Reprinted from: Picard, M.D., ed., 1985, Geology and energy resources, Uinta Basin, Utah: Salt Lake City, Utah, Utah Geological Association Publication 12.

Manuscript accepted for publication: March 1983.

QUATERNARY FAULTING ON TOWANTA FLAT, NORTHWESTERN UINTA BASIN, UTAH

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ABSTRACT

Fault scarps up to 15 m high form a 5-km-long, northeast trending graben on Towanta Flat, an outwash plain on the southwest flank of the Uinta Mountains. Mapping, relative-age dating, and regional correlation of moraines and outwash terraces in the area indicate many of the faulted deposits on Towanta Flat are 250,000 to 500,000 years old. No scarps were mapped in outwash deposits of the "Bull Lake" glaciation that are interpreted to be 60,000 to 150,000 years old. Two backhoe trenches confirm that "Bull Lake" deposits are unfaulted. Colluvial stratigraphy and soil development in a third trench, across a 5-m-high graben scarp, suggest at least three "pre-Bull Lake" surface faulting events with stratigraphic displacements of 2 to 3 m and a recurrence of 50,000 to 100,000 years. Individual fault scarp slip rates derived from scarp and trench data are 0.02 to 0.06 mm/yr, but there is no net tectonic offset across the graben. Although the Towanta Flat scarps may be a response to regional Quaternary tectonic stresses, the scarps are of very limited extent and their orientation does not match that of planes defined by microearthquake studies in the area.

INTRODUCTION

Huddle et al (1951) first suggested that late Tertiary faulting was present on Towanta Flat, an outwash plain along the south flank of the Uinta Mountains (Fig. 1). Hansen (1969a, 1969b) described the topographic scarps on Towanta Flat (Fig. 2) as representing late Quaternary faulting and estimated the youngest displacement to date from 32,000 to 11,000 yr BP (years before present) based on the inferred age of the faulted Quaternary deposits. Osborn (1973) concurred with Hansen's findings, but also suggested that the faulting could be even younger. Anderson and Miller (1979) also assigned a late Quaternary age to the Towanta Flat scarps. Ritzma (1974) suggested these scarps are associated with a much larger east-west structural feature that he named the "Towanta Lineament."

Following the occurrence of a Richter magnitude 4.5 earthquake in the general area of Towanta Flat on September 30, 1977, the Utah Geological and Mineral Survey (1977) reported this main shock and the hundreds of aftershocks that were recorded through October, 11, 1977, occurred along the "Towanta Lineament." The report also stated there are surface manifestations of relatively recent movement along the lineament, citing Towanta Flat, where displacements have occurred "perhaps as recently as 4,000 to a few hundred years" before present.

An indirect implication of this report is that earthquakes large enough to produce surface displacement are recurring on Towanta Flat at a rate comparable to that for the Wasatch fault (Swan et al, 1980), one of the most active faults (definition of Wallace, 1981) in the intermountain west. Also, association of the Towanta Flat scarps with Ritzma's (1974) "Towanta Lineament" would imply latest Quaternary displacement on a segment of an inferred structure which Ritzma traces across most of the State of Utah.

TECTONIC SETTING

The scarps on Towanta Flat overlie the trace of the concealed Uinta Basin fault (Fig. 1) which is believed to be the major structural feature bounding the south flank of the western Uinta Mountains (Garvin, 1969; Ritzma, 1969). The South Flank fault is a 130-km-long normal fault dipping 60 to 80° to the south which is thought to be antithetic to the Uinta Basin fault (Campbell, 1975). The South Flank fault developed in response to major mountain-forming upthrusting involving the Uinta Basin fault during the Laramide Orogeny as the core of the Uintas locally was thrust vertically and laterally over the Paleozoic and Mesozoic sediments to the south.

The Uinta Basin fault, concealed by Tertiary sediments for its entire length, offers no evidence to evaluate the age of its most recent movement. However, the South Flank fault, exposed in many locations, is onlapped by sediments ranging from Oligocene (Browns Park Formation) through Holocene in age (Fig. 1). Martin et al (1984) did not find any evidence for displacement of these Tertiary and Quaternary sediments along the western 100-km portion of the South Flank fault suggesting that the major isostatic and tensional adjustments in the uplifted block were completed by the early Oligocene.

An aftershock study following the September 30, 1977 magnitude 4.5 M_L earthquake by Carver et al (1983) identified an aftershock zone striking N. 10° E. with dip 45° ESE. 5 km northwest of the Towanta Flat scarps. Composite focal-mechanism solutions for the aftershocks indicate normal faulting and agree well with the planar zone defined

