Impact of the changes in the chemical composition of pore water on chemical and physical stability of natural clays

A review of natural cases and related laboratory experiments and the ideas on natural analogues for bentonite erosion/non-erosion

Erik Puura, Eridicon OÜ, Estonia

Kalle Kirsimäe, University of Tartu,
Institute of Ecology and Earth Sciences, Estonia

January 2010

SKB

Impact of the changes in the chemical composition of pore water on chemical and physical stability of natural clays

A review of natural cases and related laboratory experiments and the ideas on natural analogues for bentonite erosion/non-erosion

Erik Puura, Eridicon OÜ, Estonia

Kalle Kirsimäe, University of Tartu,
Institute of Ecology and Earth Sciences, Estonia

January 2010

Summary

A scientific literature survey was compiled with the specific objective to find information for smectite mobilization and/or retention in natural clay formations caused by contact with water with low ionic concentrations such as can be expected during and after an ice age. Evidence was sought if smectite particles are lost from the clay to the water and if accessory minerals that remain could form a growing filter slowing down or stopping further loss of smectite.

Bentonites are present in geological layers for hundreds of millions of years. There is limited exchange with surrounding layers, eg K transported into the bentonite layer from surrounding shale layers leading to the increased illite % in smectite-illite of the bentonite. Another process is silicification of surrounding layers leading to lowered permeability of surrounding rocks.

Geological literature data on historical bentonites do not consider colloid formation in low ionic strength water as relevant mechanism for smectite mobilization. However there are no studied cases where this could be a relevant mechanism (as proposed by colloid release scenario).

Soil researchers have studied the mechanism of colloid release in laboratory experiments and have found that there has to be an abrupt change in infiltrating water quality leading to 'osmotic explosion'. Clogging the pores in the lower part of the soil column has followed, leading to dramatic decrease of hydraulic conductivity in vertical profile and increased surface runoff. So, although limited, there are literature evidences of clay colloids release from bentonites/smectites caused by low-ionic circumneutral water.

The geological settings to look for natural analogue studies include

(1) Bentonite/smectite similar to what is used in repository.

(2) Water similar to the composition of glacial meltwater.

(3) Scenario similar to what is proposed in the bentonite erosion project.

The problem related to the study of historical bentonite profiles is the geological changes that have occurred in bentonites over geological time scales. The bentonite erosion project has to provide the scenarios for approximately 100,000 years, but the geological deposits have been changed and subjected to various conditions, many of those uncertain, during tens and hundreds of millions of years. The field studies of weathering of the historical K-bentonite deposits could provide interesting and new information, but the relevance related to the bentonite erosion project is questionable.

Svensk sammanfattning

Denna rapport redovisar en litteraturundersökning som syftar till att finna information om mobilisering eller kvarhållning av smektit i naturliga lerformationer som har varit i kontakt med vatten med låg jonstyrka som kan härröra från smältande glaciäris. Information söktes rörande smektit som kan ha försvunnit från lerformationer och om andra fina partiklar kan ha lämnats kvar och bildat filter som förhindrat eller fördröjt vidare erosion.

Bentonitleror återfinns i hundratals miljoner år gamla geologiska formationer. De är isolerade men det sker lite utbyte av material till exempel kalium med omgivande skifferlager vilket leder till en ökande andel illit genom smektit-illit omvandling. En annan förändring är en ökande andel av kiseloxid i materialet vilket leder till minskande hydraulisk konduktivitet.

Den geologiska litteraturen om gamla bentoniter behandlar inte frågan om smektitmobilisering med vatten med låg jonstyrka. Det finns dock inte några studerade fall där detta skulle kunna vara en relevant frigörelsemekanism.

Forskare som sysslar med jord har studerat kolloidfrigörelse i laboratorieexperiment och har funnit att en plötslig och kraftig ändring i vattnets sammansättnig kan leda till "osmotisk explosion". Porerna i nedre delen av jordpelaren sätts igen och leder till att vatten inte kan tränga ned i jorden utan rinner av på ytan. Det finns sålunda en begränsad information om mobilisering av smektit från bentoniter förorsakat av färskvatten.

Denna studie av naturliga analogier har behandlat följande geologiska förhållanden

(1) Bentonit/smektit liknande det som kan användas i slutförvar.

(2) Likande vatten som kan komma ifråga vid glaciärsmältning.

(3) Scenario likande de som behandlas i erosionsprojektet.

