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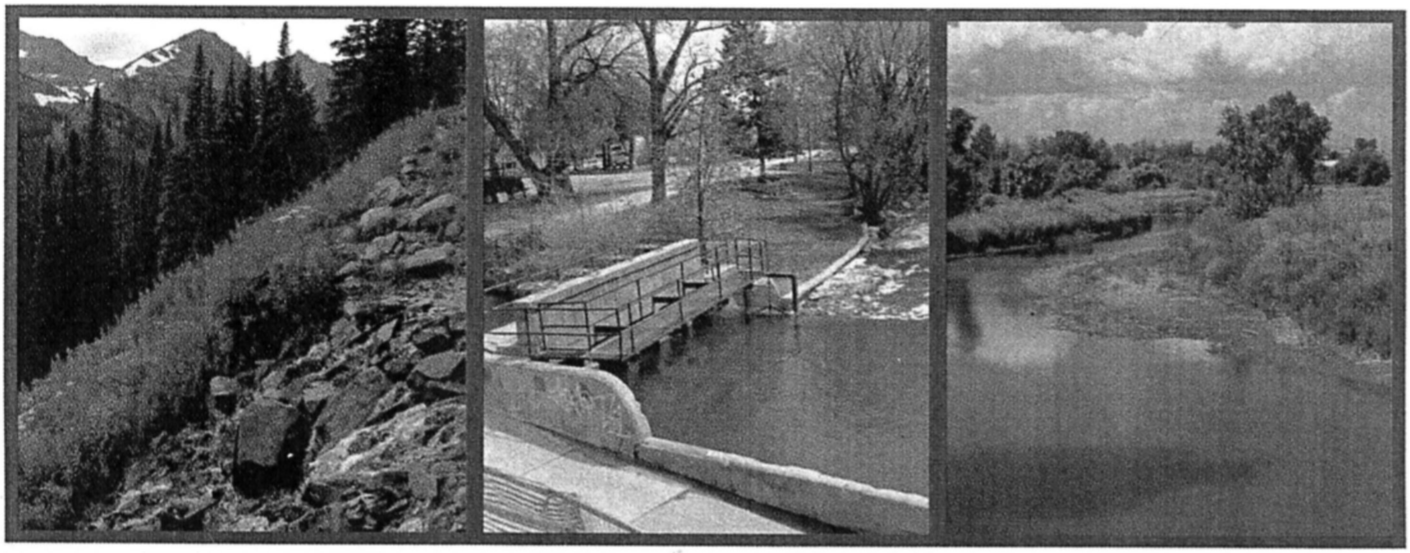
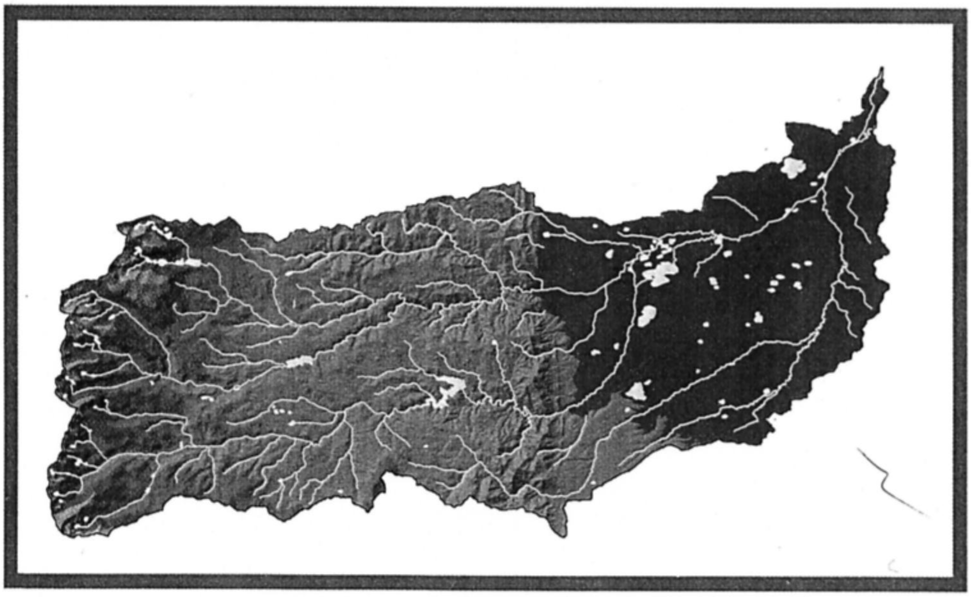
Comprehensive Water Quality of the Boulder Creek Watershed, Colorado, During High-Flow and Low-Flow Conditions, 2000

Water-Resources Investigations Report 03–4045





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

Comprehensive Water Quality of the Boulder Creek Watershed, Colorado, During High-Flow and Low-Flow Conditions, 2000

Sheila F. Murphy, Philip L. Verplanck, and Larry B. Barber, editors

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 03-4045

Denver, Colorado
2003

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Chapter 7 - Quantitative Mineralogy and Particle-Size Distribution of Bed Sediments in the Boulder Creek Watershed

By Daniel E. Kile and Dennis D. Eberl

Abstract

Twenty-four bed-sediment samples were collected from Boulder Creek and several of its tributaries to assess particle-size distribution and mineralogical composition. Changes in particle-size distribution were correlated with stream gradient, and also with stream mixing. Samples were analyzed by X-ray diffraction, and their quantitative mineralogy was determined with a recently-developed computer program. Mineralogical changes are evidenced in post-confluence stream mixing, and correlated with the underlying rock type of the surrounding drainage and stream channel.

INTRODUCTION

This study was undertaken to assess the mineralogy of stream bed sediments in the Boulder Creek Watershed. A knowledge of the mineralogical composition of these sediments can permit an assessment of: (1) a relation between mineralogy and sediment size fraction, (2) mineralogical differences in sediment samples that originate from different geological provinces, (3) the influence of tributary input on mineralogy, (4) downstream trends of the sediment mineralogy, and (5) the possible effect of mineralogy on water chemistry.

Determination of quantitative mineralogy by X-ray diffraction (XRD) methods has been problematic because a given mineral can generate variable peak intensities as measured by the XRD detector. This variation is due in part to compositional variability of the minerals (such as can occur within a mineral solid solution series) or by variable grain orientation (e.g., as controlled by cleavage and sample preparation); additional variation can also be caused by sample heterogeneity.

New methods for sample preparation have largely eliminated signal variability caused by non-randomness of the sample mounts, while revised protocols for internal standard addition, external standards preparation, and a recently-developed computer program that provides a detailed fitting of specific 2θ regions have facilitated an accurate quantification of mineralogical components of heterogeneous samples.

