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**ACID-NEUTRALIZING POTENTIAL OF MINERALS IN
INTRUSIVE ROCKS OF THE BOULDER BATHOLITH IN
NORTHERN JEFFERSON COUNTY, MONTANA**

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ABSTRACT

Experimental studies show that fresh granitic rocks of the Boulder batholith in the Boulder River headwaters near Basin, Montana have significant acid-neutralizing potential and are capable of neutralizing acidic water derived from metal-mining related wastes or mine workings. Laboratory studies show that in addition to the acid-neutralizing potential (ANP) of minor amounts of calcite in these rocks, biotite, tremolite, and feldspars will contribute significantly to long-term ANP.

We produced 0.45 micrometer-filtered acidic (pH = 2.95) leachate for use in these ANP experiments by exposing metal-mining related wastes to deionized water in a waste:leachate ratio of 1:20. We then exposed these leachates to finely-ground and sized fractions of batholith rocks, and some of their mineral fractions for extended and repeated periods, for which results are reported here. The intent was to understand what reactions of metal-rich acidic water and fresh igneous rocks would produce.

The reactions between the acidic leachates and the bulk rocks and mineral fractions are complex. Factors such as precipitation of phases like Fe-hydroxides and Al-hydroxides and the balance between dissolved cations and anions that are sulfate dominated complicate analysis of the results. Research by others of acid neutralization by biotite and tremolite attributed a rise in pH to proton (H^+) adsorption in sites vacated by K, Mg, and Ca. Destruction of the silicate framework and liberation of associated structural hydroxyl ions may contribute to ANP. Studies by others have indicated that the conversion of biotite to a vermiculite-type structure by removal of K at a pH of 4 consumes about six protons for every mole of biotite, but at a pH of 3 there is pronounced dissolution of the tetrahedral lattice.

The ANP of fresh granitic rocks is much higher than anticipated. The three bulk Boulder igneous rock samples studied have minimum ANP equivalent to about 10-14 weight percent calcite. This ANP is in addition to that provided by the 0.36-1.4 weight percent calcite present in these samples. The total rock ANP is thus equivalent to that of many sedimentary rocks that are generally believed to be among the most efficient for attenuation of acidic waters.

The long-term ANP contributed by biotite, tremolite, feldspars, and possibly unidentified minerals in these rocks, as well as calcite, are all important with regard to their natural remediation of degraded water quality originating from Fe-sulfide rich mineral deposits and the associated mine wastes and acid-mine drainage water.

INTRODUCTION

This study is an examination of the acid-neutralizing potential of Boulder batholith rocks and their mineral constituents in an abandoned-mine lands study area in the Basin and Cataract Creek drainages that are Boulder River headwaters in northern Jefferson County, Montana. Exploration and mining during the last century sought production of Au, Ag, Pb, and Zn from pyrite-rich quartz veins that penetrate granitic rocks (quartz monzonites and granodiorites) of the Boulder batholith (Ruppel, 1963). Wastes from metal exploration and mining activities in the area aggregate more than 100,000 tons

(Metesh and others, 1994; Metesh and others, 1995, and Marvin and others, 1996). Several of these waste piles were sampled and exposed to deionized water in USGS laboratories to determine their acid-generating capacities and the amounts of dissolved potentially toxic metals such as Fe, Cu, Zn, As, Cd, and Pb (Desborough and Fey, 1997). The pH of most of the mine waste leachates was about 3, and the associated dissolved metal concentrations were sufficiently high to indicate potential water quality degradation.

In the fall of 1996, and subsequently, Nimick and Cleasby (1998) measured the pH and dissolved metals in the drainage waters downstream from the waste piles and found that pH values for these waters were about 6 or greater; the amounts of dissolved metals such as Fe, Cu, Zn, As, Cd, and Pb were relatively low. One can infer from their data that either natural leaching of mine wastes is not significant, or the acidic leachates from the mine wastes are neutralized by rock, soil, alluvium, or water.

Although the acid-neutralizing potential of the soils is relatively low because of the gymnosperm forest litter, the acid-neutralizing potential of the granitic rocks is significant. Studies by Desborough and Fey (1997) found small but significant amounts of calcite in the fresh granitic rocks. Because we detected small amounts of calcite using alizarin-red stain tests (Dickson, 1965) on 5 X 10 cm sawed rock slabs, we initially thought calcite was entirely responsible for the acid-neutralizing potential of these rocks. Quantitative analyses of total carbon done subsequently on 15 fresh bedrock samples were computed to calcite concentrations. Tests of acid-neutralizing potential versus calculated calcite concentrations showed that for samples with the lowest calcite concentrations of about 0.1 to 0.4 weight percent, calcium carbonate alone could not account for the acid neutralization or consumption that was measured in the laboratory (Desborough and others, 1998). In general, we find that for <0.044 mm mean diameter (<325 mesh sieve size) high purity limestone, one gram of the limestone will nearly neutralize (to pH of 5 to 6) about 10,000 grams of acidic sulfate leachate with an initial pH of about 3.00. Thus one of the Batholith rock samples with a computed concentration of 0.21 weight percent calcite, should only nearly neutralize about 21 ml of acidic solution of pH of about 3.0—not 70 ml as measured by Desborough and others (1998, table 7).

