OPERATIONAL VALIDATION OF ENVIRONMENTAL GEOCHEMISTRY AT THE STILLWATER MINE, NYE MT[1]

Lisa Bithell Kirk, P.G.[2], Melanie McCleary[2] and Randy Weimer

Abstract. Stillwater Mining Company produces platinum and palladium ore from a 1-to-3 meter wide zone, referred to operationally as the J-M reef, within a layered ultramafic- to-mafic cumulate intrusive deposit at Nye, Montana. The braggite and cooperite $(Pt, Pd, Ni)_xS_y$ ore minerals occur in association with the sulfide minerals chalcopyrite ($CuFeS_2$), pyrrhotite ($Fe_{1-x}S$), pentlandite$(Fe,Ni)_9S_8$, and minor pyrite (FeS_2), so that sulfide-bearing rock is for the most part mined as ore. Sulfide minerals posing a risk of acid generation occur almost exclusively in the ore zone, so that little risk associated with waste rock and underground workings was anticipated when the mine was originally permitted in the 1980's. This conclusion is being revisited through an operational validation program underway at the Stillwater Mine, which seeks to evaluate the baseline conclusion that ARD potential is low in mine waste materials. Samples from the gabbro (n= 15), norite (n= 16), anorthosite (n= 9), and troctolite (n=6) lithologies, identified through careful geological characterization, have been studied for whole rock geochemistry and acid generation potential. Results of this work do not support further assessment of acid drainage risk using kinetic test methods. Composites have been developed from these samples for studies of trace element release potential by lithology using the meteoric water mobility procedure. The data confirm the original baseline conclusion of low risk to water resources, which has also been substantiated through monitoring in surface and groundwater at the mine site. A limited number of confirmation samples will be collected in future operations.

Additional Key Words: geological characterization, PGE mineralization, acid base accounting

---

[1] Paper was presented at the 2006 Billings Land Reclamation Symposium, June 4-8, 2006, Billings MT and jointly published by BLRS and ASMR, R.I. Barnhisel (ed.) 3134 Montavesta Rd., Lexington, KY 40502.

[2] Lisa Bithell Kirk, Principal Geochemist, Enviromin, Inc., PO Box 1685, Bozeman MT 59715 and Melanie McCleary, Environmental Geologist, Stillwater Mining Company, 2562 Nye Road, Nye MT, 59061.

Proceedings America Society of Mining and Reclamation, 2006 pp 363-
DOI: 10.21000/JASMR06010363
http://dx.doi.org/10.21000/JASMR06010363

Introduction

The Stillwater Mine is located 90 miles southwest of Billings, Montana on the Stillwater River in the Beartooth Mountains. The Stillwater Mining Company (SMC) produces platinum and palladium ore from a layered ultramafic-to-mafic cumulate intrusive deposit known as the Stillwater Complex. The deposit is mined underground from two surface locations, at the Stillwater Mine located at Nye, Montana and more recently, at the East Boulder located near Big Timber, Montana (Fig. 1). Early in mine life, little risk to water quality from waste rock was anticipated as metal and sulfide-rich minerals occur almost exclusively within the ore zone and not in waste rock. Apart from nitrate loading as a result of blasting, no mine drainage problems have been observed at the Stillwater Mine during the 20-year history of operations. Ongoing environmental management programs led SMC to initiate an operational validation program in 2003, with a goal of collecting environmental geochemical data to support the ongoing waste rock management program.

The purpose of the operational geochemistry program was to evaluate potential for acid rock drainage formation and trace element release from rock currently being mined, and if possible, to correlate recently mined waste rock with historical waste based on geological characterization and mining practices. Numerous investigators have shown the importance of geological and mineralogical understanding in proper selection of test methods and application of results to waste management (Jambor, 2003). Based on the geology of the mined rock, mineralogical and whole rock geochemical analyses were used to fingerprint volumetrically significant (greater than 1 weight percent) waste lithologies. Sampling of these lithologies as a part of routine operations over a two year period from multiple locations throughout the Stillwater Mine produced a representative suite of samples for geochemical analysis. Static testing of acid generation potential using the modified Sobek method (Lawrence and Wang, 1997) of acid base accounting identified no risk of ARD formation. Potential for release of trace elements, including metals, is currently being evaluated through meteoric water mobility testing of composites based on the whole rock and static testing work. This paper summarizes the sampling and analysis plan in use at the Stillwater Mine and presents initial results of the operational monitoring program. Results underscore the importance of thorough geological characterization in support of environmental geochemical assessment.

Stillwater Mine History

The original Stillwater Mining Company was incorporated in 1884 with the purpose of mining Cu and Ni from the Stillwater Complex. Although chromite may have been discovered in the 1890’s, it was first mined in 1905 on Little Rocky Creek at the eastern end of the complex. Samples were analyzed for Pt group elements (PGE’s) as early as the 1930’s, but it wasn’t until 1973 that the major PGE zone, the J-M Reef, was discovered by the Johns-Manville Corporation. To mine the laterally continuous J-M Reef, a parallel development travel/haulage way is driven and core drilling completed to locate the ore and determine profitable mining areas. The development rock is waste and is either gob-filled underground in completed ore production stopes, or is brought to the surface to be added to the East Side Waste Rock Storage Site. The relationship of the waste rock to the ore zone is shown in Fig. 2.

