COMPARISON OF MEASURED AND MINERALOGICALLY PREDICTED VALUES OF THE SOBEK NEUTRALIZATION POTENTIAL FOR INTRUSIVE ROCKS[1]

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Abstract. Twelve specimens of intrusive rocks, ranging from granitic to ultramafic, were ground and subjected to the static-test neutralization-potential (NP) protocol so that the results could be compared with those computed by using the NP values previously obtained by Sobek tests of the constituent minerals. The quantitative mineralogy of the rocks was determined by Rietveld refinements of X-ray powder diffraction data, and was supplemented by optical microscopy, fizz tests, and analyses of total carbon to determine the presence of carbonate minerals. Despite the igneous nature of the suite, most samples were found to be carbonate-bearing; optical microscopy and fizz tests of the coarse (minus 6 mm) fractions were observed to be more sensitive to the presence of carbonates than was the minus 60-mesh fraction that is used in the Sobek protocol. For some minerals, notably olivine and serpentine, the acid-digestion period in the Sobek test has a pronounced effect on the resulting NP, and this part of the test protocol is in need of new standardization. Mineralogical prediction of the NP values is sensitive to the composition of the plagioclase because these feldspars are typically a major component of igneous rocks and the NP of the calcic end-member, anorthite, is about 12 times that of the sodic end-member, albite.

Additional Key Words: static tests, acid drainage, particle size, acidification period, plagioclase composition, Rietveld method, quantitative mineralogy, calculated NP.

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Introduction

The use of static tests is almost universally accepted as an essential part of predictive investigations related to acid mine drainage (AMD). The most widely used static test is either that of Sobek et al. (1978) or modifications of it, and generally the performance of various static tests is assessed by comparison to the Sobek results (Lapakko, 1994, 1996; Adam et al., 1997; Lawrence and Wang, 1997; White et al., 1999). The importance of static tests is that they are commonly used on a 'stand-alone' basis in AMD monitoring, and in AMD prediction the results typically are used to make decisions about mine planning. These decisions may directly affect the planned disposal of wastes, or they may determine which of the potential wastes require further investigation, such as follow-up kinetic tests. Incorrect performance of static tests, or inappropriate interpretation of the results, can therefore have far-reaching environmental and economic repercussions.

Despite the widespread utilization of static-test results in environmental applications, much remains to be learned about the correlation between weathering of a mineral assemblage in field situations and the behaviour of the same minerals during a static test. Weathering of sulfide-bearing wastes can be simplified as consisting of two opposite but interacting reactions, namely, those that generate acidity as a result of sulfide oxidation, and those that attenuate the acidity via the base that is released from the companion non-sulfide minerals. The capacity of a mineral or waste to contribute base is referred to as the neutralization potential (NP). Only the NP, and only as it is measured by the Sobek test, is dealt with here. However, it is possible to adhere strictly to the Sobek static-test protocol and yet obtain a range of NP results because some of the test parameters are not rigidly defined; the same looseness applies to other protocols, not just the Sobek test.

The approach in the present paper is to point out some of the factors, other than the mineralogy, that result in different measured NP values for samples that may not be identical, but nonetheless qualify as identical within the Sobek and other static-test protocols. Some of these factors became evident while pursuing the primary objective, which was to use the measured Sobek NP values of individual minerals as the basis for calculating the NP of a diverse suite of intrusive rocks for which the quantitative mineralogy was determined as an intrinsic part of the project. An inherent part of the objective was comparison between the calculated NP and the measured NP for each bulk rock to assess the degree of correlation and to seek explanations for any divergences.

Materials and Methods

The rocks were hand specimens purchased from Ward's Natural Science Ltd. Catalogue numbers and the descriptive data that were provided with the specimens are given in Table 1, which also includes information discussed in subsequent paragraphs. The rock names provided have been retained. Each rock was subsequently cut with a diamond saw to obtain a polished thin-section for optical microscopy, and a portion of each specimen was crushed to minus 6 mm, whereupon a small split was removed and most of the remainder was crushed to minus 60 mesh (–250 µm) for the Sobek NP tests.

Table 1. Rock specimens, localities, and fizz ratings for the intrusive suite.

No.	Label	Fizz Rating	Observations for –6 mm fraction	PTS*
1[†]	biotite granite	slight	disseminated calcite, rapidly exhausted	yes
2	granodiorite	nil	nil fizz	no
3	syenite	nil	calcite in a few (<5%) rock chips	no
4	monzonite porphyry	nil	calcite in a few rock chips	yes
5	hornblende diorite	nil	nil fizz	yes
6	diabase	nil	nil fizz	no
7	hornblende gabbro	nil	nil except for one fracture surface	yes
8	gabbro	nil	calcite at one point only	yes
9	anorthosite	slight	numerous fizz points, rapidly exhausted	yes
10	pyroxenite (harzburgite)	nil	calcite at one point only	yes
11	mica peridotite (kimberlite)	nil	calcite at one point only	yes
12	andesine	nil	fracture-controlled calcite	yes