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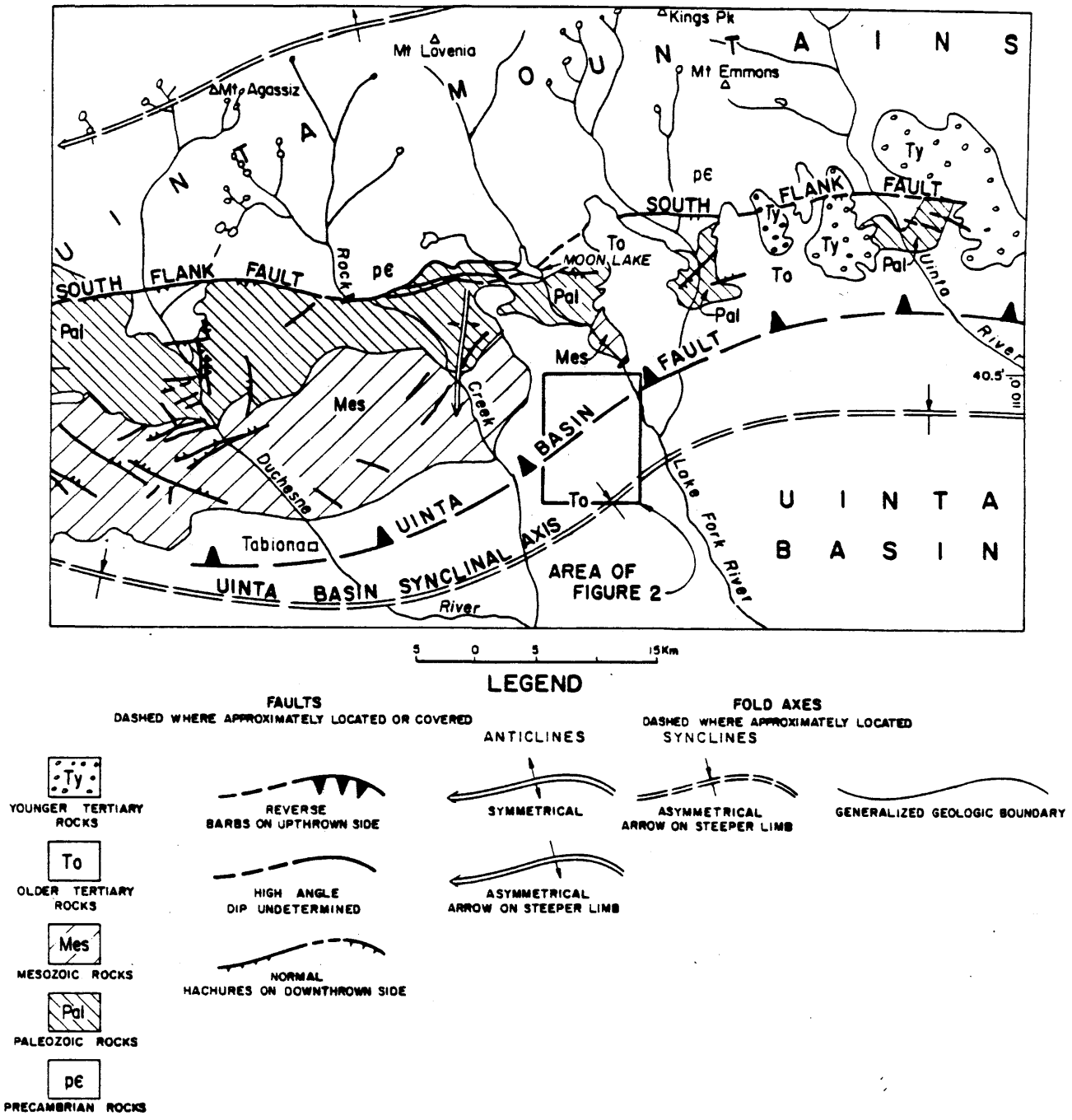
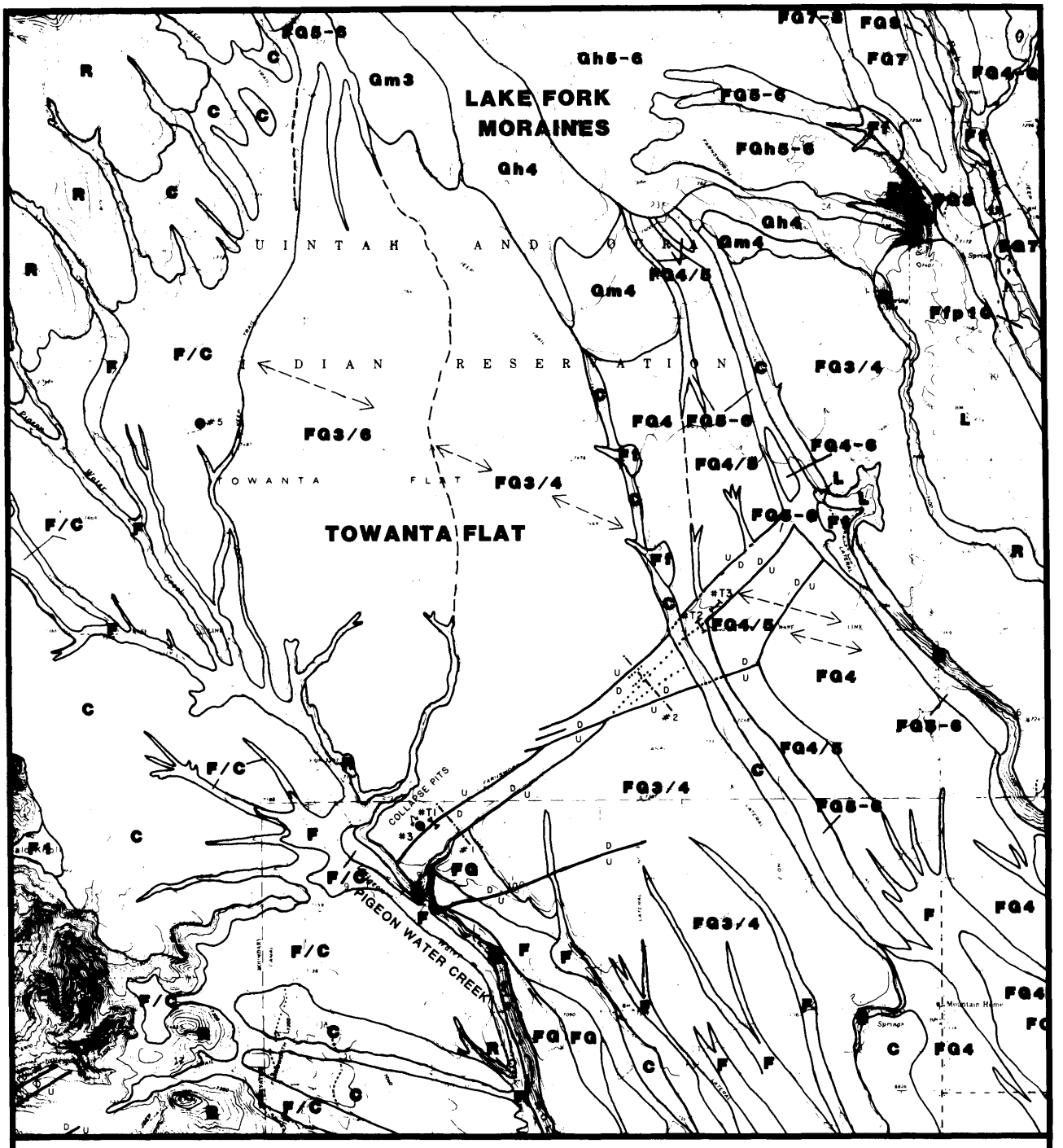


Figure 1.—Geologic sketch map of the south flank of the Uinta Mountains and the adjacent northwestern Uinta Basin in northeastern Utah (modified from Campbell, 1975). Major geologic structures and the area of Figure 2 encompassing Towanta Flat are also shown. Note that the Uinta Basin fault is concealed along its entire length (see text).

Figure 2.—Quaternary geology map of Towanta Flat using a genetic-morphologic-relative-age mapping system based on systems used by Canada Soil Survey Committee (1978) and Keaton (1980). Note that the digit portion of the map units refers to relative-age groups (RAGs) based on a sequence of seven levels of outwash terraces along the Lake Fork River (Table 1 and text). RAG 10 consists of Holocene floodplain deposits. The age of units without relative-age designations is uncertain. The location of faults, air photograph lineaments, exploratory trenches, resistivity survey lines, and the collapse pits near Pigeon Water Creek are also shown. All the mapped faults on Towanta Flat are marked by topographic scarps. The location of concealed faults in the graben is inferred from the resistivity data. The dashed arrows show the approximate location of groups of air photograph lineaments. Trench 3 intersects one of these lineaments. Trench 2 intersects a northeast-trending lineament (shown as an inferred concealed fault) on trend with a 2-m-high scarp. Mapped bedrock (R) consists of the Tertiary Duchesne River Formation (Anderson and Picard, 1972).



