REDUCING SULFIDE OXIDATION IN MINING WASTES BY RECOGNIZING THE GEOMICROBIAL ROLE OF PHOSPHATE MINING WASTES - A long journey 1991-2014[1]

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Abstract: Oxygen has been considered the main driver of the weathering processes in mining wastes, omitting the role of microbes. Among many approaches to control oxygen access to the wastes, *in situ* treatment of the mineral surface has been tried since the late eighties. Various materials including NPR (Natural Phosphate Rock) were added with the expectation of finding an iron-phosphate coating. Irregular and inconsistent results were obtained when the effluents were evaluated according to NPR stoichiometry; however, the lower dosages showed some improvements in the effluents. Since the results did not consistently produce iron phosphate, any positive effects on effluents were considered accidental and the approach abandoned.

We suspected microbes at work based on basic ecological considerations. Hence 1991, we began experimenting on tailings and waste rock with additions of NPR, postulating that if chemo-lithotrophic microbes on the mineral surface accelerate oxidation, then heterotrophic (oxygen-consuming) microbes would reduce oxidation. Samples from tailings plots where NPR was tilled into the surface were tested for pore-water quality after eight years. Effluents from waste rock exposed outdoors in drums were monitored for 2.7 years. Repeatedly, the one-time addition of NPR produced effluents with elevated pH and low metal acidity. Later, microscopic investigations of the rocks found an organic layer on the mineral surfaces. Investigations by scientists in 6 different universities confirmed the presence of a biofilm as the cause of the reduced acid generation. In 2013, heterotrophs were identified and quantified as they covered the surface of German lignite, following a bioleach testing protocol starting at pH around 1. These findings conclusively showed that the development of heterotrophic biofilms and improved effluents from sulfidic mine wastes are a consequence of adding waste NPR.

We conclude that sufficient evidence has been gathered to prove that the geo-microbial control or *in situ* control of sulfide oxidation is a viable concept. It needs to be pursued to control or curtail acid mine drainage now and in the future. In this paper, we document the evolving ecological thought process over 23 years of research, which lead step by step toward understanding of the effects of NPR on the reduction of sulfide oxidation.

Additional Key Words: Microbes, Sulfide Oxidation, Biofilms, Natural Phosphate Rock, Geo-microbiology

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Background

Acid mine and rock drainage are highly undesirable consequences of mining metals and are accepted as some of the most severe environmental challenges of the mining industry. The chemical reactions of weathering which lead to metal-laden and acidic water emerging as seepages from mining wastes are well documented. Microbiologists have identified microbes as the major catalyst in this reaction, increasing the weathering or oxidation rate up to 500,000 to 1,000,000 times (Dave and Tipre, 2012).

As mining methods changed from underground to open pit, waste piles have increased in volume and areal extent, exposing more mineral surfaces to weathering and microbial attack. Over a decade ago, tailings production by the global mining industry from milling ore was estimated to be several hundred thousand tons per day (Jakubick and McKenna, 2003). For every ton of ore mined and milled, large quantities of water are contaminated and waste rock piles cover large expanse of land, while milled tailings fill lakes or valleys. Hence atmospheric precipitation falls on ever increasing areas of mining wastes and contacts more mineralized rock surfaces increasing the volume of contaminated effluent emerging as mine or rock drainage leading to increased environmental deterioration (Hudson–Edwards et al., 2011).

After many decades of intensive efforts to control the metal-laden drainage from mining wastes, significant progress has been made, but problems still remain. The major driver of weathering is considered by industry, governments, regulators, consultants, and many scientists to be oxygen. Hence waste management methods focus mainly on reducing oxygen access to the wastes. The role of microbes in the process has been generally ignored. Gradually the perception has emerged that AMD and ARD (Acid Mine and Rock Drainage) are regrettable consequences of mining which need to be accepted, rather than solved.