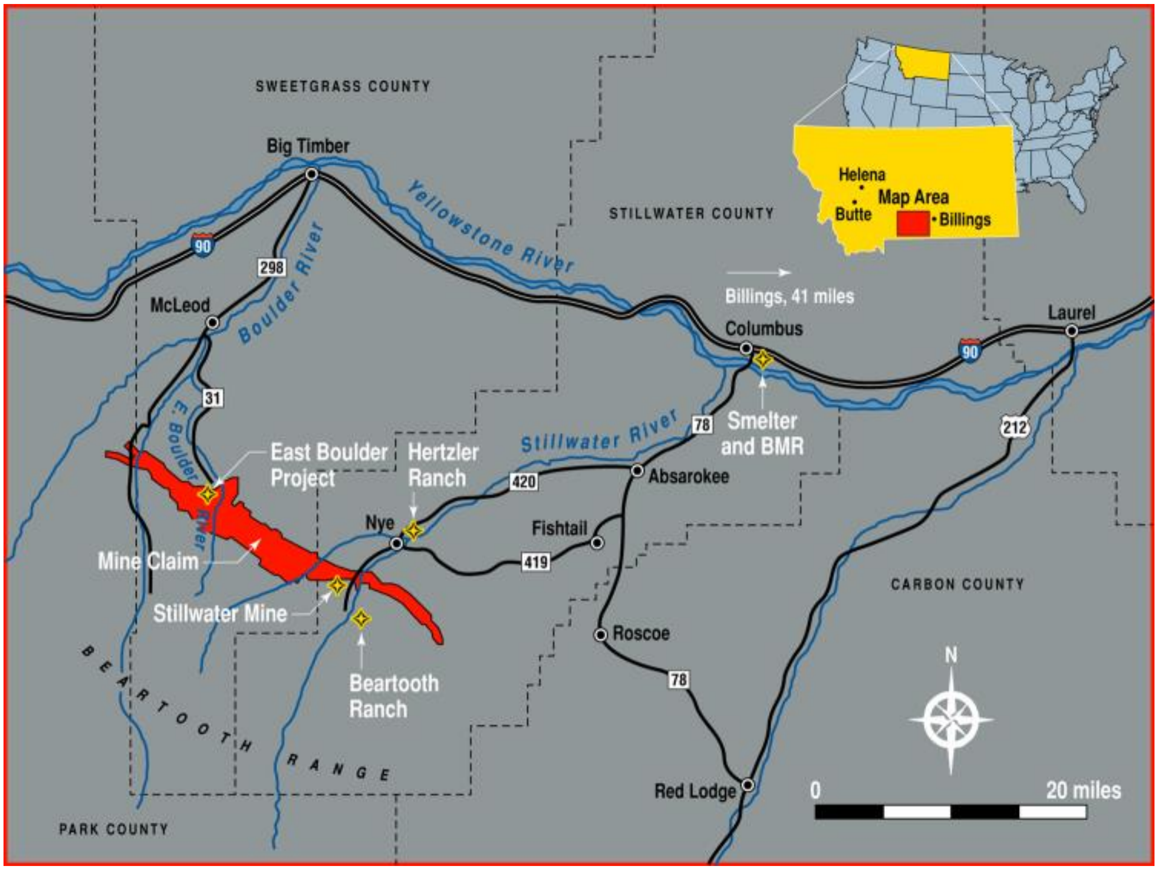

Figure 1. Location of the Stillwater Mine, Nye MT.

<u>Stillwater Mine Geology</u>

The Stillwater Complex is a layered ultramafic-to-mafic intrusion with an estimated 5500m of layered rocks preserved between the intrusive lower contact and the pre-Middle Cambrian unconformity that bound the complex. The Complex has been grouped into three main stratigraphic series--the Basal series, Ultramafic series, and the Banded series. The Basal series, lowermost in the complex, is in contact with basement rock and is approximately 150 m thick. The 1000 m thick Ultramafic series is next in sequence and overlain by the Banded series, which hosts the Pt-Pd deposit. Zientek et. al., 1985, provides an excellent overview of the stratigraphy of the complex.

The Banded series makes up more than three-fourths of the exposed thickness of the complex and is subdivided into the Lower, Middle and Upper series, which is further broken into lithologic zones as shown in Fig. 3. The three lowermost zones in this series mined by SMC, and discussed in this paper, are *Norite I*, *Gabbro I*, and *Troctolite-Anorthosite I* as defined by Zientek (Zientek et. al., 1985). The *Norite I* zone consists of plagioclase-bronzite cumulates and can be identified at the base of the section along the entire length of the complex. The overlying *Gabbro I* zone is comprised of cumulates containing plagioclase, bronzite and augite. Next in sequence is *Troctolite-Anorthosite I*, which is a complex succession of olivine-, plagioclase-, bronzite-, and augite-bearing cumulates and pegmatoidal rocks. This zone is especially important because it hosts the J-M Reef, which is generally 1 to 3 m thick and is distinguished by small concentrations (0.5-1 vol%) of sulfides which contain PGE's.

