Can natural Stratification prevent Pollution by Acid Mine Drainage?

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Abstract

Acid mine drainage (AMD) from underground or open pit mines is considered one of the most problematic liquid pollutants in the mining environment. Therefore, it is crucial for mine operators to either prevent AMD or to purify the water once it emerges to surface water courses. Though a number of AMD prevention techniques exist, they are not as far developed as would be necessary for preventing AMD discharges regularly. Therefore, the standard method to eliminate pollutants, acidity and solids from AMD are active or passive treatment techniques. After mining ceases, it would be of importance to have methods available that can either prevent the discharge of AMD or the treatment is conducted *in-situ* of the abandoned mine. Various authors investigated or proposed to use the effects of natural stratification as a means to prevent AMD discharging from abandoned mines.

Natural stratification is the layering of water bodies, in this case in a flooded underground mine, by water of various chemical or physical properties. These physicochemical differences result in density differences which, consequently, may cause the stratification of mine water bodies. Stratification in flooded underground mines has long been known to occur under certain conditions, but a detailed study of its causes has not been conducted yet. This paper will present stratification investigations in flooded underground mines and investigate if natural stratification is able to prevent surface water courses from being polluted by AMD.

Based on the *Straßberg*/Germany, the *Georgi Unterbau*/Austria, the Frances Colliery/England and the 1B Mine Pool/Canada, the natural stratification and its causes will be described and the reasons for its breakdown be discussed. The presentation will describe the stratification pattern, the water chemistry and why the systems cannot be used as reliable options for long term *in-situ* remediation. It will not considered forced stratification which can be caused by manmade structures.

One of the key findings of this investigation is that natural stratification is not stable and can be broken down by a variety of external forces. Proposing to use natural stratification as a means for *in-situ* remediation or to prevent the discharge of AMD to the environment is therefore not feasible. In case of their breakdown, the polluted AMD will cause damages to the natural environment if no other means for water treatment are available. Consequently, for a full understanding of stratification in flooded underground mines, more work will be necessary and analogue laboratory as well as numerical models need to be conducted for a better understanding of the processes involved.

Key words: Mine water, stratification, pollution prevention

Introduction

Mine water pollution is a threat to nearly all areas in the world where mining played a substantial economic role in the past or today (Younger et al. 2002). This pollution can arise from tailings dams, waste rock deposits, soil contamination from using chemicals or from mine water *sensu stricto* (Wolkersdorfer 2008). In nearly all cases, where treatment or remediation measures are employed to eliminate this pollution, active treatment methods are the method of choice. Yet, these methods are costly and operators and authorities around the world are trying to identify methods to reduce the costs of site clean-up or water treatment (Zinck and Aubé 2010). Since the 1980ies, methods have been developed for polluted mine sites (Chapman et al. 1988) and are still under investigations in various mining regions around the world (Novhe 2012), *in-situ* methods being one of these passive methods being investigated (e.g. Elina 2009; Harrington et al. 2015). Though these *in-situ* methods for mine water treatment have been probed or where developed, they are currently not used to a grade that might technically be feasible.

Off the potential pollution arising from working or abandoned mine sites, acid mine drainage (AMD) is one of the most problematic pollutants (Blowes et al. 2014; Kelly et al. 1988), as it usually contains elevated acidity loads or potentially toxic elements (PTE). Yet, also circumneutral or alkaline mine drainage might pose problems and can severely pollute receiving water courses or the environment around a polluted mine site (Nordstrom 2011). Usually, the sources for this mine water pollution are the disulphides within the mined voids, i.e. in the open pit mines or underground mines (Stumm and Morgan 1996). It would therefore be favourable if the sources of this pollution could be eliminated or sealed off. One of the methods proposed by various authors is to use the natural stratification in underground mines to keep the more polluted water within the mine (Melchers et al. 2015; Wolkersdorfer 1996; Wolkersdorfer 2006; Wolkersdorfer 2008). Yet, the most common mine water treatment options to date are active or passive methods (Bejan and Bunce 2015).

