Late Quaternary Displacement on the Morgan Fault, A Back Valley Fault in the Wasatch Range of Northeastern Utah

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

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1500–I

CONTENTS

	Page
Abstract	I1
Introduction	1
Acknowledgments	1
Back Valleys of the Wasatch Range	1
Morgan Valley	2
Morgan Fault	2
Age of Quaternary Deposits Adjacent to the Central Section of the Morgan Fault	5
Trench Investigations of Quaternary Faulting on the Central Section of the Morgan Fault	12
Stratigraphy in Trench M4	13
Trench Investigations of Quaternary Faulting on the Central Section of the Morgan Fault—Continued	
Ages of Faulted Deposits	I15
Events in Trench M4	15
Other Trenches	16
Slip Rates on the Morgan Fault	16
Quaternary Slip Rates	16
Cenozoic Slip Rates	16
Conclusions	17
References Cited	17

ILLUSTRATIONS

		Page
FIGURES 1, 2.	Maps showing:	
	1. Location of the Morgan fault, the Wasatch fault, and other middle or late Quaternary faults in northeastern Utah	I3
	2. Cenozoic geology of Morgan Valley	4
3.	Generalized topographic profiles and geologic section parallel to the Morgan fault drawn along the crest of the footwall escarpment and along the hanging wall at the base of the escarpment	6
4, 5.	Maps showing surficial geology of:	
	4. Central section of the Morgan fault	7
	5. Southern end of the central section of the Morgan fault, showing locations of trenches at the Robeson Springs trench site and sampling sites	8
6.	Log of trench M4 at the Robeson Springs trench site, showing faulted middle and late Quaternary colluvial deposits at the southern end of the central section of the Morgan fault	14

TABLES

		Page
TABLE 1.	Selected properties of soils on alluvial, colluvial, and lacustrine sediments along the Morgan fault, Morgan Valley, north-central Utah	I10
2.	D-alloisoleucine/L-isoleucine ratios in the total amino acid fraction and calculated ages for *Oreohelix* cf. *strigosa* from alluvial and colluvial sediments along the Morgan fault, Morgan Valley, north-central Utah	12

LATE QUATERNARY DISPLACEMENT ON THE MORGAN FAULT, A BACK VALLEY FAULT IN THE WASATCH RANGE OF NORTHEASTERN UTAH

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

ABSTRACT

The Morgan fault is a 16-km-long north-trending normal fault bounding the eastern side of Morgan Valley, a back valley of the Wasatch Range. A history of late Cenozoic surface displacements on the Morgan fault is suggested by triangular facets preserved on the footwall escarpment of the fault, back-tilted erosion surfaces adjacent to the fault, and the preservation of a 1,000-m-thick fanglomerate in the hanging wall of the fault. Trenches across the Morgan fault show that middle Pleistocene colluvial deposits are displaced about 4 m and Holocene deposits are displaced about 1 m. Amino acid ratio minimum age estimates on shells, radiocarbon dating of peat deposits, soil development indices, displacement data, and stratigraphic correlations of late Quaternary deposits among the trenches suggest a minimum average middle to late Pleistocene slip rate of about 0.01 to 0.02 mm/yr for the Morgan fault. Stratigraphic relations in one of the trenches suggest that repeated surface displacements on the fault have been about 1 m or less, an indication that paleoearthquakes of magnitude 6½ to 7 have occurred on the fault.

INTRODUCTION

Most neotectonic studies in Utah have emphasized the hazard posed by the occurrence of large-magnitude earthquakes on the Wasatch fault (Swan and others, 1980; Schwartz and Coppersmith, 1984), but fault maps (Anderson and Miller, 1979; Nakata and others, 1982) and other studies show late Quaternary (less than 125 ka) faults east of the Wasatch fault, including those in Cache Valley (Swan and others, 1983; Nelson and Sullivan, this volume), Bear Lake Valley (Williams and others, 1962), the Bear River fault zone (West, 1986), and Strawberry Valley (southeast of Kamas Valley, fig. 1) (Nelson and Martin, 1982; Nelson and Van Arsdale, 1986). A diffuse band of contemporary seismicity including earthquakes as large as magnitude 5.7 and extending through this area about 20 km east of the Wasatch fault (Arabasz and others, 1980, this volume) suggests that additional late Quaternary faults may be present.

ACKNOWLEDGMENTS

This study was part of a regional seismotectonic study for the assessment of seismic hazards to U.S. Bureau of Reclamation dams in the Wasatch Range in central Utah (Sullivan and others, 1986). The staff of the Bonneville Construction Office of the U.S. Bureau of Reclamation in Provo, Utah, provided the logistical support essential to the completion of this work. We especially thank both Leyland Kippen and the Union Pacific Railroad for permission to excavate on private properties. Edward Baltzer and Carol Krinsky (geologists formerly with the U.S. Bureau of Reclamation) assisted in the trench logging. Dean Ostenaa (U.S. Bureau of Reclamation, Denver, Colo.) reviewed early drafts of this manuscript. Soils analyses by Rolf Kihl (Institute for Arctic and Alpine Research (INSTAAR), University of Colorado) are appreciated. Nelson determined amino acid ratios in the INSTAAR Amino Acid Geochronology Laboratory, with the help of Dan Goter and under the direction of Gifford Miller.

BACK VALLEYS OF THE WASATCH RANGE

The back valleys of the northern Wasatch Range are in the transition zone between the eastern Basin and Range

Manuscript approved for publication November 20, 1990.

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

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

Manuscript submitted to editors (following internal review) May 1986.
Manuscript accepted by editors July 1986.
Manuscript approved for publication November 20, 1990.

province and the Middle Rocky Mountains and Colorado Plateaus provinces. This zone is coincident with late Cretaceous and early Paleogene thrust faults of the Sevier thrust belt (Armstrong, 1968). Seismic reflection data generated for oil and gas exploration, locally detailed surface mapping, and seismologic investigations in the transition zone indicate a complex interaction between these stacked thrust faults and younger normal faults (Royse and others, 1975; Lamerson, 1982; McKee and Arabasz, 1982; Smith and Bruhn, 1984). The back valleys are structural and physiographic basins exhibiting less late Cenozoic structural relief than morphologically similar basins in the Basin and Range (Zoback, 1983; Sullivan and others, 1986). Gilbert (1928) suggested recent displacement on some faults in Cache Valley, Ogden Valley, Morgan Valley, and Kamas Valley, structural basins in the Wasatch Range that he termed "back valleys" (fig. 1). Late Quaternary displacement has been inferred on faults in Ogden Valley, near Mantua, and on the East Canyon fault (Sullivan and others, 1986). Other unstudied late Cenozoic normal faults that may have Quaternary displacement are the Crawford Mountains fault and faults in the Bear River Range (Sullivan and others, 1986).

MORGAN VALLEY

Morgan Valley is a 25-km-long, 10- to 15-km-wide, northwest-trending back valley, located 20 km east of the Wasatch fault, that was described by Gilbert (1928) as a structural trough similar to Ogden and Cache Valleys to the north. Eardley (1944) later described Morgan Valley as a syncline but subsequently recognized the role of normal faulting in the development of the valley (Eardley, 1955). Most recently, Morgan Valley has been interpreted as an asymmetric graben bounded on the east by the Morgan fault (Hopkins, 1982; Hopkins and Bruhn, 1983).

Cenozoic deposits of three ages, separated by angular unconformities, are present in Morgan Valley and suggest a deformational history dating from the Eocene. The conglomerates of the Eocene Wasatch Formation, dipping 40° to 65° to the east and northeast, are exposed on the western margin of the valley unconformably overlying Paleozoic and Mesozoic sedimentary rocks (Mullens and Laraway, 1973; Bryant, 1984). The overlying tuffaceous sandstones and conglomerates of the Norwood Tuff, described and dated as late Eocene to early Oligocene by Eardley (1944), are exposed throughout the valley dipping 10° to 40° to the northeast. Schick (1955) and Coody (1957) mapped a fanglomerate unconformably overlying the Norwood Tuff on the eastern side of the valley (Thv, fig . 2) that they informally correlated with the Huntsville fanglomerate (informal name), which is mapped in Ogden Valley and near the East Canyon fault (fig 1).

MORGAN FAULT

The 16-km-long Morgan fault is mapped on the eastern side of Morgan Valley at the base of an escarpment formed in Paleozoic and early Tertiary rocks (Mullens and Laraway, 1973). The escarpment consists of three linear 5- to 8-km-long sections that correspond to en echelon steps in the trace of the fault and to differences in escarpment height and elevation of hanging-wall deposits (figs. 2, 3). There are no fault scarps in unconsolidated deposits along the three sections of the fault. However, triangular facets along the base of the escarpment that are 100 to 250 m high and slope 20° to 25° suggest that Quaternary displacements have occurred on all sections of the fault.

Evidence suggests that Cenozoic displacement may be greatest on the northern section of the fault. On the basis of (1) the correlation of thrust faults mapped on Durst Mountain in the footwall of the Morgan fault with those exposed on the western side of the valley and (2) the thickness of Cenozoic deposits in the valley, Hopkins (1982) concluded that 6,800 m of Cenozoic normal displacement has occurred on the northern section of the fault. Along this section of the fault, tilted late Cenozoic erosion surfaces are cut on the Huntsville fanglomerate (fig. 2), which overlies the Norwood Tuff in the hanging wall of the fault. Schick (1955) concluded that this fanglomerate is of Pliocene(?) age and suggested that it was displaced by the Morgan fault. Recent mapping (Mullens and Laraway, 1973; Hopkins, 1982) indicates that this fanglomerate dips 5° to 38° into the fault and also suggests that the fanglomerate is faulted. Although triangular facets are also present on the southern section of the fault, Cenozoic displacement appears to be less there than it is on the northern section (Hopkins, 1982, p. 35).

Our investigation of the late Quaternary displacement history of the Morgan fault focused on the central section of the fault, where Quaternary alluvial fans (Qaof) set into the Huntsville fanglomerate suggest displacement by the Morgan fault (figs. 2, 3 , 4). We infer this topographic low on the hanging wall of the fault to be a 0.5- to 1-km-wide graben filled with alluvial fan deposits that is bounded on the east by the main scarp of the Morgan fault and on the west by an inferred east-facing antithetic fault (fig. 4). Dissected alluvial fan deposits (Qaof) slope 6° to 9° to the southwest within this inferred graben. The lower 50 m of some of the facets slope 1° to 3° more steeply than their upper portions. Thus, we infer the surface trace of the fault to be at the 50- to 100-m-