Mine drainage and environmental destruction due to mining have become a public concern. The problem has become the focus of many studies and income units for sectors of society. The income that the problem generates institutionalizes and entrenches certain industrial sectors. Thus, a real solution is met with strong resistance. Further, the translation into a practicable economic technology is nearly impossible, as all stakeholders need to be involved. Mine waste management therefore begs the question posed by Wilson (2008) in an article entitled “Why are we still struggling with acid rock drainage?" He succinctly summarized the physical, chemical and geotechnical limitations of handling mine waste and concludes on page 51,

> "*While it is clear that we have yet to develop a universal solution to ARD, it appears we do have great opportunities to discover and implement new methods for the management of mined earth structures*."

Although he did not state it specifically, he may have meant that great opportunities lie ahead in understanding and developing methods using microbes in the geochemical cycles of nearly all elements on earth. Microbes inhabit all ecosystems and flourish in extreme conditions such as those of mining wastes. Microbial processes are ignored in mine waste management, as are the effects associated with the scale of observation. Lüttge and Arvidson (2008) show that observations made at different scales can lead to misinterpretations of the reactivity and processes on the mineral surface. Microbes not only dramatically affect the reaction kinetics of weathering, but they alter the surface topography of the mineral surface by leading to precipitating secondary minerals. This is very significant for mine waste management methods as scales between reactions at the mineral surface and those within the waste rock pile can be 6-12 orders of magnitude apart. The weathering starts in corrosion pits on the surface of the pyrite crystals at the nanometer scale, while waste rock piles and tailings dumps encompass hectares or square kilometers.

To reduce these scale problems, field testing on a large scale in or on a waste depository is essential for success. Further it is equally important to carry out the tests over a representative time frame covering all seasons. Although this is expensive it is needed to understand whether or not waste management methods are applicable and sustainable over the long term. In this paper we highlight the ecological and geo-microbiological rational behind our search for a sustainable, ecological approach to mine waste and water management, integrating microbial processes and those of scale and time. Although we have published much of this research, the overarching ecological principles have never been presented and are not apparent from individual publications.

The ecology of the waste depositories and its microbes

Waste rock piles and tailings ponds are essentially broken up, low-mineralized rock (ground-up rock with low mineralization). Given their large extent they look like wastelands, void of life forms. These waste depositories are very harsh environments, both physically and chemically. Due to the pyrite and/or other sulphidic minerals in the rocks, when atmospheric precipitation occurs, acidic and iron- and other metal-laden water emerges from the wastes. Wächtershäuser

(1990) postulated that the first metabolic cycles of life were created within such an environment due to the catalytic action of pyrite. He formulated the Iron-Sulphur world hypothesis as a possible evolutionary origin of life. This may be irrelevant to the miner, but it indicates to an ecologist that these wastes represent a primitive ecosystem, one which is arrested in its primordial stage, dominated by corrosive, oxidative weathering processes and accelerated by chemo-lithotrophic microbes. Missing in this ecosystem are habitats which would promote reductive processes supported by heterotrophs. Reductive microbial processes need carbon or organic matter to flourish. It follows that the foundation of an ecological approach to mine waste management has to aim to alter the microbial habitats within the mine waste management area so as to promote habitats for heterotrophs where the weathering and oxidation take place on the mineral surface.

<u>Source Control – the key to ecological mine waste management</u>

Achieving control over weathering of the mineralized rock surfaces has been pursued by a number of workers adding various chemicals, including phosphate materials, and bactericides to pyritic mine wastes (Evangelou, 1995; Olson et al., 2006; to name just a couple). Most additions worked for a while, but did not produce the desired long-term effect, as the coatings were not stable. Natural Phosphate Rock (NPR) was tested in coal waste extensively in the field and the laboratory (Meek, 1983, 1991; Renton and Stiller 1988; Renton et al., 1988; Hart et al. 1990; Ziemiewicz, 1990; Hart and Stiller, 1991; Georgopoulou et al., 1996; Belzile et al., 1997; to name some of the most active groups). NPR was added to the waste, based on the assumption that an iron phosphate coating would form on the mineral surface. Hence dosing of the NPR was calculated reflecting the mass of pyrite in the wastes and that of phosphate in the NPR. A stoichiometric chemical reaction was expected, but lower dosages of NPR produced better results than higher dosages. The approach was abandoned for various reasons.

