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Innovative approach to reduce acid mine water drainage (AMD) and dump failures on example of German lignite mining

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Abstract. The impact to water resources is a critical issue in mining. The exploitation of a mine can influence surface water systems, like rivers, lakes, swamps, and groundwater systems, like aquifers, seriously. The impact concerns and the pumping of water out of the mining area, relocation of water bodies, changes in water quality, and the creation of new water bodies and hydraulic systems in the environment in and around the mining area. The since 1990 lasting mine closure activities of coal, uranium, salt and other mines in Germany shows the dimension of the impact, and the long term character of establishing a new, self-regulating surface and groundwater system with a stable volume and quality of water. Because of the presence of sulfidic minerals like pyrite and marcasite in the overburden and in the coal of lignite mines, the well-known phenomena of Acid Mine Water Drainage (AMD) becomes an important issue in public awareness and in permission processes. The Frame Water Regulation of European Union not more allow an impact to the water systems in the future. For running projects measures must developed to decrease or avoid the impact to water systems. The article deals with a new developed and successful applied method, how to reduce the impact to the water quality by AMD. The solution was founding by balancing of potential acid and buffer geological material in the overburden and interburden, and their selective mining and dumping by a zero AMD strategy. The strategy has the target, that potential acid and buffer materials are been dumped in layers on each other, so that the acid production is immediately buffed by the soils around. The second part is, to avoid and reduce the oxygen access to the sulfidic soils, e.g. by covering the working levels with neutral soil and seed of grass, immediately behind the excavators and spreaders. The precondition was the establishment of a quality model of the hydrogeochemical behavior of the over- and interburden formations by using the drill hole data. In a second step an accurate mine planning and operation system was introduced. The monitoring shows, that since introducing the new technology, no acid mine water runs out

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of the dumps. Significant is, that the introduction of the new approach of planning and operation of the waste material in the mining company not requires technical changes or additional resources. A side effect is that with the reduction of AMD, possible production of CO_2 in the dumps by interaction of acid and carbonates reduced. This is relevant for the dump stability and the ecology of the mining project.

Key words: acid mine drainage, advanced mining technology, buffering, dump structure, geochemistry, glacial till, groundwater, mine water, slope and dump stability, soil liquefaction, pyrite weathering, trace metals.

1. Introduction to the problems

The densely populated Central German region is rich in lignite. In addition to an energetic use of the lignite, the material use will become more important in the future. Due to the annual extraction of approx. 180 million t of lignite and removal of approx. 1 billion m³ of overburden, valuable land will been used. Most of the overburden immediately backfilled in the out mined area creating internal dumps. In addition, outside dumps can created. These dumps should have good geotechnical as well geochemical conditions [1; 2].

One task during the groundwater re-rise in the future dumps of lignite mines, is the influence on surrounding water bodies as result of the pyrite weathering in the overburden. This sulfide weathering caused by the air contact during the excavation of the overburden and geochemical changes especially with a release of iron, sulfate and H^+- ions into the dump water.

Weathering of Pyrite

$$FeS_2 + H_20 + 3{,}5O_2 \rightarrow Fe^{2+} + 2H^+ + 2SO_4^{2-} \quad or$$

$$FeS_2 + 1{,}5H_20 + 3{,}75O_2 \rightarrow Fe(OH)_3 + 4H^+ + 2SO_4^{2-} \quad \circlearrowleft \quad \text{pH-level} \downarrow$$

Figures 1 shows a typical geological and technical situation in a lignite mine.

This partial weathering of sulfide is be embedded in a variety of hydro-geochemical buffer reactions. The essential buffers against the released H^+-ions are carbonate-, alumo-silicate/hydroxide- and alumo-silicate-buffers. Of particular importance is the first stage buffering (carbonate buffering).

Buffering by Carbonates

$$MetalCO_3 + 2H^+ \rightarrow Metal^{2+} + H_20 + CO_2 \quad \circlearrowleft \quad \text{pH-level} \uparrow$$

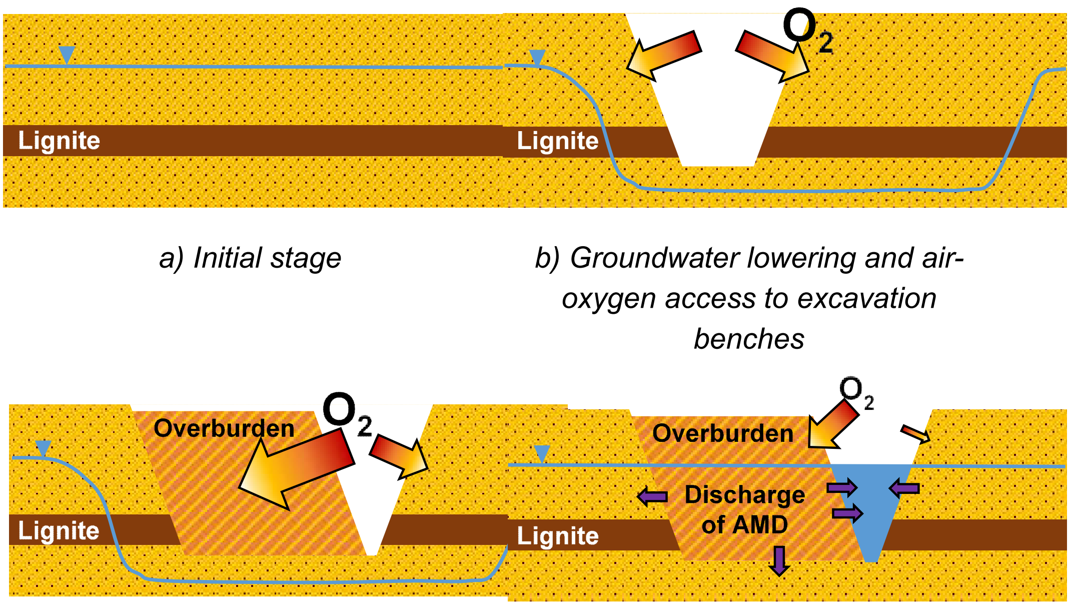
Therefore, the mass ratio of geogenic carbonates and the capacity of acidification and buffering have great importance. Only after the collapse of the buffer results a decrease of the pH-level and the release of iron and heavy metals.

