See page 435.

ORIGIN OF TERRACE DEPOSITS

The character and distribution of the gravel terrace deposits in the Yampa River basin strongly suggest that they are principally the product of glaciation. Terrace deposits are most distinct and are found at the greatest number of different levels near those places that received a large influx of coarse-grained sediment from glaciers. Also, gravel terrace deposits do not persist far downstream, except in large valleys that are joined by tributaries that drain glaciated areas.

The limited extent of gravel terrace deposits away from glacial sources is particularly well illustrated in the vicinity of the town of Yampa (Fig. 12) because of the contrast in lithology and color between the terrace deposits and local bedrock. Terrace deposits at the head of the Yampa River are composed almost entirely of basaltic and andesitic rock derived from the volcanic flows that form the Flat Tops of the White River Plateau. These deposits overlie relatively light-colored, soft, fine-grained sedimentary rocks, mainly poorly consolidated sandstone of the Browns Park Formation and Mancos Shale. The contrast in color and landform is striking, particularly between the coarse, dark-colored, durable volcanic clasts of the terrace deposits and the fine-grained, light-colored, soft sandstone of the Browns Park Formation. Equally striking is the apparent rapid decrease in outwash in a downstream direction. The terraces of the upper Yampa become indistinct 9.5 to 10.5 km downstream from the terminal moraines of Bull Lake and pre–Bull Lake age. Neither the Browns Park Formation nor the Mancos Shale is a source of much gravel, other than a few clasts of Precambrian rock recycled from the basal conglomerate of the Browns Park Formation. Hence, beyond the limit where volcanic clasts are abundant, distinct terraces disappear because alluvium derived from the Browns Park Formation and Mancos Shale is too easily eroded to maintain terrace forms without abundant clasts of volcanic rock.

The distribution of terraces along the Elk River described earlier illustrates the same point. Terraces are distinct where the Elk River emerges from the Park Range, but more or less disappear beyond 5 km downstream from that point. For the next 13 km, the Elk River flows through a broad valley in which distinct terrace remnants are lacking, and sheetwash and fan alluvium obscure remnants of low terraces and cover large parts of the valley floor. About 18 km downstream from where it leaves the Park Range, the river enters a 2.5-km-long canyon wherein it is joined by Big Creek and Mad Creek (Fig. 12), both of which contained valley glaciers that nearly reached the Elk River. From the downstream end of this canyon to the Yampa River, terraces are prominent landforms and include the thickest terrace deposit (16 m) observed in the basin.

The Yampa River received coarse sediment from multiple sources; therefore, its terrace system persists farther downstream than that of valleys with a single source of coarse sediment. Even so, terraces begin to become indistinct a short distance downstream from Craig. Except for a few remnants of the 35-m terrace near Juniper Hot Springs, the terrace sequence more or less ends at Craig. Unglaciated tributaries of the Yampa River have poorly developed terrace systems, and the terrace remnants that do exist are mostly of late Pleistocene and Holocene age and are relatively close to the valley floors.

NORTHWESTERN UINTA BASIN*

Alan R. Nelson and Gerald D. Osborn

INTRODUCTION

Although the late Cenozoic history of the Uinta Mountains has been studied in some detail (e.g., Powell, 1876; Atwood, 1909; Bradley, 1936; Hansen, 1965, 1969), the geomorphic development of the adjacent Uinta Basin (Fig. 1 and Plate 4A) has received relatively little attention. Atwood (1909) mapped outwash deposits of two episodes of glaciation along the northern edge of the basin. Kinney's (1955) lower strath terraces along Ashley and Brush creeks were correlated with moraines of three glaciations in the Uinta and Whiterocks River drainages. Osborn (1973) mapped deposits of eight glacial episodes in the Yellowstone and Uinta River drainages using morphostratigraphy and limited surface weathering and soils data. In a study of Quaternary faulting, Martin and others (1985) used similar methods, with more detailed data on relict paleosols, to reinterpret part of the sequence along the Lake Fork River. Regional mapping by Bryant (1991) covers the northwestern basin, and surficial deposits in the eastern basin are shown by Carrara (1980).

Alluvial deposits in the Uinta Basin are divided into outwash, floodplain alluvium of main streams, and pediment deposits. Most of this discussion centers on the extensive outwash deposits that extend southward from the Lake Fork, Yellowstone, Uinta, and Whiterocks drainages in the northwestern basin and their relationship to the deposits of the central streams of the basin, the Duchesne and Green rivers. The sequence of fluvial events for the Lake Fork and Uinta rivers is discussed in detail; sequences in other drainages with less extensive deposits (Plate 4A) appear similar.

