Geomorphology of Cement Creek and its Relation to Ferricrete Deposits

By Kirk R. Vincent, Stanley E. Church, and Laurie Wirt

Chapter E16 of

Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado

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Professional Paper 1651

U.S. Department of the Interior
U.S. Geological Survey

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Abstract

Latest Quaternary landforms, composed of gravel and peat, in the lower 11 kilometers of Cement Creek were mapped and dated in order to understand the geomorphic history of the area and thus provide a geomorphological context for understanding the formation of ferricrete, as part of the Animas River watershed study.

The San Juan Mountains were nearly covered by alpine glaciers during the latest Pleistocene and presumably numerous times before. During the most recent episode, generally referred to as the Pinedale glaciation, ice was about 520 meters thick at the present site of Silverton and 430 meters thick at the present site of Gladstone. That glaciation ended about 12,000 ^{14}C years ago, and except for till, the sediments along Cement Creek were likely deposited after that. Other deposits apparently formed during deglaciation, including a canyon-filling stream-gravel deposit, a localized stream terrace about 20 meters higher than the valley floor, and a large landslide. Prominent alluvial fans, located at the mouths of most tributaries, also probably began to accumulate as soon as ice disappeared from the floor of the Cement Creek valley. The fans probably accumulated rapidly until the surrounding hillslopes became stabilized by vegetation, which may have taken many centuries. The largest fans, or pairs of fans, aggraded the valley bottom perhaps more than 20 meters and caused Cement Creek to aggrade upstream of them. This resulted in a segmented longitudinal profile of the Cement Creek valley that is still present, because the bulk of the fan deposits have not been removed by Cement Creek. More than 6,000 years ago, however, Cement Creek partially breached the toes of the fans, incising through as much as 5 meters of fan sediment. This, in turn, caused the fans to become incised by their tributary streams. Between 3700 B.C. and A.D. 400 (5,650 to 1,550 cal. yr B.P.) Cement Creek migrated laterally, but its bed remained at the level of the present streambed. Starting about A.D. 400, which is slightly before the Medieval Warm Period, Cement Creek began to aggrade and rose as much as 3 meters above its previous level. Cement Creek incised back to its previous level, leaving behind a prominent stream terrace, between A.D. 1330 and A.D. 1700. This incision may have occurred before A.D. 1500 and perhaps about A.D. 1440. Incision of the Cement Creek terrace is roughly synchronous with the beginning of the Little Ice Age. Aggradation and incision of the Cement Creek terrace were not caused by local base level processes, and may have been the result of climate change, although the precise mechanisms involved are not known. Recent human activities, in contrast, have had little influence on the shape and physical processes of Cement Creek. The influence of human activities on geochemical process is beyond the scope of this study, with the exception of ferricrete formation.

Iron compounds locally cement clastic sediment of all origins, creating conglomerate-type ferricrete. Most ferricrete exposures are dry and presumably are inactive, and most are prehistorical in age. Defining the timing of conglomerate-type ferricrete cementation is problematic, even where the depositional age of the clastic sediment is precisely known, because cementation could have occurred at any time after clastic deposition. Cementation of distal fan sediment must have occurred more than 6,000 years ago, because that is when the ground water in the gravel was permanently drained by stream incision. A spring-deposited ferricrete encased charcoal that is 4,500 cal. years old, so presumably conglomerate ferricrete also formed during the middle Holocene. Stream gravels deposited in the past 500 years are also cemented by iron compounds. We conclude that ferricrete formed in Cement Creek clastic sediment at various times and locations throughout the Holocene, and thus most ferricrete is unrelated to mining.

Exposures of ferricrete are spatially discontinuous and do not correspond to the rate of emergence of ground water during the low-flow season. This suggests that the geochemical conditions necessary for ferricrete formation are not uniform in the watershed.

Exposures of wet, possibly active ferricrete are almost invariably located where there are sedge wetlands (underlain by peat) on an adjacent terrace. We conclude that both wetlands and wet ferricrete result from the perennial emergence of ground water that originated in tributary subbasins, rather than from Cement Creek itself. One must take care when using peat

to date stream incision because peat can continue to accrete in wetlands after stream incision. This continuing accretion occurs because the water supply to wetlands is from emerging ground water that originated in tributary subbasins, not from the main stream. Thus, the presence of sedge peat in subalpine settings like Cement Creek is a paleo-environmental indicator of the emergence of ground water from the valley sides.

Introduction

Cement Creek, which flows into the Animas River at Silverton (fig. 1), was presumably named for the ferricrete so prevalent in Cement Creek basin. Iron-rich precipitates cement alluvium and colluvium, forming conglomerates, and also accumulate in iron springs and bogs as relatively pure deposits with few clasts incorporated. Both types of deposits are called ferricrete. Acidic geochemical conditions leading to the precipitation of ferricrete can adversely impact surface water chemistry and riparian ecology and thus are of environmental concern. Therefore, several studies investigated the physical, hydrologic, and geochemical conditions of ferricrete formation, in order to help understand the geochemical processes before and after mining began. Verplanck and others (this volume, Chapter E15) present a classification of ferricrete, and the spatial distribution of ferricrete in the region is documented on plate 2 of Yager and Bove (this volume, Chapter E1). Wirt and others (this volume, Chapter E17) explore the geochemical and hydrologic processes of formation of ferricrete, using Cement Creek as a major example. This chapter provides the geomorphological context for those chapters. Our study focuses on Cement Creek from the confluence with South Fork Cement Creek (near the Gladstone site) to the canyon mouth at Silverton (fig. 1).

Purpose and Scope

The purpose of this study is to provide the geomorphological context for the formation of ferricrete along Cement Creek by investigation of the following:

- The location and nature of clastic sediment that is locally cemented with iron-rich compounds. Alluvial deposits influence the movement of ground water, which is the medium of transport of the iron and the medium from which the iron compounds precipitate.
- The history of incision of alluvial deposits, because that influences the location of oxidation of iron-rich waters. Incision can cause dewatering of clastic sediment and a shift in the location of ferricrete formation.
- The dating of aggradation and incision of alluvium along Cement Creek, thus providing constraints on the timing of ferricrete formation within, or on, clastic sediment.

In so doing, we also contribute to an understanding of the Holocene geomorphic history and processes of Cement Creek, and of the region in general.

Setting and Historical Background

This chapter documents the nature and history of landforms along the lower 11 km of Cement Creek, from Gladstone to Silverton, and at the mouths of its major tributaries (fig. 1 and pl. 5). Cement Creek flows through a subalpine valley located in the San Juan Mountains of San Juan County, Colo., and joins the Animas River at Silverton. In the study area, Cement Creek ranges in altitude from 2,828 to 3,182 m, but the surrounding hillslopes extend up to mountain tops that reach 4,111 m. Those hillslopes are dominated by exposed bedrock and tundra vegetation above the treeline (at about 3,600 m), and are dominated by Engelmann spruce and subalpine fir below the treeline. In the valley bottom, alluvial fans are dominated by spruce forest and open grasslands; stream terraces and flood plains support thickets of bog birch and willow, sedge wetlands, and spruce forests.

The Silverton weather station records mean annual temperature of 1.7°C (35°F) and about 61 cm average annual precipitation (National Weather Service data), but precipitation is about twice that in the surrounding mountains (von Guerard and others, this volume, Chapter B). Although precipitation in the area is predominantly snowfall, rain is delivered by summer thunderstorms and by Pacific tropical storms in the fall. Peak streamflows generally result from spring snowmelt, but substantial flows result from tropical storms in the fall (von Guerard and others, this volume, fig. 3; Pruess, 1996).

The bedrock geology, and the mineralization that made the area famous, are discussed by Yager and Bove (this volume, pl. 1) and Bove and others (this volume, Chapter E3). For this chapter the salient aspect of the bedrock geology is that it is composed of erosion-resistant volcanic rocks. Thus talus deposits are common, hillslope soils are thin and coarse textured, and alluvial deposits are coarse and contain little silt and clay. Blair and others (2002) presented the late Quaternary geologic history of the region, and we complement their work by subdividing certain map units along Cement Creek and by providing age constraints that were previously lacking. Atwood and Mather (1932) mapped the extent of glaciation in the San Juan region. Few if any surficial deposits predate the last glaciation; thus, the landforms we discuss are latest Pleistocene and Holocene in age.

Hard-rock mining was extensive in the Cement Creek watershed during the late 19th century and through most of the 20th century (Church, Mast, and others, this volume, Chapter E5, fig. 1), and the toxic effects of metals released by human efforts are the subject of several chapters in this volume. We conclude, however, that the actions of humans have had little lasting impact on the physical form (beyond localized disturbance) or physical function of Cement Creek and adjacent wetlands. We do not address chemical impacts.

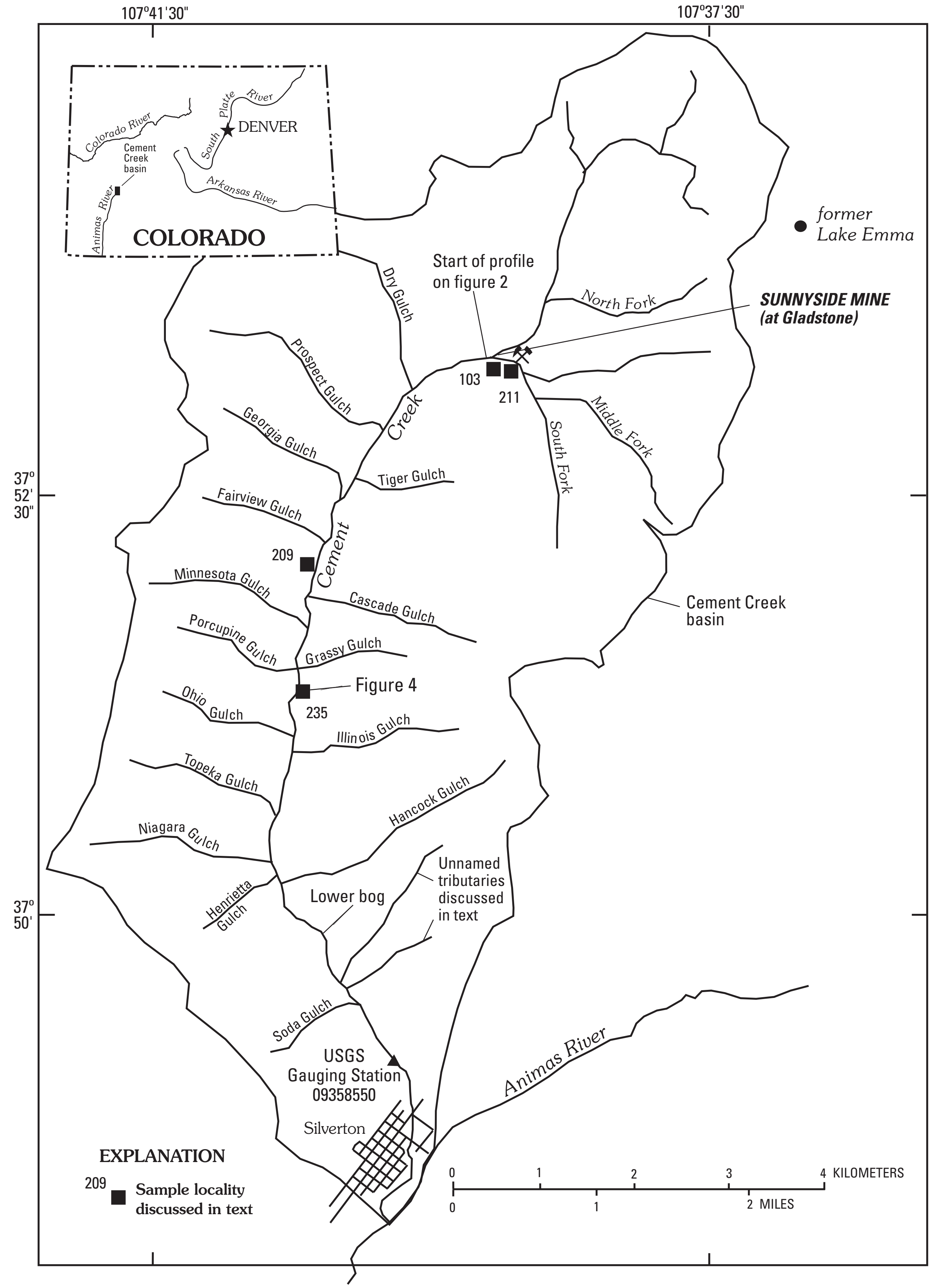


Figure 1. Location of Cement Creek and its major tributaries, near Silverton, San Juan County, Colo.

Two historical floods are noteworthy and both involve the Gladstone site, at the upstream end of our study reach (fig. 1, pl. 5). One flood occurred on October 5, 1911, and is the flood of record on the Animas River (Durango Evening Herald, 1911). It is informally named after Gladstone because that is where the largest 24-hour rainfall (21 cm) for the storm was measured (Pruess, 1996). The second flood involved a bizarre event that occurred on June 4, 1978, when the bed of Lake Emma (a glacial tarn), having been literally undermined, accidentally caved into the Sunnyside mine below (Jones, this volume, Chapter C, figs. 26–29). A torrent of sediment and lake water drained through the mine workings, gushed out of the American tunnel portal at Gladstone (mine # 96), and rushed down Cement Creek (Bird, 1986). Neither flood, however, had a major physical impact on the geomorphology of Cement Creek that is identifiable today.

Methods

In order to understand the Holocene geomorphic history and processes of Cement Creek, and thus place ferricrete formation into a geomorphological and temporal context, we employed four methods. These involved mapping fluvial landforms (pl. 5) and surveying their longitudinal profile (figs. 2 and 3). The stratigraphy and sedimentology of clastic and peat deposits were documented (for example, fig. 4), and the deposits were dated using radiocarbon (table 1) and tree rings.

Field Methods

Landforms were mapped in the field onto a photographic base (about 1:6,200) by standard field methods. The mapping from this study is presented on plate 5. This effort added detail and age constraints to the previous work of Blair and others (2002), which was regional in scope. Blair and others identified five surficial geologic map units in the Cement Creek watershed, in addition to colluvium and bedrock hillslopes and areas disturbed by human activities. We developed 11 map units, which are used to distinguish alluvial fans, stream terraces, the flood plain and active channel of Cement Creek, glacial till, landslide deposits, and areas obscured by human activity. Exposed bedrock and colluvial hillslopes were not mapped. The sedimentology and stratigraphy of stream and wetland deposits were inspected at numerous cutbank exposures along Cement Creek, and the stratigraphy of one important site is illustrated in figure 4.

