Hard pan formation on mining residuals

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Abstract. Hard pan formation is a widespread natural phenomenon which is able to reduce erosion by wind and water, prevent water infiltration and air circulation due to particle agglutination and pore filling, and to accumulate high amounts of potentially toxic elements in secondary mineral and gel phases. The process is driven by capillary forces, occurs with different climates from the polar circle to the equator, and is depending on material composition, climate, and deposition history. The size of matrix flow cells and the development of focused rock drainage systems controls the effectiveness of this self-sealing process.

Introduction

Hardpan formation is a widespread natural phenomenon. It is known from semi-arid to arid climates such as calcrete, silcrete, ferricrete, but has been observed also in humid and tropical areas. These crusts are in general characterized by reduction of pore volume and permeability, relative or absolute increase or depletion of certain elements as well as by the formation of characteristic mineral phases stable under these environmental conditions (Thornber et al. 1987).

This natural phenomenon can be observed and characterized macro- and microscopically, chemically and geophysically already a few years after deposition on anthropogenic depositories like slagheaps, tailings, waste rock, etc. (Blowes et al. 1991; Chermak and Runnells 1996; Dold and Fontboté 2001; Rammlmair 1996; Schuiling & van Gaans, 1997, Ettner and Braastad 1999; Hammarstrom et al. 1999; McGregor et al. 1998; Jung et al. 2000; Grissemann et al. 2000; Rammlmair and Grissemann 2000; Rammlmair et al. 2000; Niederleithinger et al. 2000).

The processes of hardpan formation on anthropogenic depositories is of interest since the generation of hardpans will positively influence the natural attenuation processes in multiple ways. The process may last several to hundreds of years showing all stages from onset to final. The chemical and mineralogical inventory will be controlled by the precursor material, but will show individual patterns even in homogeneous matter.

The aim of this paper is to highlight the process of hardpan formation and to focus on some of the aspects supporting natural attenuation.

Field observations

A number of depositories – slagheaps, tailings, low grade ore etc.- have been investigated from the polar circle via humid, semiarid to arid climates to elucidate their potential in forming hardpans. Hardpans could be documented in all climatic zones and all materials ranging in size from the sub-mm- to meter- scale either at the surface or under a cover of a few cm of non-aggregated particles (Fig.1). The hardpans show an extreme variety in density ranging from incipient edge agglutination to almost 100% pore filling.