[†] Catalog numbers: 1 = 47E3629, Westerly, Rhode Island; 2 = 47E3684, St. Cloud, Minnesota; 3 = 47E7944, Magnet Cove, Arkansas; 4 = 47E5124, Boulder County, Colorado; 5 = 47E2679, Salem, Massachusetts; 6 = 47E2624, Jersey City, New Jersey; 7 = 47E3314, Salem Neck, Massachusetts; 8 = 47E3309, Duluth, Minnesota; 9 = 47E0559, Split Rock, Minnesota; 10 = 47E6479, Nye, Montana; 11 = 47E6154, Yellow Dog, Michigan; 12 = E0024, not given.

*Observation of the presence of [yes] or absence of [no] carbonates in the polished thin-section (PTS) of the whole-rock sample.

For the quantitative mineralogy a portion of the minus 60-mesh fraction was ground to <5 µm in a McCrone micronizing mill and was examined by X-ray powder diffraction (XRD) by step-scanning from 3º to 70º 2θ with Cu$K\alpha$ X-radiation in a Siemens D5000 diffractometer. The XRD data were refined using the Rietveld program Topas 3.0 (Bruker AXS, 2004). Details of the procedure are given by Raudsepp and Pani (2003). Supplementary mineralogical data were obtained with a Philips XL-30 scanning electron microscope with a coupled energy-dispersion spectrometer, and plagioclase compositions were determined with a Cameca electron microprobe. All of the instruments are housed in the Department of Earth and Ocean Sciences at the University of British Columbia.

The analyses for total carbon were obtained in the Mining and Mineral Sciences Laboratories (MMSL) at CANMET, Ottawa, Canada. The samples were mixed with metallic iron and were heated in a Leco induction apparatus to evolve the carbon as carbon dioxide gas, which was then analyzed quantitatively by an infrared detector. All analyses were done in duplicate and the average value is reported; the maximum deviation in the results obtained is ±15% of the reported value. The NP values of the rocks and minerals were determined at MMSL, mainly in duplicate, and a few in triplicate. Although the procedures for carrying out the Sobek NP test are given elsewhere (Sobek et al., 1978; Morin and Hutt, 1997; Price, 1997), the various steps are summarized below to facilitate the discussion of variables within the protocol. Specific items of note in the current study are that the initial heating after acidification of a sample was done by immersing the flask and its contents in a water bath thermostatically maintained at 90 ºC. The acidified solution was carefully monitored until its temperature reached that of the bath, and the reaction period at 90 ºC was stopwatch-timed to 15 min. The addition of NaOH was by autotitration.

The Sobek Test for NP

The sample is ground and screened to pass 60 mesh. A small portion is removed and tested separately by adding a few drops of 25% HCl to establish the 'fizz' rating, which is the effervescence ensuing from the dissolution of acid-soluble carbonate minerals. The fizz rating governs the volume and normality of HCl to be added to a 2 g sample in a 250 mL Erlenmeyer flask: for no fizz, 20 mL of 0.1 *N* HCl; slight fizz, 40 mL of 0.1 *N*; moderate fizz, 40 mL of 0.5 *N*; strong fizz, 80 mL of 0.5 *N*. The appropriately acidified 2 g sample is heated to near boiling (but not boiled) until gas evolution from the decomposition of the sample is no longer visible, whereupon distilled water is added to make a total volume of 125 mL. The solution is then boiled for 1 min, cooled to room temperature, and titrated to pH 7 by using NaOH whose normality is the same as that of the HCl applied in the acidification step. The NP corresponds to the mL of HCl that were consumed, and commonly is expressed, as for all values reported herein, as kilograms of $CaCO_3$ equivalent per tonne of sample. Thus, the NP of calcite is 1000.

Effects of Protocol Variables

Fizz Test

The four generalized categories that are used to rate the fizz results are indicative of the subjective nature of the fizz test. It is well known that acidification of a sample for one category will give a different result than acidification to a different level. For example, a 'moderate' rating will yield a higher NP than will the acidification for a 'slight' rating, because the higher normality and volume of acid will promote the dissolution of most minerals. In this study, the fizz tests were performed on both the –60 mesh and the –6 mm fractions, and the reaction was observed both megascopically and under a binocular microscope. Whereas 10 of the 12 pulverized samples were given a nil fizz rating on the basis of megascopic observation, samples crushed to –6 mm and checked for reaction by using a binocular microscope showed that carbonates were much more widespread. Moreover, the combined binocular and petrographic observations indicated that only 2 of the 12 samples were carbonate-free (Table 1). This seemingly high incidence of carbonate-mineral occurrence in intrusive rocks is not considered to be anomalous; rather, the results are in accord with the data of White et al. (2005), who examined 100 granitoid rocks from various localities and concluded that calcite is universally present.