The outwash plains and terraces are covered with bouldery gravel of quartzite and some chert in a sand matrix; clast size decreases and clast roundness increases with distance from the Uinta mountain front. In the central basin, these outwash deposits merge with mainstream flood-plain deposits along the present and former courses of the Duchesne and Green rivers. The outwash terraces extend with few breaks from the moraines at the mountain front to the terraces in the central basin. The continuity of the terraces and the coarse quartzite gravel lithology of the central basin deposits show that gravel deposition in the basin is a response to aggradation during glacial periods. Deposits of some

*Volume editor's comment: Although the Uinta Basin lies within the Colorado Plateau province, as the latter is usually defined, this subchapter is included within the Rocky Mountain basins chapter because its methods of study and correlations of stratigraphic units pertain most specifically to those in the Rocky Mountain basins chapter.

TABLE 2. HEIGHTS, LONGITUDINAL PROFILE CHARACTERISTICS, INDICES OF SOIL DEVELOPMENT, ESTIMATED AGES, AND INCISION RATES FOR RELATIVE-AGE GROUPS OF ALLUVIAL SURFACES IN THE NORTHWESTERN UINTA BASIN

			Indices of Soil Development for Relict Paleosols											Incision Rate	
						Clay[6]		Carbonate[6]							
RAG[1]	Relative Height[2] (m)	Surface Profile[3]	Rubification[4]	Clay Films[4]	Profile Index[5]	Maximum Percent	g/cm²	Maximum Percent	g/cm²	Maximum Stage	Maximum Percent Weathered Clasts[8]	Regional Relative Age[9]	Estimated Numerical Age (ka)	Mountain Front[10] (m/kyr)	Basin Center[11] (m/kyr)
1	220-330	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	85	n.d.	V+	90	Late Pliocene to early Pleistocene	>1,000	<0.33	n.d.
2	132-170	D	n.d.	n.d.	n.d.	n.d.	n.d.	52	n.d.	IV	70	Early to middle Pleistocene	>500	<0.34	<0.53; 0.15[16]
3	55-85	D[12]	71	94	70	28	10.9	68	26.9	IV	70	Middle Pleistocene	400-800[14] (500)	0.17	0.43
4	45-50	D[12]	75	163	82	38	16.4	71	20.7	V-	70	Pre-Bull Lake	250-500[15] (300)	0.17	0.17
5	35-45	D	66	90	44	32	7.0	6	Trace	III	10	Bull Lake	130-150[15] (140)	0.25-0.32	0.04-0.09
6	10-30	C[13]	19	2	9	9	0.6	1	Trace	II	0	Pinedale	12-70[15] (15)	0.66-2.0	0.21-0.41

[1]Relative-age groups of alluvial surfaces.
[2]Relative height of surfaces above modern Lake Fork or Uinta Rivers. RAG 2 contains at least 4 terraces; RAG 5, two terraces; and RAG 6, three terraces. Projection of some older surfaces into the central basin gives much greater heights.
[3]Relationship of reconstructed profile of alluvial surface to the profile of the next older surface in a downstream direction. D = diverging, C = converging. Remnants of RAG 1 surfaces are too small to reconstruct profiles from them.
[4]Mean total property index of Harden (1982) and Harden and Taylor (1983) calculated using software of Nelson and Taylor (1985).
[5]Mean nonarid index of Harden and Taylor (1983).
[6]Mean value calculated by method of Machette (1985a) using software of Nelson and Taylor (1985).
[7]Terminology of Machette (1985a). Based on descriptions from 48 sites throughout the basin, most of which were not sampled for laboratory analysis.
[8]Clasts from B or C horizon which can be broken by hand.
[9]Indicates corresponding geochronologic unit or informal regional allostratigraphic unit with probable time-transgressive boundaries based on major weathering and morphologic breaks in the local late Quaternary sequence.
[10]Calculated from estimated age and terrace height near moraines at the mountain front.
[11]Calculated from estimated age and terrace height near the Duchesne-Uinta or Duchesne-Lake Fork confluences.
[12]RAG-3 and RAG-4 profiles have lower gradients than RAG-2 profiles because the Lake Fork River followed a longer course to the Duchesne River during RAG-3 and RAG-4 time. If stream lengths had been the same for each RAG, all these profiles would diverge downstream.
[13]The 30- and 10-m terraces (near moraines) converge while the 20-m terrace diverges due to stream capture which shortened the course of the Lake Fork River.
[14]Minimum amino-acid ratio age estimate and normally-magnetized sediment conformably overlying alluvial surface suggest indicated age range (Fig. 15).
[15]Estimated numerical age based on dating studies of Pierce and others (1976), Colman and Pierce (1981), Porter and others (1983), and Shroba and others (1983), and on correlation of outwash surfaces with major periods of glaciation indicated by the marine oxygen-isotope record (Imbrie and others, 1984). Figure in parentheses is our best estimate, which we used to calculate the incision rates.
[16]Estimate from date of Hansen (1984) (245 m of downcutting of Green River since the early Pleistocene).

