Late Quaternary History of the James Peak Fault, Southernmost Cache Valley, North-Central Utah

By ALAN R. NELSON *and* J. TIMOTHY SULLIVAN, U.S. BUREAU OF RECLAMATION

ASSESSMENT OF REGIONAL EARTHQUAKE HAZARDS AND RISK ALONG THE WASATCH FRONT, UTAH

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LATE QUATERNARY HISTORY OF THE JAMES PEAK FAULT, SOUTHERNMOST CACHE VALLEY, NORTH-CENTRAL UTAH

By ALAN R. NELSON[1] and J. TIMOTHY SULLIVAN[2]

ABSTRACT

The James Peak normal fault is marked by a northeasterly trending 7-m-high scarp that cuts outwash fans of Bull Lake age on the northern flank of James Peak. The occurrence of two surface-faulting events, each having about 2 m of displacement, on the fault in the last 140 ka indicates a late Quaternary slip rate of about 0.03 mm/yr. The degree of soil development on the outwash fans and on fault-related colluvial wedges provides only limited control on the timing of events. Average event recurrence intervals are at least 50,000 years, but recurrence may be nonuniform, and the most recent event may be as young as 30 ka. The amount of displacement during each event suggests that surface breaks may have extended north and ruptured the southern portion of the East Cache fault. If so, the James Peak fault may be a westerly splay of the East Cache fault rather than a separate valley-bounding fault.

INTRODUCTION

Comparing Quaternary fault-slip rates is a widely used means of assessing the earthquake potential of geologically young faults. The Wasatch fault poses the greatest hazard to population centers in north-central Utah because its slip rate may be several times greater and its recurrence of surface faulting 3 to 10 times greater than those of other faults in the Wasatch Mountain region (Schwartz and Coppersmith, 1984). However, other faults in the region may still pose a significant earthquake hazard, although their histories and slip rates have been documented in only a few cases (Nelson and VanArsdale, 1986; Sullivan and Nelson, this volume; McCalpin and others, this volume). Anderson and Miller (1979) and Nakata and others (1982) mapped a number of faults on which significant Quaternary slip had occurred, but other faults in the eastern Wasatch Mountains—some displaying late Quaternary (younger than 125 ka) slip—have only recently been identified (Sullivan and Nelson, 1983; Sullivan and others, 1988). One such fault, the James Peak normal fault, is marked by scarps on bedrock, outwash fans, and other alluvium on the northern flank of James Peak and extends west-southwest from the southern tip of the East Cache fault in southern Cache Valley almost to Ogden Valley (fig. 1). We will summarize trench data used to estimate a slip rate on the James Peak fault and suggest how surface breaks on the fault may relate to ruptures on the adjacent East Cache fault, which is recognized as posing a significant earthquake hazard (Swan and others, 1983).

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[1]Now at U.S. Geological Survey, Mail Stop 966, Federal Center, Denver, CO 80225.

[2]Now at Yucca Mountain Project Office, Department of Energy, P.O. Box 539, Las Vegas, NV 89109.

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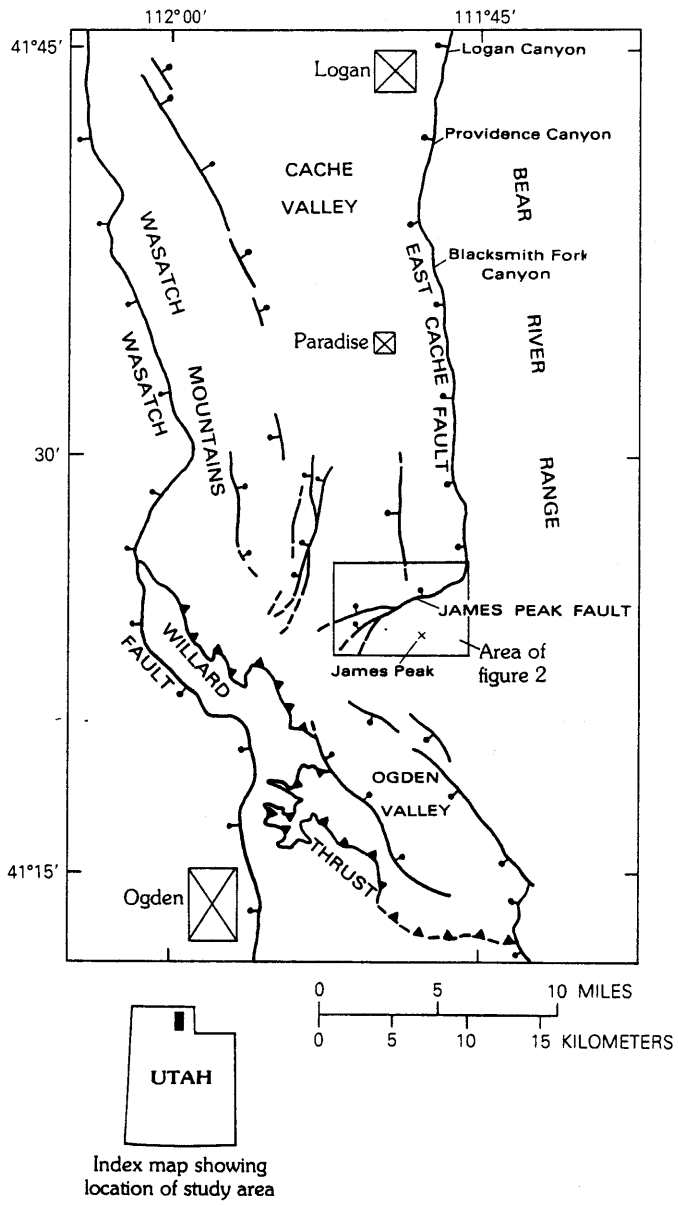


FIGURE 1.—Location of the southern Cache Valley region. Selected late Cenozoic normal faults (modified from Crittenden and Sorensen, 1985a, b) are indicated by heavy lines (bar and ball on downthrown side), dashed where approximately located. The edge of the Willard thrust fault is indicated by sawteeth on the overriding plate.

