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PALEOSEISMICITY ALONG THE WASATCH FRONT AND ADJACENT AREAS, CENTRAL UTAH

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Introduction

When Brigham Young first led the Mormons into the Salt Lake Valley in 1847, he must have been impressed by the beauty of the area, the large lake, and the spectacular mountains surrounding their chosen home. Since their arrival, Salt Lake City has flourished. The spectacular Wasatch Mountain front which contributes so much to scenery is the product of extensive Tertiary and Quaternary tectonism along the Wasatch fault zone. Today, about 85 percent of the residents of Utah reside near the front. It has long been recognized that movement along the fault zone has continued into the Holocene (Gilbert, 1890, p. 340); because of this recent history of recurrent movement on the fault zone, a large part of Utah's population is exposed to a serious seismic hazard. Evaluating the level of this hazard is the focus of a continuing, multidisciplinary research effort.

During this two-day trip, we will discuss recent advances and unresolved problems related to neotectonics in the vicinity of the Wasatch Front. We will visit several key sites along the Wasatch fault zone between Salt Lake City and the town of Nephi, where recent geologic studies have clarified the history of late Pleistocene and Holocene activity along

parts of the fault. We will also visit sites in the Basin and Range province near Scipio and Delta, and in the back valleys near Heber City to examine the characteristics of neotectonic activity in those regions. Because of the short historical and limited instrumental record of seismic activity in Utah, earthquake recurrence and tectonic displacement data derived from the types of studies that we will discuss are essential in assessing the seismic hazards in the area.

During the past decade, geologic, geophysical, and seismologic studies have substantially improved our understanding of the neotectonics in the vicinity of the Wasatch front. Reconnaissance mapping, analysis of aerial photographs (Cluff and others, 1973), detailed geologic mapping, and exploratory trenching (Swan and others, 1980, 1981; Hanson and others, 1981; Nelson, 1982; Nelson and Krinsky, 1982; Sullivan, 1982; Crone, this volume; Sullivan and Nelson, this volume) have provided some information on the frequency and amount of surface faulting and average slip rates that can be expected on the basis of geologic evidence (see Schwartz and others, this volume). Studies by Bucknam and Anderson (1979a) have shown that scarp morphology may be a useful indicator of relative age relationships, and under ideal conditions may allow estimates of the age of surface-faulting events. Bucknam and others (1980) demonstrated how geologic data can be applied to help evaluate the earthquake hazards in the region. Recent studies have provided details of the crustal structure and tried to relate the seismicity and surface faulting to crustal geophysics (Smith and Eaton, 1978; Zandt and Owens, 1980; Zoback, in press). Analyses of historical and instrumentally located earthquakes have defined the distribution of modern seismicity, identified possible seismic gaps (Figure 1), permitted seismologic estimates of earthquake recurrence, and generated some information about the geometry and mechanics of faulting in the region (Cook and Smith, 1967; Arabasz and others, 1980; Arabasz and Smith, 1981).

Despite the recent progress achieved in evaluating the earthquake hazards in the vicinity of the Wasatch front, a number of critical questions remain to be answered. The geologic evidence suggests that the Wasatch fault zone is composed of a series of individual segments. Earthquakes large enough to produce surface ruptures appear to have different spatial and temporal distributions along these segments (Schwartz and others, this volume).

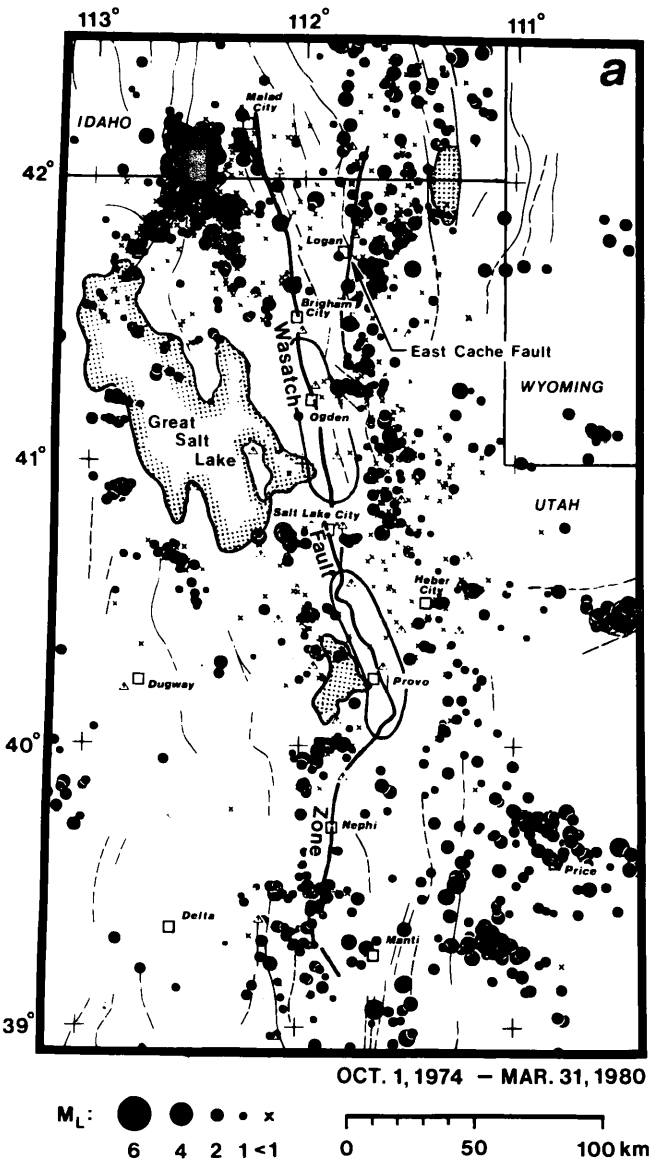


Figure 1. Epicenter map of the Wasatch front area. Major active faults shown as solid and dashed lines. Elliptical areas outline possible seismicity gaps. (From Arabasz and Smith 1980).

The degree of independence or interaction of adjacent segments of the fault zone is of paramount importance. If one segment ruptures, does that act as a catalyst to induce ruptures on adjacent segments? If segments interact and one portion of the fault zone ruptures, does that signal the beginning of a seismically active cycle? How useful and reliable is scarp morphology in evaluating the age and activity of faults? What are the advantages and limitations of regional tectonic analyses based on pedologic or geomorphic data? How does tectonic activity in adjacent ranges or intermontane valleys

influence the accumulation or release of strain along the Wasatch fault zone? The answers to these and many other similar questions can only be obtained from extensive geologic studies.

Future seismologic and geophysical studies should also address a number of other problems. Perhaps most important are the size and significance of the apparent seismic gaps, and whether these gaps are indeed precursory to major earthquakes, or if they are due to short-term fluctuations in the longer record of seismic activity. Additional monitoring of seismic activity may provide some new insight into whether discrete seismic cycles exist, and whether they occur regularly or irregularly. Geophysical studies, especially seismic reflection profiling, may clarify the structural and tectonic interaction between various fault segments, and improve our understanding of the geometry of the seismogenic faults. Clearly, much still needs to be done that requires the combined efforts of geologists, geophysicists, and seismologists.

Several segments of the road log were adapted from or quoted from previously compiled reports. We would like to acknowledge the use of roadlogs by Odiorne (1976), Anderson and others (1978), Baer and Rigby (1980), Scott and others (1982), Hanson and Schwartz (1982), and the geologic maps by Baker (1964a, 1964b, 1972, 1976), Baker and others (1966), Bromfield and others (1970), Bromfield and Crittenden (1971), and Hintze (1980).

FIELD TRIP ROAD LOG: FIRST DAY

Mileage Incremental	Mileage Cumulative	Description
0.0	0.0	Start in Salt Lake City at junction of West Temple and First South Street. Drive east on First South St.
0.1	0.1	Turn right (south) on State St. (U.S. Highway 89).
0.5	0.6	Turn left (east) on 400 South (Utah Highway 186).
1.3	1.9	Road curves to the right. Abrupt hill on the left is the East Bench fault scarp. The road gradually rises up the scarp for the next 1/4 mile. Van Horn (1972) mapped this as a major fault scarp along which movement has occurred in the last 5,000 yrs. Locally, the scarp is 30-40 m high, but it is not known how much of the scarp is the product of post-Lake Bonneville faulting (Scott and others, 1982).
1.1	3.0	University of Utah campus on the left (north). Directly below the "U" on the hills behind the campus is a prominent bench (a shoreline) of the highest stand of Lake Bonneville, an important late Quaternary stratigraphic marker along much of the Wasatch Front and in adjacent parts of the Basin and Range province. Recent studies by Scott and others (1982) indicate that the highest lake level during the late Quaternary was abandoned between 15,000 and 14,000 yrs B.P.
3.0	6.0	The prominent break about two-thirds of the way up the slope on the left is a wave-cut bench of Lake Bonneville.
0.7	6.7	Follow signs onto the Belt Highway (I-215).
0.1	6.8	View to the right (west) across the Salt Lake Valley with the Oquirrh Mountains in the distance.
3.3	10.1	Temporary end of I-215 at exit ramp to Wasatch Blvd. Continue south on Wasatch Blvd.
6.2	16.3	Junction of Big Cottonwood Canyon Rd. (Utah Highway 152) and Wasatch Blvd. (Utah Highway 210). Continue south on Utah Highway 210. The road follows the scarp and climbs onto the fan-delta complex that originated from Big Cottonwood Canyon. On the right, the fan-delta surface has been backtilted toward the east by faulting.

1.1	17.4	The fault scarp is in the grassy area on the left. For the next 1-1/4 miles, the fault scarp is prominently developed but is locally obscured by residential development. Gilbert (1928) photographed the scarps in this area as good examples of the scarps developed along the Wasatch Front in the Salt Lake City area.
1.5	18.9	The fault crosses the road at this point.
0.3	19.2	Pull off to the right on the gravel shoulder at the top of the rise. **STOP 1**. Overlook of Little Cottonwood Canyon (Figures 2 and 3). Looking south from this vantage point, recent surface faults are clearly defined where they cross the southern lateral moraine of Little Cottonwood Canyon that is underlain by "Bells Canyon till" (informal name) of Pinedale age (McCoy, 1977; Madsen and Curry, 1979). Based on stratigraphy and soil development, it is estimated that as much as a few thousand years elapsed between deposition of the till and the rise of Lake Bonneville to its highest level about 16,000 yrs ago (Scott and others, 1982). On the basis of this data, the faulted moraines are estimated to be about 19,000 yrs old. The fault zone, which is approximately 400 m wide, is marked by prominent west-facing scarps and antithetic east-facing scarps that form a graben. Individual scarps within the zone are as much as 35 to 40 m high. The cumulative net tectonic displacement across the zone is about 14.5 m (Swan and others, 1981). This displacement yields a slip rate of about 0.8 mm/yr during the past 19,000 yrs at this point along the fault zone. The view to the north shows the outwash-fan and delta complex that formed at the mouth of Big Cottonwood Canyon during the highest stand of Lake Bonneville. Turn vehicles around and retrace route to the north.
0.7	19.9	Turn left (west) on Wasatch Blvd. at the La Caille restaurant sign. The fault zone in this area is approximately 400 m wide and consists of several west-facing and east-facing (antithetic) fault scarps that displace Holocene alluvial fan and debris flow deposits.
0.2	20.1	The road turns south and traverses the scarp of an antithetic fault that forms the graben visible on the left. Lake Bonneville shoreline deposits have been backtilted 1 to 2° to the east, towards the main fault. The prominent 4- to 4.5-m-high scarp at the east edge of the pasture to the left is the westernmost trace of three *en echelon* splays that join at the southern end of the pasture to form a single 25- to 40-m-high scarp in "Bells Canyon till." Exploratory trenches across the 4- to 4.5-m-high scarp suggest a maximum average recurrence of surface faulting earthquakes of 4,000 to 4,600 yrs (Swan and others, 1981). In contrast, slip rate and displacement values give an average recurrence of 2,500 yrs.
0.5	20.6	At 11:00 is a view of the faulted moraines with a well-developed graben. We are looking along the strike of the fault.
0.5	21.1	Stop sign. Turn right (west) onto Little Cottonwood Road (Utah Highway 209).

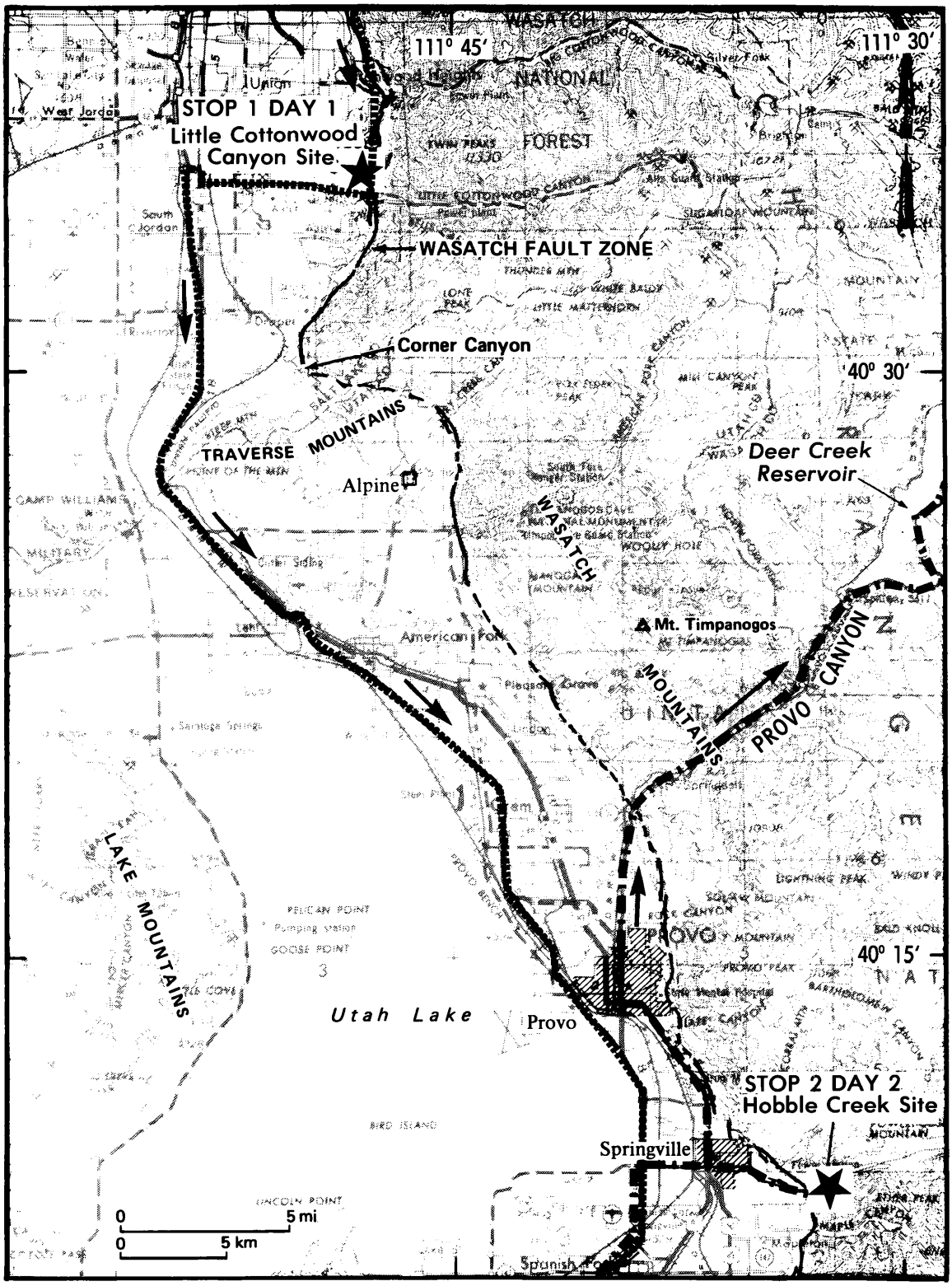


Figure 2. Map of the field trip route in Salt Lake City-Provo area. Dotted line shows the route for day 1. Dashed line is the route for day 2. Arrows show direction of route. Stars indicate locations of field trip stops. Heavy lines are locations of late Pleistocene and Holocene fault scarps; solid where well developed and dashed where less prominent. (Modified from Hanson and Schwartz, 1982.)

Figure 3. Low-sun-angle photograph of the Wasatch fault zone at Little Cottonwood Canyon. Star indicates location of field trip stop. (From Swan and others, 1981).

0.5 21.6 Cross the outwash-fan and delta complex at the mouth of Little Cottonwood Canyon that was deposited during the highest stand of Lake Bonneville.

0.7 22.3 Road descends from the Bonneville-shoreline-level outwash-fan and delta complex to a lower strath terrace graded to the Provo shoreline level. The Provo shoreline was formed by a younger, lower lake level that was probably occupied from the time that the Bonneville shoreline was abandoned between 15,000 and 14,000 yrs B.P., until about 13,500 yrs B.P. (Scott and others, 1982, p. 3).

1.3 23.6 Terraces to left and right are graded to the Provo shoreline level.

0.6 24.2 Descending from the surface of the Provo-level terrace into Salt Lake Valley.

0.6 24.8 Foreset beds of delta complex exposed in the gravel pit to the right (north).

1.4 26.2 Turn right (north) on State Street (U.S. Highway 89).

0.6 26.8 Turn left (west) on 9000 South (Utah Highway 177).

0.5 27.3 Turn left onto I-15, proceed south toward Provo.

1.7 29.0 At 3:00, the tailings piles from Kennecott Copper Company's Bingham Canyon open-pit mine are visible in the Oquirrh Mountains. The mine, the location of the copper industry's first and largest open-pit mine, currently covers about 1,800 acres and is approximately 1/2 mile deep. Since 1904, more than 3.5 billion tons of overburden and ore have been removed, producing 11 million tons of copper and lesser amounts of molybdenum, gold, and silver. The ore body is a porphyritic intrusive of late Eocene-early Oligocene age containing an average of about 0.9 percent copper.

2.9 31.9 Point-of-the-Mountain, which lies ahead to the left, is a spit at the Bonneville shoreline level. The spit was deposited by lake currents at the constriction formed by the Traverse Mountains between Jordan Valley to the north and Utah Valley to the south (Scott and others, 1982). Scarps formed by post-Bonneville movement along the Wasatch fault in the vicinity of Salt Lake City can be traced southward to Corner Canyon at the northeast end of the Traverse Mountains (Figure 2). It is difficult to demonstrate that post-Bonneville faulting occurred in the vicinity of the Traverse Mountains. Determining if a rupture can propagate through the Traverse Mountains or if a propagating rupture can jump to an adjacent *en echelon* segment is an important topic of future earthquake research. The Wasatch fault zone takes a 7-km-long eastward bend at the Traverse Mountains. This bend coincides with the intersection of the north-south-striking Wasatch fault zone with the east- trending edge of the Charleston-Nebo thrust fault and the Deer Creek fault (Zoback, in press). The coincidence of the east bend with older geologic structures suggests that portions of the Wasatch fault zone follow preexisting zones of weakness.

2.9 34.8 Sands and gravels deposited in the spit of Point-of-the- Mountain are exposed in gravel pits on the left. The highway is built on the Provo shoreline level. The change in vegetation along the scarp (brushy slope above and grassy slope below) marks the contact between the lacustrine sands and gravels, and the underlying sheared quartzite bedrock.

2.9 37.7 Passing through Jordan Narrows and into Utah Valley. The Jordan River flows northward through the gorge in the narrows and drains water from Utah Lake into Great Salt Lake.

5.6 43.3 Post-Bonneville age fault scarps are formed along this portion of the Wasatch Front. Late Pleistocene and Holocene fault scarps have not been identified along the east side of the Lake Mountains, which lie directly west of Utah Lake (Figure 2).

8.6 51.9 Geneva Steel Plant at 3:00. Utah Lake, a large fresh-water lake that fills one-fourth to one-fifth of the entire valley floor is behind the plant. In the early 1820's, fur hunters William Ashley and Jedediah Smith entered Utah Valley. Originally the lake was named Ashley Lake because Ashley's Rocky Mountain Fur Company built a fort on the lake, but shortly afterward Jedediah Smith renamed the lake "Utah Lake" (Hunt and others, 1953).

6.0 57.9 Provo exit. Continue on I-15. "Y" Mountain in the background. The city of Provo and the Provo River were named after Etienne Provost, a legendary fur hunter in the area.

5.1 63.0 At 10:00 is Hobble Creek Canyon (Figure 4) where detailed mapping and exploratory trenching have documented late Quaternary movements on the Wasatch fault. We will visit this site (STOP 2) tomorrow.

2.9 65.9 The broad, flat surface in the middle distance is a delta surface graded to the Provo shoreline.

3.7 69.6 At 11:00, the prominent mountain protruding from the Wasatch Front is Dry Mountain (Figure 4). North of Dry Mountain, the late Quaternary fault scarps are close to the base of the range, but southward they gradually die out in Payson Canyon, just to the east of Dry Mountain. On the west side of Dry Mountain, an *en echelon* segment of the fault scarps is formed in alluvial fan deposits, and continues south along the range front to Santaquin Canyon where, again, it gradually dies out. Here, a third, west-stepping *en echelon* segment begins and continues southward along the range front to Nephi. Understanding how these various segments influence a propagating fault rupture is critical to earthquake hazard assessment along the entire Wasatch Front (Schwartz and others, this volume).

2.2 71.8 West Mountain (Figure 4), on the right (west), has well-developed shorelines at the base. No evidence exists of late Quaternary a normal faulting along the base of West Mountain (Bissell, 1963).

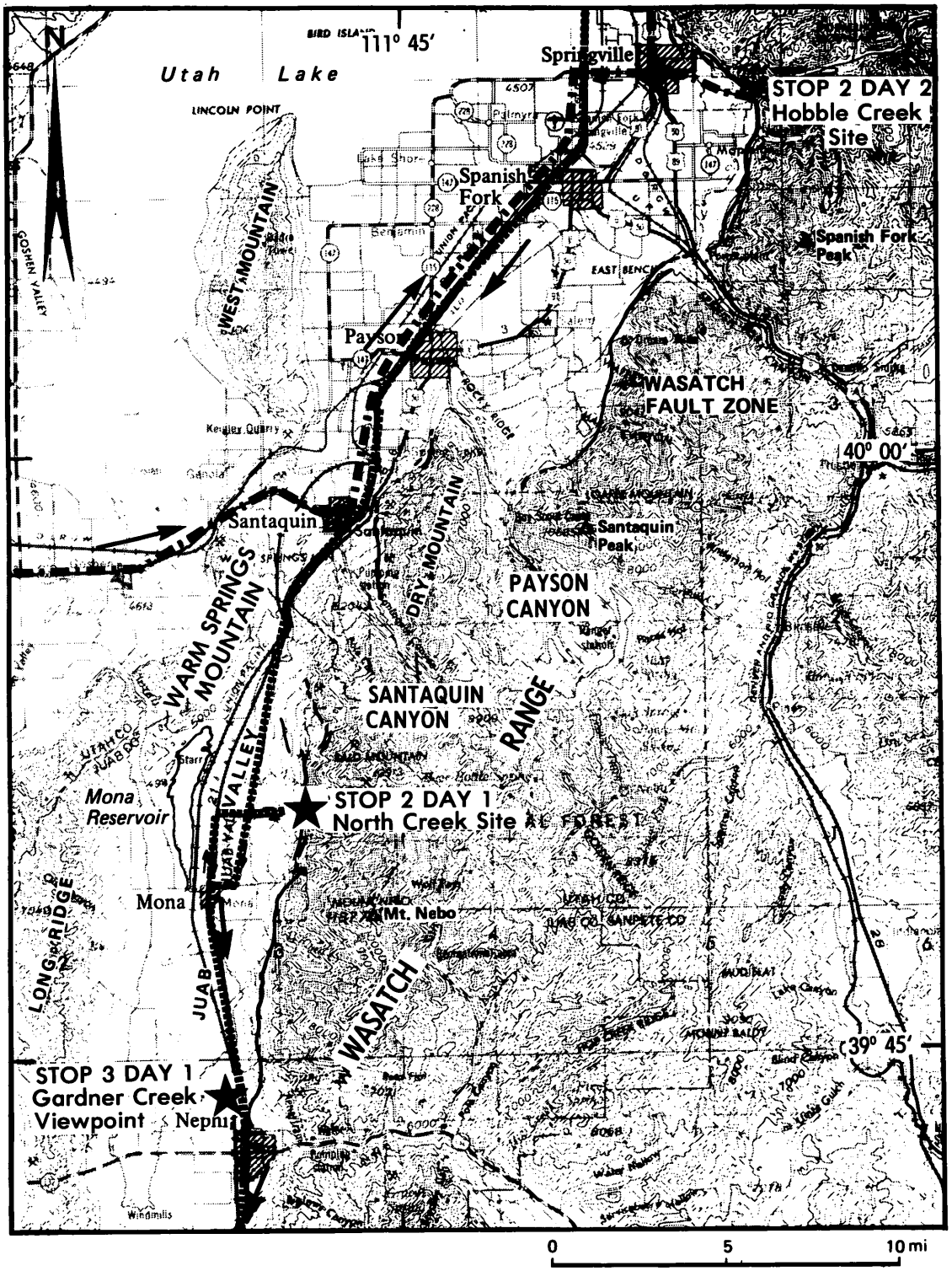


Figure 4. Map of the field trip route in the Springville-Nephi area. Dotted line shows the route for day 1. Dashed line is the route for day 2. Arrows show direction of route. Stars are locations of field trip stops. Heavy lines are locations of late Pleistocene and Holocene fault scarps; solid where well developed and dashed where less prominent (Modified from Hanson and Schwartz, 1982.)