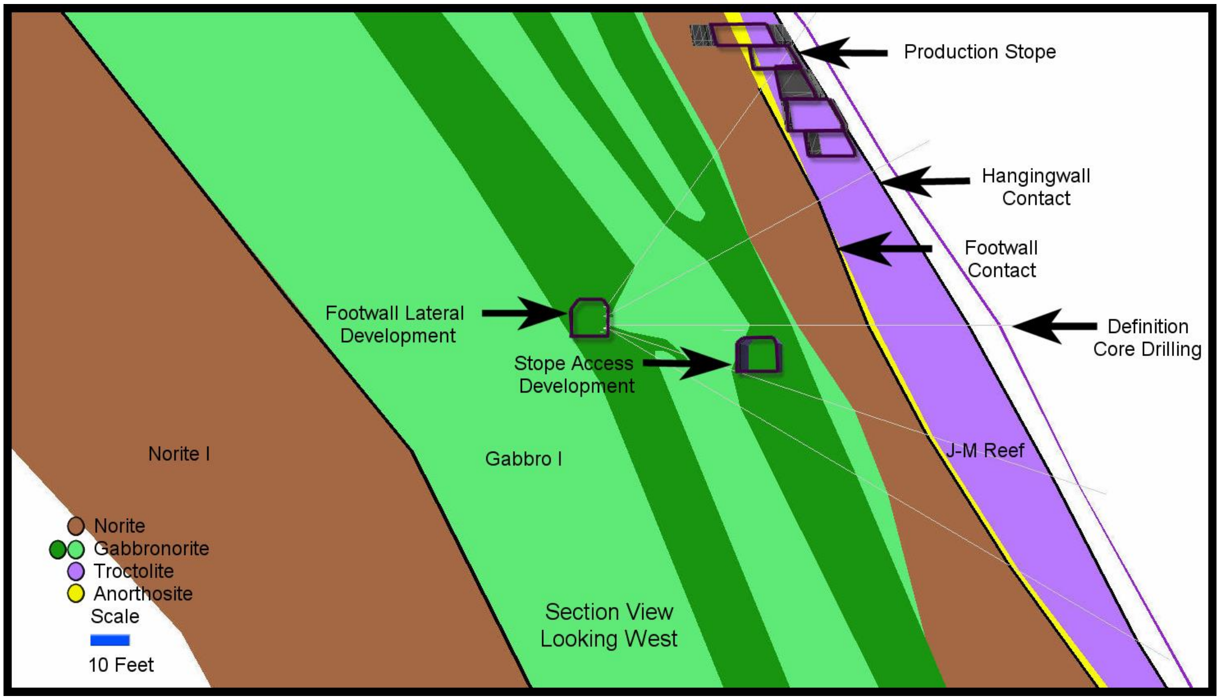

Figure 2. Conceptual cross-section (looking west) of the section mined at SMC, showing the relationship of the J-M Reef and waste lithologies to production and access stopes.

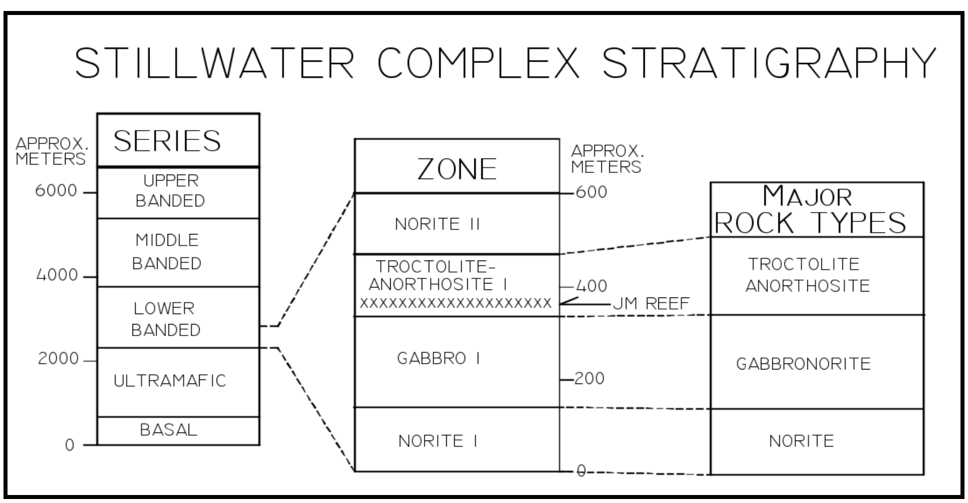

Figure 3. Stratigraphic section, showing occurrence of waste rock lithologies in the Stillwater Complex

During mining, the waste rocks stratigraphically below the J-M Reef are collectively called footwall (FW) rocks, and those above the Reef are called hanging wall (HW) rocks. Adits developed to access the deposit parallel the reef to the south and are located stratigraphically in the *Norite I* or *Gabbro I.* This is called the Footwall Lateral (FWL). During the mining process, the contact between the reef and the hanging wall rock is used by geologists to help locate the ore. Most ore is developed along this contact within reef rocks. Probe core holes are drilled ahead of, and adjacent to, the FWL to determine the location of the reef and the lithologies which will be mined as development advances. Core holes are also drilled on 50' centers to the north from these FWL's and are used to determine the location of the reef and its ore content for grade control. Production mining on the reef may be completed through ramp and fill, sublevel extraction, or captive stope methods, depending on the grade and extent of the ore, and the location in the mine. The "Upper West" part of the mine uses primarily sublevel extraction, while the "East Side" and the "Lower West" primarily use ramp and fill, and captive stope, mining methods.