GEOLOGIC SETTING

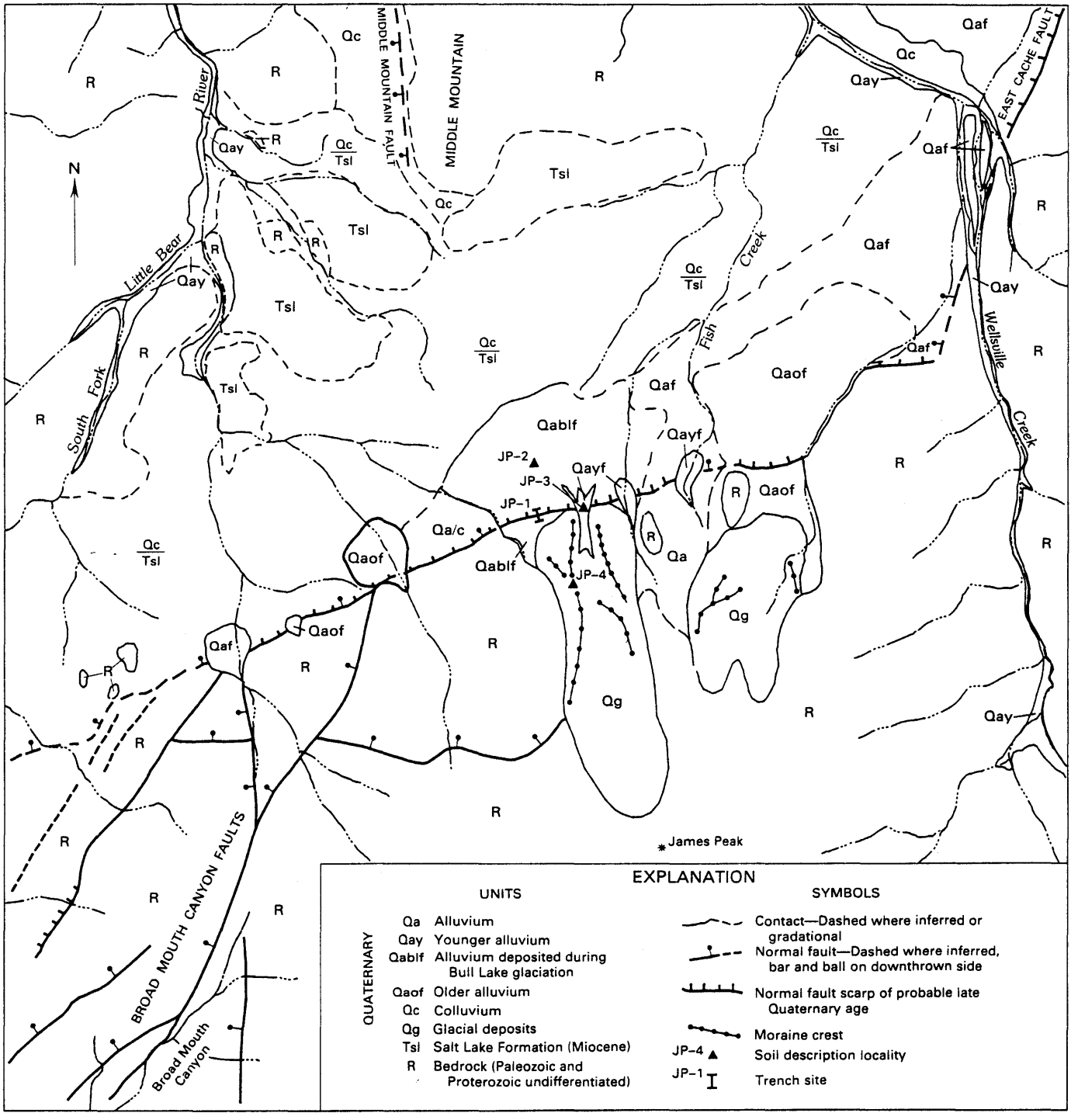
Our review of 1:58,000-scale color infrared and 1:15,000- to 1:40,000-scale black-and-white aerial photographs shows that the scarp of the James Peak normal fault is the only previously unreported fault scarp on unconsolidated deposits in the eastern Wasatch Mountains. The scarp marks the southern edge of an unnamed structural and topographic basin between James Peak and Middle Mountain (fig. 2) at the southern end of Cache Valley and 5 km north of Ogden Valley (fig. 1). The basin, about 3 km wide and 9 km long, contains Tertiary Salt Lake Formation covered by Quaternary colluvium and alluvium (Blau, 1975; Hintze, 1980). The basin is bounded on the north by highly dissected Paleozoic limestones, shales, dolomites, and quartzites and on the south by Proterozoic and Paleozoic orthoquartzites, argillites, and volcanic rocks that make up the highlands around James Peak (King, 1965; Blau, 1975; Davis, 1983).

STRUCTURE

Cenozoic structural basins termed "back valleys" occur throughout the Wasatch Mountains east of the Wasatch fault (Gilbert, 1928). Cache Valley is a late Cenozoic structural and topographic basin, bounded by normal faults, that developed in the Cache allocthon, the upper plate of the Willard (fig. 1) and Woodruff thrusts (Bjorkland and McGreevy, 1971; Crittenden, 1972; Hintze, 1980). The East Cache fault, the principal fault in the valley, is marked by triangular facets cut on the east-dipping Proterozoic and Paleozoic rocks at the western base of the Bear River Range. Geophysical data (Stanley, 1972; Peterson, 1974) compiled by Zoback (1983) suggest that the upper Cenozoic basin fill in the valley is 1.7 to 2.1 km thick. A seismic reflection profile across the East Cache fault shows that Cache Valley is an asymmetric basin, deepest on the eastern margin adjacent to the East Cache fault (Smith and Bruhn, 1984). Consistent east dips of reflectors in the late Tertiary basin fill suggest a listric geometry for the East Cache fault, although the fault plane cannot be resolved from the available data.

The James Peak normal fault, at the base of the escarpment in Proterozoic and Paleozoic rocks on the northern side of James Peak (fig. 2), marks the southern boundary of the east-west-trending basin at the southern end of Cache Valley. Isolated outcrops of Paleozoic sedimentary rocks suggest that the Salt Lake Formation may be less than 100 m thick in the basin, an indication

FIGURE 2.—Generalized Quaternary geology of the area north of ▶ James Peak. The James Peak fault scarp (hachures point down the slope of the scarp) trends northeast-southwest in the middle of the figure. An f following the unit symbol indicates that the surficial unit has alluvial fan morphology. A slash within a unit symbol shows a deposit of multiple genesis (for example, Qa/c indicates Quaternary alluvium and colluvium). Qay deposits are primarily of Holocene and latest Pinedale age (younger than 15 ka). Most Qao (Qaof) units are pre-Pinedale (older than 30 ka). Qa and Qc units are undifferentiated on the basis of age. Qc/Tsl marks thin deposits of colluvium and alluvium over Tertiary Salt Lake Formation. Most faults in bedrock south of the James Peak fault scarp are from Blau (1975). Many units (such as Qablf) contain smaller areas of younger and older deposits.