Problemet att använda historisk information om geologiska förändringar är den geologiska tidsskalan. I bentoniterosionsprojektet är tidskalan i storleksordningen 100-tusentals år medan de geologiska formationerna har varit utsatta för olika förhållanden under tiotals till hundratals miljoner år. Fältstudier av vittring av K-bentonitfyndigheter skulle kunna ge ny och intressant kunskap men det är tveksamt om detta är relevant för erosionsprojektet.

Contents

1 Overview of the problem area

Bentonite clays have been considered as buffer materials for the disposal of radioactive waste because of their low permeability, high sorption capacity, self sealing characteristics, and durability in a natural environment. The highly compacted bentonite blocks have a natural swelling potential and are thus capable of self-healing of joints/fractures that could lead to possible leakage of radionuclides from waste canisters.

Long-term perfomance of bentonite buffers has been studied from different aspects, specifically dealing with its physical and chemical stability. The main concern has been related to reactions involved with mineralogically metastable swelling smectite clay minerals (typically of montmorillonite). Studies have revealed the transformation of a montomorillonite mineral and respective change in buffer geotechnical performance. The main focus has been on possible reactions with solutions containing Fe^0 or Fe^{2+}, highly saline and/or alkaline solutions etc /Herbert et al. 2004/.

Also, the compacted bentonite blocks will be saturated by drawing moisture from the surrounding host and the saturated bentonite possesses a high swelling pressure and it is not initially in a mechanical equilibrium with the confining rock and groundwater. The swelling of the bentonite may also cause a penetration of the bentonite into open rock fractures, which is called an intrusion /Baik et al. 2007/. The fractions of the clay material are expected to move in the microfracture network of the granite altered by the excavation, primarily due to the high swelling pressure developed by the clay (5 MPa if the clay density is 1.65 g/cm^3, /Huertas et al. 2000/). Even if a mechanical drag force does not exist, the smallest particles could still move by diffusion. These diffusion processes in the granite microfractures have been evaluated by /Alonso et al. 2002/.

If the density of a compacted bentonite buffer becomes very low due to a swelling, the highly hydrated bentonite platelets become disassociated, and the macroscopic behaviour of the bentonite becomes gel-like called a bentonite gel. The individual platelets of the bentonite clay may become free and either scoured away from the surface by water moving tangentially, or else simply diffused away as free particles. The size of these platelets may be in the colloid range. The generation of bentonite particles in a region where the bentonite buffer comes in contact with the groundwater, can be important for the migration of radionuclides since most of the radionuclides are strongly sorbed onto the bentonite particles /Grindrod et al. 1999, Baik et al. 2007/.

Colloids may substantially affect contaminant migration in the environment and the dispersion of actinides in the nuclear tests areas could be attributed to colloid-driven transport /Buddemeier and Hunt 1988, Nuttal and Long 1993, Kersting et al. 1999/.

/Pusch 1999/ reported that the penetration the bentonite into a fractured rock that is a function of the density and the fracture width, while an erosion of the bentonite gel depends on its shear strength as well as on the flow rate of the water in the fractures) is negligible. The same was concluded from experiments and modeling by /Kurosawa et al. 1999/ which did show that the effect of bentonite colloids on a radionuclide transport is likely to be negligible in the performance assessment of a radioactive waste disposal in a deep geologic media.

However, /Missana et al. 2003/ shows that the bentonite colloids can effectively form at compacted bentonite and granite interface. Within compacted bentonite, the formation of colloids is not expected because of high(-er) porewater salinity and aggregation and pH that is generally between 7 and 9 where many colloidal species are at the point of zero charge /e.g. Gardiner et al. 2001/.

2 Influence of physical and chemical parameters

Flow rate

/Baik et al. 2007/ studied the erosion of bentonite particles at the interface of a compacted bentonite and a fractured granite depending at different experimental conditions – contact time, flow-rate, and geochemical parameters of groundwater (pH and ionic strength).

These studies show that the erosion of bentonite particles in their experimental set-up is a function of the total eluted volume of the groundwater at different flow rates. The concentration of the eroded bentonite particles was found to be very high at an early elution time, and then the concentration is gradually reduced to a constant value as the total eluted volume of the groundwater increases, whereas the concentration of the eroded bentonite particles increased with an increasing flow rate. In principle, a flowing groundwater imposes a shear force, τf, on the particle-particle bonds in the gel-shaped bentonite aggregates. This shear force is related to the flow velocity by Stoke's law /Pusch 1983/.

/Kurosawa et al. 1999/ suggested that groundwater velocities in a range of 10^{-5} to 10^{-4} m/s would be required to initiate a bentonite erosion; /Baik et al. 2007/ however observed significant erosion of the bentonite particles at much lower groundwater velocities of about 10^{-7} m/s.

