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Recurrent Late Quaternary Movement on the Strawberry Normal Fault, Basin and Range–Colorado Plateau Transition Zone, Utah

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Strawberry Valley lies 40 km east of the Wasatch fault, within the transition zone between the Basin and Range and Colorado Plateau Provinces in central Utah. Geologic mapping and valley geomorphology suggest that Strawberry Valley is a half-graben bounded on the east by the Strawberry normal fault. Two trenches excavated across a 7-m-high fault scarp in alluvium, subsidiary to the main trace of the Strawberry fault, expose a record of 2 to 3 fault events, each of 1 to 2 m stratigraphic displacement, over the last 15,000 to 30,000 yr, but with smaller net vertical tectonic displacements due to graben formation and backtilting. Age estimates based on soils suggest that the last surface displacement event occurred during the early to mid-Holocene. These displacement and age data suggest that recurrence rates for earthquakes large enough to produce surface ruptures on the Strawberry fault are in the range of 5000 to 15,000 yr. Subsidiary fault slip rates calculated from estimated displacement across the 7-m scarp are 0.04 to 0.17 mm/yr, while minimum longer-term late Quaternary rates on the main fault are 0.03 to 0.06 mm/yr based on ^{14}C and amino acid dating of alluvial plain cores 15 km to the south. These rates suggest a slip rate for the Strawberry fault, at most half, and probably an order of magnitude less than latest Pleistocene and Holocene rates for the Wasatch fault. Recurrence rates and the amount of displacement per event are less than for the Wasatch fault, but are similar to estimates for other faults in the eastern Basin and Range. Recurrent late Pleistocene and Holocene displacement on the Strawberry fault suggests that the late Quaternary extensional stress regime of the Basin and Range extends at least this far east in central Utah.

INTRODUCTION

Paleoseismologic and other geologic studies demonstrate continuing Quaternary faulting in the eastern Basin and Range physiographic province (Anderson, 1979; Swan et al., 1980; Hamblin et al., 1981;

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Nakata et al., 1982; Crone and Harding, 1984). Recent geophysical data and structural interpretations suggest a transition zone between the Basin and Range and Colorado Plateau Provinces that extends 50 to 100 km east of the Wasatch fault in central Utah (Shuey et al., 1973; Zoback, 1983; Smith and Bruhn, 1984). The easternmost extent of proven late Quaternary surface faulting in the transition zone south of Cache Valley (85 km north of Salt Lake City; see Fig. 1), has been along the Wasatch fault (Schwartz and Coppersmith, 1984), although present-day seismicity appears concentrated in a north–south zone 15 to 30 km east of the Wasatch fault (Arabasz et al., 1980). "Back-valley" basins (so termed by Gilbert, 1928, p. 58), such as Kamas, Heber, Round, and Strawberry Valleys, lie within this area east of the crest of the Wasatch Mountains and south of Cache Valley (Fig. 1). The morphology, distribution, and lithology of Quaternary deposits in the back valleys suggest that the east–west extensional faulting characteristic of the late Tertiary of the region (Gilbert, 1928; Eardley, 1944; Hopkins and Bruhn, 1983) extends into the Quaternary within the eastern Wasatch Mountains (Nelson and Krinsky, 1982; Sullivan and Nelson, 1983). However, back-valley faults are not generally marked by scarps in unconsolidated late Quaternary deposits except along the east side of Strawberry Valley (VanArsdale, 1979a, b; Sullivan and Nelson, 1983).

Here we document late Pleistocene and Holocene movement on the normal fault that forms the eastern margin of the easternmost back valley, Strawberry Valley (Fig. 1). An understanding of present and future crustal responses to tectonic stress in the Great Basin, including its eastern transition zone, requires detailed mapping of Quaternary faults with emphasis on fault recurrence. Although such studies help constrain theoretical work (for example, Zandt and Owens, 1980; Smith and Bruhn, 1984), the number of large reservoirs in the back-valley area, several near population centers, also makes earthquake recurrence studies socially and economically important.

STRUCTURE AND TECTONIC GEOMORPHOLOGY OF STRAWBERRY VALLEY

In the northern part of Strawberry Valley, sedimentary rocks ranging from Pennsylvanian to Tertiary age are exposed (Fig. 1). Geosynclinal rocks were thrust eastward over shelf rocks along the Strawberry Valley thrust fault in latest Cretaceous to Paleocene time (Bissell, 1952, 1959; Astin, 1977). The imbricate thrust slices exposed in the northern part of the valley are believed to project southward under the Tertiary sediments of Strawberry Valley (Astin, 1977; VanArsdale, 1979a).

The Strawberry normal fault bounds the eastern side of Strawberry Valley. The fault forms a single bedrock scarp, 100 to 230 m high, from its southern end, northward to the area of Trout Creek (Fig. 1). Deforma-

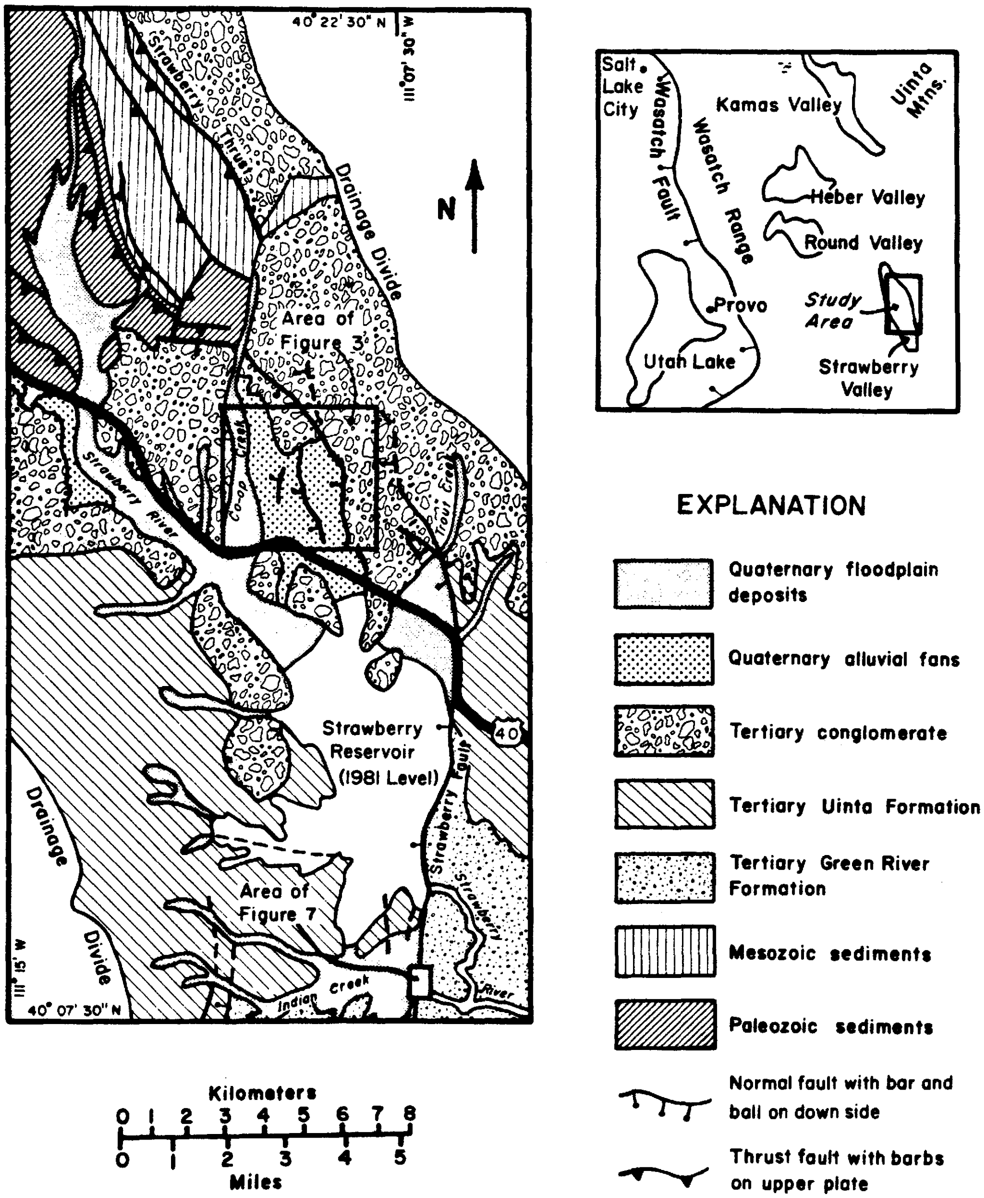


Figure 1. Geologic map of Strawberry Valley, a back valley east of the Wasatch fault, in the transition zone between the Basin and Range and Colorado Plateau Provinces in central Utah. Boxes outline the areas mapped in more detail near trench (Fig. 3) and coring (Fig. 7) sites. The leading edge of the Charleston-Strawberry-Nebo thrust underlies Strawberry Valley, which is bounded on the east by the Strawberry normal fault.

tion along the fault is principally confined to the fault zone and downthrown block, with drag folding particularly evident near Indian Creek in the southern part of Strawberry Valley (Figs. 2 and 7). Near Indian Creek the contact between the Uinta and Green River Formations is downdropped 180 m down-to-the-west. Scarp height decreases

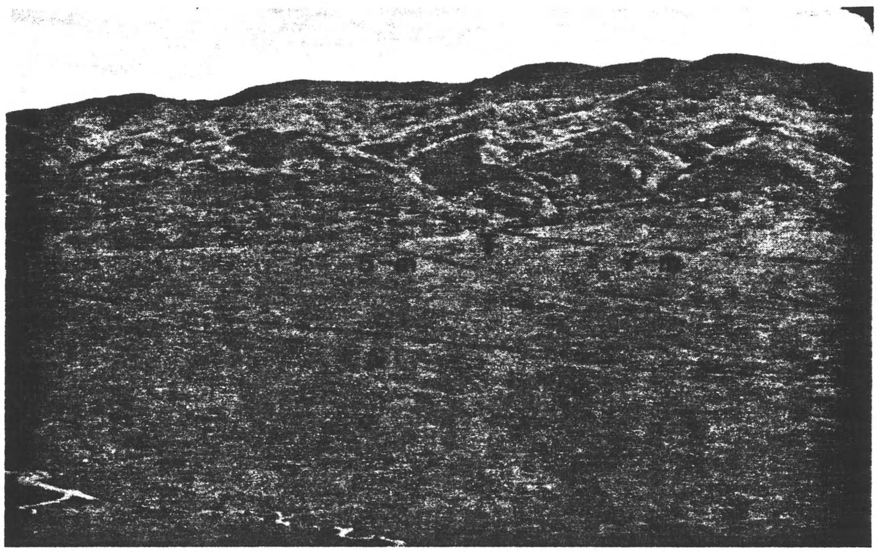


Figure 2. Eastward view of the alluvial fans between the Strawberry fault and Co-op Creek north of Strawberry Reservoir (Figs. 1 and 3) showing the two fault scarps on the fan surface (labeled 5-m and 7-m) and the main trace (MT) of the Strawberry fault (in shadow just above the fans). The terrace scarp along Co-op Creek (ST) is stream cut. Trench 1 (T) was located at the north end of the 7-m scarp.

from 180 m at Indian Creek to zero, 10.5 km south of the reservoir. Near Trout Creek, deformation within the fault zone consists of an asymmetrical graben with sandstone beds within the graben dipping 25° west. Further north, near Co-op Creek, the Strawberry fault forms multiple scarps in alluvial fans and bedrock across a zone 5 km wide (Figs. 1 and 2). Near Co-op Creek the main fault, marked by a 200-m-high escarpment, juxtaposes Quaternary alluvial fan sediments and Tertiary conglomerate. The scarps in the alluvial fans, about 1.3 km west of the main scarp, can be traced for only 3 km and are <7 m high. Near its northern end the fault swings westward through the Tertiary conglomerate, whereupon the scarp becomes difficult to follow.

Absence of a continuous north-trending, down-to-the-east fault on the west side of the valley suggests that Strawberry Valley is a tilted (half-graben) block and that the Strawberry fault is the sole basin-bounding normal fault (Threet, 1959; VanArsdale, 1979a). The fault may be listric and may merge at depth with the southern continuation of the Strawberry thrust fault (VanArsdale, 1979a; Royse, 1983).