4.4	76.2	The most prominent scarp along the range front to the left (east) is the Bonneville shoreline. The fault scarp is not easily seen from the road, but parts of it displace the Bonneville shoreline indicating post-Bonneville movement.
3.0	79.2	Exit to U.S. Highway 6 on the right. A fresh scarp with very little vegetation is at the base of the range front on the left. The scarp continues for about 5 km to the south along the west side of Dry Mountain. It displaces Holocene alluvial fan deposits that lie above the Bonneville shoreline; at the north end, the most recent scarp has a displacement of 3.0 to 3.8 m. This scarp is one of the west-stepping *en echelon* scarps that may be part of a transition zone between major segments of the Wasatch fault zone. From this point south, the fault scarp appears youthful, and may have ruptured in the past 300 years. In contrast, north of this area, at Hobble Creek, the most recent surface rupture may be older than 1,000 yrs.
1.5	80.7	Santaquin Canyon on the left. The modern drainage has incised into Upper Cretaceous and lower Tertiary sedimentary rocks.
2.0	82.7	Utah County-Juab County line. We are on a broad drainage divide between Utah Valley to the north and Juab Valley to the south. Juab Valley was barely submerged by Lake Bonneville and shows little morphologic evidence of being flooded by the lake for a long time. The floor of the valley, at an elevation of 4,880 ft, was, at most, under 220 ft of water during the Lake Bonneville high stand. The valley was not flooded during the lower Provo stand, so the lake occupied the valley for only about 4,000 yrs. The fan surface ahead (south) is probably late Pleistocene in age.
1.1	83.8	On the left, debris flow in red and yellow rocks of the Upper Cretaceous and Paleocene North Horn Formation.
3.2	87.0	Mt. Nebo (11,877 ft) at 11:00, is composed of Pennsylvanian limestones of the Oquirrh Formation. At the base of the range, at 10:00, is North Creek, our next stop (Figure 5). A fresh-looking Holocene fault scarp can be traced continuously along this portion of the range front. This is the longest (24 km) continuous Holocene scarp along the southern portion of the Wasatch fault zone. The most recent part of the scarp to rupture is highlighted by a zone of sparse vegetation that appears as a light-colored band from a distance. On the right (west) is Mona Reservoir, and west of the reservoir is Long Ridge composed primarily of Oligocene volcanic rocks. Recent mapping by E. M. Baltzer (U.S. Bureau of Reclamation, Denver) has revealed several dissected, discontinuous, subparallel scarps west and southwest of Mona along the base of Long Ridge. The east-facing scarps trend north across the alluvial fans with maximum scarp heights of 0.8 to 1.0 m. Other small, down-to-the-east normal faults in the bedrock in this area do not have any surface expression.
4.1	91.1	Turn right onto exit ramp for Utah Highway 54 (Mona). Turn right at stop sign and proceed west to Mona.

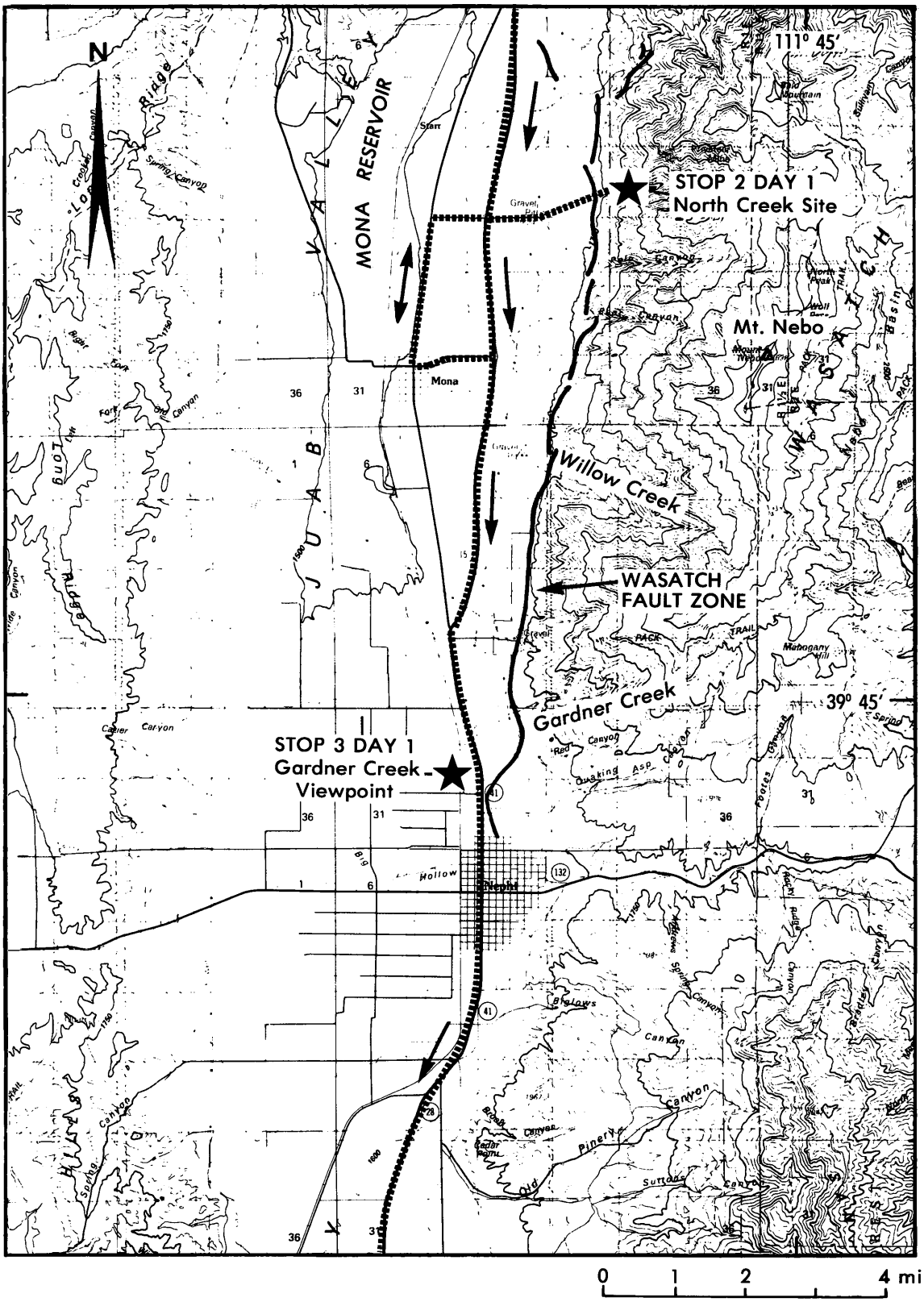


Figure 5. Detailed map of the Wasatch fault zone near the North Creek site. Dotted line shows the route for day 1. Stars indicate locations of field trip stops. Heavy lines are locations of late Pleistocene and Holocene fault scarps. (modified from Hanson and Schwartz, 1982.)

1.5	92.6	Stop sign. Turn right (north) on Main St.
2.2	94.8	Turn right (east) onto gravel road.
0.8	95.6	Passing beneath I-15 bridge.
0.7	96.3	Crossing irrigation ditch. SLOW - high water is possible. Bear left after crossing the ditch.
1.0	97.3	Bear left at fork in road and proceed approximately 40 m ahead and park. **STOP 2.** North Creek trench site (Figures 6, 7, and 8). At the North Creek site, Hanson and others (1981) have shown that three surface-faulting events, with a cumulative vertical tectonic displacement of 7.0 ± 0.5 m, have occurred during the past 4,580 ^{14}C yrs B.P. Displacements of 2.0 to 2.2 m during the most recent event (event A) and 2.0 to 2.5 m during the middle event (event B) are based on the thickness of colluvial wedges, and the height of buried fault-scarp free faces. The height of a tectonic terrace on the upthrown side of the fault scarp suggests a 2.6 m displacement during the oldest event (event C). Radiocarbon dates indicate that events B and C occurred between 4,580 and 3,640 ± 75 ^{14}C yrs B.P., and possibly as recently as 300 to 500 yrs ago. The observations at North Creek show that recurrent surface faulting events have similar displacements, but significant variations occur in the time intervals between events. Turn around and retrace route to Mona.
4.7	102.0	Turn left on 200 North at south end of Mona and follow signs back to I-15.
1.2	103.2	Turn right (south) onto I-15 southbound toward Nephi and Cedar City.
0.5	103.7	Large landslide at 10:00 is formed in the Mississippian and Pennsylvanian Manning Canyon Shale. Directly south of the landslide is Willow Creek (Figure 5) where a 5-m-high fault scarp is formed in Holocene alluvium.
3.7	107.4	At 9:00 is the Juab County gravel pit in which the fault is exposed in brecciated limestone of the Oquirrh Formation. The rake of the striations on the fault plane show nearly pure dip-slip movement at this location.
2.2	109.6	Pull off onto the gravel shoulder to the right. **STOP 3 (OPTIONAL).** Gardner Creek viewpoint (Figure 5). At this stop we can see evidence of multiple surface-faulting events along this segment of the fault. The fault scarp is at the base of the range front and, where it cuts across the older alluvium at the mouth of Gardner Creek, it is approximately 28.5 m high. The less densely vegetated lower quarter of the scarp is the product of the youngest movement and forms a 3.0- to 3.8-m-high scarp on the Holocene alluvial fan. South of Gardner Creek Canyon, the fault scarp curves to the west, away from the range front, and gradually dies out just north of Nephi.
0.2	109.8	Entering the town of Nephi.
0.4	110.2	On the left, the last expression of the fault scarp is the slight break in slope in the field and in the cross-road.

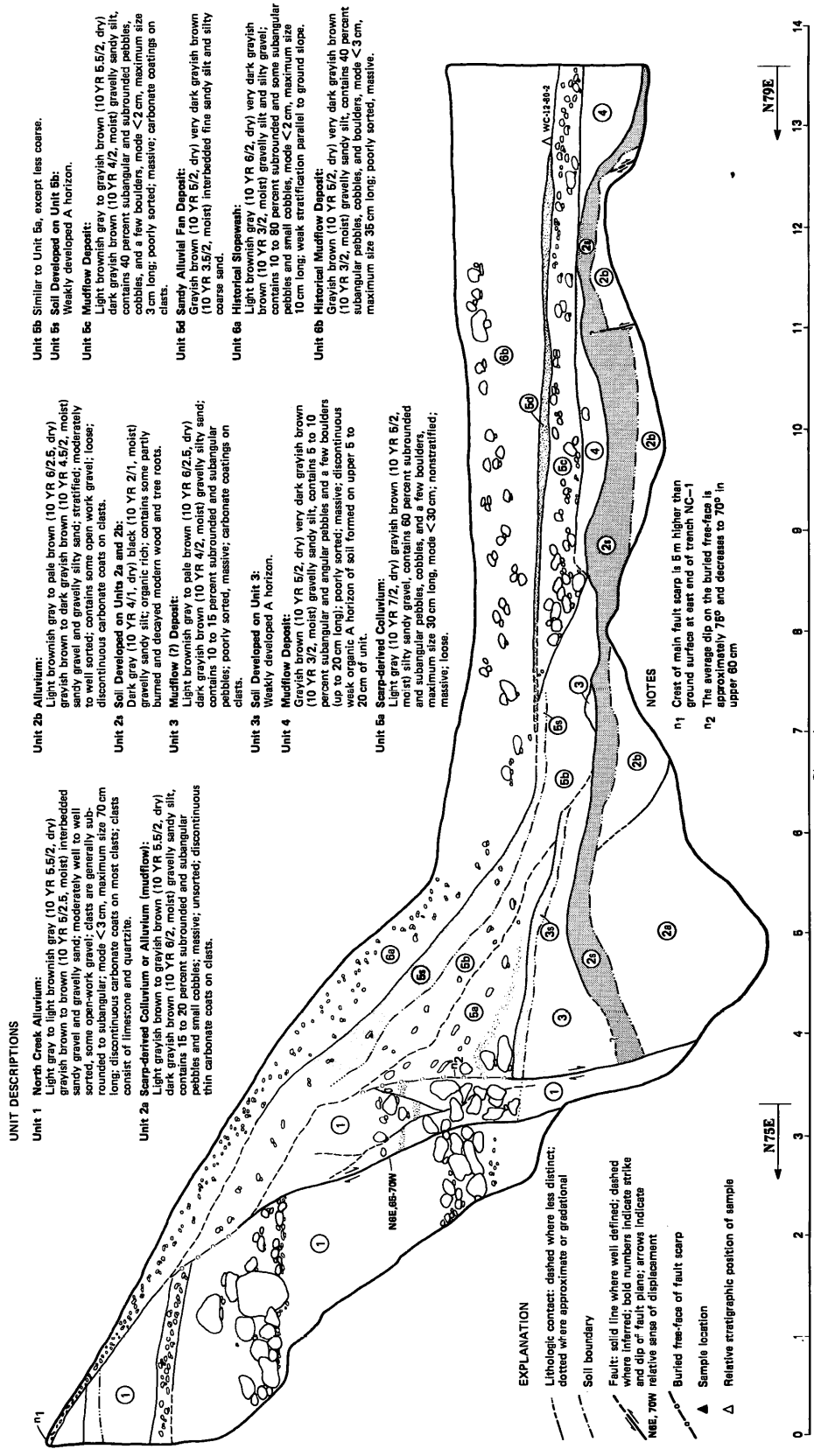


Figure 6. Map of trench NC-1 at North Creek site. (From Hanson and others, 1981.)

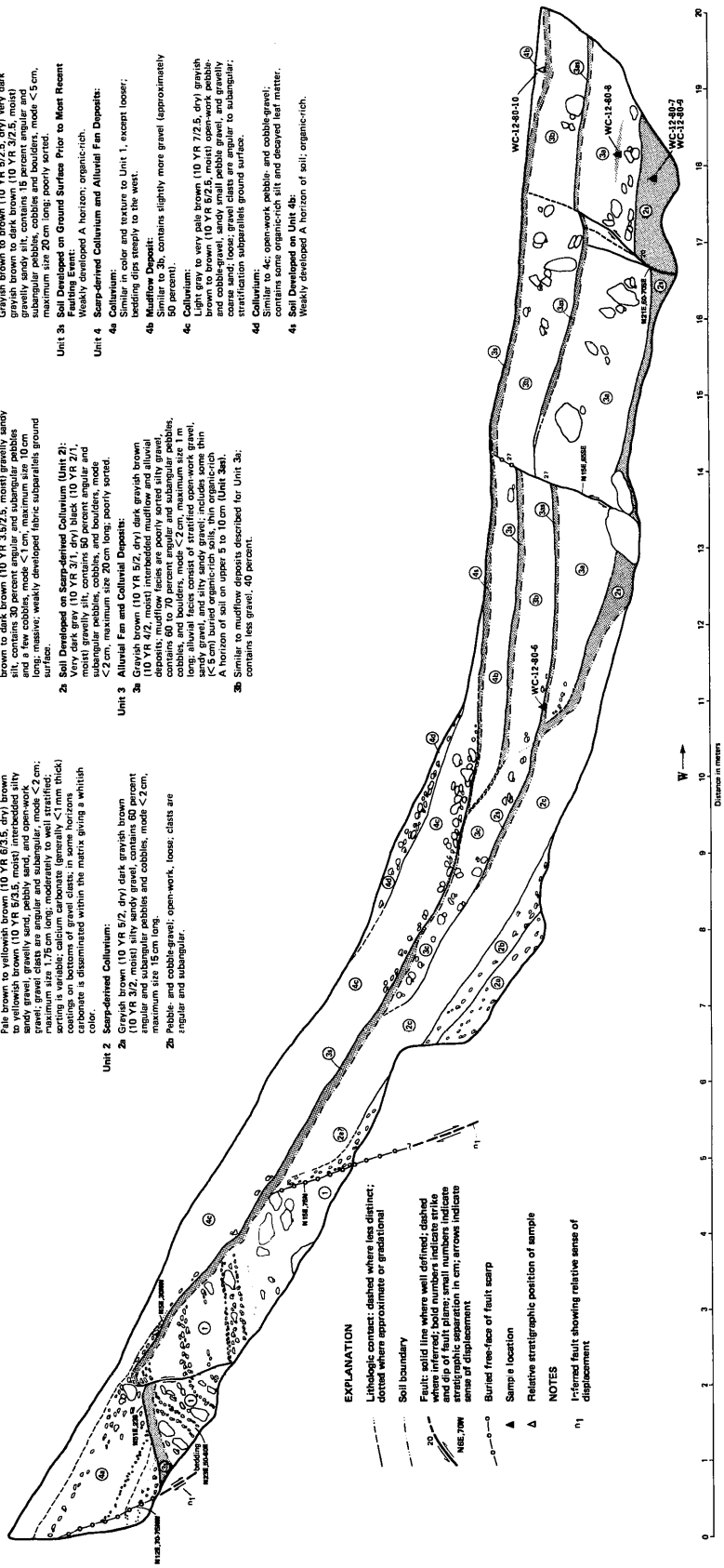


Figure 7. Map of trench NC-3 at North Creek site. (From Hanson and others, 1981.)

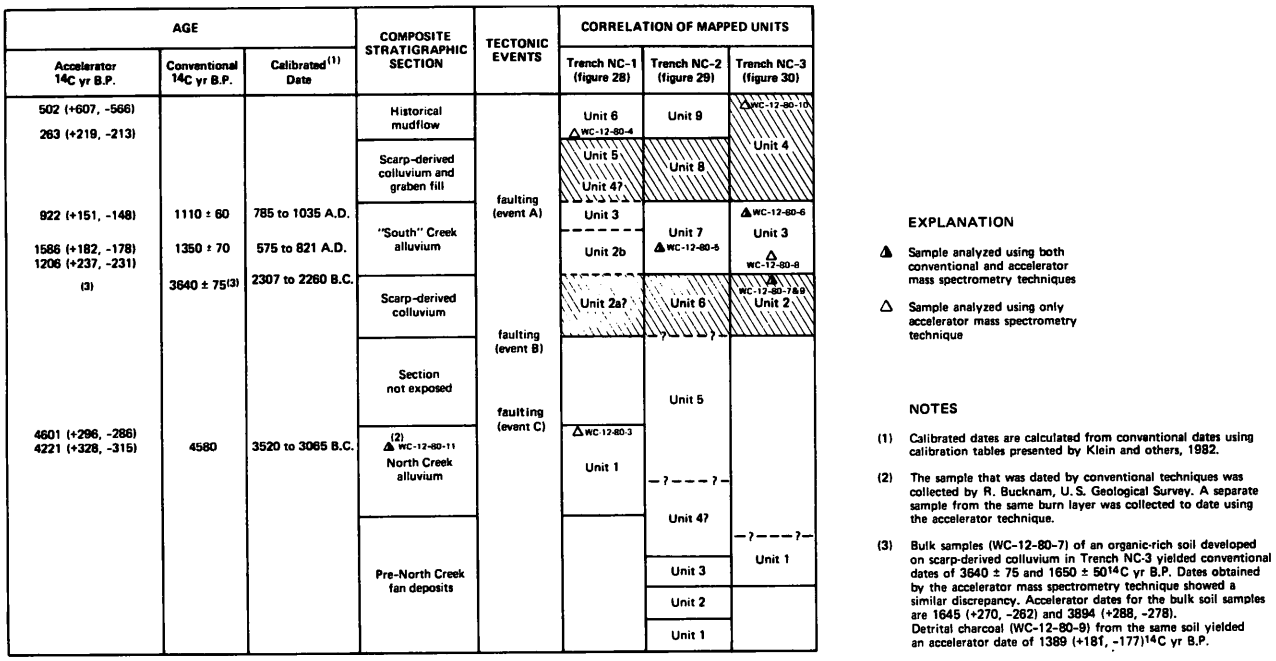


Figure 8. Summary of stratigraphy, surface faulting and radiocarbon dates from the North Creek site (modified from Hanson and others, 1981.)

1.0 111.2 Junction of Utah Highway 132. Continue straight on temporary I-15 and U.S. Highway 91.

1.1 112.3 The West Hills (Figure 9) lie to the right (west). The San Pitch Mountains, an uplifted block of the High Plateaus, are at 10:00. The San Pitch Mountains consist of subhorizontal, Paleocene and Eocene sedimentary rocks unconformably overlying Cretaceous and Jurassic rocks. The topographic expression of the Wasatch Front in this area is considerably different than the steep, rugged range front that we saw to the north near Mona. The crest of the range lies well east of the range front and a series of low hills occurs at the base of the range. Also, note that along this portion of the range, from just north of Nephi to just north of Levan, a distance of about 16 km, no Holocene scarps occur although subdued pre-Holocene scarps are locally preserved near Gardners Fork and Fourmile Creek (Figure 9). In addition, no fault scarps have been recognized in the alluvium at the base of the West Hills. From Levan to Fayette, Holocene fault scarps are discontinuous and range in length from 1.5 to 8 km.

7.6 119.9 The canyon of Pigeon Creek is at 11:00 (Figure 9). Detrital charcoal from alluvium displaced by a 3.5-m-high scarp at the mouth of the canyon has yielded preliminary radiocarbon age-dates of 1750 ± 350 and 2100 ± 300 ^{14}C yrs B.P. These dates suggest that the most recent event along this 3-km-long scarp is similar in age to the most recent event at the North Creek site.

2.0 121.9 Entering town of Levan. Continue on temporary I-15.

2.0 123.9 Driving west across Juab Valley. West Hills at 12:00 con-

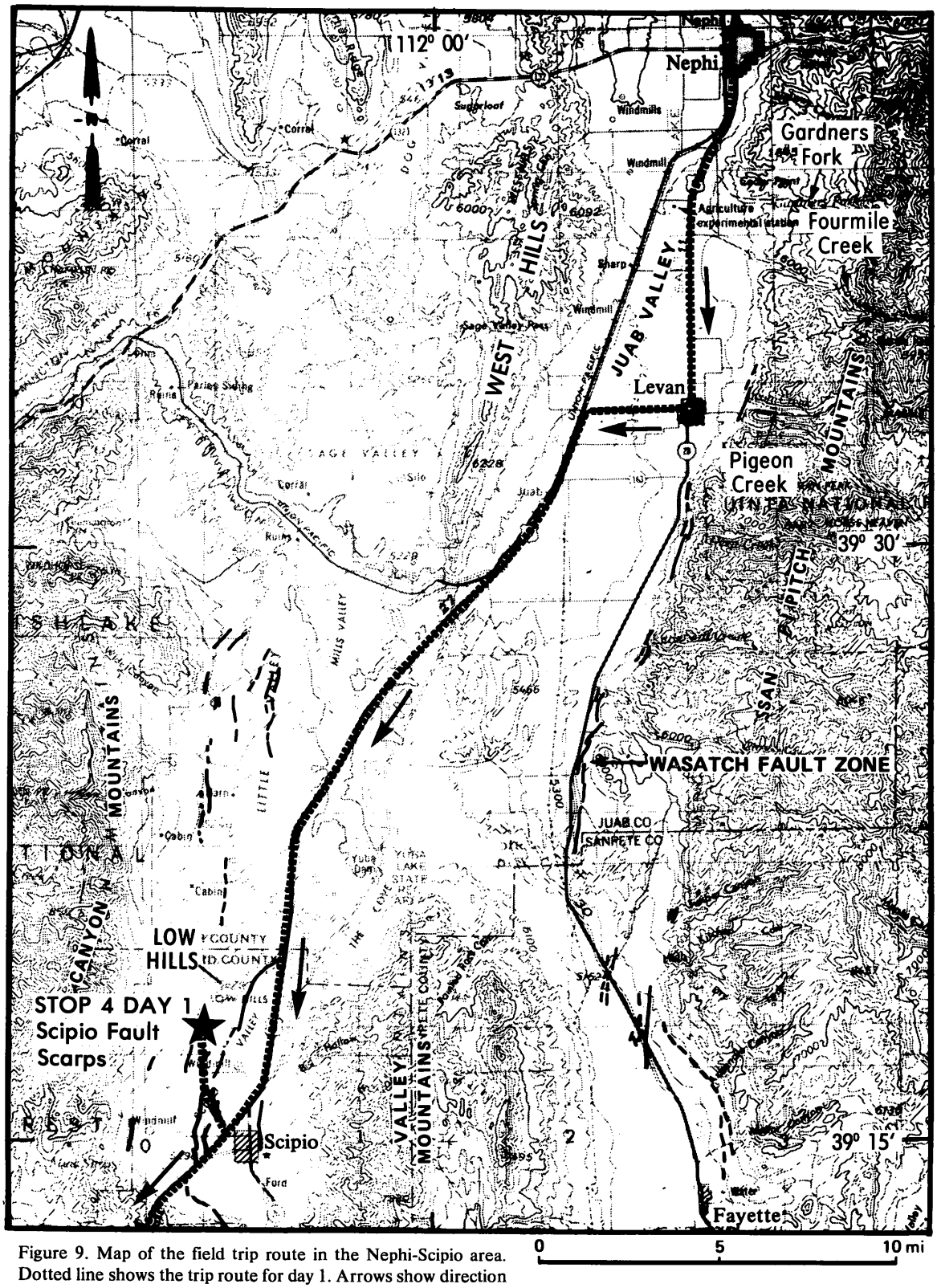


Figure 9. Map of the field trip route in the Nephi-Scipio area. Dotted line shows the trip route for day 1. Arrows show direction of route. Star indicates the location of the field trip stop. Heavy lines are the location of late Pleistocene and Holocene fault scarps (modified from Hanson and Schwartz, 1982.)

sist of Cretaceous-Paleocene North Horn Formation, Paleocene Flagstaff Limestone and Eocene Green River Formation.

1.8 125.7 Road turns to the south. Along the base of the San Pitch Mountains to the east, a fresh-looking fault scarp occurs, but note that despite evidence of some recent faulting, the range front is subdued when compared to the range front north of Nephi.

4.4 130.1 Chicken Creek Reservoir on the left.

2.7 132.8 Summit of hill, begin divided highway. Entering the Sevier River Valley. Roadcuts expose yellow and gray rocks of middle Eocene Green River Formation. The Canyon Mountains, at 1:00, are composed of Precambrian metasedimentary rocks thrust over Paleozoic and Mesozoic sedimentary rocks. Red sedimentary rocks at the base of the range are the North Horn Formation.

2.8 135.6 Exit to Yuba State Park. In the distance on the right are exposures of clastic sediments that may have been deposited in Lake Bonneville.

0.8 136.4 Red and gray cliffs on the left are probably North Horn Formation.

0.5 136.9 A large meander loop of the Sevier River lies to the right. Embankments to the left expose gray, unconsolidated gravel that contains abundant moderately rounded to well-rounded pebbles in a poorly sorted sand matrix. These gravels and those a few kilometers away to the right (west) are below the level of the high stand of Lake Bonneville, but their relationship to the lake is not known.

0.7 137.6 Crossing the Sevier River. Divided highway ends just ahead.

3.2 140.8 Outcrops on the left (east) for the next several miles are the North Horn Formation.