A longitudinal profile of Cement Creek (figs. 2 and 3) was surveyed in order to place landform surfaces and stratigraphy, ferricrete deposits, wetlands and other sites of inflowing water, and dated material into a common spatial context (fig. 5). A longitudinal profile is like a cross section, but is oriented parallel to the valley axis. The profile was surveyed using a 2-power hand level on a staff of fixed height, a surveyor's rod, and a 100 m tape. The instrument "turned" (was moved) when the down-valley shot distance reached 25 m. The altitudinal datum was taken from the contour map, and thus altitude values are approximate. The "horizontal" datum was arbitrarily set to be zero at the confluence of Cement Creek with South Fork Cement Creek (fig. 1). The cumulative down-valley tape distance was not converted to true horizontal distance, but the resulting distortion of local gradients is insignificant for our purposes. The profile transect was designed as a compromise between the valley axis and the longer course of the meandering stream. In other words, the transect crossed point bars rather than following the thalweg or center of the channel. This means that the true stream gradients are locally slightly less steep than depicted, but again this distortion is acceptable given our purposes. This also means that our tape distances differ slightly from those measured by Kimball and others (2002) during their tracer dilution study of Cement Creek. We have used their inflow data and converted their tape distances to ours by knowing distances measured in both studies at the confluences of major tributaries. The profile extends from the South Fork Cement Creek confluence (near Gladstone) for just over 10 km to the mouth of Cement Creek, dropping 332 m in altitude over this distance. The survey progressed downstream and was not closed by surveying back up the valley; rather the total fall was independently estimated from USGS topographic maps. The difference in the surveyed and map-based altitude drop is 6 m, which is excellent agreement given the ≈13 m (40-foot) contour interval of the maps.

Dating Methods and Limitations

Three dating techniques were used to establish the age of clastic and peat deposits. (1) Crosscutting relationships were used to establish the relative age of the deposits. This involved crosscutting stratigraphy of exposed sediment, and also crosscutting landforms. For example, the toes of many alluvial fans (map unit fo) are truncated, and a prominent terrace (map unit t) is found at the foot of the escarpments. The fan surfaces and sediment must be older than the terrace surface and the terrace sediment. (2) We counted the growth rings of living and standing-dead Engelmann spruce trees that were rooted in surficial sediment of the Cement Creek terrace or flood plain, to determine when the trees were established. This provides a minimum age for deposition of the sediment in which the trees were rooted. (3) Lastly, we obtained radiocarbon ages for organic material found in sediment. The dating results for 43 samples are listed in table 1 along with sample types, localities, and laboratory methods and assumptions. All radiocarbon ages were calibrated (Stuiver and Reimer, 1993), and all dates are presented in calibrated (cal.) calendar years unless otherwise indicated. Dating results for the prominent terrace (map unit t) are presented in figure 5.

Three types of buried organic material (stumps, branches, and peat or twigs in peat) were dated for this study. The reliability of radiocarbon results for dating the deposition of clastic sediment depends in part on the type of organic material

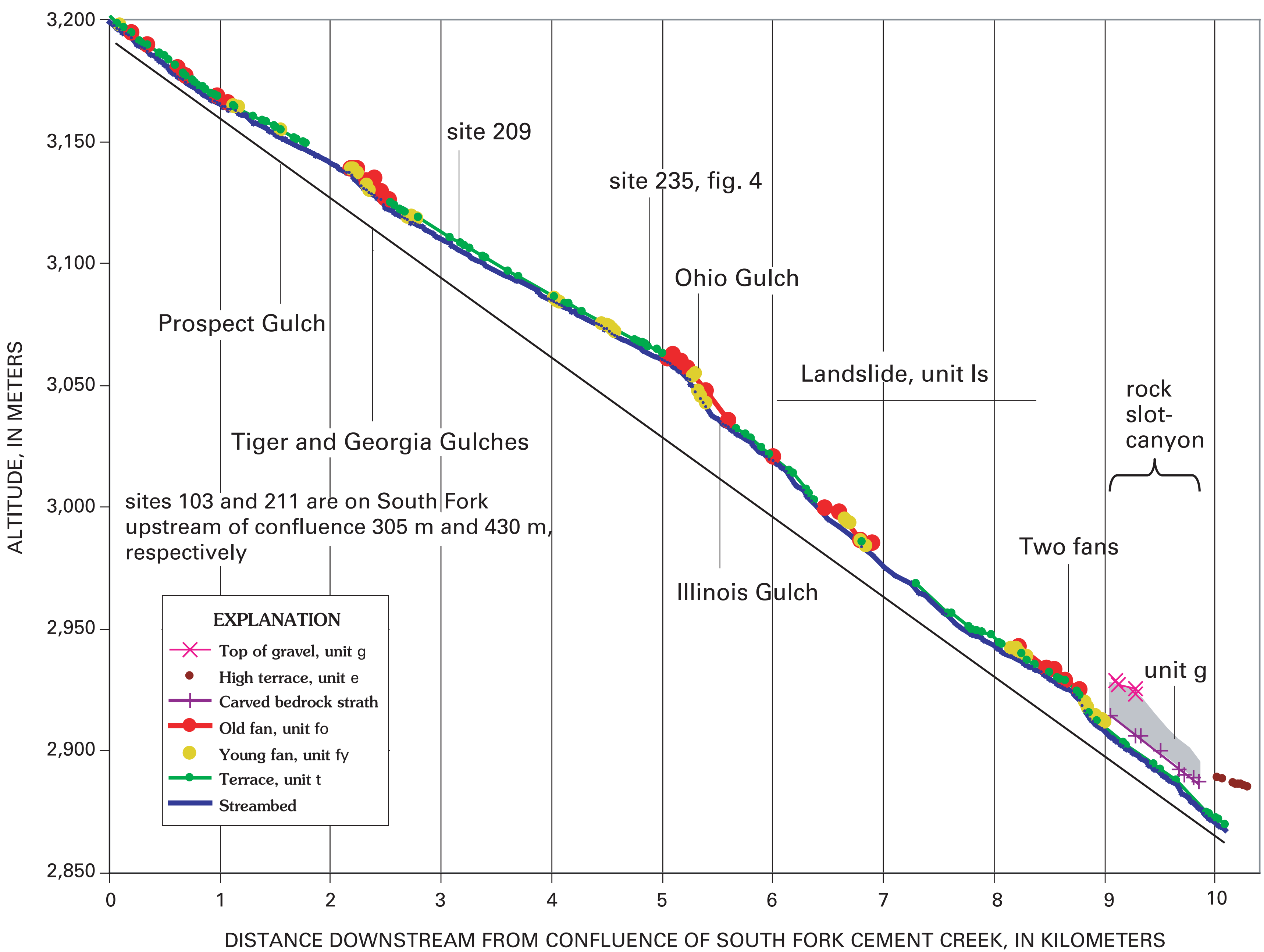


Figure 2. Surveyed longitudinal profile of bed and prominent terrace of Cement Creek, and other landforms. USGS stream gauge (Station 09358550) is located at 9.7 km. Dots represent measurements points. Straight line is drawn below profile to help illustrate convex shape of profile.

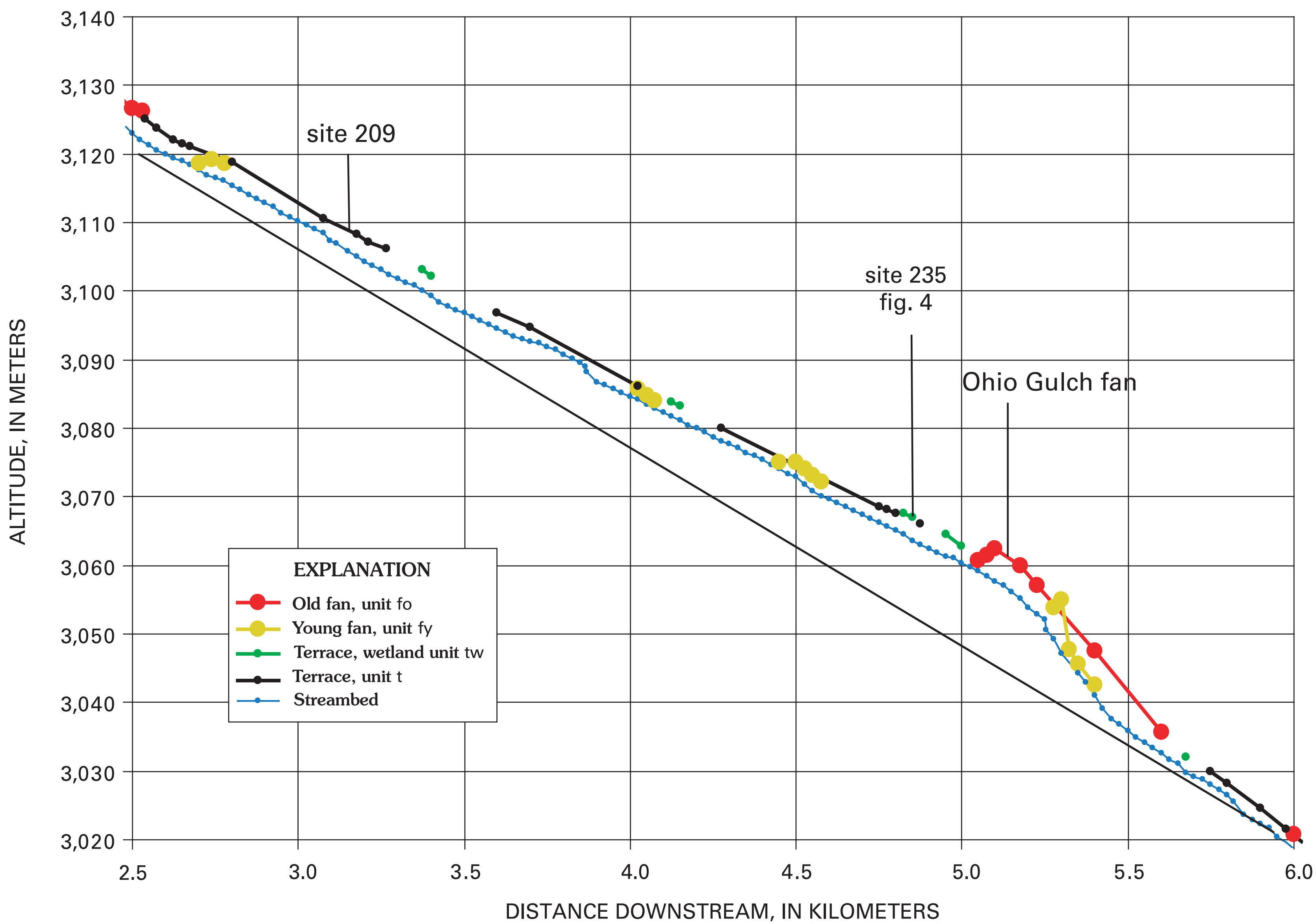


Figure 3. Surveyed longitudinal profile of bed and prominent terrace of Cement Creek (middle portion of Cement Creek profile, fig. 2, near Ohio Gulch), and tributary alluvial fans projected to the profile transect. Dots represent measurements points. Straight line is drawn below profile for reference.

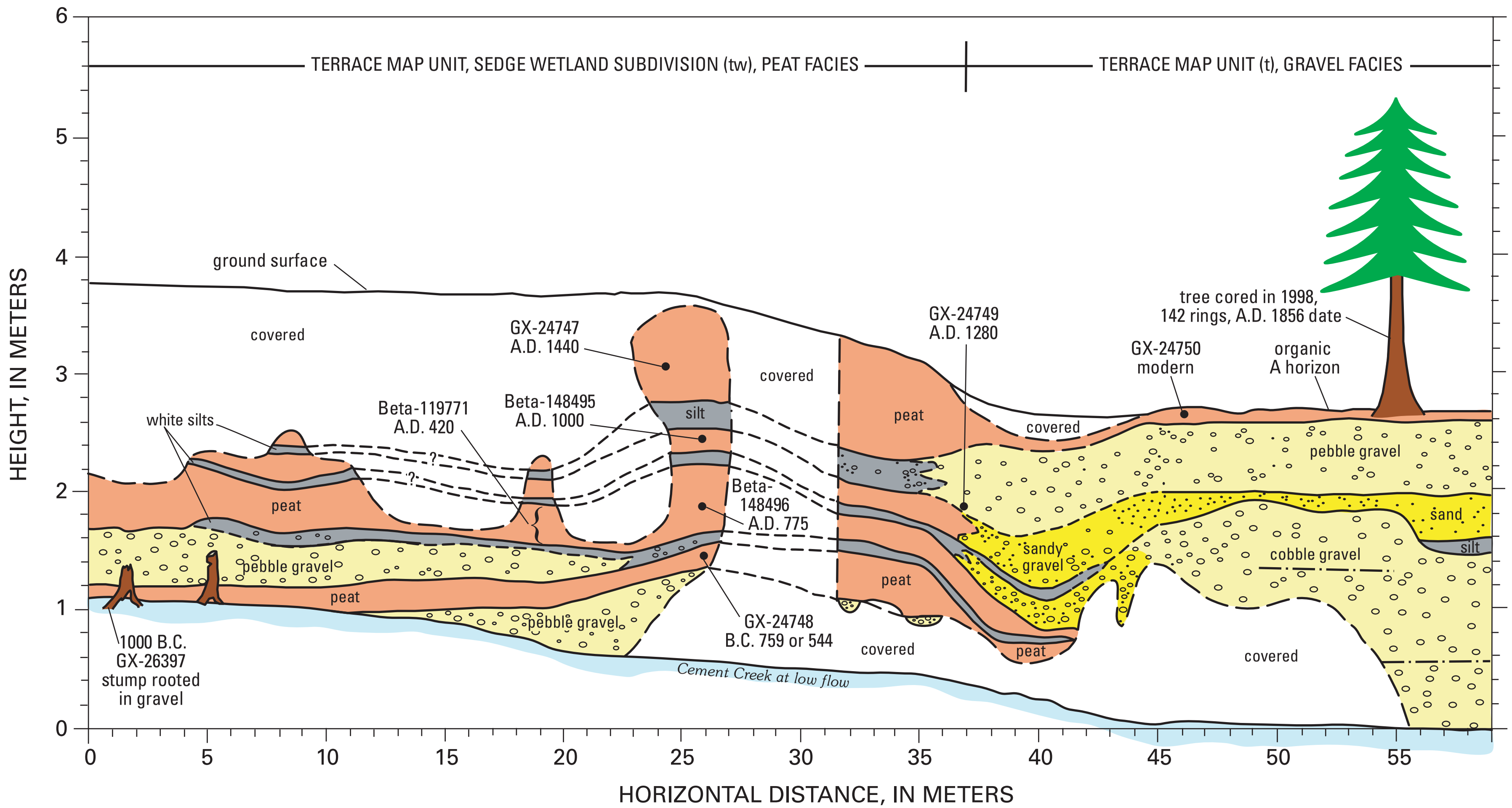


Figure 4. Stratigraphy at site 235 of the prominent terrace (map unit t) along Cement Creek. Streambank exposure is located about 400 m upstream of Ohio Gulch (at 4.85 km in figs. 2 and 3) on east side of Cement Creek.