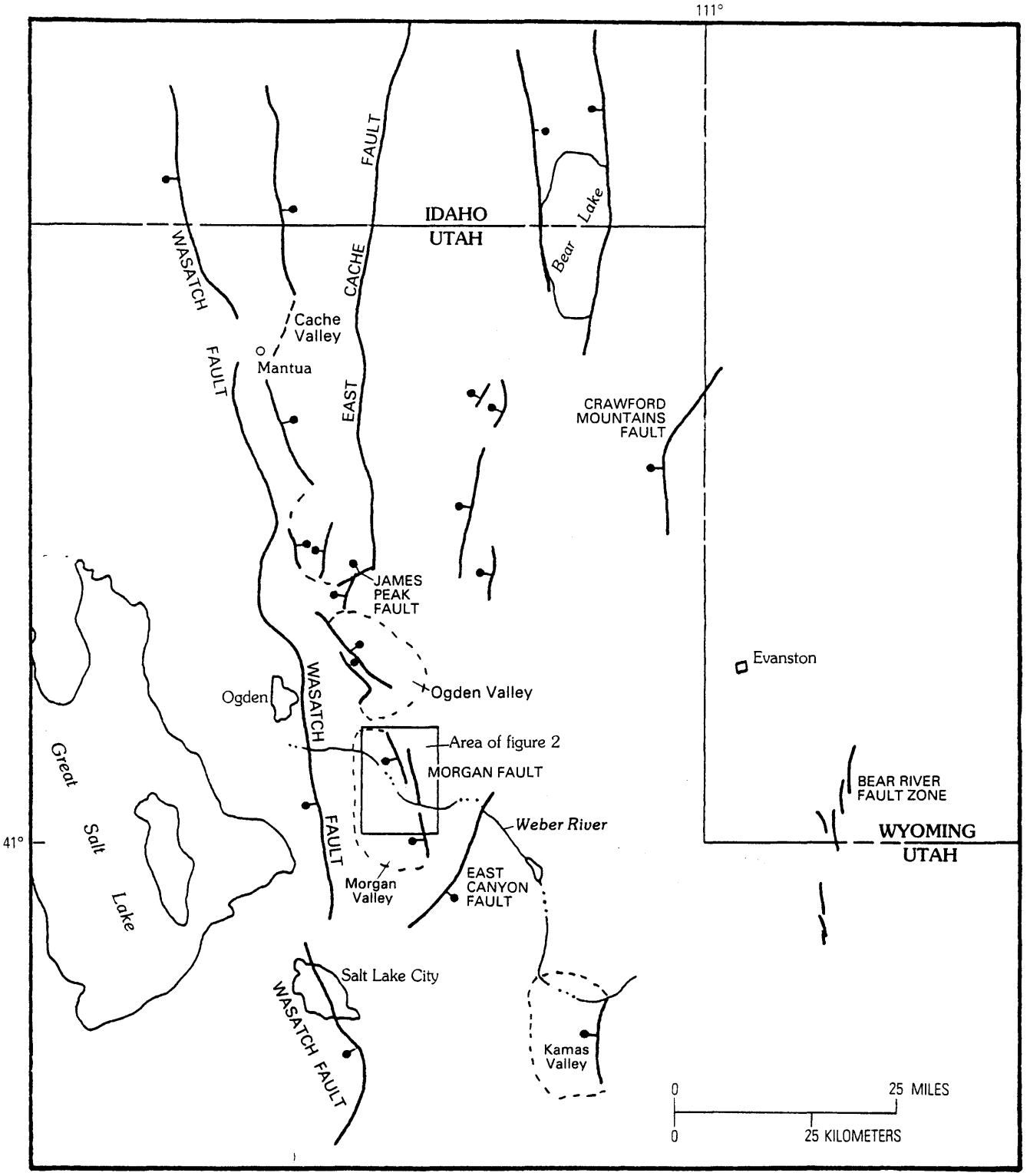
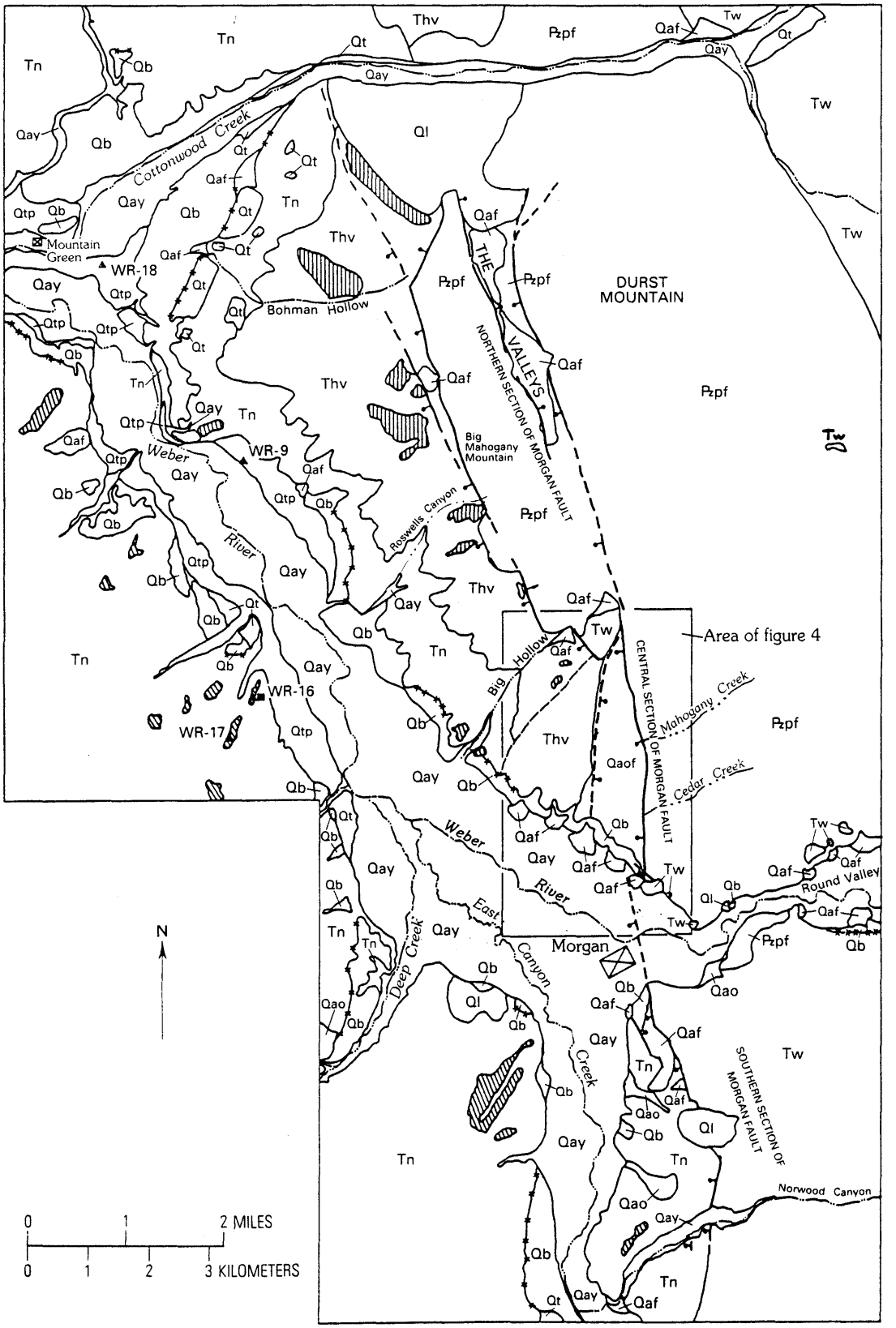


FIGURE 1.—Location of the Morgan fault, the Wasatch fault, and other middle or late Quaternary faults (ball and bar on downthrown side) in northeastern Utah. Outlines of the back valleys of the northern Wasatch Mountains are indicated by dashed lines. The area of figure 2 is shown.


Tn
Qb
Qay
Qt
Thv
Pzpf
Qaf
Tw
Ql
Cottonwood Creek
Qtp
Mountain Green
WR-18
Bohman Hollow
THE VALLEYS
NORTHERN SECTION OF MORGAN FAULT
DURST MOUNTAIN
Big Mahogany Mountain
Weber River
WR-9
Roswells Canyon
WR-16
WR-17
Area of figure 4
CENTRAL SECTION OF MORGAN FAULT
Mahogany Creek
Cedar Creek
Qaof
Round Valley
East Canyon Creek
Deep Creek
Morgan
SOUTHERN SECTION OF MORGAN FAULT
Norwood Canyon
N
0 1 2 MILES
0 1 2 3 KILOMETERS

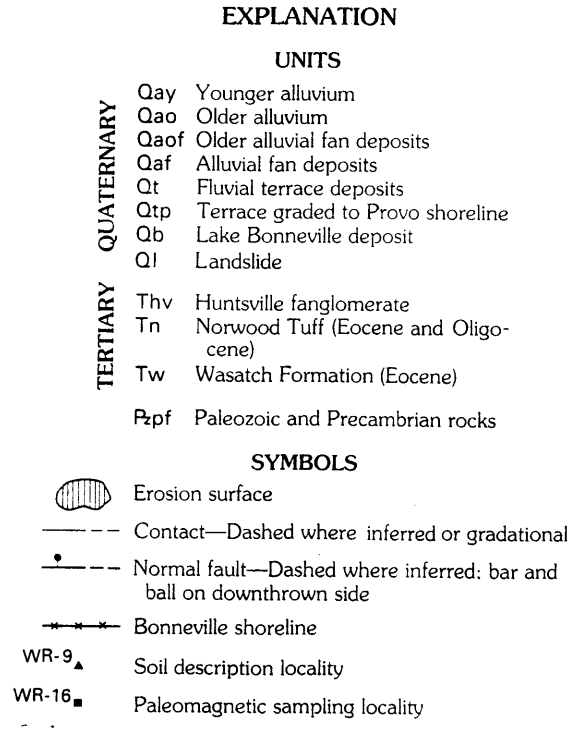


FIGURE 2.—Explanation.

wide break in slope between the facets and the fans. Although a few small, discontinuous Holocene fans along the break in slope in the larger drainages are undissected, channels (some up to 20 m deep) are incised into the surfaces of all the larger alluvial fans along the central section (fig. 4). Longitudinal profiles down these channels show that they are graded to the Bonneville shoreline along all but their lowest reaches. Knickpoints in the profiles caused by the fall of the lake (dated at 15 ka by Scott and others (1983)) do not appear to have migrated more than 100 m up the fan channels. Holocene alluvial fans have been deposited where the channels reach the flood plain of the Weber River. Thus, we conclude that most of the sediment derived from the footwall of the fault is being carried beyond the hanging-wall fan surfaces. Distinguishing tectonic responses from climatic or changing base-level responses in alluvial fan systems is difficult at best (for example, Funk, 1976; Bull, 1977), but the dissection of older fans along the central section suggests that fault slip rates are lower than stream-downcutting rates.

◀ FIGURE 2.—Cenozoic geology of Morgan Valley modified from Mullens and Laraway (1973). Reversely magnetized samples of a silty clay from the B horizon of a soil on an erosion surface west of the Weber River (site WR-16) indicate that this soil, the underlying deposits, and higher erosion surfaces in the valley are older than 730 ka (Sullivan and others, 1988). Most younger alluvium postdates the fall of Lake Bonneville from the Provo shoreline (14 ka). Fluvial terraces are all of Pleistocene age, but several ages are represented, including a terrace graded to the Provo shoreline (Qtp). The area of figure 4 is shown.

AGE OF QUATERNARY DEPOSITS ADJACENT TO THE CENTRAL SECTION OF THE MORGAN FAULT

The Quaternary deposits along the central section of the Morgan fault consist of Holocene alluvium in the major drainages, deposits of Lake Bonneville, and older colluvial and alluvial deposits at elevations above the Bonneville shoreline (fig. 4). Soils developed in the alluvium in the larger drainages (Qay, figs. 4, 5) and in the fans (Qayf, figs. 4, 5) deposited where the drainages reach the floor of Morgan Valley are weakly developed and contain no argillic B horizons. Comparison of these soils with the Holocene soils described by Shroba (1982) indicates that the alluvium is of Holocene age. Soils began forming on the buff-colored sands and silts between the present flood plain and the highest stand of Lake Bonneville in the valley following the fall of the lake about 14 to 15 ka. A soil developed on these deposits near Robeson Springs (M–2) (table 1, fig. 5) lacks an argillic horizon but contains substantial amounts of pedogenic carbonate. A sequence of older fan deposits (Qaof, figs. 3, 4, 5) derived from the mountains to the east is exposed above the Bonneville shoreline. These deposits are overlain by thin (1- to 3-m-thick) hillslope colluvium that thickens to 7 m adjacent to the Morgan fault near Mahogany Canyon. Exposures and test pits (all sampling localities, fig. 4) show thick calcium carbonate soil horizons (stages II and III of Gile and others (1966)) on both the colluvial and alluvial deposits; a 1-m-thick petrocalcic horizon (stage IV) in fan deposits was exposed beneath about 3 m of colluvium near Mahogany Canyon (locality 1, fig. 4). Thus, comparisons with similar soils developed in similar deposits elsewhere in the region (Machette, 1985a) indicate that many of these alluvial and colluvial sediments are probably of middle Quaternary age (125–730 ka). However, the differing degree of carbonate development in units of similar lithology, unconformities between most alluvial and overlying colluvial units, and uncertainty in correlating individual alluvial units in isolated exposures suggest that units deposited during a number of episodes during the Pleistocene may be present.