Stratification is the layering of water into water bodies with distinct physicochemical characteristics, such as the temperature and electrical conductivity and can be stable for a long period of time (Zeman et al. 2008). The differences in theses physicochemical characteristics result in different densities of the water and once the density differences between the single water bodies exceeds a certain threshold, a more or less stable stratification will develop in the water body. In most cases, this stratification is a natural process, occurs without actively interfering with the water body and is referred to as “natural stratification”. “Forced stratification”, on the other hand, would be stratification that is actively promoted by the installation of manmade structures or the modification of water flows. The reason for a stable stratification is a large enough density difference between the two layers and a relatively small velocity difference between them Wolkersdorfer (2008). In general, temperature differences above 10 K ($\Delta\rho$ > 2 kg/m³), total dissolved solid differences of more than 3% ($\Delta\rho$ > 20 kg/m³) or large differences in turbidity ($\Delta\rho$ > 200 kg/m³) can cause stable stratification (Kranawettreiser 1989).

This effect of stratification is well known and has been thoroughly studied in lakes or the ocean (Blanc and Anschutz 1995; Geller et al. 2013; Voorhis and Dorson 1975). Researchers and mine operators also found stratification in flooded underground mines, the first known study dating back to 1961 (Stuart and Simpson 1961), and in some cases it was assumed that this stratification can be used to omit the discharge of polluted mine water from abandoned shafts. Though natural stratification in flooded underground mines is long know, systematic studies into the causes of this stratification and if it might be possible to use it as a passive remediation method are lacking in the mine water literature. The only more detailed studies known to date with dozens of measurements and tracer tests as well as chemical investigations have been conducted by Wolkersdorfer (1996) for the *Niederschlema/Alberoda* uranium mine and for several other sites by Wolkersdorfer (2008). Most other publications usually deal with only single observations without providing details about the observed stratification.

In the light of the pollution arising from the flooded underground gold mines in South Africa’s Witwatersrand, the discussion about natural mine water stratification and how it can be used as a remediation measure is emanating again (Sheridan et al. 2015). A downhole measurement in the West Rand Consolidated’s Deep Shaft, conducted in 2000, showed that the mine pool at this time was stratified into 4 distinct layers with better quality water on the top (electrical conductivity ± 1 mS/cm) and bad water at a depth of 1078 m (± 7 mS/cm). This paper will therefore take a look at the features of stratification and tries to indicate some of the causes for stratification by investigating already existing literature and non-published results.

Methods

Existing literature and unpublished data of the first author were studied to identify cases of stratification in flooded underground mines. A lot of data is published on stratification in flooded pit lakes and natural lakes (Geller et al. 2013), but as the initial reasons that cause stratification in lakes are different from underground mines, these cases will not be discussed further. All the identified cases of mine water stratification in the literature were compared against each other. Based on these similarities, the *Straßberg*/Germany, the *Georgi Unterbau*/Austria, the Frances Colliery/England and the 1B Mine Pool/Canada were chosen as these are the most thoroughly investigated sites know. Currently, there is not enough data available to validate if all flooded underground mines eventually show stratification and how stable that stratification might be.

Measurements in the flooded shafts by the first author were conducted with various dippers, some only measuring the temperature, others the temperature and electrical conductivity (Spohr-Messtechnik GmbH, Germany; Solinst TLC, Canada; Heron Instruments, Canada; Ott Gmbh, Germany). In addition, continuously measuring downhole probes (Login Gommern, Germany) were used to monitor the physico-chemical parameters in flooded shafts. To identify chemical parameters of the mine water, a large number of chemical and physicochemical parameters were measured on mine water that was sampled depth dependent in various shafts.

Results and Discussion

Unquestionable, one of the most extensive investigations into the stratification of flooded mine shafts was conducted at the German *Hope* salt mine with the aim of investigating the flooding of a radioactive waste disposal site (G. S. F. – Gesellschaft für Strahlen- und Umweltforschung 1985; Herbert and Sander 1987). Shafts and workings were equipped with 16 stationary monitoring stations located at 4 different working levels and physicochemical measurements with mobile downhole probes were conducted in the *Hope* and *Adolfsglück* shafts. The investigations started in 1984 and continued during the whole flooding process until 1988. Detailed physicochemical measurements and calculations resulted in an extensive database which was mainly used for interpreting seismic events, the chemical evolution of the brine and the developing stratification in the two shafts. It became obvious that water with higher temperatures and electrical conductivities, i.e. mineralization, which consequently results in higher densities collects in the lower parts of the mine. This development became obvious already during the initial stage of the flooding, but became more prominent at later stages. A comprehensive, English summary of the results is given in Wolkersdorfer (2008, 330 ff).