Numerous studies of the reaction of igneous rock-forming minerals with low pH solutions have been done. Virtually all of them have used high-purity natural minerals and ultra-pure, unsaturated dilute acidic solutions of HCl or H₂SO₄ for the purpose of determining kinetic factors and the chemical reactions involved. Most relevant to the present study are the prior studies of Schott and others (1981) who studied iron-free pyroxene and amphibole, Mast and Drever (1987) who studied oligoclase and tremolite, and Acker and Bricker (1992) who studied biotite. All of these studies used agitation (stirring) or fluid flow (column, or flow-through reactor). All of the minerals partially dissolved incongruently, and the greatest dissolution rates were at the lowest pH conditions. We know of no prior studies that used igneous bulk rock samples and their respective mineral constituents for exposure to metal-laden and sulfate-rich acidic leachates. The recent study of Kwong and Furgeson (1997) examined the neutralizing potential of both rock and tailing samples but they used an HCl solution of pH = 1.0. This is inappropriate to simulate the metal-mine waste leachate in the Boulder River

headwaters and most metal-mining districts in the Western U.S. that are sulfate-rich and have a pH greater than about 2.5.

SAMPLE PREPARATION

Three fresh rock samples (FMT020, FMT022, and FMT032) were studied. These samples were chosen to represent the range in typical granitic rock samples in the study area (Desborough and others, 1998). About 30 grams of sized (0.106-0.140 mm) bulk rock was split into two fractions. One split represents the bulk rock; the other fraction was treated to separate the minerals. The first separation using heavy liquid (diluted methylene iodide, Sp. G. = 2.80) produced a quartz and feldspar concentrate and a concentrate of minerals with densities greater than Sp. G. = 2.80. Magnetite was removed from the high density minerals using a magnet. The remaining high density minerals were separated with a Franz isodynamic magnetic separator which produced concentrates of mostly biotite, mostly tremolite, tremolite and chlorite, and tremolite and biotite. Each of the five fractions was weighed to determine the weight percent of each concentrate, as shown in Table 1. After these separations, each of the bulk rock and mineral fractions were pulverized with an alumina mill and sized with stainless steel sieves to obtain a <0.044 mm fraction. Each of these mineral fractions was analyzed by X-ray diffractometer to identify major minerals and to determine the approximate mineral proportions in each fraction (table 1). Each bulk rock fraction and each mineral fraction was split using a microsplitter; one split was untreated and part of it was used for total C analysis. The other fraction was used in the first series of tests of ANP. The amounts of calcite, based on analysis of total carbon, for the three bulk rock fractions range from 0.36 to 1.40 weight percent (table 1).

Table 1. Percentages by weight of mineral fractions in the three bulk rock samples tested for acid-neutralizing potential in Table 1. Calcite concentrations were calculated from total carbon analysis of the bulk rock fraction. Other percentages determined by weighing each fraction; thus totals exceed 100 percent. For mixtures of two minerals, such as biotite and chlorite, etc. the weight percent of each is estimated from X-ray diffractometer scans.

Rock sample	FMT020	FMT022	FMT032
Mineral fractions	-----weight percent-----		
Calcite	1.40	0.36	0.95
Quartz and feldspars	91.0	80.0	80.0
Biotite 60%, chlorite 40%	0.9	biotite 8.6	biotite 3.2
Tremolite 60%, chlorite 40%	3.4	tremolite 7.9	tremolite 60%, biotite 40% 9.8
Chlorite	0.9	0	tremolite 50%, biotite 50% 3.4
Magnetite	3.9	3.8	3.1

FIRST TESTS OF THREE BULK ROCKS AND THEIR MINERAL FRACTIONS

Our tests utilized sulfate-rich acidic leachates generated by exposing 100 grams of <2.0 mm mine waste to 2 L of deionized water, at rest, for 24 hours. These mine wastes from the Boulder study area were described by Desborough and Fey (1997). These leachates were Fe-saturated and had precipitated iron hydroxides that were removed with 0.45 micrometer filters. The pH of the filtered leachate we used for the first tests was 2.95. This leachate, to which fresh rock and mineral fractions were exposed is called the *original* leachate.