We were intrigued by these results and suspected microbial involvement, but before engaging in a totally different direction we needed confirmation that it occurred naturally. We searched the literature of heap leach operations where the ore might contain traces of phosphate. In 1991, a report in the Northern Miner Magazine reported that the Gibraltar Mine’s leaching dump had stopped generating acid effluent and thereby Cu (Scott, 1991). We obtained rocks from the leach pile (Fig. 1). Investigations of these rocks by Scanning Electron Microscopy (SEM) with Energy Dispersive Spectroscopy (EDS) revealed that the coating contained mainly iron-hydroxide and not iron-phosphate and microbial populations were also evident.

Figure 1: One of the rocks from the sections of the Gibraltar leaching dump received for the surface investigations at the U of Toronto, Geology.

For ecologists, the Gibraltar rocks were evidence that the oxidation (weathering) of rock surfaces could be reduced, a goal of the ecological engineering decommissioning approach (Kalin, 1989, 1998). Microbes live in biofilms on surfaces. We hypothesized that the Gibraltar heap leach rocks stopped leaching because they were coated, not with iron-phosphate, but with a biofilm of fast-growing heterotrophs, which covered the sulphidic mineral surface, consuming oxygen. There was enough phosphate in the local minerals to provide nutrients for acidophlic heterotrophs that live in the same acidic environment as chemo-lithotrophs, but are usually outcompeted or dormant (Harrison et al., 1980). However, when conditions are changed these heterotrophs grow, consume oxygen, and or produce growth deterrents to inhibit the oxidation caused by chemo-lithotrophs (Marchand and Silverstein, 2002).

To pursue this concept further we needed to find acidophilic heterotrophs in mining wastes. At a mine sites in Quebec, Canada, we measured the abundance of oxygen-consuming heterotrophs in a milling circuit from the fresh water intake through the ball mill to the tailings discharge. The heterotrophic microbial populations varied in number, but they were present (Kalin and Smith, 1992; Kalin, 1992; Kalin et al., 1993). We were now certain that we had found a way to reduce or even inhibit the weathering rate in sulphatic mining wastes. Phosphate did not coat waste rock with iron-phosphate, but fertilized heterotrophic microbes, which out-competed the oxidizing microbes.

NPR is mined from phosphatic sedimentary rock deposits, which contain calcium-carbonate and phosphate in fossils and sea shells. It is used to fertilize acid soils, dissolves in acid and neutralizes the soil (Kanabo and Giles, 1987). This material is able to neutralize acidic mineral surfaces, thereby promoting iron precipitation and possibly allowing acidophilic heterotrophic microbes to establish.

We approached Texas Gulf Corp. (Aurora Mine, North Carolina, USA) to supply us with several train cars of washed, coarse-graded NPR waste for field experiments on tailings and waste rock. The grain size received was between 0.04 and 0.4 mm. It contained inorganic and organic carbon, and essential microbial growth nutrients. The material dissolved slowly under acidic conditions, and it was fine-grained so it could be transported with the rain to the sites of oxidation on the minerals surfaces (Table 1 from Kalin et al., 2010).

Table 1: Particle size distribution and elemental content of NPR (mg/g)

	Ca	P	Fe	Mg	K	Zn	Mn	Cu	Mo	Pb	Co
Fine Gravel 45%	68400	24400	1550	600	400	15.7	4.49	1.84	2.47	0.45	0.11
Coarse Sand 52%	37400	13300	1230	650	200	8.74	3.05	1	1.39	0.27	0.07
Medium Sand 2%	1600	433	300	0.2	0.08	1.1	1.02	1.55	0.04	0.04	0.01
Fine Sand 0.7%	533	200	100	0.23	0.12	0.41	0.36	0.49	0.02	0.02	0
Silt 0.3%	150	3	4.3	1	0.16	0.24	0.16	0.84	0.01	0.02	0
Un-Fractionated	304000	47100	5900	3630	158	388	28.6	29.7	n.a.	n.a.	n.a.

n.a. = not analyzed. Agrium tailings: fine sand 95 %, silt 5 % Agrium ore, Fine gravel 8%, coarse – medium sand 36 %, fine sand 56 %.