MIDDLE MOUNTAIN FAULT
MIDDLE MOUNTAIN
EAST CACHE FAULT
Little Bear River
South Fork
Fish Creek
Wellsville Creek
BROAD MOUTH CANYON FAULTS
Broad Mouth Canyon
James Peak
N
JP-1
JP-2
JP-3
JP-4
EXPLANATION
UNITS
QUATERNARY
Qa Alluvium
Qay Younger alluvium
Qablf Alluvium deposited during Bull Lake glaciation
Qaof Older alluvium
Qc Colluvium
Qg Glacial deposits
Tsl Salt Lake Formation (Miocene)
R Bedrock (Paleozoic and Proterozoic undifferentiated)
SYMBOLS
Contact—Dashed where inferred or gradational
Normal fault—Dashed where inferred, bar and ball on downthrown side
Normal fault scarp of probable late Quaternary age
Moraine crest
Soil description locality
Trench site
0 1 MILE
0 1 KILOMETER

that cumulative subsidence is much less here than it is in Cache Valley. North of the basin, north-dipping lower Paleozoic rocks are cut by north-trending normal faults, including the Middle Mountain fault. Near Broadmouth Canyon on the western side of James Peak, Blau (1975) mapped north-trending normal faults having estimated displacements of about 1,500 m that are about on trend with the Middle Mountain fault. Bedrock escarpments mark these north-trending faults, but north-trending scarps are not developed on the sediments in the basin. No east-west-trending faults are mapped along the northern edge of the basin, where fluvial dissection has produced extensive outcrops of the Salt Lake Formation. Thus, the basin appears to be a shallow half-graben connecting the larger and deeper grabens at the southern end of Cache Valley and the northwestern end of Ogden Valley (Zoback, 1983; Sullivan and others, 1988).

QUATERNARY DEPOSITS

Quaternary deposits in the basin consist of locally derived, bouldery colluvial deposits (unit Qc, fig. 2) in the central and northern portions that thicken and are interbedded with fan alluvium to the south. Alluvial fan deposits (Qaf), including two large, bouldery outwash fans (Qaof and Qablf) derived from the quartzites exposed on James Peak, occur along the southern edge of the basin. These fans become larger and appear to thicken from west to east; if so, this thickening may indicate downfaulting, tilting, or deeper erosion of the eastern part of the basin near Wellsville Creek and the East Cache fault. Sandy till (Qg) makes up the high, steep moraines built by the glaciers that deposited the outwash fans in two of the unnamed drainages on the northern flank of James Peak.

SCARP AND MOUNTAIN-FRONT MORPHOLOGY

Mountain-front slopes developed on bedrock along the James Peak fault are steep, especially on James Peak (26°), despite the fact that this side of the peak has been extensively eroded by glaciers. On the lower half of the mountain, eroded spurs (ridge crests) are faceted. Three breaks in slope on the spurs, as well as the north-facing faceted spur (25° slope) just west of Wellsville Creek at the eastern end of the basin (fig. 2), suggest a history of recurrent Quaternary displacements on the fault (for example, Gilbert, 1928; Hamblin, 1976). To the east, the mountain front is lower and more dissected and has gentler slopes, although here, as elsewhere, the steepest facets are at the base of the slopes along the fault. However, by comparison, the facets along the fault are smaller, less continuous, and less steep than those along the East Cache and Wasatch faults. The short (less than 7 km) mountain front along the James Peak fault makes quantitative comparisons with other mountain fronts (for example, Bull and MacFadden, 1977) of little value. Overall, the mountain-front morphology of the northern flank of James Peak suggests that Quaternary slip rates are much lower here than they are on major nearby faults such as the East Cache and Wasatch faults.

The James Peak fault scarp is expressed primarily as a scarp on bedrock over much of its length, but, along the central part of the fault, the scarp offsets alluvial and colluvial deposits and the large alluvial fans (units Qablf and Qaof, fig. 2) issuing from the glaciated drainages on the northern flank of the mountain. The scarp is generally higher (10–30 m) and steeper (20°–35° maximum slope angle) on bedrock (or thin colluvium over bedrock) than it is on fan sediments (1–4 m, 15°–30°). Where the scarp is on alluvium undissected by small drainages, it is uniformly 3 to 4 m high.

An en echelon offset at the eastern end of the scarp forms a junction with the prominent scarp at the southern end of the East Cache fault; the scarps join at about a 110° angle. The eastern half of the scarp is subdued (less than 2 m high, 20° maximum slope angle) where it crosses the apex of the easternmost alluvial fan (Qaof, fig. 2), but the scarp is steeper (20°–25°) in the Cambrian quartzite on the en echelon segment (500 m west of Wellsville Creek). The lower slopes of the Paleozoic limestone and sandstone bedrock facets, 2.7 km to the north on the East Cache fault, are steeper still (25°–30°). Just west of the large alluvial fans, the western half of the scarp is steep (22°–30° maximum slope angle) near the base of dissected facets in quartzite, but, farther west, the scarp is indistinct because the bedrock hills west of James Peak are lower and more rounded than the faceted mountain flanks to the east.

Just south of the western end of the basin, the Broadmouth Canyon normal faults trend about N. 30° E. through low, dissected bedrock hills (Blau, 1975). A major topographic boundary between the western flank of James Peak and the lower hills to the west marks the largest normal fault, which exhibits 1,500 m of throw, that extends into Broadmouth Canyon. One large topographic step (120 m difference in elevation) and several smaller ones (most down to the northwest) (fig. 2) that parallel the largest fault are interpreted as related subsidiary faults.

AGE OF FAULTED DEPOSITS

Our chronology of Quaternary deposits and the scarps bounding or cutting them near James Peak is based on the morphology and relative position of fans, moraines, and scarps and on the data from four soils developed on

deposits in the largest glaciated drainage. Most mapped Quaternary deposits are undifferentiated as to age (fig. 2), but even the oldest are probably no more than a few hundred thousand years old.

The height of topographic scarps along the Broadmouth Canyon faults suggests Pliocene to Quaternary—but not necessarily late Quaternary—displacement. Most of the faults cannot be traced into the Salt Lake Formation in the basin to the north; thus, they appear to be buried by Tertiary sediments. However, in two areas where the Broadmouth Canyon faults meet the James Peak fault, faint lineaments extend into dissected Salt Lake Formation sediments; exposures are not sufficient to resolve the relationships between the lineaments and the faults. Although the Broadmouth Canyon faults may join the James Peak fault, the young scarp on the James Peak fault indicates that the Broadmouth Canyon faults have been displaced by it.

The steep, continuous scarp on the alluvial fans along the central part of the James Peak fault suggests late Quaternary displacement on the fault. However, except for the smallest, youngest fans, which lack scarps where the fault crosses them, fans of significantly different ages (on which to compare scarp heights) were not identified. Topographic profiling across the scarp was difficult because of the thick alder-aspen forest and the soft, loose, organic-rich soil on the surface of the scarp. For this reason, profiling to obtain estimates of displacement and relative age (for example, Bucknam and Anderson, 1979) was not attempted.