3.2 144.0 Crest of rise. Entering Millard County and Scipio Valley (Figure 9). Canyon Mountains to the right (west) and Valley Mountains to the left (east). The Valley Mountains are an uplifted block of the High Plateaus composed of Upper Cretaceous and lower Tertiary sedimentary rocks. Japanese Valley, at the crest of the Valley Mountains, is a graben; several fault scarps as much as 4 m high occur in the alluvial fill in the graben. Witkind (1982) speculates that the Valley Mountains may be diapiric in origin and that Japanese Valley may be a collapse feature formed when salt from the Jurassic Twelve Mile Canyon member of the Arapien Shale was removed.

2.5 146.5 To the left is a subtle, elongate depression in the unconsolidated valley alluvium that has been described by Bjorkland and Robinson (1968) as the result of subsidence of solution cavities that formed along faults in the carbonate bedrock beneath the alluvium. From 3:00 to 4:00, at the base of the southeast flank of the Low Hills, the trace of a fault scarp can be seen above the zone of dense sage cover. A several-meter-high, light-colored band

represents the most recent Holocene(?) movement that offsets alluvium derived from the Low Hills.

1.4 147.9 In the distance on the right (west), across the flat bottom of Scipio Valley, is a prominent scarp that truncates the broad alluvial fan extending eastward from the Canyon Mountains. This scarp is our next stop. The Pavant Range is at 11:00 and the Valley Mountains are at 9:00 (east).

0.7 148.6 Turn-off to Utah Highway 26 and the town of Scipio is on the left. Continue on temporary I-15 (U.S. Highway 91) and prepare to turn right.

1.0 149.6 Turn right (west) onto gravel road that has a signpost for John Williams Canyon at the entrance.

0.2 149.8 Turn right (north) and follow main gravel road for 1.8 miles through series of left (west) and right (north) turns. On north-trending segments of the road, fault scarps are visible to the left.

1.6 151.4 Road turns left (west) toward a conspicuous fault scarp visible at 10:00 to 11:00.

0.7 152.1 On the left, a road goes to a gravel pit excavated into the fault scarp. In the fall of 1982, a high-resolution seismic-reflection profile was run along this road to study the near-surface geometry of the fault. We will comment on the preliminary results of this study at the next stop. The scarp is conspicuous for the next kilometer or so and its height increases.

1.4 153.5 Go through gate and pull off road to the right. **STOP 4.** Scipio fault scarps (Figure 10). The prominent scarp at this stop is a composite of multiple surface ruptures. The youngest event produced scarps up to 6 m high, and is particularly conspicuous at the mouths of washes which dissect the older scarp. The older scarp ranged up to 17 m high. In one area, the surface displacements of the entire scarp exceed 21 m. The scarp height at this point has been increased by backtilting. The youngest event at this location has a surface displacement of 1.7 m and a maximum slope angle of more than 32°. These scarps face eastward in contrast to the west-facing scarps along the Wasatch fault zone. The scarps here appear to be very youthful in comparison with other fault scarps in alluvium in western Utah. The scarp has steep slopes, an angular, rather than rounded crest, and is developed in all Quaternary deposits except those in modern washes. Several sizeable washes have a knickpoint only a few meters upstream from the scarp indicating little readjustment of the disturbed streambed. Measurements of profiles along the scarp show a relationship between scarp height and slope angle (Bucknam and Anderson, 1979a) that indicates that the scarp is Holocene in age, probably on the order of several thousand years old. Return to temporary I-15 after closing gate.

3.8 157.3 Stop sign. Turn right (south) on temporary I-15 towards Holden.

0.5 157.8 The fault scarp at 3:00 shows

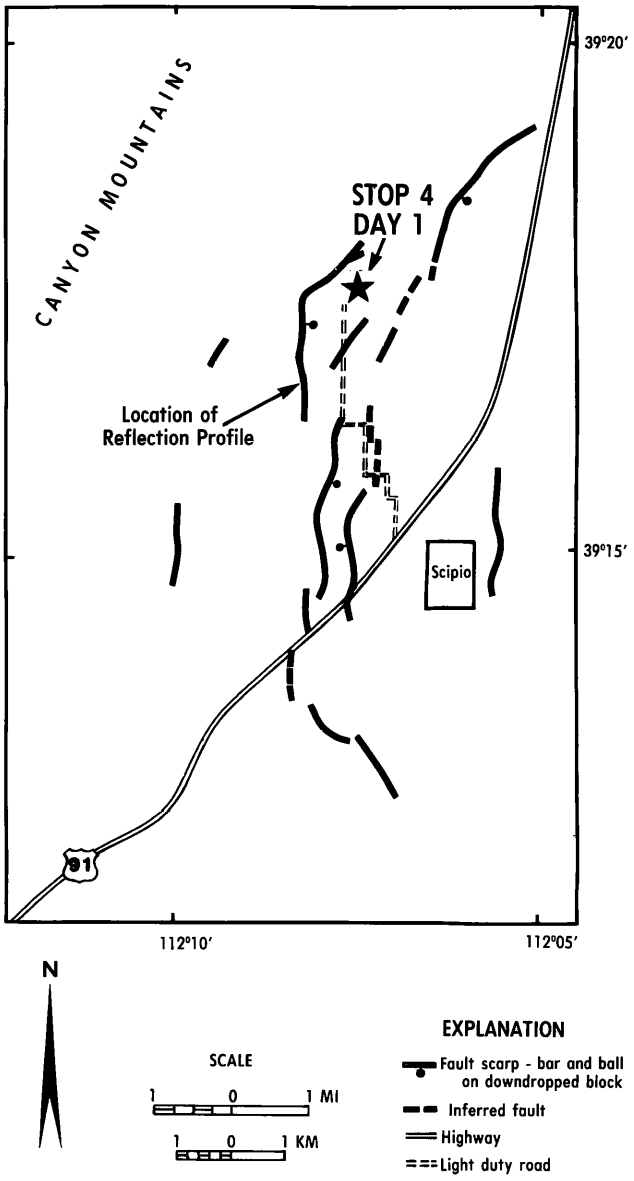


Figure 10. Map of major fault scarps in the Scipio area (from R. C. Bucknam, unpublished data.)

no evidence of a young rupture. At 11:00 is the north end of the Pavant Range, an upthrown block of the High Plateaus that consists of lower Paleozoic rocks thrust over Paleozoic and Mesozoic rocks. Unconformably overlying the thrust are gently east-dipping Upper Cretaceous and Tertiary sedimentary rocks. At the south end of the range, the entire sequence is buried by Tertiary volcanic rocks.

4.2	162.0	Summit of Scipio Pass. At the summit of the pass, limestones, dolomites, and interbedded shales of the Ordovician Pogonip Group are exposed in the road cuts (Sprinkel and Baer, 1982).
3.0	165.0	Low hills to the right and exposures along the road are composed of Tertiary Salt Lake Formation.
2.1	167.1	Turn right at Exit 178 and follow signs to U.S. Highway 50. We are entering the Sevier River basin.
1.6	168.7	Pavant Butte (Figure 11), at 2:00, is a basalt cone with a potassium-argon date of 30,000-70,000 yrs (Hoover, 1974). Basalt flows near the butte and south of it are dated at 30,000-22,000 yrs. Pavant Butte is near the north end of an extensive province of late Cenozoic, bimodal basalt-rhyolite volcanism.
2.0	170.7	Turn right onto U.S. Highway 50 to Delta. The town of Holden, straight ahead, is built at the level of the Bonneville shoreline.
5.9	176.6	At 10:00 is an area of active sand dunes. The elongate trend of the dunes indicates that they were deposited by southwesterly winds.
6.2	182.8	Road on the right goes to McCornick, Utah. Canyon Mountains on the right (east).
0.3	183.1	Bear left at fork in the road and continue on U.S. Highway 50 to Delta.
14.8	197.9	Entering Delta, Utah. End of first day of the trip. Delta is named for a large delta that the

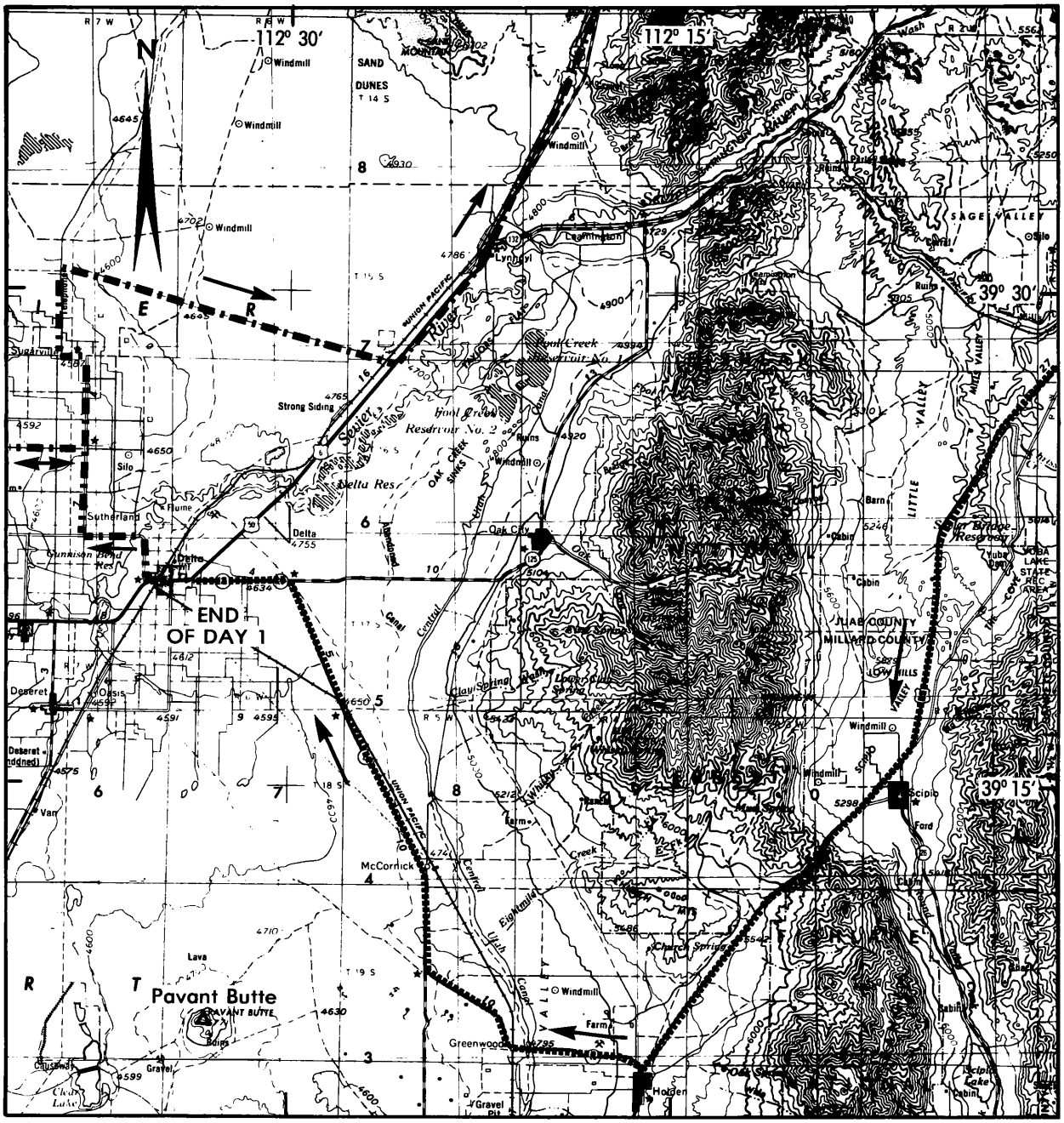


Figure 11. Map of the field trip route in the Delta area. Dotted line shows the route for day 1. Dashed line is the route for day 2. Arrows show direction of route.

ancestral Sevier River built into Lake Bonneville (Bucknam and Anderson, 1979b).

FIELD TRIP ROAD LOG: SECOND DAY

Start road log at the west end of Delta at the railroad overpass.

Mileage		Description
Incremental	Cumulative	
0.0	0.0	Drive west out of Delta on U.S. Highway 50 over the railroad overpass (Figure 12).
0.5	0.5	Continue straight at the "Y" in

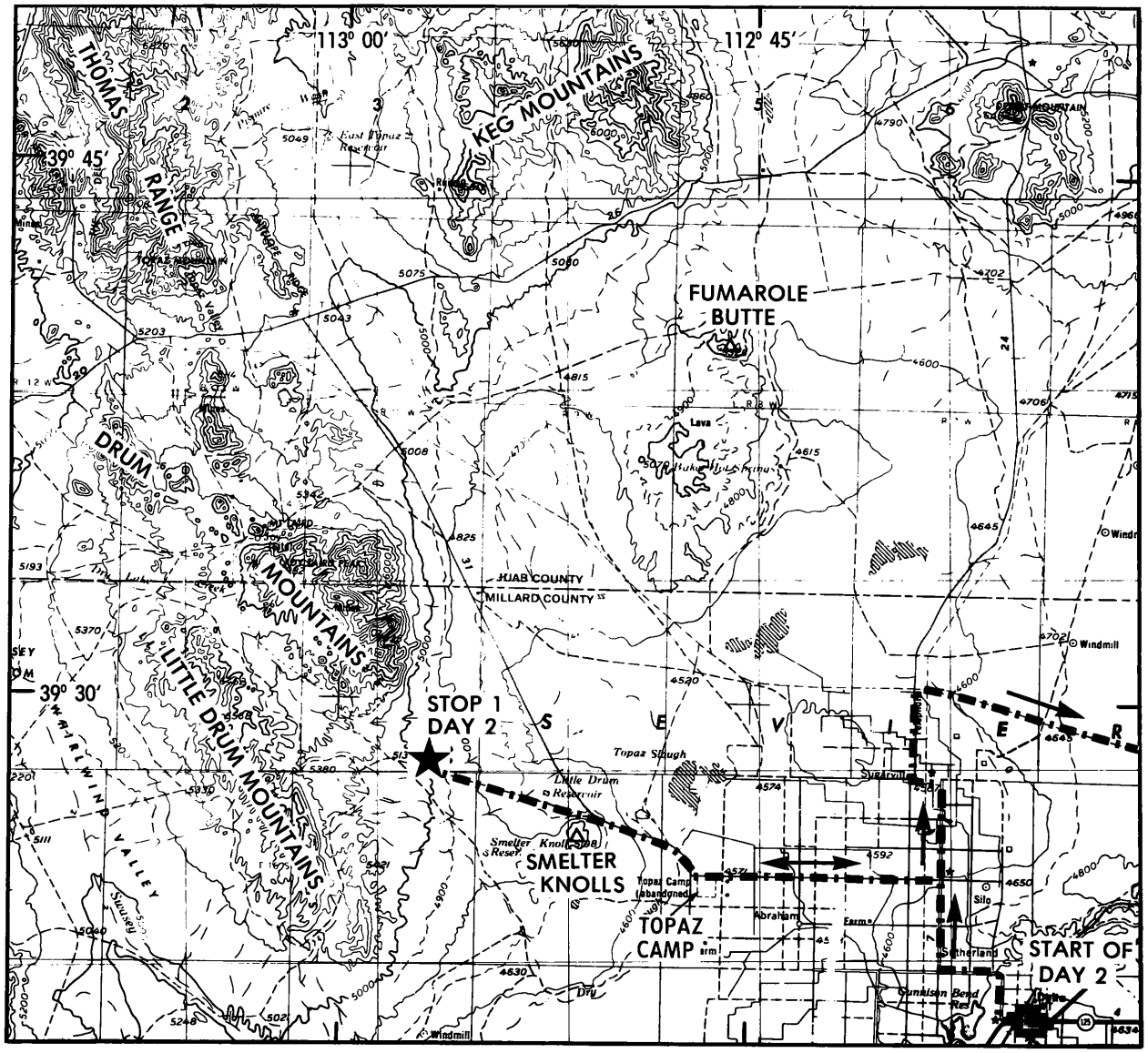


Figure 12. Map of the field trip route in the Drum Mountains area. Dashed line is route for day 2. Arrows show direction of route. Fault scarps are shown on Figure 13.

		the road toward the town of Sutherland.
0.1	0.6	Road curves to the right (north). Drum Mountains at 10:00. Canyon Mountains at 3:00.
1.5	2.1	Road curves to the left (west).
0.3	2.4	Crossing the Sevier River.
1.8	4.2	Turn right (north) on paved road toward Sutherland.
0.9	5.1	Entering the town of Sutherland. Continue straight.
2.0	7.1	Prepare to turn left (west).
0.2	7.3	Turn left (west) on gravel road toward Topaz site.
1.1	8.4	Crossing intersection. Continue straight. The House Range is at 11:00, the Swazey Mountains are at 12:00, the Drum Mountains at 1:00, the

Keg Mountains at 2:00, the Simpson Mountains at 3:00, and the Sheeprock Mountains and West Tintic Range at 4:00. The House Range and Swasey Mountains are composed almost entirely of interbedded Cambrian limestones and shales containing a diverse trilobite fauna. A number of trilobite species first identified in these rocks have been named after local landmarks or residents. The Keg Mountains consist primarily of Oligocene and Miocene volcanic rocks. Both the Simpson Mountains and Sheeprock Mountains consist of Precambrian sedimentary rocks of the Sheeprock Group (Hintze, 1980), Cambrian Prospect Mountain Quartzite, and Ordovician limestones and shales. The West Tintic Mountains are mainly Tertiary volcanic rocks with scattered exposures of Mississippian, Cambrian, and Precambrian sedimentary rocks.

6.9	15.3	On the left is a monument marking the Topaz site, a major internment camp for thousands of Japanese-Americans during World War II.
0.3	15.6	Cross cattle guard and follow main road curving to the right (north).
0.4	16.0	Gentle curve to the left. Drum Mountains are at 12:00 and Smelter Knolls are at 10:00. The southern part of the Drum Mountains consist of faulted Precambrian metamorphic rocks which are overlain by Cambrian Prospect Mountain Quartzite and Cambrian limestones and shales. The north end of the Drum Mountains and the adjacent Thomas Range directly to the north are composed of upper Eocene to upper Miocene rhyodacites, rhyolites, and crystalline, vitric, and ash-flow tuffs ranging in age from 42 to 6 m.y. They were erupted from the nearby Thomas caldera and Dugway Valley cauldron (Lindsey, 1982).
1.0	17.0	Fork in the road, bear left.
0.8	17.8	Fork in the road, bear left.
1.3	19.1	Small ridge of Quaternary basalt at 3:00. Smelter Knolls, on the left, are composed of 6.1-m.y.-old tholeiitic basalt, 3.4-m.y.-old rhyolite, and 0.3-m.y.-old basaltic andesite (Peterson and others, 1978).
0.5	19.6	Fork in the road, bear left toward Swazey Spring.
0.5	20.1	Pale yellow lacustrine muds on the left were deposited on the flanks of Smelter Knolls. The prominent notch halfway up Smelter Knolls is the wave-cut bench of the Provo Lake level.
0.8	20.9	Approaching a small ridge where road swings to the right and then left. Use caution and keep to the right side of the road. This ridge may be, in part, a lacustrine bar that was deposited in the restriction between the basaltic ridge, immediately north of the road, and Smelter Knolls, south of the road. White and yellow lake muds are exposed on the west side of the basaltic ridge. The Little Drum Mountains at 11:00 are an Oligocene volcanic center.
0.4	21.3	The slight drop in the road, down to the west, is a 1-m-high

fault scarp. Small filled fractures and deformation in the lake sediments can be observed in the little drainage gully next to the road where the trace of the fault crosses the road. The prominent scarp at 9:00, approximately 1 km away, is formed by a lacustrine bar.

0.5 21.8 The northward continuation of the fault scarp that we crossed at mile 21.3 can be seen as a low ridge at about 4:00, approximately 1 km away.

2.1 23.9 Crossing cattle guard.

0.6 24.5 Crossing a small, down-to-the-west fault scarp and a small graben.

0.1 24.6 Ascending a prominent east-facing fault scarp that forms the west side of the graben.

0.4 25.0 Crossing arroyo channel.

0.3 25.3 Pull off to the edge of the road and park. **STOP 1.** Drum Mountains fautl scarp and trenching site (Figure 13). The most complete set of fault-scarp profile data in the eastern Basin and Range province has been collected from the scarps along the east flank of the Drum Mountains. The scarps form a north-trending zone approximately 30 km long and 5 km wide and range in height from 0.7 to 7.3 m. Because several of the scarps cut a large, Provo-level lacustrine bar, the faulting is younger than the age of the shoreline, or approximately 13,500 yrs B.P. (Scott and others, 1982). A comparison of the morphometric data from these fault scarps with data from nearby well-developed shoreline scarps of the highest stand of Lake Bonneville indicates that the fault scarps are of similar age to the shorelines, rather than being significantly younger (Bucknam and Anderson, 1979a). In comparison, diffusion-equation modeling of the Drum Mountains fault scarps indicates an age on the order of 5,000 years or less (S. M. Colman, 1982, written communication; T. C. Hanks, 1982, written communication). A trench dug at this site provides some insight into the characteristics and age of the faulting (Crone, this volume). Preliminary studies of the post faulting colluvial deposits in nearby exposures suggest an early Holocene age for the faulting.

Return on route toward Delta.

1.1 26.4 The series of ridges between 11:00 and 12:00 are basaltic volcanic rocks that trend generally north. Along strike, north of the ridges, are outcrops of Paleozoic carbonates protruding through the Quaternary valley-fill alluvium. These ridges and outcrops may be associated with a 12-km-long fault system that extends from Smelter Knolls northward to Fumarole Butte (Figure 12). To the north, at 10:00, is Fumarole Butte, a Quaternary volcanic center, that is composed of rhyolite, basalt, and basaltic andesites ranging in age from 6.2 m.y. to 0.31 m.y. Fumarole Butte is part of the Crater Springs KGRA (Known Geothermal Resource Area); thermal springs with water temperatures of 94°C are located near the butte, and deeper reservoir temperatures are estimated to be 155°C (Peterson and others, 1978).

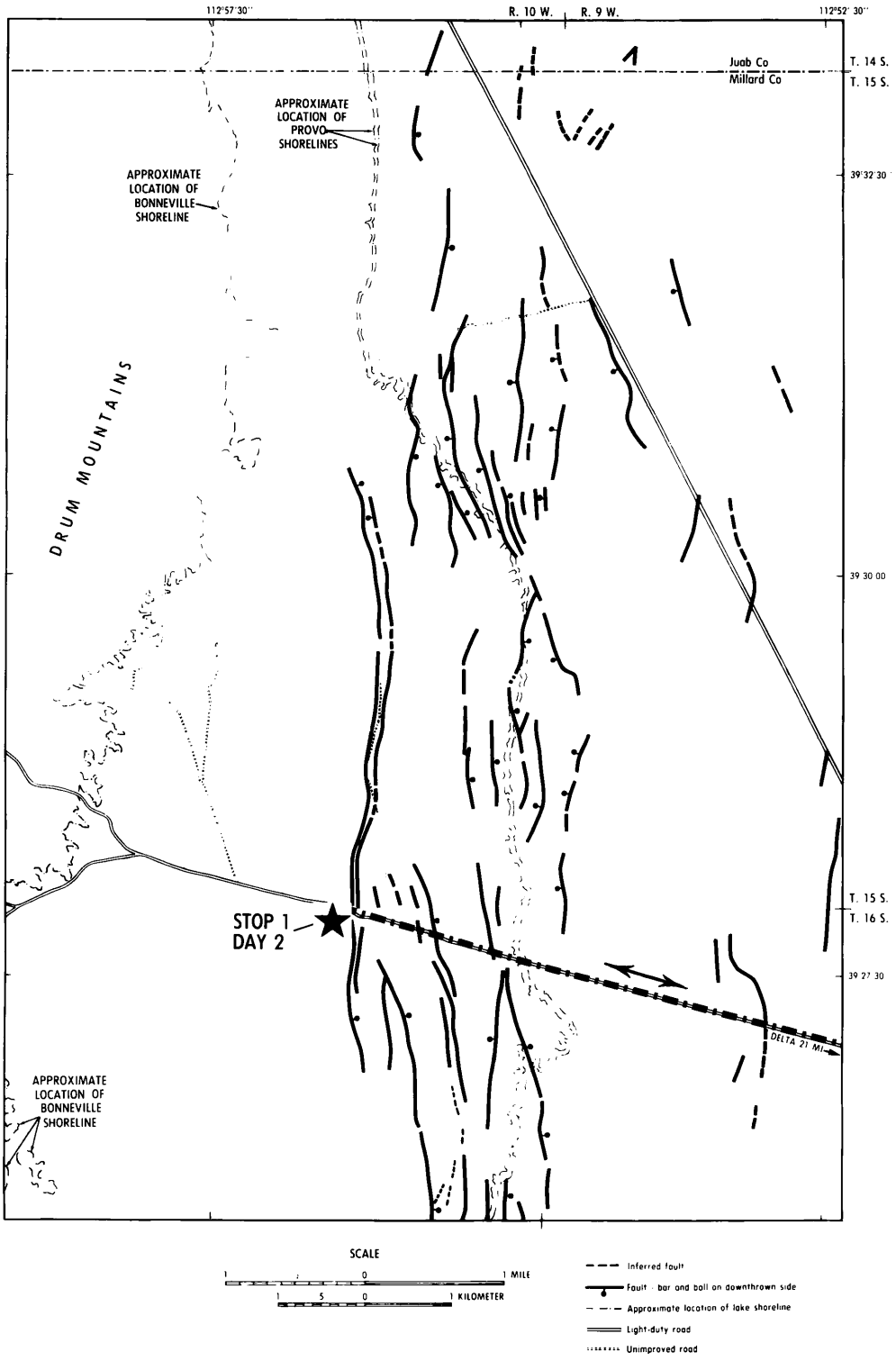


Figure 13. Map of major fault scarps in the Drum Mountains area. Heavy dashed line is the trip route. Arrows show direction of route. Star indicates location of field trip stop. Location of faults are from R. C. Bucknam (unpublished data).