Another long term study of stratification in flooded mine shafts was conducted by Wolkersdorfer (1996) at the 2000 m deep Niederschlema/Alberoda, Germany uranium mine; at that time the deepest metal mine in Europa. These studies comprised of 200 physicochemical and 477 chemical studies in seven, 380 to 761 m deep mine shafts and a large scale tracer test. Water sampling and mobile downhole probes (temperature, electrical conductivity, pH, redox, water velocity) as well as dippers (temperature) were used during the investigations and a comprehensive, partly unpublished dataset was produced (the results discussed here are based on a re-examination of the dataset published together with the inaugural version of the before mentioned thesis). Without going into details, it could be shown that the deeper portions of the mine always contain water with a lower quality and that the water quality in the interconnected sections of the mine usually showed similar physicochemical and chemical properties. A total of 19 downhole redox measurements were conducted in the shafts when the on-site situation allowed lowering the probe. To protect the redox probe, continuous measurements were only possible up to a water depth of 167 m. Without exception, all measurements showed a decrease of the redox potential, with the lowest redox-potentials in the deepest parts of the shafts. Identical results were obtained by Snyder (2012), who measured redox potentials in seven shafts in Butte, Montana/USA up to 300 m water depths. These low redox potentials at the Niederschlema/Alberoda site were also connected to lower Fe_{tot}- and U-concentrations in the mine water. As-concentrations showed a positive correlation and SO_4-concentrations are not affected by the redox potential of the mine water. Based on the tracer test's results nearly the whole mine is well interconnected and the mean effective mine water velocity ranges between 1 and 20 m/min with an overall average around 1 m/min.

A large number of mostly unpublished depth dependent physico-chemical and chemical measurements were conducted at the flooded *Straßberg*/Germany fluorspar mine. These data were compiled by DMT (Rüterkamp and Meßer 2000) and are partly published in various articles (Kindermann 1998; Kindermann and Klemm 1996; Klemm and Kindermann 1996) with an English compilation in Wolkersdorfer (2008, 318 ff). This mine has four day-shafts of which three were used for man and material haulage, and the three sections of the mine are joined by two adits on the 5th and 9th working level. Two of these shafts (*Überhauen* 539 and *Hauptschacht*) have been easily accessible for *in-situ* measurements and showed the development of a stratification between the start of flooding in 1992 and 1997 (Kindermann 1998). This stratification consisted of two layers with water of distinctive chemical characteristics: highly contaminated water in the deeper parts and less contaminated water in the shallower parts of the mine. Both layers showed a water quality improvement over time. It was therefore decided to stop pumping and treating the mine water from the *Hauptschacht* (main shaft) and construct three dewatering adits into the less contaminated upper layer. The idea was to discharge the less contaminated water into the receiving streams and treat the water only until the water quality improves even more as the less contaminated layer gets less contaminated. Yet, immediately when the three dewatering adits were completed in 1998, the stratification broke down, the discharging water quality substantially worsened and the total annual flow increased by 2 Mm^3. This was caused by the fact that the newly constructed adits allowed for open convection loops, resulting in a complete mixing of the mine water pool. Eventually, a full scale mine water treatment plant was constructed and treats the polluted mine water before it is discharged in to the receiving Uhlenbach stream.

One of the main differences between the three before mentioned mines and the *Georgi Unterbau*/Austria is the fact that the latter has only one main shaft, where the mine water discharges into the 320 m long dewatering adit (Wolkersdorfer 2008, 325 ff). This blind shaft, constructed in 1900, is 100 m deep and connects to the 20, 40, 70 and 100 m levels of the mine (Pirkl 1961; Schmidegg 1953). Between 2000 and 2002, several depth dependent measurements of the temperature and electrical conductivity as well as discrete chemical measurements of the mine water were conducted. In addition, two tracer tests took place. The physico-chemical and chemical measurements identified two distinct layers of mine water with only small differences in their chemical and physico-chemical properties. Though these differences resulted only in minor density differences of the mine water layers, the stratification remained consistent throughout the whole time of investigation. Yet, it was damaged instantly, when 200 kg of a NaCl tracer was injected into a small connecting blind shaft, but was naturally restored half a year later. A tracer test with a solid tracer showed no tracer from the lower layer of mine water at the point of discharge of the shaft, which also could be proven by a numerical model of the flooded mine (Unger 2002).