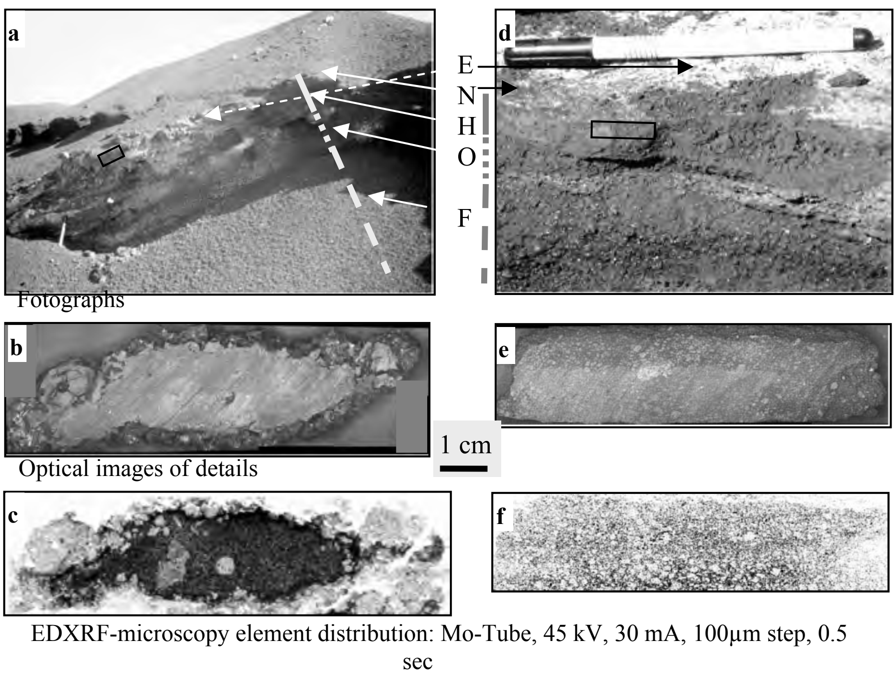

Fig. 1. Example of hardpan profile on a slagheap (Selebi Phikwe, Botswana) showing efflorescence (E), not agglutinated particles (N), hardpan (H), an highly oxidized layer (O) and primary unoxydized material (F). At the flank within 10 yrs a 40 cm dense hardpan has evolved (a). On the lorry road the broken spheres are compacted, and a 3 cm thick dense hardpan was formed within one year (d). The optical image of detailed sections of the hardpans show coarse and fine grained slag particles from the flank (b, c) and the road (d, e), respectively, agglutinated by secondary Ni-Cu-phases or -gels. The inverted EDXRF-elemental scans show high Ni-Cu-concentration in dark, particles in grey (c,e).

At the moment the scattered data do not allow to quantify the hardpan formation potential of a certain material in a certain climatic zone, but qualitative and process information can be already obtained at this stage of research.

Slag material often appears to be highly reactive depending on glass content and phase crystallinity and composition. This material might form already within one to ten years very compact hardpans.

On the other hand tailings derived from modern treatment plants often show very small amounts of reactive material only. The potential for hardpan formation might be limited or is far beyond effectiveness.

Alteration pattern

After deposition material will be exposed to weathering and diagenesis. The available and accessible surface area of the particles will interact with fluids, gases, bacteria, fungi and plants. Particles are composed of phases some of which are highly reactive, whereas others will not react in a visible way. Just after deposition dust particles and finest grains attached to coarser particles will provide elevated surface areas. The instantaneous accessibility of the micro-particles will cause expulsion in form of fluids highly enriched in soluble matter. Depending on the climatic premises and reaction time span, the generated solutions might be able to contribute to rock drainage.

With propagating alteration the accessibility and availability will become reduced by a number of factors such as loss of finest particles due to dissolution or particle transport in macro pore systems, loss of accessible highly reactive phases by selective leaching (Fig.2), shrinking cores in homogeneous matter, protective coatings and rims due to precipitation, reactions and bleaching. Thus, spontaneous dissolution will become reduced and diffusion will be the dominant control.

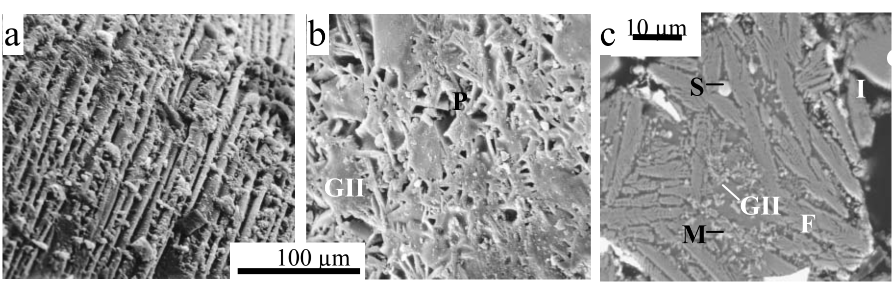

Fig. 2. Example of selective leaching of slag material from Selebi Phikwe, Botswana. (Leaching conditions 1minute in 30% H_2O_2 steam, 25°). SEM-SE images of fayalite strings with micro- channels of leached glass II from the slag sphere surface (a), and of plagioclase lath with pores from the core (b), and SEM-BSE image of polished section of a fragmentafter 150 days SOXHLET leaching at pH7 with fayalite (F), magnetite (M) sulfide spheres (S) and partially leached alkali-rich glass II.

Since dumping of material occurs over a mine's lifetime, above dissolution steps will intermingle over a long time span.

The alteration of particles has an important side effect. Selective dissolution of phases or particles (Fig.2) might enhance the surface area up to a factor of 10,000. The retention capacity of water will increase substantially.