Geology personnel determine whether a material will be shipped as waste or ore based on visual estimates of sulfide content and ultimately decide the final rock placement. These estimates are based on experience from mapping the reef production stopes as well as samples which are taken regularly to calibrate the geologist's estimates. Development headings are not mapped by geologists on a regular basis due to the fact that much historical data has been gathered showing these rocks do not contain significant sulfides. The probe drill holes are also logged and any material that may contain sulfide is sampled. Rock determined to be waste in production stopes may be shipped to the East Side Waste Rock Storage Site. In the upper west part of the mine, sublevel extractions are gob-filled with waste rock mined in the area as much as possible to avoid the need to ship waste from the mine. The lower west and east side do not have the availability of space to gob-fill waste rock, due to the use of the ramp and fill (and captive stope) mining methods, so this rock is shipped to the waste rock pile more regularly than material from the upper west. Understanding of the mining process is thus important to assessing variation in historically mined rock.

Operational Sampling Program

During the operational geochemistry study, four rock types were identified as significant waste rock units, which include norite, gabbronorite, anorthosite, and troctolite (Table 1). In all, 46 samples were analyzed, with 31 samples taken from FWL (primary) development headings, 9 samples in stope accesses (secondary development), and 7 samples from reef waste rock in the stope (production) headings. Approximately 54% of all waste rock from primary and secondary development is norite, 31% gabbronorite, 13% anorthosite, and 2% troctolite, all of which may be placed on the East Side Waste Rock Storage Site. Sampling locations are shown in Fig. 4.

Table 1. Stillwater Mine waste rock lithology descriptions, frequency of occurrence and number of samples.

Waste Rock Unit	Lithologic Description	Wt % in mined waste	No. recent samples	No. historical samples
Gabbronorite	plagioclase, bronzite, augite cumulate	31	15	30
Norite	plagioclase and bronzite cumulate	54	16	33
Anorthosite	plagioclase cumulate	13	9	33
Troctolite	plagioclase and olivine cumulate	2	6	22

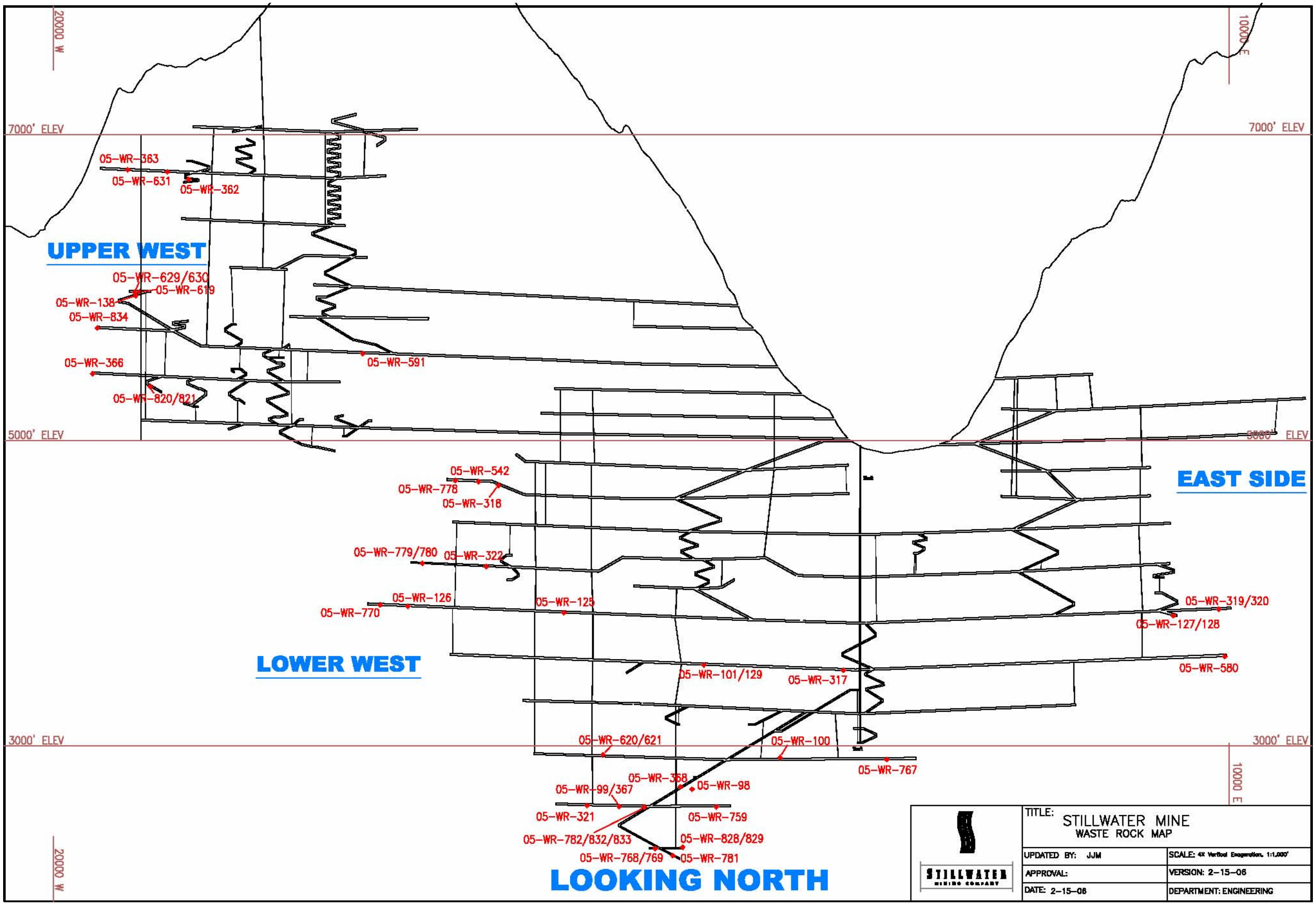

Figure 4. Map of the Stillwater Mine showing location of operational geochemistry validation samples.