The half-graben structural style of Strawberry Valley is reflected in certain of its geomorphic features. Easterly rotation of the Strawberry Valley block resulted in the cutting of narrow canyons on the east (uplifted) side of the valley where Indian Creek and the Strawberry River cross the Strawberry fault (Fig. 1) and in deposition of extensive alluvial fan complexes near Co-op Creek on the downthrown side of the fault. Aggradation of Indian Creek and the Strawberry River on the

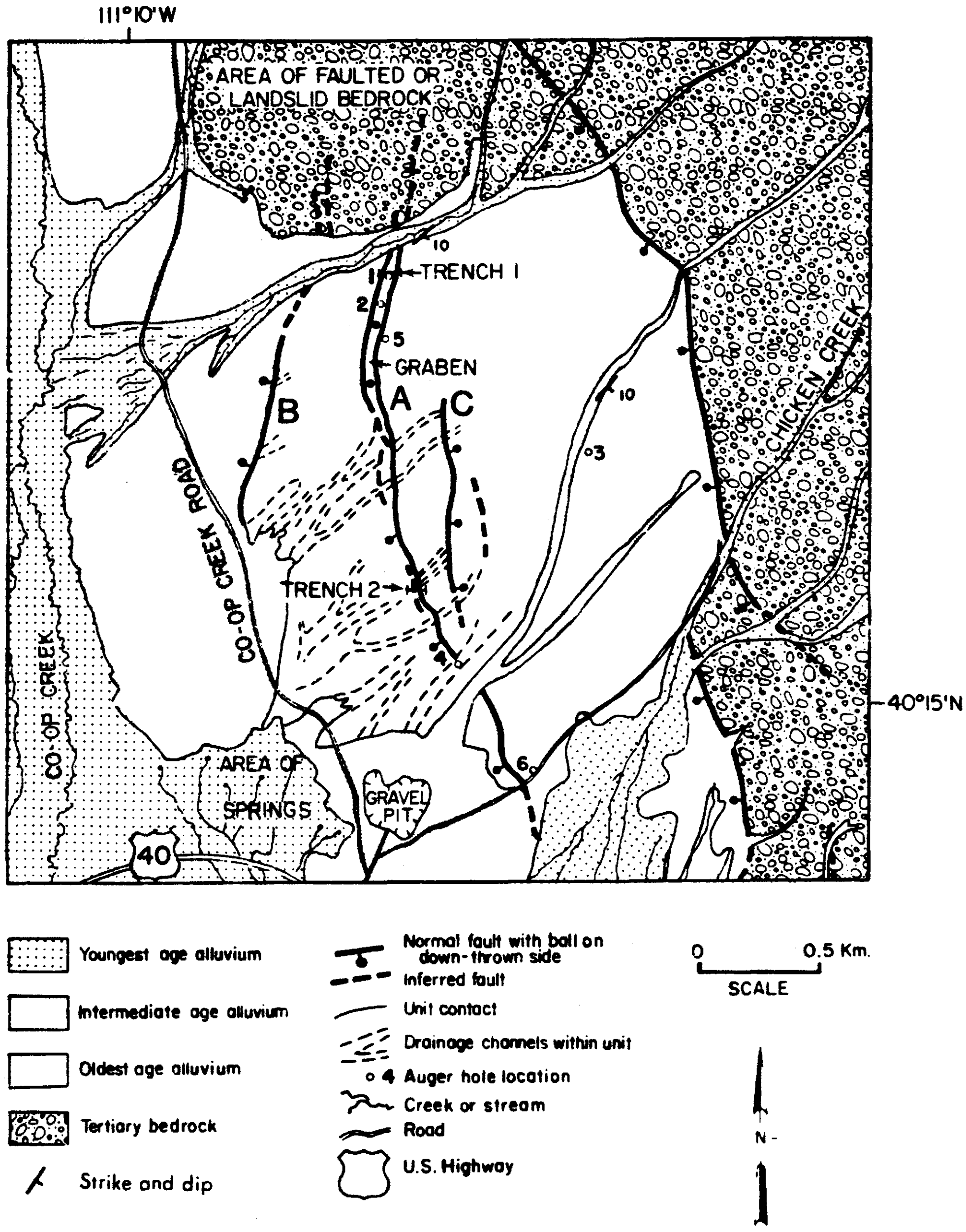


Figure 3. Geologic map of the alluvial fans and fault scarps east of Co-op Creek and north of Strawberry Reservoir (Fig. 1). The 7-m scarp (A) with trenches CC-1 and CC-2 (Figs. 4 and 6), the 5-m scarp (B), the 2-m scarp (C), auger holes, and drainage channels on the fans are shown. The main trace of the Strawberry fault is marked by the en echelon scarps that bound bedrock on the eastern edge of the oldest alluvium. The small drainage channels on the fans are not shown.

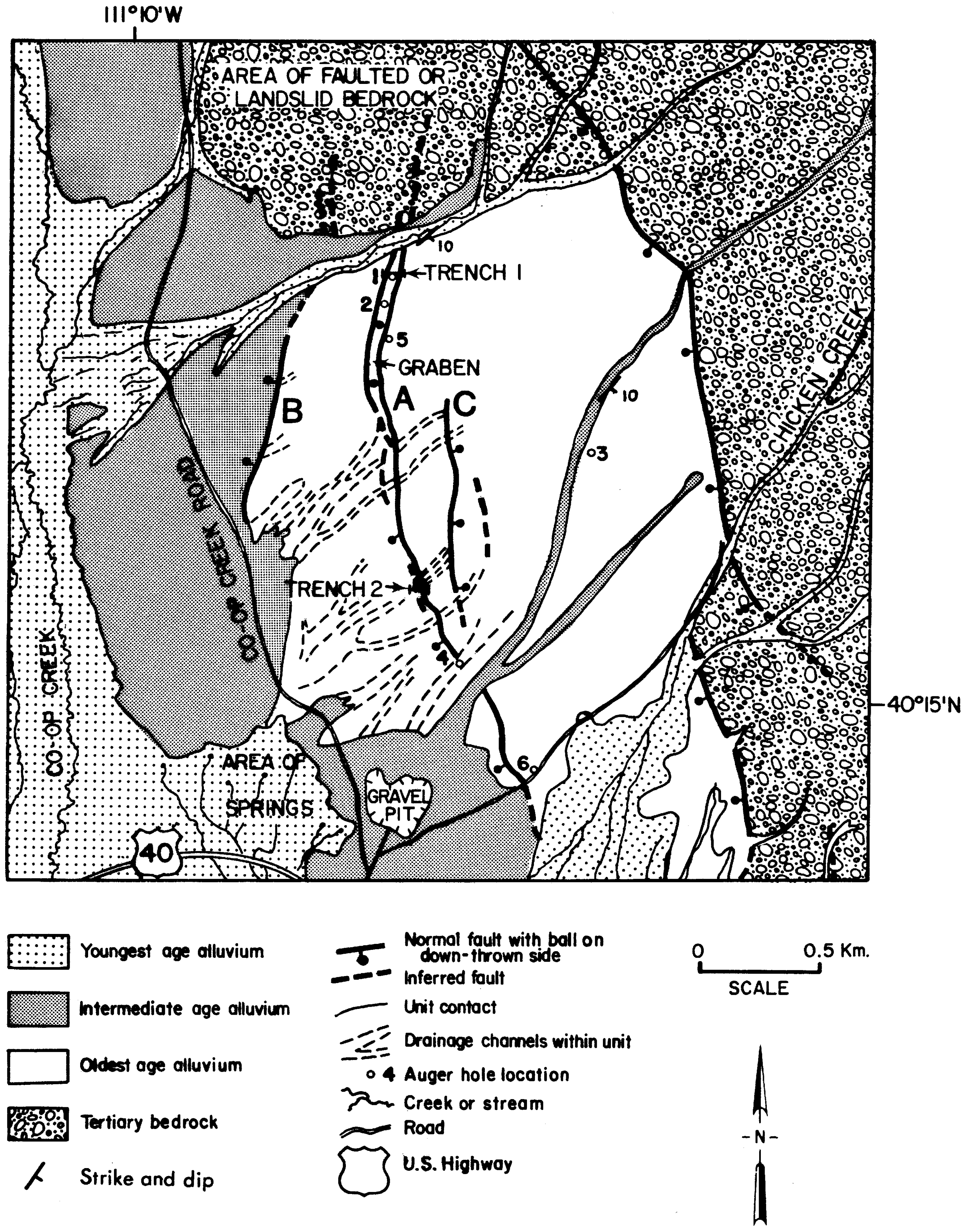

111°10'W
40°15'N
AREA OF FAULTED OR LANDSLID BEDROCK
TRENCH 1
GRABEN
A
B
C
TRENCH 2
CO-OP CREEK ROAD
CO-OP CREEK
CHICKEN CREEK
AREA OF SPRINGS
GRAVEL PIT
40
Youngest age alluvium
Intermediate age alluvium
Oldest age alluvium
Tertiary bedrock
Strike and dip
Normal fault with ball on down-thrown side
Inferred fault
Unit contact
Drainage channels within unit
4 Auger hole location
Creek or stream
Road
U.S. Highway
0
0.5 Km.
SCALE
N

Figure 3

rotated block is indicated by the thick alluvial fill west of the fault and alluvial drowning of bedrock inliers in the center of the valley adjacent to Strawberry Reservoir. Fault scarps on the alluvial fans near Co-op Creek reflect primarily down-to-the-west displacement (Figs. 2 and 3).

The only evidence suggestive of separate segments on the Strawberry fault is the en echelon pattern of the main trace of the fault north of Strawberry Reservoir (Fig. 1). The linearity and similar height and steepness of the bedrock escarpment along most of the length of the fault suggest that displacement events of similar size and recurrence have been evenly distributed along the fault during the Quaternary. Thus, the geology or geomorphology of the fault zone cannot be used to subdivide the fault into separate segments with differing fault histories. However, this does not necessarily imply that the entire length of the fault ruptured during each surface faulting event.

Based on their north–south orientation, limited length (Fig. 3), and height relative to the main scarp, the scarps in the alluvial fan sediments near Co-op Creek appear to mark subsidiary faults with much less total displacement than the main fault. Although these scarps may represent most of the displacement within the fault zone during the fault events which produced them, it is more likely that larger displacements occurred on the main fault during these events. Small facets on the scarp or other signs of late Quaternary displacement were not found on the main trace of the fault, but erosion obscures evidence of this type in less than a few thousand years. Topographic profiles down the axis of the alluvial fans show no evidence of warping of the fan surfaces, but small (<3 m) amounts of localized deformation would not be noticeable. For these reasons, we cannot assume that the displacement represented by the scarps was the total displacement in the fault zone during the events which produced the scarps.

Asymmetry in the shape of the drainage channels on the alluvial fans near Co-op Creek (Fig. 3) suggests that the block on which the fans rest may have been tilted to the south during faulting. The largest streams, which begin in the mountains east of the fans, have symmetric cross sections, are deeply incised into the fans, and have smooth profiles where they cross the two prominent fault scarps. Large channels that begin on the fans have asymmetrical cross sections (steep southern banks and gentle northern banks), but also have smooth channel profiles where they cross the scarps. Conversely, small channels which begin on the fans also have asymmetric cross sections, but have knickpoints in their profiles just above each of the two scarps. The greater erosional capacity of the larger streams has apparently removed any knickpoints in their channel profiles at the scarps, whereas the smaller streams have not been able to regrade their profiles. Small alluvial fans have been deposited at the base of scarps where the small fan channels have been vertically displaced. Bedrock exposed in the two large channels has been tilted 10° to the southeast (Fig. 3) suggesting that the asymmetry of some channels may be the result of greater stream incision against the southern channel banks due to tilting of the fan complex down to the south. Microclimatic control of slope processes is an alternative explanation of channel asymmetry (e.g., Dohrenwend, 1978), but because of the southeastern dip of the bedrock we favor a tectonic interpretation.