METHODS

Sample Collection

Bed sediment samples were collected at 17 sites in June 2000 (high flow), and at 6 sites in October 2000 (low flow; fig. 7.1, tables 7.1 and 7.2). Site descriptions are provided in Murphy and others (2003). From 0.5 to 1 kg of sample was collected from each site near the stream bank in areas where finer-grained particle sizes were more likely to predominate (in eddies, behind rocks, etc.) and stored in plastic Ziplock™ bags. At the BC-aSV site, two samples from different locations were collected.

Sample Preparation

Samples were dried at 85°C for 18 hours and sieved using a Rototap shaker for 12 to 15 minutes. Eight fractions were collected, using mesh sizes of 2.5, 5, 10, 18, 35, 60, 120, and 230 (corresponding to 8, 4, 2, 1, 0.5, 0.25, 0.125, and 0.063 mm respectively). Weights for each size fraction were recorded (tables 7.1 and 7.2).

Samples from three particle sizes, <0.063, 0.063-0.125, and 0.125-0.250 mm, were analyzed

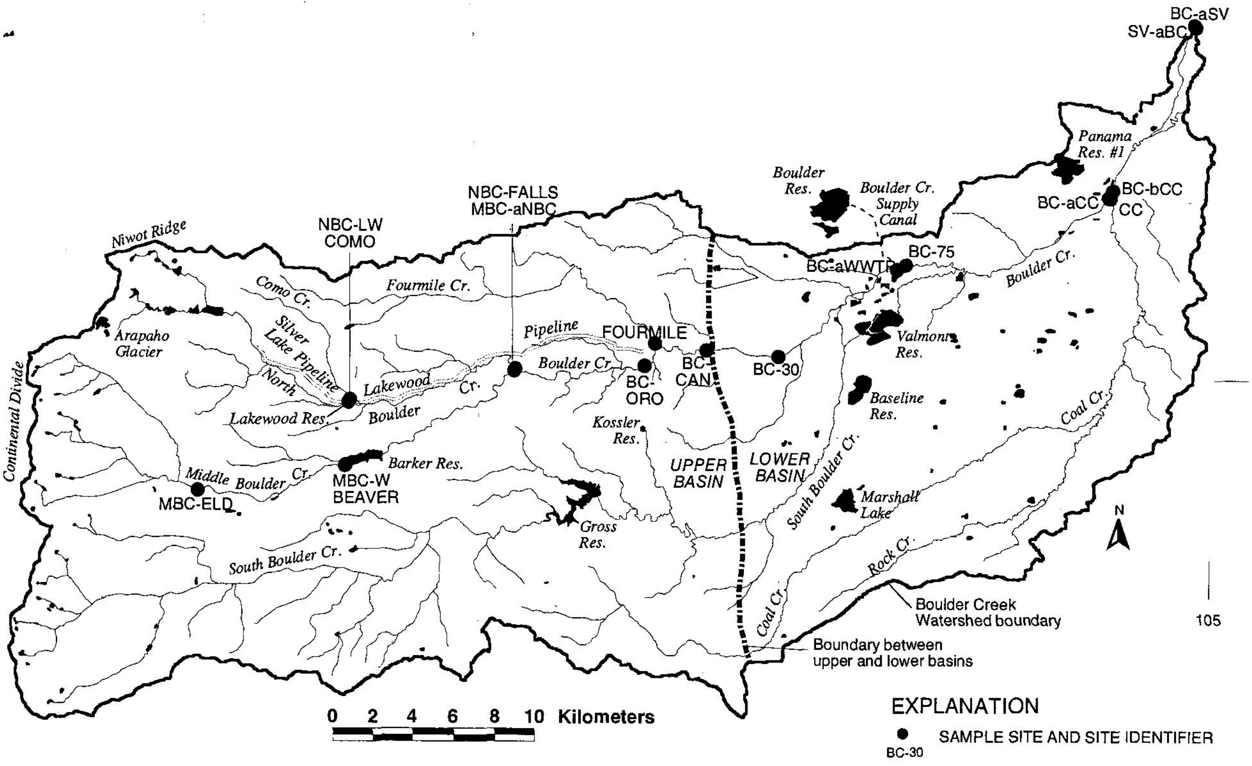

Figure 7.1. Map showing Boulder Creek Watershed and sampling sites.

with XRD, as it was presumed that these sizes best represent the clay-size minerals and overall mineralogy (including accessory minerals) of the sediment (Barber and others, 1992; Barber, 1994).

Samples were prepared for quantitative XRD analysis by weighing 3.0 g sediment and adding to it 0.333 g zinc oxide (U.S.P., J.T. Baker), which constituted a 10 weight percent internal standard for quantification. This mixture was ground with 4 mL methanol for 5 minutes in a McCrone Micronizing Mill using cylindrical corundum elements; the grinding step reduces particle size to less than 20 µm, and provides a narrow particle-size distribution, which maximizes random grain orientation. The slurry was oven-dried at 80°C, sieved through a 0.38-mm sieve (McCrone), and then side-packed in an XRD holder using a frosted glass slide (Ward's Natural Science) on the open side of the holder during packing to assure random orientation.

Qualitative analyses for smectite, vermiculite and chlorite were done from oriented preparations using the <63 µm sediment fractions. A sample slurry (~80 mg sample in 2 mL distilled water) was prepared from each sample, overlaid on glass slides, and air dried under a heat lamp for routine scanning. These preparations were subsequently saturated in ethylene glycol (85°C, 18 hours) to verify the presence of smectite, and heated to 250°C to differentiate vermiculite from chlorite.