Moreover, physical models and experiments by /Pusch 1999/, it was suggested that high flow rates could cause an erosion of a fully water-saturated bentonite clay with the critical flow velocities of 10^{-3} m/s for tearing off 0.5 μm particles, 10^{-4} m/s for 1 μm particles, 10^{-5} m/s for 10 μm particle aggregates, and 10^{-7} m/s for aggregates larger than 50 μm.

In contrast /Baik et al. 2007/ observed at the flow velocity of the groundwater through the fracture granite core ranging from $1.5 \cdot 10^{-5}$ to $1.5 \cdot 10^{-7}$ m/s the average diameters of the eluted bentonite particles from 543 to 1,364 nm, 0.54–1.36 μm respectively.

The mobilisation of bentonite particles in dynamic experiments is also studied by /Missana et al. 2003/ who observed the mobilisation of the clay particles and colloids in the water flow direction. They found that the concentration of the particles depended on the water flow rate (from 0.17 to 0.49 ml/d): the higher the water flow, the higher the concentration of solid detected in the eluted water, but the maximum colloidal concentration observed in the water eluted in their experimental configuration was very low (< 1 ppm). Consequently the mechanical erosion process was suggested. The diameter (hydrodynamic diameter) of the suspended particles was typically < 3 μm.

/Missana et al. 2003/ observed also that in their dynamic experiments, the concentration of particles did not depend on the water salinity supports the hypothesis of the "mechanical" generation.

Fluid composition

According to /Baik et al. 2007/ has been reported that bentonite particles eroded by a flowing groundwater are in fact aggregates consisting of thin stacks of montmorillonite flakes and these aggregates have sizes and shapes that are determined by the groundwater chemistry and the mode of a gel formation /Pusch 1983/. These factors also determine the nature and strength of the particle bonds that operate in as well as between the aggregates. The rheological properties of bentonite (montmorillonite) suspensions has been throughout studied in order to elucidate the mechanism by which a gel formation occurs /e.g. Yong and Warkentin 1975, Delgado et al. 1986, Chen et al. 1990, Permien and Lagaly 1994, Benna et al. 1999, Luckham and Rossi 1999, Duran et al. 2000, Janek and Lagaly 2001, Penner and Lagaly 2001, Lagaly and Ziesmer 2003, Tombácz and Szekeres 2004, Ouhadi et al. 2006/.

/Benna et al. 1999/ proposes two main mechanisms by which a gel can be formed from a starting suspension: (1) electrostatic attraction between negatively charged faces and positively charged edges of clay particles; and (2) repulsion of long-range electrostatic double layer. These mechanisms depend strongly on pH of the solution.

/Baik et al. 2007/ found that at an early stage of an elution, the concentration of the eroded bentonite particles decreases as the ionic strength of the groundwater increases. However, the opposite was abserved at a later stage of an elution when the concentration of the eroded bentonite particles increased as the ionic strength of the groundwater increases. This different dependency of the erosion on the ionic strength can be explained by aggregation of the bentonite particles. In their experiment at the ionic strength of the groundwater > 0.1 M $NaClO_4$ the gel formation was inhibited. At the same time the bentonite particles were increasingly aggregated due to a reduced stability of the bentonite particles at the high ionic strength as the contact time increases.

Gel formation was enhanced at ionic strengths of 0.001 M $NaClO_4$, but the bentonite particles themselves were stable at a low ionic strength and thus the concentration of the eroded bentonite particles will become invariable as the contact time increases.

/Missana et al. 2003/ found that the presence of bentonite colloids could be particularly significant in low saline groundwater ($\leq 5 \cdot 10^{-3}$ M) and at basic pH. The also found that the generation of colloidal material from the compacted clay follows the formation of a bentonite gel at the water/clay interface.

/Kaufhold and Dohrmann 2008/ undertook a detailed comparative study of different bentonite types dealing with detachment of colloidal particles. Their study concerned not only bentonites (montmorillonites) with different exchangeable cation composition, but other parameters as montmorillonite content, layer charge density (distribution), crystal chemistry of montmorillonites, morphology of (quasi)crystals, and intergrowth between different components (amongst others) were considered. Their experimental results show a significant variation of the degree of detachment of colloidal particles of the different bentonites and that some bentonites tend to release colloidal particles which cannot be removed from dispersion even by ultracentrifugation.