Most Quaternary chronology studies in the Rocky Mountain region have divided deposits of the most recent major glaciations between the Bull Lake glaciation and the Pinedale glaciation; older deposits have been designated as pre-Bull Lake (Madole, 1976; Pierce, 1979). These groupings are usually based on relative age data such as relative position in the landform sequence, landform morphology, degree of soil development, and surface-weathering characteristics (Birkeland and others, 1979). Because the data used to subdivide these deposits into relative age groups are usually compared only for sites within a single mountain range or drainage basin, deposits in different ranges or basins elsewhere in the region that have been assigned to the same relative age group may not be the same age (Pierce, 1979; Porter and others, 1983). Colman and Pierce (1981) have identified moraines in Idaho probably dating from about 60 to 70 ka, intermediate in age between the accepted ages of 15 and 25 ka for most Pinedale deposits and 130 and 150 ka for Bull Lake deposits. Thus, deposits placed in the Bull Lake relative age group in some drainages might be as young as 60 to 70 ka. Following Pierce (1979) and Porter and others (1983), we use "Pinedale" and "Bull Lake" to name the more recent major Quaternary glaciations in the Rocky Mountains and assume ages for the deposits of each glaciation by comparing our soils data with similar data from numerically dated glacial deposits (Pierce and others, 1976; Porter and others, 1983; Colman and Pierce, 1986).

Soil development indices are an objective way of comparing the degrees of development of soils (Birkeland, 1984). The soil properties that vary the most systematically with time in the Rocky Mountain region include horizon thickness, color, texture, and calcium carbonate accumulation (Shroba and Birkeland, 1983). Ways to express changes in these properties include simple, widely used soil development indices (for example, depth to base of observable oxidized parent material and increase of maximum percentage of clay), profile summations (Machette, 1985), and the indices of Harden (1982) and Harden and Taylor (1983). Harden's indices refine those of Bilzi and Ciolkosz (1977) and incorporate, in a quantitative way, most of the concepts represented by development indices used previously in the Western United States. The profile development index (Harden, 1982) (fig. 3) is particularly useful because the degree of development of all selected properties can be objectively summarized by a single value.

We followed Harden and Taylor (1983) in using *X–Y* plots to compare indices for the soils that we described and sampled near the trench site (table 1, fig. 2) with those for soils of known age elsewhere in the Wasatch Mountains (fig. 3). Soils on a lateral moraine (JP–4) and on the outwash fan in front of it (JP–2) were described to determine whether the deposits were Bull Lake or Pinedale. For comparison, a Holocene soil (JP–3) was described on very coarse, bouldery alluvium in a narrow channel where the moraines are narrowly breached. The thick soil developed on the colluvial wedges in the trench (JP–1) was also described to help estimate the age of the wedges. Soils JP–1 and JP–2 are developed in deposits of more than one age. To help estimate the time interval represented by the degree of soil development in each of the younger deposits as well as by the degree of development of the whole soil, we calculated soil indices for each depositional unit of these two soils (table 1, fig. 3).

Soil development indices (fig. 3) calculated by using field and laboratory data show that the outwash gravels (unit Qablf, fig. 2) in the lower parts of soils JP–1 and JP–2 are in relative age group (RAG) 2 and are probably chronocorrelative with outwash from the Bull Lake glaciation. Although it is possible that this outwash significantly postdates the last interglacial (about 125 ka) (discussed above), the reddish clay-rich argillic horizons of these soils suggest that they began forming about 140 ka.

Soil JP–4 on the steep, high, left-lateral moraine (fig. 2) is poorly developed, and its soil indices are lower than

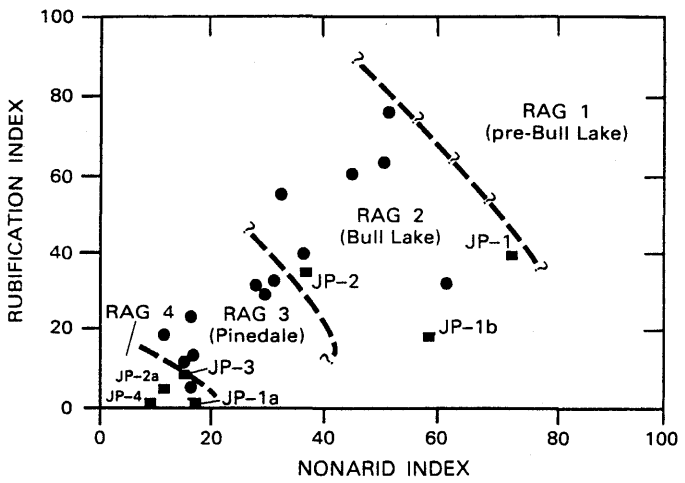


FIGURE 3.—Rubification versus nonarid soil development indices (solid squares) (after Harden, 1982; Harden and Taylor, 1983) for soils near the trench site (fig. 2, table 1). Point JP-1a is a plot of indices for the upper 83 cm of soil JP-1 (unit 4, fig. 4), JP-1b is for the upper 205 cm of the same soil (units 3 and 4), JP-2a is for the upper 53 cm of soil JP-2, and JP-1, JP-2, JP-3, and JP-4 are indices for the entire profiles. Dashed lines divide the diagram into four relative age groups (RAG's) defined by indices from soils of known age (marked by solid circles) elsewhere in the eastern Wasatch Mountains (Nelson and Krinsky, 1982; Sullivan and others, 1988, p. 54). Question marks indicate that we do not know if the dashed lines forming approximate boundaries between RAG's can be extended, because we have no development indices for soils in the areas beyond the dashed lines. Comparing the degree of development of soils in these RAG's with that of soils on glacial deposits elsewhere in the Rocky Mountain region (Madole, 1976; Pierce, 1979; Shroba and Birkeland, 1983; Colman and Pierce, 1986) suggests that soils in RAG 4 are of Holocene age or a little older (younger than 12 ka), those in RAG 3 correlate with glacial deposits of Pinedale age (15–25 ka), those in RAG 2 may be of Bull Lake age (130–150 ka), and those in RAG 1 are older than Bull Lake.

the indices for most soils on tills and outwash of the Pinedale glaciation (fig. 3). However, the till on which the soil is developed is derived entirely from quartzites, which do not weather easily. In addition, the steep slopes and narrow crests of the moraines indicate that this soil may have been partially stripped by erosion on the moraine crest. Thus, both because soil development proceeds so slowly in quartzite-derived tills and because of erosion, the moraine is probably much older than the soil indices suggest.