EXPLANATION

DESCRIPTION OF MAP UNITS

Ff 4-6

GENETIC SYMBOL	MORPHOLOGIC QUALIFIER	RELATIVE AGE GROUP
F - FLUVIAL	f - FAN	1 THROUGH 10, OLDEST TO YOUNGEST
G - GLACIAL	m - SUBDUED MORAINE	/ SIGNIFIES AREA OF DEPOSITS OF SEVERAL RELATIVE AGES
FG - GLACIOFLUVIAL	h - HUMMOCKY MORAINE	- SIGNIFIES UNCERTAINTY OF AGE)
C - COLLUVIAL	fp - FLOODPLAIN	
L - LANDSLIDE		
R - BEDROCK		

/ SIGNIFIES AREA OF DEPOSITS OF MIXED GENESIS — SIGNIFIES UNCERTAINTY OF GENESIS)

SCALE 0 1 Km

BASE: MOUNTAIN HOME USGS 1:24,000 QUADRANGLE

SYMBOLS

- GEOLOGIC CONTACT
- GRADATIONAL GEOLOGIC CONTACT
- FAULT (U / D)
- FAULT CONCEALED
- SITE NUMBER
- SOIL PROFILE DESCRIPTION SITE
- TRENCH SITE
- TRENCH NUMBER
- TREND OF AIR PHOTO LINEAMENT
- RESISTIVITY LINE

Table 1.—Indexes of soil development and estimated ages for profiles on moraines, outwash, and alluvial deposits in the Towanta Flat area and Lake Fork River and Yellowstone River Valleys, Utah.

Relative-age group (RAG)	Parent material	Relative elevation[1] (m)	Color index[2]	Max clay		Max carbonate			Max weathered clasts (%)[6]	Estimated relative age[7]	Estimated absolute age (10^3 yr BP)
				%	g/cm^3[3]	%	g/cm^3[4]	stage[5]			
9	till		24	6	—	0	0	0	0	"late	12-15[8]
	outwash	7	50	2	—	0	0	0	0	Pinedale"	
7-8	till		40	7	0.03	20	0.15	II	0	"Pinedale"	15-70[8]
	outwash	20	60	9	0.03	1	0.01	0	0		
5-6	till		80	20	0.24	46	0.08	II+	2	"Bull Lake"	60-150[8]
	outwash	36	72	32	0.33	6	0.01	I−	10		
4	till		80	20	0.11	25	0.13	III−	20	"pre-Bull	►130[8]
	outwash	48	72	38	0.32	71	0.34	V−	70	Lake"	
3	till		60	18	0.02	24	0.07	IV	30	"pre-Bull	250-500[8]
	outwash	84	80	28	0.11	68	0.31	IV	70	Lake"	
2	alluvium	132	—	—	—	52	—	IV	70	Quaternary	►500
1	alluvium	330	—	—	—	85	—	V+	90	Quaternary	►500

[1]Elevation above the present Lake Fork River.
[2]Maximum dry color of B/C horizon, index of Buntley and Westin (1965) except that a numerical notation of hue (2.5 YR = 12, 5 YR = 10, 7.5 YR = 8, 10 YR = 6, 2.5 Y = 4) is multiplied by chroma (e.g., Meierding, 1977, p. 189).
[3]Method of Machette (1978) substituting percent clay for percent carbonate; bulk density estimated from measurement of selected samples (Table 2); 10 percent initial clay assumed for RAG 3 and 4 deposits, 5 percent for younger deposits.
[4]Method of Machette (1978); bulk density estimated from measurement of selected samples (Table 2).
[5]Terminology of Gile et al (1966) and Bachman and Machette (1977).
[6]Clasts which can be broken by hand.
[7]Quotation marks are used to emphasize our use of these terms as informal regional quasi-geologic-climate units with time-transgressive boundaries based on major weathering and morphologic breaks in the local late Quaternary sequence.
[8]Based on dating studies summarized by Pierce et al (1976), Rosholt (1980), Colman and Pierce (1981), Porter et al (1983), and Shroba et al (1983).
[9]Amino acid age estimate discussed in text.

by the aftershock hypocenters. A 6-month study of microearthquake activity 3 years later by Martin (1982; 1983) yielded a similar distribution of hypocenters and similar composite focal-mechanism solutions. These results indicate east-west extension in this area (Carver et al, 1983; Martin, 1982) and agree well with the results of Preston (1966; cited in Carver et al, 1983) who made overcoring measurements using photoelastic strain gages 50 km to the south. However, no north-south trending normal faults are mapped in the area.

The close proximity of the Towanta Flat faults to the subsurface trace of the Uinta Basin fault suggests that some of the observed surface displacement might be due to differential compaction of the Tertiary sediments above the upturned Paleozoic and Mesozoic strata adjacent to the Uinta Basin fault at depth. A similar style of faulting has been observed in the Tertiary deposits that overlie the Sparks thrust on the north flank of the Uintas (Fig. D in Ritzma, 1956). However, compaction should produce small displacements fairly continuously over a long period rather than discrete displacements of several meters at widely spaced time intervals (discussed below).

AGE OF TOWANTA FLAT

The Towanta Flat outwash plain (Fig. 2), deposited by glaciers from the Lake Fork River valley, was first mapped by Atwood (1909) and in more detail by Hansen (1969a, 1969b) and Osborn (1973, p. 78). We estimated the age of Towanta Flat by mapping it as part of the sequence of outwash terraces along the Lake Fork River which slope southward from the Lake Fork moraines and then correlating these terraces with similar dated sequences in the Rocky Mountain region (Table 1).

The outwash terraces along the Lake Fork River can be divided into seven different levels (numbered 3 through 9 on Table 1) based on their relationship with the moraines and/or elevation above the Lake Fork River. High, isolated remnants of older alluvial surfaces in the area are placed into two older relative-age groups (RAG 1 and RAG 2 on Table 1) while the youngest outwash deposits (terrace level 9) were assigned to relative-age group 9 (RAG 9). In contrast to Osborn (1973, p. 35), we feel the degree of soil development (indicated by various indexes on Table 1) in profiles on the middle level outwash terraces allows them to be easily grouped into three categories of different relative

age (RAG 4, RAG 5-6, RAG 7-8; Table 1). Most of these outwash surfaces grade into the Lake Fork moraines, and the major relative weathering breaks on the terraces indicated by soil development are the same as those suggested by the surface weathering and soils data collected from the moraines (Nelson, 1982). Using these weathering breaks, we correlate all but our oldest relative-age groups with the widely used stratigraphic terms for glacial events in the Rocky Mountain region (Table 1). However, the absolute-age estimates for these events have changed considerably since Hanson (1969a, 1969b) estimated the age of the deposits that he attributed to Bull Lake glaciation on Towanta Flat.

The large, high-level outwash plain (FG 3/4 on Fig. 2) of Towanta Flat grades into the subdued moraines of RAGs 3 and 4. Channels on the surface of Towanta Flat show it was partially covered by braided streams during both periods of moraine deposition, making the surface a mixture of both RAG 3 and RAG 4 outwash. The western edge of Towanta Flat (FG 3/6 on Fig. 2) was partially dissected by meltwater streams issuing from RAG 5-6 moraines at the northwest corner of the flat where they overrode the older moraines at the edge of the mountains.