6.4	32.8	Road intersecting from the left, continue straight.
0.7	33.5	Road intersecting from the left, continue straight.
0.4	33.9	Crossing Topaz Slough.
0.9	34.8	Road curves to the left and crosses cattle guard.
0.3	35.1	Topaz site on the right.
8.0	43.1	Stop sign at intersection with paved road. Turn left (north) on paved road (Figure 12).
3.3	46.4	Slow, sharp curve to the left (west).
0.9	47.3	Turn right (north).
1.0	48.3	Slow, road becomes gravel road, continue straight.
2.1	50.4	Stop sign at intersection with paved road. Turn right (east) toward U.S. Highway 50.
3.2	53.6	Entrance road to the Intermountain Power Project (IPP) construction site. The project is a coal-fired, 3,000-megawatt power-generating facility scheduled to be completed in 1989 at an estimated cost of $9 billion. When completed it will be the largest coal-fired power plant in the world and will require about 8 million tons of coal annually. Approximately 42 percent of the power will be distributed to cities and towns in Utah; the remaining 58 percent will be purchased by southern California municipalities. However, recent reductions in electric power consumption may result in substantial reductions in the plant's designed power generating capacity. Continue straight.
6.6	60.2	Active sand dunes on left.
2.2	62.4	Entrance road to the Brush-Wellman beryllium processing plant on the left. The plant processes ore from the "beryllium tuff member" (informal name) of the Spor Mountain Formation. The Blue Chalk mine, located at Spor Mountain about 5 km north of the Drum Mountains, is the major source of ore. The "beryllium tuff member" is about 60 m thick and contains tuffaceous breccia, stratified and ash-flow tuff, bentonite, and tuffaceous sandstone and conglomerate. The tuff member probably was mineralized between 7 and 21 m.y. ago (Lindsey, 1982). The ore contains an average of 8 percent fluorite, 0.7 to 1.1 percent BeO, and 0.002 to 0.015 percent U_3O_8. Beryllium deposits were first discovered in the area in 1959 (Bullock, 1981).
0.4	62.8	Stop sign. Intersection with U.S. Highway 50 and U.S. Highway 6. Turn left (north).
0.8	63.6	Sevier River on the right.
4.1	67.7	Entering town of Lynndyl which was originally settled as a railroad town.
0.8	68.5	Junction of U.S. Highway 50 and U.S. Highway 6 with Utah Highway 132. Continue straight on U.S. Highway 50 and U.S. Highway 6.
2.3	70.8	Entering Juab County. The Gilson Mountains at 1:00 consist of Mississippian limestones thrust over the Permian-Pennsylvanian Oquirrh Formation (Figure 14).
4.5	75.3	The prominent notch at the base of the hill on the right (east) and the scarp directly north of the hill is the high-

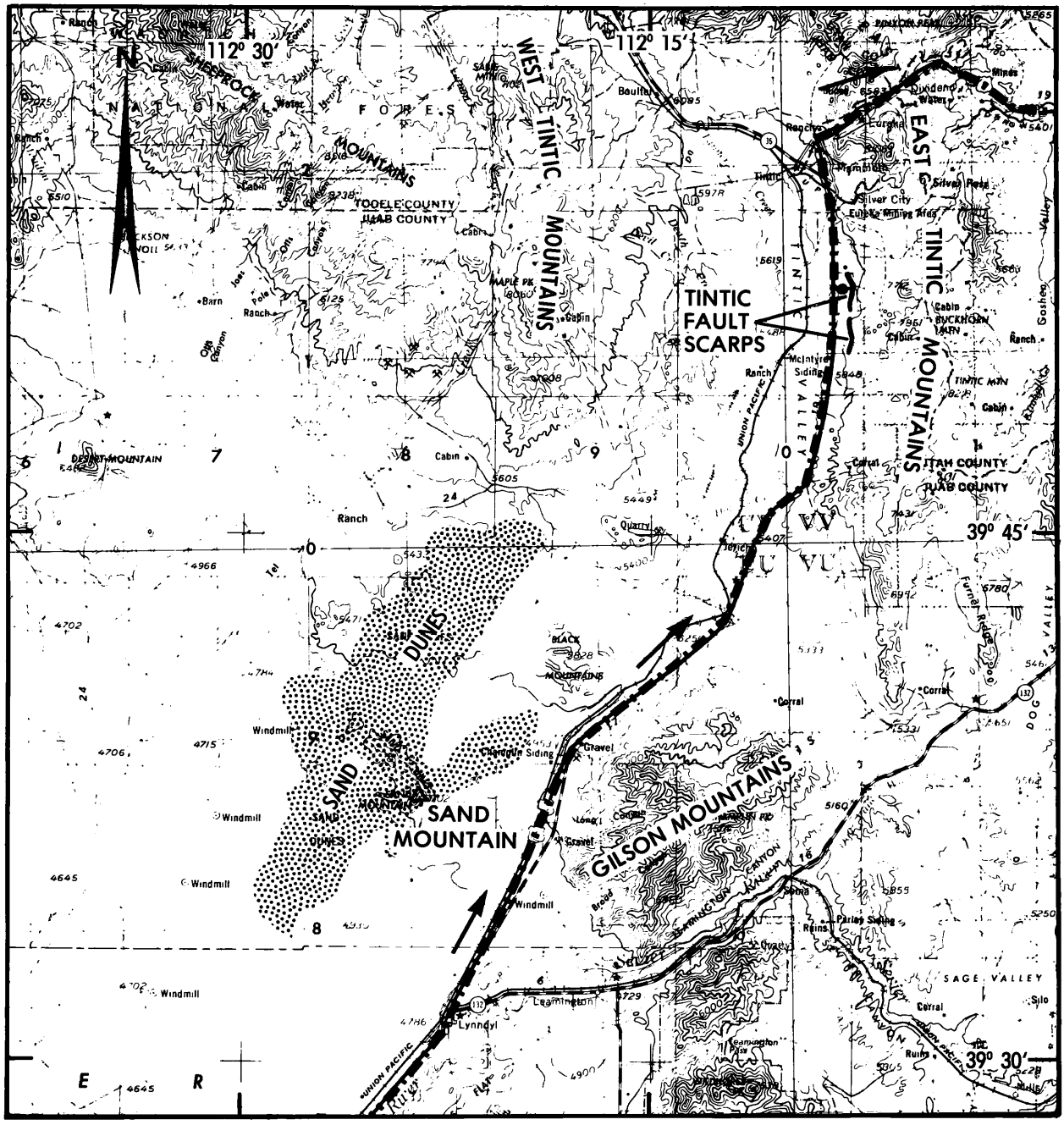


Figure 14. Map of the field trip route in the Tintic area. Heavy dashed line is the trip route. Arrows show direction of route. Heavy blacklines are fault scarps (from Bucknam and Anderson, 1979b). Bar and ball on downthrown side of fault.

stand Lake Bonneville shoreline.

2.0 77.3 The active dune field on the left covers about 200 km^2 and is designated the Little Sahara Recreation Area. Sand Mountain, surrounded and partially covered by the sand dunes, is composed of Cambrian and Ordovician limestones. On the right at 1:00 is an old alluvial fan. A scarp was formed on the distal portion of

the fan by erosion during the highest stand of Lake Bonneville. Profile data from scarps of known age such as this one are useful for comparison with profile data of other scarps of unknown age.

0.9	78.2	The prominent notch in the hills on the right is a wave-cut bench formed at the high stand of Lake Bonneville.
2.4	80.6	Gravel pits on the right are in a Lake Bonneville gravel bar.
4.5	85.1	Entrance road to Little Sahara Recreation Area on the left. Continue straight. We are proceeding north through Tintic Valley (Figure 14). The West Tintic Mountains, on the left at 11:00, primarily consist of Oligocene volcanic and intrusive rocks with outcrops of Mississippian, Cambrian, and Precambrian sedimentary rocks at the north end. The outcrops and roadcuts in the valley expose the Tertiary Salt Lake Formation.
10.9	96.0	The north-striking, 2- to 3-m-high scarp located approximately 200 m east of the highway is part of the Tintic fault scarps mapped by Bucknam and Anderson (1979b). The scarps parallel to the highway for about the next kilometer (Figure 14).
3.4	99.4	Tailings piles at 2:00 are from the mines in the Tintic Mining District.
1.1	100.5	Road to the right goes to Silver City. Continue straight.
0.1	100.6	Fork in the road. Junction of U.S. Highway 6 with Utah Highway 36. Continue straight on U.S. Highway 6 toward Eureka.
3.3	103.9	Entering Eureka, the largest town in the Tintic Mining District. Ore was discovered in 1869, and since then the district has yielded more than $350 million of silver, copper, and gold, more than half of which has been silver. The Tintic Standard Mine is the second largest native silver mine in the U.S.; at the 1,000 ft level the mine broke into the "Tintic Standard Pothole" that yielded $80 million worth of ore. Paleozoic sediments in the area are folded into a broad syncline, extensively faulted, and have been intruded and covered by porphyritic monzonites and quartz latites that range from 33 to 15 m.y. in age. The ore bodies are massive replacements of fractured and faulted limestone of the Cambrian Ophir Formation. The mineralization, mid-Oligocene to Miocene in age, was produced by ore solutions that ascended along faults in the limestone. The ores are primarily silver-lead and argentiferous copper, zinc, and gold ores (Bateman, 1950; Morris and Magensen, 1978).
1.2	105.1	Entering Utah County. Wasatch Mountains are in the distance at 12:00.
1.8	106.9	Caution! Winding road ahead for the next several miles. Outcrops along the road for the next kilometer are sedimentary rocks of Cambrian through Mississippian age. Further along the road are exposures of Oligocene volcanic rocks.
1.6	108.5	Mount Nebo at 12:00.
3.6	112.1	Descending the east flank of

		the East Tintic Mountains into Goshen Valley. Warm Springs Mountain, a ridge consisting of Tertiary volcanics and Paleozoic sedimentary rocks, separates the valley from the Wasatch Front (return to Figure 4).
1.8	113.9	Entering the town of Elberta.
0.3	114.2	Junction with Utah Highway 68 on the left. Continue straight toward Santaquin.
2.5	116.7	Entering town of Goshen.
2.0	118.7	The Bonneville shoreline is a conspicuous bench approximately one-third of the way up the side of Warm Spring Mountain at 1:00 (Figure 4).
4.5	123.2	Santaquin Canyon at 1:00.
0.7	123.9	Entering the town of Santaquin.
1.0	124.9	Approaching I-15 interchange. Prepare to take I-15 north.
0.3	125.2	Turn left onto entrance ramp for I-15 north toward Provo and Salt Lake City.
3.7	128.9	Payson-Salem exit. Lake Mountains at 9:00.
0.7	129.6	A Lake Bonneville wave-cut bench is present approximately 3 km to the east, just below the "P" on the hill.
1.5	131.1	Benjamin-Payson exit.
2.7	133.8	Spanish Fork exit. Spanish Fork Peak (10,192 ft) is at 2:00 (Figure 4). The lower slopes of Spanish Fork Peak, between Hobble Creek Canyon on the north and Spanish Fork Canyon on the south, display excellent examples of faceted spurs above the highest stand Lake Bonneville shoreline. This is one of the classic localities that led Davis (1903) to recognize that the faceted spurs are a characteristic that results from continuing displacement along the Wasatch fault. Hamblin (1976) interpreted at least eight episodes of late Cenozoic recurrent movement on the Wasatch fault at Spanish Fork Peak on the basis of the faceted spurs and the associated pediments.
6.1	139.9	Approaching Springville exit. Prepare to exit.
0.4	140.3	Exit at Springville. Turn right (east) toward Springville.
1.9	142.2	Overpass, entering town of Springville.
0.3	142.5	Stop light at junction with U.S. Highway 89. Continue straight on Hobble Creek Canyon Road. The town of Springville is built on an alluvial-fan surface of middle Holocene age.
2.2	144.7	Road traverses a surface that may be underlain by a thin veneer of alluvium that was deposited as part of the flood plain of Hobble Creek when the creek was graded to the level of the Provo shoreline. The broad, lower surface to the right is underlain by fluvial gravels graded to a level below Provo, but above the level of Utah Lake.
0.3	145.0	Good view of a fault scarp beyond the cultivated fields to the left. Ahead, the road crosses a fan of early to middle Holocene age.
0.6	145.6	On the left, the steep embankment is cut into the upthrown

block of the fault, exposing fluvial gravels that were deposited when Hobble Creek was graded to the Provo Lake level.

0.1 145.7 Intersection with Maple Canyon Road, stay left.

0.1 145.8 Large gravel turn-out on the left. Pull into the turn-out and park. **STOP 2A.** Overview of the Hobble Creek site (Figures 15 and 16). Walk up the gravel road to the gate. From here, the following features can be seen to the south: the Bonneville shoreline (approximately 15,000 yrs old), Provo terrace (13,500 yrs old), post-Provo, pre-Utah Lake terrace (middle Holocene), main Wasatch fault scarp, and broad zones of backtilting of the Provo and post-Provo surfaces toward the main scarp. Detailed geologic mapping and trenching studies (Swan and others, 1980) at this site indicated six to seven surface-faulting events during the past 12,000 to 13,000 yrs. Three or four of these events appear to have occurred in the interval between formation of the Provo terrace and the post-Provo pre-Utah Lake terrace, and formed strath terraces along Hobble Creek on the upthrown side of the fault. Three additional events have occurred since the middle Holocene and are indicated by relations observed in trenches excavated across a faulted alluvial fan (STOP 2B). The average recurrence interval for the six to seven events ranges from 1,700 to 2,700 yrs. At the mouth of Hobble Creek, cumulative net tectonic displacement of the middle Holocene terrace is 7 to 8.5 m and net tectonic displacement of the Provo terrace is 11.5 to 13.5 m (Figure 16). Scarp heights in this area exceed surface offsets due to back tilting of the alluvial surfaces. The average displacement per event ranges from 1.6 to 2.3 m and the slip rate for the past 13,500 yrs is constrained at 1.0 ± 0.1 mm/yr. Turn west toward Springville.

0.6 146.4 Turn right onto a gravel road towards Hobble Creek trench site. This is a private road. **STOP 2B (OPTIONAL).** Hobble Creek trench site (Figure 17). Three trenches excavated across the main fault scarp and graben at this stop provide recurrence information for the interval between the middle Holocene and the present. A 50- to 65-m-wide graben is formed in deposits of a large alluvial-fan complex that grades to the post-Provo pre-Utah Lake surface. The graben is bounded on the northeast by the main fault scarp and on the southwest by a series of antithetic fault scarps. The height of the main fault scarp decreases southeastward from 15 m near the center of the graben to 11.8 m near the apex of the youngest alluvial-fan segment that partially buries it. The relations between scarp-derived colluvial units, mudflow and fan deposits, and faults observed in one trench indicate that three surface faulting events have occurred since the middle Holocene. Field relationships and scarp-profile data suggest no major surface faulting at this location during the past 1,000 yrs (Swan and others, 1980).

0.1 146.5 Leave trench site. Turn left onto Hobble Creek Road and

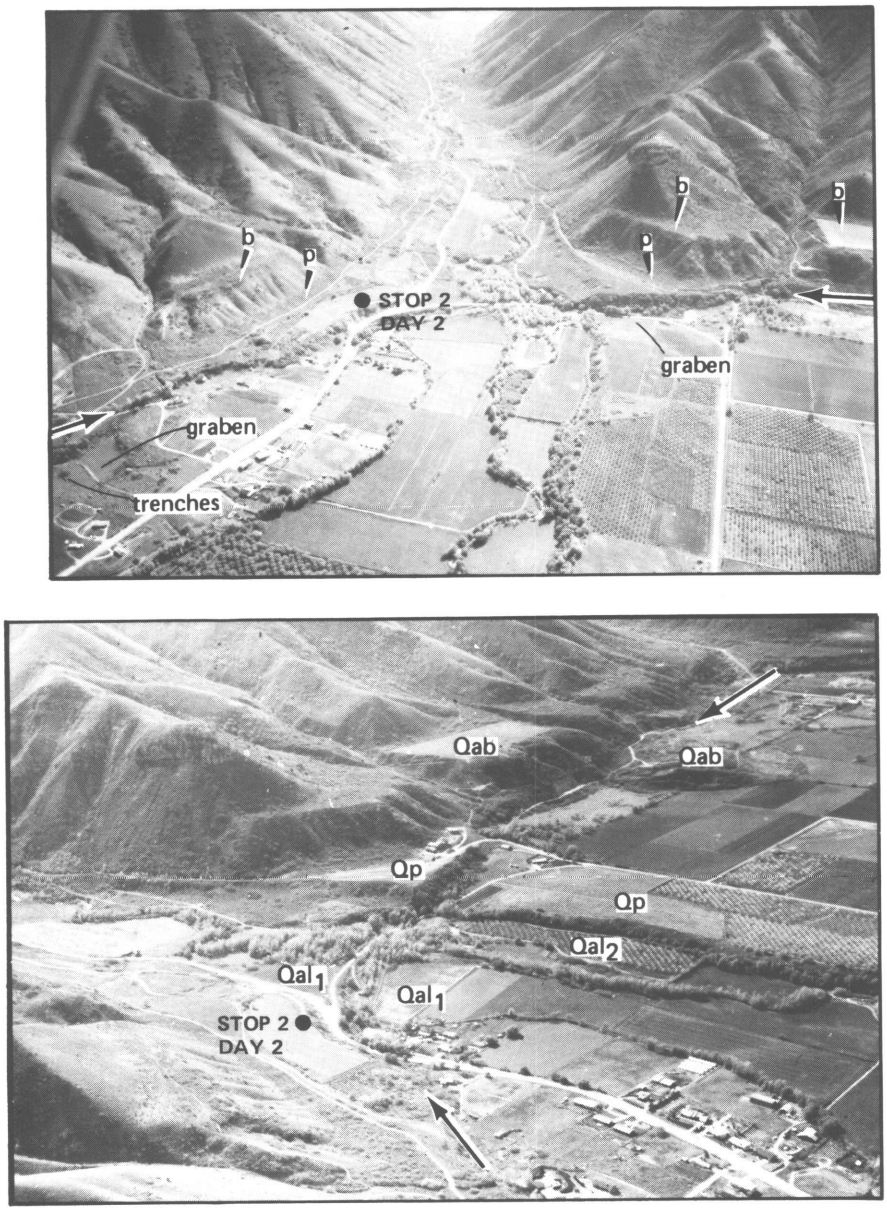


Figure 15. Aerial photographs of the Hobble Creek site (from Swan and others, 1980). **a**) Aerial view looking east toward mouth of Hobble Creek Canyon showing main fault scarp (arrows), graben, location of trenches, and the Bonneville (b) and Provo (p) shorelines; **b**) Aerial view toward the southeast along the main fault scarp (arrows) showing the progressively lower scarps in the successively younger deposits at the Hobble Creek site. From oldest to youngest, the deposits and the associated scarp heights are: Bonneville lake deposits (Qab), 60 m; Provo fan-delta deposits (Qp), 28.5 m; post-Provo pre-Utah lake deposits (Qal_3), 12.5 m; and the modern flood-plain deposits (Qal_4), which do not appear to be displaced.

retrace route to the east, towards the canyon mouth.

0.4 146.9 Turn right (south) onto Maple Canyon Road. The road crosses the main fault as it descends towards Hobble Creek and the post-Provo pre-Utah Lake surface. This surface has been rotated an average of ½° toward the east across a 200-m-wide zone on the downthrown side of the fault.

0.2 147.1 Cross Hobble Creek. The road and vineyards are in a pronounced graben formed by the 25-m-high main fault to the left (east) and two prominent antithetic fault scarps to the right (west). The Provo terrace surface on which the orchard is located has been tilted back towards the main fault scarp.

0.2 147.3 Road curves to the right and becomes 1600 North. The

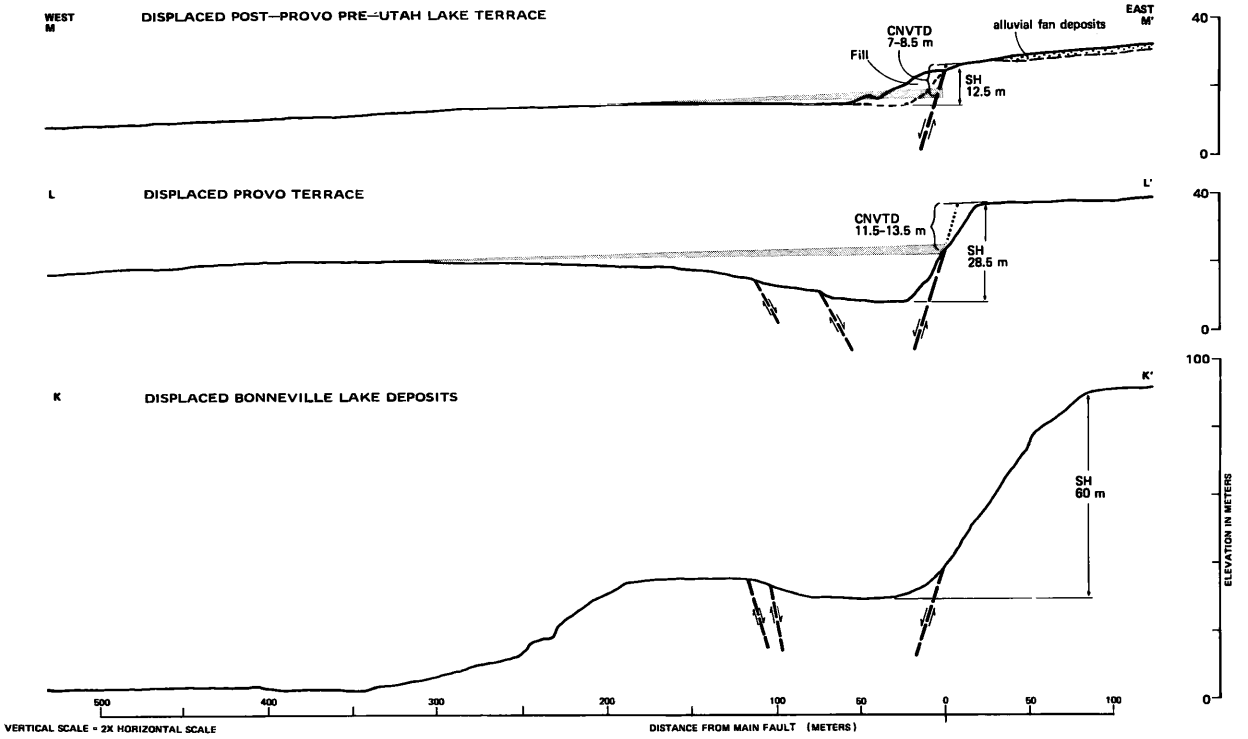


Figure 16. Topographic profiles of fault scarps at Hobble Creek showing progressively higher scarps in successively older deposits. The two upper profiles show the relationship between the apparent displacement (scarp height, SH) and the cumulative net vertical tectonic displacement (CNVTD) across the deformed zone. The shaded lines are the projection of the gradient of the undeformed lower surface back toward the scarp. Estimating the cumulative net vertical tectonic displacement of the Lake Bonneville deposits is difficult because of uncertainties in the correlation of stratigraphic markers across the fault zone (modified from Swan and others, 1980.)

broad zone of back-tilting can be seen in the cultivated fields to the left (south) as well as in the orchard to the right (north). At this location, the Provo terrace surface has been rotated an average of 1½° to the east across a zone extending 385 m west from the main scarp. Near the main fault, the surface dips as much as 3° to the east.

0.2 147.5 This is the approximate flexure point marking the western margin of back-tilted zone. West of this point, the Provo terrace surface resumes its normal dip of 1° to the west.

2.2 149.7 Intersection of 1600 North and Main Street (U.S. Highway 89). Turn right onto Main Street.

1.2 150.9 Cross intersection of 400 South (Hobble Creek Road) and continue north on Main Street.

1.8 152.7 Junction with Utah Highway 75 to the west. Continue straight.

3.7 156.4 Stop light. Bear left and stay on U.S. Highway 89.

0.7 157.1 Stop light at University Avenue. Junction with U.S. Highway 189. Turn right on U.S. Highway 189, northbound toward Heber City.

5.9 163.0 Junction with Utah Highway 52. Continue on U.S. Highway 189 toward Heber City. Entering Provo Canyon (Figure 2).

