben. Width of zone affected by tilt (m) is also given. Example: 8(b)5 means 8° of backwards (anti-slope) tilt of the downthrown block within 5 m of the main fault.

[13] Reference for source of original trench logging; see separate reference list.

[14] I indicates insufficient information. For example, on many trench logs, the complete scarp profile is not portrayed, so Position of Fault (%) cannot be calculated.

[15] NA means not applicable. For example, if only one fault plane is present, the width of the zone is negligible.

[16] Ranges result from a large (0.8 m) diameter boulder caught in the fault zone.

[17] Trench EO-4 was excavated across a large antithetic scarp opposite trench EO-1.

[18] 86° in upper 1.5 m; 73° in lower 0.5 m of exposure.

[19] faults extend up to 43 m downhill of the main fault, but tilt extends 70 m away from fault on downthrown side.

[20] 90° in upper 1 m; 70° in lower 1 m of trench.

[21] faults within 1 m of main fault, but tilt extends 13 m from main fault.

[22] 65° in upper part of trench, 76° in lower part.

[23] Trench AF-1 actually crossed 2 fault scarps, a smaller upper one (1 u) and a larger lower one (1 l).

[24] Trench AF-2 was excavated across a large antithetic scarp.

[25] A poor estimate because the scarp was modified by erosion.

[26] Dip of the fault which occurs in the center of the scarp, amidst 10 other faults; may not have the maximum displacement.

[27] 52° on main displacement zone, 77° on longitudinal step faults on downthrown block.

[28] arithmetic mean of all values. I's and NA's indicate the absence of a feature, so are included in calculations as zeros.

[29] standard deviation. Although calculated for all parameters, it is only valid for those parameters with a normal distribution. Parameters such as Number of Faults on the Downthrown Block, dominated by 1's or 2's with occasional high values (18-21) clearly are not normally distributed; in such cases, the value of the standard deviation often exceeds the value of the mean.

[30] 86° in upper 3.2 m, 74° in lower 1.5 m of trench.

[31] estimate made difficult by large krotovina at fault plane.

[32] 90° in upper 1 m, 75° in lower 2 m of trench.

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