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**CHEMICAL AND MINERALOGICAL CHARACTERISTICS AND ACID-NEUTRALIZING POTENTIAL OF FRESH AND ALTERED ROCKS AND SOILS OF THE BOULDER RIVER HEADWATERS IN BASIN AND CATARACT CREEKS OF NORTHERN JEFFERSON COUNTY, MONTANA**

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## ABSTRACT

The results show that igneous bedrock in the Basin and Cataract Creek basins has a high acid-neutralizing potential. Our studies of acid-generating properties of 19 mining – related waste piles of 500 tons or more in this area showed that leachates (of mining waste after 24 hour exposure) of samples from 16 piles had a final mean pH of 3.3, whereas leachate samples from three piles had a final pH of between 5.9-6.8. The pH of stream water is routinely higher than 7.0 at all but one monitoring site in the Basin and Cataract Creek basins (Nimick and Cleasby, 1998). Results of these two studies show that if significant amounts of acid are generated from the waste piles, the resultant drainage is buffered by bedrock, alluvium, soil, or stream water.

To test the buffering capacity of geologic materials, we designed laboratory tests that would determine the acid-neutralizing potential of representative bedrock and soils through the use of solutions that simulate water interacting with mine wastes. In a prior study, 100-g samples of <2.0 mm mine waste from various sites were exposed to 2 liters of deionized water at rest for 24 hours and the final leachate pH was measured. In the present study, the acidic solutions (pH = 2.90-3.00) generated by the previous study were filtered (0.45 micron) and mixed with crushed, <0.050 mm fractions of samples of both fresh and altered bedrock and a <2.0 mm fraction of the soils. The ratio of rock and soil exposed to the acidic solution for 24 hours at rest was 1:20 for the initial tests. After exposure of 11 samples of granite bedrock to the acidic solution, the mean final pH of the liquid was 6.72. Interaction of four fresh samples of Elkhorn volcanic rocks with the acidic solution yielded a mean final pH of 7.00. The reaction of seven samples of silicified altered rocks from Jack Mountain with the solution yielded a mean final pH of only 3.90, and 13 soil samples provided a mean final pH of 4.20.

Igneous bedrock of the study area contains minor, but important, amounts of calcite. Calcite was not detected in any of these igneous rocks using three different X-ray diffractometer units. Similarly, prior petrographic studies of about 250 thin sections of the igneous intrusive rocks from the Basin 15-minute quadrangle reported no carbonate minerals. However, using a chemical stain (alizarin red) on large (10 X 10 cm) sawed rock slabs, we found dispersed calcite in all but one fresh igneous sample. Small amounts of calcite appear to be partly responsible for the acid-neutralizing capacity of the fresh igneous rock. Minor amounts of other carbonates that were not detected may also contribute to the acid-neutralizing potential of these rocks. The rapid neutralization of acidic solutions observed for the igneous rocks (5-30 minutes) is consistent with carbonate dissolution.

The high acid-neutralizing potential of this igneous bedrock, which is widespread in the Basin and Cataract Creek Basins, has favorable implications for the siting of a repository for acid-generating waste because the bedrock can be expected to neutralize some or perhaps all of the acid generated by waste in the repository.

## **INTRODUCTION**

Buxton and others (1997) identified the Basin and Cataract Creek headwaters of the Boulder River in northern Jefferson County, Montana as containing abandoned mines that contribute significantly to water quality degradation. Our study here is an attempt to characterize the chemical and mineralogical properties and acid-neutralizing potential of fresh rocks, soils, and altered Elkhorn volcanic rocks of Jack Mountain in the Basin and Cataract Creek drainages. Our studies document the chemical and mineralogical properties of rocks and soils that are proximal to, but that are not associated with the aquatic pollution potential of metal-mining related wastes studied by Metesh and others (1994), Marvin and others (1996), and Desborough and Fey (1997).

The rocks and soils within the study area are more areally extensive than the mining-related wastes and the now abandoned metal-bearing veins explored and mined during the last century. Thus the present study is focused on the non-anthropomorphic, or natural aspects of the area that may significantly influence water quality in the Boulder River headwaters. The quantitative and qualitative data given here will be useful in evaluating the influence of natural or indigenous characteristics of rocks and soils on the biota.

## **METHODS OF STUDY**

A total of only 15 samples of fresh rock were taken because of the sparse occurrence of outcrops or man-made exposures in roadcuts. Samples ranged from 5-13 kg and were trimmed in the laboratory to remove surface oxidation effects before crushing and sizing. A fine fraction (<0.050 mm) of each sample was exposed to acidic leachates to determine acid-neutralizing potential. A large (5 X 10 to 8 X 15 cm) slab of 0.5-1 cm thickness was obtained from each sample for textural studies and alizarin-red stain tests for calcite (Dickson, 1965). A 70 gram sample obtained from the 1-4 mm sized fraction of each crushed sample was pulverized for X-ray diffraction mineral studies, bulk chemical analysis, and a test to determine what high-density mineral are present.

Seven samples of hydrothermally altered Elkhorn volcanic rocks were collected from three sites along the road leading to the summit of Jack Mountain. These ranged from only about 0.5-1.0 kg because the rock is intensely fractured at intervals of about 10 cm or much less. Samples were prepared in the same way as the fresh igneous rocks and were studied using the same laboratory tests.

Soil samples were collected from 13 sites (fig. 2); these were taken from the upper 10 cm and samples ranged from about 3.5-6 kg. Samples were dried (40<sup>o</sup> C) in the laboratory and sized to obtain a <2.0 mm fraction for chemical, mineralogical, and leaching studies.