The bouldery surfaces, narrow crests, and steep slopes of the moraines on the northern flank suggest that they were built during the Pinedale glaciation, but the indices for soils developed on the outwash apron in front of the moraines suggest an older age, probably before the last interglacial (more than 125 ka). The most probable interpretation of the age of the moraines is that the Pinedale and Bull Lake glaciers extended the same distance downvalley but that, during the Pinedale glaciation, high Bull Lake lateral moraines protected all but the center of the fan surfaces from burial by younger outwash. Thus, the outwash fans that are displaced by the James Peak fault (Qablf and Qaof, fig. 2) are probably primarily of Bull Lake age (130–150 ka).

Soil JP-3 and the uppermost parts of JP-1 (JP-1a) and JP-2 (JP-2a) are only weakly developed and fall in RAG 4 (fig. 3). Cambic and weak argillic B horizons have developed in the mixed fine-grained sheetwash and loess deposits in the upper parts of soils JP-1 and JP-2. Soil JP-3 has a weak argillic horizon but no increase in hue or chroma to bright reddish colors (table 1). Soil indices suggest a Holocene or very latest Pleistocene age for this soil, and its position near the main stream channel of the largest drainage basin on the northern flank also suggests that it is of Holocene (probably late Holocene) age. Argillic horizon development in deposits this young is probably caused by a locally high rate of eolian dust influx (fine silt as well as clay) from the large areas of exposed Bonneville lake sediments in southern Cache Valley. Shroba (1980) has also described argillic horizons from deposits of early to middle Holocene age along the Wasatch fault.

FAULT-DISPLACEMENT HISTORY

To estimate the sizes, number, and ages of the more recent surface-displacement events on the James Peak fault, a single trench was excavated across the 7-m-high scarp on the outwash fan 200 m west of the left-lateral moraine (fig. 2). Dense aspen forest and soft soils prevented access to all other promising trench sites. The trench exposed white, coarse, sandy, quartzite-derived outwash (unit 1, fig. 4) on which was developed a reddish argillic horizon (unit 1bB, fig. 4) overlain by bouldery, silty colluvial wedges (unit 2, fig. 4). The wedges were overlain by silty colluvial units (units 3 and 4, fig. 4) marked by thick cambic and argillic B horizons. Despite the slumping and raveling of the very loose, unconsolidated outwash in the lower trench walls, we were able to expose the fault zone and former free face of the scarp at the southern end of the trench. A topographic profile across the scarp indicates that the fan has been displaced about 4.2 +0.6/−0.2 m at this site. The stratigraphic relations, unit contacts, lithologies of the outwash and the colluvial wedges, and soils developed on them do not clearly show whether one event of about 4-m displacement or two events of about 2-m displacement occurred on the same fault in the trench. As we will discuss later, we favor a two-event interpretation.

On the basis of regional correlation of map and trench units as suggested by the soil development indices of figure 3, we infer the following sequence of events:

TABLE 1.—*Selected properties of soils on the northern flank of James Peak, north-central Utah*

Profile	Trench log unit	Horizon[1]	Average depth (cm)	Parent material	Munsell dry color	Estimated percentage by volume			Percentage by weight[2]			Organic matter[3] (percent)
						Pebbles (0.2–8 cm)	Cobbles (8–25 cm)	Boulders (>25 cm)	Sand (2–0.5 mm)	Silt (50–2μm)	Clay (<2 μm)	
JP–1	4b	A1	0–10	Colluvium-loess	7.5YR 2/2	10	2	0	20	57	23	9.4
	4b	A2	10–46	.....do.....	7.5YR 3/2	10	2	0	22	54	24	8.8
	4a	Bw	46–83	.....do.....	7.5YR 5/3	10	5	0	28	51	21	3.2
	3bB	2Bt1	83–100	.....do.....	7.5YR 5/4	10	5	0	26	53	21	2
	3Ba	2Bt2	100–205	.....do.....	7.5YR 6/4	25	15	0	28	48	24	.7
	2	3Cox/3Bt	205–248	Scarp colluvium	7.5YR 7/4	20	20	2	33	45	23	.6
	1bB	4Bt	248–278	Outwash	5YR 4/6	30	30	10	54	18	28	.3
	1	4Cox	248–390+	.....do.....	7.5YR 7/3	30	30	10	90	8	3	.2
Extra samples[4]	2b	3C	260	Scarp colluvium	7.5YR 7/4	10	15	25	36	45	19	.9
	2a	3C	355	.....do.....	7.5YR 6/4	10	20	20	21	39	40	.4
JP–2		Ap	0–10	Sheetwash-loess	10YR 6/3	20	25	0	29	52	19	5.2
		A	10–20	.....do.....	7.5YR 6/4	20	25	0	28	52	20	3.7
		Bt	20–53	.....do.....	7.5YR 6/4	20	25	0	37	37	26	1.4
		2Bt	53–85	Outwash	2.5YR 4/6	50	25	0	72	17	11	.6
		2BC	85–114	.....do.....	5YR 7/4	50	25	0	88	7	5	.2
		2Cox	114–136+	.....do.....	5YR 7/4	40	35	1	84	11	5	.3
JP–3		A1	0–16	Loess-alluvium	7.5YR 4/3	15	20	25	35	53	12	13.4
		A2	16–41	.....do.....	7.5YR 5/3	15	20	25	41	41	19	5.2
		Bt	41–85	.....do.....	7.5YR 5/4	15	20	25	63	27	10	1.2
		2C	85–132+	Alluvium	7.5YR 7/3	25	20	30	82	13	5	.4
JP–4		A1	0–13	Sheetwash-till	7.5YR 3/3	20	5	10	62	31	8	10.4
		A2	13–48	.....do.....	7.5YR 4/3	10	20	10	66	27	6	3.6
		2Bt	48–72	Till	7.5YR 8/1	20	10	10	72	20	9	.4
		2C	72–105+	.....do.....	7.5YR 8/0	20	15	10	81	15	4	.4

[1]Horizon nomenclature of Guthrie and Witty (1982) and Birkeland (1984).

[2]Particle size distribution of <2-mm fraction obtained by using sieve-pipette methods (for example, Carver, 1971) and a Sedigraph for some silt-clay fractions from which organic matter has been removed by Jackson's (1956) method. No samples contained carbonate.

[3]Determined by Walkley and Black's (1934) method.

[4]From center of units 2a and 2b at distance *m* (fig. 4).