of the oldest Quaternary surfaces contain some sandstone, limestone, and shale clasts along with the quartzite, and interbedded slack-water units are common. Because most of the glaciated parts of the Uinta Mountains are underlain by Precambrian quartzites, some of these older central basin deposits may not be related to glaciation. Pediment deposits, formed by local fluvial processes adjacent to backwearing slopes, are most common east of the Uinta River and south of the Duchesne River (Plate 4A).

ALLUVIAL SURFACES AND CHRONOLOGY

The high erosion surfaces and lower fluvial terraces of the northwestern Uinta Basin are divided into six relative-age groups (RAGs), numbered 1 through 6 from oldest to youngest. These groups do not include alluvial deposits at or near the same height as modern flood-plain deposits or the lowest, youngest (late Pinedale) outwash terraces south of the mountain front. Relative-age group assignments for the older alluvial surfaces in the Uinta Basin are based primarily on height above the modern rivers, but the younger groups are distinguished by relative-weathering and soils data (all soils studied are relict paleosols) collected from the sequence of outwash terraces along the Lake Fork, Yellowstone, and Uinta rivers (Table 2) (Osborn, 1973; Martin and others, 1985). Amino acid racemization and paleomagnetic data at one locality set numerical-age constraints on one surface of RAG 3. The degree of preservation of stream-cut scarps and braided channels on outwash terraces also helps group them into relative-age categories. Longitudinal profiles of river terraces are used to correlate surfaces elsewhere in the basin with the Lake Fork–Yellowstone sequence (Plate 4B).

Soil-development indices (Table 2), such as those that measure rubification, clay-film development (Harden, 1982), and total clay and $CaCO_3$ accumulation (Machette, 1985a), were useful for distinguishing soils developed on the surfaces of the younger RAGs, but the only soils studied in detail were the relict paleosols on outwash terraces along the mountain front in the northwestern corner of the basin. Soils in the interior of the basin differ considerably in morphology from mountain-front soils and

probably also differ in their rate of development (Reheis, 1987a). The morphologic stage of $CaCO_3$ development in soils on the surfaces in the basin gives only a broad indication of the age of the surface (Table 2).

RAG 1

High-level isolated remnants of pediments and mainstream gravels are placed in RAG 1. These surfaces are more than 400 m lower than the highest erosion surfaces on the south flank of the Uinta Mountains, which are probably of Pliocene age (Osborn, 1973). RAG 1 units include erosion surfaces (defined by Kinney, 1955, p. 127) cut on the Uinta and Duchesne River formations with only a thin (<1 m) quartzite gravel lag remaining (e.g., Tower Ridge, Plate 4A), as well as areas with a thicker (>3 m) cover of coarse-grained quartzite gravel suggestive of glaciofluvial deposition. Except for the Talmage surfaces, which were probably deposited by an ancestral Rock Creek that was a tributary of the Lake Fork River (Plate 4A), remnants of RAG 1 surfaces are 50 to 200 m higher than those of RAG 2, and in some exposures have the most extensive soil-carbonate development of any deposits mapped (stage V of Machette, 1985a). Most surfaces and deposits of RAG 1 are believed to be of early Pleistocene age, although some may predate the Quaternary.

RAG 2

Relative-age group 2 includes a number of remnants of outwash, mainstream gravels, and pediment deposits which lie well below RAG 1 surfaces, but are higher than the more extensive outwash surfaces of RAG 3 (Table 2). Isolated strath-terrace remnants covered with only a few meters of gravel predominate in the central basin, but nearer the mountains, remnants of former outwash plains are larger and gravels thicker (>10 m; e.g., John Starr Flat, Plate 4A). Outwash surfaces and correlative moraines along the Uinta and Yellowstone rivers are well preserved because later shifts in the river channels (Uinta River to the east, Yellowstone River to the west) kept the surfaces from being eroded or covered by later glacial deposits.