## **MINERALOGICAL AND CHEMICAL CHARACTERISTICS OF IGNEOUS BEDROCK**

Preliminary data for some bulk chemical and mineralogical aspects and acid-neutralizing potential of seven samples of igneous bedrock were reported for the study area by Desborough and Fey (1997). An additional eight samples of igneous bedrock are

included in the present report, along with more complete chemical data for major, minor, and trace elements for the seven samples included in the preliminary report (table 1). Sample sites are shown on Figure 1. Except for As, all of the major, minor, and trace elements reported in Table 1 for bedrock samples are in the normal range for these rocks. Four samples range from 11 to 16 ppm As, which is three to five times the As values of 1.0-2.6 ppm commonly found in granitic rocks (Kabata-Pendias and Pendias, 1984, table 106). All of the other As values are less than 10 ppm. Instrumental neutron activation analysis of samples FB031 and FB035 showed 17 ppm and 9 ppm of As, respectively. Therefore at least one third of the bedrock samples analyzed have anomalous concentrations of As.

**Table 1.** Concentrations of selected elements in 15 fresh igneous bedrock samples in Basin and Cataract Creek drainages, northern Jefferson County, Montana. Determined by induction coupled plasma-atomic emission spectroscopy.

Sample	FB007B1	FBO07B2	FB007B3	FBO13	FMT010	FMT011	FMT012
Lat., deg.	46.3086	46.3086	46.3086	46.35	46.3314	46.2703	46.3305
Long., deg.	112.3025	112.3025	112.3025	112.2606	112.3283	112.2189	112.2094
Rock Type	batholith intrusive	batholith intrusive	batholith intrusive	batholith intrusive	batholith intrusive	batholith intrusive	Elkhorn volcanic
Al %	8.6	7.8	8.1	8.2	8	8.7	8.9
Ca %	2.7	2.2	1.9	1.7	3.1	2.9	2.3
Fe %	3	2.7	2.5	2.1	3.5	3.6	2.5
K %	2.9	3.4	4	4	3.2	3.6	3.2
Mg %	0.96	1	0.92	0.7	1.5	1.4	0.68
Na %	2.6	2.4	2.3	2.2	2.3	2.2	2.6
P %	0.11	0.08	0.06	0.04	0.08	0.09	0.06
Ti %	0.26	0.3	0.28	0.22	0.44	0.41	0.32
Ag ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2
As ppm	12	< 10	< 10	< 10	< 10	< 10	< 10
Au ppm	< 8	< 8	< 8	< 8	< 8	< 8	< 8
Ba ppm	960	730	630	720	770	780	1200
Be ppm	2	2	2	2	2	2	2
Bi ppm	<10	< 10	< 10	< 10	< 10	< 10	< 10
Cd ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ce ppm	78	86	76	83	88	86	80
Co ppm	11	22	28	17	20	20	12
Cr ppm	34	38	41	26	39	31	16
Cu ppm	72	11	34	24	35	23	1
Eu ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ga ppm	17	14	12	16	18	18	17
Ho ppm	< 4	< 4	< 4	< 4	< 4	< 4	< 4
La ppm	46	49	43	48	49	49	44
Li ppm	27	31	42	35	31	33	13
Mn ppm	770	720	550	380	650	720	550
Mo ppm	< 2	< 2	< 2	< 2	4	< 2	< 2
Nb ppm	14	21	22	16	15	17	17
Nd ppm	38	37	39	35	43	40	46
Ni ppm	11	13	13	9	16	13	6
Pb ppm	28	24	25	16	17	12	14
Sc ppm	9	9	8	7	13	12	9
Sn ppm	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Sr ppm	690	450	400	370	440	470	580
Ta ppm	< 40	< 40	< 40	< 40	< 40	< 40	< 40
Th ppm	15	28	26	35	25	27	12
U ppm	< 100	< 100	< 100	< 100	< 100	< 100	< 100
V ppm	70	80	71	59	120	110	61
Y ppm	16	20	17	17	25	21	22
Yb ppm	2	2	2	2	3	2	2
Zn ppm	90	62	58	40	62	54	43

Table 1--continuation

	FMT020	FMT021	FMT022	FB031	FMT032	FMT034	FB035	FMT036
Lat., deg.	46.243	46.2966	46.2969	46.3655	46.3222	46.3303	46.3106	46.3139
Long., deg.	112.242	112.2466	112.2471	112.3533	112.2425	112.2352	112.275	112.2239
Rock Type	batholith intrusive	porphyritic intrusive	batholith intrusive	Elkhorn volcanic	batholith intrusive	batholith intrusive	Elkhorn volcanic	Elkhorn volcanic
Al %	8.5	8.3	8.7	8.6	8.7	8.9	9.8	9.4
Ca %	2.6	2	3	3.2	3.1	3.1	3.6	3.5
Fe %	3.1	1.9	3.7	3.5	4	4.3	3.4	4.0
K %	3.7	2.9	3.4	2.7	3.5	3.6	2.8	3
Mg %	1	1.5	1.4	1.2	1.5	1.6	0.9	1.2
Na %	2.4	2.4	2.2	2	2.1	2.1	2.9	2.3
P %	0.07	0.05	0.08	0.09	0.09	0.09	0.09	0.11
Ti %	0.32	0.24	0.36	0.41	0.41	0.38	0.43	0.42
Ag ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
As ppm	< 10	< 10	15	16	< 10	< 10	< 10	11
Au ppm	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8
Ba ppm	1100	1200	850	1100	820	850	1200	1200
Be ppm	2	2	2	1	2	1	1	2
Bi ppm	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Cd ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ce ppm	65	39	71	67	63	76	60	70
Co ppm	11	12	18	13	24	17	15	14
Cr ppm	39	47	40	27	28	40	16	28
Cu ppm	36	18	53	17	36	33	2	3
Eu ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ga ppm	20	21	19	23	24	18	19	20
Ho ppm	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4
La ppm	39	24	41	39	37	46	35	42
Li ppm	20	54	31	22	27	24	26	19
Mn ppm	660	390	690	860	740	780	760	850
Mo ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Nb ppm	20	15	22	22	22	21	23	22
Nd ppm	33	20	36	35	34	38	34	37
Ni ppm	11	22	15	6	14	14	4	6
Pb ppm	18	22	34	16	18	20	12	14
Sc ppm	11	6	12	12	13	14	10	12
Sn ppm	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Sr ppm	530	370	540	670	480	470	760	600
Ta ppm	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40
Th ppm	22	7	21	9	20	24	9	11
U ppm	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100
V ppm	89	41	110	100	120	130	86	100
Y ppm	17	8	21	22	21	23	20	25
Yb ppm	2	< 1	2	2	2	2	2	3
Zn ppm	67	66	88	100	73	74	73	73