For the bulk rock fractions, 1 gram of material was exposed to 100 ml of *original* leachate; for the separated mineral fractions, 0.5 grams of each fraction was exposed to 50 ml of *original* leachate. Thus the ratio of solids:*original* leachate was 1:100 for all four tests.

Each of four exposures of rock or mineral fractions to *original* leachate ranged from about 93 to 98 hours for each exposure. The pH measurements for all of the samples were done side-by-side within about five minutes for each set of four or five samples (table 2). After termination of each of the first two sets of tests, the leachates of each sample were filtered (0.45 micrometer), acidified, and refrigerated prior to leachate analysis by inductive coupled plasma (ICP)-atomic emission spectroscopy (AES) using an Optima 3000 instrument. The initial composition of the *original* leachate was also determined by ICP/AES methods for comparison with the leachates after exposure to bulk rocks or mineral concentrates.

Table 2 gives the results for the final leachate pH values for each of four exposures of bulk rock and the separate mineral concentrates to the *original* leachate of initial pH of 2.95. The pH data given in Table 2 show that the ANP of bulk rock and quartz and feldspar fractions for all three samples are nearly depleted after the second tests. However, the other minerals continued to react and significantly increase pH in the solutions during the third and fourth tests. It is clear from the data shown in Table 2 that biotite and tremolite in Boulder Batholith rocks have substantial ANP when exposed to acidic leachates.

Table 2. Acid-neutralizing potential of three Boulder batholith bulk rocks and mineral fractions exposed to *original* leachate of pH = 2.95. Ratios of solid:leachate were 1:100. Solids were <0.044 mm and each exposure period was 93-98 hours. Fresh *original* leachate was used for each test. Values are the pH at the end of each exposure of each solid to the *original* leachate.

Test	bulk rock	FMT020			
		quartz and feldspar	biotite 1. & chlorite	tremolite & chlorite	
First	7.34	3.85	7.59	7.83	
Second	3.99	3.10	6.24	6.22	
Third	3.03	2.95	5.01	4.48	
Fourth	3.03	2.97	4.49	4.04	
FMT022					
			biotite	tremolite	
First	4.40	4.16	6.50	6.35	
Second	3.46	3.52	4.78	4.19	
Third	3.11	3.20	4.39	3.81	
Fourth	2.98	3.00	4.00	3.26	
FMT032					
			biotite	tremolite & biotite	tremolite & biotite
First	5.95	4.25	6.25	7.72	7.83
Second	4.12	3.72	4.61	5.28	5.94
Third	3.55	3.30	4.11	4.32	4.50
Fourth	3.15	3.09	3.88	4.04	4.09

The estimated ANP of the bulk rock and mineral fractions, based on final pH values of each of four serial tests are given in Table 3. These data are also given in terms of H⁺ removal, capture, or neutralization, and efficiency of ANP, in percent, based on the amounts of H⁺ removed from all the leachates divided by the amounts of H⁺ initially present. These data are presented in this manner to facilitate understanding of the relative acid-neutralization process. It is clear from the data given in Table 3 that the biotites and tremolites and their mixtures have acid-neutralizing potential (on a weight basis) that significantly exceed those of both the bulk rock and the quartz and feldspar fractions.

Table 3 Estimated acid-neutralizing potential (ANP) of bulk rock and mineral fractions based on final pH values of each serial leachate test shown in Table 1. Bold values are computed to moles/L of H⁺ removed from leachate per gram of sample. Total moles/L of H⁺ in all four leachates is 4.8 X 10⁻⁴. ANP values in brackets [---] are= moles/L H⁺ / 4.8 X 10⁻⁴ and are given to reflect comparative acid-neutralizing efficiencies of the samples.

Moles/L of H ⁺ X 10 ⁻⁴ removed or neutralized per gram						
FMT020						
	bulk rock 2.75	quartz and feldspars 1.43	biotite and chlorite 4.75	tremolite and chlorite 4.67		
ANP	[57 %]	[30 %]	[99 %]	[97 %]		
FMT022						
	2.34	2.66	biotite 4.63	tremolite 3.91		
ANP	[49 %]	[55 %]	[96 %]	[81 %]		
FMT032						
	3.61	3.04	biotite 4.54	tremolite and biotite 4.64	tremolite and biotite 4.67	
ANP	[75 %]	[63 %]	[94 %]	[97 %]	[97 %]	