Based on their relative position, RAG 2 deposits probably date from early to middle Pleistocene. Because they are only 50 to 100 m above more extensive RAG 3 deposits of similar lithology, most are probably much closer in age to RAG 3 deposits than to RAG 1 deposits. Soil development on RAG 2 surfaces is similar to that on RAG 3 and RAG 4 surfaces; erosion at the edges of the surfaces where RAG 2 soils are exposed probably truncated the soil profiles.

RAG 3

Extensive RAG 3 outwash plains south of the Lake Fork River and less extensive outwash surfaces east of the Yellowstone River and west of the Uinta show that during the most extensive glacial advances of RAG 3, the main channels of the Lake Fork and Uinta rivers lay to the west of their present locations, while the Yellowstone River flowed east of its present course. Similar surfaces along Montes Creek, which are probably mostly of RAG 3 age, extend almost continuously from Neola to the Duchesne River southeast of Roosevelt (Plate 4A). These relationships suggest capture of the Yellowstone River by a tributary of the Lake Fork River and capture of the Uinta River by a Duchesne River tributary, subsequent to RAG 3 deposition.

More distal outwash remnants of RAGs 4 and 5 form a great, curving series of terraces north and east of the present Lake Fork River, extending as far east as Roosevelt. They show that the lower Lake Fork River followed a more northeasterly course and joined the Duchesne River several kilometers northeast of its present confluence during this part of the Pleistocene. The position of the benches along Montes Creek indicates that the Lake Fork and Uinta Rivers joined before meeting the Duchesne.

North of Duchesne, a series of surfaces (the western part of Blue Bench, Plate 4A) steps down westward toward the Duchesne River. These surfaces and the correlative West Bench on the west side of the river indicate that the Duchesne River once flowed to the southeast but gradually shifted its course westward during RAG 2 through RAG 3 time.

RAG 3 surfaces are lower and therefore younger than RAG 2 surfaces, but the numerical age of RAG 3 surfaces is poorly constrained. Indices of soil development do not aid in distinguishing RAG 3 surfaces from younger or older surfaces (Table 2). However, amino acid and paleomagnetic analyses (Martin and others, 1985, p. A27) of samples from fine-grained slack-water deposits overlying RAG 3 gravels at the mouth of Antelope Creek set limits on the age of RAG 3 deposits (Fig. 15 and Plate 4A). Amino acid ratios on snails in these sediments suggest an age of 480 ± 100 ka for the snails (Fig. 15). Normally magnetized samples of the slack-water deposits show they are less than 750 ka. These age estimates for the slack-water sediments are minimum ages for the underlying gravel, which correlates with the RAG 3 deposits of South Myton bench (Plate 4B). No soils or other evidence of a major unconformity are found at the contact of the gravel with the slack-water deposits; thus, the gravel is probably not much older than the deposits. Long-term (>120 ka) rates of pedogenic carbonate accumulation measured elsewhere in Utah (0.14 to 0.26 $g/cm^2/kyr$) by Harden and others (1985), Machette (1985b), and Colman and others (1986) applied to carbonate data for our most carbonate-rich RAG 3 soils (36 g/cm^2, higher than mean values shown in Table 2) yields ages of 140 to 260 ka. However, because our analyzed soils are near the mountain front rather than the center of the basin, they probably contain less than the maximum amount of carbonate for deposits of this age. In summary, RAG 3 deposits probably date from at least 400 ka, but because conformable overlying slack-water deposits are normally magnetized, RAG 3 deposits probably do not pre-date the Brunhes-Matuyama boundary (750 ka).

RAG 4

The RAG 4 outwash terraces along the Lake Fork River are more continuous than older or younger surfaces, and so the RAG