Morphometric analysis of profiles across fault scarps on alluvium is a widely used method of estimating the recency of fault movement in the Basin and Range Province (Nash, 1980; Colman and Watson, 1983; Hanks et al., 1984; Mayer, 1984). The sharp crests and steep slopes of the scarps and the small, displaced drainage channels on the alluvial fans (Figs. 2 and 3) suggest that the scarps are probably <100,000 yr old. Topographic profiles across the scarps are smooth, with no apparent facets, suggesting the scarps are not the result of multiple displacement events less than a few thousand years old. Following Wallace (1977) and Bucknam and Anderson (1979), we attempted to use the relation between a fault scarp's height and its maximum scarp–slope angle to estimate the age of the alluvial fan scarps (VanArsdale, 1979a; Nelson and Martin, 1982). However, because (1) there is such large scatter in our data from the alluvial fan scarps (correlation coefficient, *r*, of 0.60), (2) the scarps are the product of multiple fault events (discussed below), and (3) flows from Co-op Creek were periodically diverted down the graben, eroding portions of the 7-m scarp, our height-maximum-angle data are not suitable for comparisons with other scarp data sets.

SLIP RATES AND RECURRENCE INTERVALS ON THE STRAWBERRY FAULT

The fault scarps crossing the alluvial fan complex near Co-op Creek and the alluvial plain sediments near Indian Creek (Fig. 1) were trenched and cored, respectively, to estimate the age and size of late Quaternary displacement events on the fault (Figs. 5 and 8). Because no scarps in unconsolidated deposits were evident along the main trace of the Strawberry fault, two backhoe trenches were excavated across the subsidiary, 7-m-high, easternmost scarp at the north edge of the Co-op Creek alluvial fans (Fig. 3). Lithology, degree of stratification, degree of soil development, sharpness of stratigraphic unit contacts, the geometry of units, and the relationship of unit contacts to the present ground surface were used to interpret the genesis of units.

Co-op Creek Trench One

Trench one (CC-1) exposed stratified alluvial fan deposits, including braided steam and debris flow deposits, in the upthrown block and along the western third of the trench in the downthrown block (units 1 through

7, Fig. 4). Based on projections of the 3–4° slope of the fan surface, which were measured from topographic profiles extending well above and below the trēnch site, the net vertical tectonic displacement of unit 7 (methods of Swan et al., 1980) across the graben (stations 32–68, Fig. 4) is only about 1.2 ± 0.2 m, although the scarp is 7 m high. In the main graben, alluvial fan units 1–5 have been dropped below the bottom of the trench and may have been partially eroded by streams flowing through the graben (see discussion below). However, because unit 8 at station 45 extends to the base of our excavation (see note 4, Fig. 4), units 1 and 2 appear to be displaced at least 6 m. In the main graben portion of the trench (between stations 33 and 63, Fig. 4) we interpret moderately sorted, poorly to moderately stratified units (8 and 10) as alluvium. These units were apparently derived from fan alluvium and scarp-derived colluvium that was reworked by intermittent streams flowing from the drainage which presently truncates the graben on the north (Fig. 3) down the axis of the graben.

Age of Faulted Deposits

The degree of soil development is our best evidence with which to assess the age of the alluvial fan surface. The soil developed on unit 7 has an argillic B horizon (unit 7B) of variable thickness, averaging 60 cm thick (profile 1, Table I, Fig. 4). Clay coats the clasts to a greater degree in this horizon than in others, although all coarse units probably contain some infiltrated clay. Above unit 7B are eluvial units (7E, 16) of similar lithology, but with very little clay. Along most of the trench these units are interpreted as alluvial fan deposits with E and BA horizons developed on them from which clay has been eluviated into the Bt, although in some areas they are clearly colluvial. The thickness of these units is quite variable, perhaps due to increased eluviation through coarser zones in unit 7 or to ground disturbance by burrowing or tree-uprooting. Carbonate with stage I morphology (Gile et al., 1966), related to the present soil profile, has accumulated well below the B horizon in unit 5 (Fig. 4). Similar alluvial fan sediments with argillic horizons were encountered in auger holes 3, 4, 5, and 6 elsewhere on the fan surface (Fig. 3) indicating much of the fan surface is about the same age as the area near CC-1.

Assessment of the age of this soil is difficult because of the lack of independently dated soils on similar materials in the region with which to compare it. Comparison of the argillic horizon in this profile with those described from glacial deposits in the Rocky Mountain region (Madole, 1976; Pierce, 1979; Shroba and Birkeland, 1983) suggests a Bull Lake (about 60,000 to 150,000 yr) to older Pinedale (about 30,000 to 70,000 yr) age (nomenclature and ages of Porter et al., 1983). However, the criteria of Shroba (1980, 1982) for soils along the Wasatch Front (45 km to the

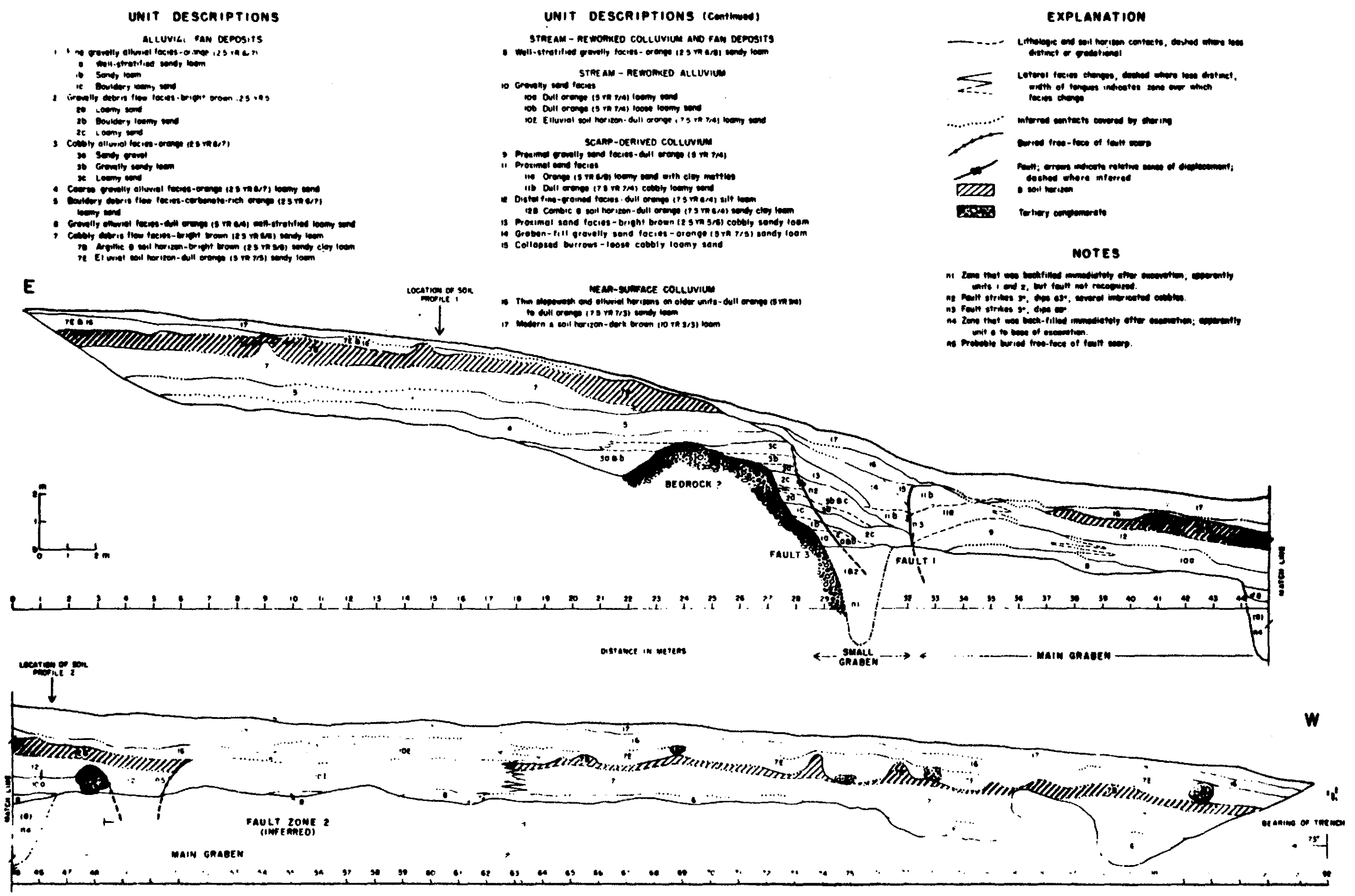


Figure 4. Geologic map of Co-op Creek trench 1 excavated across the 7-m scarp graben (Figs. 1 and 3). Fault 3 was not recognized prior to mapping the trench; it must extend through the excavated but unshored and unmapped lower portion of the trench between stations 29 and 32 (n1).

UNIT DESCRIPTIONS

ALLUVIAL FAN DEPOSITS

1 Fine gravelly alluvial facies-orange (2.5 YR 6/7)
- 1a Well-stratified sandy loam
- 1b Sandy loam
- 1c Bouldery loamy sand

2 Gravelly debris flow facies-bright brown (2.5 YR 5/7)
- 2a Loamy sand
- 2b Bouldery loamy sand
- 2c Loamy sand

3 Cobbly alluvial facies-orange (2.5 YR 6/7)
- 3a Sandy gravel
- 3b Gravelly sandy loam
- 3c Loamy sand

4 Coarse gravelly alluvial facies-orange (2.5 YR 6/7) loamy sand

5 Bouldery debris flow facies-carbonate-rich orange (2.5 YR 6/7) loamy sand

6 Gravelly alluvial facies-dull orange (5 YR 6/4) well-stratified loamy sand

7 Cobbly debris flow facies-bright brown (2.5 YR 5/6) sandy loam
- 7B Argillic B soil horizon-bright brown (2.5 YR 5/8) sandy clay loam
- 7E Eluvial soil horizon-dull orange (5 YR 7/5) sandy loam

UNIT DESCRIPTIONS (Continued)

STREAM - REWORKED COLLUVIUM AND FAN DEPOSITS

8 Well-stratified gravelly facies- orange (2.5 YR 6/8) sandy loam

STREAM - REWORKED ALLUVIUM

10 Gravelly sand facies
- 10a Dull orange (5 YR 7/4) loamy sand
- 10b Dull orange (5 YR 7/4) loose loamy sand
- 10E Elluvial soil horizon-dull orange (7.5 YR 7/4) loamy sand

SCARP-DERIVED COLLUVIUM

9 Proximal gravelly sand facies-dull orange (5 YR 7/4)

11 Proximal sand facies
- 11a Orange (5 YR 6/8) loamy sand with clay mottles
- 11b Dull orange (7.5 YR 7/4) cobbly loamy sand

12 Distal fine-grained facies-dull orange (7.5 YR 6/4) silt loam
- 12B Cambic B soil horizon-dull orange (7.5 YR 6/4) sandy clay loam

13 Proximal sand facies-bright brown (2.5 YR 5/6) cobbly sandy loam

14 Graben-fill gravelly sand facies-orange (5 YR 7/5) sandy loam

15 Collapsed burrows-loose cobbly loamy sand

NEAR-SURFACE COLLUVIUM

16 Thin slopewash and elluvial horizons on older units-dull orange (5 YR 7/4) to dull orange (7.5 YR 7/3) sandy loam

17 Modern A soil horizon-dark brown (10 YR 3/3) loam

EXPLANATION

Lithologic and soil horizon contacts; dashed where less distinct or gradational

Lateral facies changes; dashed where less distinct; width of tongues indicates zone over which facies change

Inferred contacts covered by shoring

Buried free-face of fault scarp

Fault; arrows indicate relative sense of displacement; dashed where inferred

B soil horizon

Tertiary conglomerate

NOTES

n1 Zone that was backfilled immediately after excavation; apparently units 1 and 2, but fault not recognized.

n2 Fault strikes 3°, dips 63°; several imbricated cobbles.

n3 Fault strikes 5°, dips 88°.

n4 Zone that was back-filled immediately after excavation; apparently unit 8 to base of excavation.

n5 Probable buried free-face of fault scarp.