Despite the detection of small amounts of calcite in most of the intrusive suite, only two samples were rated as having a slight fizz, in accordance with the Sobek protocol. All of the other samples were, therefore, tested for NP on a 'no fizz' basis. An unexpected outcome of the fizz tests is that the coarse fraction (–6 mm) proved to be more sensitive to the presence of minute amounts of calcite, probably because the calcite remained as concentrations, the mass of which provided a more persistent effervescence. The persistence factor also introduced uncertainty as to the fizz rating when effervescence was noted but quickly ceased, thereby suggesting that only a small amount of calcite was present, but probably in an insufficient amount to warrant an increase in the fizz rating. A retrospective examination of the calcite content and fizz ratings indicates that the division between ratings of slight fizz and no fizz was made at about 1 wt. % calcite.

Methods for quantifying the carbonate content in relation to fizz ratings have been suggested by Skousen et al. (1997), Frostad et al. (2003), and others. In dealing with environmental assessments of metalliferous deposits it is common practice to determine a sample's inorganic carbon content, which is then converted to $CaCO_3$ equivalence to obtain an indication of the proportion of NP_{total} that is present as $NP_{carbonate}$. The $NP_{carbonate}$ value is deemed to be 'readily available' NP, thus contrasting with the bulk of the remaining NP, which is likely to be released only over the long term. However, because the four Sobek fizz categories correspond to 50, 100, 500, and 1000 kg of $CaCO_3$ per tonne of material (Frostad et al., 2003), the $NP_{carbonate}$ content also provides an indication of the appropriate fizz rating of the sample. Thus, in our study all of the samples should have been rated as 'no fizz' despite the observed effervescence.

Particle Size

The Sobek protocol requires that the sample be screened to pass 60-mesh sieve, but no lower size limit is stipulated. However, particle size can have a significant effect on NP values (Fig. 1; Jambor and Dutrizac, 2002). In a previous study of the NP contributed by specific minerals (Jambor et al., 2002), most of the specimens used were coarse-grained and of museum quality; thus, the bulk of the pulverized particles would have consisted of monocrystals rather than of polycrystalline aggregates, thereby minimizing the number of potentially reactive crystal sites. Moreover, most of the specimens were crushed manually rather than mechanically, and repeated crushing and screening were used to accumulate the NP test-samples. The initial coarse size and the preparation method served to minimize the amount of fine particles and, therefore, to minimize the NP values that were obtained for these mineral standards. Although the rocks tested in the current study were mechanically ground, all members of the suite are coarse-grained. The expectation was that the differences in grain sizes between the rocks versus those of the mineral standards would have the effect of producing lower calculated versus measured NP values, but that the differences would not be appreciable.

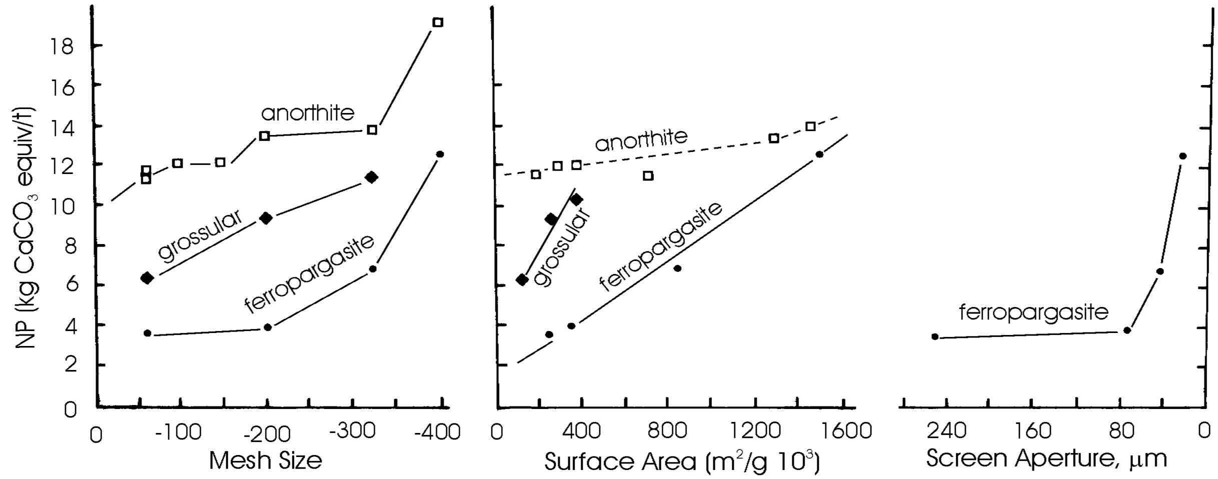

Figure 1. Effect of mesh size and surface area on the NP of anorthite (plagioclase group, An_{67}), ferropargasite (amphibole group), and grossular (garnet group). Data are from Jambor and Dutrizac (2002).