We used three relative dating methods in an attempt to estimate more accurately the ages of the older colluvial and alluvial sediments along the central section of the Morgan fault—two measures of the degree of soil development and amino acid ratios measured on fossil gastropod shells in the deposits.

Soil development indices (Harden and Taylor, 1983) provide an objective way of comparing the degree of soil

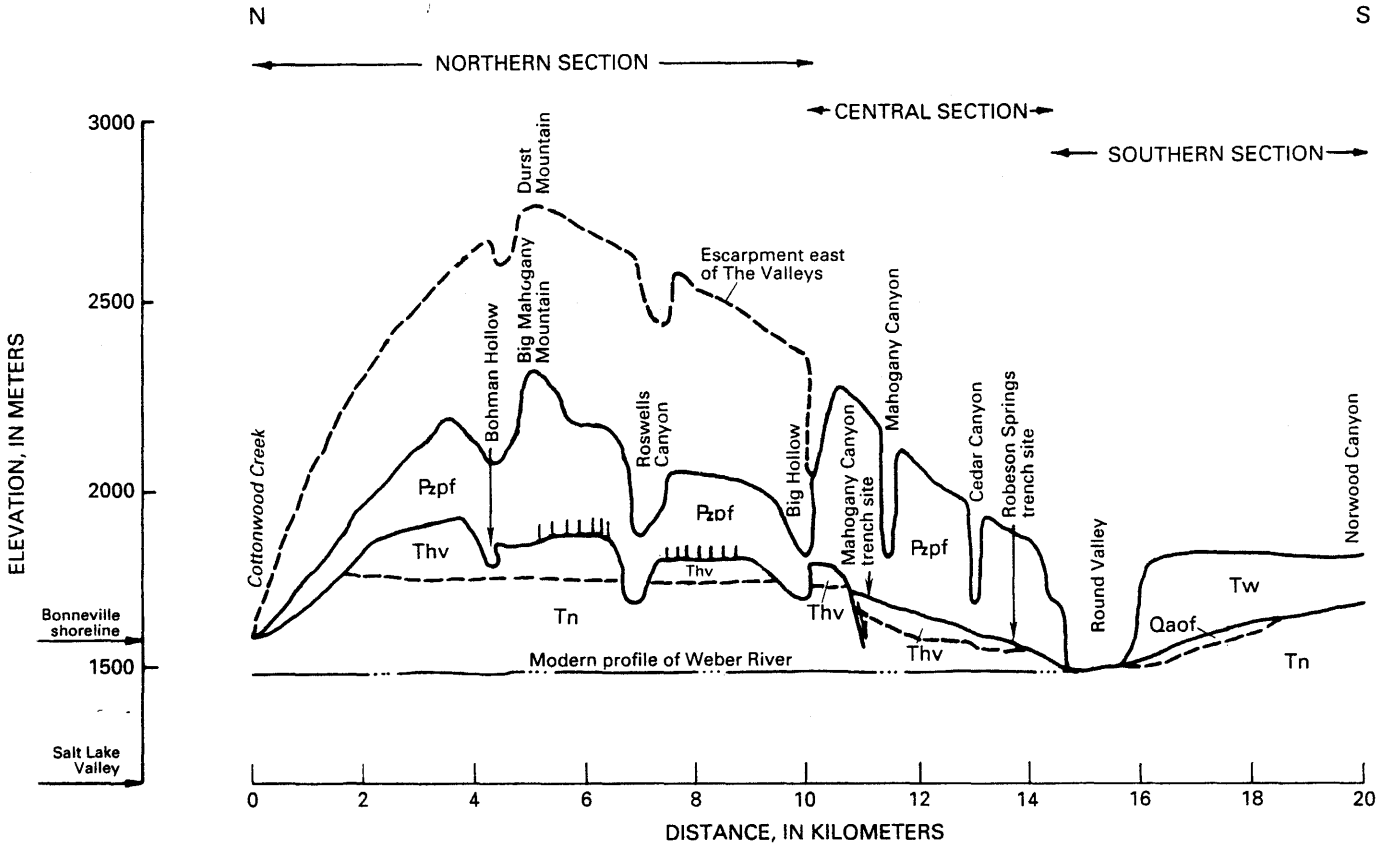
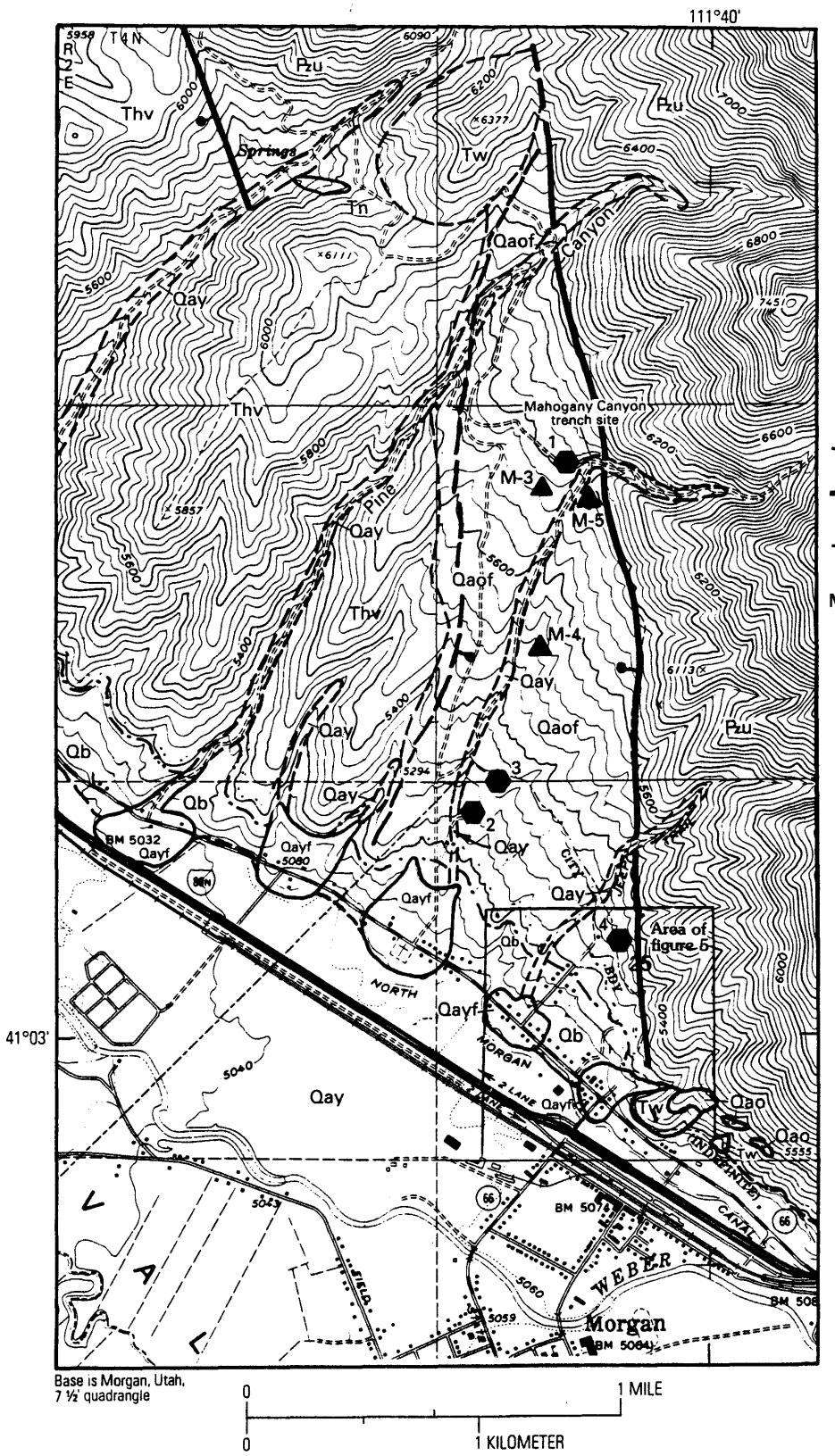


FIGURE 3.—Generalized topographic profiles (solid lines) and geologic section parallel to the Morgan fault drawn along the crest of the footwall escarpment and along the hanging wall at the base of the escarpment. Profiles are from a 1:62,500-scale map having a vertical exaggeration of approximately 6:1. The approximate position of the contact between the Huntsville fanglomerate (Thv) and the Norwood Tuff (Tn) is shown by a dashed line north of Mahogany Canyon. Thv is overlain by older alluvial fan deposits south of the antithetic fault at Mahogany Canyon. The modern profile of the Weber River and the locations of erosion surfaces (hachured lines) are also shown. Geologic units are the same as those used in figure 2.

development on deposits of unknown age with that on deposits of similar lithology in areas where numerical ages are available (Birkeland, 1984). Several calibrated (independently dated) soil profiles available from Morgan Valley (discussed by Sullivan and others (1988)) include soil M–6, which overlies a peat dated at $832^{\circ}_{\wedge}\pm100$ ka (Beta–9244) in a trench near Robeson Springs (table 1, fig. 5); soils (M–2, table 1; WR–9, WR–18, fig. 2) on both fine and coarse materials younger than the Bonneville shoreline (14–15 ka); and profile WR–16, which has a reversely magnetized B horizon that shows it to be older than 730 ka (fig. 2). The variable but high carbonate content of the soils described on alluvial and colluvial deposits along the central section of the Morgan fault (table 1, fig. 4) makes the indices of Harden and Taylor (1983) (table 1) less useful in estimating the age of these soils than in estimating the ages of many of the soils elsewhere in the Wasatch Range (Sullivan and others, 1988).