Nuttall et al. (2002) conducted investigations in the Frances Colliery/England. During a pump test in one of the flooded shafts, they encountered a substantial deterioration of the water quality and a scaling of the equipment within 4 hours (Croxford et al. 2004). Subsequent depth dependent measurements in the shaft identified a stratification with water of higher electrical conductivities in the lowermost parts of the shaft and water with better quality overlaying this highly contaminated mine water body. While SO_4-concentrations in the upper layer were in the range of several hundred mg/L, they reached 4000 mg/L in the lower layer. This increase is accompanied by a decrease in pH from around 7 to 5. Later electrical conductivity measurements in this shaft by Wyatt et al. (2014) showed that the stratification still persisted in 2012 with electrical conductivities around 4 mS/cm in the uppermost layer and 14 – 15 mS/cm in the lower one. It was also observed that the redox potential increased from 50 to 150 mV during the initial phase of the pump test but decreased to 0 mV once the deep water was pumped. During the course of the pump test the mine water's redox potential increased again to 100 – 150 mV (Elliot and Younger 2007) indicating a mixing with less reducing water.

A different case compared to the before mentioned mines is the flooded 1B Mine Pool on Cape Breton Island/Canada. No single shaft exists, but a number of inaccessible inclines and adits and many boreholes into the mine water pool (Shea 2009). In 14 boreholes, the water temperature and the electrical conductivity was measured with downhole probes between 2009 and 2010 (Secka 2010). Instead of discrete depth dependant samples, mine water samples were taken after pumping clear a selection of these wells. It became obvious that a layering of the mine water exists. Part of that layering might be a result of the hydrodynamics in small diameter wells and does not represent the overall layering in the whole mine. Yet, the mine water chemistry clearly indicates that there is a stratification in the mine pool with a lower water quality in the deeper parts and a better water quality in the shallower parts of the mine pool (Chimhanda 2010). Fe_{tot}-concentrations in these deeper layer can reach up to 300 mg/L while the upper layer has Fe_{tot}-concentrations of 30 mg/L and less. No correlation of the redox potential and the contamination load could be show, which might be due to the sampling procedure.

Conclusions

All the above mentioned cases of stratification are a result of natural processes occurring in a flooded underground mine. In none of these mines, the mine layout was modified such as to promote the build-up of layers with different water qualities. It can therefore concluded that many mines develop a more or less stable natural stratification. In all cases discussed above, the water quality in the deeper water body of the mines is worse than the water quality in the shallower parts of the mine, which is obvious, because the fresh water infiltrating into a flooded underground mine as groundwater or surface water is usually unpolluted and has a lower density than the mine water. It therefore "floats" on top of the higher contaminated mine water which, consequently, has a higher density. Yet, the *Georgi Unterbau* case shows that mines with only one shaft develop a less stable stratification as the stratification broke down when a NaCl tracer was injected into the shaft.

As has been shown in the *Straßberg* fluorspar or the Francis Colliery mines, the stratification immediately breaks down when the water is pumped from depth or when a convection loop is allowed to build up. In the case of the Western Pool of the flooded Witwatersrand gold mines, pumping from deeper depths, as suggested by Sheridan et al. (2015), would therefore continually cause a forced flow and mixing in the deepest sections of the mine pool where the water quality is always bad. This would result in low quality, possibly acidic mine water that has to be treated until perpetuity. Yet, if the mine water is allowed to rise as high as possible, a layer with a better water quality will very likely develop on top of the less quality water. Consequently, if the water pumped from this layer does not exceed the mine water recharge, which means that no forced flow between the higher and lesser contaminated mine water is caused, it is possible to use natural stratification to lower the treatment costs of polluted mine water. More tracer tests, *in-situ* measurements in shafts and analogue mine models are necessary, to understand the detailed reasons behind building up of natural mine water stratification and how this knowledge can be used in the future to force stratification in mines.