X-Ray Analysis

Samples were analyzed on a Siemens D-500 diffractometer equipped with a copper radiation source, a graphite monochromator, and a scintillation detector. Quantitative scans were run at 40 kV and 30 mA. Detector slits were set at 1°, with a 2.3° Soller slit between the X-ray tube and the detector. Scans were run from 2 to 65°, with 2 seconds/step and 0.02 degrees per 2θ step. Qualitative scans were run at 2 to 35°, one

Table 7.1. Sediment particle-size fractionation data, June 2000

[>, greater than; <, less than; bold font indicates that X-ray diffraction was performed on sample. For site descriptions, see Murphy and others, 2003]

Site	Weight (in grams) of fraction within indicated particle-size interval (in millimeters)									
	>8	4-8	2-4	1-2	0.5-1	0.25-0.5	0.125-0.25	0.063-0.125	<0.063	Sum
Middle Boulder Creek/Boulder Creek										
MBC-ELD	26.74	4.25	7.46	37.45	149.89	251.74	49.76	3.29	0.73	531.31
MBC-W	5.27	67.65	94.64	52.33	20.87	43.76	20.00	3.61	0.98	309.11
MBC-aNBC	8.86	8.67	25.67	32.51	48.36	60.56	25.94	10.68	3.38	224.63
BC-ORO	1.00	3.67	45.34	82.73	59.99	51.27	**24.97**	**6.52**	1.20	276.69
BC-CAN	2.00	24.90	130.10	157.23	109.25	57.76	10.48	1.10	0.23	493.05
BC-30	3.96	10.69	36.28	62.20	63.10	58.31	30.65	19.52	9.08	293.79
BC-aWWTP	4.14	10.88	16.10	14.77	15.83	18.21	15.55	15.33	18.13	128.94
BC-75	38.14	5.52	3.34	14.69	47.63	66.20	13.25	3.46	1.21	193.44
BC-aCC	54.28	41.28	38.05	22.04	11.91	30.95	**21.88**	**4.60**	0.93	225.92
BC-bCC	0.00	0.00	0.00	0.07	0.68	4.21	**25.35**	**53.91**	**54.70**	138.92
BC-aSV #1	8.68	0.00	5.63	45.20	113.10	35.21	1.72	0.28	0.09	209.91
BC-aSV #2	16.54	8.86	8.33	9.83	15.02	21.20	**31.10**	**33.44**	**14.46**	158.78
Tributaries										
NBC-LW	2.37	8.19	19.02	35.67	48.14	38.76	24.38	11.47	7.73	195.73
NBC-FALLS	6.24	4.76	11.28	27.70	65.68	109.24	46.55	14.26	6.37	292.08
BEAVER	0.00	3.61	1.90	6.91	39.34	93.16	40.75	11.38	5.52	202.57
FOURMILE	0.00	9.92	93.33	163.83	157.80	93.02	**18.54**	**2.69**	2.26	541.39
CC	0.00	1.56	1.47	6.34	20.97	17.68	**29.57**	**79.97**	**93.12**	250.68
SV-aBC	14.53	0.00	4.94	9.04	15.17	78.80	**135.59**	**84.84**	**26.97**	369.88

Site	Percentage within indicated particle-size interval (in millimeters)									
	>8	4-8	2-4	1-2	0.5-1	0.25-0.5	0.125-0.25	0.063-0.125	< 0.063	Sum
Middle Boulder Creek/Boulder Creek										
MBC-ELD	5.03	0.80	1.40	7.05	28.21	47.38	9.37	0.62	0.14	100
MBC-W	1.70	21.89	30.62	16.93	6.75	14.16	6.47	1.17	0.32	100
MBC-aNBC	3.94	3.86	11.43	14.47	21.53	26.96	11.55	4.75	1.50	100
BC-ORO	0.36	1.33	16.39	29.90	21.68	18.53	9.02	2.36	0.43	100
BC-CAN	0.41	5.05	26.39	31.89	22.16	11.71	2.13	0.22	0.05	100
BC-30	1.35	3.64	12.35	21.17	21.48	19.85	10.43	6.64	3.09	100
BC-aWWTP	3.21	8.44	12.49	11.45	12.28	14.12	12.06	11.89	14.06	100
BC-75	19.72	2.85	1.73	7.59	24.62	34.22	6.85	1.79	0.63	100
BC-aCC	24.03	18.27	16.84	9.76	5.27	13.70	9.68	2.04	0.41	100
BC-bCC	0.00	0.00	0.00	0.05	0.49	3.03	18.25	38.81	39.38	100
BC-aSV #1	4.14	0.00	2.68	21.53	53.88	16.77	0.82	0.13	0.04	100
BC-aSV #2	10.42	5.58	5.25	6.19	9.46	13.35	19.59	21.06	9.11	100
Tributaries										
NBC-LW	1.21	4.18	9.72	18.22	24.60	19.80	12.46	5.86	3.95	100
NBC-FALLS	2.14	1.63	3.86	9.48	22.49	37.40	15.94	4.88	2.18	100
BEAVER	0.00	1.78	0.94	3.41	19.42	45.99	20.12	5.62	2.72	100
FOURMILE	0.00	1.83	17.24	30.26	29.15	17.18	3.42	0.50	0.42	100
CC	0.00	0.62	0.59	2.53	8.37	7.05	11.80	31.90	37.15	100
SV-aBC	3.93	0.00	1.34	2.44	4.10	21.30	36.66	22.94	7.29	100

Table 7.2. Sediment particle-size fractionation data, October 2000

[>, greater than; <, less than; bold font indicates that X-ray diffraction was performed on sample. For site descriptions, see Murphy and others, 2003]

Site	Weight (in grams) of fraction within indicated particle-size interval (in millimeters)									
	>8	4-8	2-4	1-2	0.5-1	0.25-0.5	0.125-0.25	0.063-0.125	<0.063	Sum
Middle Boulder Creek/Boulder Creek										
MBC-ELD	149.23	82.01	55.49	51.03	49.89	25.55	**5.60**	**1.60**	1.11	421.51
MBC-W	42.99	90.91	108.09	80.54	47.41	64.98	30.10	6.00	1.68	472.70
BC-aSV	117.71	21.10	44.57	87.46	130.09	71.89	13.05	2.03	0.53	488.43
Tributaries										
NBC-LW	0.00	1.47	11.47	26.10	56.57	80.17	51.75	19.54	6.72	253.79
COMO	31.49	3.16	1.88	0.78	1.85	31.44	60.78	19.88	8.27	159.53
SV-aBC	150.10	41.14	30.96	33.29	42.90	38.06	14.39	7.71	4.70	363.25

Site	Percentage within indicated particle-size interval (in millimeters)									
	>8	4-8	2-4	1-2	0.5-1	0.25-0.5	0.125-0.25	0.063-0.125	<0.063	Sum
Middle Boulder Creek/Boulder Creek										
MBC-ELD	35.40	19.46	13.16	12.11	11.84	6.06	1.33	0.38	0.26	100
MBC-W	9.09	19.23	22.87	17.04	10.03	13.75	6.37	1.27	0.36	100
BC-aSV	24.10	4.32	9.13	17.91	26.63	14.72	2.67	0.42	0.11	100
Tributaries										
NBC-LW	0.00	0.58	4.52	10.28	22.29	31.59	20.39	7.70	2.65	100
COMO	19.74	1.98	1.18	0.49	1.16	19.71	38.10	12.46	5.18	100
SV-aBC	41.32	11.33	8.52	9.16	11.81	10.48	3.96	2.12	1.29	100

second/step, and 0.1° per 2θ step. Other procedural details are given in Środoń and others (2001). Results were quantified by comparison of the sample XRD patterns against known mineral standards, from which mineral intensity factors (MIFs) were computed using the RockJock computer program (Środoń and others, 2001; Eberl, 2003). Non-clay minerals scanned include the plagioclase feldspars (albite, oligoclase, labradorite), alkali feldspars (e.g., microcline), and iron oxides (magnetite, hematite), in addition to amphibole group minerals, dolomite, and quartz. Clay and mica-group minerals scanned, comprising the phyllosilicates, include phlogopite, $1M_d$ illite + smectite + vermiculite, and $2M_1$ illite; $1M_d$ and $2M_1$ are polytypes that are related to the stacking orientation of the tetrahedral-octahedral-tetrahedral layers of phyllosilicates, which include most of the common illite and muscovite minerals.