X-ray diffraction studies show that orthoclase, intermediate plagioclase (andesine to oligoclase), and quartz are the major minerals in the intrusive rocks. Ruppel (1963) reported that plagioclase ranges in composition from An<sub>25</sub> to An<sub>50</sub> and averages about An<sub>40</sub>. Biotite and amphibole (tremolite) together range in concentrations from five to 15 percent (Ruppel, 1963). Heavy mineral concentrates obtained by mechanical panning (English and others, 1987) revealed minor or trace amounts of magnetite, chlorite (clinochlore), apatite, and zircon, in addition to biotite and tremolite. Heavy mineral concentrates obtained from five grams of the < 0.090 mm fraction revealed one to four pyrite grains in nine of the 15 samples, but this amounts to less than about one part per million (ppm). The sample containing four grains of pyrite was a porphyritic dike (FMT021, table 1) which has the most abundant calcite. Therefore, the acid-generating potential of the intrusive rocks, based on pyrite content, is minimal.

All of the 15 bedrock samples were initially tested or retested for acid-neutralizing potential using filtered (0.45 µm) acidic leachates of initial pH = 2.90 obtained by leaching of metal mine-related wastes from this area that were studied by Desborough and Fey (1997). One gram of the <0.090 mm fraction of each of the 15 samples of bedrock was exposed to 20 ml of the leachate for 24 hours. The initial and final pH of each of these tests are listed in Table 2, along with the measured weight losses of the solids after exposure to the leachate. The final pH of the leachate for the 11 intrusive rocks of the Boulder batholith listed in Table 2 averaged 6.7 (from initial pH of 2.90). The final pH of the leachate for four samples of Elkhorn volcanic rocks averaged 7.0 (table 2). Thus the igneous bedrock of the area has a high acid-neutralizing potential. This is partly because small amounts of calcite are present in most, or all, of the fresh bedrock samples of the Boulder batholith in the study area, based on our alizarin-red chemical stain tests of large sawed rock slabs. Prior petrographic studies of many samples of these rocks by others (Ruppel, 1963) did not report calcite, or any other carbonates. Preliminary studies show that biotite, and perhaps tremolite, and chlorite may contribute significantly to the acid neutralizing potential of these rocks. This aspect is examined later in this report.



**Table 2.** Acid neutralizing potential of fresh crystalline rocks determined by exposing one gram of a <0.090 mm fraction of each to 20 ml of acidic (pH = 2.90) mine waste leachate for 24 hours. Weight losses of solids are also given.

Sample No.	final pH 24 hr.	weight loss, percent
<b>Intrusive rocks of the Boulder batholith</b>		
FB007B1	5.22	0.9
FB007B2	4.30	1.1
FB007B3	7.07	1.6
FB010	7.45	1.3
FMT011	7.53	1.2
FB013	4.42	1.1
FMT020	7.70	4.5
FMT021	7.88	7.1
FMT022	6.83	5.4
FMT032	7.76	4.7
FMT034	7.72	4.3
<b>Elkhorn Mountain volcanic rocks</b>		
FMT012	5.32	1.9
FB031	7.75	5.0
FB035	7.73	4.5
FMT036	7.23	4.3

## HYDROTHERMALLY ALTERED ELKHORN VOLCANICS AT JACK MOUNTAIN

Rocks along the access road to the fire tower and radio transmission towers in the southeast ¼ of sec. 24, and the northeast ¼ of sec. 25 , T 7 N, R 5 W were examined and sampled. Sample localities are shown as JM samples on Figure 1. The altered area is at least one km long and 0.3 km wide, but has not yet been mapped in detail. These rocks were mapped as Elkhorn volcanics by Ruppel (1963). Although protolith for these rocks was Elkhorn volcanic rocks, based on sparse fragments of fresh material in the area, they have been intensely fractured and silicified. The chemical composition of several samples of these altered rocks are given in Table 3 which shows that they have anomalous concentrations of molybdenum, and most of the major cations (e.g. Na, Mg, Ca) and Fe of the fresh or unaltered Elkhorn volcanic rocks, have been depleted (compare with table1). The SiO<sub>2</sub> concentrations average more than 80 weight percent for the seven samples analyzed. X-ray diffraction data show that quartz, a white mica, and