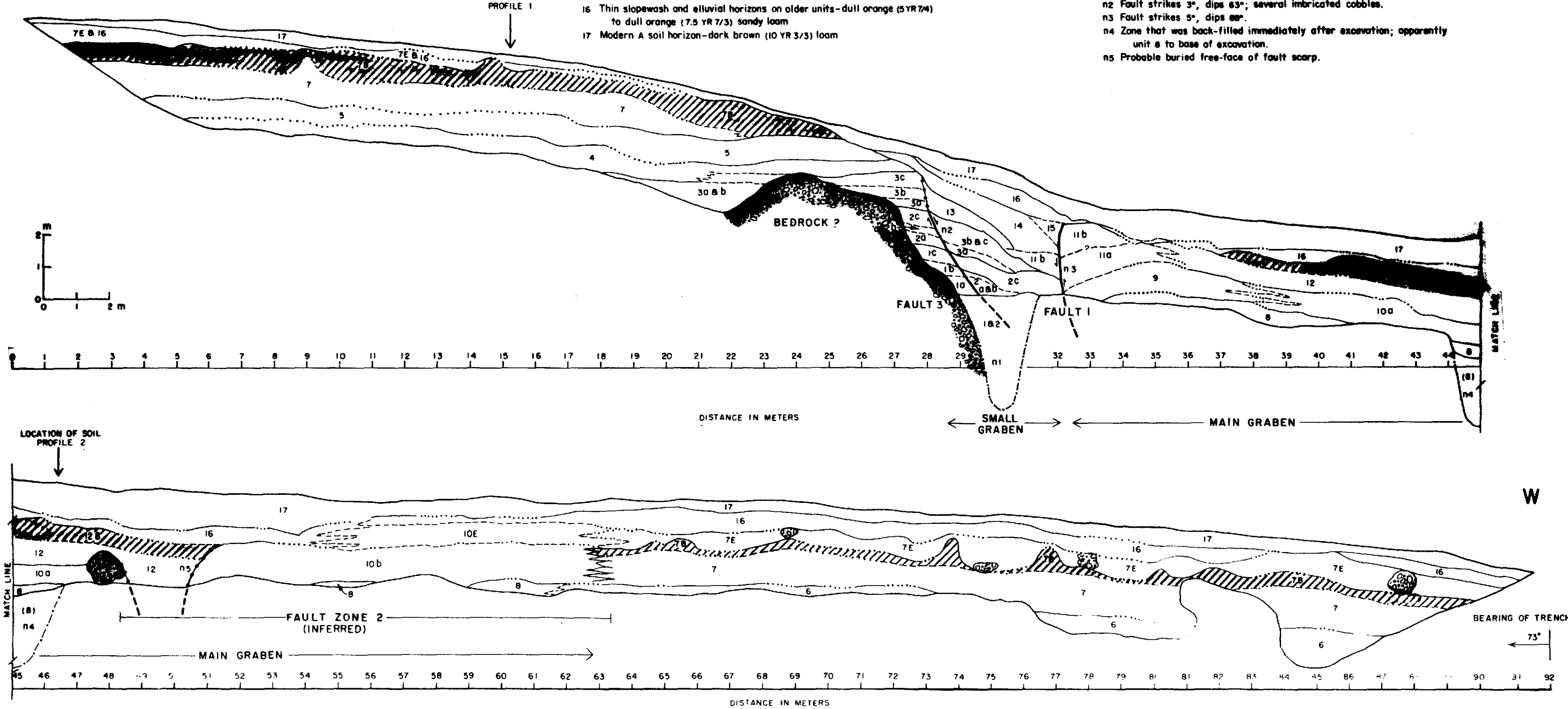


Figure 4

Table I. Data summary for soil profiles from Co-op Creek trenches. (Leaders (---) indicate no data; tr=trace).

Profile	Horizon[1]	Average depth (cm)	Parent material	Munsell dry color	Estimated percent by volume			Percent by weight[2]			Percent carbonate[3]	Percent organic matter[4]
					Gravel (0.2–8 cm)	Cobbles (8–25 cm)	Boulders (>25 cm)	Sand (2–0.5 mm)	Silt (50–2 μm)	Clay (<2 μm)		
Co-op Creek Trench 1												
1	A1	0- 10	Colluvium	10YR 3/3	10	25	5	45	36	19	0	10.1
	A2	10- 38	--do---------	10YR 3/3	10	25	5	49	33	18	0	3.4
	2E	38- 60	Alluvial fan	5YR 7/5	10	25	5	57	28	15	0	0.3
	2Bt	60-114	--do---------	2.5YR 5/6	10	20	2	52	25	23	0	0.2
	2C	114-149	--do---------	2.5YR 5/6	25	10	0	55	26	19	0	0.3
	2Ckj	149-210	--do---------	2.5YR 5/7	25	10	0	54	28	18	12	0.2
	3Ckj	210-273	--do---------	5YR 6/7	10	5	30	80	14	6	11	0.1
	4Ckj	273-334+	--do---------	5YR 6/7	30	15	0	64	22	14	8	tr
2	A1	0- 26	Colluvium	7.5YR 4/3	5	0	0	--	--	--	--	--
	A2	26- 58	--do---------	7.5YR 4/3	5	0	0	--	--	--	--	--
	A3	58- 80	--do---------	7.5YR 4/3	5	0	0	--	--	--	--	--
	E	80-110	--do---------	7.5YR 5/4	1	0	0	--	--	--	--	--
	2Bw	110-155	--do---------	7.5YR 6/4	1	0	0	--	--	--	--	--
	2C	155-230	--do---------	7.5YR 6/4	1	0	0	--	--	--	--	--
	3C	230-300+	Alluvium	7.5YR 6/4	15	20	5	--	--	--	--	--
Co-op Creek Trench 2												
3	A1	0- 11	Colluvium	7.5YR 5/4	10	0	0	38	40	22	0	7.3
	A2	11- 76	--do---------	7.5YR 5/4	10	0	0	40	38	23	0	2.6
	A3	76-105	--do---------	7.5YR 5/4	10	0	0	40	38	22	0	2.3
	Bw	105-149	--do---------	5YR 6/7	15	5	0	36	42	22	0	0.5
	2CB	149-183	--do---------	5YR 7/3	20	10	0	61	30	9	0	0.2
	2C1	183-204	--do---------	5YR 7/5	20	20	0	64	28	9	0	0.1
	2C2	204-279	--do---------	5YR 7/5	20	20	0	60	28	12	0	0.1
	3C	279-360+	Alluvial fan	2.5YR 5/6	5	10	0	49	29	22	0	0.2

[1]Horizon nomenclature of Guthrie and Witty (1982) and Birkeland (1984).
[2]Particle-size distribution of <2-mm fraction using sieve-pipette methods (for example, Carver, 1971) and Sedigraph for some silt-clay fractions with prior removal of carbonates and organic matter using methods of Jackson (1956).
[3]Percent carbonate by method of Dreimanis (1962).
[4]Percent organic matter by method of Walkley and Black (1934).

west) indicate weak argillic horizons can develop in early Holocene (7000 to 10,000 yr) to late Pleistocene (15,000 to 25,000 yr) deposits.

Strawberry Valley is 1200 m higher than the piedmont along the Wasatch Front, with a 4–5°C MAT (mean annual temperature) (vs. 10°C MAT for the Wasatch Front) and 61 cm MAP (mean annual precipitation) (vs. 43 cm for the Wasatch Front). Higher precipitation in Strawberry Valley should result in more rapid clay translocation, but the dust-influx rate is probably much higher along the Wasatch Front (due to its location on the eastern margin of the Bonneville Basin) than on the Strawberry fans. Considering these factors, we interpret the relatively weak argillic horizon development in profile 1 (considering the amount of clay in the parent material) as indicating that this soil is much younger than Bull Lake deposits elsewhere in the region, but is older than Bonneville-age soils along the Wasatch Front. These age estimates suggest active deposition on the fan surface near the fault scarps probably last took place during pre-Bonneville or Pinedale time (15,000 to 70,000 yr).

More precipitation than is now present may have been required to activate the Strawberry fan surface, which is now inactive (Astin, 1977), although large (>1 m), recurrent displacements on the main trace of the Strawberry fault (for which we have no evidence) (Fig. 3) could have produced the same effect. Temperature estimates for the last glacial period in the region proposed by Pierce (in Porter et al., 1983) suggest higher precipitation rates were not likely until the climatic warming that led to Pinedale deglaciation (about 15,000 to 30,000 yr). Pierce and Scott (1984) inferred that a major episode of gravel deposition took place on alluvial fans in Idaho during Pinedale deglaciation. If we make the same assumption for the Strawberry fans, a best estimate for the age of the sediment on most of the fan surface is roughly 15,000 to 30,000 yr.

The lack of well-developed soil profiles on any of the buried colluvial units exposed in CC-1 suggests that there have been no long periods of scarp stability since they were deposited and thus, that all colluvial sediments are relatively young. The soil on the fine-grained colluvium in the middle of the trench is weakly developed (profile 2, Table I). We interpret the slightly higher clay content of unit 12B relative to unit 12 in this soil to the gradual fining upward of the parent material in this unit rather than to argillic horizon development; if this interpretation is correct, unit 12B is a cambic B horizon.

Age assessment of the colluvial units is also difficult because there are no numerically-dated soils from a similar setting with which to compare them. However, the lack of an argillic horizon in the fine textured colluvium of unit 12 and comparisons with Bonneville-age soils described from fine-grained lake sediments (Shroba, 1980) suggests that profile 2 on the younger colluvium is not significantly older than mid-Holocene.

Sequence of Faulting and Deposition

Based on the lithologies, stratigraphic relationships, and estimated ages of units in CC-1, the following sequence of events is inferred (Figs. 4 and 5):

(1) Units 1 through 6 were deposited successively on the alluvial fan by small braided streams and debris flows prior to 15,000 – 30,000 yr; there may be unrecognized unconformities between some of the units.

(2) Unit 7 was deposited about 30,000 – 15,000 years ago, as a debris flow over the entire area. A thin mantle of colluvium was deposited by slopewash processes as soil development on unit 7 began.

(3) One or more faulting events (faulting event a, Fig. 5) offset units 1 through 7 down to the west near station 32 (fault 1). The amount of displacement during this event(s) is unknown because later fluvial erosion in the main graben may have removed some of the upper portion of the down-dropped alluvial fan units and the base of the graben was not exposed. Down-to-the-east antithetic faulting somewhere between stations 48 and 63 (fault zone 2) probably occurred simultaneously, thus forming a graben parallel with the present main scarp.

(4) Intermittent diversion of part of the stream flow in the tributary to Co-op Creek just north of the trench (Fig. 3) took place through the graben, reworking both colluvium in the graben and alluvial fan sediments and depositing them locally as unit 8. During the same period a proximal colluvial wedge (unit 9) was deposited on unit 8 adjacent to the eroded scarp (unit 8 may consist mostly of scarp-derived colluvium east of station 39). This wedge could be a depositional response to renewed displacement on fault 1, but the parallel dip of the indistinct upper and lower contacts of unit 9 suggest it was more likely due to continued erosion of the scarp produced just prior to the deposition of unit 8 (see below). During or following the deposition of unit 9, the tributary of Co-op Creek was diverted intermittently along the graben, reworking the distal part of the wedge to form unit 10a. The genesis of units in the western part of the graben is far from clear, but the gradational facies changes between unit 10b (a graben-filling fluvial deposit) and unit 7, and between units 8 and 6, suggest lateral westward stream erosion of units 6 and 7. We hypothesize that an antithetic fault scarp forming the western edge of the graben (fault zone 2) diverted the stream against the free face of the scarp, obliterating any evidence of a fault. Unit 10E is interpreted as an eluvial horizon developed on unit 10—the equivalent of unit 7E, but both vertical and lateral contacts are very gradational.