If our work was going to be deemed practical by the mining industry, we needed to use a simple, one-time application. Essentially, the application would entail dumping it on the waste rock pile. In the tailings application, the material would need to be tilled into the tailings surface, into the phreatic zone where the acid is generated through seasonal fluctuations of the water table.

We named these two application tests as Phosphate Heterotroph Inhibition of Oxidation (PHITO) for the tailings field plots and Inhibition With Phosphate (IWP) for the waste rock experiments.

PHITO: Phosphate Heterotroph Inhibition of Oxidation

NPR applications would be tilled into tailings to a depth of 10 to 15 cm. As acidic water rose and fell in the tailings, contact with the NPR would form a hardpan of $FeOH_3$. Organic amendments and grass seeds were then applied over the tilled surface to prevent erosion. The hardpan was expected to promote run off and prevent oxygen penetration to the lower tailings strata. The thick organic surface layer would incubate heterotrophic microbial populations which would further reduce oxygen penetration in the tailings.

Field plots were established on uranium and fresh pyrrhotite tailings in Ontario and in a concentrator spill area of a poly-metallic mine in Newfoundland, Canada. The plots in Ontario were set up in 1992 and sampled in 2000 (U and pyrrhotite) allowing 8 years outdoor exposure. The plots in the concentrator spill were set up in 1999 and sampled in 2003, four years later. The samples were kept in plastic bags, allowing oxygen access for several months. Slurries were prepared with water and the supernatant monitored for several months at room temperature. The supernatant was acidified and the tailings were dried and ground in a hand mortar and sent for Inductively Coupled Plasma Spectroscopy (ICP) for elemental content including phosphate (Kalin et al., 2003 and Kalin, 2009; Table 2). These slurries made from treated and untreated tailings showed remarkable differences. Although these data are from a limited number of samples, NPR-treated tailings generally had much lower metal concentrations, higher pH's, and lower acidities.

Table 2: Elemental supernatant chemistry of slurries of tailings

	Uranium		Pyrrhotite		Polymetalic		*Waste rock*	
Elements ($mg.L^{-1}$)	Control	NPR	Control	NPR	Control	NPR	Control	NPR
	N=1	N=1	N=1	N=1	N=2	N=2	N=3	N=6
Al	50	<0.005	870	120	89	5	3.98	0.42
Ca	560	630	500	490	485	510	41	122
Cu	0.59	0.001	0.68	17	86	0.07	14	4.13
Fe	18	0.01	43	0.1	1053	0.02	3.77	0.32
P	0.03	0.05	0.22	6.9	0,16	0.04	0.20	0.13
S	630	510	4460	1060	3020	500	126	123
Zn	0.98	<0.005	9.3	5.3	2085	22	78	22
pH	2.67	6.75	3.06	3.84	3	5	4.06	6.09
Cond.(µS/cm)	3410	1682	7180	4030	6725	1690	*n.a.*	*n.a.*
Eh (mV)	734	584	758	661	784	467	*n.a.*	*n.a.*
Acidity ($mgCaCO_3.L^{-1}$)	656	39	6715	1090	5544	87	257	76

n.a. - Not available

At another Cu/Zn mine waste management area in northern Ontario, thirty tons of coarse gravel NPR were spread on tailings (45% pyrite and 4% pyrrhotite) in 2003. The application was supposed to develop a hardpan and promote a thick vegetation cover to prevent water penetration into the tailings which should lead to improvements or at least no deterioration in the groundwater. Piezometers in the tailings have been sampled sporadically since 1987 and resampled in 2002. To date no follow up sampling has taken place (Fig. 2).