Table 1. Data for radiocarbon samples collected along Cement Creek, organized by site, landform, type of sample, and stratigraphic position.

[Note that "B.C." and "A.D." are both placed before dates in this table—for better readability and quicker recognition]

Field No.	Lab No.[1]	$\delta^{13}C$ per mil[1]	^{14}C age years B.P.[2]	Calibrated ages[3]: Intercept(s)[4]	Calibrated ages[3]: 1-sigma range[5]	Calibrated ages[3]: 2-sigma range[5]	Height above water, m[6]	Distance on profile[8], m; comments
Samples from flood-plain sediments (map unit p) at various locations along Cement Creek								
Wood not in growth position:								
00-ABFC-207B	Beta-147014	–25*	Modern (117 %)[7]				0.85	5,690
00-ABFC-207A	Beta-147013	–25*	Modern (100 %)[7]				0.3	5,690
00-ABFC-205	Beta-147012	–25*	30±40	A.D. 1953	A.D. 1951–1955	A.D. 1897–1915 A.D. 1949–1955	0.25	3,050
00-ABFC-204B	Beta-147011	–25*	180±70	A.D. 1670–1950	A.D. 1650–1880 A.D. 1920–1950	A.D. 1530–1560 A.D. 1630–1950	0.6	1,755; 20 OGR[9].
00-ABFC-210	Beta-147020	–25*	230±70	A.D. 1660	A.D. 1640–1680 A.D. 1740–1800 A.D. 1930–1950	A.D. 1490–1890 A.D. 1910–1950	1.0	7,560; wood in alluvial ferricrete.
Stumps in growth position:								
00-ABFC-213	Beta-147030	–25*	Modern (101 %)[7]				0.3	7,850
00-ABFC-208	Beta-147015	–25*	90±70	A.D. 1890–1950	A.D. 1680–1760 A.D. 1804–1954	A.D. 1660–1955	0.3	1,325; 30 OGR[9].
00-ABFC-204A	Beta-147010	–25*	180±50	A.D. 1670–1950	A.D. 1660–1690 A.D. 1730–1810 A.D. 1920–1950	A.D. 1640–1950	0.1	1,755; 20 OGR[9].
Samples from stratigraphic site 209, located on figs. 1, 2, and 3 (lat 37.8680° N., long 107.6745° W.)								
Wood from flood-plain sediments (map unit p):								
00-ABFC-209F	Beta-147019	–25*	70±70	A.D. 1951	A.D. 1685–1732 A.D. 1808–1926 A.D. 1948–1955	A.D. 1665–1784 A.D. 1789–1955	1.2	3,180; wood in sand.
00-ABFC-209D	Beta-147018	–25*	220±50	A.D. 1660	A.D. 1650–1680 A.D. 1770–1800 A.D. 1940–1950	A.D. 1530–1560 A.D. 1630–1690 A.D. 1730–1810 A.D. 1920–1950	1.0	3,180; wood in peat.
00-ABFC-209B	Beta-147016	–25*	230±60	A.D. 1660	A.D. 1640–1680 A.D. 1770–1800 A.D. 1940–1950	A.D. 1510–1600 A.D. 1620–1700 A.D. 1720–1820 A.D. 1840–1880 A.D. 1920–1950	0.2	3,180; wood in silt.
Wood in gravel (of map unit t) beneath unconformity at base of flood-plain sediments (map unit p):								
00-ABFC-209C	Beta-147017	–25*	1,910±70	A.D. 90	A.D. 30–150	B.C. 50–A.D. 250	0.0	3,180

Table 1. Data for radiocarbon samples collected along Cement Creek, organized by site, landform, type of sample, and stratigraphic position.—Continued

Field No.	Lab No.[1]	$\delta^{13}C$ per mil[1]	^{14}C age years B.P.[2]	Calibrated ages[3] Intercept(s)[4]	1-sigma range[5]	2-sigma range[5]	Height above water, m[6]	Distance on profile[8], m; comments
Samples from stratigraphic site 211, located on fig. 1; site is 430 m[8] up South Fork Cement Creek (lat 37.8879° N., long 107.6490° W.)								
Wood in gravel of flood plain (map unit p):								
00-ABFC-211B	Beta-147022	–25*	110±50	A.D. 1700–1950	A.D. 1680–1740 A.D. 1800–1930	A.D. 1660–1960	1.1	30 OGR[9].
Stump in growth position at surface of terrace (map unit t):								
00-ABFC-211F	Beta-147025	–25*	300±60	A.D. 1640	A.D. 1500–1660	A.D. 1450–1670 A.D. 1770–1800	3.75	10 OGR[9].
Stumps in growth position within gravels of terrace (map unit t):								
00-ABFC-211D	Beta-147024	–25*	1,110±70	A.D. 960	A.D. 880–1000	A.D. 770–1030	2.73	10 OGR[9].
00-ABFC-211C	Beta-147023	–25*	1,670±70	A.D. 400	A.D. 260–290 A.D. 320–430	A.D. 230–540	0.95	30 OGR[9].
00-ABFC-211A	Beta-147021	–25*	1,690±80	A.D. 380	A.D. 250–430	A.D. 140–540	0.65	30 OGR[9].
Samples from stratigraphic site 103, located on fig. 1; site is 305 m[8] up South Fork Cement Creek (lat 37.8895° N., long 107.6507° W.)								
Wood from gravel of apparent flood plain (map unit p), in unconformable contact with terrace sediment (map unit t):								
99-ABFC-103G	GX-26409	–22.4	440±50	A.D. 1440	A.D. 1430–1480	A.D. 1410–1520 A.D. 1590–1620	0.10	
Wood from gravel section of terrace (map unit t) on right bank:								
99-ABFC-103K	GX-26396	–22.4	570±100	A.D. 1330–1400	A.D. 1300–1440	A.D. 1270–1490	1.85	
99-ABFC-103I	GX-26395	–23.8	1,030±40	A.D. 1000–1020	A.D. 980–1020	A.D. 900–920 A.D. 960–1150	1.35	
99-ABFC-103H	GX-26394	–23.4	1,540±40	A.D. 538	A.D. 435–564 A.D. 572–577 A.D. 589–597	A.D. 423–620	0.9	
Peat or twigs from peat section of terrace (map unit subdivision tw) on left bank:								
00-ABFC-212A	Beta-147026-AMS	–23.9	2,300±40	B.C. 390	B.C. 400–370	B.C. 410–360 B.C. 290–230	2.85	Peat.
00-ABFC-212B	Beta-147027-AMS	–28.1	3,680±40	B.C. 2040	B.C. 2130–2010	B.C. 2190–2170 B.C. 2150–1940	1.8	Peat.
00-ABFC-212C	Beta-147028	–25*	4,920±70	B.C. 3680	B.C. 3770–3650	B.C. 3920–3870 B.C. 3810–3630 B.C. 3560–3540	0.17	Twig in peat.
Stump in growth position from gravel beneath peat section (map unit subdivision tw) on left bank:								
00-ABFC-212D	Beta-147029	–25*	4,960±80	B.C. 3710	B.C. 3900–3890 B.C. 3800–3660	B.C. 3960 - 3640	0	20 OGR[9].
Samples from stratigraphic site 235 (see fig. 4), on figs. 1, 2, and 3; site is 400 m upstream of Ohio Gulch (lat 37.8557° N., long 107.6754° W.)								
Wood in peat of terrace (map unit subdivision tw):								
98-ABB-235t3	GX-24750	–27.4	Modern (108 %)[7]				2.6	4,875
98-ABB-235p0	GX-24747-AMS	–23.1	470±50	A.D. 1440	A.D. 1410–1450	A.D. 1330–1340 A.D. 1400–1490	2.4	4,853
98-ABB-235t4	GX-24749	–26.5	725±120	A.D. 1280	A.D. 1210–1330 A.D. 1340–1390	A.D. 1030–1430	1.45	4,866

Table 1. Data for radiocarbon samples collected along Cement Creek, organized by site, landform, type of sample, and stratigraphic position.—Continued

Field No.	Lab No.[1]	$\delta^{13}C$ per mil[1]	^{14}C age years B.P.[2]	Calibrated ages[3] Intercept(s)[4]	1-sigma range[5]	2-sigma range[5]	Height above water, m[6]	Distance on profile[8], m; comments
Samples from stratigraphic site 235, continued								
Peat of terrace (map unit subdivision tw):								
00-ABF-C235-3a	Beta-148495	–25*	1,040±60	A.D. 1000	A.D. 970–1030	A.D. 890–1150	1.85	4,854
00-ABF-C235-4a	Beta-148496	–25*	1,240±50	A.D. 775	A.D. 700–870	A.D. 670–895	1.3	4,854
96-ABS-123	Beta-119771	–26.7	1,640±70	A.D. 420	A.D. 260–270 A.D. 340–470 A.D. 480–530	A.D. 240–560 A.D. 570–580 A.D. 590–600	1.0±0.1	4,848
Wood in peat of terrace (map unit subdivision tw):								
98-ABB-235p3	GX-24748-AMS	–27.2	2,490±40	B.C. 759–544	B.C. 765–519	B.C. 792–409	0.87	4,854
Stump in growth position from gravel beneath peat section (map unit subdivision tw):								
99-ABFC-109	GX-26397	–24.5	2,840±80	B.C. 1000	B.C. 1180–1190 B.C. 1120–900	B.C. 1260–1230 B.C. 1220–820	0.0	4,830; 20 OGR[9].
Samples of wood or charcoal from terrace sediments (map unit t) at various locations along Cement Creek								
99-ABFC-122A	Beta-135103	–22.6	3,610±50	B.C. 1950	B.C. 2030–1880	B.C. 2140–1870 B.C. 1840–1810 B.C. 1800–1780	0.2	1,865; charcoal in silt beneath wetland.
99-ABFC-111	GX-26398	–22.5	1,680±40	A.D. 388	A.D. 263–276 A.D. 337–418	A.D. 256–304 A.D. 316–432	0.3	495; wood in alluvial ferricrete.
99-ABFC-130C	GX-26404-AMS	–22.2	2,470±40	B.C. 757–541	B.C. 762–482 B.C. 467–412	B.C. 787–405	0.9	4,950; wood in inter-peat silt.
Samples of wood from terrace sediments along Middle Fork Mineral Creek (lat and long locations indicated)								
00-ABFC-201	Beta-147007	–25*	790±70	A.D. 1260	A.D. 1190–1280	A.D. 1050–1100 A.D. 1140–1300	0.7	37.8448° N. 107.7318° W.
00-ABFC-202A	Beta-147008	–25*	870±50	A.D. 1180	A.D. 1060–1230	A.D. 1030–1270	0.4	37.8441° N. 107.7290° W.
00-ABFC-200	Beta-147006	–25*	4,520±70	B.C. 3340–3200	B.C. 3360–3090	B.C. 3500–3460 B.C. 3380–3000 B.C. 2980–2940	1.2	37.8451° N. 107.7323° W.

Table 1. Data for radiocarbon samples collected along Cement Creek, organized by site, landform, type of sample, and stratigraphic position.—Continued

Field No.	Lab No.[1]	$\delta^{13}C$ per mil[1]	^{14}C age years B.P.[2]	Calibrated ages[3] Intercept(s)[4]	Calibrated ages[3] 1-sigma range[5]	Calibrated ages[3] 2-sigma range[5]	Height above water, m[6]	Distance on profile[8], m; comments
Miscellaneous samples from Cement Creek basin								
Sample of wood at base of colluvium and on contact with till (lat 37.8926° N., long 107.6477° W.):								
98-ABFC-177C	GX-26406	–22.8	9,150±50	B.C. 8290	B.C. 8450–8280	B.C. 8530–8260		
Sample of wood in alluvial ferricrete in Cement Creek above Gladstone (lat 37.8959° N., long 107.6463° W.):								
99ABFC-176C	GX-26405	–24.3	2,170±70	B.C. 200	B.C. 360–110	B.C. 390–40 B.C. 30–20 B.C. 10–0	0.0	
Wood in iron spring deposit overlying colluvial ferricrete in Dry Gulch (lat 37.8641° N., long 107.6791° W.):								
99ABFC-185D	GX-26407	–21.4	380±40	A.D. 1481	A.D. 1447–1622	A.D. 1437–1638	1.0	
Charcoal from bog iron deposit overlying canyon-filling gravel (map unit g):								
99ABFC-141A	GX-26392	–24.4	4,010±110	B.C. 2560–2490	B.C. 2830–2350	B.C. 2880–2200	25	9,275

[1]Two commercial laboratories, Beta Analytic Inc (Lab. No. Beta-xxxxxx) and Geochron Laboratories (Lab. No. GX-xxxxx), analyzed the radiocarbon samples. Sample analysis done using accelerator mass spectrometry is denoted with the letters AMS. For $^{13}C/^{12}C$ results marked with an asterisk (*) the values were estimated to be –25 per mil based on values typical of the material type.