(5) Renewed down-to-the-west faulting at station 32 (fault 1; event b, Fig. 5) resulted in a thick colluvial wedge (unit 11). The higher percentage of cobbles in unit 11b than in unit 11a, and blebs of clay which may be fragments from an argillic horizon, suggest that this wedge may

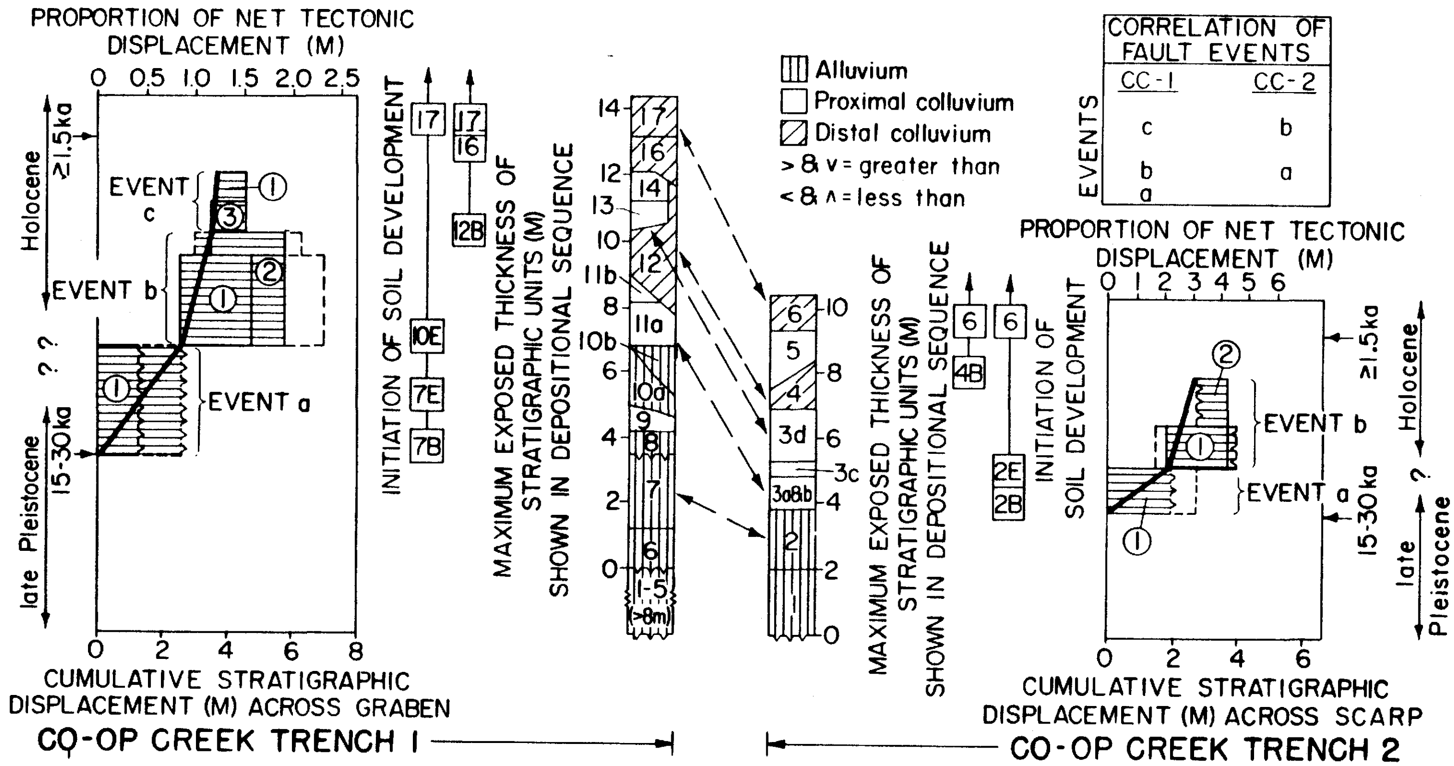


Figure 5. Displacement–time diagrams for Co-op Creek trenches 1 and 2 showing maximum exposed stratigraphic unit thickness (on scaled edge of columns) (ruled pattern indicates genesis), cumulative displacement [both stratigraphic and net vertical tectonic (Swan et al., 1980)], periods during which soil horizons formed (small squares indicate approximate time of initiation of development of soil horizon), and limited time-control points. The height of rectangles in the displacement-time portion of the diagram corresponds with the thickness of units produced as a response to that displacement event. Solid horizontal lines indicate measured stratigraphic displacement (often minimum or maximum values), dashed lines are estimates of displacement for some events based on double the maximum thickness of colluvial wedges, and ruled areas indicate our best displacement estimates considering the geometry of stratigraphic units (these are the values used for cumulative displacement). Circled numbers in displacement rectangles show the fault (zone) (Figs. 4 and 6) where the displacement event occurred. The correlation of stratigraphic units between trenches indicated by the heavy dashed arrows also applies to fault events (lower case letters on diagrams; also see table in upper right corner of Fig.).

reflect the inverted stratigraphy of units exposed in a former free face of units 1–7 at this location. Colluvial units 9 and 11 (and possibly the eastern 6 m of unit 8) were faulted and backtilted on fault 1 during this event, as shown by the eastward dip on the faint unit 9 contacts at station 33. Unit 10 is apparently displaced down to the east about 0.8 to 1.8 m at station 50, with a smaller antithetic displacement at station 49. The sharp contacts between units 10 and 12 at stations 48 and 51 were interpreted as fault-scarp or possibly erosional-scarp free faces which were buried by unit 12 with no subsequent displacement. The interfingering facies relationships of unit 12 (fine, distal colluvium) with unit 11 (proximal scarp-derived colluvium) near station 35 suggest that this second inferred displacement in fault zone 2 was contemporaneous with event b on fault 1. Apparently, the tributary to Co-op Creek cut to below the level of the north end of the graben during this period and no longer flowed parallel to the scarp (Fig. 3).

(6) During the early to mid-Holocene, additional fine colluvium was deposited (with an increasingly finer eolian component in the upper part of unit 12), which filled the small graben at station 49. Soil development continued on units 7 and 10 with the thickening of units 7B, 7E, 10E, and 16 (particularly in areas of gentler slope).

(7) The final surface displacement event was expressed as a down-to-the-west fault of about 1 m displacement at station 29 (event c, fault 3), 3 m east of fault 1. The shear zone is thin (1 to 5 cm wide) and difficult to discern in places because of the lithologic similarity of the alluvial fan units. The down-to-the-east displacement of what we interpret to be the upper part of colluvial wedge 11b shows that a down-to-the-east fault (almost vertical) of about 0.9-m displacement at station 32 (event c; fault 1) formed at about the same position as the previous fault at station 32, but with the opposite sense of displacement. This produced a graben block between 28 and 32 which was tilted westward, apparently with some drag or slumping (10 to 20 cm) of units 11 and 9. Thus, total displacement across the scarp during this event appears to be very small (about 20 cm, Fig. 5). Two units of proximal scarp-derived colluvium were deposited into the graben between faults 1 and 3 immediately after faulting. Unit 13 was derived from the units 3–4 scarp and was then covered by more gradual deposition of material (unit 14) derived from both of the scarps of the small graben and surface colluvium (unit 16) from the E horizon of soils above the main scarp (fault 3). Relationships are obscured at station 32 where loose, brown colluvial material (unit 15) is highly burrowed. While rapid eluviation took place in the sandy colluvium of unit 14, soil development on units 7, 10, and 12 (12B) continued with the thickening of units 7E, 10E, and 16. Soil development continued in the late Holocene with deposition of material making up the present A horizon (unit 17) over the whole trench by slopewash and eolian deposition with a higher deposition rate in the main graben.

Co-op Creek Trench Two

A second trench (CC-2), excavated across the 7-m fault scarp 1.6 km south of CC-1 (Fig. 3), exposed alluvial mud and debris flow sediments (Fig. 6) similar to those in CC-1, except that the sediments were finer grained and the lower half of the upthrown block consisted of clayey silt with very few clasts (unit 1). Auger hole 4 (Fig. 3) shows that sediment similar to unit 1a extends to a depth of 7 m on the downthrown side of the scarp just south of CC-2. CC-2 contains colluvial units very similar to those in CC-1, but unit contacts in the older colluviums are even more gradational and difficult to trace. Subtle lithologic changes within unit 3 suggest it was produced by several colluvial events. Projection of the fan surface across the scarp suggests about 2.6 ± 0.2 m of net vertical tectonic displacement at CC-2.

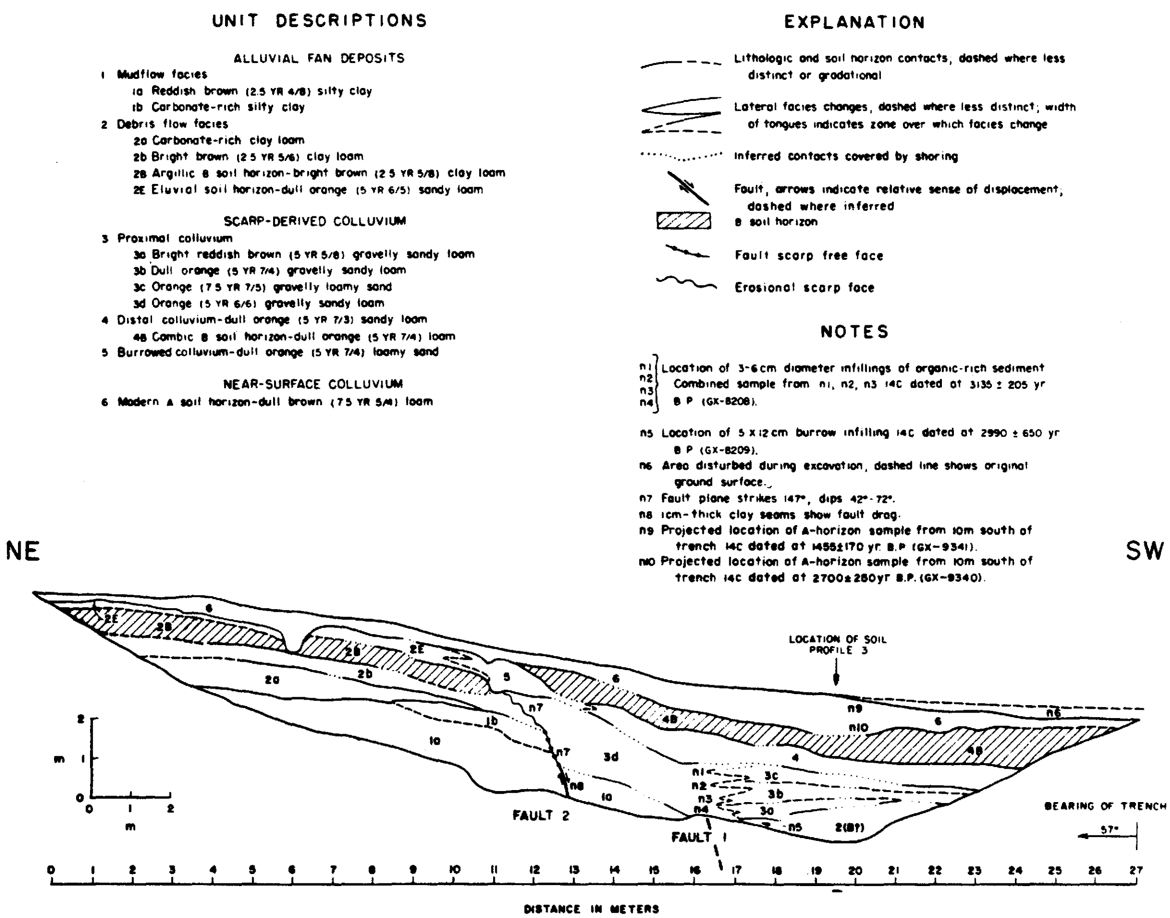


Figure 6. Geologic map of Co-op Creek trench 2 across the 7-m scarp about 1.6 km south of Co-op Creek trench 1 (Figs. 1 and 3). The location of ^{14}C-dated samples (Table II) is also shown. A unit in this trench similar to unit 16 in CC-1 was too thin and discontinuous to map and was therefore included with units 2E, 4B, and 5.