Measuring the rates of total pedogenic carbonate accumulation in soils is another method that has proven useful for estimating the age of soils in a number of areas in the arid and semi-arid Western United States (Machette, 1985a). Age estimates based on total carbonate values cannot be relied on for soils significantly younger than the last interglacial (125 ka) (unless many independent age estimates for similar soils in the region are available) because of probable major changes in carbonate accumulation rates over this period. However, over longer time spans, multiple cycles of climate change tend to attenuate accumulation rate changes; as a result, age estimates for older soils are relatively more accurate

FIGURE 4.—Surficial geology of the central section of the Morgan fault, modified from Mullens and Laraway (1973). See figure 2 for location. Older alluvial fan deposits have an estimated age of more than 400 ka, and colluvial deposits (not shown here) are inferred to range in age from Holocene to older than 400 ka. The upslope inflections in contour lines on unit Qaof mark channels incised into the older alluvial fan deposits. Younger alluvium and alluvial fan deposits postdate Lake Bonneville deposits (16–14 ka) in the valley. Sampling localities and the area of figure 5 at southern end of the central section are shown. ▶



EXPLANATION

QUATERNARY

- Qay Younger alluvium
- Qayf Younger alluvial fan deposits
- Qb Deposits of Lake Bonneville
- Qaof Older alluvial fan deposits
- Qao Older alluvium

TERTIARY

- Thv Fanglomerate—Subrounded cobble and boulders in red-brown sandy silt
- Tn Norwood Tuff—Light-gray tuffaceous sandstone
- Tw Wasatch Formation—Red sandstone and conglomerate

PALEOZOIC

- Pzu Paleozoic sedimentary rocks, undivided

- Geologic contact—Dashed where approximately located
- Morgan fault (solid) and inferred antithetic fault (dashed), bar and ball on downthrown side
- Highest Bonneville shoreline
- 1 Amino acid sampling locality
- M-4 Soil test pit locality

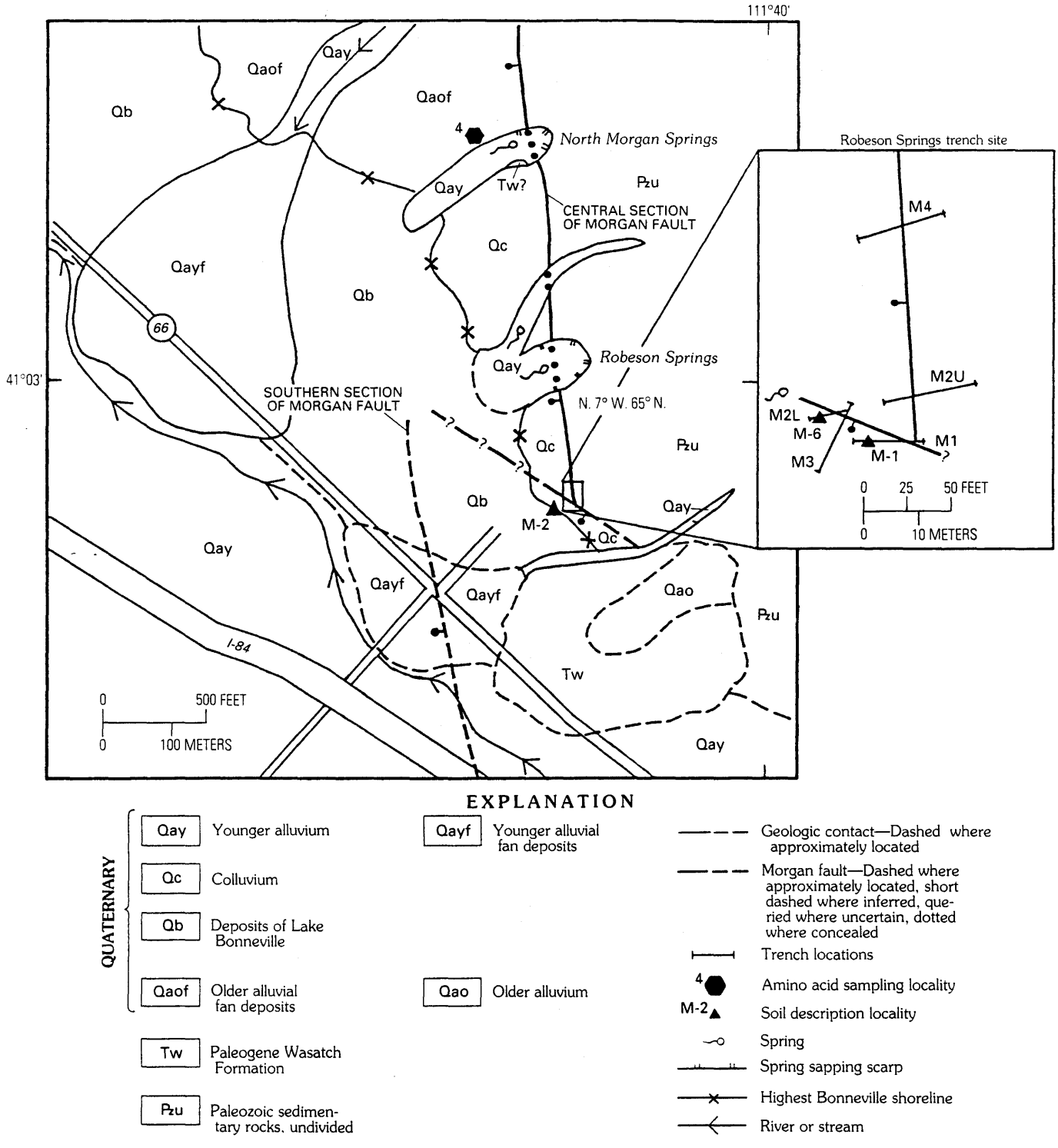


FIGURE 5.—Surficial geology of the southern end of the central section of the Morgan fault, showing locations of trenches at the Robeson Springs trench site and sampling sites.

age estimates for older soils (Machette, 1985b; Colman and others, 1988).

Machette's (1985a) methods were used to calculate amounts of carbonate, in grams per square centimeter, in the total profile for the Morgan soils and to compare them with values for carbonate-rich soils in the northern Wasatch Range having some independent age control. Sullivan and others (1988) calculated latest Pleistocene-Holocene (0–15 ka) carbonate accumulation rates of as much as 1 g/cm^2 per thousand years from two soils (M–2 and M–6, table 1) in Morgan Valley and one soil in Heber Valley (about 65 km to the south). However, ground water may have added carbonate to the soil in profile M–2, and primary carbonate values are difficult to estimate for all soils. The longer term (0–150 ka) rate of Sullivan and others (1988)—0.5 g/cm^2 per thousand years (again based on only three soils along the Weber River, fig. 1)—is roughly half the latest Pleistocene-Holocene rate. Because the back valley soils are located east of the crest of the Wasatch Range, it is unlikely that latest Pleistocene-Holocene carbonate accumulation rates are higher than the 0.5 g/cm^2 per thousand years calculated by Scott and others (1982) for soils of similar age near Salt Lake City. Rates of about 0.15 g/cm^2 per thousand years for Fisher Valley (Colman and others, 1988), 0.14 g/cm^2 per thousand years for the Beaver area (Machette, 1985b), and maximum rates of 0.14 to 0.26 g/cm^2 per thousand years for Spanish Valley (Harden and others, 1985) elsewhere in Utah indicate that middle and late Quaternary rates in the eastern Wasatch Range may well have been less than 0.2 g/cm^2 per thousand years. We use 0.5 g/cm^2 per thousand years as a maximum rate to estimate minimum ages of 70 to 100 ka for the soils in profiles M–3, M–4, and M–5 (table 1). These calculations suggest that soils on the alluvial fans (unit Qaof, fig. 4) are certainly older than 50 ka and probably date to before the last interglacial age (125 ka). Because the fans are being eroded, even finite soil ages would be minimum ages for the fan sediments.

Amino acid ratios derived from analysis of the organic matrix within carbonate fossils have proven useful in the relative dating and correlation of a variety of Quaternary stratigraphic units worldwide (Wehmiller, 1982). This methodology, termed aminostratigraphy by Miller and Hare (1980), is valid within a region as long as all samples have had very similar temperature histories and if the amino acids in the species analyzed racemize at about the same rate (Williams and Smith, 1977). Although most studies have used marine mollusks (Wehmiller, 1982), recent work indicates that amino acid ratios from nonmarine gastropods are useful for relative dating (Miller and others, 1982; Scott and others, 1983; Nelson and others, 1984; Barnes and others, 1986). The Paleozoic carbonates and alluvial fan surfaces having carbonate-rich soils along the central section of the Morgan fault provide a favorable environment for lime-loving terrestrial gastropods. The large terrestrial gastropod *Oreohelix* cf. *strigosa* is abundant in the surface litter along the trace of the fault, and fragments and whole shells of this species were found in the older alluvial fan sediments (Qaof) and overlying colluvium (Qc) at four sites (fig. 4, table 2). Ratios of D-alloisoleucine to L-isoleucine in these samples in the alluvium are greater than 0.4, whereas those in the colluvial units range from 0.20 to 0.57; these ratios suggest that the shells are of several ages.

Accurate numerical age estimates are difficult to obtain from amino acid ratios. Such estimates require accurate kinetic models of amino acid racemization in the mollusk genera of interest, along with estimates of the temperature histories of the fossil samples. A ±1° uncertainty in the effective diagenetic temperature (EDT) (integrated chemical effect of the sample's temperature history) results in a 20 percent uncertainty in the age estimate, and we have no way of estimating the uncertainty in our EDT's. Although the diagenetic models that we used were developed by using different genera (table 2), the models for many genera differ little, and there is no reason to think that these models do not apply to *Oreohelix* shells in Morgan Valley.

We used two kinetic models to calculate (minimum) ages for our samples (table 2). The linear model assumes a constant rate for the isoleucine racemization reaction in shells but probably applies only to our younger samples, because the reaction rate has been shown to decrease markedly in older samples (Wehmiller, 1982). One of several possible nonlinear models suggests much greater ages for the older samples. A few of the samples that were collected less than 2 m below the surface may have been affected by seasonal temperature changes (which would increase their apparent age), but, because the alluvial fan sediments are being eroded, most samples must have been buried more deeply during most of their burial history. If the shallower samples were less than 2 m deep for their entire burial history, the maximum possible surface heating effect would reduce our calculated ages by about half (for example, Wehmiller, 1977). Because of large uncertainties in sample temperature histories and appropriate kinetic models, only the linear-model age estimates (table 2) are used—and they are only minimum age estimates. However, enough is known about EDT's in the region and the reaction rate in gastropods to suggest that the samples from the colluvium exhibiting ratios of 0.20 and 0.27 are less than 200 to 400 ka and less than 300 to 500 ka, respectively.

Thus, on the basis of six samples (table 2), the older alluvial fan deposits are thought to be older than 400 ka. The colluvial deposits overlie these older fan deposits at

TABLE 1.—*Selected properties of soils on alluvial, colluvial, and lacustrine sediments along the Morgan fault, Morgan Valley, north-central Utah*

[—, not detectable]