The evolution of micro-porosity and micro-channels due to selective leaching is further responsible for a strong increase of capillary force-driven transport, which again will speed up precipitation of gels, and secondary efflorescent phases at the wind and temperature controlled oscillating capillary rim.

Since reaction affects a number of phases the acidity and neutralization potential will compete in pH-micro-domains eventually causing spontaneous collapse of dissolved and colloidal matter in the form of gel-coating of particle surfaces or colloform-textured pore fillings.

These processes of dissolution, transport, reaction, and precipitation have to be regarded as highly dynamic and complex systems. They are concentrated in certain portions of a heap and may speed up certain processes and able to limit other ones.

The oscillating capillary rim will cause precipitation of dissolved matter over a wide zone in loose material at the flanks, where the wind pressure might be highly variable and within a narrow zone at the more compacted top of the heap where temperature variations might dominantly control evaporation.

Even most of the early precipitates are highly soluble and as efflorescent material often instantaneously available during later rainfalls hardpans still will evolve progressively with time. It is important to note that even highly soluble matter such as micro-crystallites of KCl or NaCl will survive rainfalls, due to the limited accessibility, generated by the precipitated matter in the evolving hardpans.

In the water saturated portion of a slagheap reducing conditions prevail, whereas in the under-saturated zones oxidation is the controlling feature. In this portion dissolution of a number of phases is easier to achieve than in the saturated part. Since the boundary zone in general is oscillating according to the daily and seasonal changes, availability of dissolvable matter is provided for an extended time period.

Fluid pathways

Depending upon their depositional history depositories might show significant inhomogeneities such as layering, crossbedding, changing degrees of sorting, compaction, consolidation, composition etc. These primary inhomogeneities will be diagenetically superimposed and are responsible for the development of micro-, meso- and macro-pore domains and therefore for highly variable hydraulic conditions.

A number of transport phenomena can be differentiated. The micro-pore or matrix flow takes place within the fine intragranular pore space, and appears to be relatively homogeneous, slow and achieves semi-equilibrium conditions due to the long reaction times. Besides the slow seepage an upward capillary transport in the inter-and intra-granular areas as well as along grain surfaces takes place.

On the other hand macro-pore transport occurs along pores, which are substantially larger, then the micro-pores. In depositories these macro-pore systems are provided by primary inhomogeneities during deposition and consolidation cracks or induced by earthquakes or landslides (Blowes et al. 1991; McGregor et al. 1998; Walder et al. 2000).

Selker et al. (1999) have shown that with a given gradient (gravity) the transport velocity in a macro-pore channel will increase with the square of the diameter, whilst the amount of the transported matter will increase by 10^4 relative to the surrounding matrix. But not all of the dissolved material will leave a depository via macro-pore channels as acid rock drainage (ARD). Part of it will feed the unsaturated matrix via capillary transport. In humid climate the matrix might be saturated and exchange might therefore be limited.

Macro-pore channels are additionally characterized by particle transport. Finest particles might form thin layers at the channel walls thus limiting the exchange with the confining matrix (Pivetz and Steenhuis 1995). This channel sealing process will be supported by evaporation from the matrix towards the macro-pores and precipitation of dissolvable and un-dissolvable matter as small hardpans speeding up the transport process, but limiting the reaction time.

Another aspect, which might appear to be of prime importance, is the development of so-called finger zones in tailings or other fine-grained wastes. Hill and Parlange (1976) showed that water spilled on dry and unstructured soil would follow distinct and isolated fingerlike zones. The diameter of these finger zones is indirectly proportional to the characteristic grain size distribution. In silt (Ø approx. 0.01 mm) and in coarse sand (Ø app. 1 mm) finger diameters of 100 cm and 2 cm, respectively will be achieved. This amount can be doubled under extreme water supply condition (Parlange et al. 1990).

Such a finger zone will remain active until the soil will become absolutely dry again, or saturated (Glass et al. 1998, and might last hundreds of years. These fingers are substantially harder then the un-weathered matrix (Selker et al. 1999). Such long-living drainage zones should - according to Walder et al. (2000) - be next to the sporadically apparent macro-pore channels basically responsible for ARD.