The dispersion as well as colloid stabilization was found to depend on pH and ionic strength. Detachment of colloidal particles of bentonites depends on the amount of exchangeable Na^+, pH, and ionic strength, whereas they conclude that Na^+ and pH are related. /Kaufhold and Dohrmann 2008/ suggest that the amount of exchangeable Na^+ represents the most important parameter with respect to detachment of colloidal particles at low ionic strength. Importantly the probability of detachment of colloidal particles from bentonites in a given environment was found to be higher higher in case of Na^+ bentonites than in case of Ca^{2+} bentonites. They suggest that selection of a Ca^{2+} bentonite as a technical barrier in a repository would reduce the probability of detachment of colloidal particles.

/Villar 2006/ performed a similar set of experiments to study the infiltration properties of repository backfill materials (granite/bentonite mixtures) depending on water salinity. He used 70/30 wt.% granite/bentonite mixtures that were treated with deionised and 1.2% salinity water. However, his results show that the soluble calcium and sodium are leached from the hydration surface and concentrate just a bit farther away when the permeant is deionised water. The concentrations in the rest of the block remain quite constant and similar to the initial one, which points to a small movement of the soluble salts already present in the material as a result of saturation with deionised water. On the contrary, when the permeant was saline water, advection promotes the movement of both ionic species – which behave in a similar way – farther from the hydration surface as the infiltration time is longer.

Physical stability of bentonite

The experimental results of /Baik et al. 2007/ show that bentonite particles can be eroded and mobilized at the interface of the compacted bentonite and fractured granite by a flowing groundwater depending upon the contact time, the flow rate of the groundwater, and the groundwater chemistry. The erosion of bentonite particles was increased with an increasing flow rate of the groundwater. However, /Baik et al. 2007/ concluded from that the erosion of bentonite particles by a flowing groundwater will not significantly reduce the physical stability and performance of the compacted bentonite buffer. This agrees with /Pusch 1999/ who suggested that although the erosion of particles is possible and evident the physical integrity of the clay mass is little if at all affected.

Nevertheless, /Missana et al. 2003/ and /Baik et al. 2007/ as well as other authors conclude that erosion of the bentonite particles due to a low ionic strength groundwater flow will generate bentonite particles, which can serve as a source of the colloids facilitating radionuclide migration through rock fractures.

3 Geological analogues

Old bentonite deposits

A variety of bentonite deposits has been observed by geologists. During volcanic eruptions, ash deposition occurs during a couple of weeks, eg 2 m thick layer of bentonite accumulates at about 1 million times higher rate than carbonate sedimentation – generally, carbonate beds develop at the rate 1 m / 20,000–30,000 years. In an non-eroded geological deposit, bentonites remain for hundreds of millions of years. For example, Middle Ordovician K-bentonites were formed 450 million years ago and are still there. The major changes occur when the deposits are eroded – both in the original deposit as well as in the newly formed sediment as a result of transport of bentonite particles.

For geologists, bentonite layers provide an excellent possibility for geological correlation of sedimentary beds, as each characteristic layer formed as a result of a volcanic eruption has a special chemical and mineralogical composition. On Figure 3-1, the correlation of Ordovician sedimentary beds is presented. In Estonia, these layers are continuous, whereas in Sweden, only few outcrops of the remains of the Ordovician sedimentary rocks are found, meaning that in other parts, these have been eroded by glaciers.

During the geological history, various processes are known to have been impacted K-bentonites. In Kinnekulle (Sweden), diabase magmatism occurred 300 My ago, forming 60-m covering layer over bentonites, followed by Quaternary erosion that left only some local remains of that covering layer. Upper Cretaceous K-bentonites in Montana have also undergone the thermal event. The main recorded changes are illite % change in illite-smectite in the vertical profile and silicification of the under- and overlying layers. When bentonite bed is surrounded by shales, K^+ has diffused into the bentonite layer and the % of illite closer to the shale layer has risen /Brusewitz 1986, Pusch and Madsen 1995, Altaner et al. 1984/.

In conclusion, bentonites are present in geological layers for hundreds of millions of years. There is limited exchange with surrounding layers, eg K transported into the bentonite layer from surrounding shale layers leading to the increased illite % in smectite-illite of the bentonite. The other followed process is silicification of surrounding layers leading to lowered permeability of surrounding rocks.