Horizon[1]	Average depth (cm)	Parent material	Munsell color	Estimated percentage by volume			Percentage by weight[2]			Organic matter[3] (percent)	Carbonate[4] (percent)	Soil profile index[5]	Total pedogenic carbonate[6] (g/cm^2)
				Pebbles (0.2–8 cm)	Cobbles (8–25 cm)	Boulders (>25 cm)	Sand (2–0.5 mm)	Silt (50–2 μm)	Clay (<2 μm)				
Profile M–1													
A	0–10	Slopewash colluvium	10YR 6/2	5	0	0	27	56	18	1.7	16.5	15	63
Bwk	10–23	do	10YR 5/3	5	0	0	28	52	21	1.2	24.9		
Bkm	23–50	do	10YR 8/0n	5	0	0	28	58	15	.5	43.7		
Bk1	50–84	do	7.5YR 8/2	5	0	0	18	75	7	.4	48.9		
Bk2	84–161	do	7.5YR 7/3	2	0	0	14	79	7	.3	35.6		
C	161–228+	do	7.5YR 7/3	2	0	0	28	62	11	3.3	—		
Profile M–2													
Ap	0–9	Loess and lake sediments.	7.5YR 5/3	0	0	0	21	73	6	1.5	—	15	19
A	9–20	do	7.5YR 5/3	0	0	0	22	70	9	1.1	—		
Bw	20–42	Lake sediments	7.5YR 6/4	0	0	0	44	43	13	.3	—		
Cox1	42–50	do	7.5YR 7/4	0	0	0	50	40	11	.1	5.5		
Bk1	50–61	do	7.5YR 7/4	0	0	0	44	45	11	.2	13.9		
Bk2	61–71	do	7.5YR 8/3	0	0	0	39	47	15	.4	35.5		
Bk3	71–107	do	7.5YR 8/3	0	0	0	6	81	14	.1	21.7		
Cox2	107–155+	do	7.5YR 7/3	0	0	0	6	82	12	.1	13.0		
Profile M–3													
Ap	0–10	Loess and alluvium	7.5YR 5/3	10	10	2	28	57	15	6.5	—	19	35
Bt	10–32	do	7.5YR 5/3	10	10	2	20	52	28	3.4	14.3		
2Bkm	32–35	Alluvium	7.5YR 8/0	20	5	2	17	66	17	1.2	50.4		
2Bk	35–73	do	7.5YR 8/3	20	5	2	20	66	14	.4	56.0		
2Bt	73–128	do	7.5YR 6/3	5	0	0	19	73	7	.2	21.6		
3Ckm	128–135+	do	7.5YR 8/1	20	10	2	27	41	32	.3	51.0		
Profile M–4													
A1	0–13	Loess and colluvium	7.5YR 4/3	10	5	1	22	57	20	4.5	21.6	12	49
A2	13–37	do	7.5YR 4/3	10	5	1	22	62	16	3.2	28.0		
2BA	37–50	Alluvium	7.5YR 7/3	30	1	0	36	50	15	1.3	53.8		
2Bk	50–71	do	7.5YR 7/4	30	1	0	31	43	26	.7	54.6		
3Ck	71–120	do	7.5YR 8/3	10	5	2	17	73	10	.4	47.6		
3C	120–140+	do	7.5YR 7/3	10	5	2	19	53	29	.2	39.8		

TABLE 1.—*Selected properties of soils on alluvial, colluvial, and lacustrine sediments along the Morgan fault, Morgan Valley, north-central Utah*—Continued

Horizon[1]	Average depth (cm)	Parent material	Munsell color	Estimated percentage by volume			Percentage by weight[2]			Organic matter[3] (percent)	Carbonate[4] (percent)	Soil profile index[5]	Total pedogenic carbonate[6] (g/cm^2)
				Pebbles (0.2–8 cm)	Cobbles (8–25 cm)	Boulders (>25 cm)	Sand (2–0.5 mm)	Silt (50–2 μm)	Clay (<2 μm)				
Profile M–5													
Ap	0–9	Loess and colluvium	7.5YR 5/3	15	10	1	24	58	18	4.7	—	14	40
A	9–30	do	7.5YR 5/4	15	10	1	21	53	26	2.7	12.8		
BA	30–44	do	7.5YR 7/4	15	10	1	29	48	23	1.4	46.1		
2Bkm	44–52	Alluvium	7.5YR 8/2	20	10	0	32	48	20	.4	47.9		
2Bk	52–88	do	7.5YR 8/3	20	10	0	38	43	19	.4	46.6		
3CB	88–138	do	7.5YR 7/4	40	1	0	31	48	21	.2	41.6		
4C	138–149+	do	7.5YR 7/4	5	0	0	34	48	18	.2	46.0		
Profile M–6													
Ap	0–16	Slopewash colluvium	7.5YR 4/2	5	0	0	31	56	13	9.8	10.7	16	7
A	16–37	Colluvium	7.5YR 4/3	5	0	0	28	55	17	3.4	19.8		
Bt	37–69	do	7.5YR 5/3	5	0	0	30	55	14	2.2	25.0		
Ck	69–98	do	7.5YR 7/3	5	0	0	33	57	10	1.4	12.4		
2C1	98–135	do	10YR 7/3	10	0	0	28	49	23	.9	36.4		
2C2	135–175+	do	10YR 7/3	5	2	0	23	50	27	1.0	11.6		

[1]Horizon nomenclature of Guthrie and Witty (1982) and Birkeland (1984), except that the master K horizon is not used.

[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 carbonates and organic matter have been removed by Jackson's (1956) method.

[3]Method of Walkley and Black (1934).

[4]Method of Allison and Moodie (1965, p. 1387).

[5]Nonarid index of Harden and Taylor (1983).

[6]Method of Machette (1985a).

TABLE 2.—*D-alloisoleucine/L-isoleucine ratios in the total (free + peptide-bound) amino acid fraction and calculated ages for* Oreohelix *cf.* strigosa *from alluvial and colluvial sediments along the Morgan fault, Morgan Valley, north-central Utah*

[—, age not calculated]

INSTAAR lab no.[1]	Depth below surface (m)	Number of sample preparations	Mean total aIle/Ile ratio[2]	Minimum age estimate (ka)		Location[5]	
				Linear kinetic model[3]	Nonlinear model[4]	Site	Unit
Modern surface float (mean annual temperature 7.2 °C–7.7 °C)							
DAN–194	0	8	0.025±.005	—	—	1	—
North Morgan Springs							
DAN–190	>4	3	0.61±.05	709–777	1,511–1,660	4	Qaof
Gravel pit							
DAN–207	2.3	3	0.27±.06	317–289	—	2	Qc
DAN–209	.7	3	.35±.06	422–386	—	2	Qc
DAN–189	3	2	.41±.06	456–503	—	2	Qaof
DAN–208	5.5	3	.43±.04	485–530	—	3	Qaof
Mahogany Canyon roadcut							
DAN–198	>1.6	3	0.30±.04	337–369	—	1	Qc
DAN–193, 195, 196, 197, 199	>2	8	.49±.06	582–637	861–942	1	Qaof
Trench at site M6, Mahogany Canyon[6]							
DAN–206	1.7	3	0.20±.01	214–234	—	1	Qc
DAN–201	5.0	3	.35±.05	400–438	—	1	Qc
DAN–200	5.1	3	.57±.03	691–757	1,350–1,478	1	Qc
DAN–203	6.0	3	.40±.05	463–508	—	1	Qc
DAN–204	4.8	3	.44±.03	515–564	—	1	Qaof
DAN–205	5.8	3	.46±.03	542–593	677–740	1	Qaof

[1]Institute for Arctic and Alpine Research, University of Colorado, Boulder, Colo.

[2]aIle/Ile ratio (peak area) measured by using methods of Miller and Hare (1980). Mean ratios include one standard deviation. Extraneous values rejected by using methods of Dixon (1965).

[3]Age calculated by using a linear kinetic model of isoleucine racemization (equation 18 of Williams and Smith (1977)), where $k=0.77$; a modern ratio of 0.025 for *Oreohelix* cf. *strigosa* (A.R. Nelson, unpub. data, 1984); Arrhenius parameters determined for *Vallonia* by Nelson and others (1984); values of constants in the Arrhenius equation (equation 9 of Williams and Smith (1977)); and an effective diagenetic temperature for the late Quaternary in this region of 8 °C less than the present mean annual temperature (Nelson and others, 1984) (for example, Wehmiller and Belknap, 1982). Age range calculated by using ±0.25 °C range in estimated effective diagenetic temperature.

[4]Age calculated by using a nonlinear model, a Quaternary effective diagenetic temperature (see footnote 3) (for example, Wehmiller and Belknap, 1982), and the same relationships used in the linear model, except that the reaction rate is assumed to decrease to one-fifth the initial rate for samples having aIle/Ile ratios greater than 0.4.

[5]As seen in figure 4. Qc not mapped.

[6]Trench discussed in detail by Sullivan and others (1988).

all the sampling sites. The lowest ratio obtained from colluvium, in the trench near Mahogany Canyon, suggests an age of more than 200 ka. Higher ratios from other colluvial units indicate either that these units are older or that shells in the slope colluvium are reworked from the older fan deposits. The minimum age estimates from the soil carbonate data are consistent with these age estimates from amino acid ratios.

TRENCH INVESTIGATIONS OF QUATERNARY FAULTING ON THE CENTRAL SECTION OF THE MORGAN FAULT

The Morgan fault is exposed at the base of the escarpment in 2-m-high exposures at Robeson Springs (fig. 5) as a planar, N. 7° W.-striking, 65° W.-dipping sheared contact between Paleozoic carbonates and light-brown silty colluvium. Sheared and altered dolomite is exposed for a distance of about 15 m to the east in the footwall of the fault, but no other shears are evident in colluvial deposits in the exposure, which extends about 25 m west of the fault. This exposure and additional exposures at North Morgan Springs (fig. 5) showed that unconsolidated deposits, exposed above the Bonneville shoreline, were displaced by the Morgan fault in a narrow zone at the base of the triangular facets on the escarpment.

The Robeson Springs trench site is located at the southern end of the central section of the Morgan fault (fig. 5). The linear trace of the footwall escarpment ends

at a small, east-trending ephemeral drainage south of the trench site. South of this drainage, red sandstone and conglomerate of the Wasatch Formation are exposed dipping 40° to the west and extending across the projection of the central section of the fault. Projecting the southern section of the fault north across the Weber River indicates that the Morgan fault steps westward about 200 m between the southern and central sections (figs. 2, 5).

At the Robeson Springs site, five trenches were excavated at or near the break in slope at the base of the footwall escarpment of the Morgan fault (fig. 5). Two of these trenches (M2U and M4) exposed the main trace of the Morgan fault. Another normal fault trending northwest between the central and southern sections of the Morgan fault is exposed in trenches M2U, M1, and M3. The Cambrian and Devonian dolomite that forms the escarpment is exposed in all the trenches. To the east, it is overlain by Devonian and Mississippian sedimentary rocks that generally dip to the west but that have been complexly folded and faulted (Mullens and Laraway, 1973). In trenches M2U and M4, colluvial deposits overlie the dolomite in the hanging wall of the fault, but, in the exposures at North Morgan Springs, the colluvial deposits overlie older alluvial fan deposits that are correlated with similar deposits exposed at four locations north of the Robeson Springs site (figs. 4, 5).