pyrophyllite, are the dominant minerals in these samples, and andalusite is present in three of the seven samples. Heavy mineral concentrates show that magnetite, and many primary minerals present in unaltered Elkhorn volcanic rocks have been removed by the alteration. Molds or casts of pyrite cubes remain in these altered rocks which shows that minor sulfide mineralization was associated with the alteration. Because of the destruction of magnetite by the hydrothermal solutions, geophysical magnetic data might reveal the areal extent of the alteration because the magnetic response of these rocks should be minimal. The chemical, mineralogical, and physical characteristics of this extensively altered area indicates passage of high temperature, acid-rich solutions that might be associated with a Cu and or Mo porphyry system or acid-epithermal system that may lie under the hydrothermally altered area. The acid-neutralizing potential of these samples is minimal as seen in the test data in Table 4. The resistance to weathering caused by extensive silicification of the volcanic rocks at Jack Mountain is the primary reason that it forms one of the most prominent peaks in the study area. The closely spaced fractures in the altered rock and the low acid-neutralizing potential of these rocks (table 4) indicate that they would not be suitable for a mine-waste repository site due to their very high permeability and their minimal acid-neutralizing potential. Other areas of unaltered bedrock may be more suitable for metal-mining related waste repository sites.

**Table 3.** Concentrations of selected elements in seven altered Elkhorn volcanic rocks from Jack Mountain in the Basin and Cataract Creek drainages, northern Jefferson County, Montana. Determined by induction coupled plasma-atomic emission Spectroscopy.

	JM023A	JM023B	JM024A	JM024B	JM024C	JM024D	JM025
Lat., deg.	46.3449	46.3449	46.3405	46.3405	46.3405	46.3405	46.3397
Long.,deg	112.284	112.284	112.2894	112.2894	112.2894	112.2894	112.2897
Rock Type	silicified volcanic	silicified volcanic	silicified volcanic	silicified volcanic	silicified volcanic	silicified volcanic	silicified volcanic
Al %	5.7	5.6	6.5	6.6	6.9	7.3	7.1
Ca %	0.01	0.01	< 0.005	< 0.005	< 0.005	0.006	0.01
Fe %	1.2	1.9	1.4	1.2	1.2	1.3	0.82
K %	0.54	0.74	2.6	2.6	2.8	3	3.3
Mg %	0.01	0.02	0.12	0.12	0.14	0.08	0.62
Na %	0.06	0.06	0.06	0.06	0.06	0.06	0.05
P %	0.03	0.04	0.02	0.02	0.02	0.01	0.01
Ti %	0.06	0.05	0.08	0.08	0.09	0.09	0.1
Ag ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2
As ppm	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Au ppm	< 8	< 8	< 8	< 8	< 8	< 8	< 8
Ba ppm	2200	840	390	420	440	1600	1500
Be ppm	< 1	< 1	< 1	< 1	< 1	< 1	3
Bi ppm	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Cd ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ce ppm	45	130	81	53	63	71	86
Co ppm	11	< 1	4	2	13	2	2
Cr ppm	4	5	5	10	7	4	4
Cu ppm	6	7	9	10	7	5	9
Eu ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ga ppm	6	8	9	9	10	9	13
Ho ppm	< 4	< 4	< 4	< 4	< 4	< 4	< 4
La ppm	32	88	50	39	43	43	50
Li ppm	2	2	5	6	5	2	12
Mn ppm	13	64	38	50	48	34	87
Mo ppm	4	5	6	26	8	2	< 2
Nb ppm	12	11	18	15	18	20	16
Nd ppm	15	47	35	21	28	26	39
Ni ppm	< 2	< 2	< 2	2	< 2	< 2	3
Pb ppm	12	16	14	17	15	< 4	58
Sc ppm	< 2	2	5	6	6	4	4
Sn ppm	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Sr ppm	56	120	13	24	21	40	34
Ta ppm	< 40	< 40	< 40	< 40	< 40	< 40	< 40
Th ppm	13	28	16	12	11	13	16
U ppm	< 100	< 100	< 100	< 100	< 100	< 100	< 100
V ppm	11	20	15	17	16	13	13
Y ppm	3	6	22	5	11	6	15
Yb ppm	< 1	< 1	2	< 1	1	< 1	2
Zn ppm	6	8	21	31	29	14	41

**Table 4.** Acid-neutralizing potential of altered Elkhorn volcanic rocks at Jack Mountain determined by exposing one gram of a <0.090 mm fraction of each to 20 ml of acidic (pH = 2.90) mine waste leachate or 24 hours. Weight losses of solids are also given.

Sample No.	final pH 24 hr.	weight loss, percent
JM023A	3.59	4.2
JM023B	3.67	4.6
JM024A	3.85	4.2
JM024B	4.08	4.4
JM024C	3.97	4.2
JM024D	3.93	4.6
JM025	4.18	4.2

### GEOCHEMISTRY OF SOILS

Soil sample sites are shown on Figure 2. The chemical compositions of 13 soil samples are given in Table 5. The minimal, but significant acid-neutralizing potential of the < 2 mm fraction of the soils are given in Table 6. The low acid-neutralizing potential of the soils chiefly reflects the influence of the gymnosperm forest which yields litter that results in acidic soil conditions. Eight soil samples were taken adjacent to bedrock sample sites (Figs. 1 and 2). Four soil samples (SB026-SB029) were taken along the margin of, but 3-10 m above, the unnamed stream that drains the mine waste deposits of the Bullion mine area. These four samples have an average of 24 ppm of As, which is about twice that of the four soil samples (SB007, SB010, SMT011, and SMT036) taken at sites remote from mining activity. Soil sample SB030, taken about 3 m above the present stream level and above overbank deposits of Basin Creek, has the highest As concentration (48 ppm). This sample is downstream from the Buckeye/Enterprise mine and associated waste. This sample was taken to evaluate pre-historic, or natural metal contributions to the soils. These five anomalous As concentrations in soils downstream from the largest mine waste piles in the area are believed to show that the anomalous amounts of As probably accumulated prior to historic mining activity.