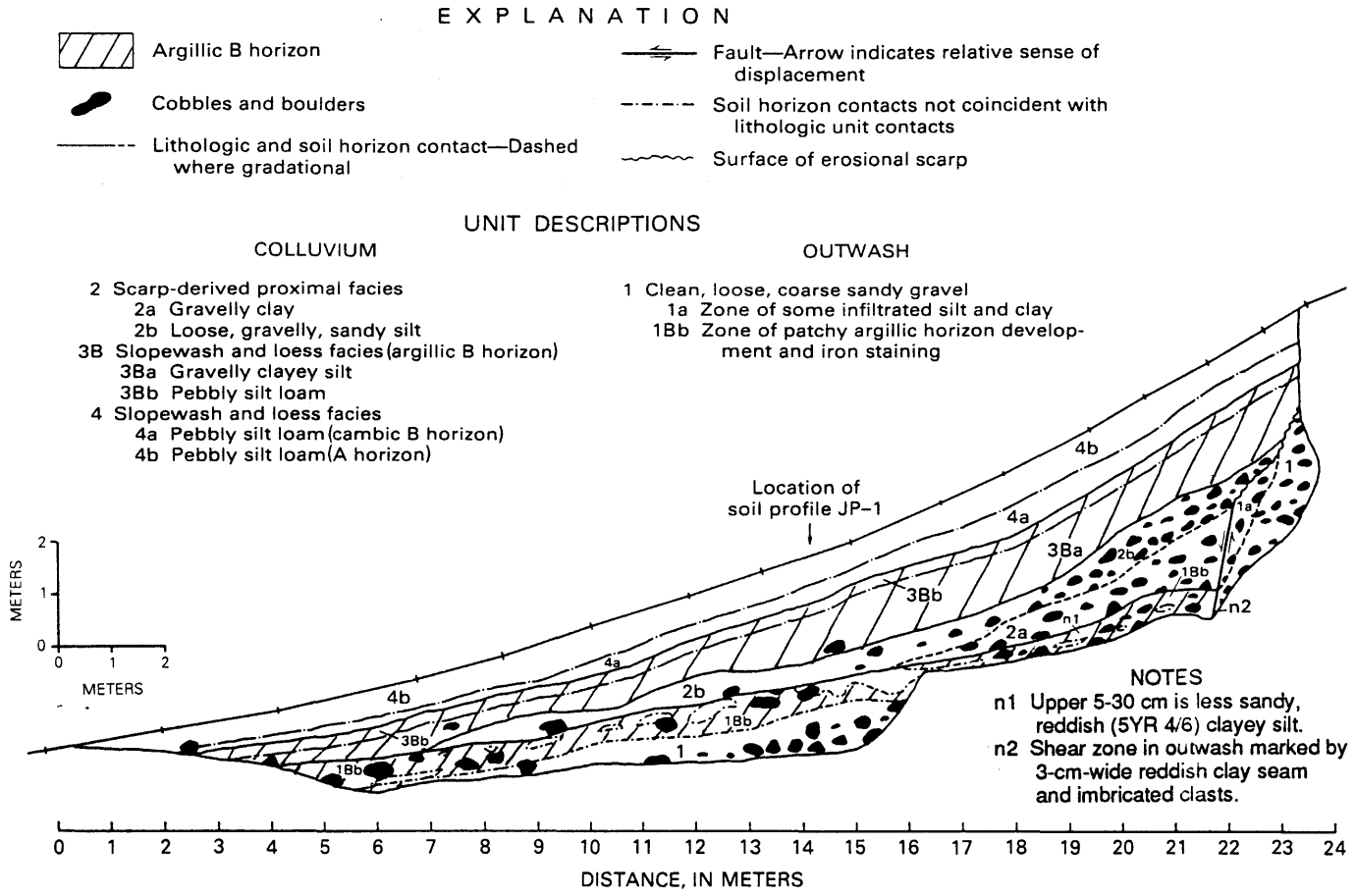


FIGURE 4.—Log of the eastern wall of the trench across the scarp of the James Peak fault (fig. 2). The segmented line at the top of the log is the central portion of topographic profile JP-1 measured across the site by using the methods of Bucknam and Anderson (1979). To trench as high as possible on the scarp, the trench was dug in two parts; the first part (0–12 m in distance) was backfilled before the second part (12–19 m in distance) was dug. Lowercase letters in unit symbols indicate sublithofacies, and B marks argillic B horizons. The lithology of the proximal colluvial wedges—units 2a and 2b—suggests that the scarp was formed by two surface-faulting events (see text).

1. Moraines and an extensive outwash fan were deposited on the northern flank of James Peak, probably during the Bull Lake glaciation (about 130–150 ka). Soils developed on stable areas of moraines and outwash, but gradual erosion prevented well-developed soils from forming on moraine crests. The length of time required to develop the reddish argillic B horizons on the outwash is difficult to estimate, partly because the soil north of the trench site (JP–2) appears to have been stripped. The fact that the argillic horizon and the fine-grained units overlying it are thin suggests that soil JP–2 has been eroded, perhaps by meltwater in braided outwash channels (which did not reach the trench site) during the later Pinedale glaciation. These horizons may have developed rapidly because of high rates of dust influx owing to the silt and clay from lake sediments exposed in Cache Valley to the north. Because the B horizons on these deposits are much more strongly developed than the B horizons on late Pinedale or Holocene deposits, these horizons must have taken at least a few tens of thousands of years to develop, perhaps as long as 70,000 years.
2. Surface faulting vertically displaced the outwash (unit 1, fig. 4) about 1.6 to 2.2 m down to the north. A proximal colluvial debris wedge (unit 2a, fig. 4), formed by spall, slump, and slopewash, rapidly buried the argillic horizon developed on the outwash (unit 1bB, fig. 4) and the lower part of the free face of the scarp. The source of the bouldery debris wedge, which has a matrix of silty clay (table 1), must have been the surface colluvium of similar lithology overlying the outwash on top of the scarp (not exposed in our trench). The uppermost part of unit 1bB near the fault is mapped as part of the soil developed on unit 1. But the thickening of the reddish clayey silt near the

top of unit 1bB (note 1, fig. 4) and the inclusion of reddish clayey peds in the matrix of less reddish clayey silt near the base of unit 2a suggest that material along the contact between units 1bB and 2a may be fragments of an argillic horizon eroded from the crest of the scarp immediately after the event. We infer that none of the loose, sandy outwash (unit 1, fig. 4) was exposed in the free face by this event; if it had been, the free face would have slumped almost immediately after faulting and contributed much coarse sand to the debris wedge. Equilibrium scarp degradation models at gently sloping sites suggest that the maximum fault displacement is about two times the maximum colluvial wedge thickness (for example, Nash, 1981). However, the steep slope above the site and the inferred active surface transport processes (discussed below) suggest that the amount of vertical displacement during this event was probably not much greater than the wedge thickness (1.6 m).