0.2 163.2 Outcrops of Mississippian

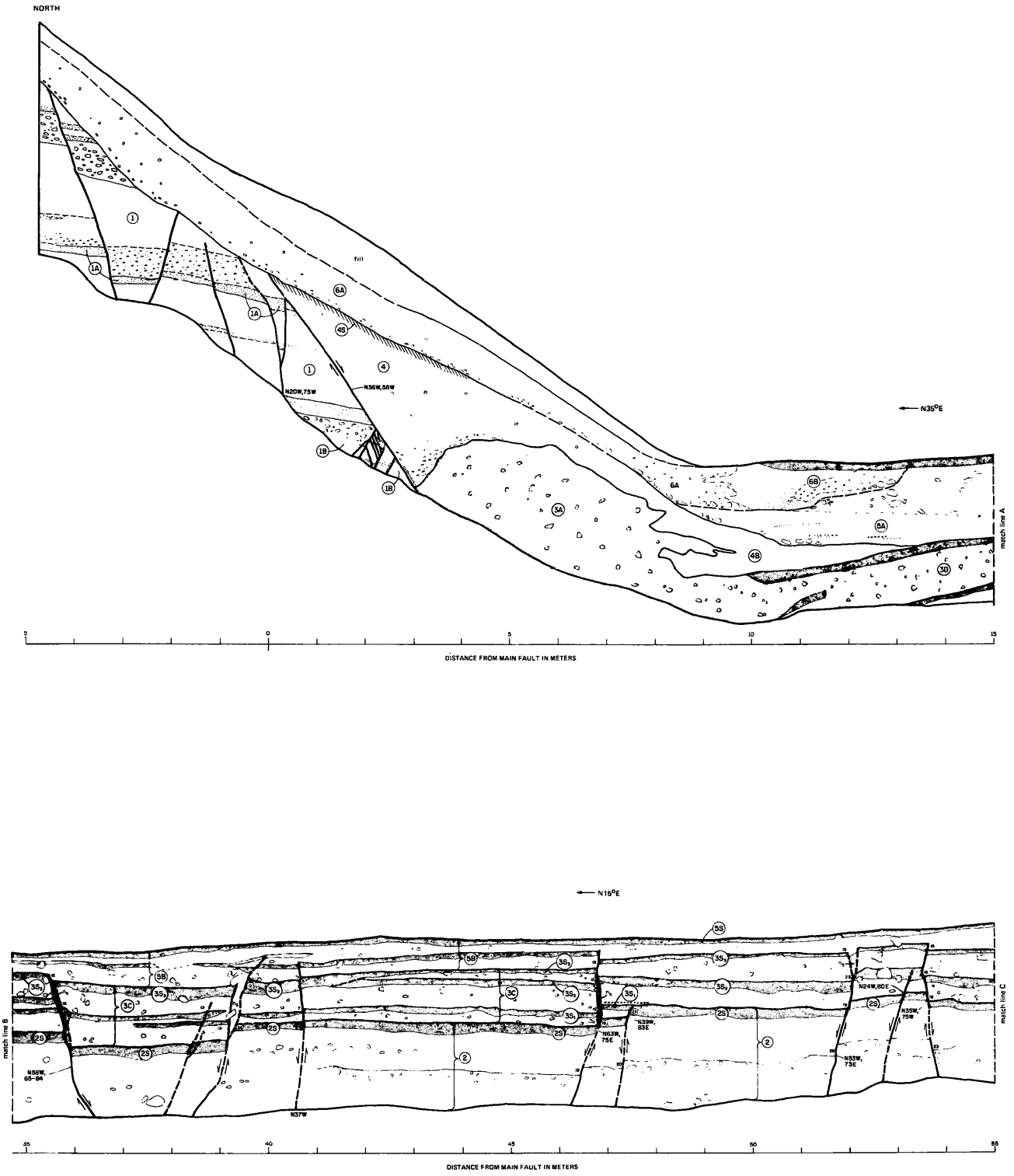
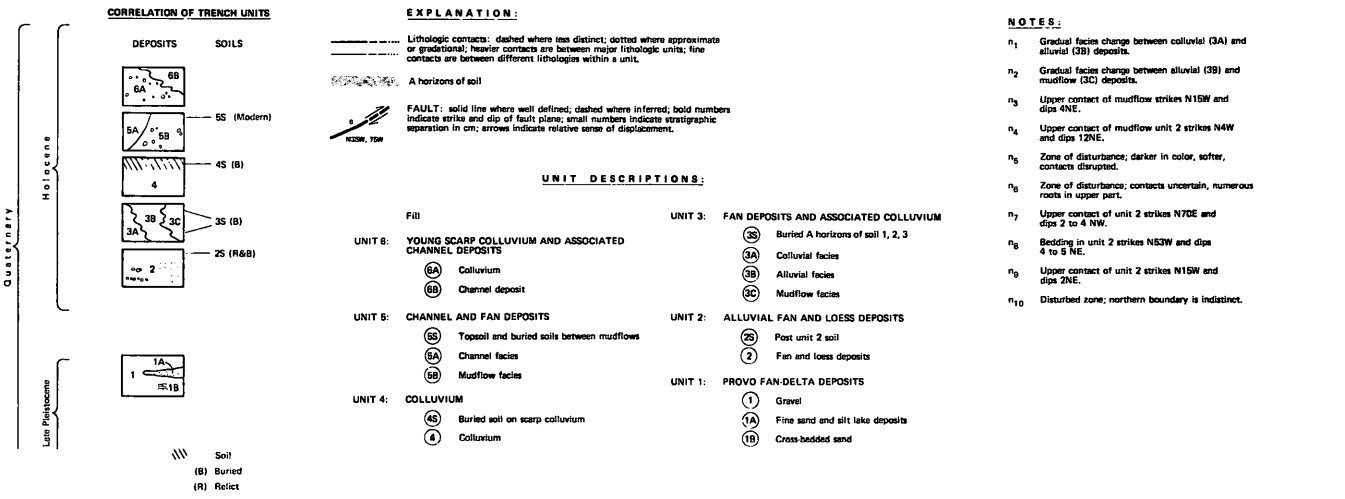
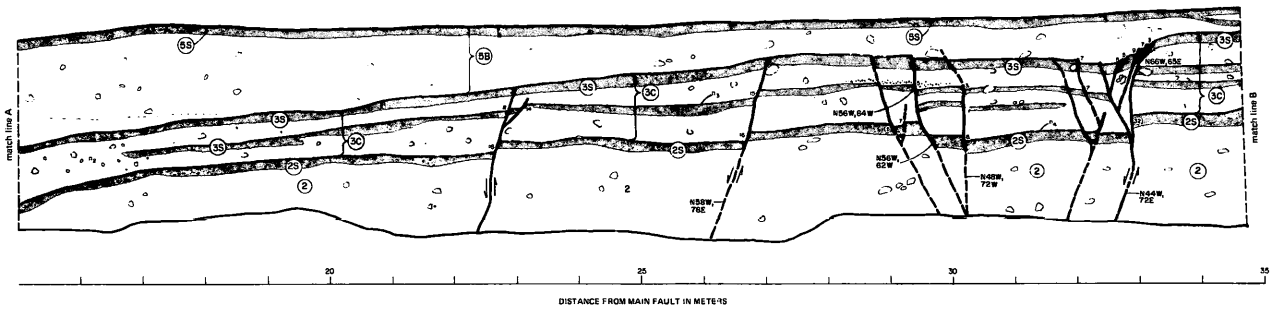
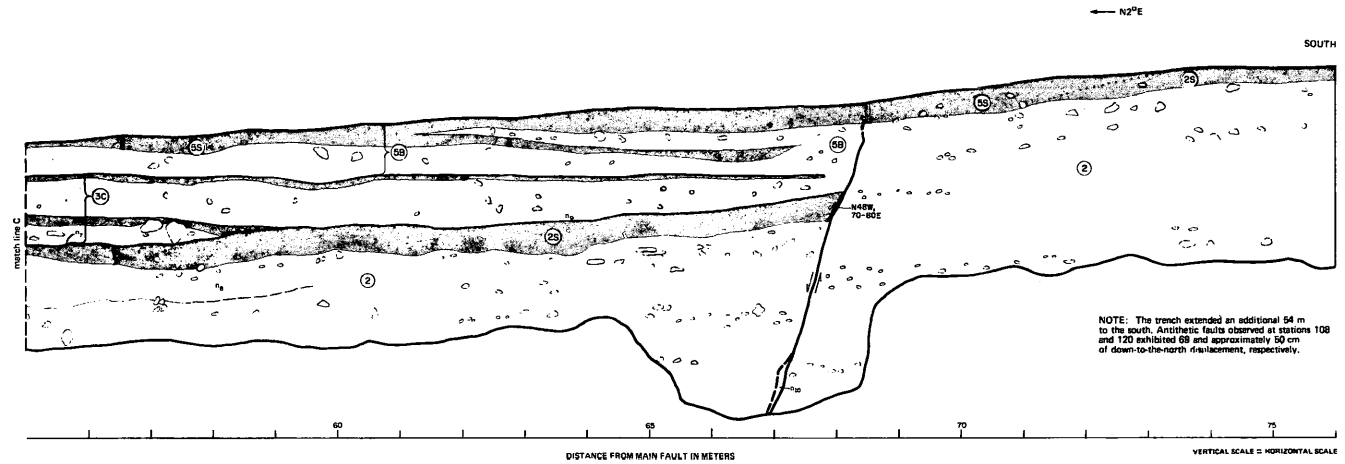


Figure 17. Map of trench at Hobble Creek site (STOP 2B) (from Swan and others, 1980)


CORRELATION OF TRENCH UNITS
DEPOSITS
SOILS
Quaternary
Holocene
Late Pleistocene
6S
6A
6B
5S (Modern)
5A
5B
4S (B)
4
3S (B)
3B
3C
3A
2S (R&B)
2
1A
1
1B
Soil
(B) Buried
(R) Relict
EXPLANATION:
Lithologic contacts: dashed where less distinct; dotted where approximate or gradational; heavier contacts are between major lithologic units; fine contacts are between different lithologies within a unit.
A horizons of soil
FAULT: solid line where well defined; dashed where inferred; bold numbers indicate strike and dip of fault plane; small numbers indicate stratigraphic separation in cm; arrows indicate relative sense of displacement.
N23W, 70W
UNIT DESCRIPTIONS:
Fill
UNIT 6: YOUNG SCARP COLLUVIUM AND ASSOCIATED CHANNEL DEPOSITS
6A Colluvium
6B Channel deposit
UNIT 5: CHANNEL AND FAN DEPOSITS
5S Topsoil and buried soils between mudflows
5A Channel facies
5B Mudflow facies
UNIT 4: COLLUVIUM
4S Buried soil on scarp colluvium
4 Colluvium
UNIT 3: FAN DEPOSITS AND ASSOCIATED COLLUVIUM
3S Buried A horizons of soil 1, 2, 3
3A Colluvial facies
3B Alluvial facies
3C Mudflow facies
UNIT 2: ALLUVIAL FAN AND LOESS DEPOSITS
2S Post unit 2 soil
2 Fan and loess deposits
UNIT 1: PROVO FAN-DELTA DEPOSITS
1 Gravel
1A Fine sand and silt lake deposits
1B Cross-bedded sand
NOTES:
n1 Gradual facies change between colluvial (3A) and alluvial (3B) deposits.
n2 Gradual facies change between alluvial (3B) and mudflow (3C) deposits.
n3 Upper contact of mudflow strikes N15W and dips 4NE.
n4 Upper contact of mudflow unit 2 strikes N4W and dips 12NE.
n5 Zone of disturbance; darker in color, softer, contacts disrupted.
n6 Zone of disturbance; contacts uncertain, numerous roots in upper part.
n7 Upper contact of unit 2 strikes N70E and dips 2 to 4 NW.
n8 Bedding in unit 2 strikes N53W and dips 4 to 5 NE.
n9 Upper contact of unit 2 strikes N15W and dips 2NE.
n10 Disturbed zone; northern boundary is indistinct.


match line A
match line B
N56W,64W
N56W, 62W
N48W, 72W
N44W, 72E
N58W, 76E
N66W,65E
20
25
30
35
DISTANCE FROM MAIN FAULT IN METERS


N2°E
SOUTH
match line C
N48W, 70-80E
NOTE: The trench extended an additional 54 m to the south. Antithetic faults observed at stations 108 and 120 exhibited 68 and approximately 50 cm of down-to-the-north displacement, respectively.
60
65
70
75
DISTANCE FROM MAIN FAULT IN METERS
VERTICAL SCALE = HORIZONTAL SCALE

Great Blue Limestone on both sides of the canyon.

0.3 163.5 Local landslide on the south side of the canyon. The hummocky topography is typical of that produced by slow creep of the Mississippian and Pennsylvanian Manning Canyon Shale into the valley.

0.1 163.6 Outcrops of the upper part of the Great Blue Limestone on the south side of the road show flow-folded structures. The gravel quarries directly ahead are in sediments that filled this part of the Provo River Canyon as deltas built into Lake Bonneville at the Provo level and higher levels.

0.5 164.1 Cross canal. Fossils of Pleistocene mammals have been found in the sediments in the gravel pits to the south. Across the canyon to the north, hummocky topography is caused by slumping Manning Canyon Shale.

0.2 164.3 Ahead, to the north, the aqueduct is about at the plane of a major thrust-fault zone, the Charleston-Nebo thrust, in which the overlying block has apparently moved eastward.

0.8 165.1 Turn-off to Squaw Peak Road, leading southward up a subsequent valley carved in Manning Canyon Shale. This is the same shale that is slumping into the canyon, forming the hummocky topography on the north side of the valley.

1.1 166.2 A spectacular fold in the basal part of the Oquirrh Formation is exposed in the high canyon wall south of the road, near a small side road heading up the canyon.

0.5 166.7 Cross Provo River at Rotary Park. Upper part of the Manning Canyon Shale is exposed in cuts to the south. Bridal Veil Falls is the location of the Wasatch Mountain Railroad (Heber Creeper) depot. The falls, which flow over the Lower Pennsylvanian West Canyon Member of the Oquirrh Formation (as used by Nygreen, 1958), are fed by springs in the cavernous upper part of the limestone, more than 305 m above the valley floor. Periodically, the ornamental retaining wall in the parking lot area is broken by avalanches and ice falls that flow down the south side of the canyon during heavy winter and spring snowstorms.

1.3 168.0 The highway skirts the toe of the Slide Canyon alluvial fan. Slide Canyon also has a history of repeated avalanches and snowfall debris slides. In 1978, slides produced a debris fan 15 m deep and more than 0.8 km wide across the highway.

0.3 168.3 Cross the West Aspen Grove fault that juxtaposes the upper part of the Oquirrh Formation on the east against the lower part of the Oquirrh Formation on the west. The canyon has a steep, V-shaped profile in areas where it cuts into the lower part of the Oquirrh Formation. To the east, the geologic structure rises, and locally, the Provo River has eroded through the Charleston thrust fault, exposing rocks beneath the fault plane. The canyon is wider where these sub-thrust rocks are exposed.

0.9 169.2 Road junction to Vivian Park. The wide area of Vivian Park is where sub-thrust rocks are

exposed. Just east of Vivian Park, the road crosses the down-to-the-west East Aspen Grove fault. Up the canyon, the lower part of the Oquirrh Formation is exposed in the upthrown block. We are still on the upper plate of the Charleston thrust.

1.2 170.4 Junction with road to Aspen Grove, Alpine or Timpanogos Loop, and Sundance Ski Resort. The alluvial terrace east of the junction is related, in part, to glaciation on the east side of Mt. Timpanogos to the north and, in part, to landslides damming the Provo River farther down the canyon. This terrace has been preserved at various locations up the canyon, from here to Heber Valley. Cambic B horizons in the soil developed on this terrace suggest that it is older than fluvial terraces at similar elevations above the river but closer to the Wasatch fault zone.

0.2 170.6 Utah County-Wasatch County line. Fractured limestones of the Oquirrh Formation that are exposed along the road lie immediately above the Charleston thrust fault.

0.6 171.2 Heber Creeper (Wasatch Mountain Railroad) bridge across the Provo River to the right. Notice the undulations in and slides next to the road that is constructed on the brecciated Oquirrh Formation and Manning Canyon Shale. The road here is just above the plane of the thrust fault.

0.2 171.4 The Charleston thrust is exposed in the Sulphur Springs window. The Oquirrh Formation has been thrust over the Manning Canyon Shale, but in the window, the Manning Canyon Shale that lies below the thrust is exposed. The exposure of easily eroded shale is the reason for the broad, open valley ahead. The hummocky landslide topography to the south is also characteristic of areas of exposed shale.

0.8 172.2 Gravelly-appearing, brecciated thrust-fault zone high on the north side of the canyon. Note the hummocky landslide topography in a proposed housing development on the south.

0.3 172.5 The canyon widens markedly at the Canyon Meadows housing development. The high terrace to the north was probably formed by landslides in the Manning Canyon Shale, damming the Provo River downstream. The highest terrace (Weeks Bench) has a soil with a > 2-m-thick argillic horizon with up to 50 percent grusified clasts. These soil characteristics suggest an age of at least 150,000 yrs for the terrace. Soils on intermediate level terraces have been disturbed during construction of the Deer Creek Reservoir dam, but the soil on a low terrace, 5 m above the river, suggests an age of perhaps a few tens of thousands of years. For the next 3.2 km, the undulations in the highway are produced by downslope movement of the Manning Canyon Shale.

1.2 173.7 Cross beneath overpass for the Heber Creeper. The earthfill dam for Deer Creek Reservoir is visible directly ahead.

0.5 174.2 Cross over the spillway to the north edge of the dam. Ahead, notice the intense fracturing of the upper Oquirrh quartz sand-

stones that are related to a complex fault zone at the damsite. Despite this fracturing in the abutment, seepage from the dam has been minimal during its 48-year history.

1.1 175.3 The road curves away from the Deer Creek Reservoir onto the large alluvial fan that was derived from Sunday Canyon to the southwest.

2.0 177.3 Cross Round Valley Creek at the junction with the road south to Wallsburg. Ascend the hill and look behind at the alluvial fans on the southwest side of Round Valley. The linear scar a few hundred meters east of the highway is the site of a 40-m-long trench across a prominent vegetation lineament that has no topographic expression. Sullivan and Nelson (this volume) believe that Round Valley, like other back valleys of the Wasatch hinterland to the north, is bounded by faults with Quaternary displacement, but the undisplaced alluvial fan units in this trench show that the vegetation lineament is not related to faulting. Round Valley, with alluvial fans on both sides of the valley, has as continuous a distribution of late Quaternary deposits on its margins as any of the back valleys. However, except for the bedrock contact at the apex of the fans, no known scarps exist that may be related to faulting.

0.9 178.2 The road curves from Round Valley, through a roadcut of deeply weathered and fractured Oquirrh Formation that is overlain by fine-grained colluvium or alluvium, along Deer Creek Reservoir, and into Heber Valley. On the upper left side of the roadcut, a stage IV soil carbonate horizon suggests that the soil is more than 100,000 yrs old on the basis of a comparison with carbonate horizons in soils in the Salt Lake City area (Scott and others, 1982, p. 43). Paleomagnetic samples of the alluvium have a component of reversed magnetization, suggesting that the alluvium is at least 730,000 yrs old. In the next roadcut to the north, the presence of rounded cobbles of Keetley Volcanics (which crop out along the east side of Heber Valley 14 km to the northeast) are evidence that the ancestral Provo River once flowed through the area at this elevation (Baker, 1976).

1.0 179.2 The Twin Creek Limestone is exposed beneath the Charleston thrust in several places to the north, for example, in the small, rounded hill just west of the wide pullout.

0.4 179.6 Brecciated limestone and quartzite of the lower Oquirrh Formation are exposed in roadcuts on the south side of the road. Exposures in the alluvial fans on the west side of the reservoir show late Pleistocene and Holocene cut and fill sequences of three ages. Amino-acid analysis of gastropod shells in these deposits may provide a more precise estimate of the age of the alluvium.

0.5 180.1 Mylonite zones in brecciated rocks of the Oquirrh Formation.

0.6 180.7 Entrance to small fishing camp. The island in the reservoir to the north is composed of Twin Creek Limestone that

lies beneath the Charleston thrust fault. The hills to the east and south are Mississippian and Pennsylvanian rocks that lie above the thrust fault. Note the brecciation in rocks near the top of the island.

1.1 181.8 Junction of Utah Highway 113 (to north). Continue northeast on U.S. Highway 189 into Heber Valley. Heber Valley is a triangular-shaped back valley about 13 km on a side; it has about 400 m of topographic relief on the south and northeast sides and 1000 m on the northwest side. This relief, gravity data (Peterson, 1970), and water-well logs that suggest over 100 m of alluvium in the valley, all indicate that the valley is fault-bounded (Sullivan and Nelson, this volume). The Charleston thrust fault is inferred to strike east-west from its outcrop on the west shore of Deer Creek Reservoir. It crosses Heber Valley, but is concealed by alluvial fill; it changes strike to the southeast. In the southeast corner of the valley, between Center and Lake Creeks, it is buried beneath Oligocene volcanic rocks. Brecciated quartzites and limestones of the allochthonous Oquirrh Formation form the southern margin of Heber Valley (Sullivan and Nelson, this volume, Figure 2a). The ground surface in the Charleston-Heber City area consists of coalescing alluvial fans that were deposited by Daniels, Center, and Lake Creeks. These deposits have soils with cambic B horizons that suggest a late Pinedale age (about 15,000 yrs B.P.) for much of the valley floor (Figure 18).

0.8 182.6 Eardley (1933) interpreted the truncated alluvial fans in the hills along the south end of Heber Valley to be remnants of a higher level of the alluvial floor. He felt the remnants resulted from tilting of the Wasatch Mountains by movement on the Wasatch fault, and a subsequent change in base-level in Heber Valley after the knick-point migrated eastward up Provo Canyon. Anderson and Miller (1979), and Kaliser and Whiting (1981) have suggested that one of these scarps (STOP 3) is a late Quaternary fault scarp (Sullivan and Nelson, this volume, Figure 2b).

0.9 183.5 Turn right (east) onto road towards Daniels.

0.8 184.3 Continue east past the intersection with Smithfield Road. To the right (south), a 600-m-long, 11-m-high scarp at the base of the Big Hollow alluvial fan is visible through the trees west of the quarry.

0.6 184.9 Turn right (south) onto Big Hollow Road.

0.4 185.3 Bear left after entering the quarry and continue east on the dirt road below the scarp. The south wall of the gravel quarry exposes a steeply dipping reverse fault that displaces highly fractured quartzites of the Oquirrh Formation. The fault is probably related to the Charleston Thrust, but it also strikes nearly parallel to the scarp at the base of the fan to the east.

0.2 185.5 Continue along the base of scarp, but notice, to the south, a small roadcut in the surface of the fan at the crest of the

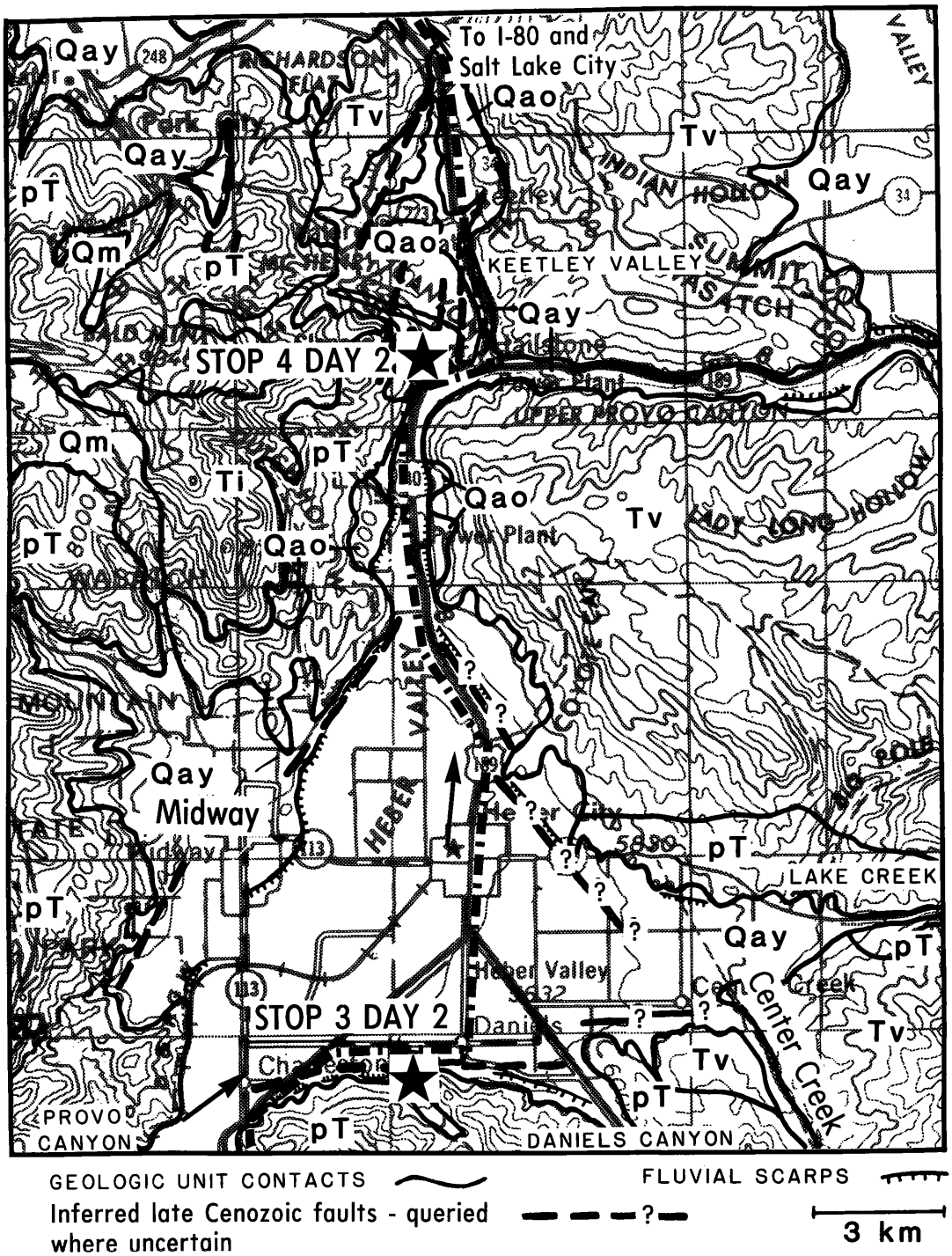


Figure 18. Geologic map of the Heber Valley-Keetley Valley area. Contour interval is 200 ft. Heavy dashed lines are inferred late Cenozoic faults, queried where very speculative. Inferred faults are based on back valley physiography, gravity data, water well logs and, in Keetley Valley, on drilling data and refraction surveys. Hachured lines show fluvial scarps. Map symbols are: pT-pre-Tertiary bedrock; Tv-Tertiary Keetley Volcanics; Ti-Tertiary intrusives; Qao-older Quaternary alluvium; Qay-younger Quaternary alluvium. Dashed line is route for day 2. Arrows show direction of route. Stars show locations of field trip stops.

scarp that exposes a soil with a well-developed stage III carbonate horizon. This stage of soil carbonate suggests an age on the order of 100,000 yrs for this part of the fan when compared to soils in the Salt Lake City area (Scott and others, 1982). Soils on the eastern part of the fan show that part of it is much younger. Paleomagnetic samples from this cut are normally magnetized.

0.1 185.6 Continue west on the dirt road and turn right (north) on a secondary dirt road and then left (west) through a barbed-wire gate.

0.1 185.7 Unless the road is dry, we will walk south along the edge of the field and then west along the base of the scarp to the site of a former exploratory trench across the scarp. **STOP 3.** Daniels trench site (Sullivan and Nelson, this volume, Figure 2). This scarp was considered to be one of the better candidates for a fault scarp in upper Quaternary deposits in the back valleys. At the base of the scarp, the trench exposed rounded fluvial gravels of Daniels Creek that were overlain by Holocene scarp colluvium (Sullivan and Nelson, this volume, Figure 3). This suggests that this scarp, as well as the others along the south edge of the valley, is partially fluvial in origin and was cut by Daniels Creek probably about 15,000 yrs ago. Retrace route up Big Hollow Road to the north.

0.9 186.6 Turn right (east) towards Daniels.