A large 2-km-wide meltwater channel, which is floored over most of its surface with outwash of RAG 4, extends north-south across Towanta Flat (Fig. 2). Soils on the main surface of the meltwater channel are similar to those on the higher Towanta Flat surface (RAGs 3 and 4) suggesting a similar age. Within the main meltwater channel are much smaller outwash channels which head in the moraines of RAG 5-6. Soil profiles developed on this outwash (in trenches 2 and 3, discussed below), although eroded, suggest the channels are older than RAG 7-8.

Two lines of evidence indicate the main Towanta Flat surface is considerably older than even the present estimates of the age of "Bull Lake" glacial deposits (correlated with RAG 5-6 deposits, Table 1). Using the average rate of carbonate accumulation calculated by Machette (1978) for a sequence of paleosols near Albuquerque, New Mexico, the percentage of carbonate in the RAG 3 and Rag 4 outwash soils on Towanta Flat indicates ages of 280,000 to 490,000 yr BP. Unless carbonate accumulation rates are much higher in the Uinta Basin than in New Mexico, the carbonate-rich soils suggest most of the surface of Towanta Flat is much older than "Bull Lake" events elsewhere in the Rocky Mountain region (Table 1).

Using topographic profiles of the outwash terraces along the Lake Fork River, Towanta Flat can be correlated with South Myton Bench, 36 km to the southeast near the confluence of the Duchesne and Lake Fork Rivers (Osborn, 1973, plate 7). Coarse outwash gravels that we correlate with Towanta Flat are exposed in a gravel pit in the bench at the mouth of Antelope Canyon on the south side of the Duchesne River. Fine alluvium which overlies the coarse gravels is normally magnetized indicating an age of <730,000 yr BP, and amino acid analyses of terrestrial gastropod shells in the fine alluvium give an age estimate of 375,000 ± 120,000 yr BP for the gastropods (Nelson, 1982). Thus, parts of the main Towanta Flat outwash surface are at least 250,000 to 500,000 years old (RAG 3), some of the surface and much of the large meltwater channel are younger than this but more than 130,000 yr BP (RAG 4), and the younger channels within the meltwater channel are 60,000 to 150,000 yr BP (RAG 5-6) (Table 1).

SCARP OFFSET AND EXTENT OF FAULTING

Nine fault scarps are present on Towanta Flat about 6 km south of the mountain front (Fig. 2). The primary set of scarps trends N. 50-55° E., generally parallel to the major structures in the area (South Flank fault, Uinta Basin fault, and Uinta Basin axis) while a secondary set trends N 70° E. (Hansen, 1969b). The scarps bound a graben that varies in width from 170 to 610 m. The scarps extend from immediately east of Pigeon Water Creek to near the eastern margin of the meltwater channel, a distance of about 5 km. The scarps are 1 to 15 m high on the main Towanta Flat surface (RAG 3/4), but are only 1 to 8 m high on the younger RAG 4/5 deposits in the meltwater channel. Segments of many of the scarps, particularly those in the meltwater channel, have been steepened by erosion from small younger streams. Topographic profiles across the graben show there is no net tectonic offset across it.

Two electrical resistivity profiles across the graben (Meiiji Resource Consultants, 1980), indicated in Figure 2, were used to locate faults and estimate the amount of offset of the contact between the Tertiary Duchesne River Formation and overlying outwash. Line 1 defines a normal fault with about 25 m of offset on the southeastern edge of the graben, but the simple resistivity expression of the normal fault on the northwest side of the graben is obscured, possibly by an open cavern at depth. Three collapse pits, the largest measuring 37 by 27 by 12 m deep, developed along the northern fault near the western end of the graben (Fig. 2) after the irrigation canal running along the scarp had been operating for about 30 years. Possibly, piping of canal water along the fault plane in the underlying Duchesne River Formation created voids that caused the collapse of the canal. The collapse pits support the resistivity interpretation of an open cavern obscuring the fault. Results from line 2 show that the graben contains a small horst block in the subsurface that has no topographic expression. The resistivity data suggest that the bedrock surface along the northwest-bounding scarp is displaced about 15 m, but that the center of the graben may contain gravels 25 m thick. Near the southeast end of line 2, outcrops show about 23 m of bedrock relief on the southeast-bounding scarp where a small drainage has exposed the bedrock on the downthrown block.

Like Hansen (1969b), we found no direct evidence that the Towanta Flat scarps extend east of the meltwater