3. After the argillic horizons had formed and probably after the first fault event, soil development on the lower part of the outwash fan continued. However, the steep (20°–25°) slope of the fan above the trench site, the lack of well-developed B horizons on the proximal wedges, and the high clay content of surface colluvium above the scarp suggest that creep and solifluction may have been the dominant slope processes during periods of cold, moist climate (onset of Pinedale glaciation, about 75 ka?) during or after the deposition of the first proximal wedge. These processes may have eroded existing soils or prevented well-developed soils from forming at and above the site.
4. A second displacement event on the same fault moved unit 2a down against the outwash. The loose, sandy lithology of the proximal debris wedge (unit 2b, fig. 4) that was produced following this event indicates that some outwash was exposed in the free face in addition to the bouldery, clayey silt (not exposed in the trench) overlying the outwash. Erosion of the scarp following the first event also probably reduced the proportion of bouldery silt to outwash exposed in the free face during the second event and resulted in a sandy wedge. Slumping of the outwash in the lower part of the free face helped to spread loose debris downslope and buried the debris wedge from the first event. The loose debris produced a thin wedge (unit 2b, fig. 4) that extended farther downslope than the first wedge (unit 2a, fig. 4); this geometry is typical of debris wedges produced by the second and third events on multiple-event scarps (Ostenaa, 1984). Displacement during the second event is more difficult to estimate from the thickness of the debris wedge; it must be close to the difference between the total topographic displacement across the scarp and the displacement of the first event (4.2 m−(1.6–2.2 m)=2.0–2.6 m). We could not measure total throw because the top of the outwash unit in the footwall was not exposed in the trench. The lack of any evidence of soil development on the debris wedge resulting from the first event suggests that the two events may have occurred less than a few tens of thousands of years apart. However, the active surface processes on the steep fan (discussed earlier) could also have eroded a moderately developed soil or prevented one from forming. It is also possible that weak soil development near the top of wedge 2a is masked by later development of more strongly developed soils on units 2b and 3Ba (fig. 4). An alternate interpretation that must be considered is that both units 2a and 2b are proximal debris wedges produced following a single displacement event of about 4 m. This interpretation would explain the absence of (1) an abrupt contact between units 2a and 2b, (2) any evidence of soil development on unit 2a, and (3) deformation of the first debris wedge (unit 2a) during the second event. The apparent overlap of the time estimates for pre-first event and post-second event soil-forming intervals (discussed later) would also be explained by a single event. Clear evidence of shearing along the contact between units 2a and 1a was not observed, but three cobbles were imbricated parallel with the contact near the base of unit 1a, and the outwash is so unconsolidated that evidence of shearing may not have been preserved. Possibly, unit 1a is a fissure that filled with outwash that slumped from the free face after a second event. In any case, the stratigraphic relations near the fault show that most of unit 2a must have been deposited immediately after faulting, and its lithology shows that this unit was derived from units that contained little sand. Because we find it difficult to explain how a thick proximal debris wedge could be deposited adjacent to an almost vertical free face of loose, sandy outwash several meters high in such a way that the outwash contributed no sediment to the wedge, we favor a two-event fault history. In addition, 2-m displacement events are much more typical of faults in the region, even faults that are much longer than the James Peak fault (for example, Schwartz and Coppersmith, 1984).
5. A silty colluvial wedge (unit 3B, fig. 4) was deposited over the proximal debris wedges by wash erosion of the scarp crest and by rill and wash transport of fines from above the site. The thickness and high silt content of the wedge (table 1) suggest that it has a strong eolian component, probably owing to exposed lake sediments in Cache Valley. As the deposition

rate of the colluvial wedge decreased, B horizon development in the upper part of the wedge became more distinct and culminated in a 122-cm-thick argillic horizon (table 1) on the wedge. Because of its position on the scarp slope, this soil is not directly comparable to soils in more stable landscape positions whose age is better known. We interpret this soil as forming in a climate not greatly different from the present; thus, it must either predate the main Pinedale glaciation (18–25 ka) or postdate the fall of Lake Bonneville from its high stand (15 ka) (Scott and others, 1983). The total amount of clay in this soil (9 g/cm^2) in comparison with regional rates of clay accumulation (for example, Colman and others, 1988) and most other soil indices (fig. 3) for this part of the soil on unit 3 suggest an age as great as 100 to 150 ka because these horizons are so thick. However, the limited soil reddening and weak B horizon structure, the probable high rate of dust influx during part of the history of the site, and the likelihood that some of unit 3 is derived from clay-rich soils upslope all suggest a much younger age. Thus, we estimate that this soil, which postdates both fault events, developed over a period of 30,000 to 70,000 years.

6. Finally, an episode of rapid slopewash deposition, probably marked by some eolian influx, produced a silty colluvial unit (unit 4, fig. 4) that is very similar to unit 3. A weak cambic B horizon (unit 4a) and a thick, silty A horizon (unit 4b, fig. 4) on this unit indicate a Holocene age (soil JP–1a, fig. 3). Deposition during the warmer and probably drier Altithermal of the middle Holocene (Baker, 1983) is likely.

SLIP RATES AND RECURRENCE

The topographic profile across the scarp at the trench site (fig. 4) shows that the outwash, most likely about 140 ka, is displaced about 4.2 m for an average late Quaternary vertical slip rate of 0.03 mm/yr on the James Peak fault.

Because the soils developed on the outwash and on the colluvium overlying the faulting-related wedges provide only maximum and minimum age estimates for the wedges, the true intervals of time between surface-faulting events are difficult to estimate. Although displacement data for each of the two fault events are uncertain, scarp erosion models that consider the position of the scarp at the foot of a steep slope, the thickness of the first colluvial wedge, and the volumes and lithologies of both wedges suggest that the second event may have been larger than the first. We estimate average displacements of about 1.8+0.4/−0.2 m for the first event and 2.4+0.8/−0.6 m for the second event. The reddish argillic horizon on the outwash beneath the colluvial wedges probably required at least several tens of thousands of years (we assume more than 30,000 but perhaps even 70,000 years) to develop before burial. This well-developed soil adjacent to the fault shows that no significant displacement occurred on the fault for a long period of time after outwash deposition ceased. Thus, the first event could have occurred as early as 110 ka (140–30 ka) or as late as 70 ka (140–70 ka). The thick argillic horizon on unit 3B (fig. 4), which postdates the second displacement event, also suggests a soil-forming interval of at least 30,000 and perhaps 70,000 years. Given these broad constraints, a time interval of 80,000 years (110–30 ka) is available in which the two events could have occurred. If we take the mean of possible times at which each event occurred (first event 90 ka, second event 50 ka), the events are separated by 40,000 years (90–50 ka). Because the maximum estimates of the length of the soil-forming intervals following each event overlap, no minimum estimate of the length of this period can be made. If the two events were separated by 40,000 years, the recurrence interval between these events and earlier and future events would be more than 50,000 years (50,000+40,000+50,000=140,000 years). Thus, the average recurrence interval for the two events since 140 ka is at least 50,000 years, but the lack of a soil between the two debris wedges suggests nonuniform recurrence. However, if there was only one event (discussed earlier), it probably occurred about 70 ka.