RESULTS

Size Fractionation

Size-fractionation data for samples collected in June and October, 2000, are given in tables 7.1 and 7.2 and displayed in figures 7.2 and 7.3. Particle-size classification is adapted from Tickell (1965). Additionally, the particle-size distribution data for all samples have been smoothed using a cubic spline method (R. F. Stallard, U.S. Geological Survey, oral commun., 2001; values for phi taken from Office of Water Data Coordination, 1977) to represent the data as a continuous distribution (figs. 7.4 and 7.5). The "percent per phi interval" (Krumbein and Pettijohn, 1938, p. 76-90) is a measure of the weight-based percent of particles within a given range of mesh sizes. Figure 7.6 presents a comparison of particle-size distributions for bed sediment samples from 5 sites collected in both June and October, 2000.

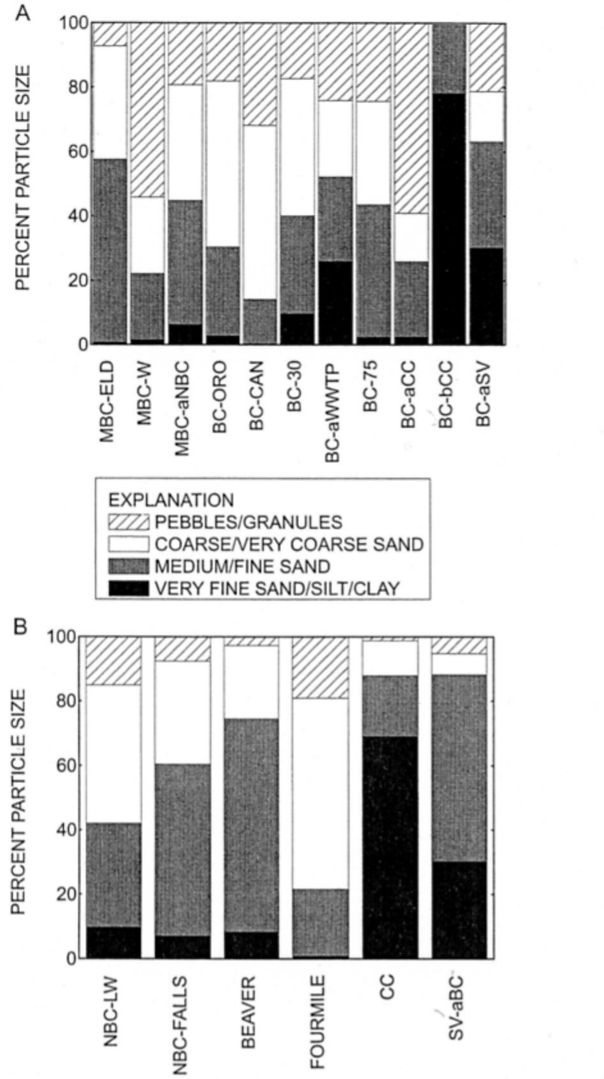

Figure 7.2. Sediment particle-size fractionation data for (A) Middle Boulder Creek/Boulder Creek sampling sites and (B) tributary sampling sites, June 2000.

Several factors can render an assessment of particle-size distribution ambiguous, and conclusions must therefore be regarded with caution. For example, differences in particle-size distributions are highly dependent on the exact depositional environment in the river channel from which the sample was taken. This is clearly evidenced by the two samples collected at site BC-aSV (table 7.1), where the percentages in the respective size fractions differ significantly. Moreover, clay-size minerals are sometimes found in abundance in some of the "non-clay" size fractions. This is likely due to adhesion to grain surfaces, and also to the weathering and alteration of feldspar minerals that results in the formation of clays as an integral constituent. Despite these uncertainties, some observations of a general nature can nevertheless be made.

There are no significant trends in particle-size distribution (within limits of variability for sample collection) along the course of Boulder Creek for the larger size fractions, whereas there are some definite differences noted (table 7.1, figs. 7.2 and 7.3) in some sediments for the smallest size fractions (<0.063 and 0.063-0.125 mm). The smaller-size fractions constitute a negligible portion of the samples from upper Boulder Creek; in contrast, the sample from Coal Creek is composed predominantly of particles less than 0.125 mm (fig. 7.2). This observation is likely due to minimal clay content in the igneous and metamorphic source rocks in the upper Boulder Creek Watershed, and partly due to a higher stream gradient (and therefore higher flow rates) in the mountainous terrain. Moreover, spline curves for BC-ORO, BC-CAN, and BC-30 (fig. 7.4) show downstream trends of decreasing particle size. Two sediment samples from upper Middle Boulder Creek (MBC-ELD and MBC-W) show a bimodal particle-size distribution,

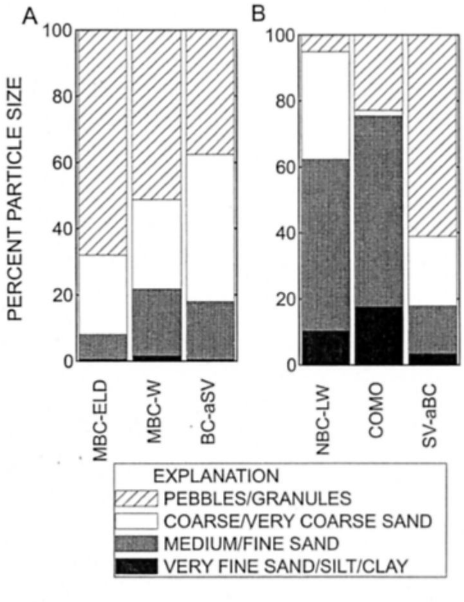

Figure 7.3. Sediment particle-size fractionation data for (A) Middle Boulder Creek/Boulder Creek sampling sites and (B) tributary sampling sites, October 2000.