Length of Acidification

Once the volume and normality of the acid have been determined from the results of the fizz test, the requisite acid is added to the sample and the suspension is heated to nearly boiling, but not boiled, until reaction is complete. Completion is taken as the point at which no gas evolution is visible and the particles settle evenly over the bottom of the flask (Sobek et al., 1978).

Although much has been written about the subjectivity of the fizz test, little attention has been paid to the effects that the time and temperature of the acidification stage can have on NP values. Consequently, the method and rapidity of heating a sample to 'nearly boiling' vary in different laboratories and a corollary is that the duration and temperature of the acidification stage also vary. The effect of these variables may not be great for minerals that have low solubilities, and therefore low NP values (e.g., K-feldspar, and albite *sensu stricto*), but for highly acid-soluble non-carbonate minerals, such as olivine and serpentine, the effects can be so profound as to dominate the NP result (Fig. 2). Unless the acidification stage of the Sobek protocol has been standardized as was done here, detailed comparisons of the NP values of rocks containing minerals such as olivine and serpentine are of doubtful value.

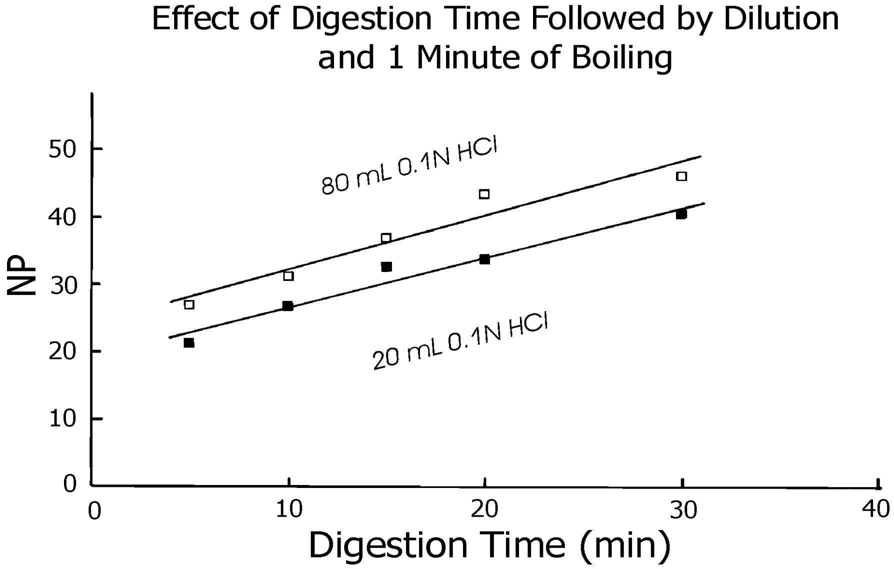

Figure 2. Effect of acidification time and acid volume on the NP value of antigorite serpentine.

NP Values of Specific Minerals

To calculate the NP of a rock the weight percentages of the constituent minerals were determined by XRD (Appendix 1), and it was then necessary to assign to each mineral a specific NP value. The initial assignments were based on data reported by Jambor et al. (2002). Analcime, nepheline, and thomsonite-Ca were found to be present in some of the rocks, and NP values were obtained from newly prepared monomineralic samples of these minerals. Where data were available for several minerals within a group, such as the amphibole group, the NP was selected to represent the common rock-forming species rather than averaging the whole range. The assigned NP values for the various minerals are given in Table 2. It is important to bear in mind that the assigned values are intended to convey the magnitude rather than the precise value to be expected for the NP of a particular mineral or mineral group.

Table 2. Selected Sobek NP values for minerals or groups.

Group/mineral	NP[†]	Ref.	Group/mineral	NP	Ref.
Quartz	0	–	Garnet/almandine	3	3
K-feldspar	1	1	/grossular	6	3
Plagioclase/albite, An_{0-20}	1	2	Olivine/forsterite	38	3,4,5
albite, An_{20-30}	2	2	Serpentine	32	2
albite, An_{30-40}	4	2	Talc	2	3
albite, An_{40-50}	5	2	Magnetite	2	3
anorthite, An_{50-60}	6	2	Ilmenite	1	est.
anorthite, An_{60-70}	8	2	Hematite	2	3
anorthite, An_{70-80}	10	2	Nepheline	25	2
$>An_{80}$	12	2	Analcime	11	2
Amphibole	3	3	Thomsonite-Ca	13	2
Pyroxene	5	3	Calcite	1000	–
Mica/muscovite	1	1	Dolomite	1085	calc.
/phlogopite	8	3,4	Siderite	863	calc., 6
Chlorite/clinochlore	6	3,4			

[†] All NP values are in kg $CaCO_3$ equivalent per tonne of material.