Especially the following mining processes may be responsible for the access of air and water to the iron sulfides (Fig. 2):

− the lowering the groundwater level

− the exposure of the rock surface to the air by loosening the structure of the rock mass and by processing the rock thus mined

− the dumping/depositing of rock and of the processing residues.



a) Initial stage

b) Groundwater lowering and air-oxygen access to excavation benches

c) Oxidation of the overburden on excavation benches and on/in overburden dumps

d) Uncontrolled discharge of AMD into ground- and surface water

Fig. 1. Stages (a) to d)) of AMD in a surface mine.

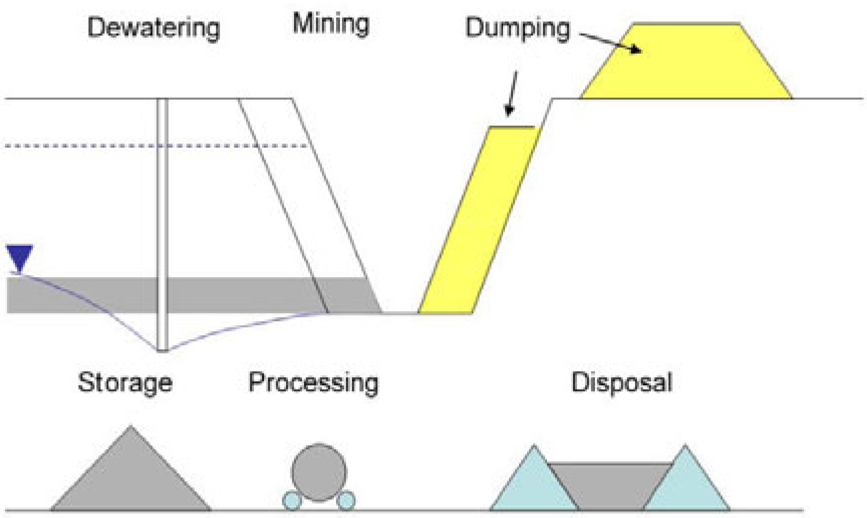


Fig. 2. Sources of AMD.

The lowering of the pH-value, the formation of sulfates and the release of cations may have a negative effect on the soil and water quality. Plants can hardly grow anymore and life in the water is virtually impossible at a pH-value of less than 3.5. Carbonates and heavy metals can dissolve and been washed away. This process is especially critical, when the heavy metal concentrations in the solution assume dimensions that will endanger the environment and/or the health.
The process of acidic water formation is a phenomenon occurring all over the world in the mining sector, both in surface and underground mining, as soon as there are iron sulfide minerals and the reaction conditions are satisfied. In Germany, this applies to tertiary, sulfide-containing sediments that exposed in the course of lignite mining and then dumped again. The same conversion processes also continue in hollow spaces underground and on dumps of disused ore and spar mines, where these undesired release processes, especially the release of heavy metals, are still occurring after hundreds of years.
These processes are not only of anthropogenic origin but have also natural causes.

2. Measures again acidic water formation

The process of acidic mine water formation can be influenced by mine planning and operation. A prerequisite would be sufficient knowledge of the geogenic acidic potential, i.e. a geo-chemical characterization of the soils/ rocks have to excavate. The climatic conditions as well as the existence and sensitivity of protected goods that may be affected by acid water must also be given due regard. Hence, a clear distinction must be made between the effects and the appropriateness of the measures against acidic water in arid, deserted areas on the one hand and in densely populated, humid climates, on the other.
Mine planning can ensure thru the ensuing proper mining operations that the formation of acidic water prevented at all (primary measures) or that the unavoidable formation of acidic water minimized and neutralized (secondary measures). Tertiary measures will have to planned, when it is impossible to control the acidic water within the required limits (quantity and quality) during the mining operations.

3. Primary measures

According to the above chemical processes, the protons can be released primarily by preventing the sulfide minerals from getting into contact with oxygen and water. As an example, it is possible to exclude the oxygen from the air by using underwater mining techniques (Fig. 3).
In order to implement the primary measures, the position of the working levels in open-cast lignite mines, where the rock has settled in layers, can be arranged in such a way that they are placed above the sulfide-containing strata (A in Fig. 4), so that they will be prevented from getting into contact with the oxygen in the air.

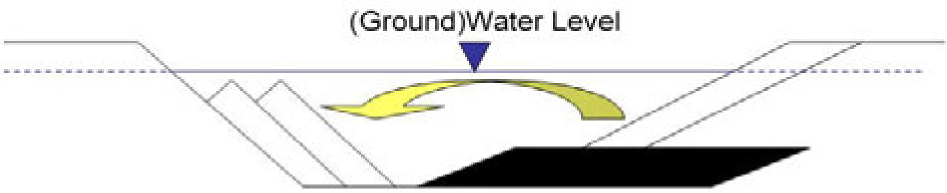


Fig. 3. Mining under water to avoid AMD (Example: Kovin coal mine, Serbia).