Geological literature data on historical bentonites do not consider colloid formation in low ionic strength water as relevant mechanism for smectite mobilization. However there are no studied cases where this could be a relevant mechanism (as proposed by colloid release scenario).
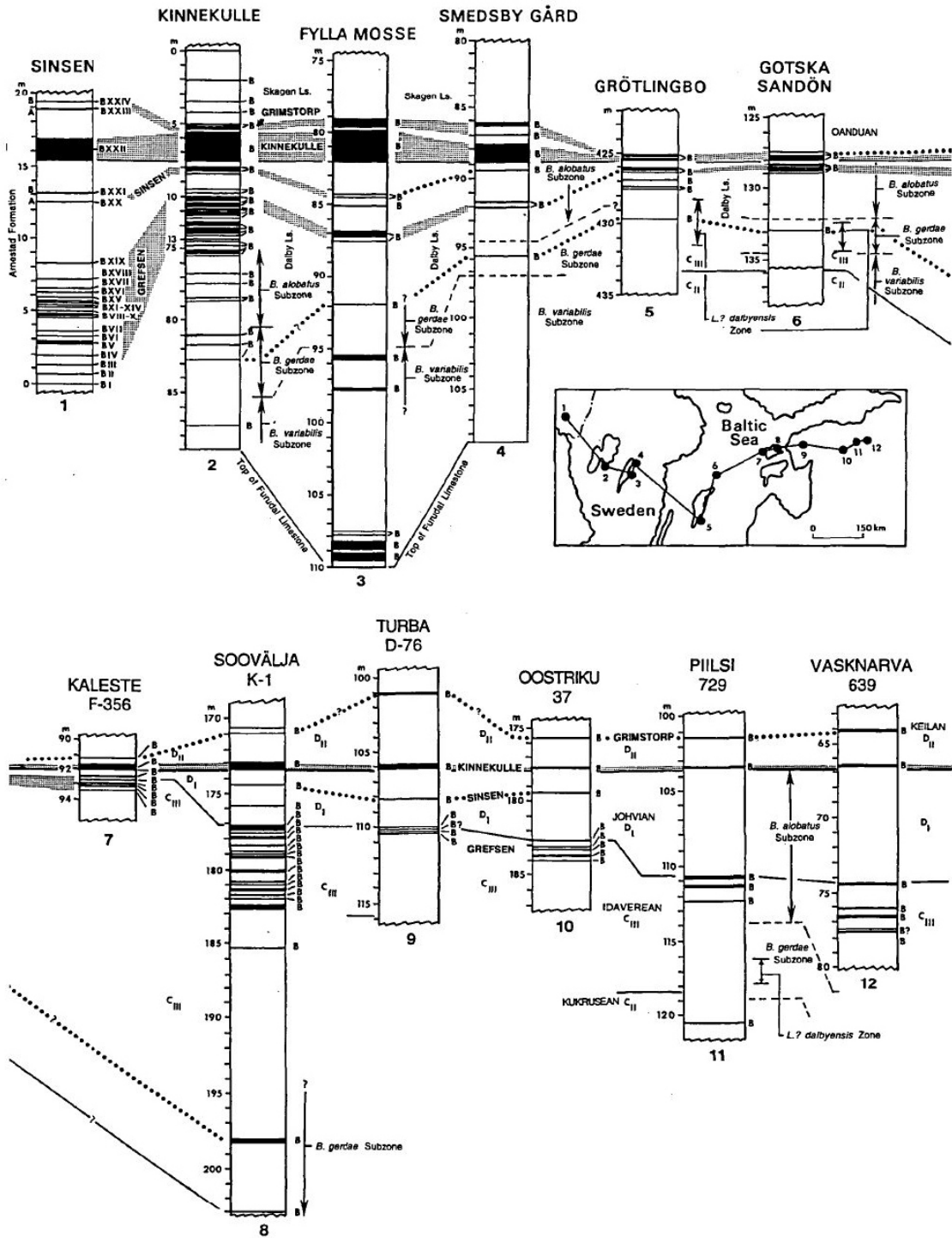
Figure 3-1. *Geological correlation of Middle Ordovician K-bentonites in Baltoscandia by /Bergström et al. 1995/.*

Examples of soil weathering

Dispersion of smectite rich soils is a known geological phenomenon. Similar problems are frequently addressed in soil studies, where soil erosion problems occur specifically in arid-to-semiarid environments with sodic clay-rich soils predominating. A sodicity process enhances the deterioration of the hydraulic properties of the soil, which, in turn, could increase surface runoff and erosion and impair soil drainage.

In soils the dispersion of clay rich soils is related to breakdown of clay aggregates due to reduction adhesion between the particles inside the aggregates under saturated conditions /Ghezzehei and Or 2000/. In soils the swelling and dispersion cause hydraulic conductivity (K) reduction by plugging of soil porosity /Shainberg and Letey 1984/. However, swelling and dispersion can affect the soil properties differently depending on electrolyte concentrations /Pupisky and Shainberg 1979/. If the ionic concentration is > 10 mmol/L (flocculation value) then clay swelling is the main process reducing K, and clay dispersion and migration of the dispersed particles into conducting pores is dominant at lower values /Pupisky and Shainberg 1979/.