Table 4 gives the concentrations of major ions in the *original* leachate and the concentrations of major ions gained or lost by the first two leaches of each fraction. The negative values for Fe and Al probably reflect precipitation of Fe(OH) and Al phases, or adsorption, due largely to the high final pH of the leachates. The greatest amounts of Ca in the leachates for both the first and second leaches are in those fractions in which tremolite is dominant. The greatest amounts of K in the leachates for both the first and second leaches are in those fractions in which biotite is dominant. High Mg content of the leachate is associated with the presence of chlorite (clinochlore) with biotite, but significant Mg increases were also detected in leachate reacted with both biotite and tremolite (table 4). The two most pure biotite fractions (FMT022 and FMT032) show, on an atomic basis, that about 1.5 times more K than Mg was present in the leachate.

We can presume that much of the dissolved Ca in the leachates (table 4) is from calcite. The amounts of calcite in each untreated split from each bulk rock and mineral fraction were determined by measuring total C using a coulometer. These values were converted to percent of calcite, assuming all of the C is present in calcite and these data are shown in Table 5. Also shown in Table 5 are the percentages of calcite calculated on the basis of dissolved Ca in the first and second leachates (table 4), assuming all of the

dissolved Ca is from calcite. It is apparent that virtually all of the calcite was consumed by the end of the second leach, except for the biotite concentrates. Inspection of the pH values given on Table 2 for the final values (pH) after the third and fourth leach reveals that the biotite and biotite and tremolite concentrates still had significant acid-neutralizing potential. For the first two leachates, plots of pH versus dissolved Ca, dissolved Mg+K, and dissolved Ca+Mg+K, respectively, were made for all of the samples. The only reasonable correlation ($R^2 = 0.84$) of dissolved cations and final leachate pH was for Ca+Mg+K (mg/L) as shown on Figure 1, which is taken to indicate that tremolite and biotite contributed significantly to acid-neutralizing potential. Unfortunately, the third and fourth leachates were not analyzed for cations.

We can calculate from the pH data for the four sequential leaches of these 13 samples of both bulk rock and mineral fractions that calcite alone (determined from total C analyses), cannot account for all of the acid-neutralization. Between about 0.4×10^{-4} and 2.5×10^{-4} moles of H^+ were neutralized that cannot be attributed to the amounts of calcite in the samples, based on calcite concentrations calculated from the total C analyses. Based on all of the data presented here, these acid-neutralizing effects must be due to interactions of the silicate fractions with the leachates.

Inspection of the values of dissolved Si in the leachates (table 4) shows that with the exception of two samples (FMT020 quartz and feldspar and FMT022 bulk rock), the second leach has significantly more Si than the first leach. This indicates that significant amounts of the silicate minerals such as biotite and tremolite were partially dissolved.

Table 4. Concentrations of major ions in *original* leachate (pH = 2.95) and concentrations of major ions gained or lost (-) by the final leachate after the first and second exposure to *original* leachates. Analysis by ICP-AES of 0.45 micrometer filtered leachates

	Al	Ca	Fe	K	Mg	Na	Si
	-----milligrams per liter-----						
<i>original</i> leachate	2.9	14	7.4	4.2	4.3	4.7	2.6
FMT020							
bulk rock							
First leach	-2.9	45	-7.4	3.9	2.7	1.7	1.3
Second leach	3.8	12	-3.8	2.7	3.0	1.8	6.3
quartz and feldspar							
First leach	4.7	16	-5.7	4.0	2.3	4.1	5.2
Second leach	5.4	6	-3.8	2.5	1.6	2.7	4.6
biotite and chlorite							
First leach	-2.8	12	-7.4	40	25	4.4	1.0
Second leach	-2.9	10	-7.4	14	22	2.2	7.4
tremolite and chlorite							
First leach	-2.8	60	-7.4	5.8	18	3.0	1.0
Second leach	-2.9	38	-7.4	3.0	11	1.4	5.6
FMT022							
bulk rock							
First leach	-0.8	15	1.2	9.9	5.1	8.4	8.4
Second leach	8.1	3.5	-7.1	4.3	2.2	1.6	6.2
quartz and feldspar							
First leach	5.8	12	-6.5	14	2.9	8.4	8.4
Second leach	12	7.5	-7.1	4.5	1.9	3.5	9.4
biotite							
First leach	-2.9	3.0	-7.4	51	17	3.3	5.8
Second leach	-1.3	10	5.6	25	14	3.0	15
tremolite							
First leach	-2.8	28	-7.4	6	18	3.2	6.3
Second leach	2.7	18	-0.8	4.4	11	3.3	13