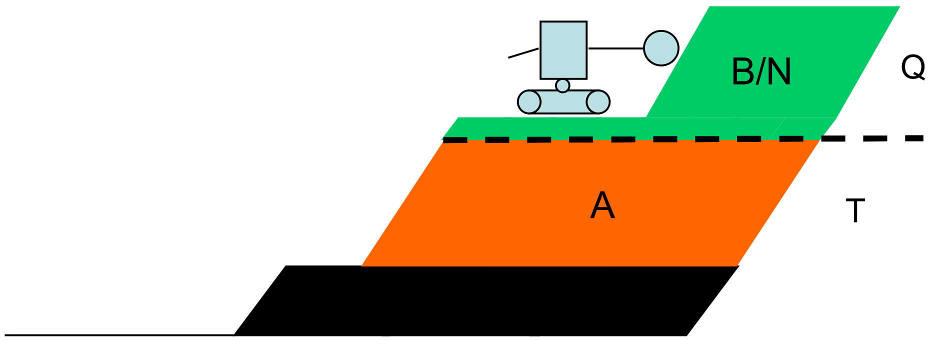


Fig. 4. Working level in pH-base/neutral material (B/N) to avoid AMD (Q-quaternary rocks, T-tertiary rocks, A-potential acid rock, Example: Schleenhain lignite mine, Germany).

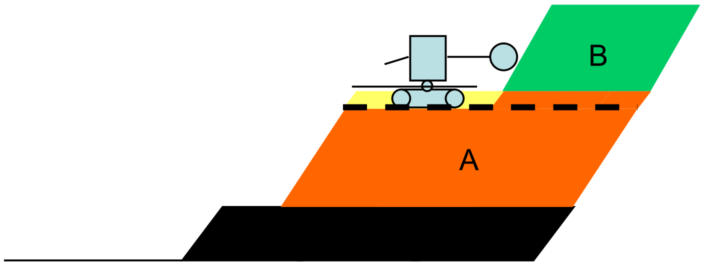
Another tool to reduce AMD is the reduction of the range of dewatering in the surrounding of the mine, where sulfidic material occur, so that less material come in contact with air-oxygen which replace the water in the pores. This measure can be realized by a safety minimum of ground water lowering or through establishing a sealing wall on the mine boundary.

4. Secondary measures

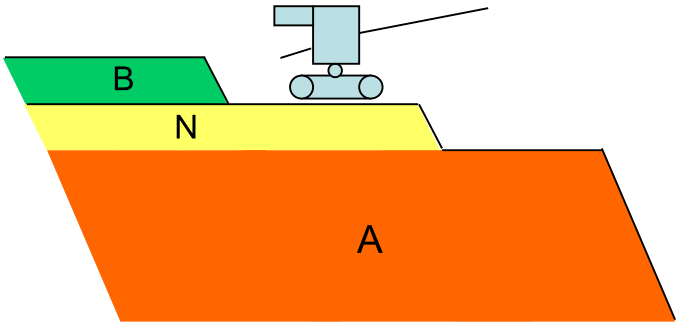
The formation of acidic water usually cannot completely avoided in a mine, so that the following secondary measures aimed at reducing the formation of acidic water can take:

– reducing the reaction time and volume
– buffering the unavoidable proton surplus by alkaline buffer components.

The reaction time can reduced by planning faster mining and dumping processes. If sulfide-containing rocks remains on the surface of, say, slopes or interfaces for a longer period, they can covered with neutral, cohesive materials, followed by a seed of grass, to reduce the acidic water formation (Fig. 5).



a)



b)

Fig. 5. Covering of working level with pH-Neutral material to avoid AMD (Example: Schleenhain lignite mine, Germany) a) excavation bench, b) dump bench.

In the case of dumping sulfide-containing overburden internally, the future groundwater level will have to be taken into consideration. Since the air will be excluded once the groundwater level rises again in the lower area of the dumpsite, rock with a higher acidic water potential (A+ in Fig. 6) should be dumped here, to stop the acidification process as early as possible. This effect was and argued as a reason to dump sulfide-containing rock below the sea water level. Additional the compaction of the acid potential material give the effect of reduction of the reaction space and air-oxygen presence in the pores of the dumps.
Contrary to that, chemically neutral rock (N) or rock with a low acidification potential (A-) is supposed to dump in the unsaturated zone above the groundwater level. This must especially observed when the quality of the upper aquifers is of the essence for protected goods, e.g. nature preservation areas (Fig. 6).
If acidic water is generated in open sub-surface spaces that are created by mining activities and then permanently filled with air, i.e. above the groundwater level, the backfilling of preferably alkaline material may stop, or at least delay, the further sulfide conversion.

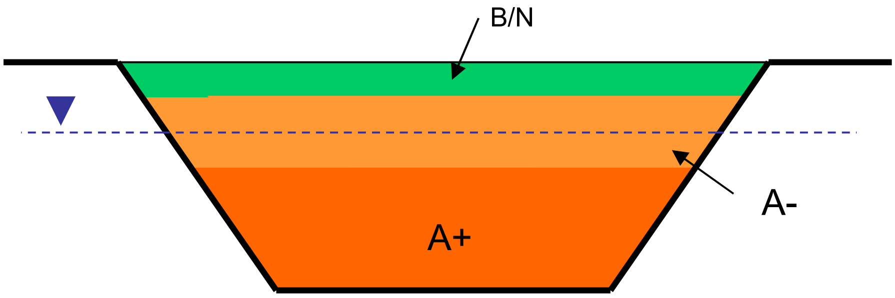


Fig. 6. Acid mine rock (AMR) dumping below groundwater level to stop AMD (Example: Lichtenberg uranium mine, Germany).