RELATIONSHIP TO THE EAST CACHE FAULT

The location of the James Peak fault at the southern end of the East Cache fault suggests that their surface-rupture histories may be related. Blau's (1975) mapping showed that the East Cache fault is abruptly terminated at its high-angle intersection with the James Peak fault (fig. 2), because no north-trending fault extends up Wellsville Creek. The James Peak fault is also oriented at near-right angles to the contemporary regional extensional stress field (Zoback and Zoback, 1980). However, portions of the Wasatch fault that intersect at high angles have ruptured concurrently during the Holocene (Nelson and Personius, 1990), and similar fault patterns are found along late Quaternary fault zones elsewhere in the Basin and Range (for example, Wallace, 1979). The morphology of the bedrock scarps on the Broadmouth Canyon faults (fig. 2) does not suggest recurrent late Quaternary displacement but also does not preclude some Quaternary slip. These scarps trend southwesterly, nearly parallel to the southern part of the East Cache fault. We speculate that the Broadmouth Canyon faults may be the southernmost part of a Quaternary rupture zone encompassing all three faults.

Some of the larger surface-displacement events on the James Peak fault may have ruptured part of the East Cache fault. Empirical relations between the amount of surface displacement and fault rupture length (Bonilla and others, 1984) suggest that more than 7 km of surface faulting is associated with events that produce the 2 m of displacement that we infer from our trench stratigraphy. On the Wasatch fault, surface displacements of 1.6 to 2.6 m are thought to be associated with ruptures on fault segments 30 to 60 km long (Schwartz and Coppersmith, 1984). The 1983 Borah Peak, Idaho, earthquake had a maximum displacement of about 2.5 m and a total rupture length of 36±3 km (Crone and Machette, 1984). Thus, even if small, unrecognized ruptures occurred on the Broadmouth Canyon faults during the events recorded at James Peak, at least 15 to 20 km of the southern part of the East Cache fault may also have ruptured. Near the southern end of the East Cache fault, Swan and others (1983) could not determine the age of most recent displacement because the main trace of the fault is well above the Bonneville shoreline at the range front and because scarps along the fault are almost completely masked by younger (post-Provo shoreline, younger than 14 ka) (Scott and others, 1983) alluvial fans. Mullens and Izett (1964) also did not find evidence of surface faulting in the Paradise area (fig. 1). Thus, any scarps along the East Cache fault related to the James Peak events are probably covered by younger deposits. Farther north along the East Cache fault near Logan, Utah (fig. 1), Swan and others (1983) concluded that two 1- to 2-m post-Bonneville surface-displacement events have occurred on this part of the East Cache fault for a slip rate of 0.10 to 0.2 mm/yr for the last 15,000 years. The first event occurred between the high stand of Lake Bonneville (15–16 ka) (Scott and others, 1983) and its catastrophic fall to the Provo shoreline (14–15 ka). The second event postdates the Provo level of the lake and predates alluvial fans thought to be about 6 to 10 ka. Excavations at several places along the East Cache fault have also revealed post-Bonneville displacements (B.N. Kaliser, oral commun., 1981), but these investigations are undocumented. Thus, the average recurrence interval on the section of the East Cache fault marked by the post-Provo scarps near Logan since the high stand of Lake Bonneville appears to be about 7,000 years, but the actual interval between events could be as short as 2,000 to 3,000 years (Swan and others, 1983).

Estimates of the thickness of basin fill in southern Cache Valley (Zoback, 1983) and topographic relief on the bedrock escarpment of the East Cache fault, both of which decrease south of Logan, suggest that total displacement on the fault also diminishes to the south. Late Pleistocene scarps are mapped along the fault at least as far south as Blacksmith Fork Canyon (Cluff and others, 1974; Swan and others, 1983), but Swan and others (1983) speculated that the rupture near Logan may die out south of Providence Canyon.

Site-specific fault slip data indicate differing histories for the East Cache and James Peak faults, but little reliable information on the southern half of the East Cache fault is available to distinguish among several possible relations. One possibility is that displacements on the James Peak fault occur near the end of surface ruptures produced by very large but infrequent (average recurrence interval of more than 50,000 years) earthquakes that break a large part (more than 50 km) of the East Cache fault. The length of these ruptures and the fact that the amount of displacement near the center is likely to be greater than that near the end of the rupture segment indicate that these earthquakes would be as large as or larger than those inferred on the central segments of the Wasatch fault (Bonilla and others, 1984; Schwartz and Coppersmith, 1984), a supposition that seems very unlikely. Alternatively, the East Cache fault may consist of unrecognized segments, the recurrence interval on the southern part of the fault (and the James Peak fault) being an order of magnitude longer than that on the East Cache fault near Logan. The southern part of the East Cache fault could also have a slip rate and a recurrence interval similar to those of the central part of the fault; if displacements were occurring near the base of the facets along the range front, on faults buried by the post-Provo alluvial fans along the range front, or on faults basinward of the alluvial fans, scarps on these unrecognized faults would be either buried or quickly eroded.

Although the apparent slip rates on the East Cache and James Peak faults differ by a factor of 3 to 6, it should be emphasized that the ages of the datums used to estimate those rates differ by almost an order of magnitude. A similar situation is reported by Machette and others (this volume), whose mapping suggests that the high slip rates and short recurrence intervals on the central segments of the Wasatch fault zone may apply only to the latest Pleistocene and Holocene; longer term, late Quaternary rates appear to be much lower, closer to those estimated for other faults in the region (for example, Nelson and VanArsdale, 1986; Sullivan and Nelson, this volume). The rapid changes in subsurface pore pressures and the isostatic loading and unloading accompanying the rise and fall of Lake Bonneville about 15 ka may have triggered many earthquakes on the Wasatch and East Cache faults and resulted in a latest Pleistocene and Holocene recurrence rate several times larger than the late Quaternary rate (Swan and others, 1983; Machette and others, this volume). Thus, we speculate that late Quaternary slip rates on the East Cache fault

and the James Peak fault, and perhaps recurrence intervals as well, do not differ nearly as much as the apparent slip rates suggest.

CONCLUSIONS

Two surface-displacement events of about 2 m each have occurred on the James Peak fault in the last 140 ka, indicative of a late Quaternary slip rate of about 0.03 mm/yr. Surface-faulting recurrence intervals are difficult to estimate because of poor age control, but the average interval between events is at least 50,000 years. The fault may be a westerly splay of the East Cache fault rather than a separate valley-bounding fault like the ones to the south. The lack of detailed slip and recurrence data from the southern half of the East Cache fault precludes determining whether the central part of the East Cache fault behaves independent of the southernmost part of the fault and of the James Peak fault or whether all parts of both faults have had a similar late Quaternary history.

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