[2]Conventional radiocarbon age ($\delta^{13}C$ corrected), based on the Libby half life (5,570 years) for ^{14}C, as reported by the laboratory in years before A.D. 1950 (B.P.). The error is ±1 sigma as judged by the analytical errors alone. The sample was crushed if necessary and dispersed in water. The eluted clay/organic fraction was treated in hot dilute 1N HCl to remove any carbonates. It was then filtered, washed, dried, and combusted in oxygen to recover carbon dioxide for analysis.

[3]Ages calibrated using the CALIB4.3 program based on Stuiver and Reimer (1993) with data from Stuiver and Braziunas (1993) and Stuiver and others (1998). The 1998 atmospheric decadal data set and laboratory error multiplier K=1 were used in the calculations.

[4]Maximum and minimum values given if the radiocarbon age intercepted the calibration curve at multiple locations. Age(s) rounded to the nearest decade if the standard deviation in the radiocarbon age was ≥50 years.

[5]Calibrated age range(s) using the intercept method. Ages rounded to the nearest decade if the standard deviation in the radiocarbon age was ≥50 years. 1 sigma = square root of (sample standard deviation^2 + curve standard deviation^2); 2 sigma = 2 × square root of (sample standard deviation^2+ curve standard deviation^2).

[6]Height above late summer (base flow) water level of stream at the site of the sample.

[7]Sample with “modern” age had the given percentage of the A.D. 1950 ^{14}C activity, and is considered younger than A.D. 1850.

[8]Distances are positions on surveyed longitudinal profile (figs. 2 and 3). Sites 103 and 211 are on South Fork Cement Creek at specified position measured upstream from confluence with Cement Creek.

[9]Specified number of outer growth rings (OGR) of the plant were sampled and analyzed.

sampled. For example, large plant stems are always older than the deposit containing them, by a day or by centuries, because they grew before being incorporated into the deposit, and they may have been exhumed (reworked) from much older deposits. Logs and branches found in clastic deposits were dated, but care was taken in interpreting their ages. Lamina of well-stratified peat are unlikely to have been reworked, but care must be taken when the history of streams is inferred from dated peat, as discussed in the section titled, “Implications of Sedge Wetlands and Peat.” Twigs found in clastic deposits were not dated because of the possibility of misidentifying a root as a plant stem. Numerous tree stumps were discovered in growth position, having been buried and subsequently reexposed by streambank erosion. A stump rooted in gravel provides a highly reliable age constraint for the gravel deposits above and below its root crown, because a rooted stump in growth position could not have been reworked. We rely most heavily on stumps rooted in gravel and peat beds that were stratigraphically linked to channel gravel-deposits.

An inherent limitation clings to “young” radiocarbon samples, because the true calendar age of such samples is difficult to determine. The shape of the radiocarbon calibration curve between calendar years A.D. 1650 and 1950 is such that a radiocarbon age between 50 and 200 years intercepts the curve at more than one point. The correct intercept can be determined only by ruling out the others with independent evidence. For that reason we based our youngest age constraints on the growth rings of trees rooted in the Cement Creek flood plain.

Results: Nature and Distribution of Landforms

The results of our field observations and dating results are presented herein following the general chronological order of the landforms. Other observations are contained in the Map Unit Explanation of plate 5. This section is largely descriptive, and most interpretations are discussed in other sections.

General Distribution of Landforms

The longitudinal profile of Cement Creek (fig. 2) is convex in overall shape, with the lower half of the profile (below 5.2 km) being steeper than the upper half. The location of the tributary fan shed from Ohio Gulch coincides with this inflection at 5.2 km. The profiles of many alluvial streams, in contrast, are typically straight or concave.

In detail, the longitudinal profile consists of numerous straight reaches, with a conspicuous pairing of less steep reaches leading to steep reaches (fig. 2). One such pairing is shown in figure 3. There are also reaches of intermediate gradient that locally separate these pairs. The approximate gradients are 0.03 m/m for the “less steep” reaches, 0.04 m/m for the “intermediate” reaches, and 0.06 m/m for the “steep reaches.” The less steep reaches are 1–3 km long, and their streambeds are composed of pebble or cobble gravel, whereas the steep reaches are only 0.1–0.4 km long, and their streambeds are composed of boulders. The three main inflection points, where the profile becomes steep, are coincident with the locations of paired alluvial fans (fig. 2) shed from tributaries. At two locations tributaries enter Cement Creek from both sides such that they are almost directly opposed. These are Tiger and Georgia Gulches, and Ohio and Illinois Gulches (figs. 1 and 2; pl. 5). At the third inflection a pair of unnamed tributaries enter Cement Creek in close proximity from the northeast (fig. 1 and pl. 5).

Several landforms are found along the entire length of the study reach, but others are restricted to or absent from the lower 3 km of Cement Creek. Alluvial fans at the mouths of tributaries are generally spaced at regular intervals, but they are few in number in the lower reach where the contributing watersheds are small (fig. 1 and pl. 5). Landforms restricted to this lower reach are among the oldest in the Cement Creek basin.

Oldest Landforms

Glacial till (map unit m) is probably the oldest surficial deposit in the study area and is found on hillslopes adjacent to Cement Creek. Till occurs locally near Ohio Gulch, and more extensively near the mouth of Cement Creek including hillslopes adjacent to the town of Silverton. The deposits consist of clasts ranging in size from pebbles to boulders in a clayey sand to sand matrix. Deposit thickness is unknown. The till was deposited principally as lateral moraines. A minimum age for the till is 9,150±50 ^{14}C yr B.P. or 10,240 cal. yr B.P., the age of a log in colluvium overlying till (sample GX-26406, table 1).

A large landslide complex (map unit ls) was mapped on the northeast side of Cement Creek and surrounding Hancock Gulch (between 6 and 8.5 km in fig. 2). This large deposit consists of angular, poorly sorted clasts of variable size and variable matrix texture. The landslide has unknown thickness. It is surrounded by bedrock composed of Silverton Volcanics (Yager and Bove, this volume, pl. 1) and has high electrical conductivity indicating that it is wet and probably composed of altered rock (Smith and others, this volume, Chapter E4). The landslide surface is hummocky, is not obviously glaciated, and is locally cut by an alluvial fan (map unit fo), but is otherwise undated. We have no documented evidence that the landslide is active at present, and it does not appear to have had a large influence on the longitudinal profile of Cement Creek (fig. 2).

Canyon-filling stream gravels (map unit g) crop out 500–800 m upstream of the mouth of Cement Creek (between 9 and 9.3 km in fig. 2). These form nearly vertical cliffs of gravel on both sides of Cement Creek, and the top of the section is about 25 m higher than the streambed. The bottom of the section is about 9 m higher than the streambed and rests on a carved-bedrock platform that slopes downstream (fig. 2). The deposits are poorly sorted, weakly stratified, clast-supported, subrounded cobble gravel that has a sand matrix. The gravels are weakly imbricated and stratification dips about 1° down Cement Creek. The gravel is strongly cemented with iron oxides. A minimum age for the gravels is 4,500 yr B.P., from charcoal (sample GX-26392 in table 1) found in bog-iron spring deposits capping the gravel. Other age constraints are inferred in the section titled, "Earliest Geomorphic History."

A single remnant of a high stream terrace (map unit e) is about 20 m higher than the valley floor and is inset into a glacial moraine on the northwest side of the town of Silverton. The terrace deposits are well-rounded, clast-supported cobble gravel with a sand matrix, and have unknown stratification and thickness. The terrace surface is close to and is inclined away from the mouth of Cement Creek (fig. 2) and thus was likely formed by Cement Creek. The terrace surface projects to the base of the section of canyon-filling stream gravels (map unit g) in the Cement Creek canyon (fig. 2). The terrace thus formed after unit g.

Alluvial Fans

Alluvial fans in the Cement Creek valley emanate from tributaries and were classified as either old inactive fans (map unit fo) or young and active, or possibly active, fans (map unit fy) that are inset into the older fans.

Old alluvial fans emanate from the mouths of nearly all of the tributary gulches. The deposits consist of poorly sorted, subangular to subrounded, pebble to boulder gravel, and either are weakly stratified and clast supported with a sand matrix or are nonstratified and partially supported by a matrix of sand, silt, and some clay. The maximum exposed thickness is 6 m. Most of the fans are incised. On all of them, the bar and swale topography of the streams that formed them has been largely obscured by surface-intensive processes. The old fans are thus inactive, although some are sites of snow avalanche run-out. At and above Dry Gulch (at 1 km in fig. 2), the distal surfaces of the fans smoothly merge with the Cement Creek terrace (map unit t). Downstream of Dry Gulch, however, the toe of every fan is truncated by an erosional escarpment and the fan surfaces project as much as 5 m higher than the Cement Creek terrace (fig. 3). One streambank exposure reveals a buried disconformity where fan deposits are truncated and overlain by terrace deposits. These fans thus became inactive before the terrace formed, prior to 6 ka as discussed in the following section. Certain fans appear to have influenced the shape of Cement Creek's longitudinal profile (figs. 2 and 3), as mentioned in the section titled, "General Distribution of Landforms."

The young alluvial fans are typically inset into and are smaller than the older fans. The largest tributaries have young fans, whereas the smaller tributaries typically do not have young fans. The deposits consist of poorly sorted, subangular to subrounded, pebble to cobble gravel (with few boulders); they are either weakly stratified and clast supported with a sand matrix, or nonstratified and partially supported by a matrix of sand, silt, and some clay. The maximum exposed thickness is 2 m. The distal surfaces of these fans either merge smoothly with the Cement Creek terrace or are truncated by erosional escarpments. Many of these fans are active, such that roads that cross them occasionally require maintenance after water-flow or debris-flow events. The young fans may have been active for more than the last 6,000 years.

Cement Creek Terrace and Flood Plain

A prominent stream terrace, a remnant of a former flood plain, is found nearly continuously along Cement Creek and is designated map unit t and subdivision tw. The terrace surface is 1.5–3.5 m higher than the streambed. The terrace is typically 5–25 m wide, but locally may be as wide as 70 m. The maximum exposed thickness of the terrace deposits is 3.5 m. These deposits consist of two facies, one gravel and the other peat, which interfinger as shown in figure 4. Where the gravel facies is exposed, its surface is dominated by grasses or forest. Where the peat facies is exposed, its surface is dominated by sedge wetlands, including relict and active beaver ponds, or thickets of willow and bog birch. Where they occur adjacent to each other, the surfaces of gravel sections are generally 0.5–1 m lower than the surfaces of peat sections, as illustrated in figure 4. Where the wetlands were large enough to be mapped separately they are designated with map unit tw.

The gravel facies is poorly sorted, weakly stratified, clast-supported, subrounded pebble or cobble gravel with sand matrix. Locally the gravel contains thin or medium (3–30 cm) beds of sand and sand lenses. The peat facies is subhorizontally stratified thin to thick (3–100 cm) beds of peat. Locally the peat contains very thin or thin (1–10 cm) beds of white or very light gray silt, which locally grade laterally into channel sands and gravels (fig. 4). The white silt layers contain no macrofossils of aquatic or terrestrial life forms (Elisabeth Brouwers, written commun., 2001). They have elevated aluminum contents, but no identifiable aluminum-bearing minerals were identified by X-ray diffraction (Rhonda Driscoll, analyst, 2001; mineralogical data in database, Sole and others, this volume, Chapter G). These observations are interpreted in the conclusions section titled, "Implications of Sedge Wetlands and Peat."

The terrace deposits represent roughly synchronous channel and flood-plain aggradation, followed by stream incision, as interpreted in the conclusions section titled, "History of the Cement Creek Terrace and Flood Plain." Dated materials found within terrace gravels, or dated peat observed to interfinger with gravels, are herein distinguished from dated peat located above gravels or not stratigraphically linked to gravel. The reason for this distinction is that peat continued to accrete after Cement Creek incised, as discussed in the section titled, “Implications of Sedge Wetlands and Peat.”

Dated materials from the terrace sediment span the past 6,000 years (table 1 and fig. 5). Dated materials that are both directly associated with terrace gravels and located close to (within 1 m of) the present streambed level range in age from 3700 B.C. to about A.D. 400 (5,650–1,550 cal. yr B.P.). After A.D. 400, successively younger materials are found at successively higher positions within the gravel facies. Some dated peat samples, in contrast, are substantially older than gravels at the same stratigraphic level (fig. 5). The youngest datable material clearly associated with terrace gravels (sample GX-26396, table 1) has an age of A.D. 1330 or 1400 (620 or 550 cal. yr B.P.), and provides a maximum age constraint on the cessation of gravel aggradation and thus stream incision. Two dated samples that are stratigraphically younger than terrace gravel provide an uncertain age constraint because the organic materials could have grown before or after Cement Creek incised. The oldest age of peat overlying terrace gravel is A.D. 1440 (510 cal. yr B.P.) for sample GX-24747. A wood fragment (sample GX-26409) found in sediment near the present streambed and against terrace sediment also had an age of A.D. 1440.

The Cement Creek flood plain, or low terrace (map unit p), also consists of gravel and peat facies. The nature of the flood-plain surface and sediment is nearly identical to the terrace (unit t) just described, so only unique aspects of the flood plain are presented. The flood plain is discontinuous and is found along only one-third of Cement Creek (pl. 5). The flood-plain surface is 0.5–1 m higher than the streambed and is typically 5–60 m wide. The maximum exposed thickness of the flood-plain deposits is 1 m. About half the area of the flood-plain surface is sedge wetlands (underlain by peat), including a few active beaver ponds and localized iron bogs. The landform is generally absent just downstream of Gladstone, and may have been remobilized during the 1978 Lake Emma flood. Elsewhere, Lake Emma flood deposits have persisted on gravel bars that are slightly below the surface of this landform, suggesting that the landform is no longer being “actively constructed and maintained” by Cement Creek. As “active construction and maintenance” is the geomorphological definition of a flood plain, this landform may be a low terrace. In any case, the landform started to form before A.D. 1700, and the wetland and bog sediment continue to accumulate.