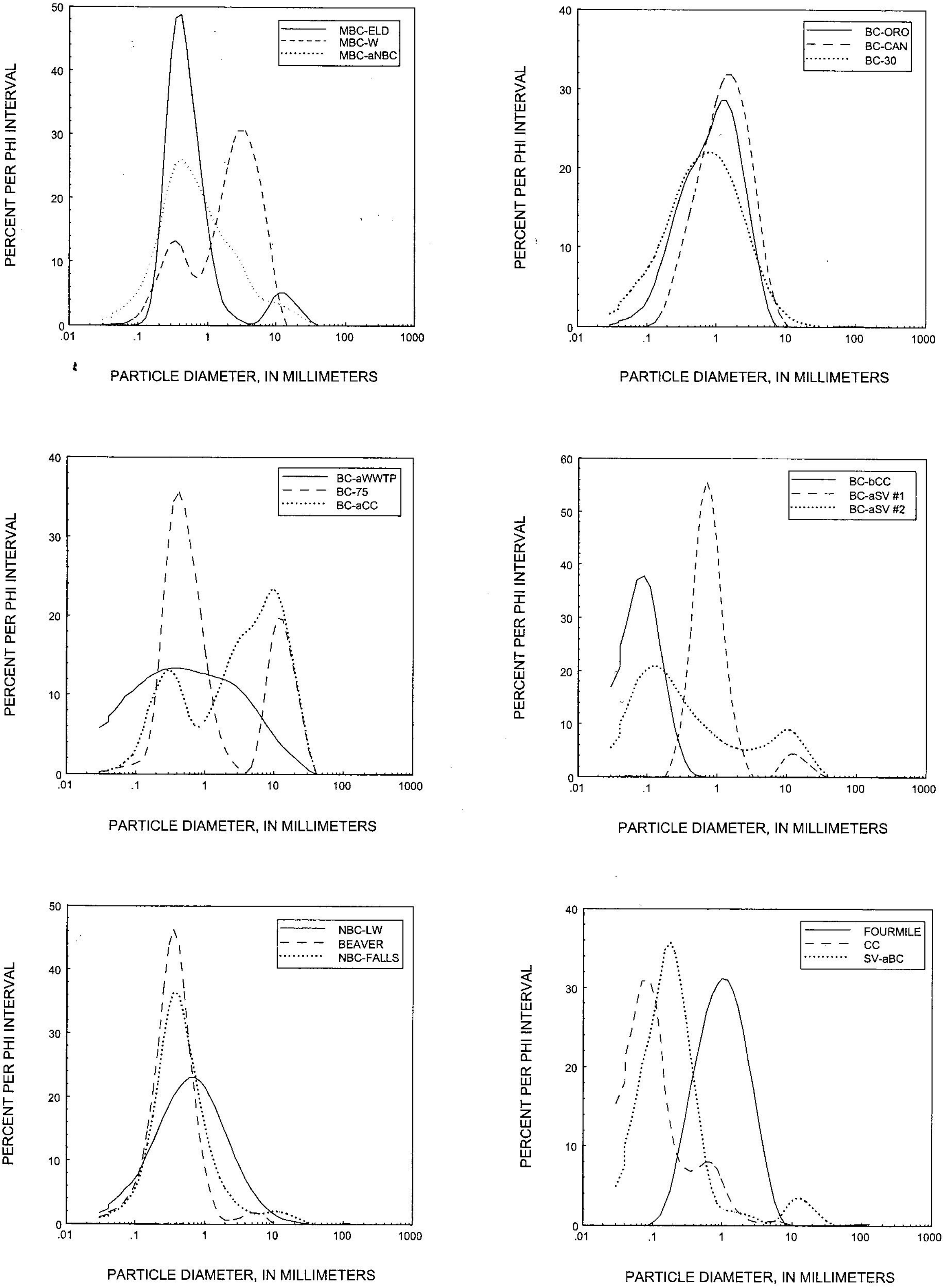

Figure 7.4. Particle-size distributions of bed sediments for Middle Boulder Creek/Boulder Creek and tributaries, June 2000.

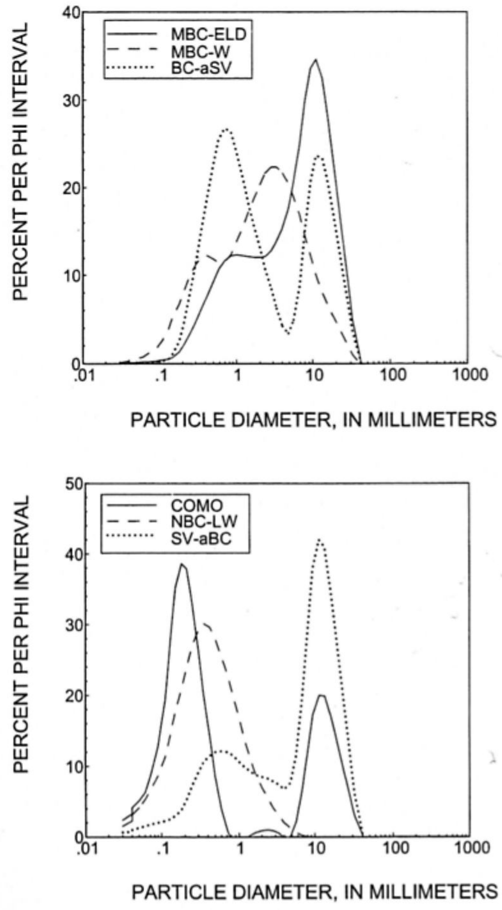

Figure 7.5. Particle-size distributions of bed sediments for Middle Boulder Creek/Boulder Creek and tributaries, October 2000.

whereas a sample collected father downstream (MBC-aNBC) shows a unimodal distribution (fig. 7.4).

The high silt load carried by Coal Creek is likely a manifestation of its low gradient and its lengthy traverse through sedimentary rocks. Boulder Creek shows comparatively higher levels of the very fine sand and silt (<0.063 and 0.063-0.125 mm) fractions at sites above the Boulder Wastewater Treatment Plant (BC-aWWTP) and below Coal Creek (BC-bCC; fig 7.2). The higher fine particulate load at the BC-aWWTP site is likely a result of its traverse through sedimentary rocks (predominantly the Cretaceous Pierre Shale) following its exit from the foothills at the mouth of Boulder Canyon (Colton, 1978; Trimble and Machette, 1979; Hall and others, 1980; Bilodeau and others, 1987). In contrast, the very high levels of the smaller size fractions at the BC-bCC site are due to the mixing of Coal Creek and Boulder Creek. Boulder Creek shows a 10-fold increase in fine particulates (<0.25 mm between the samples above and below the Coal Creek confluence (BC-aCC and BC-bCC, respectively). The Boulder Creek samples also show significant differences in mineralogy above and below the confluence with Coal Creek (see below).