On the same mine, a shallow (<4 m deep) one million m^3 lake had a gradually decreasing pH due to the groundwater discharge into the lake. These discharges add reduced iron during the winter months (under the ice cover) which precipitates as the lake turns over in spring. We needed to stabilize the sediments to prevent re-oxidation of sediment-reduced iron during spring turnover. We did this by transplanting a population of acid-tolerant moss to certain areas of the lake. Then we gradually added a total of 160 T of fine ground NPR to the sediments. The phosphate would precipitate some of the iron as iron-phosphate, while providing a nutrient source for aquatic vegetation. The introduced moss carpet flourished, and covered the lake sediments, as documented in 2006 (Fig. 3). As of 2006, the pH of the lake had stabilized. No follow up was carried out on this system for more than a decade. Recently, though, monitoring data from the regulatory body of Ontario Canada show promising results, suggesting that the lake system may have stabilized, even though there is continued input of AMD from the tailings and underground workings.

Figure 2. Tailings vegetation cover in 2006, three years after application of NPR to the surface of the tailings. NPR was to produce a hardpan to slow water movement into the tailings. Unfortunately, we were not able to sample after 2003.

Figure 3. Acidic lake outflow in 2006. Note that aquatic vegetation and aquatic moss reduce lake turnover and re-suspension of metal-laden sediments.

IWP: Inhibit with Phosphate

IWP was tested using 3 t of waste rocks (in sizes from 0.01 to 0.25 m diameter) from a zinc mine in Quebec. About 5 L of Natural Phosphate Rock was dumped onto waste rock in 70 L plastic garbage containers (drums), others were left as controls. The drums were exposed outdoors in Toronto, Canada for 2.7 years. Drums without NPR generated acid rock drainage (ARD) for the length of the experiment, while those with NPR stopped producing acid after the first winter; instead, generating a pH neutral and low acidity effluent. Effluents stayed pH neutral after being re-exposed for one season outdoors after 4.5 years of storage in a damp basement. These results were presented at conferences (Kalin et al., 1995a ,b, c; Kalin, 1998) and published (Kalin and Harris, 2005).

Applications of NPR to coarse coal waste piles at DEVCO in Cape Breton, Canada were made as part of a larger study of adding limestone (with and without compaction) and bactericides to coarse coal wastes. The seepages from the piles were monitored for several years (Fig. 4a, b). The NPR pile did not produce seepages, but had severe erosion channels on the surface. An autopsy of all piles was conducted at the end of the study to determine the cause of the absence of seepage from the NPR pile. A hardpan was documented in the NPR pile but not in any of the other piles (ADI Nolan Davis, 1995; Fig. 4b). With the hardpan, water could not penetrate the pile, so it ran off, creating surface erosion channels.