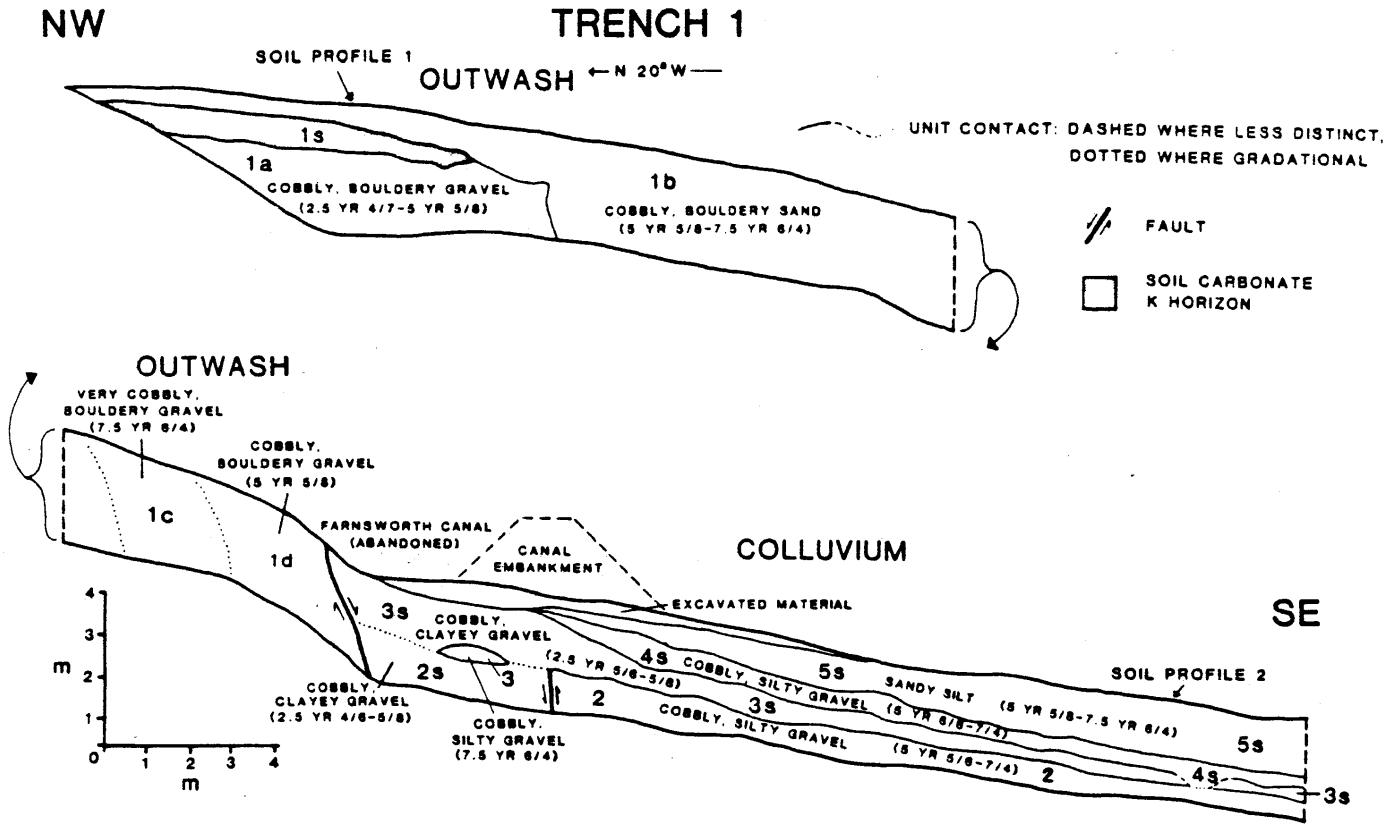


Figure 3.—Log of Towanta Flat trench 1 excavated across the southeast facing, 5-m-high scarp near the western edge of Towanta Flat (Fig. 2). Unit lithologies, Munsell colors (Oyama and Takehara, 1970), and the location of soil profiles 1 and 2 (Table 2) are shown. Outwash deposits are juxtaposed against proximal scarp colluvial deposits by the main fault striking N. 55° E. and dipping 70° SE. The antithetic fault below unit 3s strikes about N. 50° E. and dips 86° SE.

channel. However, east of the Lake Fork River (Fig. 1) the gradient of an outwash surface that correlates with Towanta Flat steepens (from 11 m/km to 17 m/km) for about 2 km to the south. This steeper gradient and a similar gradient on Towanta Flat south of the graben (19 m/km) may be due to tectonic warping (Osborn, 1973, p. 64; Ritzma, 1974).

Southwest of Towanta Flat, three faults are exposed in the Duchesne River Formation (see lower left-hand corner of Fig. 2), but erosion obscures surface traces of the faults from here to Pigeon Water Creek. These faults project toward the scarps on Towanta Flat, but none has surface expression suggesting Quaternary displacement. However, the area of mixed fluvial and colluvial deposits west of Pigeon Water Creek is lower than Towanta Flat suggesting significant post-RAG 4 erosion in this area. Thus, even if the fluvial and colluvial deposits here are relatively thin (1 to 5 m thick), they may cover post-RAG 4 displacements on extensions of the Towanta Flat faults. Even so, the total mapped length of the faults would be less than 10 km. Despite Ritzma's (1974) assertion of extensions of the "Towanta Lineament" to the west, we found no evidence of Quaternary faulting in this area (see Martin et al, 1984).

TRENCHING OF SCARPS AND LINEAMENTS

Three trenches were excavated across suspected faults on Towanta Flat to assess the age and frequency of faulting. Trench 1 was located in RAG 3 deposits across the 5-m-high scarp bounding the graben on the north near its western end. Trenches 2 and 3 were placed across prominent air photograph lineaments in RAG 5-6 deposits in the meltwater channel (Fig. 2).

TRENCH 1

Stratigraphy and Age of Units

Deposits exposed in trench 1 consist of RAG 3 outwash deposits and younger fault-scarp-derived colluviums that fill the graben (Fig. 3). The soil developed on the RAG 3 outwash deposits exposed in the northwestern end of trench 1 had a 22-cm-thick argillic horizon over a 57-cm-thick stage III (calcium carbonate morphology of Gile et al, 1966) K horizon (unit 1s, Fig. 3) (Table 2, profile 1). Similar soils were described from the main Towanta Flat surface by Nelson (1982) and are one line of evidence for our age estimate for the deposits on Towanta Flat (Table 1) discussed above.

Table 2.—Summary of horizon properties for soils developed on outwash, till, and alluvium on Towanta Flat.

Profile	Horizon[1]	Average depth (cm)	Munsell color (dry)	pH[2]	Percent by weight[3]			Estimated percent by volume			Percent organic matter[4]	Percent CO_3[5]	Bulk density[6] (g/cm^3)
					Sand (2.0-0.5 mm)	Silt (50-2 um)	Clay (<2 um)	Gravel (0.2-8 cm)	Cobbles (8-25 cm)	Bldrs (>25 cm)			
1	A1	0-6	5YR 4/4	5.6	68	21	12	0	0	0	4.7	0.1 (0)	1.70
(Fig. 3)	B1	6-16	5YR 5/5	6.5	69	17	14	20	30	0	1.8	0.1 (tr)	1.85
	IIB21tb	16-38	5YR 5/8	6.9	75	5	19	20	40	0	1.2	0.2 (1)	1.85
	IIB22b	38-48	7.5YR 6/4	7.9	82	5	13	20	40	0	0.9	31 (31)	1.50
	IIK1b	48-105	7.5YR 8/2	7.9	76	5	19	20	30	5	1.0	62 (68)	1.30
	IIIC1cab	105-190	2.6YR 4/7	8.2	77	7	16	10	40	30	0.2	7 (7)	1.80
	IIIC2cab	190-298+	5YR 5/8	8.2	82	9	9	10	40	30	0.1	7 (2)	1.90
2	AB	0-18	7.5YR 6/6	6.3	55	26	19	2	0	0	1.1	0.0	
(Fig. 3)	B21t	18-52	5YR 5/6	6.9	46	27	27	2	0	0	0.4	0.0	
	B22t	52-128	5YR 5/6	7.9	56	25	20	2	0	0	0.1	0.8	
	IIB23tb	128-174	5YR 6/6	7.9	55	24	22	30	30	10	0.2	0.7	
	IIIB24tb	174-203	2.5YR 5/6	7.7	49	20	31	25	25	20	0.2	0.6	
	IIIB3tb	203-228+	5YR 5/6	7.7	57	22	21	25	25	20	0.1	0.6	
3	B21	0-36	5YR 5/6		55	26	19	2	0	0		0.0	
(Fig. 2)	B22ca	36-46	7.5YR 8/3		—	—	—	2	0	0		44.0	
	B23ca	46-130	5YR 5/6		59	24	17	2	0	0		7.0	
	B24t	130-224	5YR 5/6		56	25	18	2	0	0		0.1	
	IIB25b	224-249	5YR 6/5		63	23	14	30	30	20		0.0	
	IIIB26tb	249-291	5YR 5/8		58	17	24	10	—	—		0.1	
	IVB27tb	291-345+	5YR 5/8		64	16	20	30	20	10		0.1	
4	A	0-19	7.5YR 5/3	6.7	47	34	19	0	0	0	4.0	0.2 (tr)	
(Fig. 4)	IIB21b	19-41	7.5YR 5/3	7.5	38	29	33	0	0	0	0.6	0.2 (tr)	
	IIB22b	41-65	10YR 7/4	7.8	40	34	26	0	0	0	0.5	0.2 (1)	
	IIB3b	65-83	2.5YR 8/3	8.2	40	37	24	0	0	0	0.5	4.0 (6)	
	IICb	83-121	2.5Y 8/3	8.3	70	19	11	2	5	0	0.1	1.0 (3)	
	IIIB3b	121-144	5YR 7/3	8.2	89	6	5	10-30	2-15	0	0.1	0.2 (1)	
	IVCb	144-246+	5Y 8/2	8.3	41	28	30	5-10	1-15	<1	0.1	0.2 (3)	
5	A	0-18	7.5YR 6/3	7.0	53	26	20	0	0	0	0.1	0.0	
(trench 3)	IIB2b	18-34	5YR 6/4	7.1	53	23	24	0	0	0	0.6	0.0	
	IIB3b	34-54	7.5YR 6/4	7.9	62	19	19	1	1	0	0.7	2.0	
	IIC1b	54-66	7.5YR 7/4	8.4	66	19	15	25	35	0	0.4	4.4	
	IIIC2oxb	66-98	7.5YR 7/4	8.3	74	13	13	15	25	1	0.3	2.6	
	IVC3b	98-130	5YR 7/4	8.4	84	8	8	20	30	1	0.1	1.2	
	VC4b	130-172+	2.5Y 7/3	8.3	65	11	24	5	5	0	0.1	1.5	
6	A	0-13	7.5YR 6/3		66	23	11	10	<1	0		0.1	
(Fig. 2)	AB	13-28	5YR 5/4		64	18	18	10	<1	0		0.0	
	B21t	28-55	5YR 5/6		64	15	21	10	2	0		0.1	
	IIB22tb	55-87	2.5YR 5/7		54	5	41	50-60	10-20	<1		0.6	
	IIIB23tb	87-108	5YR 6/7		76	3	21	5	0	0		0.2	
	IVB3b	108-140	5YR 6/6		81	3	16	40	5-20	<1		0.0	
	VCb	140-161+	5YR 6/7		58	17	26	0	0	0		2.0	