(continued)

continuation Table 4

	Al	Ca	Fe	K	Mg	Na	Si
-----milligrams per liter-----							
FMT032							
bulk rock							
First leach	-2.9	30	-7.4	12	6.7	1.4	2.1
Second leach	3.3	6.5	-1.2	5.8	5.0	1.6	8.4
quartz and feldspar							
First leach	1.2	18	-6.3	16	4.4	7.4	7.3
Second leach	11	5.5	-7.3	4.4	1.8	2.8	9.4
biotite							
First leach	-2.9	14	-7.4	40	13	2.9	5.7
Second leach	-1.3	7.5	8.5	16	8.7	1.9	11.4
tremolite and biotite							
First leach	-2.8	44	-7.4	23	12	2.4	0.6
Second leach	-2.8	28	-6.9	10	9.7	1.4	7.4
tremolite and biotite							
First leach	-2.8	50	-7.4	24	13	3.4	<0.1
Second leach	-2.9	36	-7.4	10	11	2.0	6.5

Table 5. Concentrations of calcite in untreated bulk rock and mineral fractions based on total carbon analyses, along with the amounts of calcite calculated from the dissolved Ca in both the first and second leachates.

	% calcite from total C	% calcite calculated from dissolved Ca in both leachates
FMT020		
Bulk rock	1.40	1.42
Quartz & feldspar	0.49	0.60
Biotite & chlorite	1.12	0.54
Tremolite & chlorite	2.13	2.46
FMT022		
Bulk rock	0.36	0.47
Quartz & feldspar	0.28	0.48
Biotite	0.68	0.33
Tremolite	1.16	1.14
FMT032		
Bulk rock	0.95	0.91
Quartz and feldspar	0.38	0.58
Biotite	0.94	0.56
Tremolite & biotite	1.61	1.80
Tremolite & biotite	2.04	2.14

After the fourth leach, samples of both the leached and unleached material were examined using X-ray diffraction (diffractometer) methods for comparison of peak intensities. The most significant or perceptible changes were observed for biotites and chlorites. For leached biotites the strongest peak ($hkl = 001$) had a significantly reduced intensity and was much more broad than that of the unleached material. For chlorite, the peak intensity was significantly reduced but broadening was not observed. These results are consistent with cation removal from biotite and partial dissolution of chlorite.

SECOND TESTS OF THREE BULK ROCKS AND THEIR MINERAL FRACTIONS

Although we believed that the first tests of the three bulk rock and mineral separate splits gave convincing results that the silicate fraction contributed more acid-neutralizing potential than the calcite present in these samples, we thought that further confirmation might be done with the untreated split that was analyzed for total C. In so doing, we used 0.2 grams of the untreated split for exposure to the same solution (leachate) which, after three months at rest, had precipitated Fe-hydroxides. This leachate was filtered (0.45 micrometers) prior to exposure of the 0.2 grams of bulk rock and mineral fractions to the leachate. The pH of this leachate was 2.80 (lowered because of iron hydroxide precipitation). The exposure period was 48 hours. The ratio of solid to leachate of 1:400, was insufficient to deplete the acid-neutralizing potential of some of the fractions in the first tests. Therefore, we used a mineral or rock ratio of 1:600 (i.e. 0.2 grams in 120 ml)

in the second tests. The final (48 h.) pH values for each of these tests are given in Table 6 for each bulk rock and mineral fraction. All tests were done at rest (no agitation).

Final solution pH values at the end of the second tests are given in Table 6, which shows the much higher ANP of the biotite and tremolite fractions, relative to bulk rock and quartz-feldspar. Table 7 gives the total moles of H⁺ neutralized in the leachate, the moles of H⁺ neutralized that can be attributed to calcite (based on calculations from total C analyses), the moles of H⁺ neutralized that cannot be attributed to calcite, and the non-calcite rock or mineral ANP calculated to weight percent calcite-equivalence. Table 8 gives the concentrations of major ions and sulfate in the initial leachate and the concentrations of major ions and sulfate lost to the leachate. The significantly higher amounts of Si in the biotite and tremolite leachates is taken as evidence of partial dissolution of these minerals. An attempt was made to correlate Ca in the leachate with final pH, but there is no correlation. The only dissolved cation that shows some correlation ($R^2 = 0.84$) with final pH is Mg, as shown on Figure 2.

Table 6. Acid-neutralizing potential of three Boulder batholith bulk rocks and mineral fractions exposed to mine-waste leachates of pH = 2.80. Ratios of solid:leachate were 1:600. Solids were <0.044 mm and exposure time was 48 hours; values are final pH.