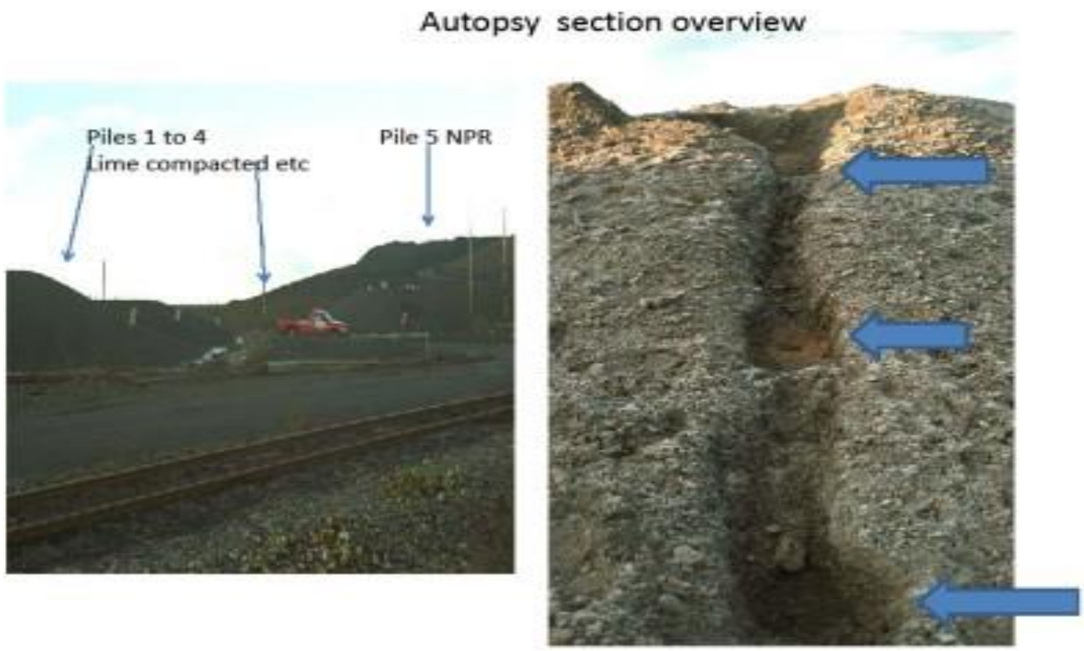


Figure 4: a) On the left side the truck gives the perspective of the size of the piles with the red pickup truck. b) On the right side the arrows point the excavated hardpan in the erosion channel.

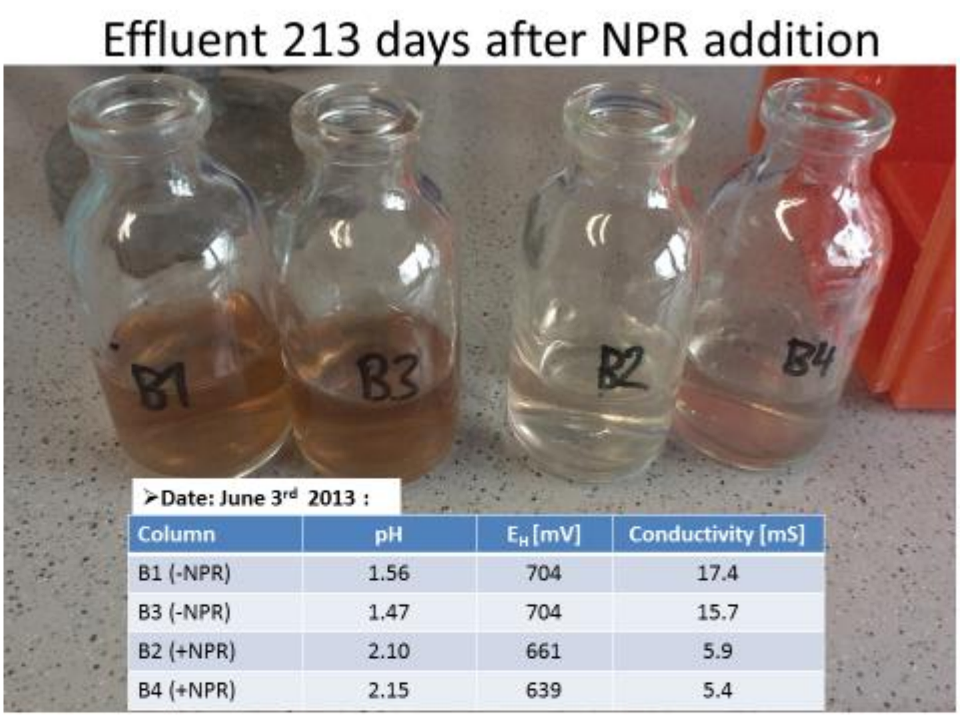
At the University of Essen a PhD study tested NPR from Morocco on German metallurgical coal, again with improved effluents (Massen, 1999). However, improved effluents (or no effluents) alone do not provide proof that microbes are covering the mineral surfaces and reducing oxygen penetration.