References: (1) Jambor et al. 2000; (2) this study; (3) Jambor et al. 2002; (4) Jambor and Dutrizac 2002; (5) Jambor et al. 2004; (6) performance in the Sobek test assuming Fe(II) is not hydrolyzed (see Skousen et al., 1997; Jambor et al., 2003).

Comparison of the bulk-rock measured NP with the initially calculated mineralogical NP revealed that a major adjustment was required. The results of a previous study (Jambor et al., 2002) suggested a two-fold division (shown by the dashed vertical line in the left diagram of Fig. 3), in which only the extremely Ca-rich members of the series albite–anorthite [$NaAlSi_3O_8$ – $CaAl_2Si_2O_8$] gave NP values >6. However, the initial assignment of low NP values to the Na-dominant members was not commensurate with the preponderance of plagioclase and with the relatively high measured NP that was obtained from some of the rocks. Consequently, a new series of plagioclase samples was acquired, and NP values were measured by using the protocol that included the timed (15 min) acidification period. The results (Table 3) show that the NP for most of the series increases linearly with increasing formula Ca (Fig. 3). This relationship is in general agreement with laboratory dissolution studies, which indicate that the rate of dissolution of the plagioclase series follows a constant slope from An 0 to at least An 76 (Stillings and Brantley, 1995).

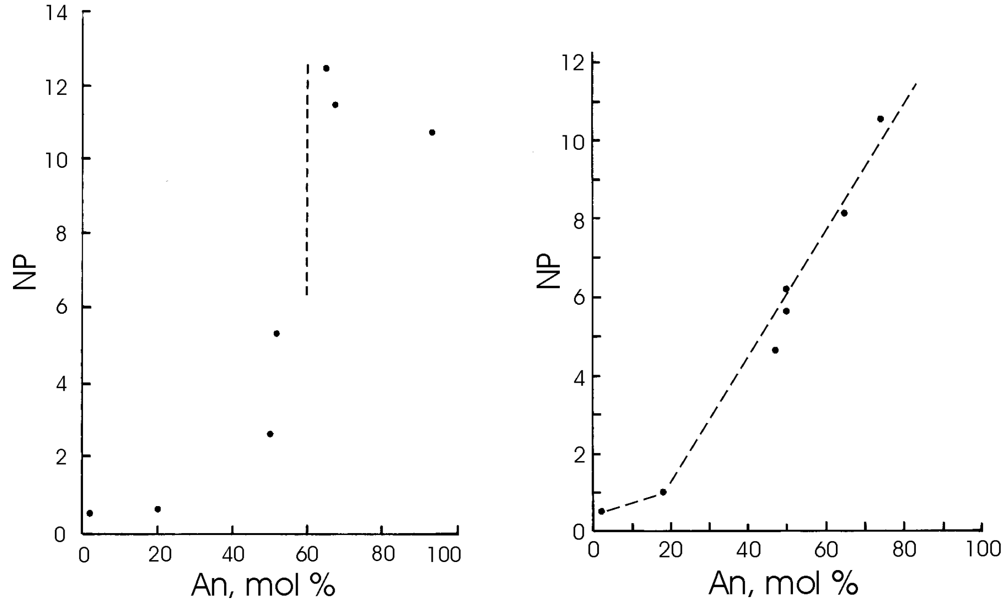

Figure 3. NP values versus the formula content of Ca (expressed as An, i.e., anorthite content) for the plagioclase series. On the left are the results obtained by Jambor et al. (2002) using a non-timed digestion period, and on the right are the results of the current study (Table 3).

Table 3. Measured NP values† for minerals in the plagioclase series.

No.	Composition	NP	Locality
1	$Ab_{98}An_2$	0.5	Amelia, Virginia
2	$Ab_{82}An_{18}$	1	Madawaska, Ontario
3	$Ab_{53}An_{47}$	4.6	Laramie Mountains, Wyoming
4	$Ab_{50}An_{50}$	5.6	Tabor Island, Newfoundland–Labrador
5	$Ab_{50}An_{50}$	6.2	‘Andesine’, Ward’s Natural Science
6	$Ab_{35}An_{65}$	8.1	Harp Lake, Newfoundland–Labrador
7	$Ab_{26}An_{74}$	10.5	Duluth, Minnesota

†Timed acidification period except for samples No. 1 (Jambor et al. 2000) and No. 2 (Jambor et al. 2004). Sample 3 is from a gabbroic xenolith at Poe Mountain (Scoates and Chamberlain 1995). The compositions of all samples were determined by electron microprobe.

Calculated Versus Measured NP

The NP values calculated from the quantitative mineralogy, and the measured whole-rock NP values are given in Table 4 and shown in Fig. 4. The calculated NP is based on the values given in Table 2 except that the NP for plagioclase was generally obtained graphically from Fig. 3 by using the average anorthite content for the plagioclase in each rock, as listed in Appendix 1.

Although the values of NP_{calc} in Table 4 include a decimal number, the inclusion is only to avoid further rounding and does not imply precision. The NP_{calc} values are approximations, and because they are particularly sensitive to the slope of the line in Fig. 4, further work to add to the data points in Fig. 4 is in progress.