Five (5) kilo samples were taken from active development and production headings. In all, forty-six (46) samples were obtained during 2004 and 2005 for analysis. The samples are composites of chips distributed as evenly as possible over the exposed rock. Development samples were taken from active faces or from the rib immediately adjacent to the face. Samples were collected within boundaries defined by a SMC geologist based on lithologic description. Each sample was split into three portions, two of which were sent immediately to separate labs for analysis. One split has been reserved for additional kinetic or leachability testing, if required.

The following paragraphs describe the waste lithologies characteristics used for identification of each unit.

Gabbronorite

The gabbronorite, also described as 2-pyroxene gabbro, is a plagioclase-bronzite-augite cumulate and is the second most abundant waste rock type in development headings. Gabbronorite can generally be easily recognized by the color of the minerals. Unless otherwise altered, the plagioclase is white to transparent, the bronzite is brown, and the augite is green. Mineral size also helps to identify this rock type. The bronzite minerals are generally 2-5mm laths, and the augites are 1-2mm laths.

Norite

Norite, a plagioclase-bronzite cumulate, is the most abundant rock type found in primary and secondary development headings, and comprises the majority of the rock brought to the surface waste pile. The norites can be identified based on color as well. The norite consists of plagioclase and bronzite, as does the gabbronorite, but does not contain augite. These bronzite minerals retain the 2-5mm lath mineral size within the plagioclase.

Anorthosite

Anorthosite, a plagioclase cumulate, is also found in smaller amounts in both primary and secondary development, as well as within the reef itself as both waste and ore. The anorthosite is a white to transparent rock containing only plagioclase, but may also contain some bronzite or augite oikocrysts.

Troctolite

Troctolite, a plagioclase-olivine cumulate, makes up a very small portion of total development material but is found in larger amounts within the reef and may be waste or ore. The olivine can be recognized by the blackness of its color. Olivine within the reef usually has a ragged texture, whereas olivine within the HW rocks is more rounded and less abundant. Troctolite in the reef may also contain bronzite or augite pegmatoids.

Sample Analyses

Each sample was studied using total metal analysis, as a screening tool for general characterization purposes, and the modified Sobek method of acid base accounting. Multi-element total metal analyses do not indicate rates of metal release, but rather provide a chemical fingerprint of waste lithologies than can be used if needed for selective waste management. These are therefore important foundational data for any waste rock management effort. These data also provide a quantitative basis for development of any composites needed for kinetic or leach testing.

Multi-element (50 element) total metal analyses were run by ALS Chemex Laboratories of Sparks, Nevada using their method ME-MS 41. A split of each waste rock sample was digested using aqua regia, followed by analysis using ICP-AES. The method description, and detection limits, can be found at *www.alschemex.com*. This method was chosen over more complete 4-acid digestions because it digests most environmentally relevant minerals, similar to the EPA method 3050 total metal extraction, but does not require use of more hazardous perchloric or hydrofluoric acids, a consideration important to potential future operational screening efforts.

Results

The distributions of a select group of trace elements (Cd, Cr, Cu, Ni, As, Mn, Zn and S) considered relevant to the environmental geochemistry of the Stillwater complex are presented in Fig. 5. Results for all rock types show a range in value skewed towards lognormal distribution with the exception of Cr which is more normally distributed. Individual lithologies can be distinguished through comparison of select elements which may be useful for potential selective waste management. For example, as shown in Fig. 6, comparison of Cu and Ni distinguishes the anorthosite and troctolite from the norite and gabbronorite lithologies.

The potential for acid generation by any of the waste rock lithologies is very low, as shown in Fig. 7. Total sulfur in all samples is less than 0.05 %, well below the generally accepted threshold of 0.3 weight % sulfide sulfur for acid generation (Jambor et al, 2000). More variation is observed in neutralization potential, which ranges from 20 to 70 T/kT as $CaCO_3$. Gabbronorite tends to have a lower average neutralization potential than troctolite, for example, with norite falling mid range. These results confirm the original conclusion that there is very low risk of ARD formation in waste rock mined from the Stillwater complex and suggest that kinetic testing of sulfide oxidation is unwarranted. This validation of the baseline model will be checked periodically with limited additional sampling as mining proceeds.

The potential for release of regulated trace elements, in the absence of acid rock drainage, will be further evaluated through leach testing of monolithologic composites developed to encompass the range of variation in total metal content (Fig. 5).