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References

Bejan D, Bunce NJ (2015) Acid mine drainage: electrochemical approaches to prevention and remediation of acidity and toxic metals. J Appl Electrochem 45(12):1239-1254. doi:10.1007/s10800-015-0884-2

Blanc G, Anschutz P (1995) New stratification in the hydrothermal brine system of the Atlantis II Deep, Red Sea. Geology 23(6):543-546

Blowes DW, Ptacek CJ, Jambor JL, Weisener CG, Paktunc D, Gould WD, Johnson DB (2014) The Geochemistry of Acid Mine Drainage. In: Turekian HD, Holland KK (eds) Treatise on Geochemistry. 2nd edn. Elsevier, Oxford, p 131-190

Chapman BM, Jones DR, Jung RF, Jones CJ, Kadletz O, Teague JWS (1988) Treatment and Utilisation of Hilton Mine Water. Proceedings, 3rd International Mine Water Congress, Melbourne:147-156

Chimhanda WB (2010) Hydrogeochemical and Isotopic Investigations of the Mine Water in the 1B Mine Pool of the Sydney Coal Field, Nova Scotia, Canada. unpubl. Master Thesis Univ. Tübingen, Tübingen

Croxford SJ, England A, Jarvis AP (2004) Application of the PHREEQC geochemical Computer Model during the Design and Operation of UK Mine Water Treatment Schemes, vol 2. University of Newcastle, Newcastle upon Tyne

Elina AV (2009) In Situ Treatment of Acid Mine Drainage by Sulphate Reducing Bacteria. Proceedings Securing the Future 2009 & 8th ICARD, Skellefteå

Elliot T, Younger PL (2007) Hydrochemical and isotopic tracing of mixing dynamics and water quality evolution under pumping conditions in the mine shaft of the abandoned Frances Colliery, Scotland. Appl Geochem 22(12):2834-2860. doi:10.1016/j.apgeochem.2007.07.007

G. S. F. – Gesellschaft für Strahlen- und Umweltforschung (1985) Untersuchungen endlagerrelevanter Vorgänge vor, während und nach der Flutung des Kalisalzbergwerkes Hope. 1. Bericht. gsf-Bericht 12/85:286

Geller W, Schultze M, Kleinmann R, Wolkersdorfer C (2013) Acidic Pit Lakes – The Legacy of Coal and Metal Surface Mines. Springer, Heidelberg

Harrington J, Harrington J, Lancaster E, Gault A, Woloshyn K (2015) Bioreactor and In Situ Mine Pool Treatment Options for Cold Climate Mine Closure at Keno Hill, YT. In: Brown A, et al. (eds) Agreeing on solutions for more sustainable mine water management. Gecamin, Santiago/Chile, p 1-10 [electronic document]

Herbert H-J, Sander W (1987) Die Flutung des Kalibergwerks Hope – Ergebnisse des geochemischen Meßprogramms. Kali und Steinsalz 9(10):326-333

Kelly M, Allison WJ, Garman AR, Symon CJ (1988) Mining and the Freshwater Environment. Elsevier Applied Science, London

Kindermann L (1998) Kontrolle geochemischer Parameter beim Wiedereinbau von Reststoffen in ein stillgelegtes Bergwerk. Wiss Mitt 7:196-201

Kindermann L, Klemm W (1996) Untersuchungen der provisorischen Wasseraufbereitungsanlage Straßberg der BST-Mansfeld GmbH (ehemalige Flußspatgrube Straßberg). Unveröff Bericht TU Bergakademie Feiberg:48

Klemm W, Kindermann L (1996) Datenerfassung zur Entwicklung der Wasserqualität in der ehemalige Flußspatgrube Straßberg. Unveröff. Bericht TU Bergakademie Feiberg, Freiberg

Kranawettreiser J (1989) Dichteströmungen, vol 2, 1st edn. VEB Verlag für Bauwesen, Berlin

Melchers C, Coldewey WG, Goerke-Mallet P, Wesche D, Henkel L (2015) Dichteschichtungen in Flutungswasserkörpern als Beitrag zur Optimierung der langzeitigen Wasserhaltung. In: Paul M (ed) Sanierte Bergbaustandorte im Spannungsfeld zwischen Nachsorge und Nachnutzung – WISSYM 2015. Wismut GmbH, Chemnitz, p 99-106

Nordstrom DK (2011) Mine Waters: Acidic to Circumneutral. Elements 7(6):393-398. doi:10.2113/gselements.7.6.393