Another technological task of mine planning and the ensuing mining operations is the selected dumping of alkaline rock and rock that is potentially generating acidic water with the aim of achieving neutralization. If protons released by the vertical and horizontal flow of the groundwater, they can be neutralized by generating buffer zones that are laterally, vertically or diffusely introduced (Fig. 7).

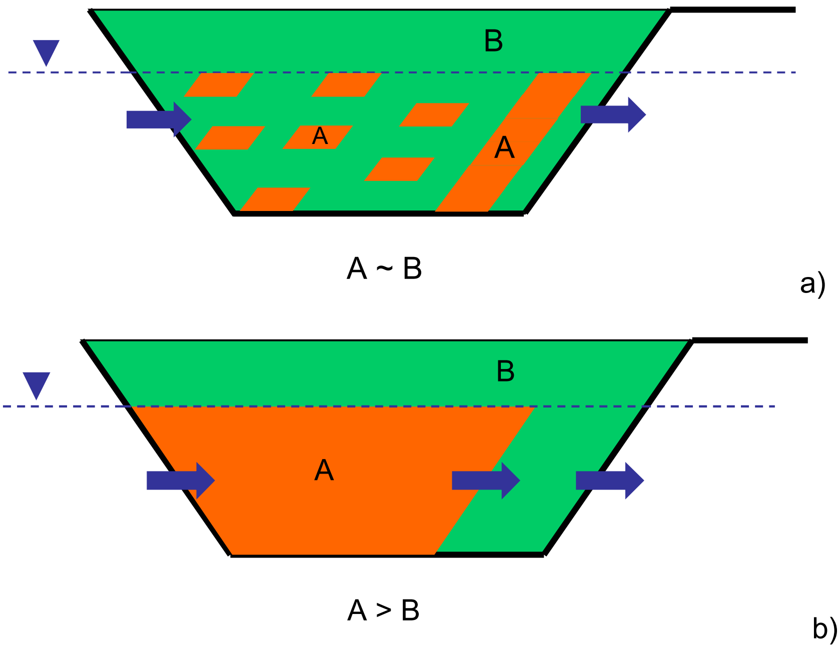


Fig. 7. Dumping of buffer zones: a) diffuse, acid and buffer potential in balance A ~ B; b) horizontal, higher amount of acid than buffer potential A > B.

The required alkaline potential must established by taking into account the pH-value of the inflowing water and the water quality of the outflowing water. If not enough natural buffer material is in the excavation process available (A>>), external alkaline materials will have to be used (Ca^{+} in Fig. 8). In general, reactive limestone is suitable for this purpose, while the lignite mining industry can fall back and on the alkaline potential of ash that generates in the coal combustion process and that has different natural and process-depending reactive lime contents.

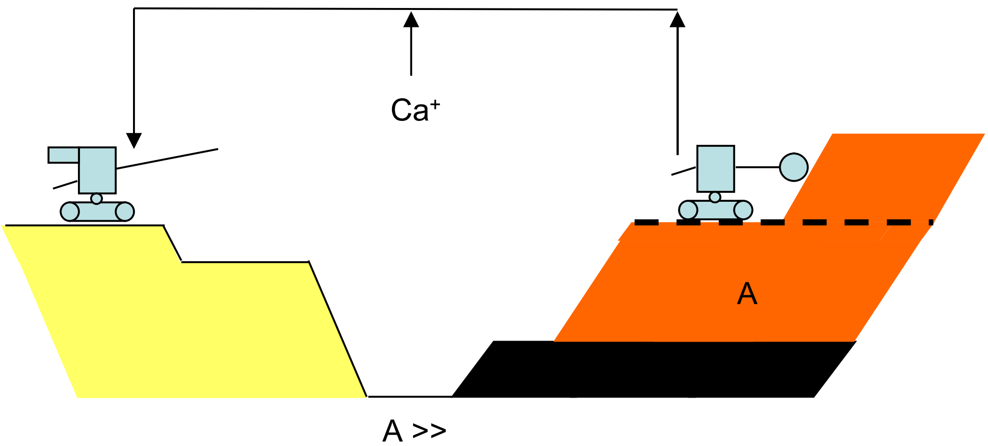


Fig. 8. Addition of buffer concentrate to the AMR after excavation
(Example: *Garzweiler lignite mine, Germany).*

5. Tertiary measures

Tertiary measures will be required, when it has not been or when it will not be possible to keep the acid potential within the limits stipulated. Admittedly, mining companies have often existed for several centuries, while the requirements concerning the fight against acidic water was introduced much later, or the primary and secondary measures have proved to be technically impossible or unreasonable. Tertiary measures can be taken during the mine operations as scheduled or in the process of remediation.

Especially the following measures can be used to protect the environment (surface water quality in rivers, and lakes, groundwater quality …), against detrimental effects:

– subsequent addition of reactive alkaline potential into dumps (AMD hotspots)
– gathering and cleaning of the acidic water (Fig. 9).