[1]Nomenclature follows Soil Survey Staff (1975), Birkeland (1974), and Gile et al (1966).
[2]Soil reaction measured with a Hack pH meter using a 1:2.5 soil/water ratio.
[3]Particle size distribution of <2 mm fraction using sieve-pipette methods (e.g., Carver, 1971) and Sedigraph for silt-clay fractions of profiles 1 and 4 with prior removal of carbonates and organic matter using methods of Jackson (1956).
[4]Organic matter determined by loss on ignition (2 hours at 450°C), corrected for structural water loss by subtracting loss on ignition of organic free silt + clay fraction.
[5]Percent carbonate by method 4 of Allison and Moodie (1965, p. 1387), values in parentheses by method of Dreimanis (1962), tr = trace.
[6]Clod method of Blake (1965, p. 381).

In the southeastern half of trench 1, the oldest scarp-derived colluvium, unit 2, is overlain by a moderately developed clay-rich paleosol (unit 3s) that has been buried by younger colluvial deposits (units 4s and 5s) (Table 2, profile 2). We interpret unit 2s to be a remnant of an argillic horizon that developed on unit 2 that was preserved in the small graben in the center of the trench (Fig. 3). Where unit 2s was not downdropped into the graben, it was apparently

Table 3.—Stratigraphic units, soils, and fault events with estimated ages, displacements, and slip rates from Towanta Flat trench 1.

Stratigraphic unit	Soil developed on unit	Fault event	Estimated age (10^3 years BP) range	Estimated age (10^3 years BP) best	Estimated length of soil forming interval (10^3 years BP) range	Estimated length of soil forming interval (10^3 years BP) best	Minimum estimated displacements from colluvial wedge thickness[1] (m) × 2	Minimum post-datum slip rate (mm/year)
1			250-500	375			(7.9)[2]	0.02
	1s				250-500	375		
2		A	130-500	300			2.1	0.02
	2s				0-150	100		
3		B	130-500	200			2.6	0.03
	3s				50-150	100		
4		C	130-450	150			2.5	0.03
	4s				30-150	100		
5			30-150	50[3]				
	5s				30-100	50[3]		

[1]Assuming a significant amount of erosion of the scarp between each fault event, the thickness of the colluvial wedge produced after each fault event will approach one-half the displacement on that event.
[2]Minimum total post-unit 1 displacement from Figure 3 (double the total exposed colluvial wedge thickness approaches this value).
[3]We interpret this unit as accumulating gradually from 100,000-150,000 years ago to present; this is an average age.

eroded prior to deposition and subsequent development of paleosol 3s. The contact between units 2s and 3s in the small graben is inferred based on the colluvial unit 3 pod between these units (Fig. 3). Colluvial unit 4 overlying the buried paleosol (unit 3s) is similar in grain size to unit 2 (Table 2, profile 2), but has stronger argillic horizon soil structure. Because units 2s, 3s, and 4s consist of well-developed argillic horizons, we have roughly estimated the length of time it took to form them (Table 3) by correlating these horizons with argillic horizons on "Bull Lake" deposits which took up to 150,000 years to develop (Table 1).

The stratigraphic relationship of unit 5 to the fault scarp in trench 1 was obliterated by excavation of the now-abandoned Farnsworth Canal (Fig. 3). The relationship was exposed, however, along the east edge of the collapse pit on the fault scarp about 200 m southwest of the trench (Fig. 2). Unit 5 does not appear to have been disturbed by faulting since its deposition.

The soil profiles (Table 2, profiles 2 and 3) developed on unit 5 suggest it has an age between RAG 5-6 and RAG 7-8. Both profiles in the fine-grained colluvial unit (probably partly of eolian origin) are difficult to compare to the soils developed on the adjacent coarse outwash parent material (Table 2, profile 1). Although clay and carbonate accumulate more rapidly in fine-grained soils, profiles 2 and 3 (developed in the same units about 100 m apart), appear more strongly developed than soils on RAGs 7-8 deposits in the Towanta Flat area (Martin et al, 1984). This soil is also more strongly developed than soils about 15,000 years old developed on lithologically similar Lake Bonneville deposits 100 km to the west (Scott et al, 1982). The maximum clay content and carbonate development in the upper part of profile 3 (Table 2) match or exceed that for profiles in RAG 5-6 deposits in the Towanta Flat area (Table 1) suggesting the colluvium in this truncated profile was deposited prior to RAG 7-8 time.

Sequence of Events

The following history of deposition and faulting is inferred from the colluvial stratigraphy and structural relationships exposed in trench 1 and the exposure in the collapse pit along the fault scarp on Towanta Flat.