Novhe NO (2012) Evaluation of the applicability of the passive treatment for the management of polluted mine water in the Witwatersrand Goldfields, South Africa. Edith Cowan University, Bunbury

Nuttall CA, Adams R, Younger PL (2002) Integrated hydraulic-hydrogeochemical assessment of flooded deep mine voids by test pumping at the Deerplay (Lancashire) and Frances (Fife) Colliery. Spec Publ – Geol Soc London 198:315-326

Pirkl H (1961) Geologie des Trias-Streifens und des Schwazer Dolomits südlich des Inn zwischen Schwaz und Wörgl (Tirol). Jb Geol B-A 104(1):1-150

Rüterkamp P, Meßer J (2000) Untersuchungen zur hydraulischen und hydrochemischen Situation in den drei Teilrevieren der gefluteten Flussspatgrube Straßberg. Deutsche Montan Technologie GmbH, Essen, p 46

Schmidegg O (1953) Die Erzlagerstätten am Reiter Kopf und am Reiter Kogel. Schlern-Schr 101:17-25

Secka AK (2010) Investigation of a potential Mine Water Stratification in the 1B Mine Pool. Chemical Engineering Department. Dalhousie University, Halifax, p vi + 15

Shea J (2009) Mine Water Management of Flooded Coal Mines in the Sydney Coal Field, Nova Scotia, Canada. Document Transformation Technologies, Pretoria

Sheridan C, Bonner R, Bruyns L, Burgess J, Drake D, Harding K, Janet JP, Rumbold K, Saber N (2015) Conceptual Project on Eliminating Acid Mine Drainage (AMD) by Directed Pumping. In: Brown A, et al. (eds) Agreeing on solutions for more sustainable mine water management. Gecamin, Santiago/Chile, p 1-10 [electronic document]

Snyder D (2012) Vertical gradients in geochemistry of flooded mine shafts in Butte, Montana. M.S., Montana Tech of The University of Montana

Stuart WT, Simpson TA (1961) Variations of pH with depth in anthracite mine-water pools in Pennsylvania; Article 37. US Geol Surv Prof Pap 0424-B:B82-B84

Stumm W, Morgan JJ (1996) Aquatic chemistry – Chemical Equilibria and Rates in Natural Waters, 3rd edn. Wiley & Sons, New York

Unger K (2002) Hydrodynamische Verhältnisse im gefluteten Unterbau des Bergwerks Großkogel/Tirol – Numerische Modellierung mit ANSYS-FLOTRAN. Unveröff. Dipl.-Arb. TU Bergakademie Freiberg, Freiberg

Voorhis AD, Dorson DL (1975) Thermal convection in the Atlantis II hot brine pool. Deep-Sea Research 22:167-175

Wolkersdorfer C (1996) Hydrogeochemische Verhältnisse im Flutungswasser eines Uranbergwerks – Die Lagerstätte Niederschlema/Alberoda. Clausthaler Geowissenschaftliche Dissertationen 50:1-216

Wolkersdorfer C (2006) Acid Mine Drainage Tracer Tests, vol 7. Proceedings 7th International Conference on Acid Rock Drainage (ICARD), St. Louis

Wolkersdorfer C (2008) Water Management at Abandoned Flooded Underground Mines – Fundamentals, Tracer Tests, Modelling, Water Treatment. Springer, Heidelberg

Wyatt LM, Moorhouse AML, Watson IA (2014) Evolution in Tidal Related Hydrogeochemisty at a Long-term Coal Mine Water Pumping and Treatment Scheme, Former Frances Colliery, Scotland. In: Sui W, Sun Y, Wang C (eds) An Interdisciplinary Response to Mine Water Challenges. International Mine Water Association, Xuzhou, p 9-13

Younger PL, Banwart SA, Hedin RS (2002) Mine Water – Hydrology, Pollution, Remediation. Kluwer, Dordrecht

Zeman J, Šupíková I, Cerník M (2008) Mine Water Stratification at Abandoned Mines and its Geochemical Model. Proceedings, 10th International Mine Water Association Congress:183-186

Zinck JMM, Aubé BA (2010) Overcoming Active Treatment Challenges. Cape Breton University Press, Sydney, NS