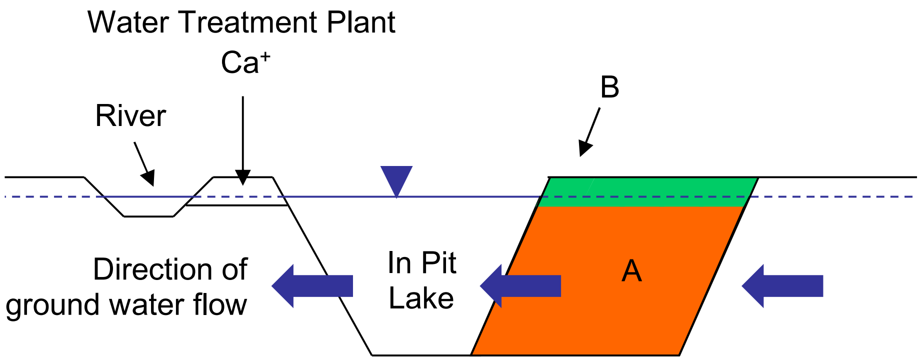


Fig. 9. Conventional water treatment plant.

Reactive alkaline material can be subsequently added to the acidic groundwater or to the acidic surface water in several ways, such as by (Fig. 10):
− Injection technique
− reactive walls in ground water flow direction
− Inlake treatment.

An effective measure to prevent the detrimental effects of water contaminated by mining are water treatment plants that are operated during or after the mining activities and that are geared to the chemistry of the water in the mine. The water will first have to be collected by suitable measures in wells, drainages, drifts etc. and cleaned. Apart from technical structures for the chemical treatment of water, naturally operating systems, such as wetlands, have also stood their test. When designing such systems, the cleaning objectives and the quantities of water to be treated need to be duly taken into account.

Alternatively, or in addition to the cleaning, the water may also be evaporated in mining regions with a negative water balance, e.g. in deserts, in order to prevent the water from being discharged into the surroundings, which may have a detrimental impact on the environment.

Tertiary measures as treatment were done, if there are already existing AMD. However, there are very high additional rehabilitation costs. Walther and al. [3] shows long periods of high release of sulfate, if no measures will take.

Furthermore the standard dumping design must comply geotechnical and hydrogeochemical aspects. By ending of the drainage in the mining area, the new dumpsites get water saturated. This leads to the desired mixture of acid and buffering water. Due to the buffer reactions CO_2 will generated. Holt N. [4, 5] describes CO_2 release in the soil system as a possible inner initial for dump failures, typical for the soil conditions of the Lausitz lignite region. Numerous dump failure events there registered. Until now it is still not fully understood, which initial led to the shear

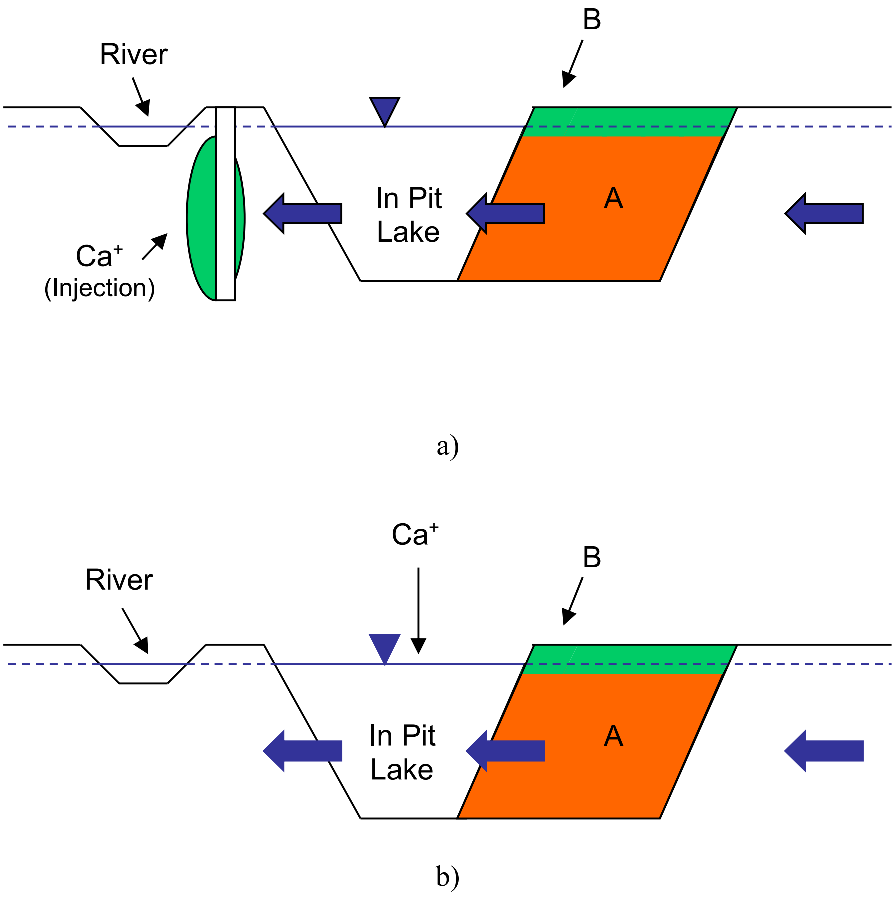
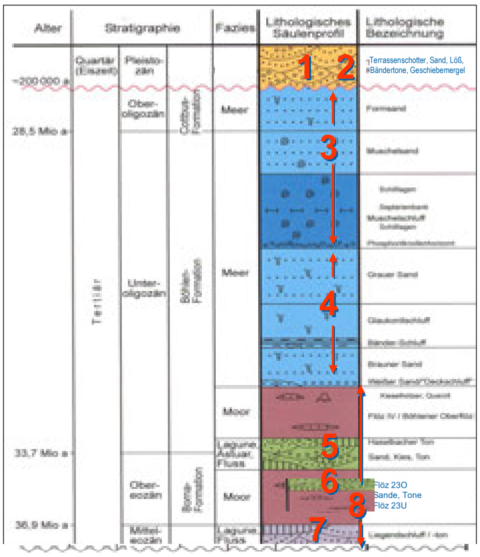


Fig. 10. Addition of reactive alkaline to the AMD a) injection, b) inlake treatment.

strength loss and soil liquefaction. Therefore, it is essential to combine geotechnical and geochemical knowledge.