There were no distinct trends in particle-size distribution between samples collected in June and October (fig. 7.6). As discussed above, variability in sediment collection may have obscured any differences that might have been present.

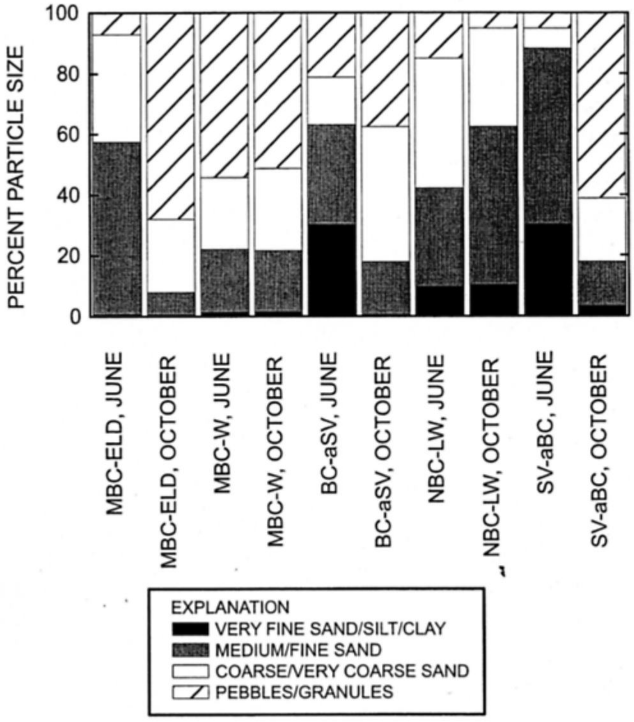

Figure 7.6. Comparison of sediment particle-size fractionation data, June and October 2000.

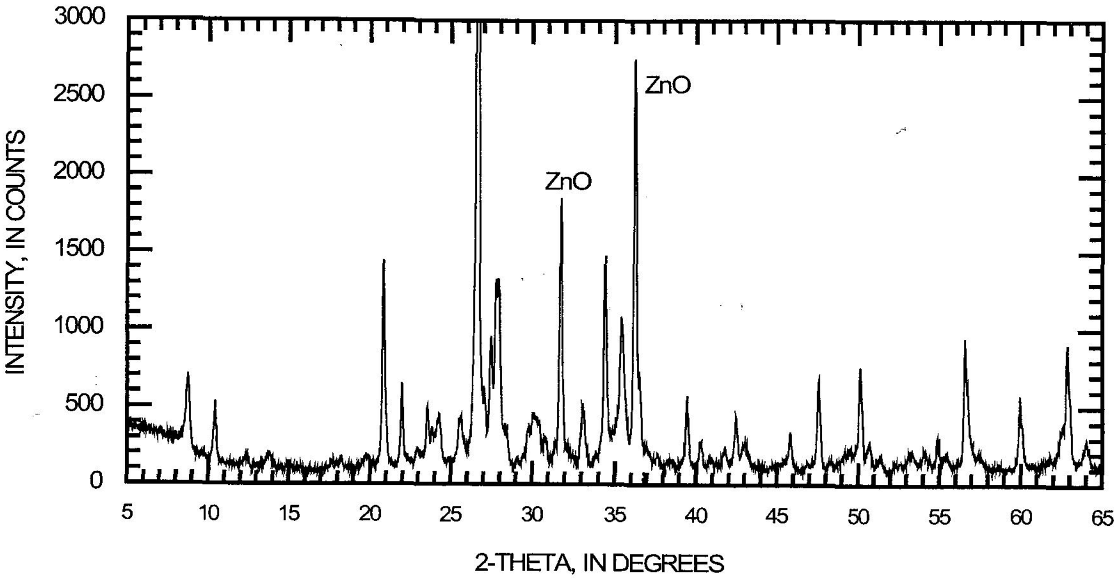

Figure 7.7. X-ray diffraction pattern for 0.063-0.125 mm fraction of sample from site BC-ORO (random mount with zinc oxide [ZnO] internal standard).

Mineralogy

Figure 7.7 shows a representative XRD pattern of a sample in a random mount with the internal zinc oxide standard added. This pattern shows peaks from all the major mineral phases present in the sediment. Several points need to be considered in interpreting XRD data. While analysis by XRD can be very accurate in quantifying major components within a mixture, it is not very good at detecting constituents that are present in trace amounts (less than about 2 percent). Thus, while small amounts of minerals, such as garnet, titanite, and zircon, may be expected to be present in a given sediment (particularly those collected in the upper drainages where Boulder Creek traverses igneous rocks), such minor constituents will not be evident on the XRD pattern. Furthermore, speciation of plagioclase by XRD analysis will not necessarily correspond to a petrologic examination by polarized-light microscopical methods, because XRD will detect the entire compositional range of plagioclase, whereas analysis by polarized-light microscopy speciates only the most sodic member in the plagioclase series (e.g., by using the Michel-Lévy method for determining the extinction angle). The cumulative percent of the minerals for a given sample will vary on either side of an ideal 100 percent because of experimental error, e.g., the mineral standard for a given species may not be exactly identical to that in the sample, resulting in an error in the corresponding mineral intensity factor or in the integrated intensities that are used to calculate the percent total. Quantitative mineralogy of sediment samples from Middle Boulder Creek, Boulder Creek, Fourmile Creek, Coal Creek, and Saint Vrain Creek is provided in table 7.3 and figure 7.8.