FMT020	
leachate pH after 48 hours	
Bulk rock	3.07
Quartz and feldspar	2.97
Biotite and chlorite	4.29
Tremolite and chlorite	4.09
FMT022	
Bulk rock	3.07
Quartz and feldspar	3.02
Biotite	4.05
Tremolite	3.65
FMT032	
Bulk rock	3.32
Quartz and feldspar	3.09
Biotite	4.01
Tremolite and biotite	4.10
Tremolite and biotite	4.26

Table 7. Calculated H⁺ neutralized, based on final pH, calculated H⁺ that calcite can “neutralize”, and the amount of total H⁺ removed or neutralized that cannot be attributed to calcite, but converted to calcite-equivalent acid-neutralizing potential (ANP), in weight percent.

	H ⁺ total moles neutralized based on final pH	H ⁺ moles that calcite present can neutralize	H ⁺ moles “removed” that cannot be due to calcite	Non-calcite rock or mineral ANP in percent calcite- equivalence
	-----H ⁺ moles X 10 ⁻⁴ -----			
FMT020				
Bulk rock	1.22	0.28	0.94	9.4
Quartz & feldspar	0.96	0.10	0.86	8.6
Biotite & chlorite	2.21	0.22	1.99	19.9
Tremolite & chlorite	2.18	0.43	1.75	17.5
FMT022				
Bulk rock	1.22	0.07	1.15	11.5
Quartz & feldspar	1.10	0.06	1.04	10.4
Biotite	2.20	0.14	2.06	20.6
Tremolite	1.95	0.23	1.72	17.2
FMT032				
Bulk rock	1.62	0.19	1.43	14.3
Quartz & feldspar	1.25	0.08	1.17	11.7
Biotite	2.16	0.19	1.97	19.7
Tremolite & biotite	2.18	0.32	1.86	18.6
Tremolite & biotite	2.20	0.41	1.79	17.9

Table 8. Concentrations of major ions and sulfate in the initial leachate (pH = 2.80) and concentrations of major ions lost to the leachates and the sulfate concentrations in leachates after the exposure of 0.2 grams of bulk rock and mineral fractions to 120 ml of leachate for 48 hours. Analysis by ICP-AES of 0.45 micrometer filtered leachates.

	Al	Ca	Fe	K	Mg	Na	Si	SO ₄
	-----milligrams per liter-----							
initial leachate	2.8	16	1.3	4.8	4.6	4.4	2.8	180
	FMT020							
Bulk rock	1.0	9.0	2.0	1.2	1.0	0.5	1.3	170
Quartz & feldspar	1.0	1.0	0.2	0.8	0.1	0.4	0.8	180
Biotite & chlorite	0.9	1.0	5.4	7.2	7.4	0.2	6.0	160
Tremolite & chlorite	1.9	14	2.4	1.2	5.2	0.4	3.9	170
	FMT022							
Bulk rock	1.9	3.0	1.4	2.5	1.5	0.6	2.2	170
Quartz & feldspar	2.6	2.0	0.2	1.8	0.4	1.3	1.7	170
Biotite	1.8	1.0	9.7	13.2	5.0	0.3	6.0	170
Tremolite	2.0	6.0	1.1	1.3	5.4	0.4	5.2	170
	FMT032							
Bulk rock	2.3	5.0	3.6	2.9	2.1	0.3	3.3	170
Quartz & feldspar	3.2	3.0	0.5	2.5	0.8	1.2	2.5	170
Biotite	1.6	2.0	8.7	11.2	4.6	0.2	5.5	170
Tremolite & biotite	1.4	10.0	5.4	5.2	4.1	0.2	3.9	180
Tremolite & biotite	1.0	11.0	4.7	6.2	4.7	0.4	4.2	170

Table 9 shows the concentrations of calcite in untreated bulk rock and mineral fractions based on total C analyses, and the amounts of calcite calculated from the amounts of dissolved Ca in the leachates. These data show that the amounts of calcite dissolved in the leachates of the biotite-rich fractions are far less than the amounts of calcite determined for these samples based on the percent of calcite determined by total C analyses. These results are taken to indicate that some calcite within the biotite-rich fractions was enclosed or isolated from contact with the leachate as if the calcite occurs chiefly as inclusions. Similar results were obtained in the first tests (table 5).

Table 9. Concentrations of calcite in untreated bulk rock and mineral fractions based on total carbon analyses, along with the amounts of calcite calculated from the dissolved Ca in the 1:600 (solid:leachate) leachate after 48 hours.