0.5 187.1 At Daniels, turn left (north) on Daniels Road towards Heber City. To the southeast is Daniels Canyon (Figure 18) which was probably largely eroded when its drainage area included some of the Strawberry Valley (Sullivan and Nelson, this volume, Figure 1). Subsequent late Cenozoic displacement on the Strawberry fault, 40 km upstream to the southeast, isolated the Strawberry Valley area from the Daniels drainage basin. As we head north, Lake Creek Valley is visible in the hills to the east (Figure 18). Soil development on the outermost moraines a few kilometers up the valley suggests a Pinedale age (about 15,000 to 25,000 yrs B.P.) for the moraines and the associated outwash that spread over this part of Heber Valley.

1.8 188.9 Turn right (east) at the stop sign at the intersection with U.S. Highway 189, turn left (north) on U.S. Highway 40, and continue north through Heber City.

2.0 190.9 A volcanic breccia, part of the Oligocene volcanic sequence which borders Heber Valley on the northeast, is exposed in a small road cut east of the highway. Directly west of here, on the opposite side of the valley, is the town of Midway, which is built on a large area of thermal springs and Quaternary tufa deposits (Baker, 1968). For the next 2 mi, discontinuous, 2- to 7-m-high, eroded scarps, in alluvial and colluvial fan deposits are visible east of the highway (Figure 18). These scarps appear to have been formed by the Provo River when it occupied this side of the valley.

2.9 193.8 Pass intersection with road to

Midway to west. The hills to the east consist of Oligocene Keetley Volcanics and those to the west, beyond the Provo River, of Triassic sandstones and siltstones. A pediment cut on both Triassic and Oligocene rocks is visible to the northwest at 10:00.

0.7 194.5 Old stone powerhouse on the right. The canal cuts above the powerhouse expose a cut and fill sequence of alluvial fan sediments similar to those recovered in cores from the basin fill farther north in Keetley Valley. Samples from this cut have a component of reversed magnetization that suggests that these deposits and the pediment at the same elevation on the opposite side of the valley are more than 730,000 yrs old.

0.7 195.2 Pass gravel road to west. A quarry just beyond the river exposes interbedded fine-grained alluvial units and grusified, rounded, cobbly gravels that lie on columnar-jointed Keetley rhyodacite porphyry.

1.3 196.5 The compound to the left, at the bridge over the Provo River, is the U.S. Bureau of Reclamation Jordanelle Project Office. Numerous bulldozer and backhoe trenches dug in the hillside to the west exposed the very complex stratigraphic and structural relationships above the right abutment of the proposed Jordanelle damsite.

0.2 196.7 To the west, the outcrop of Keetley rhyodacite porphyry with the flag painted on it lies just south of the axis of the proposed Jordanelle dam.

1.2 197.9 Intersection where alternate U.S. Highway 189 leaves U.S. Highway 40 at Hailstone. Turn left (west) off of U.S. Highway 40.

0.4 198.3 Turn right (north) on an old asphalt road and drive through the orange metal gate.

0.3 198.6 South of the road upon which we are driving, about 400 m of backhoe trenches exposed interbedded fine-grained and gravelly basin-fill sediments which cover most of Keetley Valley (Sullivan and Nelson, this volume, Figure 4). Trenches in the area have not exposed any displaced basin-fill sediments. Paleomagnetic samples from these units at several sites have a reversed magnetic component which suggests an age >730,000 yrs; this is consistent with amino-acid racemization ratios on gastropods that indicate an age of about 0.7 to 1.0 m.y. for these deposits.

0.5 199.1 Follow the lead vehicle and park. **STOP 4.** Jordanelle study area trench site (Figure 18 and Sullivan and Nelson, Figure 4). This is considered a construction area: HARD-HATS ARE REQUIRED. Walk up the hill (about 10 minutes) to a backhoe trench. A normal fault exposed in the trench juxtaposes highly weathered Oligocene Keetley andesite porphyry with Pennsylvanian Weber Quartzite. The fault zone consists of red, clayey gouge and Weber Quartzite breccia, and widens near the top of the andesite where it is truncated by the colluvial units. Within the weathered andesite porphyry east of the fault, a thin indurated zone is probably due to secondary cry-

stalline quartz filling a fracture or minor fault zone. Undeformed colluvium overlies the fault; stratigraphic relations suggest that there has not been any late Quaternary displacements on the fault exposed in the trench (Sullivan and Nelson, this volume, Figure 5). Examine the trench from the top, but STAY AT LEAST 2 FT FROM THE EDGE OF THE TRENCH. After everyone has viewed the trench, those who are most interested may enter a few at a time to examine the stratigraphy in detail (depending on the condition of the trench). DO NOT STAND NEAR THE TRENCH WHEN ANYONE IS IN IT. Retrace route to U.S. Highway 40.

1.2 200.3 Turn left (north) at intersection with U.S. Highway 40.

1.1 201.4 Farm ahead on the left. The ridge to the west is underlain by Oligocene volcanic rocks. Apparently Ross Creek, which eroded this part of the valley, was forced to the east edge of Keetley Valley by alluvial fans originating from the west. Beheaded V-shaped drainages on the west margin of Keetley Valley (visible just ahead in the distance), and the volume of basin-fill sediments indicate the drainage from some of the Park City area once drained into Keetley Valley. A down-to-the-west normal fault bounding Deer Valley (west of Keetley Valley) and related faults that beheaded these drainages must have been active during or after the deposition of the younger basin-fill sediments.

0.7 202.1 Town of Keetley. To the west beyond Keetley, are the dumps and the building associated with the long drain tunnel of the Ontario mine, one of the most recently active mines in the eastern Park City district. All the hills to the east and northeast are made up of the agglomeratic Keetley volcanic rocks. Paleomagnetic samples from the basin-fill sediments in the roadcut up the road to the northeast (at 2:00) have a reversed component of magnetization. These basin-fill sediments in Keetley Valley and the alluvial fan sediments in northern Heber Valley (Qao in Figure 18) both have a reversed component of magnetization suggesting that they are much older than the young Quaternary alluvium covering much of Heber Valley.

1.2 203.3 A few hundred meters to the east, a test pit exposed a gray, 1-m-thick ash bed lying on fine-grained, basin-fill sediments and covered by surface alluvial fan deposits. This ash is similar to the Lava Creek ash bed (600,000 yrs old), but is also similar to several other Pliocene ashes in the region (R. E. Wilcox, 1982, oral communication). Two 2-cm- thick ash beds have also been located in the roadcut just east of the highway.

1.9 205.2 Loading docks and the railroad yard to the left are for phosphate ore mined along the south flank of the Uinta Mountains in the eastern Uinta Basin. Ore is hauled here by truck and then by railroad to processing plants.

0.6 205.8 Road junction of highway to Peoa with U.S. Highways 40 and 189.

0.1 205.9 Entering Summit County. Excellent exposures of agglomeratic Keetley Volcanics are visible on both sides of the highway.

1.1 207.0 Crossing the railroad spur line into Park City. To the west, the soil developed on the terrace 8 m above Silver Creek suggests that the alluvium was deposited during the Pinedale deglaciation of the Park City area.

0.4 207.4 Junction of Utah Highway 248. Continue on U.S. Highway 40. To the west, near the skyline, beyond Park City, are northwest-dipping Mesozoic and upper Paleozoic rocks. These rocks have been mineralized in the Park City district, where Permian rocks contain sheetlike ore deposits and the older rocks contain gold-bearing veins.

3.7 211.1 Junction with I-80. Ahead and to the north, the hills are composed of Keetley Volcanics that veneer the older Mesozoic and Paleozoic rocks. Tertiary alluvial conglomerates occur on the lower slopes.

2.0 213.1 Some of the valleys in Parleys Park have steep margins that intersect at right angles to each other (visible to the south), perhaps suggesting that Tertiary and possibly early Quaternary faults are present along some of the valley margins. Soils developed on the large alluvial fan to the southwest at Park West suggest a Pinedale age for the fan.

0.8 213.9 Kimballs Junction. The vegetated slopes to the left (west) are allochthonous Triassic and Jurassic sedimentary rocks that have been thrust eastward by the Mt. Raymond thrust fault. Ahead on the right side of the highway are exposures of the Triassic Ankareh Formation, Thaynes Formation, and the red Woodside Shale.

5.8 219.7 Parleys Summit. The Jurassic Twin Creek Limestone, overlain by the Preuss Sandstone, is exposed on the north side of the highway near the summit. At one time, drainage from the western part of Parleys Park probably flowed westward down Parleys Canyon; however, Tertiary uplift of the Wasatch Range, and probable downdropping of Parleys Park, forced the drainage east of the summit to flow into the Weber River Basin. From this point to Mountain Dell Dam, notice the numerous slumps and landslides along the south side of the canyon that have been created by highway construction.

6.2 225.9 Mountain Dell Dam site. Twin Creek Limestone and red beds of the Preuss Sandstone are exposed on the right.

3.6 229.5 The Utah Portland Cement quarry is in the Twin Creek Limestone.

0.9 230.4 Traveling along axial trace of Parleys Canyon syncline. The highly fractured nature of the Twin Creek Limestone and Nugget Sandstone on both sides of the canyon has resulted in talus slides.

1.6 232.0 Crossing a trace of the Wasatch fault at the mouth of Parleys Canyon. Lake Bonneville sands and gravels are exposed north of the highway.

3.2	235.2	Crossing the trace of the East Bench fault between 13th and 7th East streets.
1.9	237.1	Approaching junction I-80 and I-15. Prepare to take I-15 north.
0.5	237.6	Take the exit for I-15 north toward Salt Lake City Center.
4.6	242.2	Take the exit for Salt Lake City Center and proceed to meeting headquarters.

END OF TRIP.

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PALEOSEISMIC INVESTIGATIONS ALONG THE WASATCH FAULT ZONE: AN UPDATE

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INTRODUCTION

In 1977, the first trenches were excavated across the Wasatch fault zone at the Kaysville site for the specific purpose of quantifying earthquake recurrence. Since then, investigations have been conducted at the Hobble Creek, Little Cottonwood Canyon, and North Creek sites along the Wasatch fault zone and at Logan along the East Cache fault (Figure 1). These investigations have yielded information on slip rate, recurrence intervals for past surface faulting earthquakes, displacement per event for past earthquakes, and fault segmentation. These data provide a basis for evaluating the late Pleistocene-Holocene behavior of the Wasatch fault zone. Results from the Kaysville and Hobble Creek sites have been presented by Swan and others (1980). This paper summarizes the data collected at all sites and discusses the implications of these data to fault behavior and earthquake recurrence.

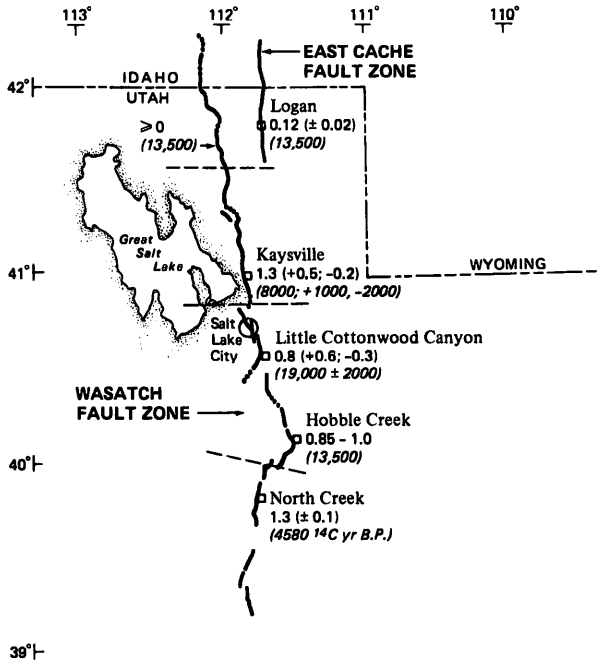
SLIP RATE

Slip rate provides a means for comparing relative behavior of different parts of a fault zone. Slip-rate data for the Wasatch fault zone are summarized on Figure 1a. The rates, which range from .85 to 1.3 mm/yr, were developed from topographic profiling of displaced surfaces that grade to the Provo shoreline, glacial moraines, alluvial fans, and stream terraces. They represent cumulative vertical tectonic displacement that has been corrected for the distortion (backtilting and graben formation) that frequently increases scarp height. The rates at the Kaysville and Hobble Creek sites differ slightly from previously published values (Swan and others, 1980) because of recent revisions in the ages of the displaced datums (Scott and others, 1982).

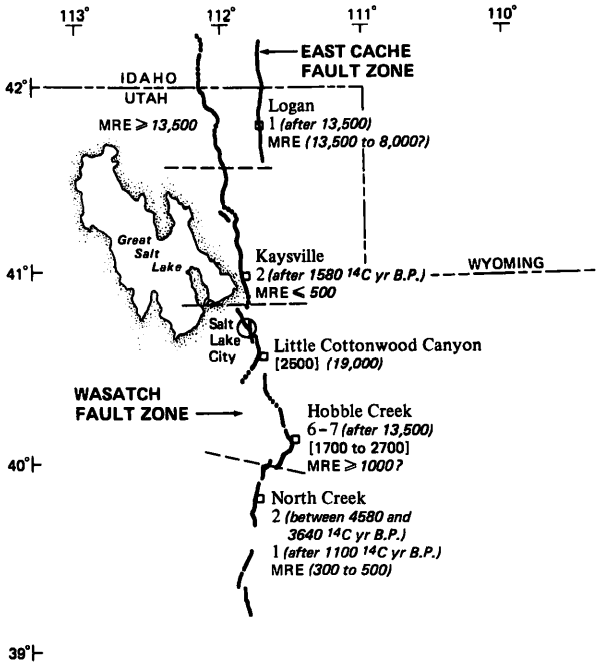
Rates based on different-aged datums may not be exactly comparable. Also, care must be exercised in extrapolating rates calculated at a point for long distances along the trace of the fault. Considering these factors, we view the slip rates as representing a generally constant rate of strain accumulation of about 1 mm/yr along the Wasatch fault zone between Gunnison and Brigham City during Holocene time. However, the incremental strain rate at specific locations is variable and the observed variations in slip rate may reflect differences in the timing of surface-faulting earthquakes along the length of the fault. The rate of strain accumulation in the Wasatch fault zone south of Brigham City is one to two orders of magnitude greater than the rate for the zone north of Brigham City, which includes the East Cache fault, and for faults in other parts of the Basin and Range province.

RECURRENCE INTERVALS

Factors that affect the evaluation of recurrence at a specific location include the completeness of the stratigraphic record, the local erosional and depositional environment, and the threshold earthquake magnitude that produces recognizable surface-fault rupture. Recurrence at individual sites along the Wasatch fault zone has been based on a combination of trenching and mapping. Trenching of normal fault scarps has shown the usefulness of scarp-derived colluvial wedges in quantifying the number of past surface faulting events. Figure 2 is a schematic diagram showing the sequence of devel-



A) Slip Rate



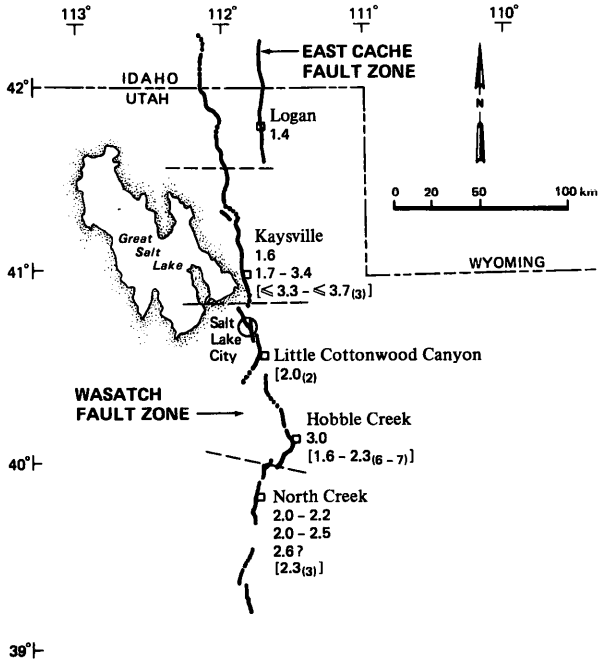
B) Recurrence

Figure 1. Summary of Fault Behavior Data for the Wasatch and East Cache Fault Zones (all data based on Hanson and others, 1981; Hanson and Schwartz, 1982; Schwartz and others, 1982; Swan and others, 1980, 1981, 1982).

A) Slip rate in mm/yr age of the displaced datum (yr B. P.) on which rate is based is shown in italics.

B) Large numerals represent the number of surface faulting earthquakes after the dates shown in italics; brackets contain average recurrence (yr) for the interval shown in italics; MRE is the elapsed time (yr) since the most recent surface faulting earthquake.

C) Measured displacement per event in meters; average displacement per event and number of events are shown in italics. Dashed lines represent proposed major segment boundaries.



C) Displacement per Event

opment of colluvial wedges. In trenches, these are commonly seen as stacked units grading away from the main fault. The number of colluvial wedges is one basis for determining the number of surface faulting events. Mapping is especially important because it helps establish many stratigraphic and structural relationships that clarify observations made in trenches and it aids in identifying secondary features such as tectonic terraces and segmented alluvial fans that also provide evidence of recurrence.

Data on the recurrence of surface faulting earthquakes along the Wasatch fault zone are shown on Figure 1b. At the Little Cottonwood Canyon and Hobble Creek sites the ages of individual events could not be determined and only average recurrence intervals could be calculated. At Kaysville, at least three events occurred within approximately the past 8,000 years; two of these occurred within the past 1,580 ^{14}C yr B.P. At the North Creek site there is evidence of three events during the past 4,580 ^{14}C yr B. P.; two of these occurred between 4,580 and 3,640 ^{14}C yr B. P. and the most recent event is estimated to have occurred within the past 300 to 500 yrs. At the North Creek site the interval between successive events was not uniform and varied from somewhat less than 1,000 years to longer than 3,000 years, indicating that the acutal interval between events can vary from the average recurrence by at least a factor of two.

DISPLACEMENT PER EVENT

Information on the amount of displacement per event for past surface faulting earthquakes is important for assessing the magnitude of past earthquakes and for developing models of earthquake recurrence. The use of colluvial wedges provides a basis for evaluating paleodisplacements. The thickness of the wedge adjacent to the fault provides a minimum value for the height of the fault scarp free face that was exposed during a surface faulting event (Figure 2). In some cases, such as the most recent event at the North Creek site, the thickness of the wedge approximates the total height of the free face produced during that event. Profiling of scarps that have experienced multiple events is also useful in obtaining displacement for the most recent event.

Displacement per event data are summarized on Figure 1c. Investigation of historical surface ruptures on normal faults in the Basin and Range, such as the 1915 Pleasant Valley earthquake (Wallace, 1980), show systematic variation in displacement along the surface trace of the fault. For the Wasatch

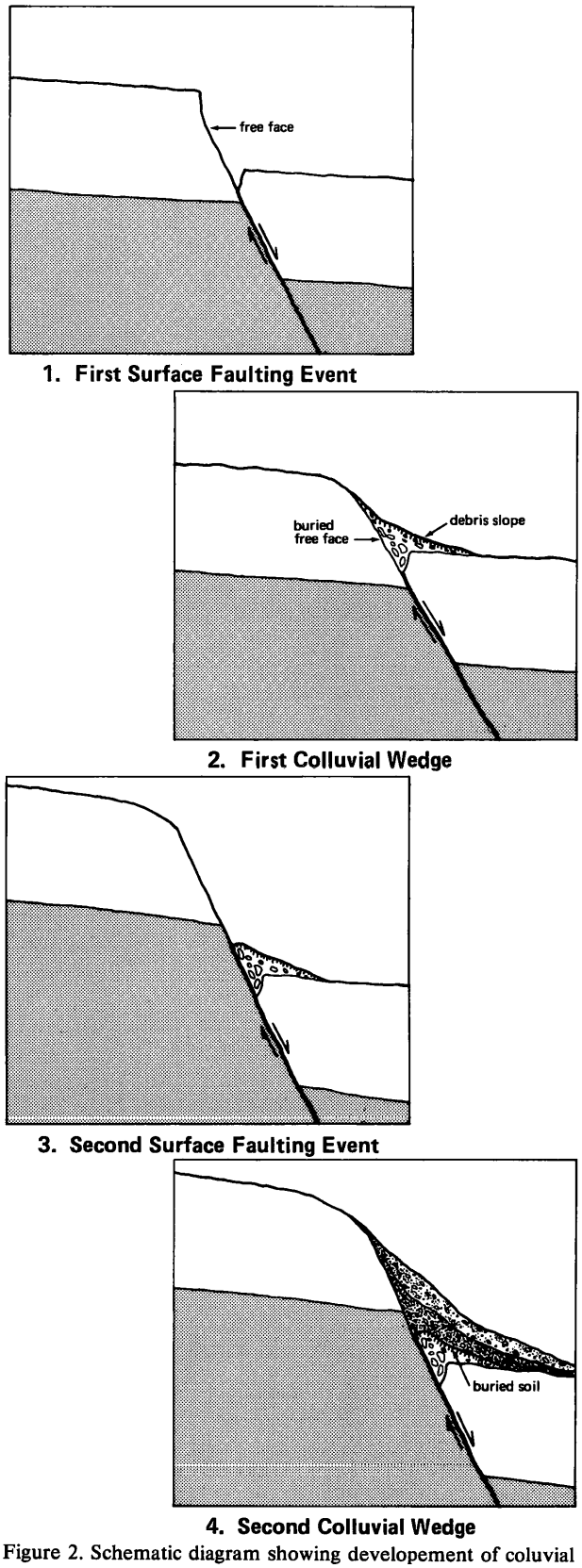


Figure 2. Schematic diagram showing developement of coluvial wedges for normal faults (from Schwartz and others, 1982).

fault zone, we do not know where individual trench sites were located along past rupture segments; therefore, it is uncertain whether an individual measurement represents a minimum, an average, or a maximum displacement of that surface faulting event. Despite these uncertainties, the data clearly show that displacement per event has been consistently large. The measured values range from 1.6 to 3.7 m, and the average displacement per event generally exceeds 2 m. The data from the North Creek site indicate that displacments at the same location along the fault can be essentially the same during successive events.

The occurrence of successive large- and similar-displacement events along the Wasatch fault zone, coupled with the variability in timing between these events and the lack of evidence of small-displacement events, has led to the development of the characteristic earthquake recurrence model (Schwartz and others, 1981). This recurrence model suggests that: a) linear frequency-magnitude distributions over a full range of earthquake magnitudes may not be appropriate for individual faults or fault segments and moderate magnitude events smaller than the characteristic earthquake may be relatively less likely to occur than the larger event, b) the magnitude of the characteristic earthquake may approximate the maximum earthquake and, c) stress application appears to be non-uniform and faults may fail in response to localized, rapid increase in stress. Similar behavior appears to characterize other Basin and Range normal faults.

SEGMENTATION

A normal fault as long as the Wasatch fault zone will only rupture along part of its total length during a surface faulting earthquake. A major question is does rupture occur randomly along the fault or are there distinct rupture segments, perhaps controlled by the geometry of the fault and by older structural trends, that behave consistently through time? Quantifying the number of potential rupture segments is a key factor in evaluating recurrence for the entire fault zone.

Swan and others (1980), on the basis of rupture lengths of historical Basin and Range surface faulting earthquakes with $M > 6\frac{1}{2} < 7\frac{1}{2}$, suggested that the Wasatch fault zone consists of 6 to 10 segments. Based on additional investigations, we presently believe there are at least four major segments (Figure 1). Selection of each segment is based to varying degrees on fault geometry, scarp morphology, slip rate, recurrence, and timing of the most recent event. The northern segment has had no identifiable surface faulting in post-Provo time. The Kaysville segment has experienced multiple displacements, including two within the past 1580 ^{14}C yr B. P. and the most recent in the past 500 years. Observations along the Hobble Creek segment suggest the most recent event may have occurred more than 1,000 years ago. Along the North Creek segment one event has occurred within the past 1,100 ^{14}C yr B. P. and probably as recently as 300 to 500 years ago, while two events occurred between 4580 and 3640 ^{14}C yr B. P.

Proposed segment boundaries are not sharply defined and may represent structurally complex transition zones several kilometers wide. The proposed boundary between the Kaysville and Hobble Creek segments occurs at a major salient in the range that is coincident with the intersection of major north-northwest and east-northeast structural trends. The Hobble Creek-North Creek boundary is associated with a change in the strike of the fault from northeast to northwest and with a salient in the range. The boundary between the Kaysville and northern segments has no well-defined expression at the surface in the older structure although it does occur about 10 km north of a large reentrant in the range front. Within the major segments, other pronounced geometric and structural changes, such as at the Traverse Mountains salient south of Little Cottonwood Canyon, suggest the occurrence of additional rupture segments. However, it is uncertain to what degree changes in fault geometry, by themselves, can be used as a basis for segmenting the fault zone. While it appears that some geometric changes and older structural trends observed at the surface have expression at seismogenic depths and may act as real boundaries or barriers to rupture, rupture propagation may bypass or take near-surface *en echelon* jumps across others.

CONCLUSION

These studies along the Wasatch fault zone have shown that geological investigations of late Quaternary faults provide a means for addressing basic questions concerning long and short term variation in rates of deformation, fault segmentation, mechanisms of stress applications, and earthquake recurrence models. The techniques used during these studies and many of the concepts that have been developed have widespread applicability for quantifying fault behavior in a variety of tectonic environments.

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AMOUNT OF DISPLACEMENT AND ESTIMATED AGE OF A HOLOCENE SURFACE FAULTING EVENT, EASTERN GREAT BASIN, MILLARD COUNTY, UTAH

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ABSTRACT

Natural exposures of, and a 17-m-long, 3-m-deep trench across a Holocene fault scarp located 30 km northwest of Delta, Utah, reveal the near-surface characteristics of the fault and the related postfaulting deposits. The scarp is part of a 30-km-long, 5-km-wide system of fault scarps that displace pre-Lake Bonneville age fluvial and alluvial sands and gravels on the bajada east of the Drum Mountains. In the trench, the 1.5-m-wide fault zone consists of sheared silty sand, and disrupted sand and gravel. An adjacent antithetic fault forms a small graben. The trench shows that the Holocene faulting resulted in 3.7 m of stratigraphic throw, considerably more than the 2.7 m of surface offset measured from scarp profiles; postfaulting alluviation and deflation of the ground surface are probably responsible for the difference. A single, undeformed colluvial wedge that was deposited at the base of the fresh scarp buried and preserved about 36 to 45 percent of the original free face and shows that the scarp was formed by one surface faulting event.