Age of Faulted Deposits

The soil on unit 2 is almost identical to that on unit 7 in CC-1; unit 2B in CC-2 is the time equivalent of unit 7B in CC-1, and unit 2E (with part of unit 5) in CC-2 is the genetic equivalent of units 7E and 16 in CC-1 (Fig. 5). Units 2a and 1b form a carbonate-rich horizon (stage I morphology) which truncates the bedding in the alluvial fan sediments, demonstrating its relationship to the present topography. Unit 4B in soil profile 3 has thin argillans coating clasts and lining pores (Fig. 6), a higher chroma than underlying horizons, but no more clay than overlying horizons (Table 1). This B horizon is lighter with less clay toward fault 2 where the unit 4 colluvium thickens (station 16 and 13) and becomes coarser, but otherwise it is very similar to unit 12B in CC-1. These features indicate unit 4B is a cambic B horizon which developed on distal colluvium as it accumulated. Based on our earlier comparisons, the degree of soil development in unit 4 suggests an early to mid-Holocene age for the colluvium.

Five small areas of organic-rich sediment in CC-2 between stations 16 and 18 (n1 through n4 on Fig. 6) were analyzed for ^{14}C in an attempt to date unit 3. Originally, these organic-rich zones were interpreted as A horizon material incorporated into ground cracks during fault displacement of the colluvium at station 16 (Nelson and Martin, 1982, p. 66). However, soil mean residence ages (Matthews, 1980) of two additional samples from unit 6 (n9 and n10 on Fig. 6) and our previous estimates of the age of colluvial units suggest that all these organic-rich zones are infilled small mammal burrows which have collapsed. Therefore, the burrow infillings, which may be as young as 1500 yr (Table II), are unrelated to faulting and these ages provide only a very minimum age for the most recent fault displacement and resulting colluvial deposition.

Sequence of Faulting and Deposition

The following history is inferred for CC-2 (Figs. 5 and 6):

(1) Units 1 and 2 were deposited as mud and debris flows prior to 15,000–30,000 yr and soil development on unit 2 began.

(2) Movement (event a, Fig. 5) on an inferred fault that was not exposed in CC-2 dropped units 1 and 2 down to the west about 2 m. Unit 2, which overlies unit 1 on the upthrown block, is missing on the upthrown side of inferred fault 1 between stations 13 and 16. Unit 2(B?) in the downthrown block has a clayey matrix like unit 1, but is also cobbly like unit 2; it is most likely the downthrown equivalent of the upper part of unit 2 (either a lateral facies change or 2B, the argillic horizon). Following faulting, colluvium (unit 3a) eroded from unit 2 on the upthrown block was deposited off of a scarp at station 16 which no longer exists.

Table II. Radiocarbon dates for samples from Strawberry Valley.

Depth (m)	^{14}C Laboratory number	Texture of sample material	Sample weight (g)		Estimated carbon (g)[2]	^{14}C date (yr B.P.)	$\delta\ ^{13}C$ (‰)
			Untreated	Clay-silt/ humus concentrate[1]			
Co-op Creek Trench 2							
0.1	GX-9341[3]	Silty sand	3146	280	>1.0	1,455 ± 170	−25.9
1.0	GX-9340	Silty sand	3278	597	>1.0	2,700 ± 250	−25.8
2.5	GX-8208	Silty sand	1500	272	0.065	3,135 ± 205	−29.6
3.5	GX-8209	Sandy silt	2950	591	0.030	2,990 ± 650	−29.0
Indian Creek Core 1							
1.7−2.2	GX-8211	Clayey silt	343	267	>1.0	8,230 ± 190	−27.0
6.6−6.9	GX-8213	Sandy clay	506	199	>1.0	>37,000	−26.7
8.9−9.2	GX-8214	Silty clay	255	167	>1.0	25,840 ± 1,300	−28.6
10.6−10.7	GX-8210	Silt and peat	345	---	>1.0	>37,000	−27.8
Indian Creek Core 2							
1.3−1.7	GX-8212	Silty sand	461	134	>1.0	2,955 ± 145	−26.7
Indian Creek Auger Hole 3							
7.3	Beta-2520	Clayey silt	767	183	0.9	11,290 ± 220	---

[1]Preparation methods of Kihl (1975). Dash indicates preparation not done.
[2]Amount of dated carbon in concentrate estimated by dating laboratory.
[3]This surface horizon sample has an apparent mean residence age (Matthews, 1980) of about 1500 yr. Because the two lower dated samples in trench 2 are burrow infillings derived from similar surface horizons, they may be as young as 1500 yr (3000−1500= 1500 yr).

Apparently, all of unit 2 near the edge of the original scarp was eroded from above unit 1a between stations 13 and 16 before displacement occurred on fault 2. Randomly-oriented fragments of argillic horizon peds in unit 3a show that this unit was partially derived from a unit like unit 2B, while the carbonate coating clasts in unit 3b may reflect erosion of carbonate-rich sediment from unit 1b. Thus, the stratigraphy of the colluvial wedge suggests an inversion of the stratigraphy probably exposed in a scarp free face just east of station 18. Less clay and brighter, more iron-oxidized colors in unit 3c indicate slight reworking of the upper part of the wedge sediments by intermittent flows off the scarp or from one of the small drainages adjacent to the site. Continued soil development on unit 2 thickened units 2E and 2B and carbonate (stage I) continued to accumulate in units 1 and 2.

(3) During the early to mid-Holocene, faulting at station 12 (event b, Fig. 5) displaced unit 1 about 1 m down to the west. The eastward dip of the faint contacts between units 2, 3a, and 3b and the change in slope of the unit 3 − unit 4 contact at station 16 suggest slight backtilting of units 3a − 3c following deposition. On this basis, we infer roughly 50 − 80 cm of down-to-the-west concurrent faulting on fault 1. However, prior to this event the upper contact of unit 1a at station 16 must have been at least as high as the contact between units 3b and 3c. Thus, unit 1a was dropped > 80 cm down-to-the-east relative to units 3a − 3c during this same event to form a graben. As seems to be the case in CC-1, a new fault forming east of the original fault caused renewed antithetic movement on or near fault 1, deforming the colluvial wedge produced by the first event and probably displacing the upper half of the wedge down-to-the east relative to the lower half. Unit 3d, which rapidly infilled the narrow graben between stations 12 and 17, was derived from material eroded from the main scarp on fault 2 and the antithetic scarp on fault 1 formed in units 3b and 3c, and possibly 3a. It should be emphasized that no discrete shear plane was recognized at the location of fault 1; we infer two displacement events on a fault here entirely from the colluvial stratigraphy and the analogous stratigraphy in CC-1. If our interpretation is correct, about 1.3 − 2.0 m of down-to-the-west displacement occurred across the 7-m scarp during event b (Fig. 5). Following the deposition of the proximal wedge (unit 3d), units 4 and 5 began accumulating by slopewash and eolian processes. Rodent burrowing is probably the explanation for the step in the base of unit 5 at station 11.

(4) Soil development continued on units 2 and 4, gradually forming a cambic B horizon on unit 4 (4B). Slight scouring by drainage along the scarp may have produced the depression in the unit 4 − unit 6 contact at stations 19 − 20. In the late Holocene, unit 6 was deposited by slopewash and eolian processes. The burrows in units 3d and 2(B?) were dug and infilled during this period, prior to 1500 yr (Table II).

Correlation of Faulting Events and Estimated Recurrence

Correlation of stratigraphic units and faulting events between the two trenches indicates that each site has had a similar history of fault displacement (Fig. 5), but more events are represented in CC-1. Units in CC-1 represent two or, more likely, three fault events, but there is evidence for only two events in CC-2. Because alluvial and colluvial units in both trenches were derived from the faulted alluvial fan sediments and transported short distances, many units of different genesis look similar. Proximal fault-scarp-derived colluvium is particularly difficult to distinguish from the stream-reworked colluvium and alluvial fan sediment into which it grades laterally. Intense rainfall on the alluvial fan may also have resulted in the deposition of units off the fault scarps, which we have interpreted as fault-related colluviums. However, small (< 0.5 m) surface displacement events are difficult to recognize because so little evidence of them is usually preserved (Schwartz and Coppersmith, 1984). Units in the downthrown block correlative with upthrown units were not reached in CC-1, and thus, one or two early fault events may also be unrecognized. For these reasons, our estimate of two to three surface faulting events on the 7-m scarp is probably a minimum value.

Stratigraphic relationships in both trenches suggest stratigraphic displacements of 1 to 2 m for each fault event. Stratigraphic displacements were estimated by measuring the contacts of faulted units, by dividing total displacement by the number of events suggested by colluvial units (e.g., Swan et al., 1980), and by doubling the maximum colluvial wedge thickness (Fig. 5). Models of scarp erosion (e.g., Nash, 1981) show that given sufficient time between fault events for scarps to erode to angles well below the angle of repose, double the wedge thickness is a maximum estimate of stratigraphic displacement. For graben-filling events b and c (Fig. 5) the wedge thickness approaches the scarp height. The displacement rectangles on Figure 5 are arranged to show that the antithetic faulting, which occurred during events b and c, reduced the net displacement for those events. Thus, the diagram shows the cumulative displacement across the area exposed by each trench, and the heavy line running through the rectangles indicates the average slip rate (time scale is non-arithmetic).

Our age estimates, based on soil development and regional correlations of Quaternary deposits, suggest these two to three surface displacement events occurred during the last 15,000 to 30,000 yr, yielding a maximum recurrence interval of 15,000 yr and a minimum recurrence of 5000 yr. These are average values only; all events could be clustered closely in time with the limitation that the last event occurred during the early to mid-Holocene.

Slip Rate Estimates

Our estimates of net vertical tectonic displacement across the 7-m fan scarp, measured from scarp topographic profiles, are much less than the stratigraphic displacements (Fig. 5) because of graben formation and backtilting. These estimates yield average slip rates of 0.04 to 0.17 mm/yr for the 7-m scarp, but it is subsidiary to the main trace of the Strawberry fault. Fault slip almost certainly took place on the 5-m-high scarp west of the trenched scarp, the 2-m-high east-facing scarp east of the trenched scarp, and/or along the main trace of the fault at the fan–bedrock contact during at least some of the events recorded in the trenches (Fig. 3). Deformation which was not expressed as surface rupture may also have occurred across the entire Strawberry fault zone. For these reasons, net vertical tectonic displacement per event and long-term slip rates across the entire fault zone cannot be accurately estimated.

Coring Near Indian Creek

South of the trench sites, Indian Creek flows from the west across a 9-km^2 alluvial plain on the downthrown side of the Strawberry fault into a 175-m-deep stream-cut valley on the upthrown block (Figs. 1 and 7). Detailed mapping of the Tertiary beds near the site and shallow seismic refraction profiling show that the main trace of the fault runs along the west edge of the bedrock spur 120 m west of the main scarp marked by the colluvium–bedrock contact (Fig. 7). The refraction profiling suggests that the fault dips westward about 58° at depth, a dip similar to that measured by Thompson (1971) on the fault in a tunnel north of Strawberry Reservoir. Refraction data also suggest that bedrock is within 4 m of the surface in the stream valley east of the bedrock scarp and greater than 60 m deep, 80 m west of the scarp (Fig. 7). These relationships suggest movement on the Strawberry fault displaced late Quaternary alluvium below the bedrock lip in the stream valley.

Eight-cm diameter push-tube samples of fine grained alluvial sediments were taken inside a hollow-stem auger west of the scarp (core 1) and east of the trace of the scarp (core 2) at the edge of the stream valley to determine the age of the alluvial fill on the alluvial plain and in the stream valley (Figs. 7 and 8). Both cores contain brown to gray-green silty clays to silty sands typical of alluvial plain sediments deposited by a meandering stream, as well as coarse sandy gravels (not sampled) deposited during periods of higher discharge. Thick beds of organic-rich clay in core 1 suggest periods of ponding, but these could be the result of the filling of oxbow lakes as well as more extensive ponding due to damming of the creek by scarps produced during discrete fault events.

During initial investigation of the Indian Creek site, an auger hole (borehole 3, Fig. 7) was drilled about 700 m north of the site of core 1.