Correlation with Historical Data

Operational validation samples have been collected recently throughout the accessible workings to represent the range of mineralogy and environmental chemistry of the Stillwater Complex. More limited geochemical test data are available for rock mined historically, which has been placed in the East Side Waste Rock Storage Site. Extensive mineralogical descriptions are available, along with limited x-ray diffraction/assay analyses of sulfur and select metals, which have been compiled for comparison with the more recently collected data. Geological characterization of waste, as discussed above, was used to select 118 samples of representative historical waste rock from drill logs (Table 1) for comparison of sulfur content. Although the analytical methods used have varied, and historical methods used would not be the current method of choice for sulfur analysis, Fig. 8 shows similar low concentrations of sulfur in the historical samples. Of particular importance is the fact that the historical data show that more than 97% of samples have total sulfur contents of less than 0.3%. This comparison further supports the conclusion that waste rock mined throughout the history of production at the Stillwater Mine has negligible potential to generate acid.

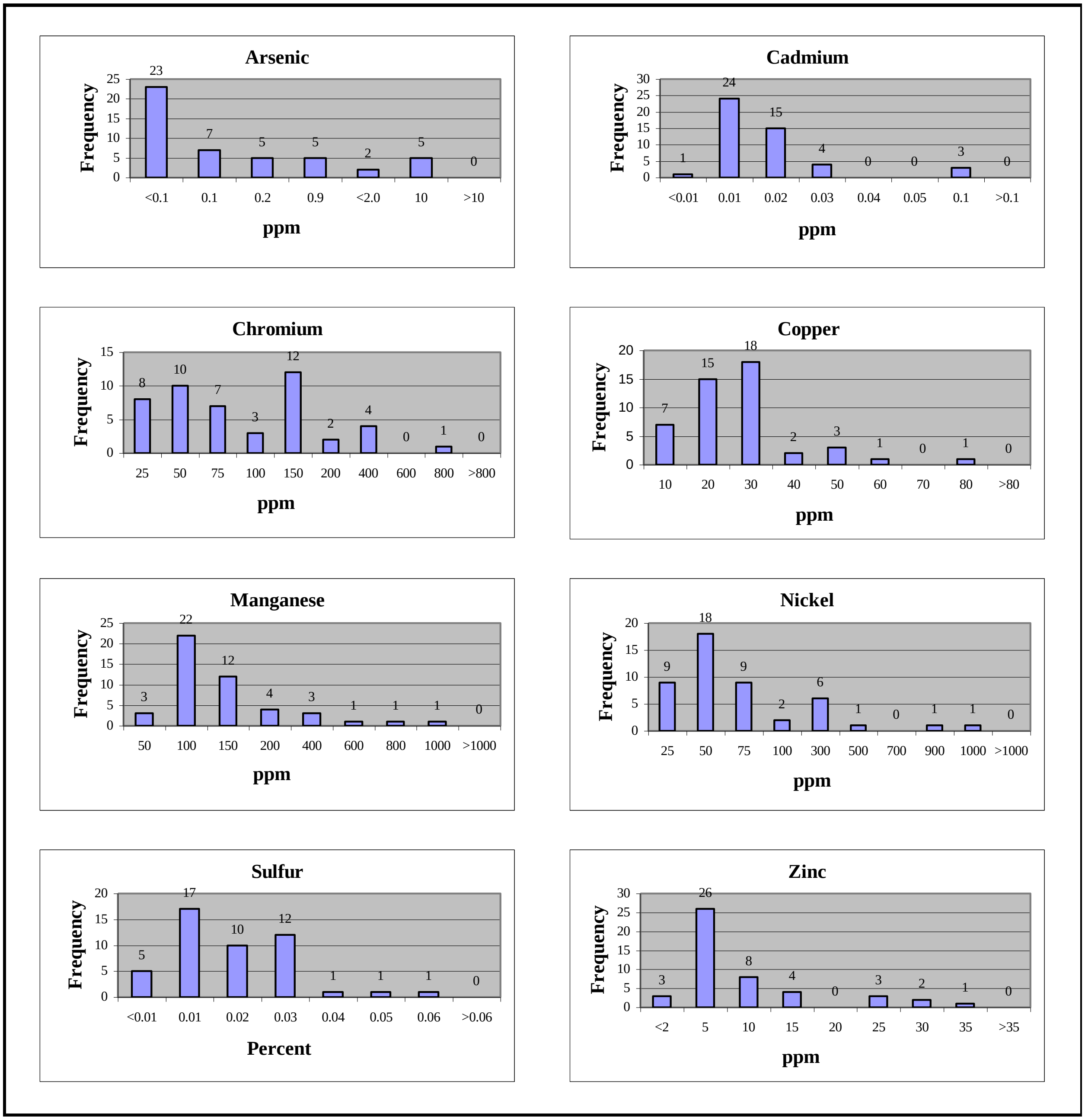

Figure 5. Distribution of select trace elements in operational geochemistry validation samples, based on analysis of total metal content using aqua regia digestion.