/Dikinya et al. 2006/ review the main grounds for clay dispersion. First of all, the release of fine clay particles is affected by ionic strength /Kia et al. 1987, Grolimund et al. 1998, Kretzschmar et al. 1999/ and is favoured by irrigation with sodium (Na^+) rich water of low ionic strength /Hajra et al.2002/. For soil systems these questions (i.e. effects of exchangeable cation and electrolyte concentration on swelling, dispersion, and permeability) have been extensively studied /Frenkel et al. 1978, Abu-Sharar and Salameh 1995, Chaudhari 2001, Quirk 2001/. Forces of attraction and repulsion in clay systems are dependent on the type and concentration of ions in solution /Aydin et al. 2004/. In the presence of monovalent ions (e.g. Na^+) the thickness of the electrical double layer is increased leading to deflocculation and dispersion, whereas it is reduced if the system is dominated by multivalent ions (e.g. Ca^{2+}) enhancing flocculation. Generally clay will more readily disperse when the electrolyte concentration in the soil solution is low enough to permit the development of sufficient double layer repulsion to overcome van der Walls attraction forces /Sumner 1993/. /Quirk and Schofield 1955/ have defined the 'threshold concentration' where structural breakdown first affects permeability and the 'turbidity concentration' where dispersed particles first appear in the flow path. Different opinions are evident in the literature as to whether swelling or dispersion is the major cause of reduced permeability in sodic soils /Shainberg and Letey 1984, Shainberg and Levy 1992, Chaudhari 2001/. Swelling is generally appreciable at high exchangeable sodium percentage (ESP) (20–25, /Aylmore and Quirk 1960/ and dispersion can occur at ESPs as low as 10 /Felhendler et al. 1974/. Larger effects on permeability were observed for silt loam soils than clay and clay loam soils /Chaudhari 2001, Chaudhari and Somawanshi 2004/.

/Keren and Singer 1988/ observed that replacement of an NaCl electrolyte solution of 10 mmol/L with deionised water led to significant clay dispersion and sharply decreased K. This decrease was followed by a sharp increase in K, as the clay was leached out of sample. They also noticed that if the electrolyte concentration was decreased stepwise, then no clay particles were found in the leachate, whereas the K decrease was only gradual without subsequent increase.

The study of /Keren and Ben-Hur 2003/ has the large amount of similarity to the bentonite erosion scenario by the glacier meltwater. In the scenario, the rainwater flushing smectite-containing soil should be circumneutral, ie in connection with acidity-buffering minerals in the uppermost layer (eg calcite), simultaneously however far below gypsum-equilibrium of Ca^{2+}.

/Keren and Ben-Hur 2003/ undertook a series of experiments to study the interaction effects of clay swelling and dispersion (and $CaCO_3$ content) on saturated hydraulic conductivity. Research carried out in Israel (column leaching of local soils) studied Chomoxeret sand from Yizre'el Valley containing 8% $CaCO_3$, saturated soil paste at pH 7.7 and 65% clay incl 57% montmorillonite. In column experiments, relative hydraulic conductivity K_s/K_{s0} during different ionic strength leaching waters was determined. Dispersion was found to be faster than swelling under abrupt leaching with low ionic strength water, clay particles were observed to plug the pores when moving downwards. Their results that agree with earlier observations by /Keren and Singer 1988/ suggest that the clay swelling is a continuous process increasing with decrease of solution concentration, whereas the clay dispersion is a rapid process and possible only at ionic strengths lower than flocculation value. The dispersion is effective only under rapid leaching with very low ionic concentration (deionized) water.

At these circumstances both swelling and dispersion occur, but the dispersion is much more rapid, probably due to "osmotic explosion" mechanism /Abu-Sharar et al. 1987, Keren and Ben-Hur 2003/. The "osmotic explosion" mechanism is explained by additional energy input required for dispersion. So, as the result of circumneutral rainwater intrusion, the colloids formed and flushing of smectites downwards was observed.

According to /Emerson and Bakker 1973/ there are two necessary conditions for clay dispersion: (a) reduction of electrolyte concentration below the flocculation value and (b) an activation energy input that initiates the dispersion. Under saturation conditions, the activation energy could be provided during rapid leaching with deionized water by a water movement into the aggregates because of steep concentration gradients between small-scale inter-porosity in aggregates with higher salt concentration and larger sediment pores with rapidly replaced by fresher pore-water composition. There is no dispersion (leaching of clay particles) if the electrolyte concentration is slowly decreased which means that clay swelling blocks efficiently the pore space and the particles do not escape.