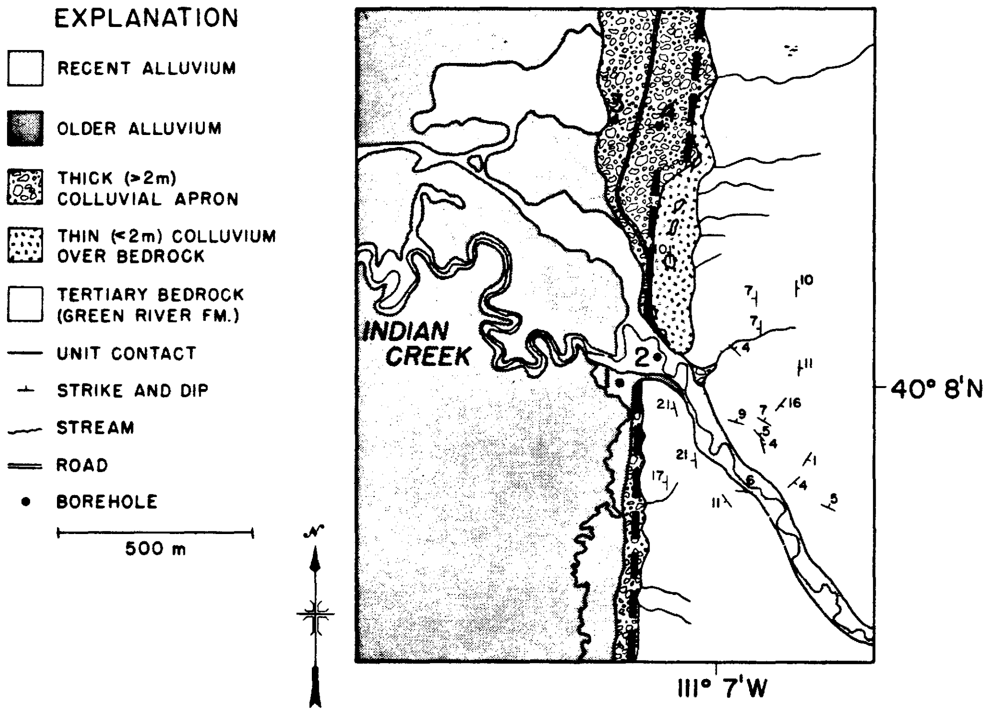
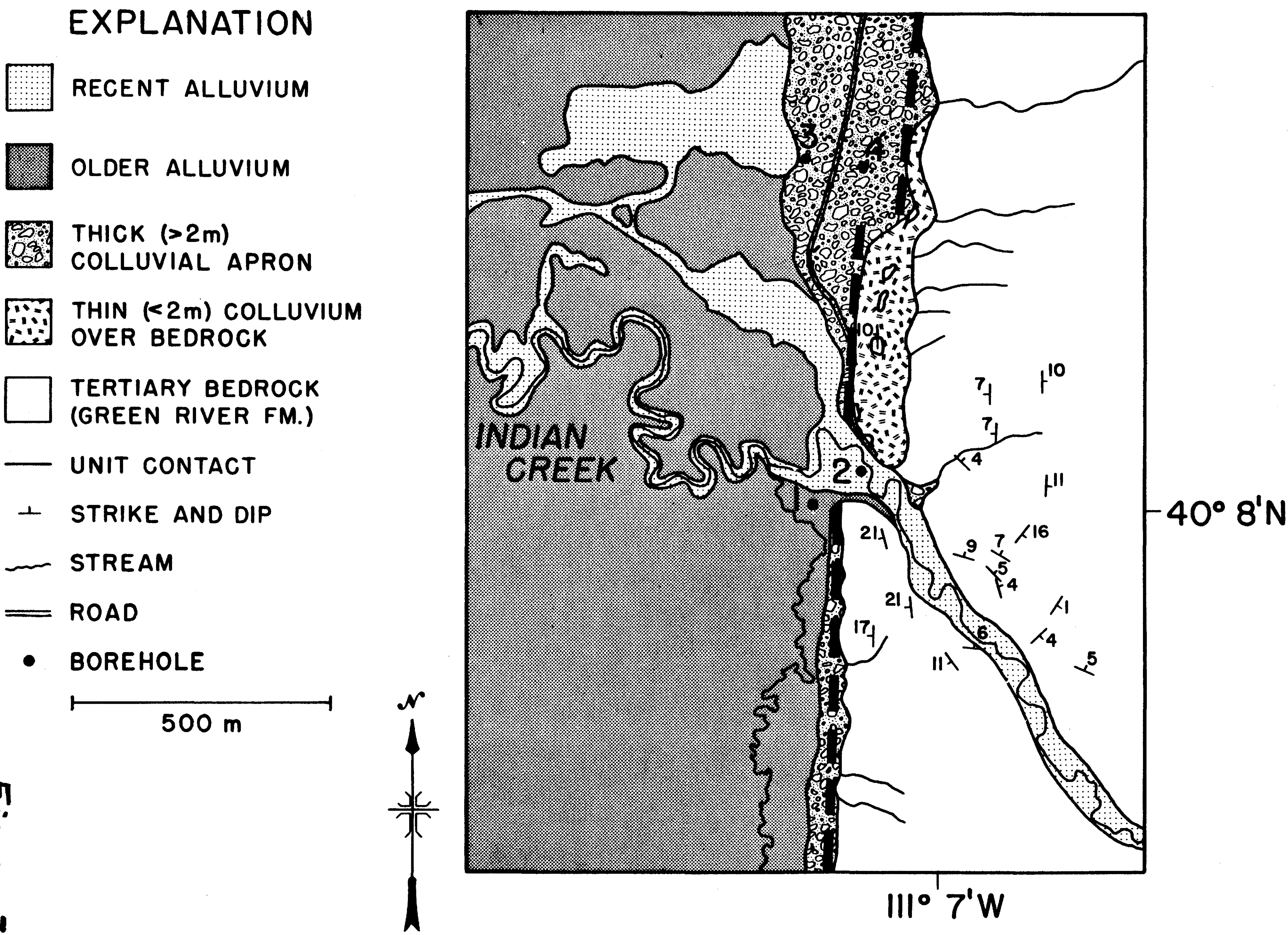


Figure 7. Geologic map of the area where Indian Creek flows across the Strawberry fault scarp (Fig. 1), showing the location of push-tube cores 1 and 2 (Fig. 8) and boreholes 3 and 4. The trace of the fault near the surface (inferred trace shown by heavy dashed line) must be near the east edge of the thick colluvial apron, but the colluvium does not appear to have been faulted. South of borehole 4 the fault may bend or make an en echelon jump about 100 m to the west. Drag occurs within 400 m of the fault, as shown by moderate west dips in the Tertiary bedrock (regional dips are about 10° E-NE). Northeast to northwest-oriented strikes measured along the canyon cut by Indian Creek may be due to the adjustments of large slump blocks.

Similar alluvial plain stream and lake sediments were encountered between 4 and 8 m depth below the distal edge of the fine grained colluvial apron extending out from the main fault scarp. Borehole 4 (Fig. 7) showed > 9 m of fine grained colluvium higher up on the apron.

Radiocarbon Dating of Core Sediments

One sample from core 2 and four from core 1 were analyzed for ^{14}C activity to determine the age of the sediment in each core (Fig. 8). A bulk sediment sample with a 2-cm peat bed was analyzed from near the base of core 1 (10.5 m), but the other samples required concentration of organics in the silt–clay fraction to obtain enough carbon for dating (Table II). Consideration of (1) the hard water effect on the carbon isotopes incorporated in the aquatic organic material, (2) the 11,300 yr radiocarbon age from the base of borehole 3 (700 m to the north), (3) the probable effects of older reworked alluvial organic material and contamination by younger



EXPLANATION
RECENT ALLUVIUM
OLDER ALLUVIUM
THICK (>2m) COLLUVIAL APRON
THIN (<2m) COLLUVIUM OVER BEDROCK
TERTIARY BEDROCK (GREEN RIVER FM.)
UNIT CONTACT
STRIKE AND DIP
STREAM
ROAD
BOREHOLE
500 m
N
INDIAN CREEK
1
2
3
4
40° 8'N
111° 7'W

Figure 7

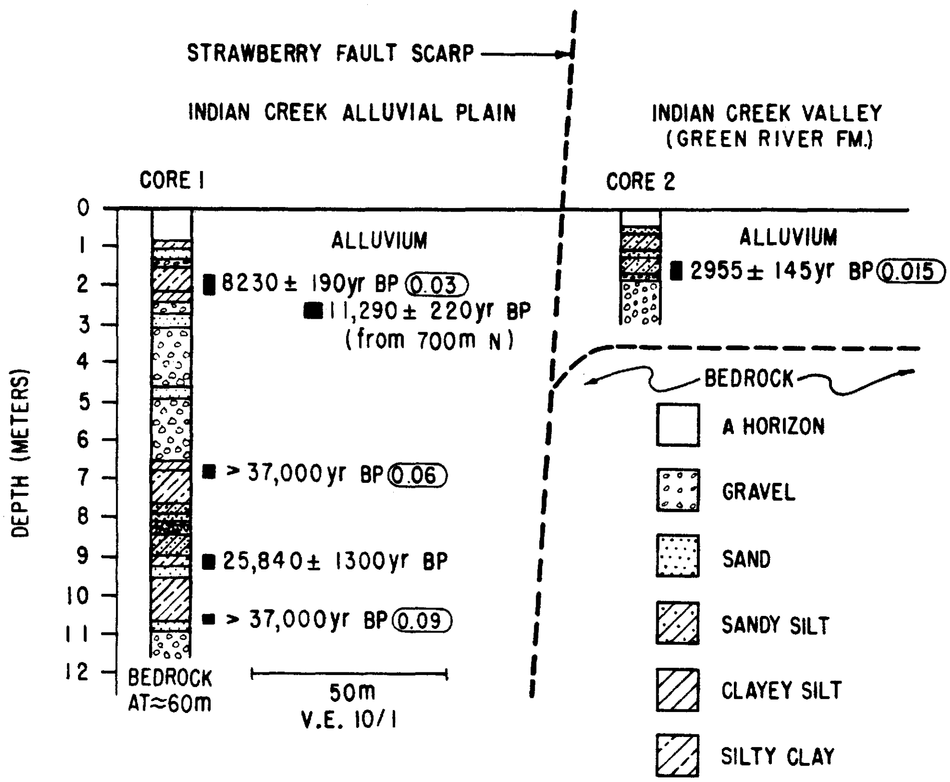


Figure 8. Schematic cross section (vertical exaggeration × 10) showing the relationship of push-tube cores 1 and 2 to the alluvial units adjacent to the scarp in bedrock of the Strawberry fault (Fig. 7). Refraction profiling was used to estimate depth to bedrock and the angle on the fault scarp below the surface of the alluvial plain. The lithology of the cores, radiocarbon dates on organic-rich sediments (including a date from the base of borehole 3 located 700 m north of this cross section), and average aIle/Ile amino acid ratios on gastropods (ovals) are also shown. Samples were not recovered from the thick gravel sections of core 1.

carbon in the dated samples, and (4) the amino acid ratios discussed below, suggests that the 3000 yr age from core 2 is a maximum, but that the 8200 yr age for core 1 is accurate. The three lower ^{14}C dates from core 1 are interpreted as minimum ages. The middle sample (Table II; Fig. 8) was almost certainly contaminated by a small amount (< 3%; Olsson, 1968) of modern carbon giving an apparent finite age to a sample, which based on the ages at 7 m and 10.5 m, is > 37,000 yr. Age and depth data from core 2 and the upper part of core 1 cannot be used to calculate fault displacement rates because about 8000 yr-old sediments on the downthrown side of the fault occur at about the same level as < 3000 yr-old sediments on the upthrown side. In addition, the rate of downcutting of Indian Creek east of the fault, although probably rapid (e.g., Hamblin et al., 1981), is not known. Thus, the minimum ages from the base of core 1 cannot be used to calculate maximum displacement rates.

Amino Acid Age Estimates From Snails in the Cores

In an attempt to obtain finite age estimates from the cores, both terrestrial and freshwater gastropods, suitable for amino acid analysis, were separated from three of the four carbon-14-dated samples from core 1 and from an additional sample from the base of the core (Table III). Only recently have amino acid ratios measured on terrestrial and freshwater gastropods been used in relative dating of Quaternary deposits (Miller et al., 1979, 1982; Rutter et al. 1980; McCoy, 1981; Harmon et al., 1983). Numerical-age estimates are more difficult to obtain because of the large uncertainties in amino acid racemization kinetics and the difficulty in estimating the effective diagenetic temperature history (EDT) of fossils (Miller and Hare, 1980; Wehmiller, 1982). However, if independently dated calibration samples are available from the same region as the samples to be dated, the approximate ages of the undated samples can be estimated.