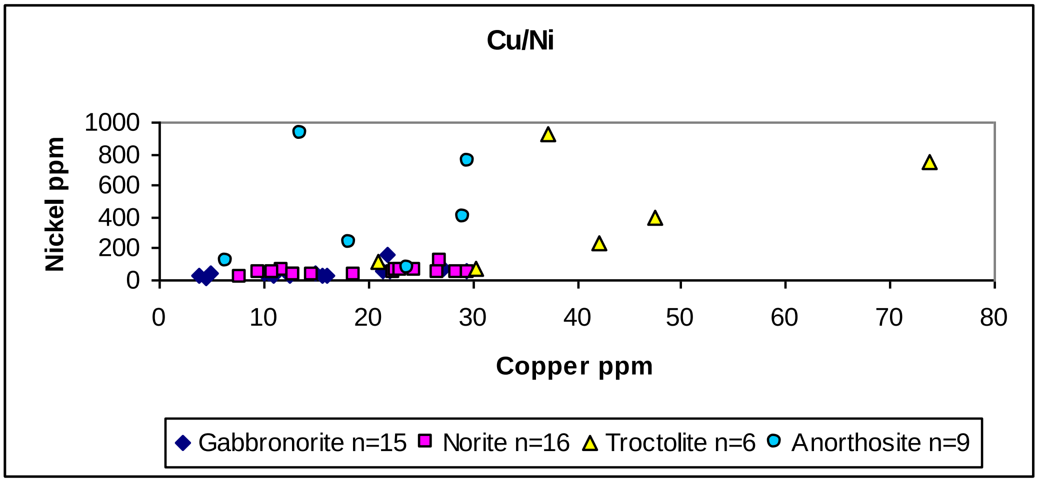

Figure 6. Comparison of copper and nickel content in waste lithologies

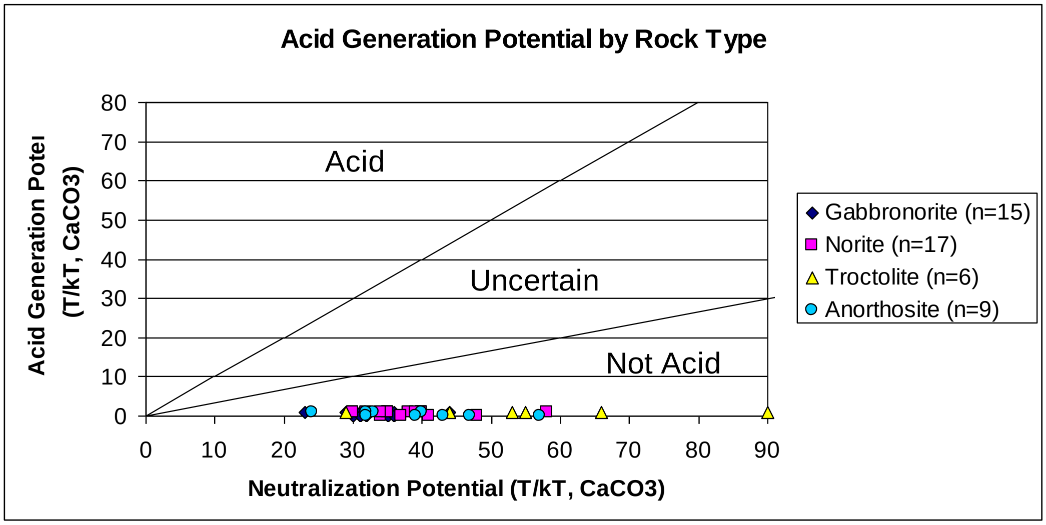

Figure 7. Comparison of neutralization and acid generation potential by waste rock type