Eleven samples of organic material from flood-plain sediment were dated (table 1), and of these 4 are modern and the remainder could be modern. Five samples could have ages of A.D. 1660 (290 cal. yr B.P.), as that is their calibration intercept-age. However, given the 2-sigma radiocarbon laboratory uncertainties, four of these could be as old as A.D. 1510 (440 cal. yr B.P.), or as mentioned, they all could be modern. The oldest materials associated with the flood plain that were precisely dated are tree stumps rooted in the flood-plain surface. For two Engelmann spruce stumps, slabs were cut and sanded, and the growth rings counted. Both stumps were observed in 1995, are situated about 1 m above low-flow water level, and retain about one-third of their bark. Both stumps had previously been cut with chain saws, but they could have been either standing dead snags or live trees when cut. One stump is located on the north side of the channel about 200 m downstream of the confluence with South Fork Cement Creek. A slab was cut from that stump: 271 growth rings were counted along one radius and 274 rings along a second radius. The second stump is located on the north side of the channel at 1.95 km in figure 2 and has 222 growth rings (Church, Fey, and Unruh, this volume, Chapter E12, fig. 21, stump shown in photograph at far right).

The active stream channel and unvegetated bars of Cement Creek (map unit c), consists of sandy pebble-gravel, cobble-gravel, and, locally, boulders. Bedrock is exposed in the bed only in the slot canyon at the mouth of Cement Creek (between 9.2 and 9.7 km in fig. 2). Stream channels are typically 5–10 m wide, but locally are as wide as 40 m.

Large areas obscured by human activities, principally related to mining since A.D. 1871, are designated with map unit h.

Distribution of Ferricrete and Wetlands

Although ferricrete is exposed at many locations along the length of Cement Creek, ferricrete is not continuous. Ferricrete exposures are most abundant in two reaches, and exposures of wet ferricrete show a correspondence with the locations of sedge wetlands. Many of the observations presented here set the stage for Wirt and others (this volume).

Ferricrete exposures visible from the channel were noted while we were surveying the longitudinal profile, and their heights above the streambed and distances downstream were measured (fig. 6*A*). We also noted whether the ferricrete was wet with water seeping from the exposure or was dry at the time, which was late summer 2000 when the flow was low (von Guerard and others, this volume, fig. 3). In general, wet ferricrete exposures are much less frequent than dry ferricrete exposures. Most surficial sediment along Cement Creek is part of the terrace and flood plain (pl. 5). For that reason most ferricrete visible from the channel consists of cemented terrace and flood-plain gravel, and these deposits do not extend higher than 3 m above the channel bed. Higher exposures are of cemented fan gravel (unit fo), colluvium, and canyon-filling stream gravel (unit g, between 9 and 9.3 km in fig. 6*A*). For convenience in discussing the spatial pattern of ferricrete and wetlands, we subdivided our study area into the upper, middle, and lower ferricrete reaches shown in figure 6*A*. The upper reach extends from the South Fork confluence to just below Fairview Gulch (from 0 to 3.3 km in fig. 6*A*; see fig. 1). The

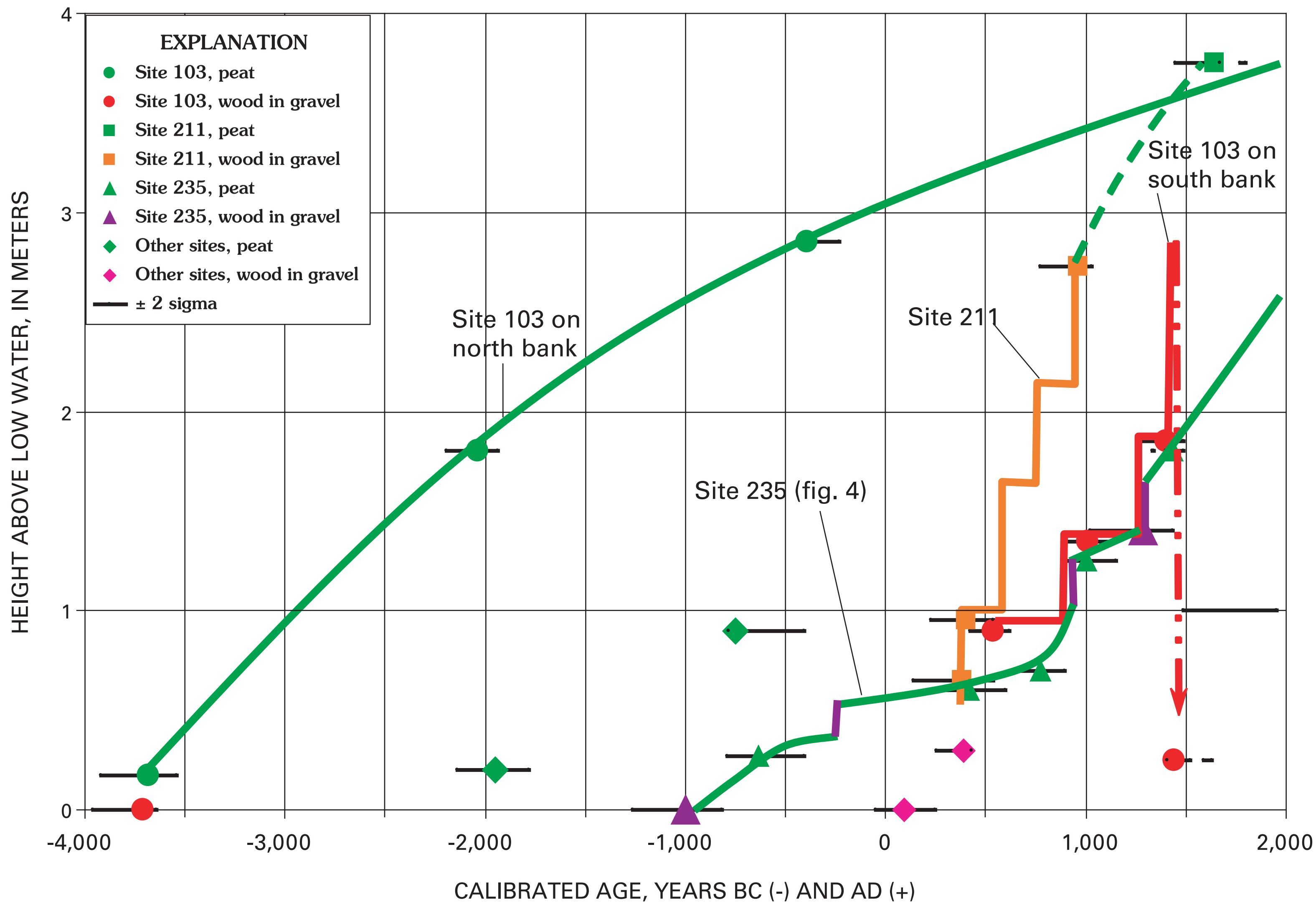
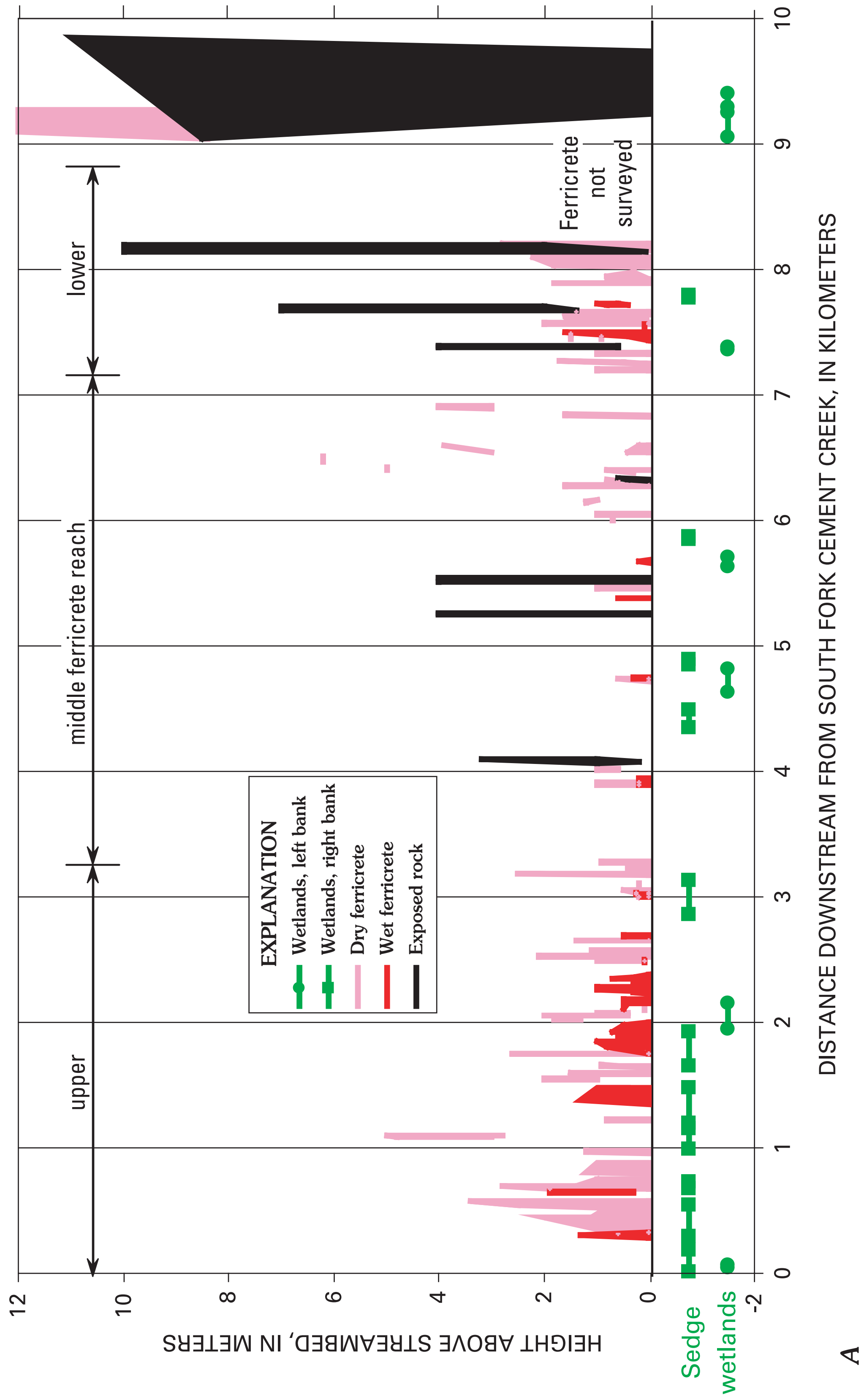


Figure 5. Time-stratigraphic relations of sediment composing the prominent terrace (map unit t) along Cement Creek, for four stratigraphic sequences (numbered localities of fig. 1), and several individual beds. See table 1 for methods and other details on radiocarbon ages, and site localities. For the stratigraphic exposure at site 235 (fig. 4) ages are plotted relative to water level at dated stump at base of the section, and the age of sample GX-24749 was placed in correct stratigraphic position at horizontal distance of 25 m in figure 4.



EXPLANATION
Wetlands, left bank
Wetlands, right bank
Dry ferricrete
Wet ferricrete
Exposed rock
upper
middle ferricrete reach
lower
Ferricrete not surveyed
HEIGHT ABOVE STREAMBED, IN METERS
DISTANCE DOWNSTREAM FROM SOUTH FORK CEMENT CREEK, IN KILOMETERS
Sedge wetlands
12
10
8
6
4
2
0
-2
0
1
2
3
4
5
6
7
8
9
10
A

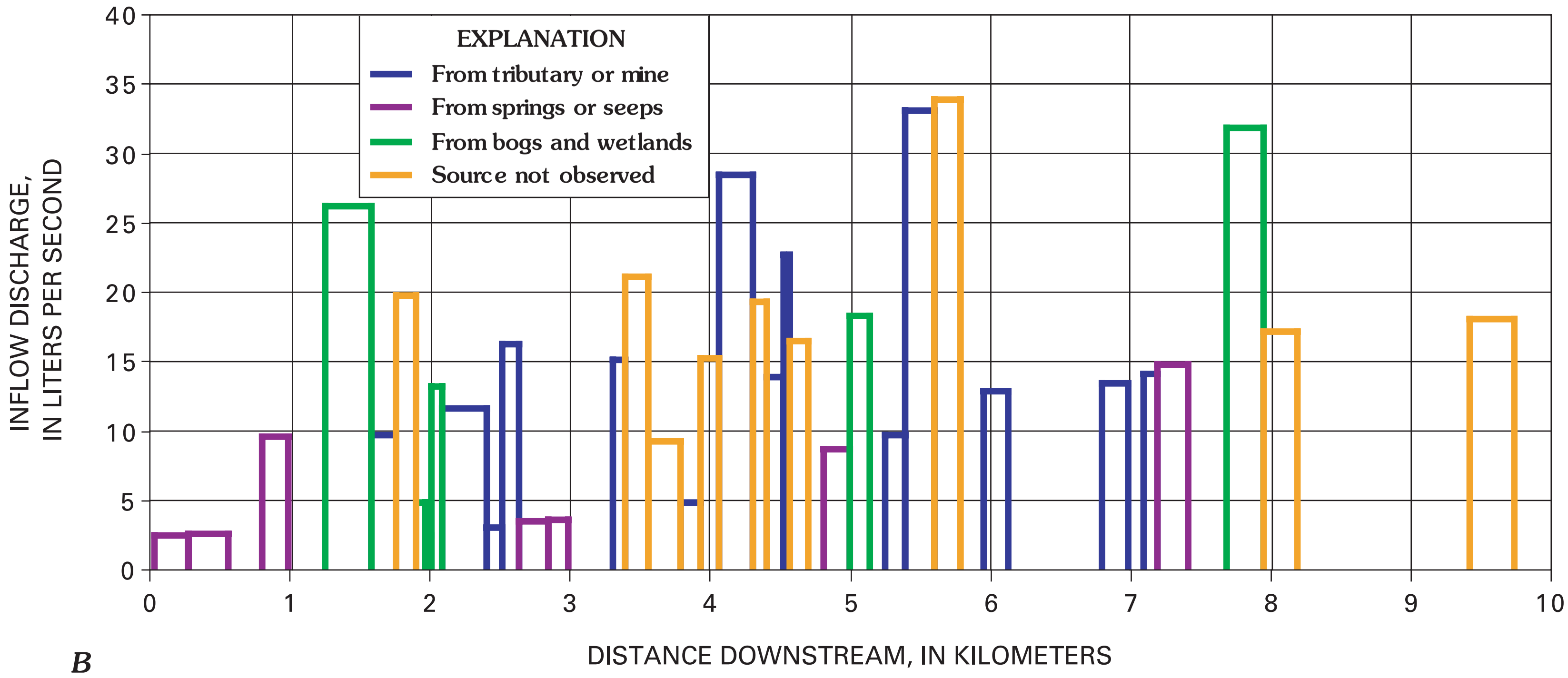


Figure 6. Ferricrete and wetland locations correlated with inflow discharge along Cement Creek. *A*, Spatial location of ferricrete exposures visible from the channel, expressed as height above streambed and location along surveyed longitudinal profile (fig. 2), and location along the profile of sedge wetlands. Ferricrete polygons show continuity and varying thickness. Bars connecting surveyed wetland points show wetland continuity. *B*, Magnitudes, and spatial locations along the longitudinal profile, of water flowing into Cement Creek during late summer 1996 (Kimball and others, 2002). Height of each bar represents change in Cement Creek discharge over a short section of stream depicted by width of bar. As such, the areas of the bars are meaningless.

middle reach extends downstream to Hancock Gulch (from 3.3 to 7.2 km in fig. 6*A*). The lower reach extends downstream to Soda Gulch (from 7.2 to 8.8 km in fig. 6*A*). Our surveying of ferricrete stopped at 8.2 km, for logistical reasons, so we rely on the ferricrete mapping of Yager and Bove (this volume, pl. 2) to define the downstream end of the lower reach to be at 8.8 km. Elsewhere our documentation of the occurrence of ferricrete is consistent with that of Yager and Bove.