Mineral surface biofilms

To confirm what we deduced from the effluent improvements, we needed to look at the mineral surface directly. Was the reduction in oxidation in the presence of NPR due to an organic coating, also referred to as a biofilm? Rocks from the drum experiments were sent to various labs for XRD, SEM and other surface analytical tests (Ueshima et al., 2003; Kalin et al., 2009; Kalin et al., 2010). These studies all confirmed that an organic coating with microbes was present. The organic coating contained inorganic precipitates, and oxygen concentrations on the mineral surface were very low.

Scientists participating in Australian Mineral Industry Research Association (AMIRA) Projects P933 and P933A also searched extensively for an iron-phosphate precipitate on rock surfaces from the drum experiments but found none (AMIRA, 2012). They found an organic coating with embedded iron hydroxides and other precipitates, but only few iron phosphate precipitates.

Although we had evidence that, with additions of waste Natural Phosphate Rock, oxidation was reduced, and biofilms covered the pyrite or sulfide, we did not know which microbial groups were involved. We approached Professor Sand's group at the Biofilm Centre at the University of Duisburg-Essen. Dr. Sand, an expert in bioleaching of metals, agreed to test NPR additions to German lignite coal utilizing his bioleach protocols. Columns with lignite were autoclaved to kill all microbes, and then inoculated with chemo-lithotrophs from Argentina (used in their bioleaching experiments). The columns started with a pH value around 1 and after 213 days the columns still produced a clear effluent (Fig. 5).



Column	pH	E_H [mV]	Conductivity [mS]
B1 (-NPR)	1.56	704	17.4
B3 (-NPR)	1.47	704	15.7
B2 (+NPR)	2.10	661	5.9
B4 (+NPR)	2.15	639	5.4

Figure 5. Effluents collected from the German lignite bioleach inhibition experiment (Bellenberg et al., 2013a).

In the presence of NPR, about 90% of microbial populations consisted of neutrophilic heterotrophs, which covered the pyrite surfaces with a 10 µm thick biofilm. Without NPR, 99% of the populations were iron-oxidizing chemo-lithotrophs in mono-layered, thinner biofilms (Bellenberg et al., 2013b). These results finally confirmed our original assumption that the process is carried out by microbes which alter the surface of the mineral, covering it with a biofilm. In all, NPR was tested on 8 different sulphidic mining wastes, by scientists in 6 different universities, in Germany, Australia and in North America, all finding microbial activity due to NPR (Table 3).

About 21 years have elapsed since we started to look at Natural Phosphate Rock, but we now have provided evidence that the process is stable over the long-term. We have tested field plots years after a single application of the NPR. We have exposed the sampled material to oxidizing conditions in storage, rehydrated them, and again collected effluents. From these experiments, we have provided evidence that the biofilms lasted more than a decade (Kalin et al., 2010).

In Table 3 we summarized the number of scientists who have repeated our experiments (Bellenberg, Fortin, Sand, Smart and Massen) and/or investigated rock from the waste rock drum experiment (Sleep, Smart and Paulo). Dr. Ferris, a bio-geochemist at the University of Toronto, contributed to the design of the waste rock (drum) experiment and supervised a 4th year thesis on the solubility of the added NPR (Kasumovich, 1996). At a later stage, he contributed to the calculations of the weathering rate and consumption of NPR during the drum experiment (Kalin et al., 2009). Dr. Ueshima, a postdoc in Dr. Fortin's Laboratory at the University of Ottawa, analyzed the surface of the rocks and carried out experiments with NPR on microbial colonization of pyrite (Ueshima et al., 2004). Dr. Smart, under a 6-year AMIRA (2012) project, tested NPR on Red Dog Mine wastes. Dr. Werker, at the University of Waterloo, did the statistical analysis of the tailings slurries prepared from the tailings plots with and without NPR, which had been stored for several years after sampling and then exposed to oxidizing conditions.