Table 4. Calculated NP values from mineralogy, and measured whole-rock NP values.

		Whole Rock[†]		C_{total}[††]		NP	
		NP_{calc}	NP_{meas}	C_{ppm}	NP_c	calcite*	Main NP sources
No.	Rock						
1	granite	10.1	8.9	850	7.2	9	calcite
2	granodiorite	3.7	8.1	100	<1	2	calcite
3	syenite	2.4	13.2	100	<1		nepheline
4	monzonite porph.	4.1	7.1	<100	<1	3	calcite
5	hornblende diorite	10.5	16.1	245	2.1	7	calcite
6	diabase	5.3	8.1	<100	<1		plagioclase
7	hornblende gabbro	9.5	17.5	350	3.0	5	plagioclase
8	gabbro	8.8	12.7	<100	<1		plagioclase
9	anorthosite**	23.4	20.2	1500	12.6		calcite, plagioclase
10	pyroxenite	30.3	26.3	400	3.4		olivine
11	peridotite	19.1	28.1	500	4.2	5	calcite, olivine, serp.
12	'andesine'	9.5	8.5	400	3.4	4	plagioclase, calcite

[†] NP_{calc} = value calculated from quantitative mineralogy; NP_{meas} = Sobek value for whole rock.
[††] C_{ppm} = measured total carbon content in ppm; NP_c = NP assuming all C is present as $CaCO_3$.
*NP value from mineralogically determined calcite content.
**Calcite content not determinable by mineralogy, and NP_{calc} includes the value from C_{total}. The NP value is for the test as 'no fizz'; for a test at 'slight fizz', the NP is 29.3.

For most rocks the calculated NP is lower than the measured NP, and the difference is pronounced for the syenite, hornblende gabbro, and peridotite. The syenite is unusual in that it is nepheline- and analcime-bearing and locally contains trace amounts of calcite (Table 1), but the reason for the appreciable difference in measured versus calculated NP is not known. For the hornblende gabbro, the plagioclase in the rock has a wide range of compositions (An 29 to 54) and is partly chloritized, especially in the most calcic portions. Avoidance of these areas during microprobe analysis may have resulted in an underestimation of the average An content, thus also lowering the calculated NP. An increase in NP_{calc} from 9.5 to only ~11 would be enough to bring the plot into an adequate alignment with the other results.

The anorthosite contains about 1% calcite, and was initially rated as having a slight fizz. Consequently, the volume of acid was increased to be appropriate for the fizz rating. However, because little of the acid was consumed by the calcite, the pH of the solution would have remained low, thereby increasing the attack on the plagioclase and increasing the NP. At a 'no fizz' rating, the agreement between the calculated and measured NP values is good (Table 4 footnote).

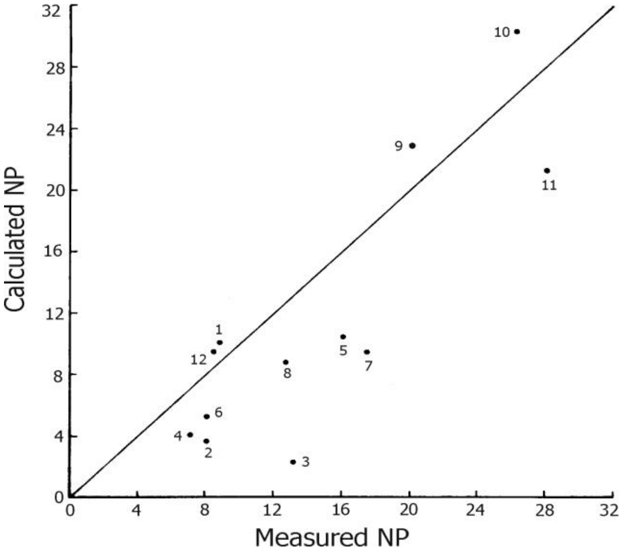

Figure 4. NP calculated from the quantitative mineralogy, versus the whole-rock measured NP. The numbered points correspond to those in Table 4.

Table 5. Measured NP values for various serpentines and samples of olivine

No.	Mineral	NP	Comments
1	antigorite	15	not timed (Jambor et al. 2000)
2	lizardite	16	not timed (Jambor et al. 2000)
3	lizardite	49	this study, on the remnant of sample 2
4	antigorite	32	this study, Figure 1
5	antigorite	24	this study; newly prepared sample of No. 4
6	antigorite	22	this study; newly prepared sample, optically finer grained than No. 5
7	forsterite	24	San Carlos, Arizona; not timed (Jambor et al. 2000)
8	forsterite	38	San Carlos, Arizona; not timed (Jambor et al. 2002)
9	forsterite	33-43	San Carlos, Arizona; not timed (Jambor et al. 2004)
10	forsterite	44	San Carlos, Arizona; this study

The reason for the low NP_{calc} of the peridotite may be related to uncertainty about the amount of NP that is derived from olivine and serpentine. Table 5 shows the range of values that have been obtained for monomineralic samples of both minerals. Both are strong acid-neutralizers, and further work with olivine may provide useful results. For serpentine, however, it may not be viable to assign a specific NP value. For example, serpentine tailings examined from the former Magnola operation at Asbestos, Quebec, consist of lizardite and antigorite, with no carbonate and only minute amounts of brucite, but the serpentines are microporous and yield NP values of about 400 when tested using the conditions for a strong fizz rating (Jambor and Dutrizac, 2002).