Along Cement Creek exposures of both wet and dry ferricrete, and also wetlands, are most abundant in the upper reach. Considering all the wet ferricrete exposures along Cement Creek, we noted that more than half occur in the upper reach. Most of the wet ferricrete exposures in the upper reach, and all the large ones, are found on the west side of Cement Creek in a short subreach. That subreach (from 1.3 to 2.4 km in fig. 6*A*) corresponds to the confluence of Prospect Gulch, which enters from the west (fig. 1). Most of the sedge wetlands, 80 or 90 percent of the area of wetlands in the upper reach, are also found on the west side of Cement Creek. In the middle reach, in contrast, both ferricrete exposures and wetlands are sparse. Ferricrete exposures are also abundant in the lower reach, but both wet ferricrete and wetlands are relatively sparse in that reach. In conclusion, where exposures of wet ferricrete occur, wetlands are usually located nearby. Where there are wetlands, however, exposures of wet or dry ferricrete are not necessarily located nearby.

Ferricrete exposures do not correspond to the magnitude of water flowing into Cement Creek or to the hydrological source of that water. During low-flow conditions the discharge in Cement Creek increases as one moves downstream, but not at a steady rate. Figure 6*B* depicts the changes in Cement Creek discharge quantified in September 1996 by Kimball and others (2002) as part of their tracer dilution study. They noted the locations and hydrological source of any visible inflowing water. By “source” we mean surface flow from a tributary stream or mine, surface flow from a bog or wetland, or subsurface flow emerging as springs or seeps. Ferricrete exposures are found in subreaches where Cement Creek gained water from each type of source, and even in subreaches where the discharge increased but no discrete source of inflowing water was observed in the field. We documented no obvious association between the occurrences of ferricrete exposures and the hydrological source of inflowing water. Ferricrete exposures are found in subreaches where the rate of water flowing into Cement Creek was relatively small and relatively large. Three exposures of wet ferricrete (at 0.65, 4.75, and 7.5 km in fig. 6*A*) and numerous exposures of dry ferricrete are located in subreaches where no increase in the base flow of Cement Creek was detected (Kimball and others, 2002). In addition, the middle reach where ferricrete exposures are least frequent (from 3.3 to 7.2 km in fig. 6*A*) is also the reach where Kimball and others (2002) found the greatest increase in the base flow of Cement Creek (fig. 6*B*). There is no obvious association between the presence of ferricrete deposits and the rate at which water flows into Cement Creek nearby.

Interpretations and Conclusions

Earliest Geomorphic History

The high San Juan Mountains were nearly covered by alpine glaciers during the latest Pleistocene (Atwood and Mather, 1932) and presumably numerous times before. During the most recent episode, generally referred to as the Pinedale glaciation, ice was about 520 m thick at the present site of Silverton and 430 m thick at the present site of Gladstone. The general timing of that glaciation is presented because it constrains the ages of deposits found along Cement Creek.

The onset of the latest glaciation in the Rocky Mountains is poorly understood, but it may have begun about 30,000 ^{14}C yr B.P. (Nelson and others, 1979). The timing of the glaciers’ maximum extent has been estimated based on radiocarbon ages for sediment of lakes impounded at ice margins near terminal moraines. Two such results are that valley glaciers reached their maximum extent slightly after 23,000 (Rosenbaum and Larson, 1983) and 22,000 ^{14}C yr B.P. (Madole, 1986). Thus it apparently took about 7,000 years (30–23 ka ^{14}C years) for the ice to advance to its maximum extent, which is a reasonable general duration for expansion of the San Juan glaciers because ice volume was large and some individual glaciers were long. Ice flowed more than 60 km from the Silverton area to the terminus at Durango. Leonard (1989) concluded that during the full glacial, summer temperatures were 8°–13° C cooler than present. The timing of the glaciers’ initiation of retreat has been estimated from radiocarbon ages of material found in sediment resting on till upstream of terminal moraines. Two such results indicate that valley glaciers began to retreat before 13,800 (Madole, 1976) and 13,700 ^{14}C yr B.P. (Nelson and others, 1979). The altitudes of the sites where those dates were obtained are relatively low, 2,640 and 2,882 m respectively. Note that the altitudes of Silverton and Durango are 2,830 and 1,990 m, respectively. A similar age of 13,700 ^{14}C yr B.P. was obtained by Madole (1980) for a high-altitude site at 3,156 m. In addition, Gosse and others (1995) concluded that glaciers began to retreat from their terminal moraines in the Wind River Range of Wyoming about that same time (assuming the years from their ^{10}Be method are equivalent to calendar years). Deglaciation probably began earlier in the San Juan Mountains, however, compared to more northerly Wind River Range. At face value, one could conclude that full glacial conditions lasted for about 9,000 years (23–14 ka ^{14}C years), and that most of the ice disappeared quite rapidly; but this may be misleading for three reasons. First, it may have taken considerable time for vegetation both to colonize the previously glaciated terrain and then to become incorporated into sediment. Second, the oldest organic material in a given deposit may not be exposed and available for sampling. Third, the duration of the unconformity between glacial and postglacial deposits is uncertain. For these reasons, estimates of when areas became ice free, based on radiocarbon dating, are likely too young by centuries if not millennia.

Cirques were the last sites to become ice free, and the cause of the disappearance of the last remaining ice may have been the anomalously warm Bölling-Alleröd interval, which occurred between 12,500 and 10,700 ^{14}C yr B.P. (Stuiver and others, 1995). Estimates for deglaciation of individual cirques in Colorado typically range from 10,000 to 12,000 ^{14}C yr B.P. Several reasons are advanced for the relatively large range in these ages. Variable relief and aspect of individual cirques made the conditions for ice retention variable. Some individual dates may be too young, for the reasons just mentioned. Lastly, there is some evidence for minor glacial advance (Menounos and Reasoner, 1997) in the Colorado Front Range, during the Younger-Dryas event between 10,700 and 10,100 ^{14}C yr B.P. (Reasoner and Jodry, 2000). Whether this minor glacial advance occurred in the San Juan Mountains is not known. One site, (former) Lake Emma at an altitude of 3,740 m, deserves discussion because it is close to Cement Creek (fig. 1). Elias and others (1991), following Carrara and others (1984), studied the lake sediment and found disparate radiocarbon ages for moss, wood, and insects. We mention only the ages for wood fragments, because wood is probably the most reliable material for dating. The oldest age for a wood fragment was 9,400±70 ^{14}C yr B.P., but that was not from the base of the lake sediment. A slightly older fragment of wood (9,580±130 ^{14}C yr B.P.) was found in a nearby bog by Carrara and others (1984). Elias and others (1991) concluded that Lake Emma was ice free "by 10,000 yr B.P. and perhaps as early as 11,000 yr B.P." Note that the oldest radiocarbon sample (GX-26406, table 1) from this study has an age of 9,150±50 ^{14}C yr B.P. for a spruce log resting on till at an altitude of 3,230 m. Clearly hillslopes adjacent to Cement Creek were forested by that time.

The oldest stream deposits along Cement Creek likely formed, or began to form, during deglaciation. During deglaciation a net loss of ice occurs as the equilibrium line shifts upstream. The terminus recedes upstream by melting and sublimation, but below the equilibrium line the ice also thins, which can lead to fragmentation of the ice. The glacier in Cement Creek was relatively narrow and more than 20 m thinner than the main glacier in Bakers Park into which it flowed. (Bakers Park is the early name for the uniquely wide portion of the Animas River valley within which Silverton is now located (Bird, 1986).) Two features suggest that the Cement Creek tributary glacier had receded from the mouth of Cement Creek, while a massive body of stagnant ice still partially filled Bakers Park. The top of the canyon-filling gravels (map unit g) currently projects to a position about 40 m higher than the current floor of Bakers Park, based on the dip of bedding (fig. 2). We interpret this deposit to be glacial outwash (from Cement Creek) that was impounded by stagnant ice in Bakers Park. After map unit g aggraded, Cement Creek incised through it as ice in Bakers Park ablated. Deposits similar in appearance occur at, and downstream of, the confluence of Mineral Creek and Middle Fork Mineral Creek (Yager and Bove, this volume, pl. 2). Those deposits are tens of meters thick and are limited in spatial extent, suggesting that they too formed behind a temporary ice impoundment.

A high stream terrace (map unit e) is inset into till about 20 m higher than the floor of Bakers Park, and its surface projects to the base of unit g gravels in the mouth of Cement Creek (fig. 2 and pl. 5). We interpret this terrace to have been formed by Cement Creek as it flowed along the margin of stagnant ice in Bakers Park. Thus, the high terrace formed during deglaciation, and there may be no other correlative landforms in the region. The large landslide in the vicinity of Hancock Gulch (unit ls, pl. 5) is not obviously active, has no obvious effect on the longitudinal profile of Cement Creek (fig. 2), and is crosscut by and thus predates an old alluvial fan (unit fo). It is plausible that when ice disappeared from that part of Cement Creek and Hancock Gulch, the release of confining pressure on the presumably saturated unconsolidated material allowed the landslide to move. Glacial till, unit m, obviously stopped forming by the end of glaciation. We suspect that the canyon-filling gravels (map unit g) and the high stream terrace (map unit e), and possibly the landslide (map unit ls), are on the order of 12,000±2,000 ^{14}C years old, because of the apparent association of those landforms with deglaciation.

Prominent alluvial fans (unit fo), located at the mouths of most tributaries, also probably began to accumulate as soon as ice disappeared from the floor of the Cement Creek valley. This timing is inferred because as small glaciers retreated up tributaries, the newly exposed rubble on hillslopes, lacking the stabilizing influence of vegetation, would have quickly become subject to sub-aerial detachment and transport process. The fans may have accumulated rapidly until the surrounding hillslopes did become stabilized by vegetation. In any case, the absence of paleosols in the fan gravels indicates that no significant pauses in deposition occurred. The fans stopped forming because their streams incised when Cement Creek breached their toes. This occurred prior to 6,000 years ago, as discussed in the next section. The bulk of the fan deposits have not been removed by Cement Creek (pl. 5), and certain fans remain the primary influence on the segmented shape of the longitudinal profile of Cement Creek (figs. 2 and 3). Certain large fans, or pairs of fans, apparently caused the Cement Creek valley to aggrade (upstream of the fans), or kept the upper reaches from incising. The Ohio Gulch fan is a particularly good example (fig. 3). This is the largest fan in the study area and thus has had the largest sediment supply, although the watershed is not particularly large (fig. 1). Compared to other subbasins, large areas of Ohio Gulch hillslopes are composed of extensively altered bedrock (Bove and others, this volume) and are devoid of vegetation, which apparently allowed rapid erosion. Cement Creek was not capable of removing all of the sediment supplied by that tributary, and Cement Creek aggraded upstream of the obstruction. The resulting segmented profile (fig. 3) is common along montane streams (Miller and others, 2001; K.R. Vincent, unpub. data, 2003), particularly where the valleys are narrow. The Cement Creek valley bottom is less than 150 m wide, in contrast to the 400 m wide bottom of the Animas River valley between Howardsville and Eureka (Vincent and Elliott, this volume, Chapter E22, fig. 1). In that Animas River reach, tributary fans enter the valley in direct opposition and at those locations cover nearly the full width of the valley floor, but without effect in that the longitudinal profile of that portion of the Animas River valley is not segmented (Vincent and Elliott, this volume, fig. 3).

History of the Cement Creek Terrace and Flood Plain

The aggradation and incision of the Cement Creek terrace may have been driven by something related to climate, so the results of two studies of postglacial climate are presented. The former Lake Emma site (fig. 1) is currently above treeline, but its lake sediments contain numerous fragments of early Holocene wood. Carrara and others (1991), using data from former Lake Emma and several bogs in the area, concluded that between 9,600 and 5,400 ^{14}C yr B.P., treeline in the northern San Juan Mountains was at least 80 m higher than at present, suggesting that average July temperatures were 0.5°–0.9° C higher than at present. Between 5,400 and 3,500 ^{14}C yr B.P., treeline was near its present-day limits, and after 3,500 ^{14}C yr B.P., it was generally lower than present (Carrara and others, 1991). Fall (1997) studied pollen and plant macrofossils from various sites in the Colorado Rocky Mountains and arrived at similar conclusions. In the early Holocene (from 9,000 to 6,000 ^{14}C yr B.P.), the climate was warmer and wetter than today, cooler and dryer conditions dominated the middle Holocene (6,000–4,000 ^{14}C yr B.P.), and the modern climatic regime was established about 2,000 ^{14}C yr B.P. with slightly warmer than present conditions persisting until about 1,000 ^{14}C yr B.P. (Fall, 1997). Shorter term climatic fluctuations also occurred during the Holocene, such as the so-called Medieval Warm Period and Little Ice Age discussed at the end of this section.