	% calcite from total C		% calcite from dissolved Ca in leachates
FMT020			
Bulk rock	1.40		1.35
Quartz and feldspar	0.49		0.15
Biotite and chlorite	1.12		0.15
Tremolite and chlorite	2.13		2.10
FMT022			
Bulk rock	0.36		0.45
Quartz and feldspar	0.28		0.30
Biotite	0.68		0.15
Tremolite	1.16		0.90
FMT032			
Bulk rock	0.95		0.75
Quartz and feldspar	0.38		0.45
Biotite	0.94		0.30
Tremolite and biotite	1.61		1.50
Tremolite and biotite	2.04		1.65

SUMMARY

The results obtained here with regard to the significant ANP of the granitic bedrock of the Boulder batholith are consistent with the pH values (mostly > 6.0) of local streams measured by Nimick and Cleasby (1998) during the past two years. The ANP of the bulk rocks and their respective mineral concentrates, measured separately, agree within about 10 percent, based on the weight percent concentrations and respective pH values of leachates to which they were exposed. Our results are consistent with prior kinetic studies by others of pure minerals exposed to high purity acidic solutions. The methods used here are relatively simple and it seems reasonable that similar passive methods of estimating bulk rock ANP could be used in other areas.

The ANP of mafic minerals observed here has obvious implications for the ANP of igneous and metamorphic rocks of other watersheds.

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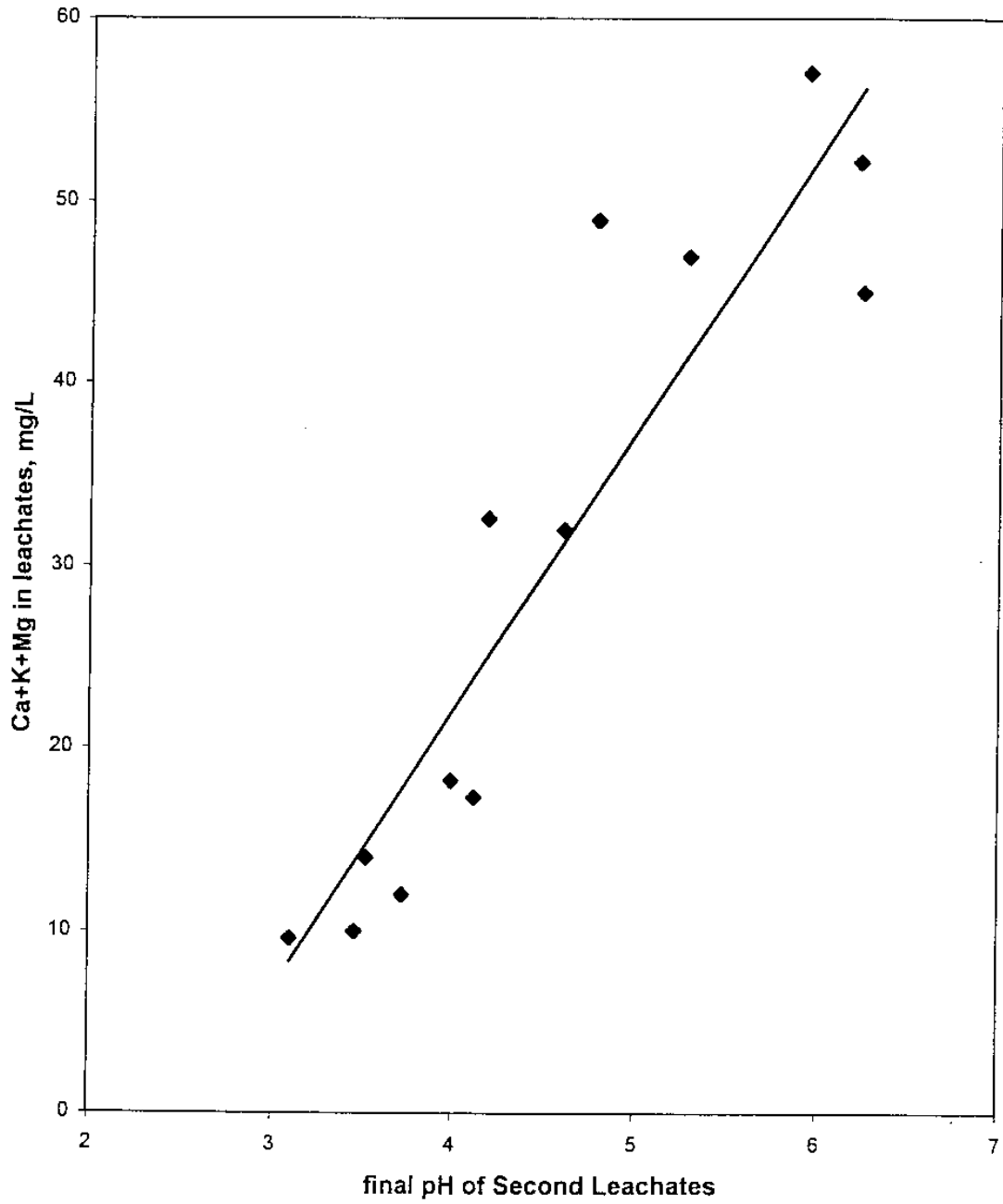


Figure 1. Relations of dissolved Ca + K + Mg in the second leachates versus final pH of the leachates.