At Indian Creek, the D-alloisoleucine/L-isoleucine ratio (aIle/Ile) in the total acid hydrolyzate (the primary ratio used in dating) of the gastropod shells (Table III) was used to evaluate the reliability of the radiocarbon dates from core 2 and to calibrate the rate of isoleucine epimerization (racemization) using the gastropod samples from the 8200 yr level in core 1 (methods of Miller and Hare, 1980). Amino acid age calculations using the EDT derived from aIle/Ile ratios in shells from the 8200 yr level in core 1 (Table III) suggest an age of 1200 to 1600 yr (using *Lymnaea* ratios) and 2.0 to 3200 yr (using *Pisidium* ratios) for the 1.5 m level in core 2, which was radiocarbon dated at 3000 yr. Thus, this data suggests that the 3000 yr sample in core 2 may have been contaminated by older carbon and that its age is too uncertain to be of use in estimating an EDT for the site or to be used in calibrating the older samples. The EDT derived from the 8200 yr calibration sample (4.9 ± 1.0°C) at 1.9 m in core 1 is only slightly warmer than the estimated MAT (mean annual temperature) of 4.3 ± 0.5°C (estimated using instrumental data in the region). Miller et al. (1982) found EDTs to be 0.5° to 2°C higher than MATs at a number of sites in the western U.S., and thus, 4.9°C seems a reasonable EDT for the Holocene period (Table III).

Because of the lower temperatures during the Pinedale glaciation, the average EDT experienced by the > 37,000 yr-old gastropods was considerably lower than the Holocene effective temperature. Two paleotemperature models for the last 125,000 yr, using temperature estimates based on the work of McCoy (1981), Pierce (in Porter et al., 1983), and Nelson et al. (1984) allow calculation of approximate age estimates for the gastropods in the cores (Table III) (methods of Miller et al., 1983, and Wehmiller, 1982). Both models assume an average EDT for the period 0 to 11,000 yr of 4.9°C (Table III) and an EDT lowering of 8.5°C for 11,000 to 15,000 yr (McCoy, 1981). Model A then uses 10°C less than MAT for

Table III. D-alloisoleucine/L-isoleucine ratios in the total (free plus peptide-bound) amino acid fraction and calculated temperatures and ages for fossil gastropods from Indian Creek cores, Wasatch County, Utah (SW¼NW¼ sec. 15, T. 4 S., R. 11W.). [(R)=reworked; (PR)=probably reworked; leaders (---) indicate no data].

INSTAAR Laboratory number (Univ. of Colo.)	Depth below surface (m)	Species	Number of shells	Sample weight (mg)	Total alle/Ile ratio[1]	^{14}C age 10^3 yr	Calculated mean EDT (°C)[2]	Calculated age (10^3 yr) for temperature models[3]	
								Model A	Model B
Core 1									
DAN-125B	1.9	cf. *Lymnaea*	1	8.2	0.030	8.2	4.4	--	--
DAN-125D	1.9	cf. *Lymnaea*	1	4.5	0.034	8.2	5.4	--	--
CAN-125E	1.9	cf. *Lymnaea*	3	8.1	0.126	(R)	---	208*	--
DAN-125J	1.9	*Pisidium*	6	6.0	0.038	8.2	6.9	--	--
DAN-125A	1.9	*Vallonia cyclophorella*	4	2.5	0.030	8.2	4.4	--	--
DAN-125H	1.9	*Vallonia cyclophorella*	4	2.6	0.030	8.2	4.4	--	--
DAN-125G	1.9	*Pupilla muscorum*	4	4.2	0.028	8.2	3.6	--	--
DAN-125C	1.9	*Pupilla muscorum*	3	3.3	0.031	8.2	4.7	--	--
DAN-126A	6.7	*Vallonia cyclophorella*	5	3.0	0.080	(PR)	---	130*	--
DAN-126E	6.7	*Vallonia cyclophorella*	7	4.2	0.065	>37	---	89	94
DAN-126F	6.7	*Vallonia cyclophorella*	3	2.2	0.064	>37	---	86	92
DAN-126G	6.7	*Vallonia cyclophorella*	2	1.5	0.068	>37	---	97	99
DAN-126B	6.7	*Pupilla muscorum*	4½	4.8	0.088	(PR)	---	146*	--
DAN-126C	6.7	*Pupilla muscorum*	4½	5.1	0.067	>37	---	94	97
DAN-126D	6.7	*Pupilla muscorum*	5	7.6	0.067	>37	---	94	97
DAN-128A	7.0	cf. *Lymnaea*	1	6.5	0.101	(R)	---	163*	--
DAN-128B	7.0	*Pupilla muscorum*	½	0.8	0.062	---	---	80	89
DAN-127	9.1	cf. *Lymnaea*	1	1.0	0.115	(R)	---	188*	--
DAN-133A	10.5	*Pisidium*	1	2.0	0.091	---	---	214*	--
DAN-133B	10.5	*Pisidium*	1	2.0	0.098	---	---	233*	--
DAN-133C	10.5	*Vallonia cyclophorella*	3	2.2	0.091	---	---	152*	--

Core 2									
DAN-130A	1.5	cf. *Lymnaea*	½	8.1	0.015	3.0	1.5	--	--
DAN-130B	1.5	cf. *Lymnaea*	½	5.2	0.014	3.0	0.0	--	--
DAN-130C	1.5	cf. *Lymnaea*	1	20.3	0.014	3.0	0.0	--	--
DAN-130D	1.5	*Pisidium*	1	3.8	0.015	3.0	3.5	--	--
DAN-130E	1.5	*Pisidium*	1	2.8	0.017	3.0	2.1	--	--
DAN-130F	1.5	*Pisidium*	1	2.3	0.018	3.0	3.7	--	--
DAN-129	1.6	cf. *Lymnaea*	1	5.1	0.036	(R)	---	10	10

[1]Alle/Ile ratio (peak areas) measured and interpreted by Nelson using methods of Miller and Hare (1980).

[2]Mean effective diagenetic temperature (Wehmiller,1977) calculated using (1) Arrhenius parameters determined for cf. *Lymnaea* by W. D. McCoy (1981), Arrhenius parameters determined by Nelson and others (1984) for *Vallonia* and *Pupilla*, and Arrhenius parameters determined for *Pisidium* by Miller and others (1982); (2) ^{14}C ages; and (3) values of constants in Arrhenius equation (No. 9 in Williams and Smith, 1977).

[3]Age calculated using equation 18 in Williams and Smith (1977) with $K'=0.77$, a modern ratio of 0.014, and two temperature models (discussed in text) with software written by G. H. Miller (Brigham and Miller, 1983). Ages >125,000 yr (indicated by an asterisk) were recalculated using an average EDT for the late Quaternary in this region of 8°C less than present mean annual temperature (Nelson and others, 1984) (for example, Wehmiller, 1982).

15,000 to 125,000 yr while Model B assumes 12°C less than MAT for 15,000 to 75,000 yr and 7°C less than MAT for 75,000 to 125,000 yr. Critical assumptions in applying the models are: (1) the ages of the calibration samples in the region are accurate, (2) linear models of reaction kinetics apply, and (3) estimated differences in MAT at the calibration sites reflect differences in long-term EDTs at the sites (Wehmiller, 1982). Age calculations suggest the shells in core 1 at 6.7 and 7.0 m date from about 80,000 to 100,000 yr and that those at 10.5 m may be 150,000 to 230,000 yr (Table III). About 10 percent of the shells appear reworked. For several reasons (discussed in the literature cited above), these age estimates are more likely to be minimum rather than maximum ages.

Slip Rate Estimates

Using the above age estimates for various levels in the cores, a range of minimum slip rates across the fault can be calculated. At least 8 m of sediment has been displaced below the level of bedrock at the base of the stream channel on the upthrown block (Fig. 8). This is a minimum estimate for the amount of sediment deposited because the rate of bedrock erosion in the channel on the upthrown block is not known. Using our age estimates (Table III), the interval of sediment between the base of the channel at 2.9 m (Fig. 8) and the 7.0-m-level in core 1 was deposited in a total of roughly 70,000 to 90,000 yr, giving a minimum slip rate of 0.04 to 0.06 mm/yr. Using ages and thickness from the 10.5-m depth gives similar rates of 0.03 to 0.05 mm/yr. Because the age of the basal alluvium in the channel on the upthrown block is uncertain and we do not have estimates of channel erosion rates, maximum slip rates cannot be calculated.

We are left with the problems of (1) evaluating the Indian Creek minimum slip rates (if the assumptions of Hamblin and others (1981) are correct actual slip rates may be twice the minimum rates), (2) whether our slip rates derived from the subsidiary 7-m scarp are reasonable estimates for the whole Strawberry fault zone, and (3) whether latest Pleistocene and Holocene (< 30,000 yr) slip rates on the whole fault zone are higher than late Quaternary (< 125,000 yr) rates. If the actual Indian Creek rates are twice our minimum rates (0.03–0.06 mm/yr) and the 7-m scarp rates (0.04–0.17 mm/yr) represent slip on the whole fault zone, then late Quaternary rates along the Strawberry fault are similar. If there is a significant difference in rates along the Strawberry fault, then rates along the northern part of the fault are probably higher than those at Indian Creek, suggesting the fault could be divided into two segments with differing histories. However, whether this postulated difference in rates is a spatial difference along the fault or a temporal difference between latest Pleistocene–Holocene rates and late Quaternary rates cannot be determined from our data.

CONCLUSIONS

Geologic mapping and valley geomorphology suggest Strawberry Valley is a half-graben bounded on the east by the Strawberry normal fault, which may merge with the underlying Strawberry thrust fault (VanArsdale, 1979a). Two trenches across a 7-m-high fault scarp in alluvial fans adjacent to the fault suggest two to three fault events, each of 1 to 2 m stratigraphic displacement, have occurred on the scarp over the last 15,000–30,000 yr, but with smaller net vertical tectonic displacements due to graben formation and backtilting. Age estimates based on soils suggest that the last surface displacement event occurred during the early to mid-Holocene; 1500 yr is a minimum age for this event based on radiocarbon-dated burrow infillings. These displacement and age data suggest recurrence rates on earthquakes large enough to produce recognizable surface displacements on the Strawberry fault (M_s = 6.5–7.0) are in the range of 5000 to 15,000 yr. Latest Pleistocene and Holocene fault slip rates calculated from estimated net tectonic displacement across the 7-m subsidiary scarp in the Strawberry fault zone near Co-op Creek are 0.04 to 0.17 mm/yr, while minimum longer-term late Quaternary rates for the main fault derived from ^{14}C and amino acid dating of alluvial plain cores at Indian Creek are 0.03 to 0.06 mm/yr. Present data prevent us from determining whether these apparent differences in rates are real, either in space or time.

Recurrent late Pleistocene and Holocene displacement on the Strawberry fault shows that the late Quaternary extensional stress regime of the Basin and Range extends at least this far east in central Utah (see also, Martin, 1982), despite the general lack of fault scarps in alluvium and other evidence of recurrent late Quaternary displacement on faults in other back valleys northwest of Strawberry Valley. Our limited slip rate data on the Strawberry fault indicate a latest Pleistocene and Holocene rate at most half, and probably nearly an order of magnitude less than, that for the Wasatch fault (Swan et al., 1980; Schwartz and Coppersmith, 1984). Recurrence rates and the amount of displacement per event are more difficult to estimate, but both are considerably lower than for the Wasatch fault; they are similar to estimates for other faults in the eastern Basin and Range (Wallace, 1984). Whether latest Pleistocene–Holocene slip rates on the Strawberry fault are higher than late Quaternary rates on the fault or than rates on faults in other back valleys or whether our latest Pleistocene–Holocene data represent only a local short-term pulse of activity which reflects a much lower, long-term rate for the eastern Wasatch Mountains (e.g., Wallace, 1984) is unknown. Resolution of these questions will require detailed studies in other back valleys of the eastern Wasatch Mountains.

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