The early Holocene history of Cement Creek is not known, but the streambed was probably at a higher level than today, having been impounded by alluvial fans. By about 6,000 years ago the stream had partly breached the fans (fig. 3), and the bed of Cement Creek was at the same level as it is today. This is evidenced by the 3700 B.C. age (5,650 cal. yr B.P.) of an upright stump found in terrace sediment at the present low-flow water level (fig. 5). During the middle Holocene, Cement Creek migrated laterally but apparently remained at the same level as it is today for about 4,400 years. This is evidenced by six radiocarbon ages from samples found within 30 cm of present low-flow water level (fig. 5), at various locations along the stream. These ages range from 3700 B.C. to A.D. 380 (5,650 to 1,570 cal. yr B.P.). In apparent contrast, one sample of peat obtained from 1.8 m higher than the streambed (fig. 5) had a radiocarbon age within this period. In the next section, we use that observation as supporting evidence that peat accumulated in sedge wetlands, and continues to accumulate, independently of the level of the gravel bed of Cement Creek.

The bulk of the deposits of the prominent terrace along Cement Creek represent channel and flood-plain aggradation, followed by stream incision. The gravel facies is the key because it represents deposition on the bed and bars of the stream. After A.D. 400 (1,550 cal. yr B.P.), successively younger materials are found at successively higher positions within the gravel facies, within all three well-dated stratigraphic sections (fig. 5). The aggradation persisted at least until A.D. 1330 or 1400 (620 or 550 cal. yr B.P.), because that is the age of the youngest datable material clearly associated with terrace gravel (sample GX-26396, table 1). The episode of channel and flood-plain aggradation was not unique to Cement Creek. A terrace is found at many locations along Mineral Creek that is similar to the Cement Creek terrace in appearance and height above streambed. Mineral Creek drains the area immediately to the north and west of the Cement Creek watershed (Yager and Bove, this volume, pl. 2). Two wood fragments (Beta-147008 and 07, table 1) from the terrace along Middle Fork Mineral Creek have radiocarbon ages of A.D. 1180 and 1260 (770 and 690 cal. yr B.P.), and these ages fall within the period of aggradation of the Cement Creek terrace.

The timing of stream incision has constraints in addition to the ones already mentioned. The oldest age of peat overlying terrace gravel is A.D. 1440 (510 cal. yr B.P.) for sample GX-24747, and a wood fragment (sample GX-26409) found in sediment near the present streambed and against terrace sediment also has an age of A.D. 1440. Interpretation of these data is tenuous, however, because the sediments encasing these two samples are stratigraphically younger than terrace gravel; thus the organic materials could have grown before or after Cement Creek incised. The Cement Creek flood plain developed after stream incision, but radiocarbon ages for that landform are inconclusive. Of the 11 dated samples of organic material from flood-plain sediment, 4 are modern. A “modern” radiocarbon age means it is younger than A.D. 1850. Five samples could have ages of A.D. 1660 (290 cal. yr B.P.), as that is their calibration intercept-age. Taken at face value, the flood plain could have been present as early as A.D. 1660. Given the radiocarbon analytical uncertainty and the problem of calibrating young samples, however, four of these samples could be as old as A.D. 1500 (450 cal. yr B.P.), or all radiocarbon samples from the flood plain could be modern. The oldest accurately dated materials associated with the flood plain are tree stumps rooted in the flood-plain surface. One Engelmann spruce stump has 274 growth rings, and since we observed this stump in 1995 the tree must have germinated by A.D. 1721 if not long before, depending on when the tree died. About one-third of the bark remained on the stump at the time of sampling, and thus it had been dead for several decades, but less than a century (J.M. Friedman, written commun., 2002). We conclude that the tree germinated around A.D. 1700, and the Cement Creek terrace necessarily incised before that. A second spruce stump has 222 growth rings, confirming the general antiquity of spruce rooted in the flood plain.

In conclusion, the Cement Creek terrace incised between A.D. 1330 and A.D. 1700, strictly based on our most conservative interpretation of the dating results. Yet the preponderance of less reliable evidence suggests that incision may have occurred before A.D. 1500 and perhaps about A.D. 1440.

The aggradation and incision of the Cement Creek terrace were not caused by local base-level processes, based on the extensive nature of the terrace and other factors. Aggradation driven by a base-level rise, such as impoundment behind an aggrading fan, does not extend long distances upstream (Leopold and Bull, 1979). Since the Cement Creek aggraded only 3 m, that distance would be on the order of several hundred meters. Yet the terrace is nearly continuous along the 10 km long study reach. The sites where synchronous aggradation was documented (fig. 6) are separated by as much as 5.3 km. (As mentioned, a similar terrace is found along Mineral Creek.) In addition an agent of base-level rise is lacking. Aggradation of a young alluvial fan might have been such an agent for localized aggradation of Cement Creek, but young fans are nearly absent from the reach above Prospect Gulch, for example, where the terrace is continuous and not segmented. Similar arguments can be made against terrace incision being caused by base-level fall, in that the stream is everywhere incised and the terrace profile is parallel to the streambed profile (figs. 2 and 3).

A common explanation for the aggradation and incision of a landform like the Cement Creek terrace is to call upon climate change (Bull, 1991), but the exact processes or process interactions are rarely understood. Indeed the onset of Cement Creek aggradation occurred after the "modern climatic regime" became established about A.D. 0 (Fall, 1997) and shortly before the so-called Medieval Warm Period, which began around A.D. 850 (Briffa and Osborn, 2002). In addition the stream incised about the time the Little Ice Age began about A.D. 1550 (Beniston and others, 1997), although the exact nature and timing of the so-called Little Ice Age are debated. In simple terms, streams aggrade because more sediment is supplied than can be carried downstream. That might result if sediment yields from hillslopes increased (due to decreased vegetation cover or some other cause) while the basic hydrology was unchanged, or if the frequency or magnitude of large floods decreased while sediment yield was unchanged. Other explanations include increased flow drag due to increased cover by riparian plants, decreasing the ability of the stream to transport sediment. Beaver foster riparian plants, and changes in beaver populations might change the density of woody riparian plants and the flow drag they create. Beaver were present in the San Juan Mountains during prehistorical times, as evidenced by the 173 growth rings we extracted from a living spruce rooted in a relict beaver dam near Gladstone, in 2000. That beaver dam was constructed before A.D. 1818. Stream incision is also explained by climate change altering the balance of sediment supply and transport, but streams can incise during single large floods, which is not exactly "climate change." When multiple streams in an area are documented to have changed in similar ways at the same time, something regional in nature like climate is assumed to be the cause. For example, Hereford (2002) summarized information for seven well-studied streams in the southern Colorado Plateau region and concluded that they had similar dynamics occurring roughly synchronously. Following a period of incision or "major channel adjustment," those streams began to aggrade about A.D. 1400, and all incised within several decades of A.D. 1880. Hereford (2002) called upon changes in the magnitude and frequency of floods as the cause of the changes. The spatial scale over which similar and synchronous, climate-driven channel changes can occur is limited, however, because the timing and nature of climate change vary spatially, and because streams vary in size and physical and biological properties and processes. The dynamics of Cement Creek were out of phase with those of the streams studied by Hereford (2002), for example, even though Cement Creek is only 400 km northeast of the area of most of the streams that he discussed.

Finally, the aggradation and incision of the Cement Creek terrace were not caused by local base-level processes, but rather something basin wide in scope. These changes may be related to climate change, but the exact mechanisms are probably not knowable.

Implications of Sedge Wetlands and Peat

Our study of the prominent terrace along Cement Creek leads to three important conclusions regarding the paleo-environment of flood-plain peat in subalpine settings. Currently, ground water from the valley margin supplies the sedge wetlands, not the mainstem stream, and this may have always been the case. Great care must be taken when one uses peat to date stream incision, because the peat can continue to accrete after stream incision. The low pH of water in the sedge wetlands has leached the inter-peat silt strata of their trace-element and some major-element constituents, and the original mineralogy of the detrital phases was converted to that of amorphous phases.

The stratigraphy of the prominent terrace along Cement Creek (fig. 4) represents a period of channel and flood-plain aggradation followed by stream incision. The aggradation occurred over a thousand years, and the surface became a terrace when Cement Creek incised more than three centuries ago, as discussed in the preceding section. The gravel facies represents aggradation of the channel bed and bars, and the peat facies represents aggradation of flood-plain sedge wetlands. These facies interfinger at their margins (fig. 4), demonstrating contemporaneous aggradation at equivalent rates, but the processes differed. Stream aggradation resulted from the deposition on the bed of coarse clastic sediment supplied from upstream, whereas wetland aggradation was dominated by the growth and local deposition of plant material. If peat accumulation had been slower than channel aggradation, low areas of the flood plain would have been filled with gravel during lateral migration of the channel. Stratigraphic evidence of this, thin peat beds between thicker gravels, was observed (fig. 4), but only locally. The silt beds found within the peat section in figure 4 can be traced laterally to where they grade into sand and gravel streambed facies. We interpret the silt beds to be the result of deposition of suspended sediment advected onto the flood plain during major floods, but the silt beds are thin and few in number. For example, in figure 4 only three silt beds are visible in a stratigraphic section representing about 2,500 years of aggradation of peat. Thus overbank flows did not supply the bulk of the flood-plain sediment, nor do they now, and apparently overbank flows did not supply the water required to support the wetland plants.

The terrace surface is 1.5–3.5 m higher than the streambed. The flood-plain deposits are inset into terrace deposits, and the flood-plain surface is 0.5–1 m higher than the streambed. Debris-flow deposits from the accidental draining of Lake Emma (Jones, this volume) are found on the channel margin just below the flood-plain level, and these appear to have experienced very little reworking since they were deposited in 1978. Streamflows probably never flood the terrace and only rarely cover the flood plain. At present, wetlands are found at various locations on both the Cement Creek terrace and flood plain. Sedges dominate these wetlands, and willow and bog birch shrubs are found locally. Relict and active beaver ponds are found locally. Even during the dry season of late summer, the wetland soils remain either moist or are covered by shallow standing water (see Yager and Bove, this volume, pl. 2, figs. 14 and 15). These wet places must be supplied by ground water seeping through hillslope colluvium or tributary fan alluvium along the valley margin. The surface of the terrace is higher where it is underlain by peat compared to where it is underlain by gravel (fig. 4). Even though the terrace may have incised as early as A.D. 1400, peat overlying gravel has ages ranging from A.D. 1440 to modern, and the wetlands are actively accumulating peat. The terrace peat sections continued to accrete in wetlands after the gravel section stopped aggrading when Cement Creek incised.

From this we draw two conclusions. As the wetlands on the terrace are still accreting, great care must be taken when one uses radiocarbon ages of peat to constrain the timing of stream incision. In our discussion of the timing of incision of Cement Creek, we used dated peat only where the peat clearly interfingers with clastic streambed sediment. We also conclude that peat beds composed of sedges in settings like Cement Creek accumulated independently from stream processes, and that they are an indicator that ground water seeping from the valley sides was the source of water in prehistorical times.

Acidic ground water has also modified thin layers of fine-grained (silty) overbank sediment within the peat. The chemistry and mineralogy of the inter-peat silt are significantly different from those of modern streambed sediment in Cement Creek, and worthy of discussion. In figure 7, we compare the chemistry of the major (7*A*) and selected trace elements (7*B*) in the inter-peat silt, modern bed sediment from Cement Creek, and premining sediment from sites B13 and B16 on Cement Creek (Church, Fey, and Unruh, this volume). Compared to both the sediment from the active bed of Cement Creek and the premining sediment samples, the inter-peat silt strata are depleted in iron, and enriched in potassium and aluminum. In addition, inter-peat samples generally have the lowest overall concentrations of calcium and magnesium, and the highest concentrations of titanium. With regard to the trace elements that reflect contributions from historical mining, the concentrations of most trace elements except arsenic (fig. 7*B*) are enriched in modern streambed sediment relative to the premining sediment samples from both sites. The median concentration of all trace elements except cadmium in the inter-peat silt is significantly less than in the lower of the two premining sediment sites.

The inter-peat silt samples represent the end result of acidic weathering of overbank sediment from the Cement Creek drainage that has been leached by acidic ground water in the sedge bogs that form the peat deposits. Results from X-ray analysis of the mineralogy of all the inter-peat silt samples failed to identify primary minerals bearing aluminum. Trace amounts of muscovite and albite were identified (Sole and others, this volume), but not in adequate abundance to account for the large amount of aluminum (>7.5 wt. percent) present in the inter-peat silt strata. Quartz was always identified. Given the low pH of water in the sedge wetlands (3.0–4.5; Wirt and others, this volume), the depleted trace-element concentrations, and the lack of primary minerals, we interpret the data to indicate that the inter-peat silt strata have been leached of many trace- and some major-element constituents. The original detrital minerals have been converted to amorphous compounds. Since their deposition, the inter-peat deposits have been a minor source of dissolved trace elements and are currently a source of amorphous aluminum to Cement Creek, as erosion removes the peat deposits.