Onset and end of ARD is dependent on a number of factors, as Pactunc and Davé (2000, 2001) have demonstrated in long term column experiments. Long reaction times in the matrix contrast with short ones in the channels. The physico-chemical properties of fluids and material will therefore change permanently (Oelkers, 1996).

These heterogeneities can be observed in the field as well as in the laboratory, and can be described mineralogically, chemically and geophysically (Morris et al. 1995; Rammlmair 1996; Campell et al. 1999; Vaughn et al. 1999; Jung et al. 2000, 2001; Grissemann et al. 2000; Rammlmair and Grissemann 2000; Rammlmair et al. 2000, 2001; Niederleithinger et al. 2000).

Structural reorganization

Heaped material, even if relatively homogeneous compared to the material before deposition, will evolve local in-homogeneities during the process of dumping, and undergo significant re-structuring during the diagenetic overprint. These sedimentologically and diagenetically superimposed structures have major influences on the fluid path dissolution, precipitation, and the water retention capacity. Interfering micro-, meso-, and macro-pore zones are responsible for the development of inaccessible cells in heaps. The dimension of such a cell might range from centimeters to several meters in diameter. Cells are bounded by more or less accessible portions of the heap. Based on this observation, several major zones which can develop vertically as well as laterally appear to be relevant for the structural development of a heap (Fig.3).

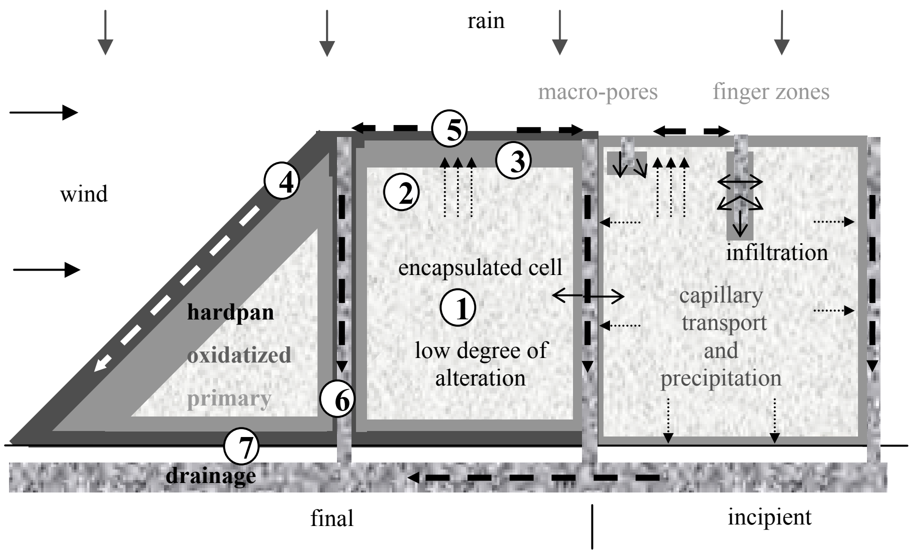

Fig. 3. Section through a slag heap showing different diagenetic stages. Zones of drainage, infiltration and capillary transport are shown in conjunction to the evolution of an oxidation rim and subsequent hardpan formation and encapsulation of cells (1-7; see text).

1. A relatively homogeneous core cell, where slow homogeneous matrix downflow predominates. This zone is controlled by long-term reaction and slow downward migration competed by upward capillary force driven transport of an almost equilibrated fluid.
2. A transition zone where cementation due to interacting fluids might cause precipitation due to sudden changes of physicochemical conditions e.g. changes of pH, fO_2. Precipitation of gels or secondary minerals might take place. If the conditions are stable over a certain time period layer like zones might develop.