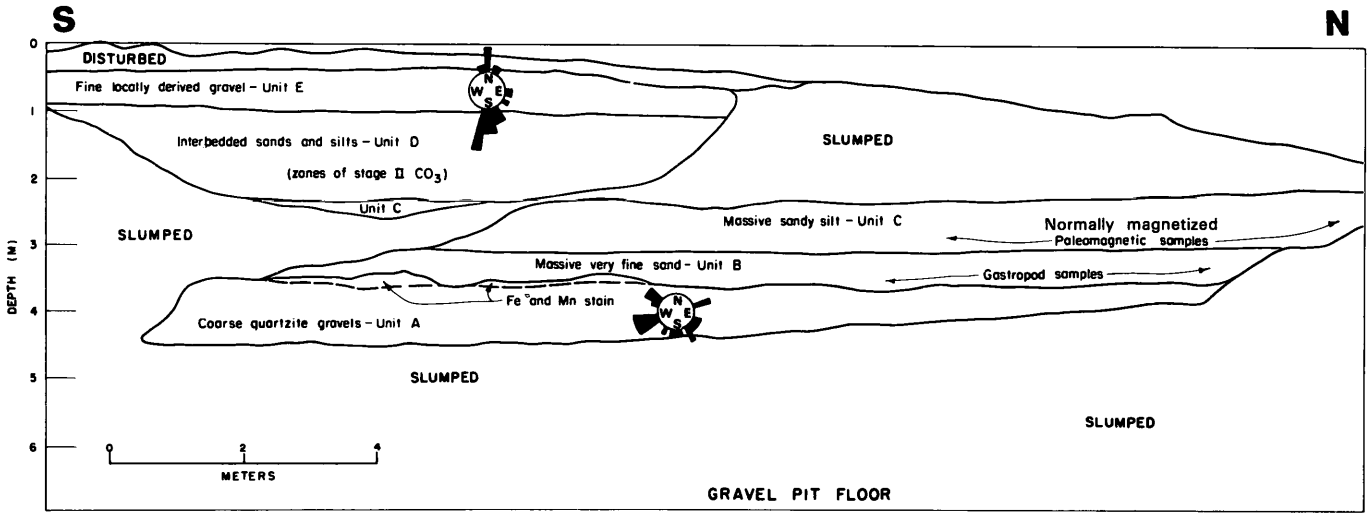

Figure 15. Sketch of stratigraphic units exposed in a gravel pit in RAG 3 terrace gravels south of the confluence of Antelope Creek with the Duchesne River (marked by solid triangle on plate 9A). The rose diagrams show the compass orientation of 50 elongate (long axis greater than 2 × short axis) pebbles in units A and E. Flow directions suggested by the pebble orientations and lithologies suggest unit A is a mainstream deposit of the Duchesne River and unit E was deposited by sidestreams flowing north into the Duchesne River Valley. Six samples from unit C, a fine-grained slack-water deposit, were normally magnetized, suggesting they are younger than 750 ka (Martin and others, 1985, p. A26). The gastropod species *Zonitoides arboreus, Euconulus fulvis, Discus cronkhitei, Vallonia cyclophorella, V. pulchella, Catinella* sp., *Pupilla blandi,* and *Gastrocopta holzingeri* (Emmett Evanoff, personal communication, 1980) were collected from unit B. Amino acid analysis of one *Catinella* shell and three *Zonitoides* shells gave total aIle/Ile ratios of 0.42 and 0.45 ± 0.01 (1 standard deviation), respectively. Using an effective diagenetic temperature of 8°C lower than present mean-annual temperature (7.7°C – 8°C = –0.3°C) (Nelson and others, 1984) and the methods of Miller and others (1983) yields an amino acid age estimate of roughly 480 ± 100 ka for these snails.

4 terraces serve as the chief reference point for the correlation of surfaces from the mountain front to the central basin. The gradient of RAG 4 surfaces along the Lake Fork (North Myton bench) is steeper than the gradient of correlative surfaces along the Duchesne River (Plate 4B) because the Lake Fork flowed north of its present position during RAG 4 time. The projection of profiles of the outwash-covered benches just north of Roosevelt to terraces of the same level north of the Duchesne River suggests that these surfaces are of RAG 4 age and confirms that the Lake Fork–Yellowstone and Uinta rivers met above their present confluence with the Duchesne River during this period.

Soils developed on terraces of RAG 4 have strong Bt horizon colors, high clay contents, and extensive development of argillans, and, in soils where carbonate morphology is best developed, significantly more carbonate than soils on younger terraces (Table 2). Outwash surfaces of RAGs 3 and 4 grade into broad eroded moraines with gentle slopes and few undrained depressions, but the RAG 3 moraines are more eroded than those of RAG 4 (Osborn, 1973; Martin and others, 1985). Deposits with similar characteristics in many parts of the Rocky Mountain region have been assigned pre–Bull Lake ages.

Total carbonate values for the most carbonate-rich RAG 4 soils (33 g/cm^2, higher than mean values in Table 2) indicate ages of 120 to 250 ka using rates determined in Utah (above); these are probably minimum ages. Total clay-accumulation rates of Shroba (1984) for soils in the Rocky Mountains (0.03 to 0.04 g/cm^2/kyr) and Colman and others (1986) for central Utah (0.11 g/cm^2/kyr), applied to RAG 4 clay data (Table 2) yield ages of 150 to 500 ka. Correlation of RAG 4 outwash surfaces with glacial stages 8, 10, or 12 of the marine record (Imbrie and others, 1984) suggests an age of 250 to 500 ka.