Some of the scarps in the Drum Mountains system displace 13,500-year-old Provo shoreline deposits, which establishes a maximum age for the faulting. An early Holocene age for the faulting is suggested from: (1) a preliminary comparison of the amount of pedogenic carbonate in the postfaulting colluvium with the carbonate in the post-Lake Bonneville soil beneath the relatively stable ground surface of the upthrown block, (2) lack of soil development beneath the paleosurface that was buried by

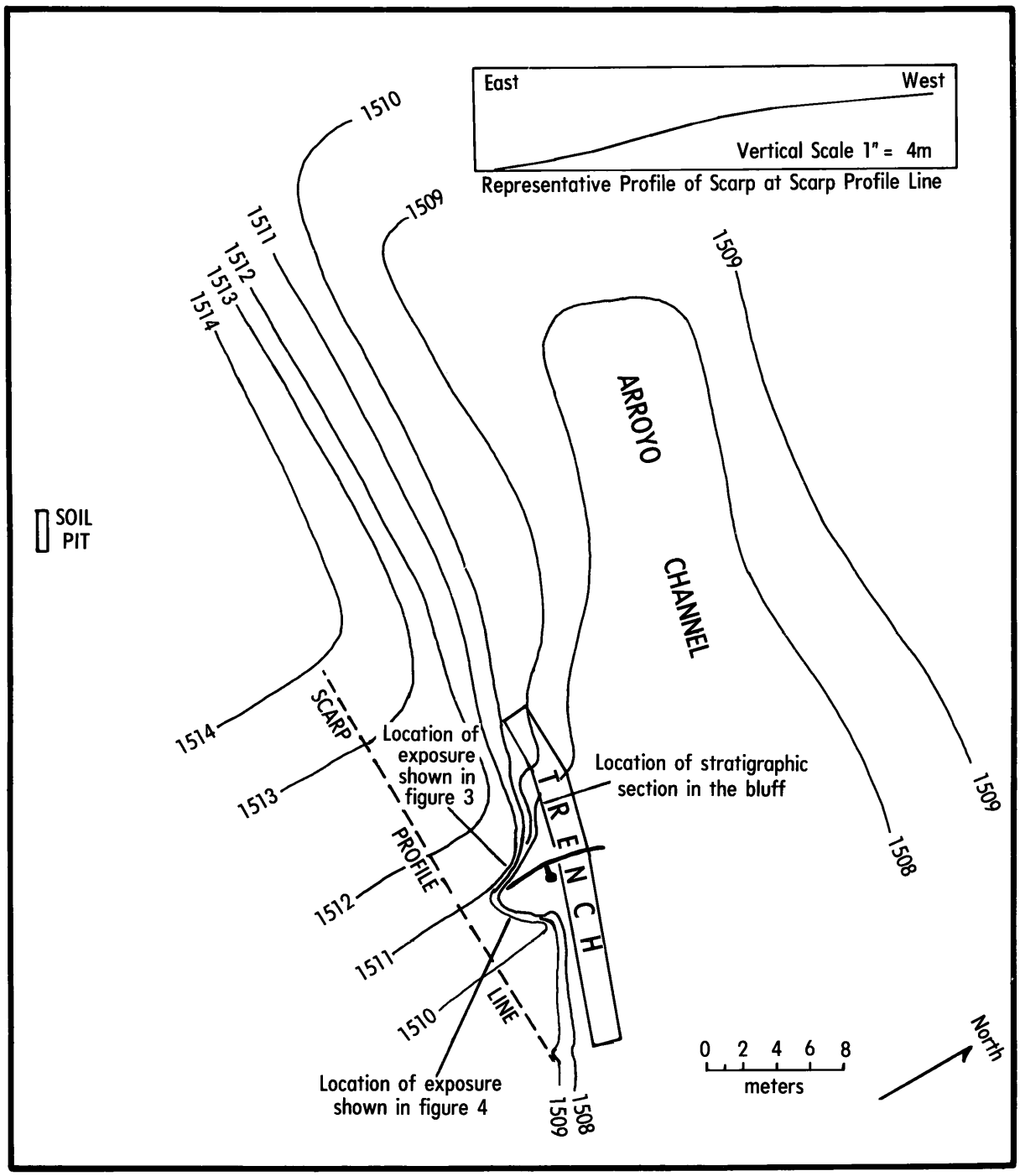

Figure 1. Sketch map showing topography, location of fault trace, soil pit, natural exposure, and a representative scarp profile in the vicinity of the trench. See also Figure 12 of the road log in this volume. Contour interval is 1 m. Fault is shown as heavy solid line with bar and ball on downthrown side. The post-Lake Bonneville soil was studied in the soil pit.

the colluvial wedge, and (3) scarp-profile data.

INTRODUCTION

A 30-km-long, 5-km-wide zone of fault scarps located approximately 30 km northwest of Delta, Utah, on the east side of the Drum Mountains (see Figure 12 of Road Log), is one of the most extensive systems of Holocene fault scarps shown by Nakata and others (1982) in the eastern Basin and Range province. The scarps displace a gently eastward-sloping bajada that is underlain by weakly indurated pre-Lake Bonneville age alluvial and fluvial sand and gravel. The scarps are thought to be all similar in age although recent scarp degradation modeling by Hanks (1982, written communication) suggests the possibility that the scarps with surface offsets greater than about 3 to 4 m may be multiple-event scarps. Data from natural exposures and a 17-m-long, 3-m-deep trench excavated in an arroyo across one of the major fault scarps provide some insight into the stratigraphy of the faulted materials, the amount of stratigraphic offset, the style of the deformation in the fault zone, the characteristics of the faulting event, and the age of faulting (Figure 1). The fault scarp adjacent to the trench site is 3.1 m high and has a surface offset of 2.7 m; the largest scarp measured in the fault system is 7.3 m high with 6.7 m of surface offset (Bucknam, 1982, written communication). The scarp lies at an altitude between the highest shoreline of Lake Bonneville and the lower Provo shoreline, a shoreline which was occupied during the regressive phase of the last lake cycle.

DESCRIPTION OF THE TRENCH

The fault zone exposed in the trench consists of a 75-cm-wide zone of sheared, carbonate-mottled silty sand adjacent to the upthrown (west) block, and an 80-cm-wide zone of disrupted alluvial sands and gravels adjacent to the downthrown block (Figure 2). Undeformed sediments in the upthrown block are in sharp fault contact with the sheared zone, however, in the sheared zone, the original depositional fabric of the sediments is destroyed. Similarly, original bedding in the disrupted sands and gravels is largely obliterated, but two intact, rotated blocks that retained their originial depositional fabric could still be identified. The sense of rotation of the blocks, a system of antithetic joints in the fault zone, and the slight westward dip of the east edge of the fault zone all suggest that a west-dipping antithetic fault probably formed a small graben.

Modern flow in the arroyo channel has preferentially scoured the relatively incompetent sediments of the fault zone, and filled the scour with a wedge of latest Holocene well-sorted sands and gravels. The absence of deformation, drag, or shearing in these gravels precludes very recent movement on the fault.

The trench exposed the near-surface part of the fault zone and the stratigraphy in the displaced blocks east and west of the fault (Figure 2). The upthrown (west) block primarily consists of sands and silty sands; the downthrown (east) block is composed of coarse sands and gravels. At the bottom of the trench (meter 10, Figure 2) in the downthrown block, a distinctive, pale-brown silty sand lies beneath the coarse sands and gravels, but no similar contact is apparent in the upthrown block in the trench. However, a similar sequence of sand and gravel overlying a pale-brown silty sand is exposed in a bluff adjacent to meters 5 and 6 in the trench (Figure 2). Correlating the silty sand across the fault indicates a total stratigraphic throw of 3.7 m; this correlation is supported by particle-size analyses.

DESCRIPTION OF THE NATURAL EXPOSURES

Two natural exposures have resulted from the arroyo incising into the fault scarp, one essentially parallel to and coincident with the fault (Figure 3), and a second nearly perpendicular to the fault (Figure 4). In the exposure nearly parallel to the fault, undeformed alluvial sediments in the upthrown block can be clearly traced to where they are truncated by the fault. The carbonate-mottled, sheared silty clay observed in the trench occurs at the base of the exposure (Figure 3). The exposure perpendicular to the scarp reveals the stratigraphy of the colluvium that buries the lower part of the free face at the base of the scarp (Figure 4). The apparent dip of the buried free face is 73° which probably approximates the true dip of the fault. The dip of the free face declines upward, probably because of erosion. The minimum length of the free face measured in the exposure is 1.4 m; the maximum is 1.8 m. Assuming a free face dip of 73° and a stratigraphic displacement of 3.7 m, an estimated 36 to 45 % of the original free face is preserved by burial.

The most striking aspect of the exposure perpendicular to the fault is the wedge of colluvium at the foot of the scarp. The alluvial sediments beneath the postfaulting colluvial deposits consist of nearly

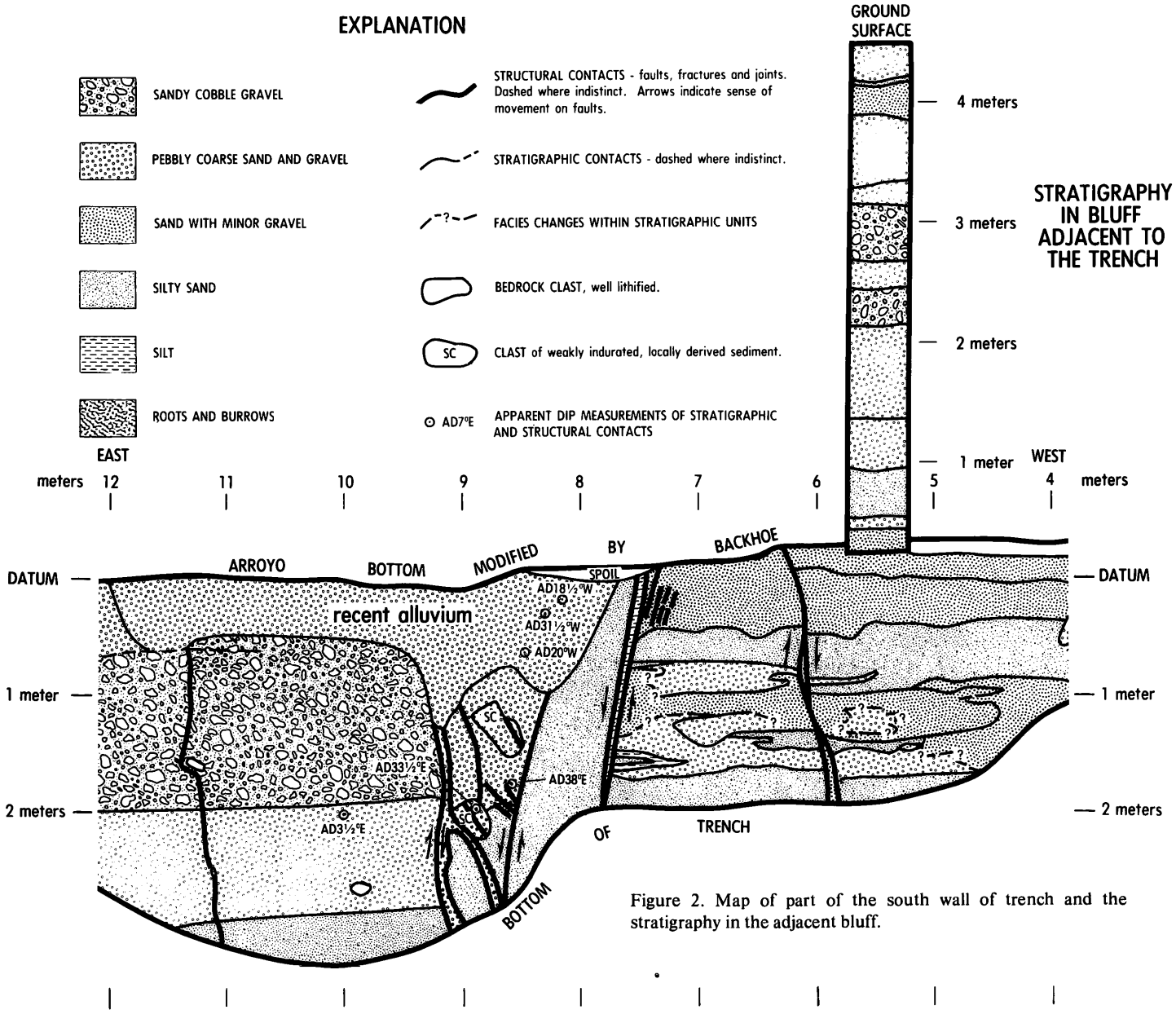

Figure 2. Map of part of the south wall of trench and the stratigraphy in the adjacent bluff.

horizontal, interbedded coarse sands and fine gravels with no recognizable soil on the paleosurface. At the base of the free face, an initially open crack was rapidly filled with debris falling off the scarp. The paleosurface was first buried by a massive, poorly sorted, very coarse, pebbly sand that contains clasts of weakly indurated sediments which spalled off the free face. At this stage, the scarp degradation was controlled by gravity-dominated processes described by Wallace (1977).

The massive sand is overlain by two east-dipping lenses of laminated, coarse to very coarse sand and, in a downslope direction, less steeply dipping pebbly gravel. The lenses of sand are probably sheet-wash deposits that accumulated on the debris slope. A free face still existed at this stage, because this deposit contains large rocks and weakly indurated sediment clasts that fell off the retreating free face.

The youngest colluvium, which extends all the way to the ground surface, is poorly sorted, massive sandy gravel. It probably represents the wash-controlled stage of degradation in which scarp modification is influenced by water movement and

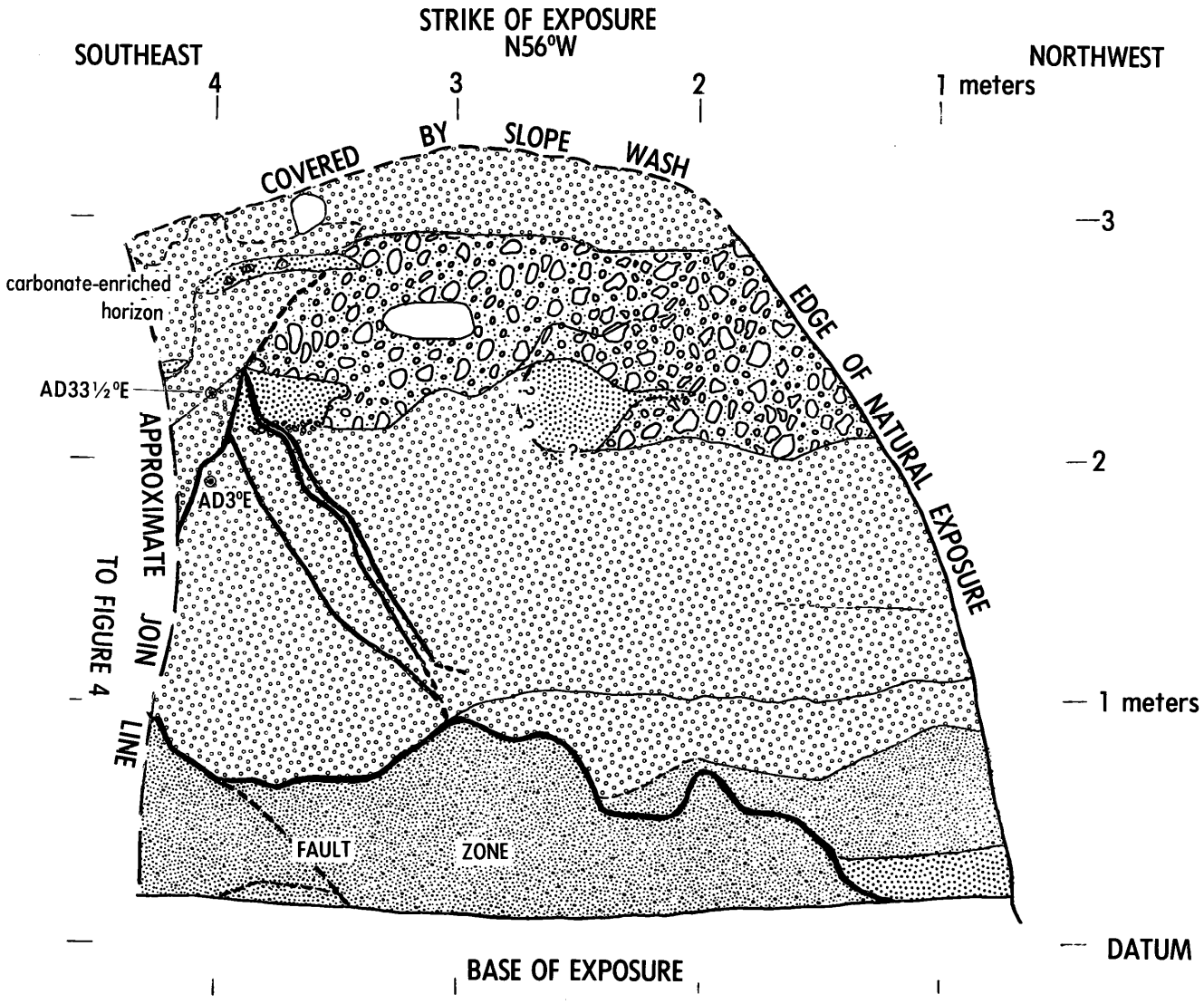

Figure 3. Map of natural exposure oriented nearly parallel to the fault. See Figure 1 for location of the exposure and Figure 2 for explanation of patterns. Southeast edge of exposure imperfectly joins with Figure 4; imperfect junction is due to curvature and irregularity of the exposures.

freeze-thaw effects (Wallace, 1977). A soil forming on the ground surface in this colluvium has a carbonate-enriched horizon that lies closer to the ground surface on the upslope edge of the exposure (Figures 3 and 4) than on the downslope, northeast edge.

DISCUSSION

The difference between the 3.7 m of stratigraphic throw on the fault and the 2.7 m of surface offset measured near the trench site is probably the result of postfaulting net erosion above the scarp, and net deposition below the scarp. Above the scarp, local patches of lag gravels and deflation pockets suggest that erosion has lowered the ground surface; the area below the scarp is primarily in a depositional setting where some alluviation has probably occurred even several tens of meters away from the scarp. The result of the alluviation and erosion is to minimize the measured surface offset.

The single, undeformed wedge of colluvium clearly indicates that the scarp was formed rapidly by one surface-faulting event that had a total throw of 3.7 m at the trench site; the scarp is not the product of tectonic creep. Empirical earthquake magnitude vs. displacement data for world-wide normal slip-faulting events (Bonilla and Buchanan, 1970; Slemmons, 1977; 1982) show that surface displace-

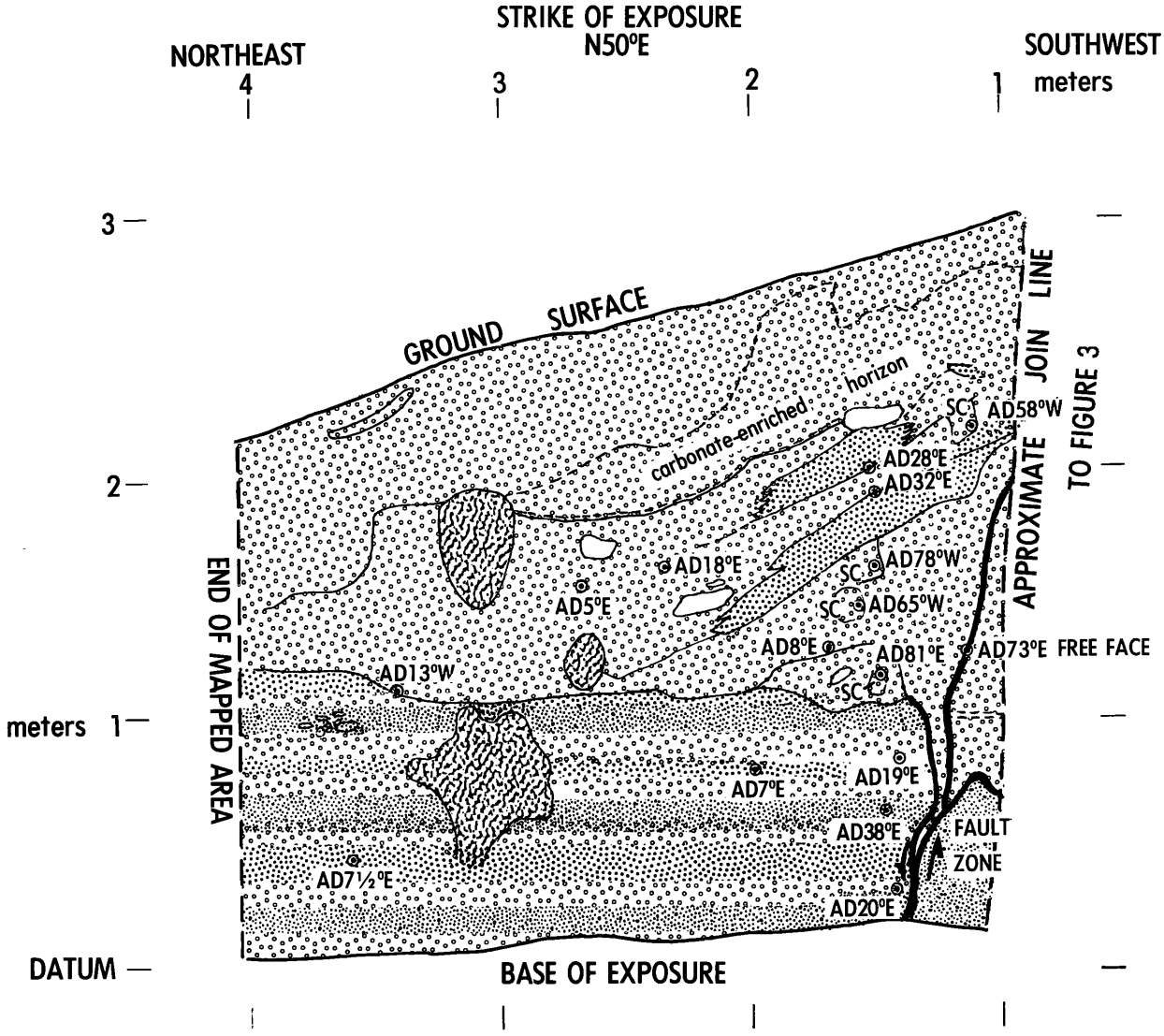

Figure 4. Map of natural exposure oriented nearly perpendicular to the fault. See Figure 1 for location of the exposure and Figure 2 for explanation of patterns. Southwest edge of exposure imperfectly joins with Figure 3; imperfect junction is due to curvature and irregularity of the exposures.

ments of 3 to 4 m typically result from earthquakes with magnitudes of about 7. However, such estimates are subject to large uncertainties related to numerous geologic variables and, therefore, should be treated cautiously.

Conflicting age estimates exist for the Drum Mountains fault scarps. The close similarity between the profiles of the fault scarps and the Bonneville shoreline suggests to Bucknam and Anderson (1979) that the shoreline and scarps are similar in age. However, diffusion-equation modeling estimates an age of about 5,000 yrs (S. M. Colman, 1982, written communication) or perhaps even younger for those scarps with surface offsets less than 3 to 4 meters (T. C. Hanks, 1982, written communication). This report provides some new geologic data that, when combined with other data, suggests broad age constraints. Some of the scarps displace 13,500-year-old Provo-level shoreline features (Scott and others, 1982), establishing a maximum age. A preliminary comparison of the percent carbonate in the soil formed in the postfaulting colluvium with the carbonate in the post-Lake Bonneville soil beneath the relatively stable ground surface of the upthrown block suggests that the soils are similar in age. This assumes that all of the carbonate

in the colluvial soil is pedogenic, and none is related to ground-water effects at the relatively steep scarp slope. The absence of any recognizable soil on the paleosurface beneath the colluvial wedge suggests that, after Lake Bonneville receded from its high stand, this surface was not subaerially exposed for a substantial time before faulting and rapid burial occurred. In addition, the wash-slope processes interpreted from the colluvial stratigraphy and the rounding of the scarp crest as observed in this scarp (Figure 1) become significant in 10,000 year old scarps (Wallace, 1977, p. 1272). All of these observations suggest an early Holocene age for the scarps.

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LATE CENOZOIC FAULTING IN HEBER AND KEETLEY VALLEYS, NORTHEASTERN UTAH

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Late Cenozoic normal faults bounding mountain ranges in northeastern Utah as well as contemporary seismicity east of Salt Lake City, indicate that Basin and Range structure extends east of the Wasatch fault (Figure 1). Neogene normal faults and associated scarps in late Quaternary deposits are found both north of the field-trip route in Cache Valley and Bear Lake Valley and south of the field-trip route in Strawberry Valley (Nelson, 1982) and on the Wasatch Plateau. The intervening area, termed the Wasatch hinterland, is a diverse geologic terrain bearing the imprint of Cretaceous thrusting, late Cretaceous to Paleogene clastic sedimentation, folding and faulting, and Oligocene volcanism.