Conclusions

The immersion time during the acidification stage of the Sobek test can have an appreciable effect on NP if the waste assemblage contains silicate minerals, the NP value of which is above average (>10). In the examined intrusive suite, the main source of NP was variably either calcite or Ca-rich plagioclase, and in ultramafic rocks the non-carbonate sources of NP were predominantly olivine and serpentine. Although K-feldspar and albite containing up to 20 mol % Ca have NP values of only ~1, further substitution of Ca in plagioclase leads to a composition-related, apparently linear, rise in NP.

The attempt to correlate the measured whole-rock NP with that calculated from the quantitatively determined mineralogy was moderately successful, but it is clear that highly detailed, and time-consuming, mineralogical studies are required to yield useful results. Although the focus of the study was the application of the Sobek test to metalliferous mine wastes, three of the principal benefits of the study are the demonstration that (1) plagioclase solid-solution has a significant impact on the NP results; (2) the protocol in static tests needs to be more tightly defined; and (3) much has yet to be learned about how static tests should be conducted and about how past and current static-test results should be interpreted.

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Literature Cited

Adam, K., A. Kourtis, B. Gazea, and A. Kontopoulos. 1997. Evaluation of static tests used to predict the potential for acid drainage generation at sulphide mine sites. *Transactions of the Institution of Mining and Metallurgy*, 106, A1-A8.

Bruker AXS. 2004. Topas Version 3.0: General Profile and Structure Analysis Software for Powder Diffraction Data. Bruker AXS, Germany.

Frostad, S.R., W.A. Price, and H. Bent. 2003. Operational NP determination – accounting for iron manganese carbonates and developing a site-specific fizz rating. *In*: G. Spears, P. Beckett, H. Conroy (eds.). Mining and the environment, Sudbury 2003. CD ROM, paper 50.

Jambor, J.L. and J.E. Dutrizac. 2002. The effect of particle size on the neutralization potential in static-test predictions of acid drainage. Vol. 2, p. 651-663. *In*: B. Björkman, C. Samuelsson, J.-O. Wikström (eds.). Recycling and waste treatment in mineral and metal processing: Technical and economic aspects. The Minerals, Metals, Materials Society, Warrendale, Pennsylvania.

Jambor, J.L., J.E. Dutrizac, and T.T. Chen. 2000. Contribution of specific minerals to the neutralization potential in static tests. Vol. 1, p. 551-565. *In*: Proc. Fifth Internatl. Conf. Acid Rock Drainage. Society for Mining, Metallurgy, and Exploration, Littleton, Colorado.

Jambor, J.L., J.E. Dutrizac, L.A. Groat, and M. Raudsepp. 2002. Static Tests of neutralization potentials of silicate and aluminosilicate minerals. Environmental Geology, 43, 1-17. http://dx.doi.org/10.1007/s00254-002-0615-y.

Jambor, J.L., J.E. Dutrizac, M. Raudsepp, and L.A. Groat. 2003. Effect of peroxide on neutralization-potential values of siderite and other carbonate minerals. Journal of Environmental Quality, 32, 2373-2378. http://dx.doi.org/10.2134/jeq2003.2373.

Jambor, J.L., J.E. Dutrizac, and P.A. Riveros. 2004. Prediction of acid mine drainage: effect of the time gap between sample crushing and the static test. Vol. 3, p. 2441-2453. *In*: I. Gaballah, B. Mishra, R. Solozabal, M. Tanaka (eds.). REWAS '04, global symposium on recycling, waste treatment and clean technology. The Metals and Materials Society, Warrendale, Pennsylvania.

Lapakko, K.A. 1994. Evaluation of neutralization potential determinations for metal mine waste and a proposed alternative. Vol. 1, p. 129-137. *In*: International land reclamation and mine drainage conference and third international conference on the abatement of acidic drainage. (Pittsburgh PA, April 24-29, 1994).

`https://doi.org/10.21000/JASMR94010129`

`Note: This was Published in 1992`

Lapakko, K.A. 1996. Characterization and static testing of ten gold mine tailings. p. 370-384. *In*: American Society for Surface Mining and Reclamation meeting (Duluth, Minnesota, June 14-18, 1992).