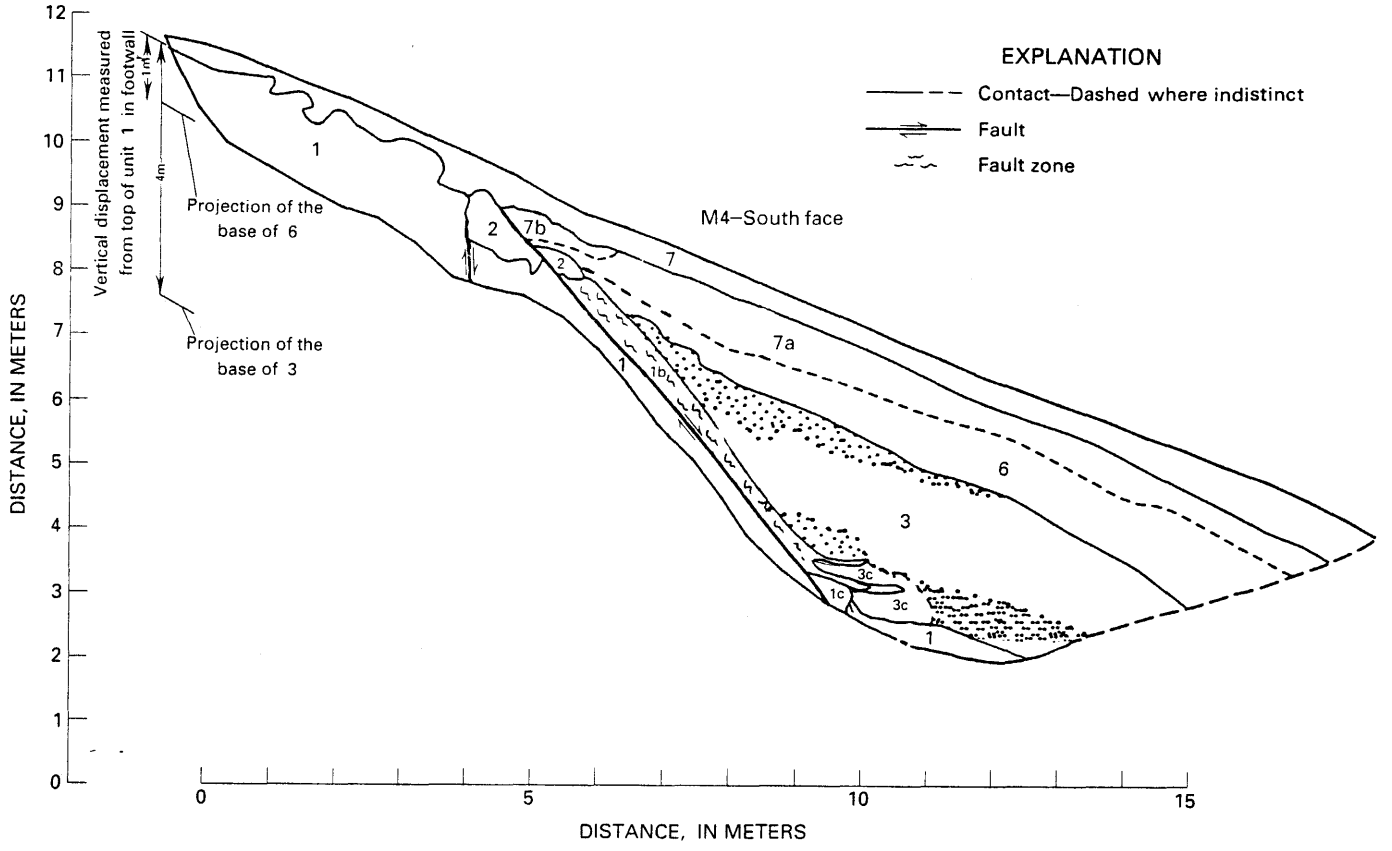
STRATIGRAPHY IN TRENCH M4

The Morgan fault is clearly expressed in trench M4 as a zone of sheared dolomite and fault gouge from within 1 m of the ground surface to the base of the trench (fig. 6). The fault zone juxtaposes colluvial deposits and bedrock along a N. 7° W.-striking, 50° W.-dipping planar contact. The eastern boundary of the fault zone is an abrupt planar shear separating fractured bedrock (unit 1) from a fine-grained fault breccia (unit 1b) derived from the bedrock. Near the base of the trench, a plastic clay gouge (unit 1c) forms part of the fault zone.

On the western margin of the fault zone, a 4-m-thick sequence of colluvial deposits has been displaced by the fault (units 3, 6, 7a, 7b, fig. 6). The colluvial deposits are all of similar lithology—clayey silts containing variable but small (less than 15 percent) amounts of dispersed angular pebbles of dolomite. Slight differences in color, clay content, carbonate content, and induration have been used to map three main colluvial units (units 3, 6, 7) and to identify separate facies (identified by lower case letters) within two of the units. Unit 3 is massive and moderately indurated and contains upper and lower zones of pedogenic carbonate (stage II). Unit 6 is siltier, lacks carbonate, and is loose and unconsolidated. Modern soil is developed in unit 7, including a cambic B horizon containing weak stage II carbonate in some parts (unit 7a).

Discrete downslope-thinning colluvial wedges that are derived from erosion of the free face of a fault scarp are typically found adjacent to faults displaying scarps more than 1 m high in unconsolidated deposits. The stratigraphy and thickness of these colluvial wedges have been used to estimate the size of the individual surface displacements on faults (for example, Schwartz and Coppersmith, 1984). Near the floor of trench M4, two 0.1-m-thick, 0.5- to 0.8-m-long fingers of fault breccia (unit 1b) are interbedded with colluvial unit 3c (fig. 6). This interbedding of fault breccia and colluvium appears to have resulted from the erosion of fault breccia from the free face of a scarp that was formed during two separate surface displacements on the fault. The colluvium between these fingers of fault breccia is 0.4 m thick, and 0.5 m of colluvium is preserved between the lower finger and the underlying bedrock. These thicknesses provide minimum estimates of the height of the scarp and of the vertical displacement that produced it.

The lack of discrete horizons within unit 3 suggests that it did not accumulate as a succession of scarp-derived colluvial wedges. Unit 3 consists of 2 m of massive pebbly, clayey silt deposited by surface wash and creep from above the trench site. The uniform thickness of fault breccia preserved adjacent to this unit along a planar 50°-W.-dipping contact indicates that unit 3 has been faulted into its present position. We interpret this unit to consist of multiple indistinguishable colluvial units that have been downdropped along the fault during successive small surface displacements and subsequently buried by continuing deposition from the escarpment above the fault. These colluvial units inferred to comprise unit 3 are lithologically identical; unconformities between them or any differences in soil development from one unit to another apparently have been masked by carbonate accumulation. On the basis of the depth of carbonate in the modern soil (unit 7a), it is thought that the pedogenic carbonate zones of unit 3 probably developed 1 to 2 m below the ground surface. The lack of interbedding within unit 3 (other than at the floor of the trench, where fingers of fault breccia divide portions of unit 3c) indicates that the displacements did not expose the fault breccia in the scarp free face. Thus, the individual surface displacements were not significantly greater than the present thickness of slope colluvium (unit 7)—about 0.5 m—on the footwall of the fault. Thus, the displacements were probably about the size of the minimum displacements inferred from the thickness of colluvium preserved below the fingers of fault breccia near the floor of the trench.



DESCRIPTION OF UNITS

7 Colluvium (HOLOCENE)—Dark brown, loose, pebbly, silt with organic material, A horizon
7b Colluvium (HOLOCENE)—Dark brown, loose, pebbly silt
7a Colluvium (HOLOCENE)—Light brown, moderately indurated, pebbly silt with cambic B and BCa horizon
6 Colluvium (HOLOCENE)—Brown, loose, clayey silt
3 Colluvium (MIDDLE AND LATE QUATERNARY)—Light brown, moderately indurated, pebbly, clayey silt. Upper and lower zones of carbonate accumulation stippled
3c Colluvium (MIDDLE QUATERNARY)—Yellowish-brown, well-indurated, pebbly
2 Colluvium (MIDDLE QUATERNARY)—Yellow, well-indurated, sandy silt
1 Bedrock (PALEOZOIC)—Dark gray, moderately weathered dolomite with no recognizable bedding, DCd of Mullens and Laraway (1973)
1b Fault breccia—Dark grey, uncemented silt-sized dolomite fragments
1c Fault gouge—Yellow plastic clay

FIGURE 6.—Log of trench M4 at the Robeson Springs trench site, showing faulted middle and late Quaternary colluvial deposits at the southern end of the central section of the Morgan fault. Sloping lines at the left are projections of displaced surfaces (the amount of the displacement is indicated).

The total displacement since the deposition of unit 3c has been estimated by projecting the base of unit 3 to the footwall of the fault at the same slope as the ground surface (fig. 6). The measured vertical displacement between the present bedrock surface and the top of unit 3 is about 4.0 m. This estimate, however, is a minimum, because this bedrock surface in the footwall must have been eroded as unit 3 was deposited.

In the upper portion of trench M4, the apparent displacement of the base of unit 6 records the most recent displacement event on the fault at this locality. Unit 6 is a key stratigraphic unit that is present in all of the trenches at the site and that overlies a dated peat deposit in trenches M2L and M3 (discussed below). The amount of this displacement has been estimated by projecting the base of unit 6 to the footwall of the fault and using the slope of the present ground surface (fig. 6). The vertical displacement measured between the bedrock surface and the base of unit 6 is about 1.0 m. The fault plane on which this displacement occurred is preserved in unit 2, a lighter colored, well-indurated pocket of colluvium, as a carbonate-impregnated plane dipping 50° to the west. We assume that this plane approximately represents the actual vertical displacement, not a minimum value, because little erosion of the bedrock surface is presumed to have occurred since the most recent Holocene event.

Estimated displacements of 0.5 to 1 m per event are small in comparison with displacements estimated for other Quaternary faults in Utah (for example, Schwartz and Coppersmith, 1984; Nelson and Van Arsdale, 1986; Nelson and Sullivan, this volume). These small displacements and empirical relationships (for example, Bonilla and others, 1984) between earthquake magnitude and the amount of surface displacement suggest paleoearthquake magnitudes of 6½ to 7 for the 16-km-long Morgan fault, as do similar relationships between earthquake magnitude and fault rupture length.

The preservation of unit 2 directly above the main fault appears to be related to an earlier displacement. A near-vertical carbonate-filled shear extends from the base of unit 2 to the floor of the trench in the bedrock east of the main fault and strikes N. 8° E. across the trench. Unit 7a and its more pebbly upslope facies, unit 7b, are interpreted to be parts of a horizon of slope colluvium downdropped to its present position by the most recent displacement event on the main fault zone. Unit 6 thins upslope to its contact with unit 2 in the hanging wall of the fault, and it is not clear if it ever extended across the fault. The predominance of silt and the lack of induration in unit 6 suggest that it consists principally of loess (or loess redeposited by surface wash) rather than slope colluvium eroded from the escarpment. Because it is the only colluvial unit in this trench and in other trenches that thickens downslope, unit 6 may have been deposited on only the lower parts of the slope and may not have extended across the fault zone.

AGES OF FAULTED DEPOSITS

Estimates of the ages of displaced colluvial deposits at the Robeson Springs trench site are based on radiocarbon dates for peat interbedded with colluvial deposits in trenches M2L and M3 and on amino acid ratios from snails in colluvial and alluvial fan deposits exposed in four other locations along the central segment of the Morgan fault. A small (3×6 m) bog deposit of peat that underlies colluvial unit 6 and overlies bedrock in the hanging wall of the Morgan fault is exposed in trenches M2L and M3. Unit 6 is correlated between trench M4 and the other trenches 32 m to the south (fig. 5) on the basis of similar lithologies and stratigraphic and geomorphic positions (Sullivan and others, 1988). Radiocarbon dates of 8,320±100 ka on peat (Beta–9244) and 9,105±270 ka on wood (GX–9968) from this deposit indicate an early Holocene age for the bog and an early or middle Holocene age for overlying colluvial unit 6.

A post-early Holocene displacement event of 1 m might be expected to have produced scarps along the central section of the fault that would still be visible today. Scarps 1 m high on gently sloping alluvial fans probably would be preserved for tens of thousands of years (Hanks and others, 1984). However, the Morgan fault is mapped at the base of a 20° to 25° sloping escarpment, and figure 6 shows that the 1-m-high scarp has been completely covered since the deposition and faulting of unit 6. Erosion and deposition of younger alluvial deposits apparently obliterated the scarp in drainages crossing the escarpment.

We infer a middle to late Pleistocene age for the older colluvial deposits (unit 3) in trench M4 by using their similar lithologies, degrees of carbonate development, stratigraphic positions, depths, and positions adjacent to the fault to correlate them with the sequence at Mahogany Creek for which we have amino acid age estimates (table 2). At Mahogany Creek, about 2.5 km north of the Robeson Springs trench site (fig. 5), a similar sequence of colluvial deposits varies in thickness from 7 m in a trench at the mountain front to about 1 m in a roadcut 180 m to the west. In the trench at Mahogany Canyon, this colluvium overlies older alluvial fan deposits in which a petrocalcic horizon containing stage IV carbonate is developed. This degree of pedogenic carbonate development suggests that the fan deposits are at least 200 to 300 ka and probably older than 500 ka. Snails from this colluvium at depths of 1 to 5 m and from other sites at similar depths have estimated ages of 200 to 400 ka or more (discussed above, table 2). However, the upper parts of unit 3 may date from the late Pleistocene (10–125 ka) because individual units cannot be correlated from Mahogany Creek to Robeson Springs.