6. Processing and solution of the problems

Further describes a new methodology to prevent the release of AMD during the active mining by applying secondary measures. In the end, there should be a dumpsite with good geotechnical and hydrogeochemical conditions.
The first step is the analyses of the geological with the definition of units for further investigations (Fig 11).



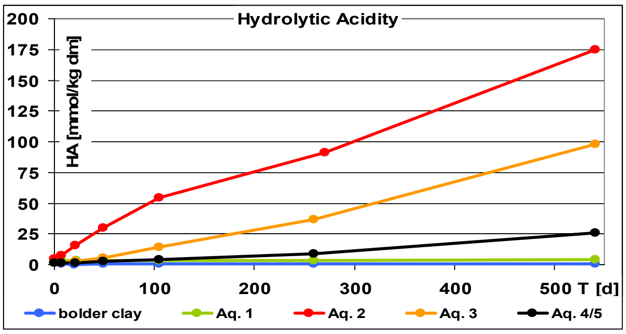
nr.	Geological investigation unit
1	Quaternary sediments (sandy)
2	Quaternary sediments (cohesive)
3	Böhlen Formation, upper part (Aq. 2.1-2.4)
4	Böhlen Formation, lower part (Aq. 2.5-2.8)
5	Tertiary Aquifer 3
6	Tertiary Aquifer 4
7	Tertiary Aquifer 5
8	Cohesive tertiary substrates

Fig. 11. Geological Scheme and investigation units of the future overburden.

In a second step weathering tests were performed to characterize the AMD potentials geochemically by measure the parameters "Hydrolytic acidity" and eluates.
In long-term experiments (>500 d), several wet soil samples of 10 fore field drillings into the five aquifers and some aquiclude units were exposed to weathering by atmospheric oxygen (Fig. 12). According the the real dump conditions the samples were stored in a climate chamber at the average soil temperature of 10 °C and were humidified periodically. In stages, the sediments were eluted and analysed for pH-level, conductivity, hydrolytic acidity, iron- and sulphaterelease.

Fig. 12. Weathering test of 6 different sediment substrates.

These tests clearly show that the oligocene aquifers (aquifer 2 and 3) are the sediments mainly inducing acidification. The low pH-values (pH 2 to 3) are coupled with a high hydrolytic acidity as well as with iron and sulphate release. The hydrolytic acidity represent the acidification as indicative parameter. In contrast, the glacial marly substrate is characterised by buffering carbonates with pH 8 to 9 and nearly no iron and sulphate release (Fig. 13).



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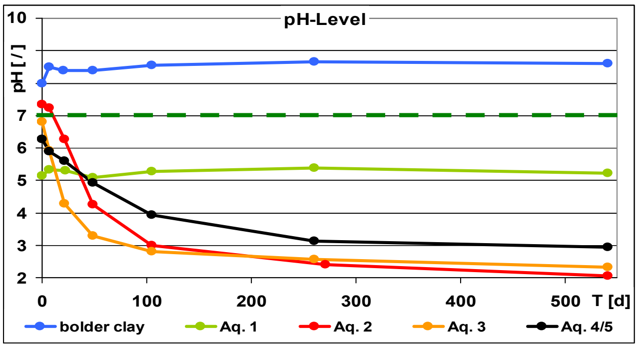

b)

Fig. 13. Results of the geological material weathering tests: a) hydrolytic acidity, b) pH-values.

At the extracted non-cohesive and cohesive units, TIC/TOC and sulfur contents were determined as well as particle size distributions by means of sieving. For the carbonate contents (TIC) it is shown that the glacial till, as the only buffering unit, has a level of up to over 1 Ma% TIC. The organic carbon parts (TOC) are concentrated in the Tertiary, also on the lower part of Aquifer 2, but are overall spread throughout the whole overburden profile. The weathering of the sediment was investigated not only in the laboratory.

In the open-cast mine a manual horizontal drilling has been performed. The samples demonstrated significant correlations between the electrical conductivities of the different sediments (aquifer 2 vs. aquifer 3 vs. aquifer 4) and between the

electrical conductivities and the duration of oxygen exposure or weathering. If the open pit edges are open for a longer period, the weathering penetrates more deeply and the conductivity is rising as a measure of the total mineralisation. The same applies for pH values, as with increasing exposure time to atmospheric oxygen pH values drop due to the weathering of geogenic pyrites. The depth of penetration of atmospheric oxygen into the hand hole varies depending on the material and weathering duration. There have been penetration depths up to 1.5 m to 1.75 m for long exposed surface mine edges.
In a third step blending according the planned mining technology by mixing the buffering marl (solid carbonate contents) with the main AMD polluter of Aquifer #2 (lower part) and #3 in various ratios was performed. The buffering tests were implemented for normal operation times. Figure 14 (right) shows, that for shorter weathering time (~50 days) a mass addition of 10 to 20% of glacial till is necessary to prevent the release of iron, trace metals and acidity and to reduce the sulphate release, for longer periods a mass addition of 40% glacial till.