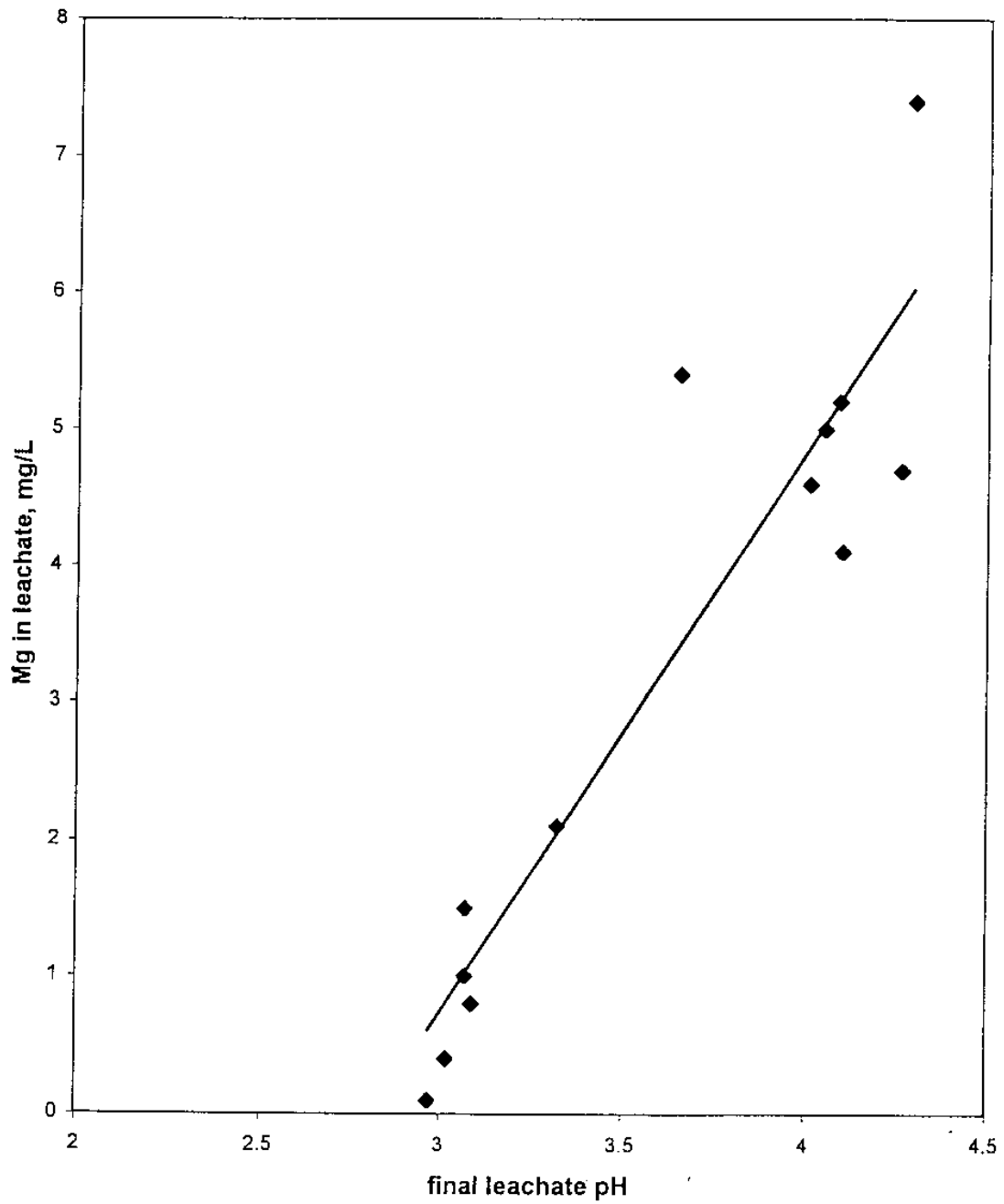


Figure 2. Final pH of leachates versus Mg concentrations in leachates.