`https://doi.org/10.21000/JASMR92010370`

Lawrence, R.W. and Y. Wang. 1997. Determination of neutralization potential in the prediction of acid rock drainage. Vol. 1, p. 451-464. *In*: Proc. Fourth Internatl. Conf. Acid Rock Drainage. MEND, Natural Resources Canada, Ottawa.

Morin, K.A. and N.M. Hutt. 1997. Environmental geochemistry of minesite drainage: Practical theory and case studies. MDAG Publishing, Vancouver, B.C.

Price, W.A. 1997. Guidelines and recommended methods for the prediction of metal leaching and acid rock drainage at minesites in British Columbia. Draft. British Columbia Ministry of Employment and Investment. Victoria, B.C.

Raudsepp, M. and E. Pani. 2003. Application of Rietveld analysis to environmental mineralogy. *In*: J.L. Jambor, D.W. Blowes, A.I.M. Ritchie (eds.). Environmental aspects of mine wastes. Mineralogical Association of Canada Short Course Volume 3, 165-180. Mineralogical Association of Canada, Nepean, Ontario.

Scoates, J.S. and K.R. Chamberlain. 1995. Baddeleyite (ZrO2) and zircon (ZrSiO4) from anorthositic rocks of the Laramie anorthosite complex, Wyoming: Petrologic consequences and U-Pb ages. American Mineralogist, 80, 1317-1327. http://dx.doi.org/10.2138/am-1995-11-1222.

Skousen, J., J. Renton, H. Brown, P. Evans, B. Leavitt, K. Brady, L. Cohen, and P. Ziemkiewicz. 1997. Neutralization potential of overburden samples containing siderite. Journal of Environmental Quality, 26, 673-681. http://dx.doi.org/10.2134/jeq1997.00472425002600030012x.

Sobek, A.A., W.A. Schuller, J.R. Freeman, and R.M. Smith. 1978. Field and laboratory methods applicable to overburdens and minesoils. EPA-600/2–78–054. National Technical Information Service, U.S. Department of Commerce, Springfield VA.

Stillings, L.L. and S.L. Brantley. 1995. Feldspar dissolution at 25ºC and pH 3: Reaction stoichiometry and the effect of cations. Geochimica et Cosmochimica Acta, 59, 1483-1496. http://dx.doi.org/10.1016/0016-7037(95)00057-7.

White, A.F., M.S. Schulz, J.B. Lowenstern, D.V. Vivit, and T.D. Bullen. 2005. The ubiquitous nature of accessory calcite in granitoid rocks: Implications for weathering, solute evolution, and petrogenesis. Geochimica et Cosmochimica Acta, 69, 1455-1471. http://dx.doi.org/10.1016/j.gca.2004.09.012.

White, W.W. III, K.A. Lapakko, and R.L. Cox. 1999. Static-test methods most commonly used to predict acid-mine drainage: Practical guidelines for use and interpretation. *In*: G.S. Plumlee and M.J. Logsdon (eds.). The environmental geochemistry of mineral deposits. Part A: Processes, techniques, and health issues. Reviews in Economic Geology, 6A, 325-338.

Appendix 1. Quantitative mineralogy (wt. %) of the intrusive rocks.

	1 gran	2 grano	3 sy	4 monz	5 dior	6 diab	7 hb gab	8 gab	9 anor	10 pyrox	11 perid	12 and
quartz	27.4	19.3		27.1		7.5		0.6				1.0
K-feldspar	31.5	23.2	36.1	20.7	4.2							4.4
plagioclase	31.6	40.5	48.8	40.9	51.6	40.5	51.1	84.5	88.5	4.8	5.9	74.0
clinopyrox.					20.8	35.8	7.0	6.2		2.7	15.7	5.9
enstatite										11.6	11.8	13.8
amphibole		11.1	3.2	2.8	2.4		13.8				2.4	
muscovite	2.7	1.6										
phlogopite		1.3	0.9	1.7	8.7		10.6				5.3	
chlorite	3.0	2.8		3.1	3.0	9.5	14.2				12.4	
forsterite								4.5		69.1	13.0	
talc											8.9	
serpentine										9.0	17.3	
ilmenite					6.7	4.1	2.3	4.2				0.2
magnetite			3.7	3.5	2.0	2.6	0.5			2.9	6.8	0.2
hematite												0.2
nepheline			3.9									
analcime			3.4						0.6			
thompsonite									10.9			
calcite	0.9	0.2		0.3	0.7		0.5		nd		0.5	0.4
Plagioclase:												
An range[†]		21-40	4-9		16-51	49-60	29-54	58-69	78-79	–	59-64	48-51
n analyses		10	9		15	13	14	15	10	3	9	6
Average An		24	6		29	55	38	61	78	78	61	50

nd: not determinable.

[†] The range of composition, expressed as An content, that was obtained by microprobe analysis of the plagioclase in each rock; *n* is the number of points that were analyzed, and 'Average An' is the average of those results.