However, /Abu-Sharar et al. 1987/ and /Keren and Ben-Hur 2003/ do not provide the time scale of the processes observed.

In conclusion, soil researchers have studied the mechanism of colloid release in laboratory experiments and have found that there has to be an abrupt change in infiltrating water quality leading to 'osmotic explosion'. Clogging the pores in the lower part of the soil column has been followed, leading to total increase of hydraulic conductivity in vertical profile and increased surface runoff. So, also limited, there are literature evidences of clay colloids release from bentonites/smectites caused by low-ionic circumneutral water.

Ideas on natural analogue studies

The geological settings to look for natural analogue studies include

(1) Bentonite/smectite similar to what is used in repository.

(2) Water similar to the composition of glacial meltwater.

(3) Scenario similar to what is proposed in the bentonite erosion project.

Dissolved ions in selected 18 glaciers meltwater mmol/l were recalculated from /Brown 2002/ and are presented in following Tables.

From Table 3-1 it is evident that glacial meltwaters are very different, but definitely $Ca^{2+} < 0.65$ mmol/l. Therefore, it is possible to use an approximation that rainwater reacted with carbonates has similar chemical composition with glacier meltwater. One should however be aware of reactions involving organic material in the soil profile.

The detailed study of the weathering profiles by geologists so far is poor. One could study weathering profiles where bentonites are exposed to infiltrated rainwater. However, the question remains if this study would tell more than laboratory experiments.

The other problem related to the study of historical bentonite profiles is the geological changes that have occurred in bentonites over geological time scales. The bentonite erosion project has to provide the scenarios for approximately 100,000 years, but the geological deposits have been changed and subjected to various conditions, many of those uncertain, during tens and hundreds of millions of years.

In conclusion, the field studies of weathering of the historical K-bentonite deposits could provide interesting and new information, but the relevance related to the bentonite erosion project is still questionable because of the uncertainties related to the changes during tens and hundreds of millions of years.

Table 3-1. Dissolved ions in selected 18 glaciers meltwater (mmol/l).Recalculated from /Brown 2002/, Glacier meltwater hydrochemistry, Applied Geochemistry 17, pp 855–883. Green figures – lowest concentrations, red figures – highest concentrations.

	Ca+2	Mg+2	Na+	K+	HCO3-	Cl-	SO42-	NO3-
Bench (Alaska)	0.27	0.018	0.025	0.061	0.43	0.002	0.13	-
Haut d'Arolla (CH)	0.08-0.23	0.007-0.02	0.005-0.036	0.005-0.018	0.18-0.36	0.001-0.09	0.015-0.12	0-0.03
Nigardsbreen (NO)	0.0044-0.019	0.001-0.004	0.008-0.025	0.001-0.004	0.001-0.009	0.01-0.025	0.003-0.02	0.002-0.01
Gorner (CH)	0.06-0.17	0.008-0.09	0.009-0.043	0.003-0.03	-	-	-	-
Walcott (Antarct)	0.11-0.65	0.008-0.09	0.017-0.097	0.002-0.03	0.21-1.0	0.009-0.087	0.02-0.34	-
Koettlitz (Antarct)	0.04-0.05	0.003	0.011-0.034	0.0008-0.007	0.09-0.13	0.0005-0.001	0.003-0.008	-
Howchin (Antarct)	0.54-0.65	0.06-0.1	0.36-0.61	0.04-0.07	1.36-1.56	0.12-0.26	0.17-0.56	-
Ward (Antarct)	0.36-0.41	0.14-0.17	0.88-1.44	0.09-0.1	1.08-1.45	0.67-1.02	0.11-0.15	-
Berendon (CAN)	0.045-0.38	0.001-0.009	0.001-0.004	0.0004-0.005	0.23-0.79	0.025-0.027	-	-
Tsanfleuron (CH)	0.32	0.046	0.005	0.006	0.63	0.005	0.059	0.01