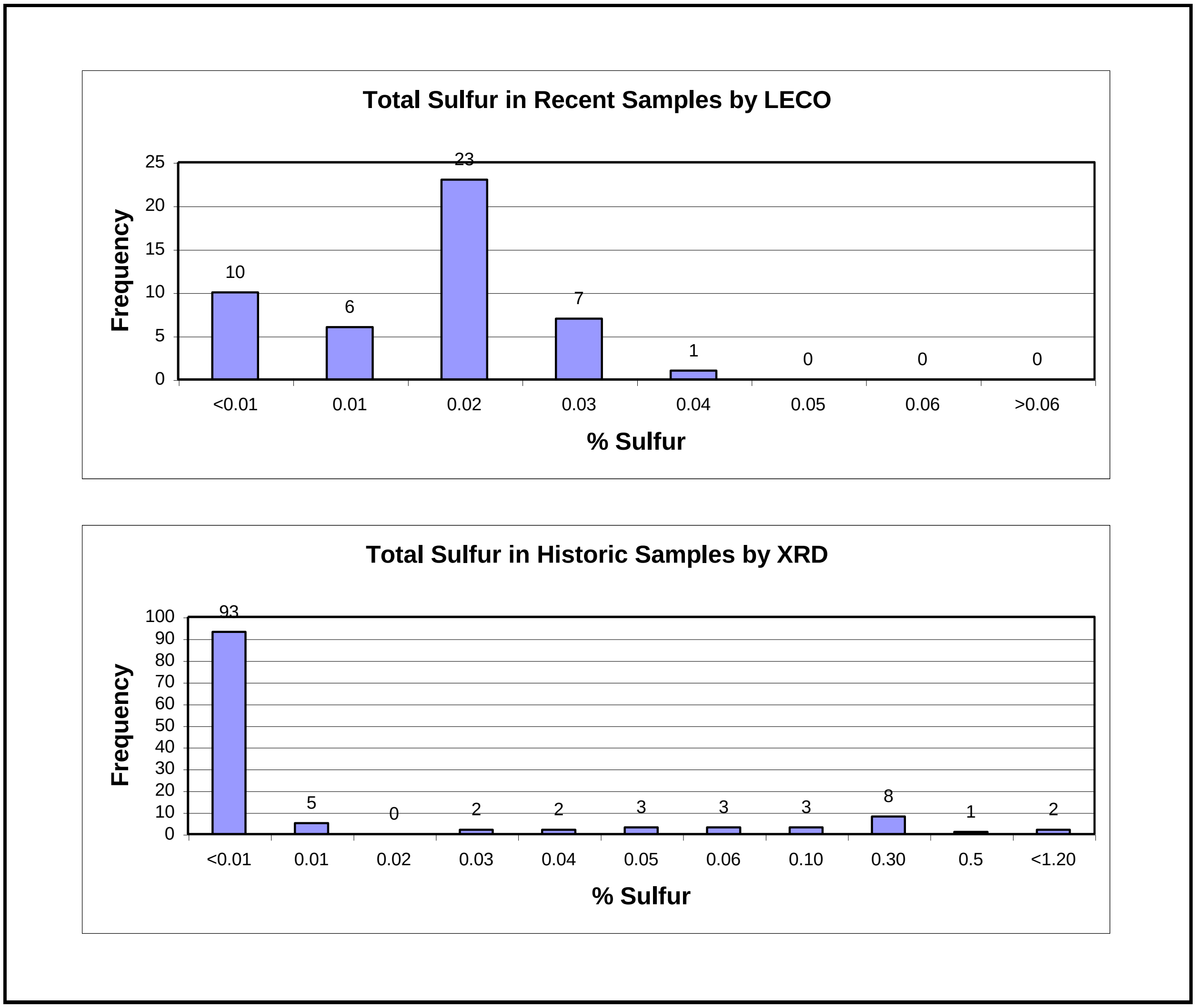

Figure 8. Comparison of recent (LECO, n=47) and historical (XRD, n=118) total sulfur analyses for waste samples from the Stillwater Mine.

Conclusions

The environmental geochemistry of waste rock produced by long-term mining operations may vary as different portions of a deposit are exposed. Ideally, baseline characterization of a deposit during permitting will fully characterize future environmental geochemistry, but initial conclusions should be validated throughout mine life. Results of the operational geochemical validation program at the Stillwater Mine support the initial mineralogy-based assumption that acid generation potential was very low and illustrate a focused, low-cost approach to validating baseline environmental geochemical models throughout mine life. The value of careful geological characterization in sampling and interpretation of acid base accounting tests, as well as correlating recent and historical data, is also demonstrated.

References

Jambor, J.L, D.W. Blowes, and C.J. Ptacek. 2000. Mineralogy of Mine Wastes and Strategies for Remediation. Ch. 7 of Environmental Mineralogy, D.J. Vaughan and R.A.l Wogelius, editors. EMU Notes in Mineralogy, Vol 2, p. 255-290. http://dx.doi.org/10.1180/emu-notes.2.7

Jambor, J.L.. 2003. Mine-Waste Mineralogy and Mineralogical Perspectives of Acid-Base Accounting. *In* Environmental Aspects of Mine Wastes, Jambor, J.L., D.W. Blowes, and A.I.M Bitchie, editors. Min. Assoc. Canada Short Course Series Vol. 31, 2003. p. 117.

Lawrence, R.W. and Wang, Y., 1997. Determination of Neutralization Potential in the Prediction of Acid Rock Drainage. In Proceedings of the Fourth International Conference on Acid Rock Drainage, Vancouver , B.C., Canada, May 31 to June 6, 1997, vol. 1, p. 449-464.

Page, N.J., Zientek, M.L., Lipin, B.R., (Bob) Mann, Schmidt, E.A., Turner, A.R., Czamanske, G.K., and Raedeke, L.D.. 1985. Exploration and Mining History of the Stillwater Complex and Adjacent Rocks. *In* The Stillwater Complex, Montana: Geology and Guide. *Edited by* Czamanske, G.K. and Zientek, M.L. Montana Bureau of Mines and Geology Special Publication 92, p.77-92.

Todd, S.G., Keith, D.W., Le Roy, L.W., Schissel, D.J., Mann, E.L., and Irvine, T.N. 1982. The J-M Platinum-Palladium Reef of the Stillwater Complex, Montana: I. Stratigraphy and Petrology. Economic Geology, vol. 77, p. 1454-1480. http://dx.doi.org/10.2113/gsecongeo.77.6.1454.

Zientek, M.L., Cooper, R.W., Corson, S.R., Geraghty, E.P.. 2002. Platinum-Group Element Mineralization in the Stillwater Complex, Montana. *In* The Geology, Geochemistry, Mineraology and Mineral Beneficiation of Platinum-Group Elements. *Edited by* L.J. Cabri. Canadian Institute of Mining, Metallurgy and petroleum, Special Volume 54, p. 459-481.

Zientek, M.L., Corson, S.R., and West, R.D.. 2005. Chapter 18: Geochemical Surveys of Soil and Talus Fines and the Discovery of the J-M Reef, Stillwater Complex, Montana. *In* Exploration for Deposits of Platinum-Group Elements. *Edited by* Mungall, J.E. Mineralogical Association of Canada Short Course Series Volume 35, p. 391-407.

Zientek, M.L., Czamanske, G.K., and Irvine, T.N.. 1985. Stratigraphy and Nomenclature for the Stillwater Complex. *In* The Stillwater Complex, Montana: Geology and Guide. *Edited by* Czamanske, G.K. and Zientek, M.L. Montana Bureau of Mines and Geology Special Publication 92, p. 21-32.