Arsenic is the only trace element analyzed that is present in anomalous concentrations in the soil samples (table 5). It averages about 20 ppm for all samples. Kabata-Pendias and Pendias (1984, table 107) give the highest mean concentration for As in U.S. soils as about 8-9 ppm for "dark prairie soils" and "alluvial soils", whereas "soils over granites and gneisses" average 3.6 ppm.

**Table 5.** Concentrations of selected elements in 13 soil samples in the Basin and Cataract Creek drainages, northern Jefferson County, Montana. Determined by Induction coupled plasma-atomic emission spectroscopy.

	SB007	SB010	SMT011	SMT012	SMT020	SMT022	SB026	SB027
Lat., deg.	46.3086	46.3314	46.2703	46.3305	46.243	46.2969	46.3542	46.3597
Long., deg.	112.3025	112.3283	112.2189	112.2094	112.242	112.2471	112.3041	112.2983
Al %	7.9	8.1	8.3	8.6	9	7.6	8.2	7.7
Ca %	1.5	2	2	1.1	1.4	1.5	1.7	1.5
Fe %	3.1	3.5	4	2.6	4	4.5	3.9	3.4
K %	3.1	3.1	3	3.1	3.4	3.3	3	3
Mg %	0.6	0.87	0.85	0.61	0.67	0.74	1	0.84
Na %	1.8	1.7	1	1.2	1.7	1.8	1.8	1.5
P %	0.07	0.06	0.1	0.11	0.06	0.04	0.08	0.08
Ti %	0.31	0.33	0.34	0.27	0.38	0.36	0.33	0.33
Ag ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
As ppm	10	< 10	11	17	23	14	26	22
Au ppm	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8
Ba ppm	960	820	620	1200	880	880	860	700
Be ppm	2	2	2	2	2	2	2	2
Bi ppm	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Cd ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ce ppm	57	61	72	60	84	70	62	63
Co ppm	8	16	22	6	17	14	13	21
Cr ppm	30	40	28	20	34	51	49	34
Cu ppm	23	21	61	20	44	29	29	37
Eu ppm	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ga ppm	15	17	17	15	17	16	16	16
Ho ppm	< 4	< 4	< 4	4	< 4	< 4	< 4	4
La ppm	31	37	42	33	48	40	38	37
Li ppm	26	22	42	21	22	24	29	31
Mn ppm	580	560	840	1100	1500	710	750	760
Mo ppm	< 2	< 2	2	< 2	< 2	< 2	< 2	< 2
Nb ppm	20	21	20	21	34	18	19	19
Nd ppm	26	29	39	27	39	31	29	29
Ni ppm	10	10	14	6	13	11	14	12
Pb ppm	31	22	27	44	81	47	37	38
Sc ppm	7	10	13	8	12	9	10	10
Sn ppm	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Sr ppm	420	360	260	300	330	340	340	300
Ta ppm	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40
Th ppm	11	17	24	12	26	15	20	15
U ppm	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100
V ppm	81	110	120	62	110	150	110	100
Y ppm	11	16	22	14	23	15	15	18
Yb ppm	1	2	2	2	2	2	2	2
Zn ppm	110	68	95	88	140	120	84	100

Table 5--continuation

	SB028	SB029	SB030	SMT033	SMT036
Lat., deg.	46.3628	46.3644	46.3975	46.3239	46.3139
Long., deg.	112.308	112.3081	112.3033	112.2366	112.2239
Al %	7.5	7.1	7.6	7.2	7.9
Ca %	0.91	1.1	0.67	1.2	1.2
Fe %	3.8	2.9	2.6	3.8	3.3
K %	3	3	2.8	3.6	2.8
Mg %	0.5	0.66	0.42	0.5	0.73
Na %	1.3	1.3	1.4	1.8	1.3
P %	0.07	0.08	0.08	0.06	0.15
Ti %	0.28	0.28	0.24	0.27	0.32
Ag ppm	< 2	< 2	< 2	< 2	< 2
As ppm	24	22	48	18	19
Au ppm	< 8	< 8	< 8	< 8	< 8
Ba ppm	830	770	810	930	1100
Be ppm	1	2	2	1	2
Bi ppm	< 10	< 10	< 10	< 10	< 10
Cd ppm	< 2	< 2	< 2	< 2	< 2
Ce ppm	57	60	51	53	70
Co ppm	12	9	15	8	11
Cr ppm	38	29	35	32	28
Cu ppm	21	21	28	17	31
Eu ppm	< 2	< 2	< 2	< 2	< 2
Ga ppm	13	14	14	13	20
Ho ppm	< 4	< 4	< 4	< 4	< 4
La ppm	36	36	31	32	39
Li ppm	23	23	32	20	23
Mn ppm	350	390	800	700	1500
Mo ppm	< 2	< 2	< 2	< 2	< 2
Nb ppm	16	17	25	18	19
Nd ppm	26	29	23	24	32
Ni ppm	11	9	11	8	7
Pb ppm	31	32	61	55	28
Sc ppm	7	8	6	6	10
Sn ppm	< 5	< 5	< 5	< 5	< 5
Sr ppm	280	280	250	350	330
Ta ppm	< 40	< 40	< 40	< 40	< 40
Th ppm	10	14	17	10	8
U ppm	< 100	< 100	< 100	< 100	< 100
V ppm	120	97	69	120	89
Y ppm	10	13	13	11	18
Yb ppm	1	2	1	1	2
Zn ppm	61	65	120	140	130

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**Table 6.** Acid neutralizing potential of soils determined by exposing 5 g of < 2.0mm fraction of each to 100 ml of acidic (pH=2.90) mine waste leachate for 24 hours. Weight losses of solids are also given.