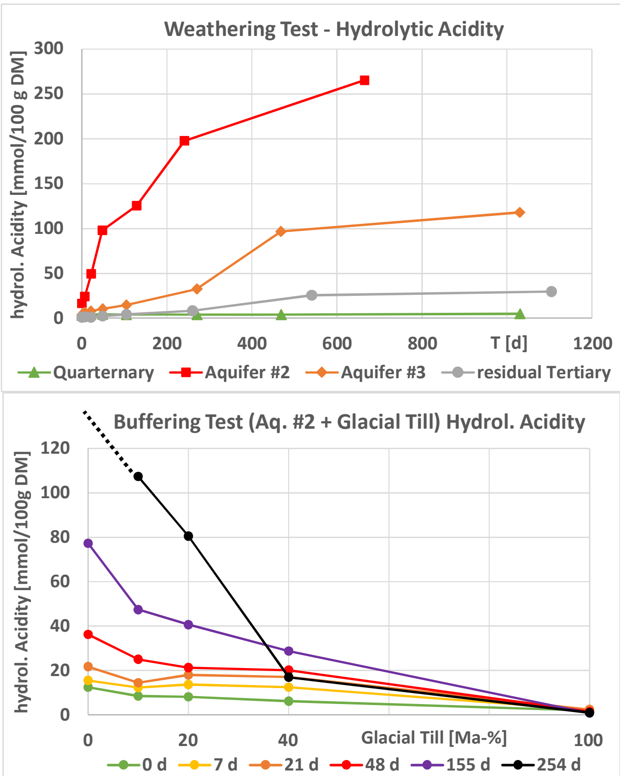

Fig. 14. Hydrolytic Acidity in Weathering Tests of different Investigation Units (left) and Buffering tests Aquifer #2 + Glacial Till (right).

To this the thickness relations between the glacial till and the sum of aquifer 2 + 3 and the boulder clay was determined and plotted as normalized for mining areas. It was shown, for example, in figure 15 for large areas that there is enough buffer material. In small areas in the west and south of the mining field is not enough buffer material is present, so this is to take into account in the planning of mining and tilting. A mass transport is necessary.

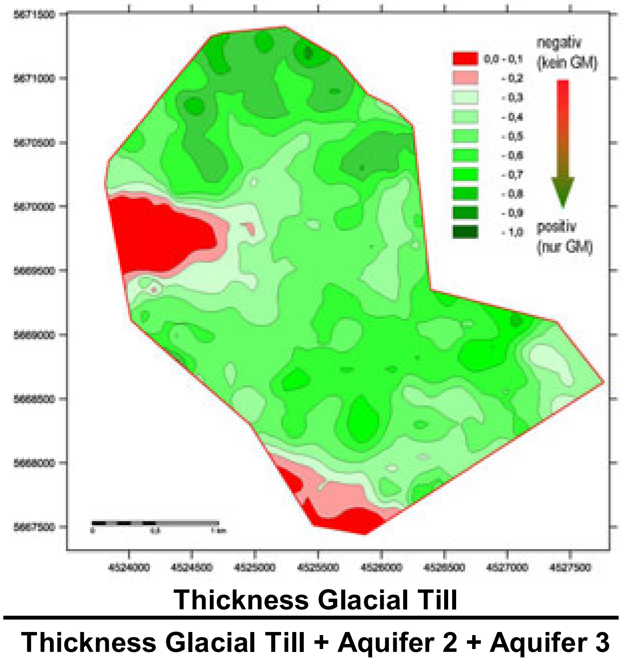

Fig. 15: Normalised Mass Ratios between Buffer and Acidic Sediments.

On the existing dump areas of the mine a groundwater monitoring was done for the characterization of the hydrogeochemical condition of these waters. It was the question to characterize the buffering by TIC and sulfate reduction (Natural Attenuation) on randomly dumped sediment masses. The results of the buffering tests were confirmed with the results of the mine water monitoring especially with the isotopic data and the contents of TIC (inorganic carbon). The effectiveness of the geogenic buffer in the field could be demonstrated. But not all measuring points had good geochemical conditions. So in the future it must be taken care on a good mixture of sediment masses. On the basis of a good geological model MIBRAG mbH has the opportunity to track all sediments from the extraction side to side on the butts and build up a 3D model butts.
Blending the dump model and the won geochemical parameters, sections can be visualized showing an approximate dump structure. Figure 16 clearly shows that the buffering quaternary (green + yellow) and acidogenic tertiary (red + orange) sediments were turned over in large packages. So there is a small contact and reaction area between the buffering and acidogenic sediments.

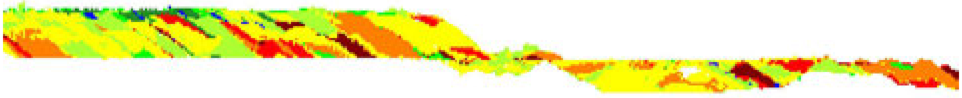

Fig. 16. Dump section, green/yellow: buffering material, red: acidogenes sediment; mining field Schleenhain (graphics MIBRAG mbH).

A qualified mixing of glacial till horizons into the problem zones is important. At the mining field Schleenhain therefore the dump strategy has changed. The sediments of the aquifer #4 and #5 and the cohesive Tertiary sediments are dumped in the lower part, cause of the background of the geotechnical stability. Then the sediments of the aquifer #2 and #3 are dumped with a substantial part of the glacial till not as compact packages, but in relatively thin layers to produce a large contact area between these materials. The spreader is turning during the mass disposition permanently. Another technological task is to minimize the oxygen exposure times of acidogenic sediments.