Figure 7.9 shows superimposed XRD patterns for clay minerals (0.063-0.125 mm fraction) from a single sample that was (1) an air-dried oriented preparation, (2) saturated in ethylene glycol, and (3) heated to 250°C. This protocol allows a qualitative assessment of smectite, vermiculite, and chlorite. Treating samples with ethylene glycol will shift the 12- to 14-Å smectite peak to 17 Å, differentiating smectite clays from vermiculite and chlorite, whereas heating the samples to 250°C collapses the vermiculite structure, shifting a peak from 14.5 to 10 Å, thus differentiating vermiculite from chlorite (chlorite spacing remains at 14.5 Å). Smectite was present in all samples. Vermiculite was minimal in Coal Creek, and

Table 7.3. Quantitative mineralogy data for bed sediments collected during June and October, 2000

[All samples were collected in June 2000 except MBC-ELD, which was collected in October 2000]

Mineral	Percentage within the indicated particle-size interval (in millimeters) for the indicated sample																			
	MBC-ELD		BC-ORO		BC-aCC		BC-bCC			BC-aSV			FOURMILE		CC			SV-aBC		
	0.063-0.125	0.125-0.250	0.063-0.125	0.125-0.250	0.063-0.125	0.125-0.250	<0.063	0.063-0.125	0.125-0.250	<0.063	0.063-0.125	0.125-0.250	0.063-0.125	0.125-0.250	<0.063	0.063-0.125	0.125-0.250	<0.063	0.063-0.125	0.125-0.250
Non-clay minerals																				
Amphibole	5	5	8	7	4	7	1	1	2	2	2	7	5	7	1	2	1	2	2	1
Microcline	16	17	15	17	13	21	10	13	14	11	13	12	12	12	9	11	13	11	14	19
Albite	6	4	2	5	0	6	5	5	2	5	6	12	7	12	4	2	4	9	8	8
Oligoclase	9	15	12	11	10	13	3	5	10	7	7	8	6	8	4	7	6	5	7	11
Labradorite	9	10	11	12	4	7	3	5	3	5	5	9	7	9	4	4	4	6	6	6
Magnetite	8	5	9	4	10	5	1	1	0	1	1	2	6	2	1	0	1	2	1	1
Hematite	4	1	3	2	5	5	1	1	0	1	1	2	4	2	0	0	1	1	1	0
Dolomite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0
Quartz	27	39	29	33	42	39	52	58	59	48	56	35	27	35	49	56	59	45	50	47
Total non-clay minerals	85	95	90	91	88	102	76	88	91	79	90	86	74	86	73	83	88	81	89	92
Clay-phyllosilicate minerals																				
Phlogopite	6	1	5	5	5	1	4	4	5	4	3	5	9	5	3	5	4	3	2	3
Illite (*1M$_d$*)+smectite+ vermiculite	0	0	8	2	7	0	21	13	10	17	12	6	6	6	25	23	12	15	6	6
Illite (*2M$_1$*)	8	5	1	6	2	4	0	2	2	3	3	8	7	8	0	0	2	2	5	5
Total clay minerals	14	6	14	13	14	6	25	18	17	23	18	19	23	19	29	28	18	20	13	14
Total all minerals	99	101	104	104	102	109	101	106	108	102	108	105	97	105	102	111	106	101	102	106

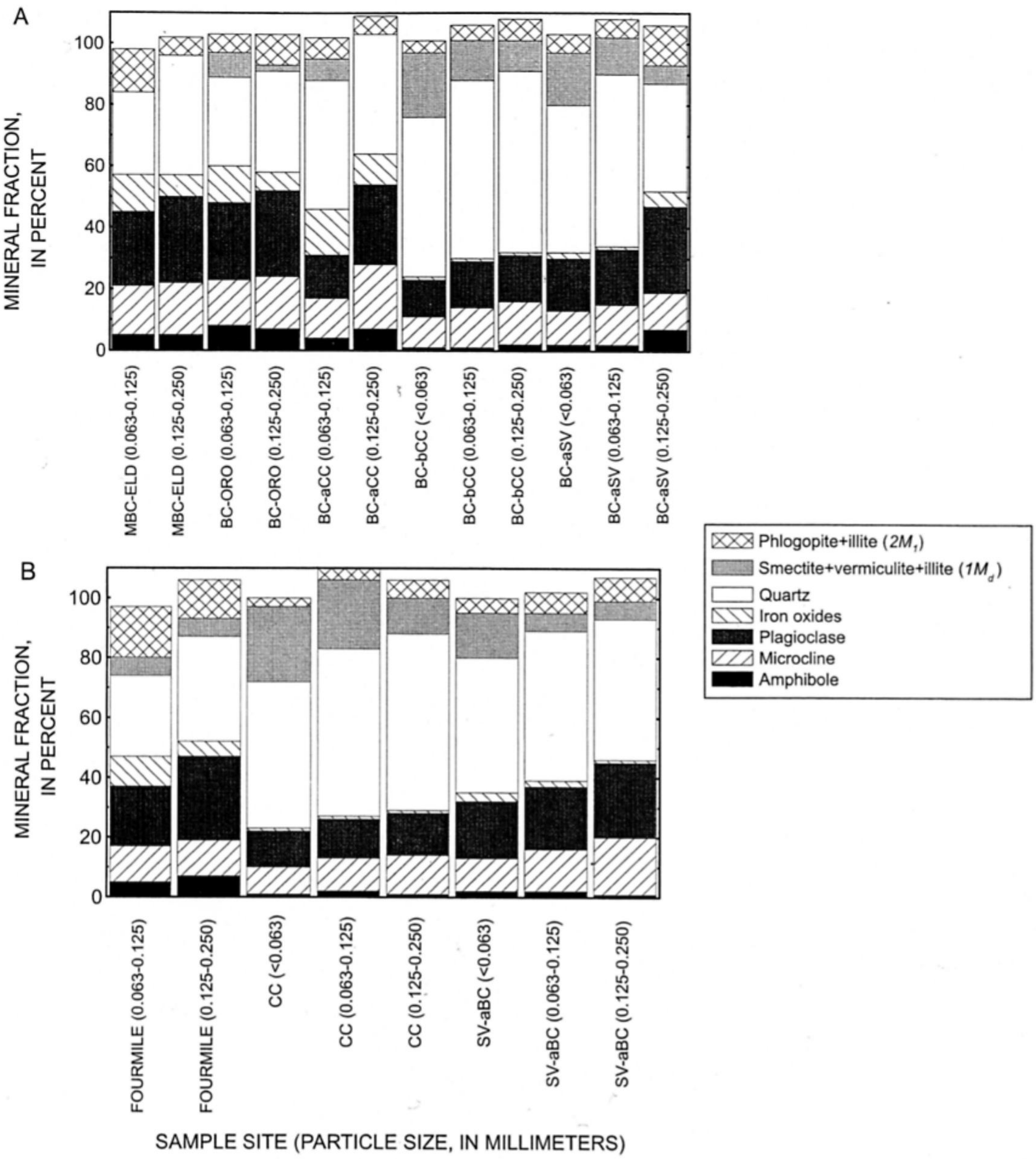

Figure 7.8. Quantitative mineralogy of sediment samples from (A) Middle Boulder Creek/Boulder Creek and (B) Fourmile Creek, Coal Creek, and Saint Vrain Creek.

absent in Boulder Creek below the Coal Creek confluence. Chlorite was not detected. Qualitative XRD data for the expandable clays are presented in table 7.4.