RAG 5

Two RAG 5 outwash terraces, one 3 to 7 m below the other, are relatively continuous from the moraines at the mountain front to the center of the basin along the north side of the Lake Fork River. These terraces diverge from the older RAG 4 terraces (Table 2), which suggests base-level lowering between the glacial advances of RAG 4 and RAG 5. The extensive RAG 5 surfaces near Ioka show that the Lake Fork was moving northward from its earlier position during this time. About 24 km to

the east, RAG 5 outwash deposits in a wide channel between older surfaces (not shown on Plate 4A) show that the confluence of the Uinta–Lake Fork drainage with the Duchesne must have been near the present Uinta-Duchesne confluence. Elsewhere, RAG 5 terraces are much less extensive. Equivalent terraces along the Uinta River have largely been eroded or covered by later outwash deposits.

Soil carbonate and clay indices and stone-weathering data separate soils on RAG 5 terraces (and moraines) from soils on older and younger deposits (Table 2). The differences in soil development and surface-weathering data between RAG 5 and 6 deposits are similar to the differences in soils and weathering between Bull Lake and Pinedale moraines in other parts of the Rocky Mountains; the relative positions of RAG 5 and 6 moraines and outwash terraces in the drainages of the north flank also compares favorably with Bull Lake and Pinedale positions elsewhere. Bull Lake deposits have been dated at about 150 to 130 ka (Pierce and others, 1976; Shroba and others, 1983), although some deposits mapped as Bull Lake may be younger (Colman and Pierce, 1981). The late Pleistocene clay accumulation rates of Shroba (1984) and our data (Table 2) suggest an age of about 140 ka for soils on RAG 5 terraces.

RAG 6

In unglaciated drainages and in the central part of the basin, RAG 6 deposits are near the level of the modern flood plain and cannot easily be distinguished from younger deposits. The higher of two continuous RAG 6 outwash terraces along the Lake Fork River (Plate 4A) is about 8 m below RAG 5 terraces, while the lower terrace merges with the flood plain 10 km below the moraines at the mountain front. The position of the flood plain of the lower Lake Fork River shows that, following formation of RAG 5, the river near Big Sand Wash was captured by a tributary of the Duchesne River, causing the Lake Fork to shift its channel from north of Ioka to south of North Myton bench during RAG 6 time.

Along the Uinta River near the moraines, the higher RAG 6 outwash terrace (7 to 10 m above the lower RAG 6 terrace) forms a fan at about the same level as RAG 5 outwash. About 7 km downstream, outwash of both RAGs is at the same height, but areas of RAG 5 outwash are preserved between braided channel deposits of RAG 6 (shown on Plate 4A as RAG 5-6). On the Whiterocks River, RAG 6 outwash is 24 m above the river at the terminal moraine, but merges with a lower terrace and the modern flood plain 7 km downstream.

RAG 6 terraces grade into narrow-crested, steep-sided moraines, which are next to RAG 5 moraines in the Lake Fork–Yellowstone and Uinta drainages. The morphology, relative position, surface weathering, and relict soil characteristics of these moraines suggest a correlation with Pinedale moraines elsewhere in the Rocky Mountains (Martin and others, 1985). The period of Pinedale (late Wisconsin) glacial advances began before 30 to 40 ka and reached its maximum 20 to 30 ka; most glaciers had receded from their outermost terminal moraines by 13 to 14 ka (Porter and others, 1983). Average total clay data (Table 2; rates as above) for RAG 6 soils suggest similar ages (15 to 20 ka).

MECHANISMS OF TERRACE FORMATION

The erosion surfaces and terraces of the Uinta Basin are a consequence of alternating periods of stream incision and stability that characterized the Quaternary history of the region. The earlier outwash terraces (pre-RAG 6) of the Lake Fork–Yellowstone River generally diverge downstream while the RAG 6 terraces converge (Table 2). Similar relationships are found along the Unita River, but the sequence is not as well preserved there. The diverging terraces were formed during basin incision by the Duchesne and Green rivers, whereas the converging terraces of RAG 6 mark a period of relative stability of those rivers following aggradation near the end of the last glaciation.

Alternating cycles of incision and stability in a river system can be caused by a variety of external factors and may be inherent in river erosion without external forcing (Schumm, 1977). In the Uinta Basin, stream captures played an important role in lowering the courses of south-flowing rivers. However, stream captures in the basin were not responsible for the lowering that produced the diverging outwash surfaces of the Lake Fork and Uinta rivers, because the position and geometry of the several levels of Leland bench near the Duchesne-Green confluence (Plate 4A) indicate that the entire Duchesne-Green system in the basin was being lowered episodically during the Quaternary (Osborn, 1973). Some periods of incision may be a response to captures on the Green River downstream of the Duchesne River confluence, but none have been reported.