Erosional/structural basins, termed "back valleys" (Figure 1) by G. K. Gilbert (1928, p. 58), are the dominant physiographic features of the Wasatch hinterland. Gilbert concluded that the Wasatch Mountains are a horst block bounded on the east by the Ogden and Morgan Valley grabens and on the west by the Wasatch fault. Eardley (1933, 1944, 1955) and his students concluded that these back valleys developed as a result of folding, erosion, and Basin and Range style faulting, and they are so interpreted on recent geologic maps (e. g., Hintze, 1980). Our compilation of water-well logs in all the back valleys confirms previous interpretations (Baker, 1964, 1976; Leggette and Taylor, 1937) that the bedrock floors of some back valleys are lower in elevation than their outlets. Closed residual gravity lows in the back valleys have been interpreted as representing significant thicknesses of low-density fill. These lines of evidence support the conclusion that the Neogene and Quaternary physiographic development of the Wasatch hinterland has been controlled in part by normal faulting

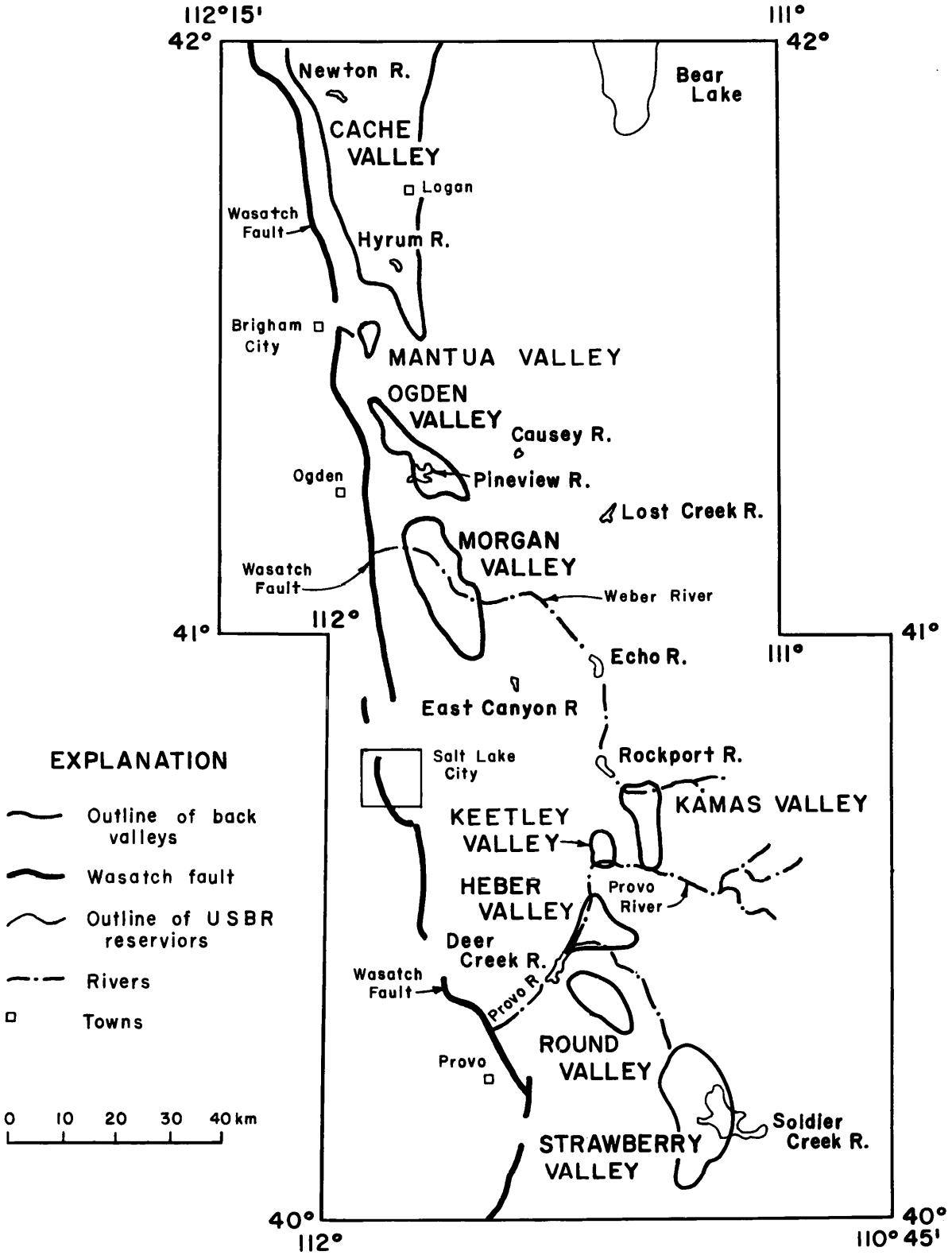

Figure 1. Map of the back valleys, the Wasatch fault, selected rivers and the U.S. Bureau of Reclamation (USBR) reservoirs in part of northeastern Utah. The trip focuses on Heber Valley and Keetley Valley, but the seismotectonic study for USBR dams encompasses all of the back valleys.

(Sullivan, 1982).

In order to determine whether fault scarps in late Quaternary deposits are evident in the back valleys of the Wasatch hinterland, we reviewed aerial photography at various scales and made several low-sun-angle overflights. While no obvious fault scarps were observed, three possibly fault-related lineaments were identified for further study. Trenches excavated across these features in Heber Valley and Round Valley revealed they have a non-tectonic origin. Exploration at a site in Mountain Meadows near Peoa is in progress.

HEBER VALLEY

Geologic maps of Heber Valley (Stokes and Madsen, 1961; Hintze, 1980; Baker, 1976; and Bromfield and others, 1970) do not show bounding faults on the margins of Heber Valley. Peterson (1970) found a 4-m/gal residual gravity low centered in the southwestern portion of Heber Valley. Assuming a density contrast of 0.5 g/cm^3 between the valley fill and bedrock, he computed a maximum thickness of 240 m for the alluvial fill. No water-well holes in the central or southwestern portion of the valley reached bedrock, with numerous holes bottoming in greater than 60 m of alluvium. The deepest hole near Charleston reached 98 m entirely in alluvium. Bedrock in the foundation of Deer Creek Dam is at a higher elevation than the bedrock floor of Heber Valley near Charleston (Baker, 1964; 1976). Thus, prior to and/or during the aggradational episodes represented by the present valley fill, the floor of Heber Valley was downdropped along unmapped faults relative to its outlet (Figure 18 in road log).

On the south side of Heber Valley scarps 2 to 20 m in height occur in alluvial fans along the valley margin. One of these, a 600-m-long linear scarp varying in height from 1 to 12 m, is a suspected Quaternary fault (Anderson and Miller, 1979). Because this feature is the best evidence for late Quaternary faulting in Heber Valley, we excavated a 36-m-long backhoe trench across the scarp where it is 6 m in height with a maximum scarp angle of 26° (Figure 2). Rounded fluvial gravels (with cobbles up to 0.3 m long of Daniels Canyon provenance) in the lower portion of the trench apparently abut undeformed, well stratified alluvial fan sediments of local origin (Figure 3). Soil profiles on both the fan deposits and the colluvial units overlying the fluvial gravels are weakly developed. Comparison with profiles on Lake Bonneville deposits (Scott and others, 1982) and on terrace deposits traceable into moraines in the headwaters of the Weber River (Figure 1) (Nelson and Krinsky, 1982) suggests an age of less than 15,000 years for both profiles. We conclude that this scarp is erosional in origin. We can only preclude surface displacements along the valley margin during at most the last 15,000 years.

KEETLEY VALLEY

Published maps of Keetley Valley (Bromfield and others, 1970; Bromfield and Crittenden, 1971) do not show late Cenozoic normal faults. However, USBR drill logs in the proposed Jordanelle damsite and reservoir in Keetley Valley reveal that bedrock of Oligocene age is at a lower elevation in the center of the valley than at the damsite at the outlet of the valley; therefore unmapped Neogene faults must be present in Keetley Valley (Figure 4 and road log). Our investigations in the valley have focused on (1) identifying valley margin and intragraben faults and (2) assessing their age of most recent displacement.

Locations of intragraben faults on Figure 4 have been inferred from subsurface bedrock topography delineated through drilling and seismic refraction profiling as well as airphoto lineament interpretation in the valley. Nine trenches in seven locations have been excavated in well stratified, undeformed basin-fill deposits across the inferred traces of intragraben faults. Paleomagnetic analyses of samples from cores taken in the basin-fill deposits, fine-grained units in trenches, and soil pits throughout Keetley Valley show that much of the sequence contains a reversed component of remnant magnetization indicating an age of more than 730,000 yrs. In the northeastern part of the valley volcanic ash occurs within fine-grained units typical of the basin-fill sequence. The ash has petrographic and morphologic similarities with the Lava Creek Ash (600,000 yrs old) as well as several Pliocene ashes (R. E. Wilcox, 1982, oral communication). Near the southern end of the valley amino acid ratios on snails from a bed of pond sediment in the basin fill suggest an age of 0.7 to 1.0 m.y. Based on this evidence we have concluded that there has been no surface displacement in at least the last 730,000 years on the inferred intragraben faults that we have evaluated.

Valley margin faults were inferred on the basis of airphotograph interpretation, limited drilling data, and electrical resistivity surveys. Two trenches in two locations were excavated across the western valley margin fault (Figure 4).

In trench J-9 (Figure 5) a fault juxtaposing the Oligocene Keetley Volcanics and the Pennsylvanian Weber Quartzite strikes N. 20° E. and dips 80° E. A

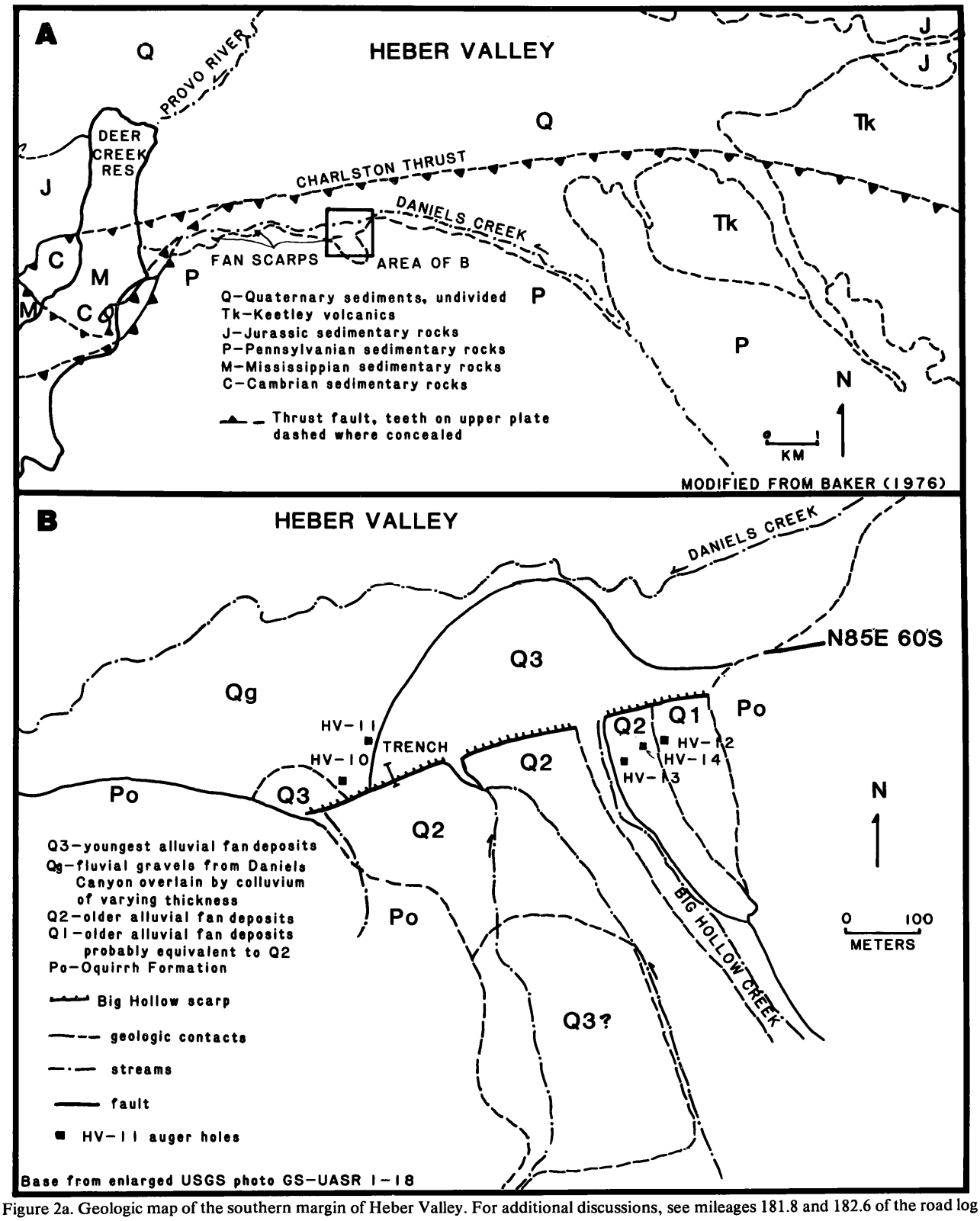

Figure 2a. Geologic map of the southern margin of Heber Valley. For additional discussions, see mileages 181.8 and 182.6 of the road log in this volume.

Figure 2b. Location of the Big Hollow fan scarp and the exploratory trench. The scarp has a strike that is similar to the strike of the reverse fault in the face of the gravel pit east of the fan. The log of the trench is shown in Figure 3. Stage III soil carbonate horizons exposed in a road cut and in an auger hole (HV-12) suggest that the eastern edge of the fan (Q1) is older than the main fan surface (Q2). The youngest fan deposits (Q3) postdate the scarp.

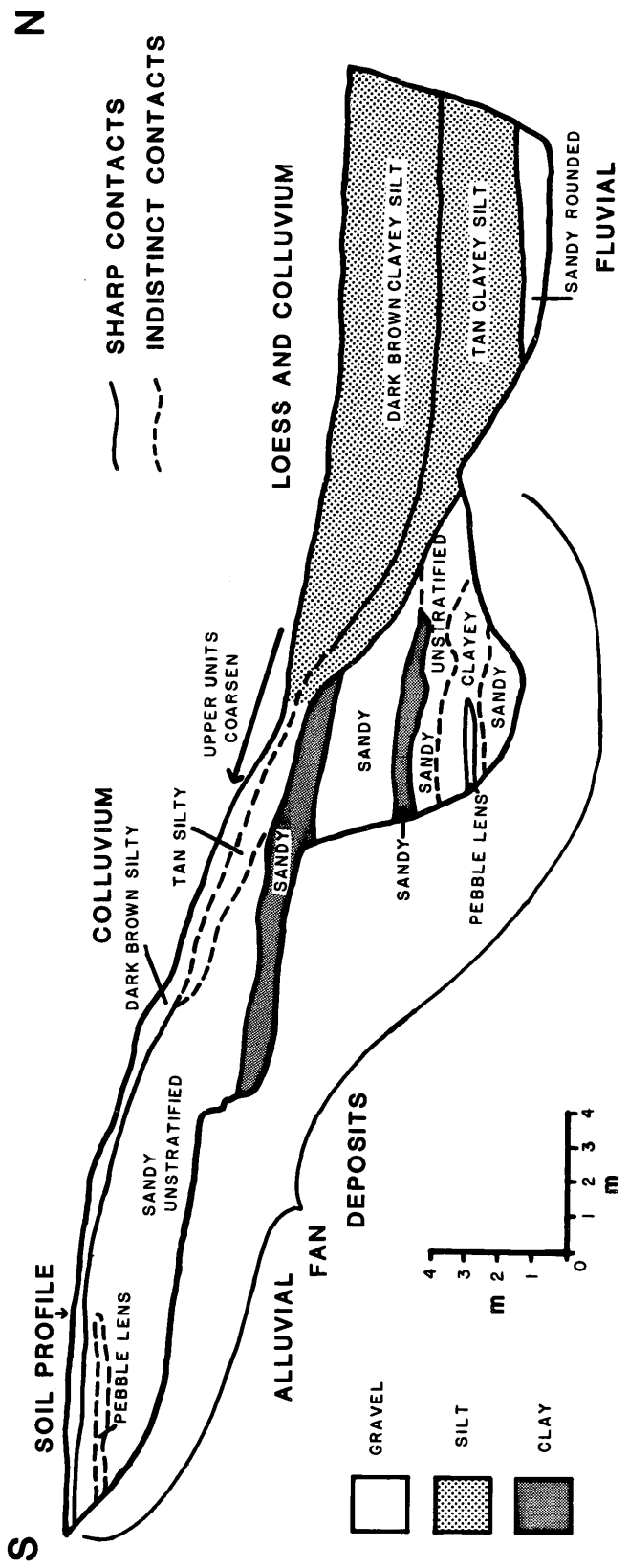

Figure 3. Log of the exploratory trench across the Big Hollow fan scarp in southern Heber Valley. The scarp has been cut in interbedded stream, mudflow, and debris flow alluvial fan deposits, apparently by Daniels Creek (figure 2a) during periods of high discharge. The younger colluvial units are gravelly where they incorporate the fan sediments. Below the scarp 5 m of loess and fine slopewash deposits have accumulated. Soils on the alluvial fan sediments and on the rounded fluvial gravels near the trench site have cambic B horizons.

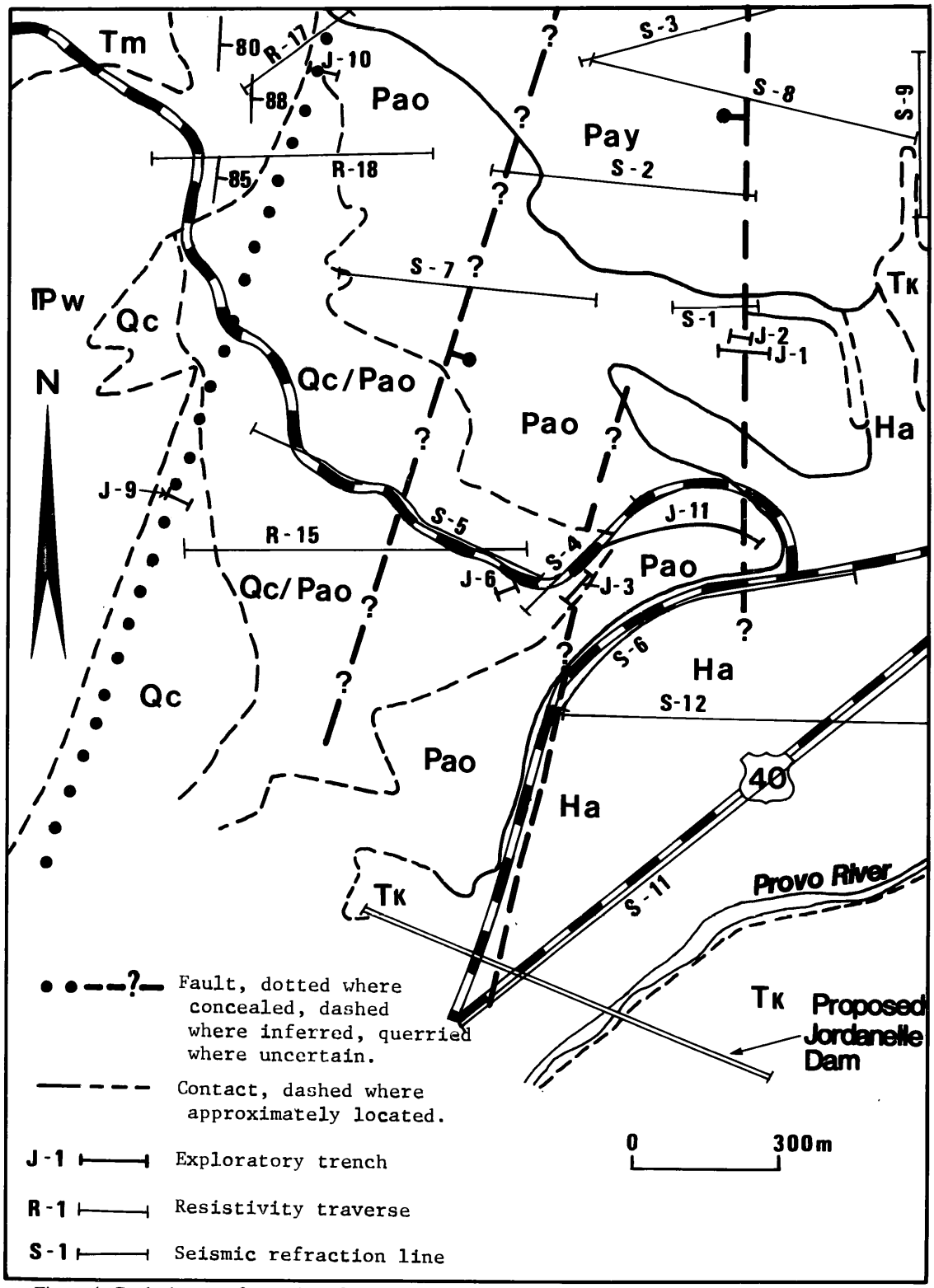

Figure 4. Geologic map of a portion of Keetley Valley; Pw - Pennsylvanian Weber Quartzite; Tm - Oligocene Mayflower stock; Tk - Oligocene Keetley Volcanics; Pao - older Pleistocene alluvial basin fill; Pay - younger Pleistocene alluvium; Qc - Quaternary colluvium (undifferentiated); Qc/Pao - Quaternary colluvium overlying older Pleistocene basin fill; Ha - Holocene alluvium. Trenches J-9 and J-10 exposed a bedrock fault on the western margin of Keetley Valley. Other faults are inferred on the basis of drilling and geophysical data. Heavy dashed black and white lines are roads.

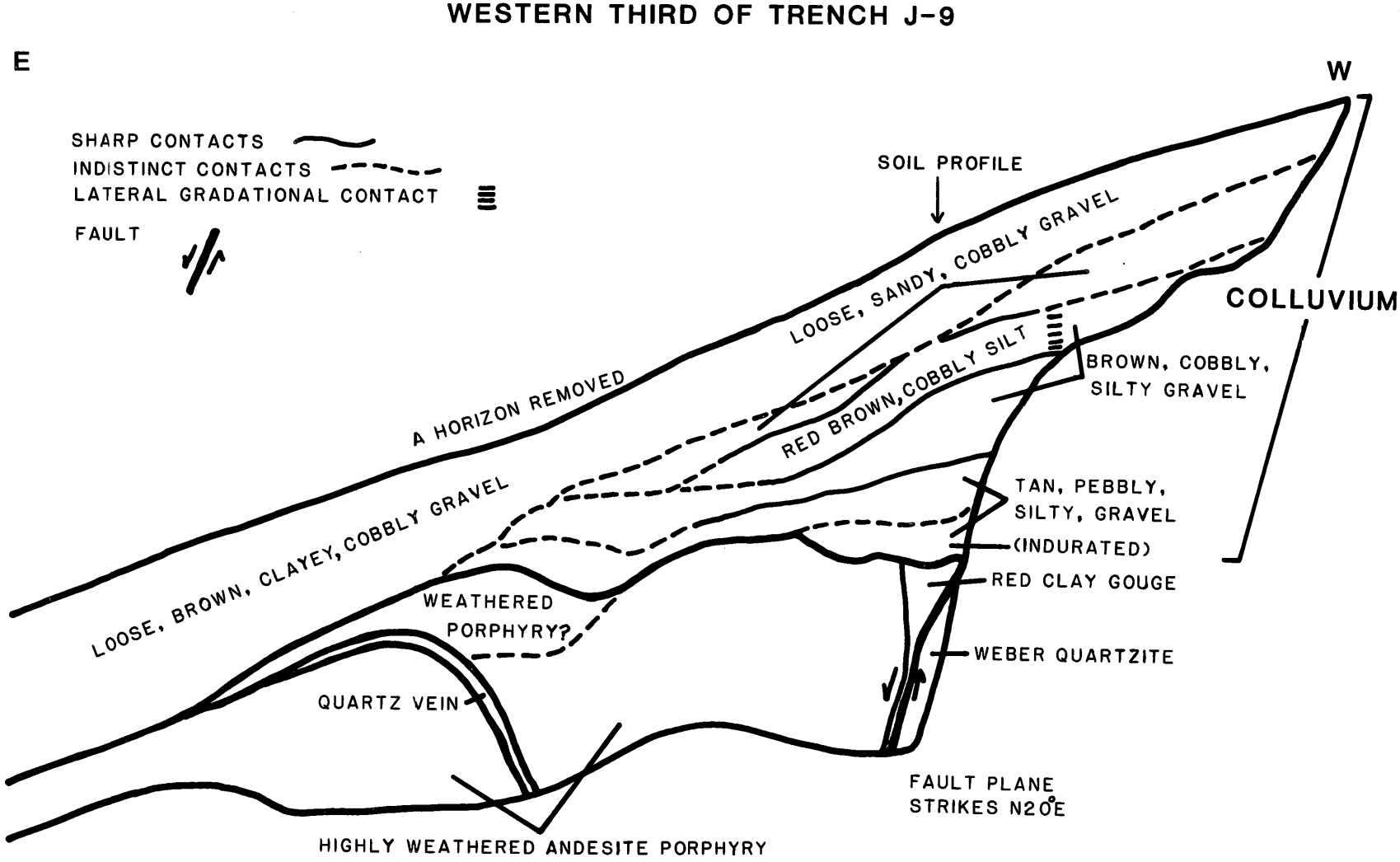

Figure 5. Log of the western third of trench J-9 excavated across a vertical fault bounding Keetley Valley on its western margin. Highly weathered, Oligocene andesite porphyry is faulted against Pennsylvanian Weber Quartzite. There is no evidence of shearing along the contacts of the colluvial units with the bedrock; therefore, the lower and middle colluviums are interpreted as post-faulting deposits. An argillic B horizon developed on the middle colluvial units (red-brown, cobbly silt) suggests a period of slope stability. This unit grades laterally into material that resembles the lower brown, cobbly, silty gravel, but this is a gradational contact and does not indicate displaced beds of the same depositional unit. The upper colluvial units are younger, derived from more recent colluvial processes, but the thick B horizon on them (loose, brown, clayey, cobbly gravel) suggests a low rate of colluvial downslope transport. Rates of B horizon development on slopes are difficult to estimate, but the B horizons together must represent at least several tens of thousands of years. See also Stop 4, Day 2 of the road log in this volume.

45° angle hole collared 24 m downslope of the trench established that the fault dips 90°. On Figure 5 the 2.1-m-thick wedge of three colluvial units overlying the andesite prophyry on the downthrown side of the fault appears to be in depositional contact with the Weber Quartzite. The oldest of these colluvial units clearly truncates the gouge and breccia of the bedrock fault zone. This wedge of colluvium could be interpreted as evidence for discrete Neogene or Quaternary surface displacements on this fault; however, unless displacement rates on the fault are lower than the local erosion rate, we would expect a significantly greater thickness of colluvial deposits on the downthrown side in fault contact with the Weber Quartzite.

Overlying the wedge of colluvium, undeformed colluvial horizons 1.5 m thick extend across the fault. Based on our estimate of the age of B horizons developed in this colluvium, there have been no surface displacement on this fault in at least the last few tens of thousands of years. This conclusion is supported by the lack of scarps in colluvial deposits (Qc on Figure 4) immediately northeast of the trench site along the projection of the fault.

CONCLUSION

Despite signficant levels of contemporary seismicity, we find no evidence for late Quaternary surface displacements in Heber or Keetley Valleys.

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