EVENTS IN TRENCH M4

On the basis of the stratigraphic relations in trench M4 and our estimates of the age of the colluvial deposits, we have interpreted the following sequence of events:

1. During the middle and late Pleistocene, units 3 and 3c were deposited as a series of 0.5- to 1.0-m-thick horizons of slopewash that were downdropped and preserved by a series of small-displacement events comprising a minimum of 3 m of displacement on the Morgan fault. Before or during this period, unit 2 was deposited as slopewash across the fault zone and displaced about 1 m on a near-vertical shear; as a result, it was preserved from erosion upslope from the main fault zone.
2. Following an interval of nondeposition of unknown duration, a depression in the hanging wall of the fault exposed in trench M2L (fig. 5) was filled with bog deposits (radiocarbon dates of 8.3 and 9.1 ka).
3. Unit 6 was deposited above unit 3 and the bog deposits principally as loess that may have been derived from exposed Lake Bonneville sediments in the valley.

4. Units 7a and 7b were deposited by surface wash across the fault zone.
5. Units 2, 7a, and 7b were displaced about 1.0 m along the main fault zone.
6. Modern surface wash continued to deposit colluvium (unit 7) on the slope across the fault zone.

OTHER TRENCHES

In trench M2U, about 30 m south of M4 (fig. 5) at the southern end of the central section of the fault, vertical relief on the bedrock surface across the projection of the fault exposed in M4 is about 3.5 m, although the fault plane is not distinct. A 1.5-m-high, near-vertical displacement of the bedrock surface striking N. 7° W. marks the Morgan fault in this trench. This step is overlain by about 1.0 m of undisplaced colluvium having the same lithology and in the same stratigraphic position as units 7 and 7a in trench M4 (Sullivan and others, 1986). If this correlation is correct, it suggests that the most recent surface displacement recorded in trench M4 did not extend south to M2U. However, below this horizon, massive colluvium about 1.5 m thick, equivalent to unit 3 in trench M4, is interpreted to have been displaced during small (less than 1 m) faulting events (Sullivan and others, 1988).

About 10 m south and west of trench M2U, a normal fault striking N. 65° W. and dipping about 50° to the southwest that is exposed in trenches M1, M3, and M2L (fig. 5) displaces fine-grained colluvial deposits equivalent to unit 3, but overlying colluvial units are not displaced. Trench M1 crosses the projection of the N. 7° W.-striking fault exposed in trenches M2U and M4 and shows that the main trace of the Morgan fault has been terminated by this northwest-striking fault, as the bedrock relationships at the trench site (discussed earlier) suggest. Because the base of the colluvium was not exposed in the hanging wall of the fault in trench M1, an estimate of the amount of displacement since the deposition of the colluvial deposits is precluded.

SLIP RATES ON THE MORGAN FAULT

QUATERNARY SLIP RATES

Mapping and trench investigations on the central section of the Morgan fault provided evidence that middle to late Pleistocene and Holocene displacements have occurred on this back valley fault. At the Robeson Springs trench site, two faults were identified: (1) the north-trending central section of the main fault that displaces middle to late Pleistocene and Holocene colluvial deposits a minimum of 4 m and (2) a northwest-trending trace of a subsidiary fault that displaces similar middle to late Pleistocene colluvial deposits. Radiocarbon dates of 8.3 and 9.1 ka provide a maximum age for the younger colluvium that has been displaced about 1 m by the main fault in trench M4. If it is assumed that the lower part of the underlying sequence of colluvial deposits in trench M4 is 200 to 400 ka, a minimum of 4 m of displacement yields a minimum middle to late Pleistocene slip rate of 0.01 to 0.02 mm/yr. Because only one event is recorded, a Holocene slip rate cannot be calculated. These Pleistocene slip rates are an order of magnitude lower than long-term Pleistocene rates on the Wasatch fault (Machette and others, this volume), but some other faults in the region may have rates nearly as low (Nelson and Van Arsdale, 1986; McCalpin and others, this volume; Nelson and Sullivan, this volume).

We interpret the colluvial stratigraphy in trench M4 as suggesting recurrent Quaternary surface displacements of 0.5 to 1.0 m. If 0.5 m most nearly represents the average size of the surface-displacement events that are represented by the 4 m of displacement in at least the last 200 to 400 ka (as the lack of discrete scarp-derived colluvial wedges in the trench suggests), about eight individual events have occurred. These estimates yield a maximum average middle to late Quaternary event recurrence interval of 25 to 50 k.y. If only four events of 1 m displacement have occurred, the maximum average recurrence interval would be 50 to 100 k.y.

CENOZOIC SLIP RATES

The effect of the late Cenozoic uplift of the Wasatch Range on the evolution of landforms in Morgan Valley depends partly on the distribution of late Cenozoic faults. Naeser and others (1983) estimated uplift rates of 0.8 mm/yr over the last 5 Ma and 0.4 mm/yr over the last 10 Ma for the north-central Wasatch Range west of Morgan Valley. As a section constructed across the northern portion of Morgan Valley by Hopkins (1982, fig. 5) shows, the faults bounding the western side of Morgan Valley as mapped by Bryant (1984) have limited displacement, and the structural relief in the valley is primarily caused by Cenozoic displacement on the Morgan fault. If the late Cenozoic slip rate on the Wasatch fault is much greater than that on the Morgan fault, the effect of this relative uplift of the Wasatch Range would be to accelerate late Cenozoic erosion in Morgan Valley. The fact that the Weber River has incised the Norwood Tuff more than 300 m in Morgan Valley (fig. 3) indicates that such erosion has occurred and suggests that the average late Cenozoic slip rate on the Morgan fault is much lower than that on the Wasatch fault.

The accumulated thickness of the Huntsville fanglomerate preserved adjacent to the northern section of the Morgan fault provides a crude estimate of the average

Cenozoic slip rate on the fault. In Hopkins' (1982) cross section, the Huntsville fanglomerate overlies the late Eocene-early Oligocene Norwood Tuff and dips 13° E. into the fault. It has an estimated maximum thickness of 1,000 m, which provides a minimum estimate of displacement since the beginning of deposition of the fanglomerate. The age of this deposit is poorly constrained; previous workers have suggested that it is of Pliocene age (Eardley, 1944; Coody, 1957). However, similar unconsolidated gravel deposits of Oligocene age have been mapped further south in the Wasatch Range overlying and interbedded with the Oligocene Keetley Volcanics (Bromfield and Crittenden, 1971; Sullivan and others, 1988). Using an age range of 5 to 35 Ma for the Huntsville fanglomerate and a minimum displacement estimate of 1,000 m yields an estimated average middle and late Cenozoic slip rate of 0.03 to 0.2 mm/yr.

The tilting of late Cenozoic erosion surfaces adjacent to the northern section of the fault also provides a crude estimate of the average late Cenozoic slip rate on the fault. In this area, locally well-preserved, gently (0.5°–1.7°) east-dipping erosion surfaces, cut on the Huntsville fanglomerate, slope up to 1.7° northeast, into the fault (fig. 2). Our observations in less dissected terrains of the Weber River drainage suggest that these surfaces probably once sloped at least 3° toward the center of the valley; therefore, we interpret the back tilting of these surfaces to have resulted from displacement on the Morgan fault. If the most steeply tilted surface, south of Bohman Hollow and 1.7 km west of the main trace of the fault, has been uniformly rotated from a 3° westerly dip to its present 1.7° easterly dip, then projection of this surface to the fault indicates about 150 m of displacement. If the erosion surface has been downdropped relative to the footwall as well as rotated, total displacement would be greater. These erosion surfaces are probably significantly older than a much lower erosion surface on the western side of the valley (fig. 2) paleomagnetically dated at more than 730 ka. Assuming an age of 1 to 5 Ma for this surface yields an average latest Cenozoic slip rate of 0.03 to 0.15 mm/yr for this section of the fault, which is consistent with the rate estimated from the thickness and age of the Huntsville fanglomerate.

These slip-rate values are poorly constrained and do not take into account probable significant variations in slip rates during the late Cenozoic. Estimates of 0.01 to 0.02 mm/yr determined at the Robeson Springs trench site for the middle to late Quaternary are at the low end of the ranges of late Cenozoic slip rates. Because we infer only one Holocene event and because our estimates of average minimum recurrence intervals range from 25 to 100 ka, we have no way of judging whether the Holocene slip rate or recurrence interval differs from our estimates for the middle to late Quaternary, as Wallace (1984) has suggested for the Great Basin and as Machette and others (1987, this volume) have suggested for the Wasatch fault. Our dating control is too imprecise to determine whether there has been a significant change in slip rates during the late Cenozoic. If there is a difference in rates, rates on the Morgan fault for the middle to late Quaternary are probably lower than those for earlier periods.

CONCLUSIONS

Quaternary surface displacements have occurred on the Morgan fault, a north-trending, range-bounding fault in the back valleys of the Wasatch Mountains. Colluvial deposits having an age of 200 to 400 ka, estimated from amino acid ratios on gastropods found in correlative deposits, are displaced a minimum of 4 m at the Robeson Springs trench site on the central section of the fault. These data yield a minimum average middle to late Pleistocene slip rate of 0.01 to 0.02 mm/yr. The tilting of late Cenozoic erosion surfaces and estimates of the displacement of a Cenozoic fanglomerate along the northern section of the fault suggest that these rates are at the low end of a range of estimates of the average late Cenozoic slip rate on the Morgan fault.

Radiocarbon dates of 8.3 and 9.1 ka on bog deposits underlying displaced alluvial units show that the most recent surface-displacement event (approximately 1 m) occurred during the Holocene. The colluvial stratigraphy in trench M4 is interpreted as showing that earlier individual surface displacements on the fault at this location have also been small (0.5–1.0 m). Because this trench site is near the end of the central segment of the fault, this estimate of individual surface displacements may be somewhat smaller than the maximum surface displacement, which is commonly used to estimate paleoearthquake magnitudes. Empirical relationships between surface displacement and rupture length, however, suggest results that are consistent with the trench data. Maximum surface displacements of 0.5 to 1.0 m are estimated for rupture of the entire 16-km-long fault from the empirical relationships of Bonilla and others (1984). These data suggest that paleoearthquakes in the magnitude range 6½ to 7 have occurred on the Morgan fault.

REFERENCES CITED

Allison, L.E., and Moodie, C.D., 1965 Carbonate, *in* Black, C.A., Methods of soil analysis, pt. 2, Chemical and microbiological properties: Madison, Wis., American Society of Agronomy, p. 1379–1396.

Anderson, L.W., and Miller, D.G., 1979, Quaternary fault map of Utah: Long Beach, Calif., Fugro, Inc., 39 p., scale 1:1,000,000.

Arabasz, W.J., Smith, R.B., and Richins, W.D., 1980, Earthquake studies along the Wasatch Front, Utah—Network monitoring, seismicity, and seismic hazards: Bulletin of the Seismological Society of America, v. 70, p. 1479–1500.

Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429–459.