Sample No.	final pH 24 h.	weight loss, percent
SB007	3.92	0.4
SB010	3.62	0.2
SMT011	7.14	0.7
SMT012	4.62	1.0
SMT020	4.80	0.2
SMT022	3.70	0.4
SB026	3.87	0.3
SB027	3.95	0.6
SB028	3.83	0.7
SB029	3.63	0.2
SB030	4.01	0.1
SMT033	3.40	0.1
SMT036	4.13	0.3

### **CARBONATE CONTENT OF FRESH ROCKS AND THEIR ACID-NEUTRALIZING POTENTIAL**

In order to better understand the acid-neutralizing potential of the fresh rocks in the study area, they were quantitatively analyzed for total carbon using a coulometer. These values of total carbon were used to calculate the weight percent of calcite, assuming that all of the carbon is present in calcite. An additional test was done to examine the results of a longer leaching period than the previous 24 hour test (table 2). One gram of each pulverized (90 % <0.050 mm) rock sample was exposed to 70 ml of Boulder mine-waste leachate of pH = 2.90 for 72 hours at rest. Table 7 gives the final leachate pH values, the weight losses of solids, and the weight percent of calcite calculated from the total carbon content of each sample. Figure 3 is a plot of final leachate pH versus the weight percent of calcite calculated from total carbon values. Regression analysis gives an R<sup>2</sup> value of 74 percent for the data, and a y-intercept value (pH) of 4.29 with a standard error of 0.25. The mean final pH value for all samples is 5.5; the mean calculated calcite content of fresh rocks is 0.5 weight percent, or 10 pounds of calcite per short ton of rock. However, there is a ten-fold range in calcite concentrations (0.13-1.56 wt. %), based on total carbon analysis. Values for CO<sub>2</sub> given by Ruppel (1963, table 3) for seven samples of similar rocks in the area correspond to calcite concentrations of <0.1 to 1.8, and average 0.6 weight percent. Calculation based on values of CO<sub>2</sub> given by Rutland and others (1989, table 1) for similar rocks in the area yield estimates of calcite concentrations as high as four weight percent.

The data given in Table 7 and Figure 3 for calcite concentrations less than about 0.4 weight percent are interpreted to indicate that a mineral, or minerals other than calcite cause some of the acid-neutralizing potential reported here because concentrations of 0.4

weight percent calcite can only neutralize about 40 ml of acidic solution of pH of 3.0. Kwong and Ferguson (1997) have reported that biotite, hornblende, and chlorite in igneous rocks have significant long-term acid-neutralizing potential. The influence of these minerals on the pH of acidic solutions is under current examination for igneous rocks in this study area, and the preliminary results show that biotite, chlorite, and amphibole concentrates have significant acid-neutralizing potential, using the acidic (pH = 2.90-3.0) leachates of the Boulder-area mine wastes.

**Table 7.** Acid-neutralizing potential of fresh crystalline rocks determined by exposing one gram of a <0.090 mm fraction of each to 70 ml of acidic (pH = 2.90) mine waste leachate for 72 hours. Calcite concentrations are given basen on total carbon concentrations. Weight losses to the leachate are listed

Sample No.	final pH 72 hr.	weight loss, percent	calcite, wt. percent (calculated)
FB007B1	4.76	2.2	0.49
FB007B2	4.45	0.8	0.16
FB007B3	5.67	2.9	0.64
FB010	5.05	1.5	0.43
FMT011	5.15	2.5	0.54
FMT012	4.80	1.7	0.37
FMT013	4.24	0.2	0.16
FMT020	7.07	1.5	1.05
FMT021	7.45	2.0	1.56
FMT022	4.52	1.3	0.13
FB031	6.96	3.8	0.59
FMT032	6.68	3.3	1.04
FMT034	5.46	3.4	0.33
FB035	5.59	5.7	0.21
FMT036	4.79	2.7	0.40

## SUMMARY

The data presented here show that the fresh bedrock of the Boulder batholith have a significant acid-neutralizing potential which is partly due to the presence of small amounts of calcite. However, it appears that minerals such as biotite, hornblende, and chlorite also contribute to their acid-neutralizing potential. These factors may be significant in considering the fresh batholith rocks for a mine-waste repository site.

The abundances of major, minor, and trace elements in the rocks of the Boulder batholith are similar to average grantoid rocks elsewhere with the exception of a few anomalous, but low concentrations of arsenic.

The intensely silicified and fractured Elkhorn volcanic rocks of Jack Mountain have anomalous amounts of molybdenum and their character resembles assemblages found high above a large mineralized porphyry system and/or epithermal Au system. The acid-



neutralizing potential of the altered rocks of Jack Mountain is low because of the strong hydrothermal leaching that resulted in the alteration.

Soil samples in the area are normal with regard to concentrations of most elements, but anomalous amounts of arsenic are present in those adjacent to drainages in which there is significant lead, zinc, and arsenic mineralization in bedrock in the Basin Creek headwaters. Most soil samples have a low acid-neutralizing potential because the gymnosperm forest litter causes them to be naturally acidic.