1. Deposition of RAG 3 (units 1a, 1b, 1c, and 1d) outwash unconformably over the Duchesne River Formation of late Eocene and/or early Oligocene age (Andersen and Picard, 1972). This contact was not exposed in the trench.
2. Soil development on the outwash surface eventually culminating in the engulfment of a well-developed argillic horizon by a stage III K horizon (unit 1s).
3. Faulting of the outwash surface, probably developing much of the graben structure present on Towanta Flat today. The number of surface faulting events is unknown, but colluvial wedges (units 2, 3s, and 4s) suggest three separate events (Table 3). Units 1c and 1d of coarse outwash but with less clay, weaker structure, and less intense color hues than units 1a and 1b were clearly disturbed by faulting during this period, but their detailed genesis is uncertain. Clasts in unit 1d near the fault are rotated with their long axes inclined to the southeast at angles up to 80°. Cumulative net vertical displacement for all events along this part of the scarp exceeds 8 m. Double the thickness of colluvial wedges adjacent to the fault provides a crude minimum estimate of displacement during each event (Table 3).

4. Erosion of the fault scarp and deposition of a cobbly proximal colluvial wedge (unit 2) on the downthrown side of the fault.
5. Possible soil development on unit 2 for which little evidence remains (unit 2s). Continued soil development on the upthrown outwash surface.
6. Additional displacement (event B, Table 3) on the main fault with an antithetic fault producing the small graben which downdropped and preserved unit 2s. Minimum displacement across the antithetic fault is 0.75 m.
7. Erosion of the fault scarp (including argillic horizons on the upthrown block) with deposition of and concurrent soil development on unit 3 (unit 3s) over a long enough period (►50,000 years estimated) to allow considerable clay movement and obliteration of erosional-depositional soil structure in units 2s and 3s.
8. Additional displacement (event C, Table 3) on the main fault.
9. Erosion of the fault scarp and deposition of a cobbly colluvial wedge (unit 4) over unit 3s.
10. Weak to moderate soil development on unit 4 (unit 4s). Continued soil development on the outwash surface away from the eroded scarp.
11. Continued minor erosion of the main scarp, deposition of colluvium mixed with eolian material to form a fine-grained wedge (unit 5s) on the downthrown block, and concurrent soil development with an argillic horizon and stage I to stage II calcium carbonate development. This process of deposition and soil development is continuing today.

TRENCHES 2 AND 3

Trench 2 was located in the meltwater channel across an air photograph lineament that is on trend with a 1- to 2-m-high fault scarp about 80 m northeast of the trench (Fig. 2). The lineament is in RAG 5-6 deposits, but the scarp is developed in RAG 4-5 deposits.

Trench 3 was also located in the meltwater channel across one of a series of discontinuous, N. 70° W. trending photograph lineaments which extend across much of the flat (Hansen, 1969b). The age and origin of the west-northwest-trending lineaments is unknown, but they do not extend into an area of mixed alluvial fan and colluvial deposits on the western edge of Towanta Flat (Fig. 2). Soil profile 6 from this area has strong colors, a high clay content, some carbonate development (stage I+) (Table 2), and no weathered clasts. These data suggest most of this material dates from RAG 5-6 and, therefore, that many of the west-northwest-trending lineaments are developed on older surfaces.

Stratigraphy and Age

Trenches 2 and 3, oriented at right angles to each other about 150 m apart (Fig. 2), exposed similar stratigraphy. Soil profiles 4 (trench 2) and 5 (trench 3) (Table 2) are difficult to interpret because the sequence of parent materials on which these soils are developed differ in age and lithology. The fine-grained material in the basal units in both trenches (units 1, 2, and 3; Fig. 4) gives them a gray-green color (2.5Y to 5Y color hues) in contrast to the red color (5YR hues) of the overlying unit 4 sediments. Parts of the basal units in both trenches have stage II carbonate morphology and 30 to 40 percent highly weathered clasts indicating these units are at least as old as RAG 4 (Table 1). The quartzite cobble lithology of these units indicates outwash deposition (similar deposits are believed to underlie most of the meltwater channel), but the gray-green clay-rich matrix suggests this sediment is derived from the LaPoint Member of the Duchesne River Formation (Andersen and Picard, 1972). Outcrops along the west side of the Lake Fork River east of the meltwater channel indicate the top of the LaPoint Member is at the same elevation as the base of the meltwater channel near trenches 2 and 3. We interpret the gradual north-to-south lateral changes in lithology of the basal units in trench 2 (units 1, 2, and 3) as facies changes produced by glaciofluvial processes. We found no evidence of displacement or shear zones in the lower trench units suggesting the airphoto lineament intersected by trench 2 is not related to post-RAG 4 faulting.

Above an unconformity at the top of the gray-green units are reddish (5YR hues) gravelly sands and silty sands (units 4 and 5) that are laterally discontinuous in trench 2 (Fig. 4), but are thicker (80 cm) and more continuous in trench 3. We attribute this irregularity to alluvial cut and fill during the most recent episode of outwash deposition (RAG 5-6) in the meltwater channel. The moderate clay contents with argillan development in some parts of units 4 and 5, the stage I carbonate morphology in trench 3 (Table 2, profile 5), and the low percentage of highly weathered clasts suggests these reddish units may be as old as the soils developed on RAG 5-6 moraines into which this youngest surface in the meltwater channel can be traced.

Above a second unconformity at the top of the reddish units are silty, partially laminated sediments (unit 6), which we interpret to be sediments deposited in ponded water in low areas in the younger outwash channel. To the southeast in trench 2, unit 6 grades into unit 7 which is sandier with some cobbles suggesting higher energy fluvial deposition. Locally, unit 6 is stratified; high-angle cross-bedding (up to 40° dip, Fig. 4) occurs in sandier parts. Small-scale folds are probably the result of soft-sediment deformation. Both units grade upward into colluvium-loess deposits which are accumulating today (unit 8). The colluvium-loess deposits are laterally continuous along the entire length of trench 2 and lie directly on RAG 4 deposits in the southeast half and RAG 5-6 deposits in the northwest half. Two depressions, each approximately 0.4 m deep and up to 0.3 m wide, were noted 8 and 11 m southeast of the northwest end of trench 2 (Fig. 4). These depressions are krotovina (animal burrows) infilled with A and B soil horizon material (unit 8) which

NW

TRENCH 2

SE

UNIT	LITHOLOGY	COLOR
1	COBBLY, BOULDERY GRAVEL	5 Y 6/3
2	SANDY CLAY	10 Y 5/2
3	CLAYEY SAND	5 Y 7/3
4	COBBLY, GRAVELLY SAND	5 YR 6/4
5	COBBLY, SILTY SAND	5 YR 5/6
6	SILTY SAND	2.5 Y 7/3-10 YR 7/5
7	COBBLY, SILTY SAND	5 Y 6/1-2.5 Y 5/2
8	ORGANIC-RICH, SILTY SAND	7 5 YR 5/3