The relation between mineralogy and size fraction observed in this study is mostly expected. For example, clay minerals are more abundant in the smaller size fractions, whereas other minerals (such as mica and feldspar) tend to be present at higher concentrations in the larger size fractions. The iron oxides show a distinct inverse relation with respect to particle size. Quartz is the major component in all samples, followed by plagioclase and microcline. Quartz and the feldspars remained relatively consistent throughout the Boulder and Middle Boulder Creek sediments, although quartz does become a more prominent constituent below the confluence of Boulder Creek and Coal Creek.

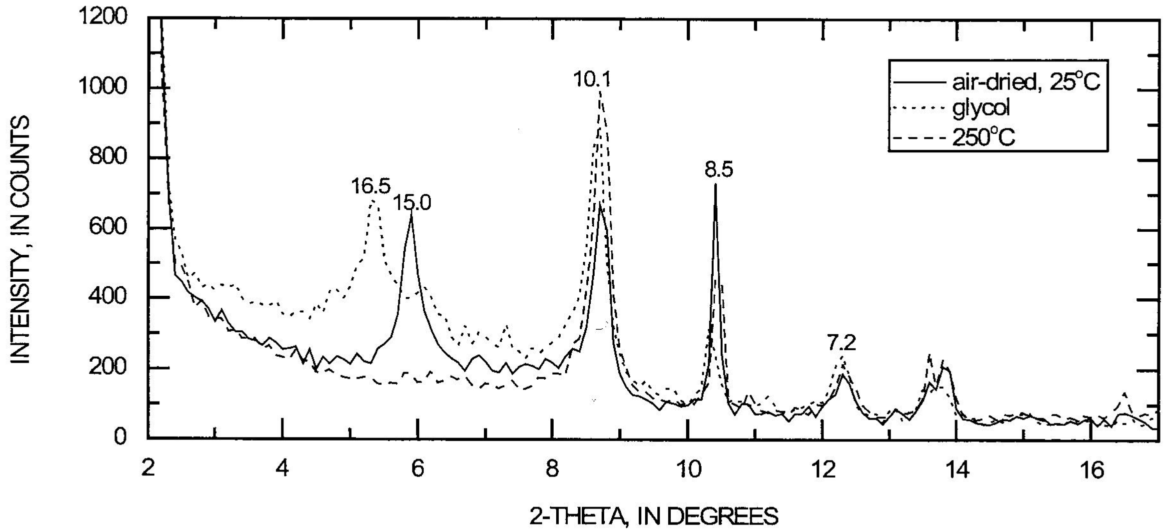

Figure 7.9. X-ray diffraction pattern for 0.063-0.125 mm fractionof sample from site BC-ORO with air drying, glycolation, and heating to 250 C. (Peaks are labeled in angstroms. Pattern shows smectite and vermiculite components.)

The Precambrian rocks and corresponding minerals that compose the upper Boulder Creek Watershed are predominantly the Boulder Creek Granodiorite (microcline, plagioclase, quartz, biotite, and hornblende, with accessory magnetite, ilmenite, hematite, allanite and sphene), the Silver Plume Quartz Monzonite (microcline, plagioclase, biotite, and muscovite), and Precambrian gneisses (with accessory cordierite, magnetite, sillimanite, garnet, and biotite).In addition, Tertiary intrusive alkali feldspar syenite and quartz syenite of Eocene age is common (Colton, 1978; Gable, 1980). As expected, the overall mineralogy of the bed sediments in the Boulder Creek Watershed, particularly for samples above the confluence with Coal Creek, is consistent with these source rocks, being composed predominantly of quartz, plagioclase, and microcline, with amphibole, magnetite and hematite present in smaller amounts.

Predictably, magnetite, hematite, and amphibole-group minerals in Boulder Creek drop off noticeably once the creek flows out of igneous source rocks and into sedimentary rocks. This is likely due to: (1) physical size reduction (as would be expected for a highly cleavable mineral such as an amphibole); (2) weathering and chemical alteration (e.g., alteration of magnetite and hematite to limonite); and (3) gravitational settling due to a reduced stream gradient and concomitant diminished flow rate. Much of the hematite in these samples likely occurs as a relatively stable martitic intergrowth with magnetite (as formed by a process of martitization, whereby primary magnetite is altered to hematite along crystallographic planes, resulting in distinctive textures), rather than as a separate phase (e.g., limonitic). Amphiboles and feldspars (microcline and plagioclase) were generally present in higher amounts in Boulder Creek above its confluence with Coal Creek; below the confluence, quartz becomes a more significant constituent.

The increased proportion of quartz in Coal Creek may be a reflection of its traverse through predominantly sandstone-bearing sediments of the Laramie and Fox Hills formations. Magnetite and amphibole-group minerals are absent from the Coal Creek sediments; these sediments are also noticeably poor in the mica *2M₁* polytype (e.g., muscovite and illite). The reduction in these constituents in Boulder Creek sediments after the Coal Creek confluence is also noteworthy,

Table 7.4. Qualitative mineralogy of expandable clays in size fraction below 0.063 millimeters

Site	Clay(s)
MBC-ELD	smectite, vermiculite
BC-ORO	smectite, vermiculite
BC-aCC	smectite, vermiculite
BC-bCC	smectite
BC-aSV	smectite, vermiculite
FOURMILE	smectite, trace vermiculite
CC	smectite, trace vermiculite
SV-aBC	smectite, vermiculite

suggesting that Coal Creek is a major sediment source to the lower Boulder Creek system.

SUMMARY

Although there is a distinct heterogeneity in particle-size distribution and mineralogy throughout the Boulder Creek Watershed, some trends are nonetheless evident. Differences in mineralogy are also noted within a given river system (e.g., Boulder Creek), and from upstream to downstream sample sites. These changes are mostly attributable to a change in the rock type (from igneous to sedimentary) over which the creek flows. For example, there is a significant increase from upstream to downstream in particle size for the < 0.25 mm fractions, as well as a decrease in the relative amounts of iron oxide minerals. The presence of amphibole-group minerals and iron oxides in the Boulder Creek system, and their absence in the Coal Creek drainage, is also likely manifest of the geology of the terrain through which the creek travels. The sediments downstream of the confluence of Boulder Creek and Coal Creek show the expected effects of dilution for these constituents.

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