3. In a zone exposed to air where dissolution and capillary transport are the dominant features, local super-saturation might be achieved, according to the actual climatic conditions. Coating of fragments, edge and face agglutination and protected (coated) micro-channels might develop.
4. At the capillary rim precipitation is the dominant feature, resulting in coatings, and agglutination of particles, grain coarsening, and finally in a reduction in pore size and volume providing relatively dense crusts/ hard pans. Two types of hard pans can be distinguished for the same time interval on a heap. (A) A dense crust on the flat top of the heap, which is characterized by accumulation of all transported matter in a very narrow zone (Fig. 1d-f). (B) On the other hand a relatively thick, but porous crust might develop at the flanks of a heap (Fig. 1a-c). This crust is basically characterized by edge agglutinated fragments / grains. The crust on the flanks might reach up to 30 times the thickness of the dense top crust. The same amount of transported matter is dispersed over a 30 times higher volume than in the flat portion. This might be due to the changing wind pressure which controls the oscillating evaporation level at the flanks
5. The uppermost portion of the heap eventually covering an impermeable crust is characterized by intensive re-dissolution, removed fines due to erosion (wind, water), accumulation of nutrients for vegetation. The re-dissolved secondary phases, depending on the immediate availability of water, redistribute the solute into the heap or might feed the macro pore channel system.
6. A network of variable spacing characterized by leaching and fast down flow (finger zones and macro pore system) focusing into a drainage system, which penetrates the heap.
7. A bottom zone of mega pores, where total physical removal of fine-grained material has occurred, due to rapidly flowing water. As there is little time for reaction, basically Fe-hydroxide coating can be observed. The development of this zone is much dependent on the grain size distribution in a heap and of the morphological feature of the bedrock.

Conclusions

Hardpan formation appears not to be confined to one climatic zone. It has been observed from the polar circle to the equator. Even in a relatively humid climate heaped depositories provide semi-arid conditions due to their morphological features. Heaps are significantly more exposed to wind, sun and rain as their natural surroundings. Vegetation in this environment is in general limited due to missing soil or even prevented by toxicity of the environment. Endemic flora might evolve.

The depositional history is an important feature for the development of focused drainage via macro-pore channels and for the development of self-isolating zones of reduced exchange, which favor the capillary transport towards the channels and the heap surfaces.

At the same heap different types of hardpans might evolve. At the flanks an oscillating zone up to several meters, depending on grain size, pore geometry and distribution, and climatic factors such as wind, sun, and rain exposure might evolve. Precipitation of secondary phases due to forced evaporation will occur over the wide zone of interaction. Starting with edge agglutination the filling of pores is a continuous process.

In contrast, at the heap top all the matter transported via capillaries focuses in a very narrow zone of a few centimeters only. The result after a few years might be a dense, almost waterproof hardpan.

The kinetics of hardpan formation is much dependent on the climatic condition, the sedimentological, mineralogical, and microbiological parameters. Almost waterproof, dense, one cm thin hard pans might develop within one year in highly reactive compacted fine grained slag. In contrast slimes with very small pyrite contents might show only first steps of hardpan generation even after 30 years. On the other hand blocky, low-grade ore with interstitial finer material might develop 15 cm thick highly resistive hardpans within some 500 years.

The formation of effective hardpans might be inhibited due to man-made disturbances, episodic rainstorms and wind erosion able to destroy the incipient crust, limited amounts of reactive material and fluids.

Acid rock drainage is an expression of the instantaneous availability of soluble primary matter and efflorescent secondary phases associated with the hardpan and accessible along the macro pore drainage channels. Acid rock drainage will persist till drainage channels are sealed or washed out and hardpans are dense enough to limit water introduction and therefore evaporation and precipitation.

Controls of the status quo of hardpan formation and effectiveness might be obtained by thermal imaging and various tomographic geophysical long-term monitoring techniques. It appears to be crucial to obtain information across a water infiltration cycle to be able to highlight zones of impermeability and of focused drainage.

Taking all observations into account a number of steps could be taken into consideration to speed up hardpan formation and therefore to reduce erosion, ARD and gas emissions. Surface compaction, grain size reduction or agglomeration, enhancement of reactive surfaces, bacterial disintegration, ARD recycling, and material mixing could be applied to one or the other depository.

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Long term storage of radioactive waste