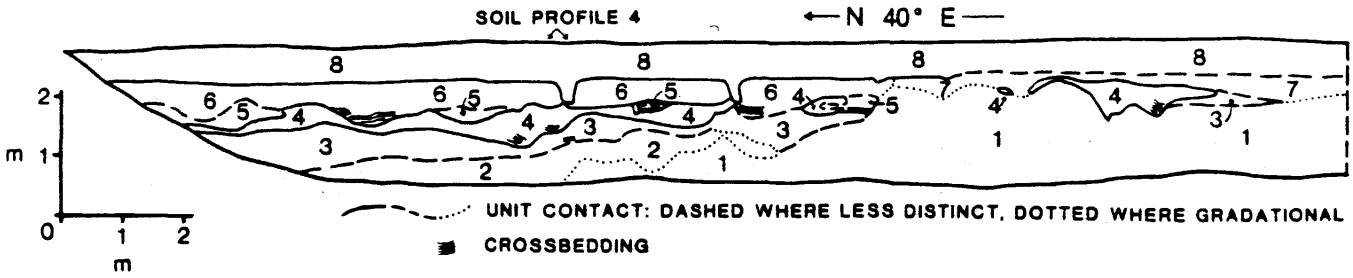


Figure 4.—Log of the northwestern half of Towanta Flat trench 2 excavated across an air photograph lineament in RAG 5-6 deposits on trend with a 2-m-high fault scarp that is developed in older (RAG 4-5) deposits to the east (Fig. 2). Units 1 through 5 are cut and fill alluvial sediments deposited in the meltwater channel on Towanta Flat. Unit 6 consists of pond deposits grading upward into loess. Units 7 and 8 are mixtures of colluvium and loess. No evidence of shearing or faulting was found in the trench.

overlies unit 6. None of these features appear to be due to shearing or faulting although some of the soft sediment deformation might be the result of strong ground motions.

The age of unit 6 is uncertain; it overlies RAG 5-6 deposits and the modern soil (units 8 and 6) is developed on it. The upper fine-grained sediments in trenches 2 and 3 contain a weak argillic horizon with argillans on ped faces (Table 2, profiles 4 and 5), but it is difficult to compare the relative age of these soils with other soils studied in the area which are developed on coarse-grained parent materials. By stratigraphic position and relative soil development, this soil is much younger than RAG 5-6. The presence of an argillic horizon does suggest this soil is more than a few thousand years old and is possibly pre-Holocene in age (for example, Scott et al, 1982). Thus, at least the lowest fine-grained pond deposits probably date from RAG 7-8 or RAG 9 (Table 1).

CONCLUSIONS

Our mapping, relative-age dating, and regional correlation of deposits in the Towanta Flat area show that the fault scarps on the flat are much older than suggested by earlier studies. The colluvial stratigraphy and soil development in trench 1 suggest at least 3 faulting events in the last 250,000 to 500,000 years along this part of the graben, and scarps of different heights in deposits of different ages also indicate multiple faulting events. No scarps were mapped in deposits we interpret to be 60,000 to 150,000 years old (RAG 5-6, Table 1) and these deposits were unfaulted in trenches 2 and 3.

Recurrence intervals and individual fault event displacements are difficult to estimate from trench 1 data. Our approach is to estimate a range of ages for each event and then select the best age estimate for each event based on the overall stratigraphic sequence in the trench (Table 3). Although all soils developed on units in the trench have been truncated by erosion, remnants of argillic B horizons permit broad estimates of the length of the soil-forming interval between faulting events. This, plus our age control on the main Towanta Flat surface, sets constraints on the ages of separate events within the overall sequence which allows us to make reasonable best estimates for the age of each event. Because we have only a minimum measurement of the total stratigraphic offset exposed in trench 1, we may not have a record of all surface faulting events since deposition of the outwash. Thus, detailed event-displacement calculations (for example, Swan et al, 1980) are not justified. Doubling the maximum thickness of the colluvial wedge produced by each event (Table 3) gives a crude minimum estimate of the displacement per faulting event of about 2 to 3 m. Recurrence intervals for surface faulting events inferred from the trench stratigraphy appear to be about 50,000 to 100,000 years. Our older age estimates may be minimum ages, but if so, recurrence rates will be even lower.

We estimate minimum slip rates across individual scarps on Towanta Flat using scarp heights and surface ages at 0.02 to 0.06 mm/yr and using the stratigraphy in trench 1 at 0.02

to 0.03 mm/yr (Table 3). Based on the measured offset of the bedrock surface in the graben, maximum slip rates should not exceed 0.09 mm/yr (23 m in 250,000 years). These slip rates are an order of magnitude lower than suggested by Doser and Smith (1982) who relied on earlier age estimates for the Towanta Flat deposits. It should be emphasized that there is no significant net tectonic displacement across the Towanta Flat graben (although there does appear to be gentle warping of the outwash surface). For this reason, slip rates on these faults cannot be used as a measure of fault zone response to regional stresses, at least in the same way as other tectonic slip rates measured across normal faults with significant cumulative displacement.

The origin and relationship of the Towanta Flat faults to regional tectonic stresses and structures are uncertain. If the faults are a response to late Quaternary stresses, their orientation does not agree well with the orientation of microearthquakes studied by Carver et al (1983) and Martin (1982). The limited lateral extent of the scarps (5 km) and their lack of net tectonic offset do not suggest a normal fault zone repeatedly active during the late Quaternary. However, multiple displacements have occurred on the scarps over a much longer period than was previously thought.

ACKNOWLEDGMENTS

We thank the staff of the Upper Colorado Region, U.S. Bureau of Reclamation in Salt Lake City and Duchesne, Utah, for logistical and mapping support, particularly Mike Deming, Jim Rogers, Steve Beason, Bob Bridges, and Dan Grundvig. Mechanical and chemical analyses of soil samples were provided by Harold Furneaux, Soil and Water Laboratory (USBR, Salt Lake City) and Rolf Khil, Sedimentology Laboratory, INSTAAR, University of Colorado. Some analyses at the University of Colorado were done with a sedigraph supported by NSF Grant No. EAR-7823693. We also thank Richard Reynolds, Paleomagnetism Laboratory, U.S. Geological Survey, Denver, for free use of his facilities for paleomagnetic analyses. Discussions with Mike Deming and Jim Rogers (USBR, Duchesne), Howard Ritzma, Bruce Kaliser (Utah Geological Survey), and Bruce Bryant (U.S. Geological Survey, Denver) were helpful. Early versions of this paper benefited from reviews by R. A. Martin, Jr., D. A. Ostenaa, L. W. Anderson, R. L. LaForge (USBR, Denver), and especially A. J. Crone (USGS, Denver). A helpful critical review by W. J. Arabasz (University of Utah) identified unwarranted assumptions and unjustified conclusions.

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