Conclusions and the Way Forward

Recently we conducted an exhaustive literature search on acidophilic and neutrophilic biofilm formation. The literature review was initiated to understand the science surrounding our initial findings that AMD could be mitigated by enhancing heterotrophic biofilms. These biofilms covered and slowed oxidizing microbes on pyrite in waste rock piles and tailing deposits. Sixteen questions of practical relevance, such as what are the triggers to biofilm formation and could NPR serve as such a stimulus? We found in the scientific literature 8 conditions which are documented to trigger biofilm formation, 5 of which could take place given the characteristics of NPR when reaching the mineral surface. The scientific evidence we uncovered in the literature strongly supports our observations that heterotrophic biofilms can outcompete chemo-lithotrophs and suppress oxidative activity. Biofilm formation is a universal process, based on microbiological, ecological and bio-geochemical principles. Our field tests on various waste materials demonstrate the universality of the process.

Table 3. Research authors, organizations, and waste types studied in the pursuit of phosphate-controlled AMD/ARD. The first 5 researchers are core scientists with Boojum Research; the others were enlisted to solve particular aspects of the search for heterotrophic biofilms.

Author	# reports	Organisation	Waste type
Kalin, M.	31	Boojum	All
Smith, M.P.	10	Boojum	Coal Nova Scotia
Fyson, A.	10	Boojum	Rock Quebec
Wheeler, W.N.	6	Boojum	All
Paulo, C.	4	Boojum	Rock Quebec
Fortin, D.	3	U of Ottawa	Rock Quebec
Meinrath, G.	2	RER	Tailings *
Ueshima, M.	2	U of Ottawa	Rock Quebec
Bellenberg, S.	1	U of Duisburg Essen	German coal
Sand, W.	1	U of Duisburg Essen	German coal
Smart, R.	1	U of South Australia	Rock Yukon
Sleep, B.	1	U of Toronto	Rock Quebec
Ferris, G.	1	U of Toronto	Rock Quebec
Harris, B.	1	U of McGill	Rock Quebec
Werker, A.	1	U of Waterloo	Tailings *
# Authors	**15**	8	8*
* Uranium, pyrrhotite and zinc tailings others sulphidic rock			

We have shown that a one-time application of Natural Phosphate Rock to both tailings and waste rock can and does foster the development of heterotrophic microbial biofilms. In the case of tailings, we have shown that tilling NPR into the top 15 cm of fresh and aged tailings can form hardpans which reduce oxygen and water entry. With waste rock, the lesson we learned from the Gibraltar heap leach system, and our own drum experiments, is that NPR can provide enough nutrients to allow heterotrophs to outcompete the acidophilic, lithotrophic microbes that catalyse the acid generation process. The early researchers were correct, phosphate does reduce oxidation of pyrite, but it does so, not as a chemical reaction, but as a biological one.

We need to look beyond engineering and chemical solutions to our environmental problems and embrace more natural and environmentally-friendly means to combat acid mine drainage. Applying Newton's third law to this situation, we can state that for every microbe that can enhance oxidation, there are other microbes that can reduce oxidation, we just need to find them, and encourage them to assist us. As Professor Amadei (2004), founder of the Engineers Without Borders from the University of Colorado, Civil Engineering stated:

> "*As we enter the twenty-first century, we must embark on a worldwide transition to a more holistic approach to engineering. This will require: (1) a major paradigm shift from control of nature to participation with nature; (2) an awareness of ecosystems, ecosystems services, and the preservation and restoration of natural capital; and (3) a new mindset of the mutual enhancement of nature and humans that embraces the principles of sustainable development, renewable resources management, appropriate technology, natural capitalism, biomimicry, biosoma, and systems thinking*."

A one-time application of NPR to mining wastes to reduce weathering and hence produce seepages which are iron free as shown in Fig. 4 must appeal to the regulatory agencies and any economically-minded mining company interested in the restoration of mining wastes and water. We believe we have provided proof of concept both in the field and over an extended time period, but this approach needs to be followed up. Is anyone interested?

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