Barnes, D.A., Clark, P.U., and Nelson, A.R., 1986, Preliminary aminostratigraphy of Mississippi Valley loess: American Quaternary Association Biennial Meeting, 9th, Champaign-Urbana, Ill., 1986, Programs and Abstracts, p. 117.

Birkeland, P.W., 1984, Soils and geomorphology: New York, Oxford University Press, 372 p.

Bonilla, M.G., Mark, R.K., and Lienkaemper, J.J., 1984, Statistical relations among earthquake magnitude, surface rupture length, and surface fault displacement: Bulletin of the Seismological Society of America, v. 74, p. 2379–2411.

Bromfield, C.S., and Crittenden, M.D., Jr., 1971, Geologic map of the Park City East Quadrangle, Summit and Wasatch Counties, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ–852, scale 1:24,000.

Bryant, B., 1984, Reconnaissance geologic map of the Precambrian Farmington Canyon Complex and surrounding rocks in the Wasatch Mountains between Ogden and Bountiful, Utah: U.S. Geological Survey Miscellaneous Investigations Map I–1447, scale 1:50,000.

Bull, W.B., 1977, The alluvial-fan environment: Progress in Physical Geography, v. 1, p. 222–270.

Carver, R.E., ed., 1971, Procedures in sedimentary petrology: New York, Wiley-Interscience, 653 p.

Colman, S.M., Choquette, A.F., and Hawkins, F.F., 1988, Physical, soil, and paleomagnetic stratigraphy of the upper Cenozoic sediments in Fisher Valley, southeastern Utah: U.S. Geological Survey Bulletin 1686, 33 p.

Coody, G.L., 1957, Geology of the Durst Mountain-Huntsville area: Salt Lake City, University of Utah, unpublished M.Sci. thesis, 63 p.

Dixon, W.J., 1965, Extraneous values, *in* Black, C.A., Methods of soil analysis, pt. 2, Chemical and microbiological properties: Madison, Wisc., American Society of Agronomy, p. 43–49.

Eardley, A.J., 1944, Geology of the north-central Wasatch Mountains, Utah: Geological Society of America Bulletin, v. 55, p. 819–894.

———1955, Tertiary history of north central Utah, *in* Eardley, A.J., ed., Tertiary and Quaternary geology of the eastern Bonneville Basin: Utah Geological Society Guidebook to the Geology of Utah, no. 10, p. 37–44.

Funk, J.W., 1976, Climatic and tectonic effects on alluvial fan systems, Birch Creek Valley, east central Idaho: Lawrence, University of Kansas, unpublished Ph.D. thesis, 246 p.

Gilbert, G.K., 1928, Studies of Basin and Range structure: U.S. Geological Survey Professional Paper 153, 89 p.

Gile, L.H., Peterson, F.F., and Grossman, R.B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, p. 347–360.

Guthrie, R.L., and Witty, J.E., 1982, New designations for soil horizons and layers and the new Soil Survey Manual: Soil Science Society of America Journal, v. 46, p. 443–444.

Hanks, T.C., Bucknam, R.C., Lajoie, K.R., and Wallace, R.E., 1984, Modification of wave-cut and faulting-controlled landforms: Journal of Geophysical Research, v. 89, no. B7, p. 5771–5790.

Harden, D.R., Biggar, N.E., and Gillam, M.L., 1985, Quaternary deposits and soils in and around Spanish Valley, Utah, *in* Weide, D.L., ed., Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 43–64.

Harden, J.W., and Taylor, E.M., 1983, A quantitative comparison of soil development in four climatic regimes: Quaternary Research, v. 20, no. 3, p. 342–359.

Hopkins, D.L., 1982, A structural study of Durst Mountain and the north central Wasatch Mountains, Utah: Salt Lake City, University of Utah, unpublished M.Sci. thesis, 50 p.

Hopkins, D.L., and Bruhn, R.L., 1983, Extensional faulting in the Wasatch Mountains, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 402.

Jackson, M.L., 1956, Soil chemical analysis, advanced course: Madison, University of Wisconsin, Department of Soil Science, unpublished laboratory manual, 656 p.

Lamerson, P.R., 1982, Fossil Basin area and its relation to the Absaroka thrust system, *in* Powers, R.B., ed., Geological studies of the Cordilleran thrustbelt: Denver, Colo., Rocky Mountain Association of Geologists. p. 279–340.

Machette, M.N., 1985a, Calcic soils of the southwestern United States, *in* Weide, D.L., ed., Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 1–23.

———1985b, Late Cenozoic geology of the Beaver Basin, southwestern Utah: Brigham Young University Studies in Geology, v. 32, pt. 1, p. 19–37.

McKee, M.E., and Arabasz, W.J., 1982, Microearthquake studies across the Basin and Range-Colorado Plateau transition in central Utah, *in* Nielson, D.L., ed., Overthrust Belt of Utah: Utah Geological Association Publication 10, p. 137–149.

Miller, G.H., and Hare, P.E., 1980, Amino acid geochronology: Integrity of the carbonate matrix and potential of molluscan fossils, *in* Hare, P.E., Hoering, T.C., and King, K., Jr., eds., Biogeochemistry of amino acids: New York, John Wiley, p. 415–443.

Miller, G.H., McCoy, W.D., and Nelson, A.R., 1982, Environmental controls in the amino acid racemization rate from continental-interior deposits [abs.]: Geological Society of America Abstracts with Programs, v. 14, no. 7, p. 565.

Mullens, T.E., and Laraway, W.H., 1973, Geologic map of the Morgan 7.5-minute quadrangle, Morgan County, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF–318, scale 1:24,000.

Nakata, J.K., Wentworth, C.M., and Machette, M.N., 1982, Quaternary fault map of the Basin and Range and Rio Grande Rift provinces, Western United States: U.S. Geological Survey Open-File Report 82–579, scale 1:2,500,000.

Naeser, C.W., Bryant, B., Crittenden, M.D., and Sorenson, M.L., 1983, Fission-track ages of apatite in the Wasatch Mountains, Utah—An uplift study, *in* Miller, D.M., Todd, V.R., and Howard, K.A., eds., Tectonic and stratigraphic studies in the eastern Great Basin: Geological Society of America Memoir 157, p. 29–36.

Nelson, A.R., and Martin, R.A., 1982, Seismotectonic study for Soldier Creek Dam, Central Utah Project: Denver, Colo., Seismotectonic Report 82–1, Engineering and Research Center, U.S. Bureau of Reclamation, 115 p.

Nelson, A.R., and Van Arsdale, R.B., 1986, Recurrent late Quaternary movement on the Strawberry normal fault, Basin and Range-Colorado Plateau transition zone, Utah: Neotectonics, v. 1, p. 1–30.

Nelson, A.R., Madole, R.F., Evanoff, E., Piety, L.A., and Scott, G.R., 1984, Quaternary paleotemperature estimates using amino-acid ratios measured on terrestrial gastropods from fluvial sequences in Colorado: American Quaternary Association Biennial Meeting, 8th, Boulder, Colo., 1984, Program and Abstracts, p. 92.

Royse, F., Jr., Warner, M.A., and Reese, D.L., 1975, Thrust belt structural geometry and related stratigraphic problems,

Wyoming-Idaho-northern Utah, *in* Bolyard, D.W., ed., Symposium on deep drilling frontiers of the central Rocky Mountains: Denver, Colo., Rocky Mountain Association of Geologists, p. 41–54.

Schick, R.B., 1955, Geology of the Morgan-Heneter area, Morgan and Summit Counties, Utah: Salt Lake City, University of Utah, unpublished M.Sci. thesis, 54 p.

Scott, W.E., Shroba, R.R., and McCoy, W.D., 1982, Guidebook for the 1982 Friends of the Pleistocene, Rocky Mountain Cell, field trip to Little Valley and Jordan Valley, Utah: U.S. Geological Survey Open-File Report 82–845, 58 p.

Scott, W.E., McCoy, W.D., Shroba, R.R., and Rubin, M., 1983, Reinterpretation of the exposed record of the last two cycles of Lake Bonneville, western United States: Quaternary Research, v. 20, p. 241–265.

Schwartz, D.P., and Coppersmith, K.J., 1984, Fault behavior and characteristic earthquakes—Examples from the Wasatch and San Andreas fault zones: Journal of Geophysical Research, v. 89, no. B7, p. 5681–5698.

Shroba, R.R., 1982, Soil B-horizon properties as age indicators for late Quaternary deposits along the Wasatch Front, north-central Utah [abs.]: Geological Society of America Abstracts with Programs, v. 14, no. 4, p. 233.

Smith, R.B., and Bruhn, R.L., 1984, Intraplate extensional tectonics of the eastern Basin-Range—Inferences on structural style from seismic reflection data, regional tectonics, and thermal-mechanical models of brittle-ductile deformation: Journal of Geophysical Research, v. 89, no. B7, p. 5733–5762.

Sullivan, J.T., Nelson, A.R., LaForge, R.C., Wood, C.K., and Hansen, R.A., 1988, Central Utah regional seismotectonic study for USBR dams in the Wasatch Mountains: Denver, Colo., Seismotectonic Report 88–5, U.S. Bureau of Reclamation, 269 p.

Swan, F.H., III, Schwartz, D.P., and Cluff, L.S., 1980, Recurrence of moderate- to large-magnitude earthquakes produced by surface faulting on the Wasatch fault zone, Utah: Bulletin of the Seismological Society of America, v. 70, p. 1431–1462.

Swan, F.H., III, Hanson, K.L., Schwartz, D.P., and Black, J.H., 1983, Study of earthquake recurrence intervals on the Wasatch fault, Utah: San Francisco, Calif., Woodward-Clyde Consultants, 8th semi-annual technical report to the U.S. Geological Survey under contract 14–08–0001–19842, 36 p.

Walkley, A., and Black, I.A., 1934, An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method: Soil Science, v. 34, p. 29–38.

Wallace, R.E., 1984, Patterns and timing of late Quaternary faulting in the Great Basin province and relation to some regional tectonic features: Journal of Geophysical Research, v. 89, no. B7, p. 5763–5769.

Wehmiller, J.F., 1977, Amino acid studies of the Del Mar, California, midden site: Apparent rate constants, ground temperature models, and chronological implications: Earth and Planetary Science Letters, v. 37, p. 184–196.

———1982, A review of amino acid racemization studies in Quaternary mollusks—Stratigraphic and chronologic applications in coastal and interglacial sites, Pacific and Atlantic coasts, United States, United Kingdom, Baffin Island, and tropical islands: Quaternary Science Reviews, v. 1, p. 82–120.

Wehmiller, J.F., and Belknap, D.F., 1982, Amino acid age estimates, Quaternary Atlantic coastal plain—Comparison with U-series dates, biostratigraphy, and paleomagnetic control: Quaternary Research, v. 18, no. 3, p. 311–336.

West, M.W., 1986, Quaternary extensional reactivation of the Darby and Absaroka thrusts, southwestern Wyoming and north-central Utah [abs.]: Geological Society of America Abstracts with Programs, v. 18, no. 5, p. 422.

Williams, J.S., Willard, A.D., and Parker, V., 1962, Recent history of Bear Lake Valley, Utah-Idaho: American Journal of Science, v. 260, p. 24–36.

Williams, K.M., and Smith, G.G., 1977, A critical evaluation of the application of amino acid racemization to geochronology and geothermometry: Origins of Life, v. 8, p. 91–144.

Zoback, M.L., 1983, Structure and Cenozoic tectonism along the Wasatch fault zone, Utah, *in* Miller, D.M., Todd, V.R., and Howard, K.A., eds., Tectonic and stratigraphic studies of the eastern Great Basin: Geological Society of America Memoir 157, p. 3–27.