Implications for the Timing and Processes of Ferricrete Precipitation

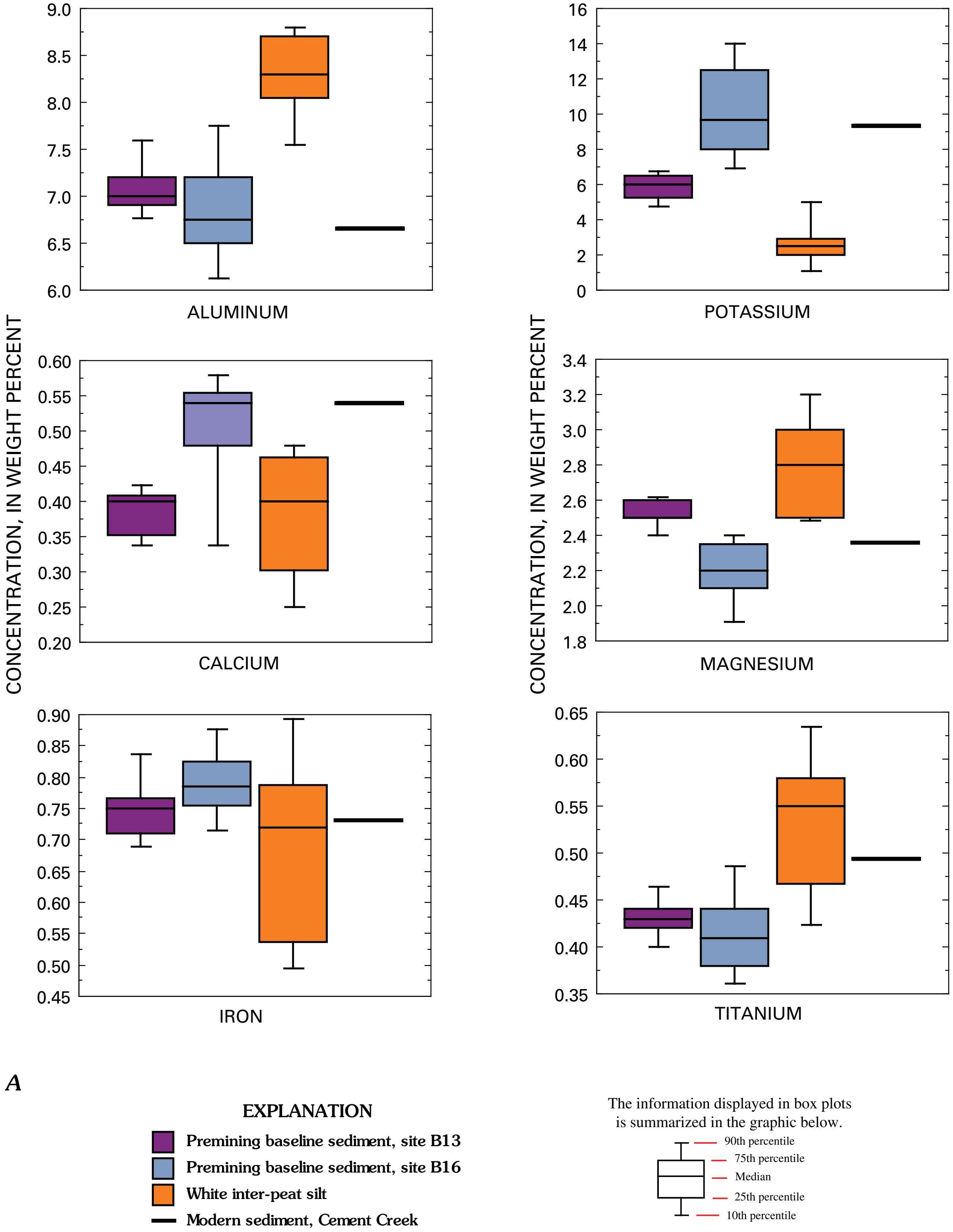
Water is required for the formation of ferricrete, because it is the medium of transport of iron and sulfur, but the locations of exposed ferricrete along Cement Creek show no correspondence with the rate of water flowing into Cement Creek during low-flow conditions and only one association with the hydrological source of water. Ferricrete exposures are found in subreaches where water flowing into Cement Creek is from tributary streams, wetlands, bogs, springs, and seeps; ferricrete is even found in subreaches where the discharge increased but no discrete source of inflowing water was observed (fig. 6*B*). Ferricrete exposures are found in subreaches where the rates of water flowing into Cement Creek are relatively large, relatively small, and not detected using the tracer method (Kimball and others, 2002). In addition, the reach where ferricrete exposures are least frequent is also the reach of greatest increase in the base flow of Cement Creek (Kimball and others, 2002). In conclusion, the hydrological source (tributary streams, ground-water seeps, and so forth) and the rates at which water flows into Cement Creek during base-flow conditions are not useful predictors of the occurrence of ferricrete deposits and might not be linked to the processes of ferricrete formation in a general way.

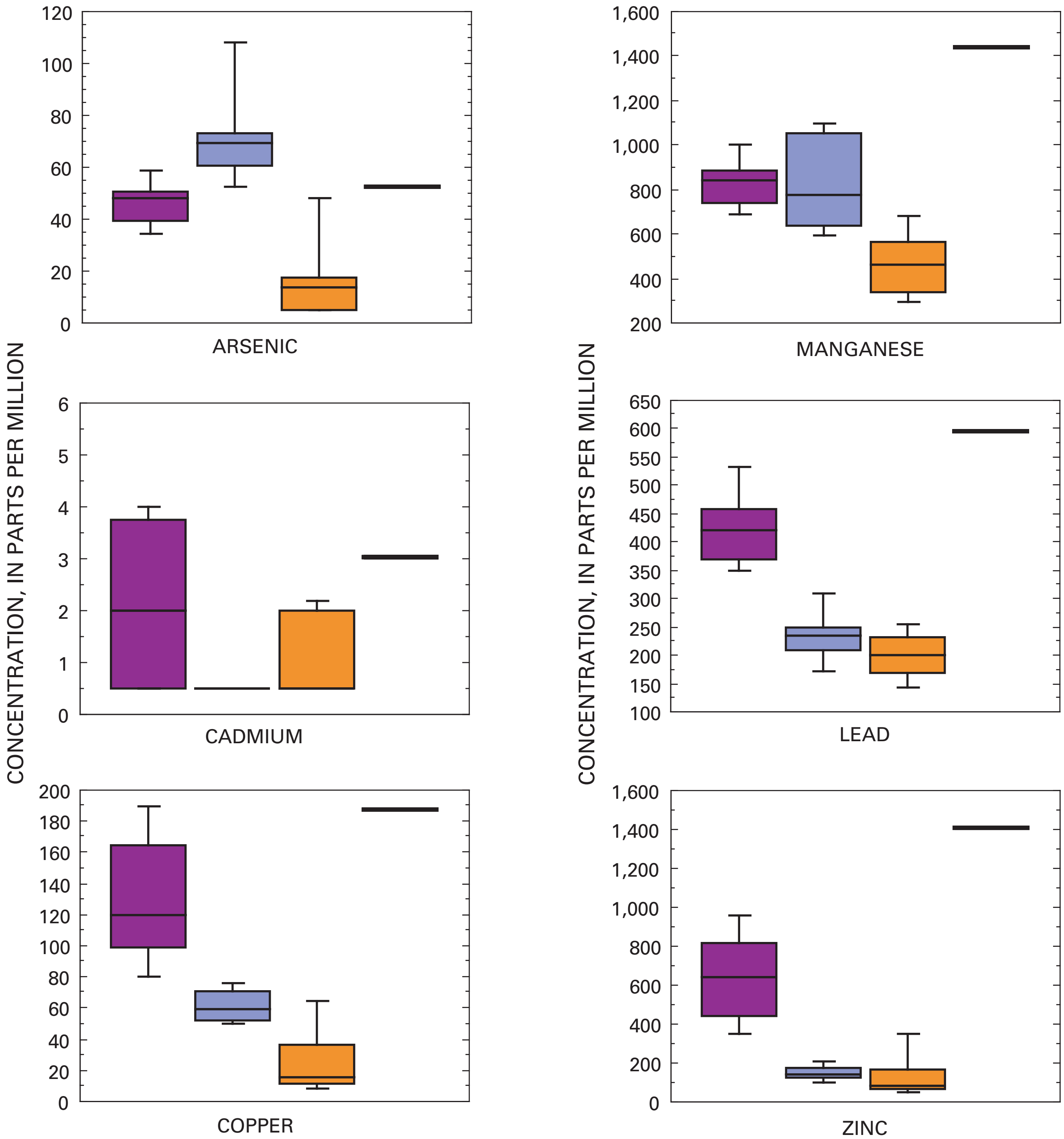
One spatial association of hydrology and alluvial ferricrete was observed by this study, and that of Wirt and others (this volume). Wet ferricrete exposures are almost invariably located where there are wetlands nearby, although the opposite is not true. Ferricrete formation is thus not caused by the wetlands; rather, both wetlands and wet ferricrete result from perennial emergence of ground water. The source of the ground water is from tributary subbasins. Where ground water passes through alluvial fan sediment or colluvium along the valley margin, it emerges in a diffuse manner, and large sedge wetlands result if broad and low gradient substrates (like stream terraces) are present. That same water eventually flows to the stream where the banks, and any ferricrete, remain moist. Localized emergence of ground water forming iron springs or bogs may indicate that the water was conducted to the surface by fracture zones in bedrock (Wirt and others, this volume).

Ferricrete accretion is thought to be variable in space and time. It requires a sustained supply of acidic iron-rich water over a sustained time frame, although it may also occur intermittently in time and spatial extent. Ferricrete that is wet during late summer low-flow conditions is presumed wet throughout the year, and could be precipitating either continuously or seasonally, depending on whether or not the geochemical conditions are optimal (Wirt and others, this volume). Ferricrete that is dry during the summer, in contrast, may be active at other times of the year or during certain wet years, but it cannot be forming continuously. As we demonstrate next, certain exposures of this dry ferricrete are no longer actively forming, and not surprisingly dry ferricrete exposures are much more common than wet ferricrete exposures along Cement Creek. Cementation of clastic sediment decreases the sediment's permeability; thus, ferricrete formation itself may decrease the flow of ground water and affect the rate and location of subsequent ferricrete formation.

The geomorphic history of Cement Creek has influenced the location and timing of ferricrete formation. Obviously, clastic sediment must be present, or alluvial and colluvial ferricrete could not form, and various clastic deposits formed at various locations along Cement Creek throughout the Holocene. The age of deposition of clastic sediment is a maximum-age constraint for the timing of ferricrete cementation, but cementation could have occurred shortly after, long after, or continually since clastic deposition. The rate of ferricrete formation may be rapid or slow. Historical sediment and cultural artifacts have become cemented or encased in ferricrete in a matter of years or decades (Verplanck and others, this volume), indicating that ferricrete formation can be quite rapid under ideal geochemical circumstances. Under less ideal circumstances ferricrete probably formed more slowly. Flood-plain gravel is locally cemented, and this must have occurred in the past 600 years. Some of the flood-plain ferricrete likely formed centuries ago, yet others, such as bog iron deposits on the flood plain, are currently forming. Most of the ferricrete in the Cement Creek watershed is prehistorical, as ferricrete exposures were abundant at the onset of mining (Comstock, 1883). Much of the ferricrete likely formed thousands of years ago, but the minimum-age constraints necessary to prove it are available at only a few exposures. The minimum-age constraints rely on the observation that stream incision permanently drained ground water from certain gravel deposits, and in one case charcoal was discovered encased in a bog iron deposit. Canyon-filling stream gravels (map unit g) form nearly vertical cliffs about 15 m high on both sides of Cement Creek (see Yager and Bove, this volume, pl. 2, fig. 3), at the mouth of Cement Creek (between 9 and 9.3 km in figs. 2 and 6*A*). These gravel deposits are strongly cemented with iron oxides. At least part of the ferricrete is 4,500 years old, given the age of charcoal (sample GX-26392, table 1) found in bog iron spring deposits capping the cemented gravel. Cement Creek incised through these gravel deposits before 6,000 years ago and probably about 12,000 years ago, and this drained the ground water from the alluvium. The horizon of active cementation probably moved downward in the section as Cement Creek incised; thus, the bulk of the ferricrete is likely early Holocene in age. Similar thick ferricrete deposits were mapped at the mouth of Mineral Creek and at Blair Gulch on the Animas River (Yager and Bove, this volume, pl. 2). The gravel deposits in Cement Creek only thinly cover bedrock, however, so some of the cementation may have occurred at seeps in the exposure face that were fed by ground water emerging from bedrock fractures nearby. The age of the bog iron deposit just mentioned, because it is younger than the timing of incision, indicates that this process occurred at least locally thousands of years after incision, and it could have occurred locally at any time during the Holocene. The timing of ferricrete formation is unequivocal for another type of deposit. Old alluvial fans (map unit fo) were emplaced perhaps 12,000 years ago and became incised before 6,000 years ago. Incision of Cement Creek and the tributary streams that formed the fans permanently drained the ground water from the near-surface, distal portions of these fans. In numerous locations we observed zones of ferricrete cropping out of erosional escarpments cut into the distal ends of the fans. The ferricrete zones are 1 to several decimeters thick, are subparallel to and are on the order of 1 m beneath the original fan surfaces, and are several meters higher than the terrace or streambed at the foot of the escarpments. These ferricrete zones must have formed before stream incision, when the ground-water levels were closer to the fan surfaces, because after incision ground water emerged from the permeable fan alluvium several meters beneath the ferricrete zones. These ferricrete zones must have formed entirely during the early to middle Holocene.

We conclude that ferricrete has been forming in the Cement Creek valley throughout the Holocene, although the locations of ferricrete formation have shifted as clastic sediment was deposited or eroded away. The rates of ferricrete formation have also been variable, because the geochemical requirements for ferricrete formation are spatially variable (Wirt and others, this volume). Low-pH iron-rich ground water is required for the formation of ferricrete. Ferricrete exposures are most frequent in reaches of Cement Creek where the ground-water supply is from subbasins composed of intensely hydrothermally altered bedrock containing abundant pyrite and other sulfide minerals (Wirt and others, this volume).


CONCENTRATION, IN WEIGHT PERCENT
9.0
8.5
8.0
7.5
7.0
6.5
6.0
ALUMINUM
16
14
12
10
8
6
4
2
0
POTASSIUM
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
CALCIUM
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
MAGNESIUM
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
IRON
0.65
0.60
0.55
0.50
0.45
0.40
0.35
TITANIUM
A
EXPLANATION
Premining baseline sediment, site B13
Premining baseline sediment, site B16
White inter-peat silt
Modern sediment, Cement Creek
The information displayed in box plots is summarized in the graphic below.
90th percentile
75th percentile
Median
25th percentile
10th percentile



B

Figure 7 (above and facing page). Box plots of *A*, major-element and *B*, selected trace-element concentrations for premining sediment samples from site B13 (*n*=23), premining sediment samples from site B16 (*n*=16) as discussed in Church, Fey, and Unruh (this volume), inter-peat silt samples (*n*=17) discussed in this chapter, and modern sediment samples from Cement Creek (*n*=10). All analytical and mineralogical data are in the database (Sole and others, this volume).

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