Most terraces in the basin are primarily a response to the changing fluvial regimes of glacial/interglacial cycles. Streams cut laterally and aggraded during glaciations (or glacial-interglacial transitions), and apparently incised during interglaciations. Such cycles probably could not cause significant cumulative incision if base levels were fixed, but cycles superimposed on a condition of steadily dropping base level could have produced the sequence of terraces in the basin. We conclude (as did Hansen, 1984) that base-level lowering in the basin is the result of late Cenozoic epeirogenic uplift. The apparent recent stability of the Duchesne and Green rivers (as suggested by converging RAG 5 and 6 terraces) may be due to a decreasing rate of uplift.

RATES OF LATE CENOZOIC INCISION

Our rates of incision for the northwestern Uinta Basin (Table 2) provide only a crude measure of the rate of uplift in the basin because our control on the age of alluvial surfaces is poor. The total amount of late Cenozoic stream incision in the center of the basin cannot be accurately determined. The amount of post-Bishop Conglomerate (Oligocene) incision in the vicinity of Vernal (Plate 4A) is about 700 m, based on projections of a pre-Bishop erosion surface (Osborn, 1973). Maximum incision

rates for the Quaternary are estimated using the heights of existing remnants of older outwash terraces and minimum ages (Table 2). A RAG 3 outwash terrace that extends to within 11 km of the Duchesne River projects to a height of 215 m above the river in the center of the basin (Osborn, 1973). An older outwash surface (RAG 2, John Starr Flat, Plate 4A) is lost to erosion about 20 km north of the Duchesne River, but at that point the surface is 50 m higher than, and diverging downstream from, the RAG 3 terrace. Even without any further divergence over the missing 20 km, the RAG 2 surface would project to about 265 m above the Duchesne River. Because the RAG 2 surfaces are the oldest evidence of glaciation in the basin, some are probably much older than our minimum age estimate of >500 ka (Table 2), perhaps dating from the early Pleistocene (1.7 to 0.7 Ma). Thus, although 0.53 m/kyr is a maximum rate (265 m in more than 500 kyr), 0.2 to 0.3 m/kyr may be a more accurate Quaternary incision rate. Hansen (1984) calculated an even lower rate of 0.15 m/kyr for the eastern Uintas for both the Pliocene and Quaternary periods, but he had no local numerical-age control.

CORRELATIONS AMONG BASINS AND UNRESOLVED PROBLEMS

Known and inferred ages for fluvial terraces in the Bighorn, Laramie, and Uinta basins and parts of the Sweetwater and Yampa rivers are based on tephrochronology, paleontology, amino acid racemization, soil development, correlation, and average incision rates calculated for the various drainages (Fig. 2). The accuracy of these ages has increased greatly since Scott's (1965) summary because more detailed mapping is available and because more terraces are known to be associated with dated volcanic ashes. However, those terraces whose ages are estimated using incision rates cannot be confidently correlated among basins due to the uncertainties involved in such calculations.

Four prominent age groups of middle and late Pleistocene terraces exist in most of the basins in this study (Fig. 2). Erosion surfaces and deposits older than 600 ka are fewer in number, and their ages are not well constrained except in the Laramie and Bighorn basins, where ashes older than the Lava Creek are associated with terrace deposits (Fig. 2). Fluvial deposits of the oldest terrace group contain the 600-ka Lava Creek ash. Along East Rosebud Creek north of Rock Creek in Montana (Fig. 1), fluvial deposits of the 600-ka terrace probably represent glacial outwash because the terrace grades to a buried till (Reheis, 1987a). A broad group of terraces includes those at 450 to 250 ka; in some basins this group includes terraces of more than one age. Two groups of younger terraces that are about 200 to 100 kyr and 40 to 15 kyr old grade to till of Bull Lake and Pinedale age, respectively, along Rock Creek, the Shoshone and Yampa rivers, and streams in the Uinta basin.

Most of the terraces described in this paper appear to be caused by glacial-interglacial climatic fluctuations. This relationship is directly demonstrated by terrace deposits of the younger age groups that grade to moraines. Terrace deposits of other age groups probably also formed in response to climatic changes, for two reasons: (1) In each basin the clast size, thickness, and form of most older terrace deposits resemble those of younger glaciofluvial deposits; and (2) a regional mechanism, such as climatic change, is required to form terraces of the same general age in widely separated basins. The times of incision (with the possible exception of terraces on the Bighorn River) apparently correspond to late glacial or early interglacial stages of the marine oxygen-isotope record (Fig. 2), suggesting that the terrace surfaces stabilized and were incised shortly after cessation of glaciofluvial sedimentation.