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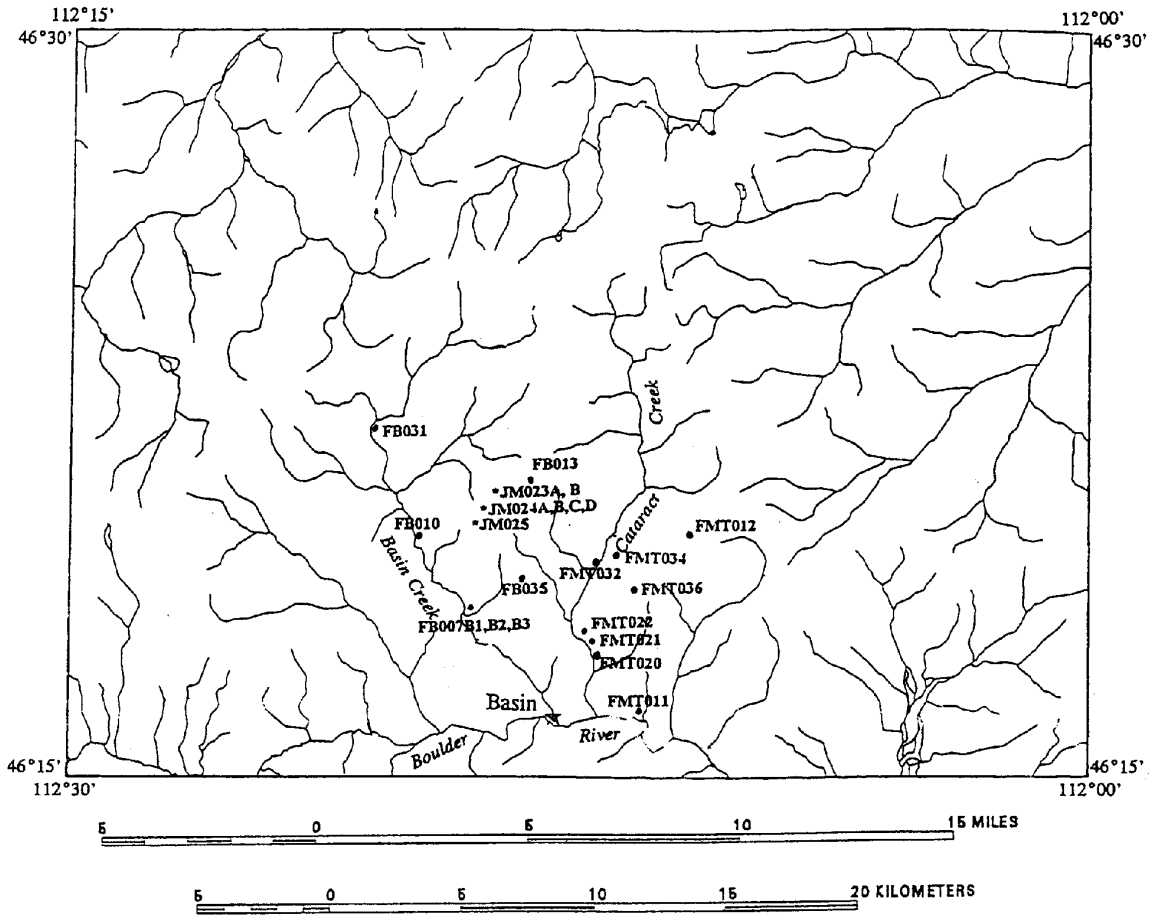


Figure 1. Map showing the locations of fresh rocks (F) and altered rocks of Jack Mountain (JM) in the Basin and Cataract Creek drainages of northern Jefferson County, Montana.