Fig. 17. Uncontrolled Formation of CO2 in carbonate tests with original glacial till (left) [6] and Geotechnical incident in lignite opencast (right) [5].

Another field of investigation of chemical behaviour of geological material concerns the gas development, which can cause instabilities in dumps. In column tests the potential geochemical initial were examined. The mixture of acidogenic and buffering original sediments creates - by dissolution of carbonate - CO_2. The combination of blocking by iron hydroxide precipitation and CO_2-formation lead to increased pressures and pulsation of the flow P [7]. For large scale, this would be the feared initial for shear strength loss and spontaneous soil liquefaction in the tipping body (Fig. 17). Therefore, flow hazardous sediments has to be stored in the lower dump.

7. Results

In addition to the results from the buffering test in the laboratory and groundwater sampling in the field, problem areas can be identified and future levels can be estimated. It can be shown that in an ordered structured way of dumping, using the buffer potential of the glacial till optimally, the minewater runoff from the tipping bodies MIBRAG mbH will only have low concentrations of iron and heavy metals. By superposing the results of different methodes of the geotechnical, geochemical and geological investigations, it is possible to mark the main problem areas and implement suitable technological counter-measures. Therefore the knowledge of the layer thickness ratios of the substantial overburden units is essential.
As another result of the research, a new dump structure was created. Rather than in unstructured blocks or conical strips, the overburden is now dumped in fine layers, so that a large contact area between the buffering substrates and the problematic aquifers will be created. Figure 7 shows the dumpsite of the open cast Schleenhain. On the right side it is possible to see the old unstructured dump area. On the left is the new layer dump structure casted by the spreader.
As a consequence of the investigation, the exposure times of the problematic sediments to atmospheric oxygen should be as short as possible and should promptly be covered by glacial till substrates or geochemically neutral sediments, e.g. clays and silts or Quaternary sediments.
The combination of the results of the buffering tests and the geological model shows that for large parts of the lignite mine Vereinigtes Schleenhain there is enough buffering material to achieve a good geochemical composition and neutral pH values in the dump body. The investigations of the tilting ground water confirm the statements of laboratory and field studies.
Thus it is possible to save the cost-intensive admixing of buffer materials such as lime or dolomite. The realization of the technology transition requires no additional major equipment. The implementation can be done with the present excavators, conveyors, conveyor switches and spreaders. However, a qualified technological control of mining, transport and deposit is necessary.
During the research activities, a new dump structure was created (Fig. 18). Rather than in unstructured blocks or conical strips, the overburden will be dumped now in fine layers to enlarge contact area between buffering and acidifying sediments.

Because of the investigation, the exposure times of the problematic sediments to atmospheric oxygen should be as short as possible and glacial till or geochemically neutral sediments should promptly cover them.

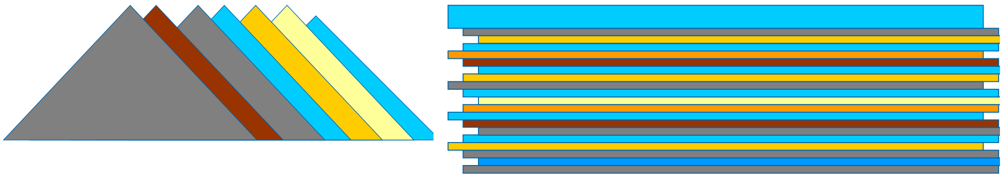

Fig. 18. Scheme of old dump structures (left)
and new dump structures with larger contact areas (right).

Modern surface mining is carried out in a manner which prevent or minimize future AMD problems as much as possible. For this purpose, an approach was developed, where geological, geochemical and technological aspects are examined. By superposing geochemistry and geology, problem areas were marked and countermeasures introduced by changeing the mining technology. So in future, there will be a significant reduction of AMD from the dumps (Fig. 19). In sum of all measures, it is possible to save the cost-intensive admixing of buffer materials such as lime or dolomite.

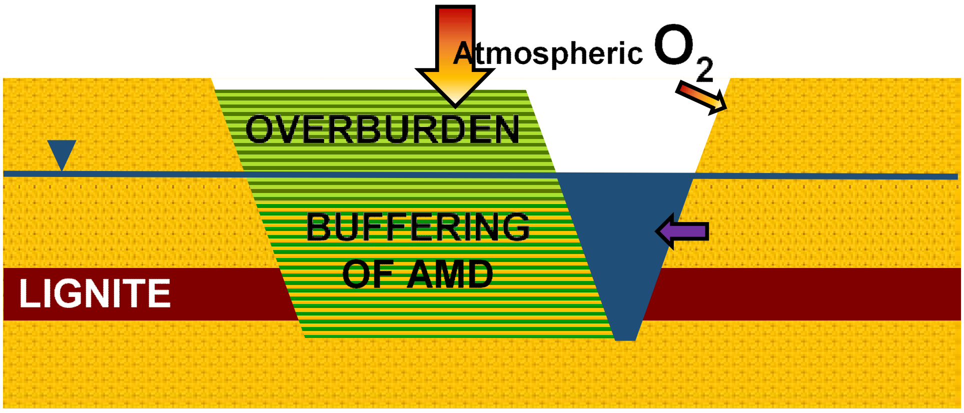

Fig. 19. Schema of structured buffering in lignite opencast mines.

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