Terrace sequences that perfectly match the glacial-interglacial cycles represented in the oxygen-isotope record (Shackleton and Opdyke, 1976; Imbrie and others, 1984) do not exist in the individual basins of this study (Fig. 2). Correlations to the marine record of terraces older than 600 ka are particularly poor. The lack of a complete record is due at least in part to local vagaries of erosion and deposition. However, a hypothesis that deserves further study is that some glaciations indicated by the oxygen-isotope record may not have been sufficiently long or strong in this part of the Rocky Mountains to cause significant changes in stream equilibria.

Some terraces may have formed in response to mechanisms other than climatic change, such as stream capture. However, the underlying causes for stream captures have not been investigated in detail. Some may be related to glaciation, as heavily loaded aggrading streams with glaciated headwaters were captured by lightly loaded headward-eroding streams with no glaciated source areas. Other captures could be related to Quaternary tectonism.

Quaternary tectonism, including both epeirogenic movements and faulting, is an important process that has affected terrace formation in the Bighorn and Uinta basins and on the Sweetwater River. The abundant, well-preserved terraces in the Rocky Mountain basins provide datums to evaluate the amount and timing of Quaternary tectonism, yet few investigations have been done. In the northern Bighorn basin, captures of the Clarks Fork and Shoshone rivers may be related to fault movements in the Pryor Mountains (Fig. 1). Along Rock Creek and the lower Bighorn River, Montana, terraces of greater age progressively diverge from the modern stream, suggesting gradual uplift of that part of the basin (Reheis, 1985). Controversy exists concerning the possible occurrence of Quaternary deformation in the Laramie Basin.

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NOTES ADDED IN PROOF

Two important publications on the Bighorn basin have come out since this chapter was written. One is a detailed map of fluvial terraces of the lower Bighorn River; the other summarizes the influence of climate and eolian dust influx on the development of soils in the northern Bighorn basin.

ADDITIONAL REFERENCES

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Chapter 14

Quaternary history of some southern and central Rocky Mountain basins

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INTRODUCTION

This chapter summarizes the current state of late Cenozoic stratigraphic knowledge in some Rocky Mountain basins (here defined as the structurally low portions of major drainage basins) that have been studied in detail since Scott's (1965) summary on the nonglacial history of the southern and middle Rocky Mountains. The Quaternary history of few of these basins has been studied as intensively as that of the surrounding mountain ranges, despite the wealth of fluvial and other types of deposits present in the basins and the potential for dating them. The areas discussed here include the Bighorn Basin in Wyoming and Montana, the Laramie Basin and part of the Sweetwater River Basin in Wyoming, the Yampa River Basin in Colorado, and the Uinta Basin in Utah (Fig. 1). Small parts of the Great Plains and Colorado Plateau physiographic provinces are included in this discussion. Correlations of deposits within and among some of the areas can now be made more confidently than in 1965 because of detailed mapping and the discovery of many more localities with dated volcanic ashes.

MODERN CLIMATE AND PALEOCLIMATE

The modern climate of basin-floor areas discussed in this study is generally semiarid. Typically, precipitation is higher adjacent to the mountain ranges and decreases basinward. For example, mean annual precipitation along Rock Creek, Montana, decreases from 64 cm at the mountain front to 37 cm 70 km downstream (Fig. 1). Mean annual temperatures range from 5° to 8°C (National Climatic Center, 1951–1980; Colorado Water Conservation Board, 1969). Most of the basin floors are vegetated by grasses and sagebrush, although more arid portions, such as the northeastern Bighorn Basin and the northwestern Yampa River Basin, are dominated by desert shrubs such as sagebrush, greasewood, and rabbitbrush.

The climate during the last glaciation was much colder than at present, which may have caused locally higher effective moisture levels because of reduced evapotranspiration. These higher moisture levels may have caused changes in vegetation, slope processes, fluvial regimes, and the depth to which pedogenic $CaCO_3$ and clays were translocated in soils. Mean-annual temperature during the last glaciation was at least 10°C lower, based on the presence of ice- and sand-wedge polygons in intermontane basins of Wyoming (Mears, 1981), depression of snowlines (Porter and others, 1983), and the occurrence of late Pleistocene fossil vertebrate faunas with tundra affinities (Walker, 1982). A similar decrease in temperature is suggested by amino

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