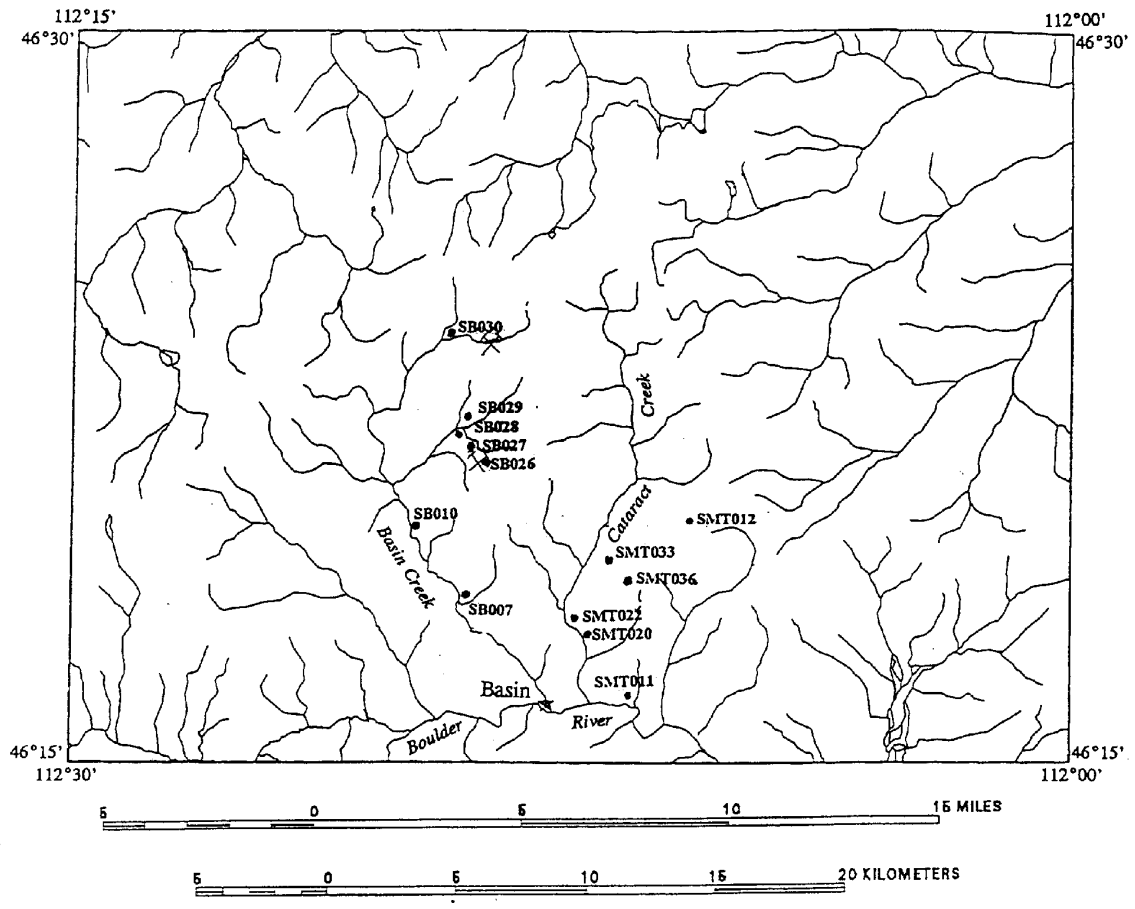


Figure 2. Map showing the locations of soil samples in the Basin and Cataract Creek drainages of northern Jefferson County, Montana.

Calcite content of fresh rocks vs. final pH of acidic (pH=2.90) Boulder leachate after 72 hours exposure to pulverized (90% <0.050mm) fresh rock samples, 1 g rock in 70 ml leachate

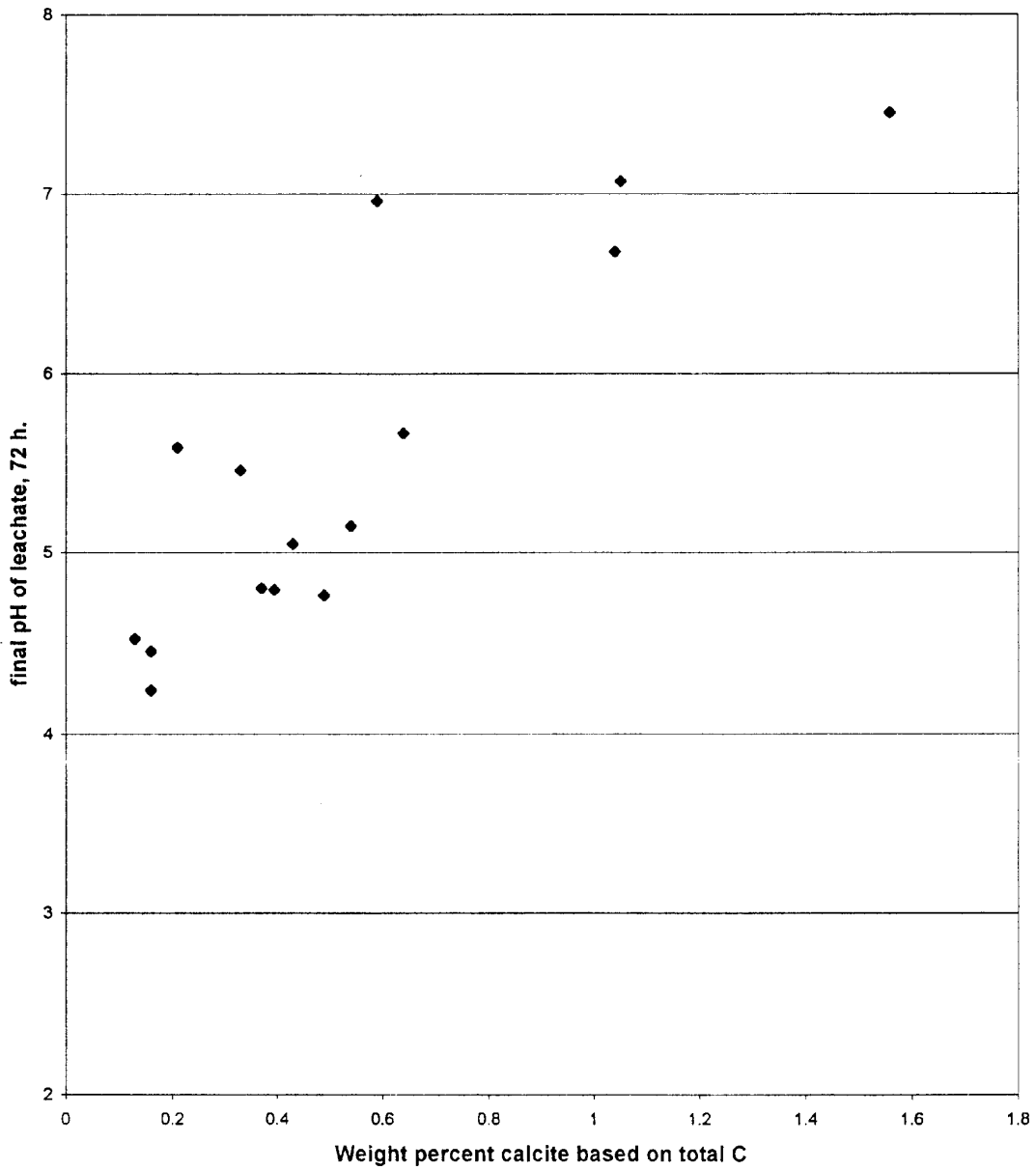


Figure 3. Relations of concentrations of calcite in fresh Boulder batholith rocks to the final pH of acidic Boulder mine-waste leachates after a 72 hour exposure.