	Ca+2	Mg+2	Na+	K+	HCO3-	Cl-	SO42-	NO3-
Chhota-Sigri	0.04-0.13	0.003-0.02	0.025-0.065	0.022-0.051	-	-	-	-
Scott Turnerbreen (CH)	0.06-0.15	0.05-0.15	0.11-0.74	0.005-0.019	0.11-0.26	-	0.048-0.10	-
Fjallsjökull (ISL)	0.10-0.14	0.016-0.03	0.03-0.12	0.003-0.007	0.19-0.3	-	0.013-0.033	-
Chamberlain (USA)	0.027-0.15	0.004-0.06	0.004-0.009	0-0.005	0.15-0.2	0.005-0.02	0.015-0.15	-
Engabreen (NO)	0.041-0.31	0.002-0.03	0.011-0.21	0-0.027	0.05-0.68	0.01-0.19	0-0.07	0-0.015
Grimsvotn (ISL)	0.18	0.06	0.48	0.012	0.57	0.09	0.066	-
Austre Okstindbreen (NO)	0.14-0.21	0.004-0.02	0.015-0.14	0.004-0.029	-	-	-	-
Argentiere (FR)	0.01-0.24	0.003-0.033	0.01-0.09	0.005-0.006	0.11-0.4	-	0.005-0.03	-

References

Abu-Sharar T M, Bingham F T, Rhoades J D, 1987. Stability of Soil Aggregates as Affected by Electrolyte Concentration and Composition. Soil Sci Soc Am J 51:309-314.

Abu-Sharar T M, Salameh A S, 1995. Reductions in hydraulic conductivity and infiltration rate in relation to aggregate stability and irrigation water turbidity. Agricultural Water Management, Volume 29, Issue 1, p. 53–62.

Alonso U, Missana T, Patelli A, Rigato V, Ravagnan J, 2002. Size effects on colloids diffusion in granite microfractures. Geochimica et Cosmochimica Acta, 66: 15.

Altaner S P, Hower J, Whitney G, Aronson J L, 1984. Model for K-bentonite formation; evidence from zoned K-bentonites in the Disturbed Belt, Montana Geology; v. 12; no. 7; p. 412–415.

Aydin M, Yanob T, Kilic S, 2004. Dependence of Zeta Potential and Soil Hydraulic Conductivity on Adsorbed Cation and Aqueous Phase Properties. Soil Science Society of America Journal 68, p. 450–459.

Aylmore L A G, Quirk J P, 1960. Domain or turbostratic structure of clays. Nature, 187, p. 1046–1048.

Baik M H, Cho W J, Hahn P S, 2007. Erosion of bentonite particles at the interface of a compacted bentonite and a fractured granite. Engineering Geology Volume 91, Issues 2–4, p. 229–239.

Benna M, Kbir-Ariguib N, Magnin A, Bergaya F, 1999. Effect of pH on Rheological Properties of Purified Sodium Bentonite Suspensions. Journal of Colloid And Interface Science Volume 218, Issue 2, p. 442–455.

Bergström S M, Huff W D, Kolata D R, Bauert H, 1995. Nomenclature, stratigraphy, chemical fingerprinting, and areal distribution of some Middle Ordovician K-bentonites in Baltoscandia. Geologiska Föreningens i Stockholm Förhandlingar, v. 117, pp. 1–13.

Brown G H, 2002. Glacier meltwater hydrochemistry. Applied Geochemistry 17, pp 855–883.

Brusewitz A M, 1986. Chemical and physical properties of Paleozoic potassium bentonites from Kinnekulle, Sweden. Clays and Clay Minerals; v. 34; no. 4; p. 442–454.

Buddemeier R W, Hunt J R, 1988. Transport of colloidal contaminants in groundwater: radionuclide migration at the Nevada test site. Applied geochemistry 3:55, p. 535–548.

Chaudhari S K, 2001. Saturated hydraulic conductivity, dispersion, swelling, and exchangeable sodium percentage of different textured soils as influenced by water quality. Communications in Soil Science and Plant Analysis, Volume 32, Issue 15–16, p. 2439–2455.

Chaudhari S K, Somawanshi R B, 2004. Unsaturated flow of different quality irrigation waters through clay, clay loam and silt loam soils and its dependence on soil and solution parameters. Agricultural Water Management, Volume 64, Issue 1, p. 69–90.

Chen J S, Cushman J H, Low P F, 1990. Rheological behavior of Na-montmorillonite suspensions at low electrolyte concentration. Clays and Clay Minerals, Vol. 38; No. 1; p. 57–62.

Delgado A, Gonzalez-Caballero F, Bruque J M, 1986. On the zeta potential and surface charge density of montmorillonite in aqueous electrolyte solutions. Journal of colloid and interface science, Vol. 113, No 1, p. 203–211.

Dikinya O, 2006. The Effects of Self-filtration on Saturated Hydraulic Conductivity in Sodic Sandy Soils. PhD Thesis. School of Earth and Geographical Sciences, The University of Western Australia. 122 pp.

Durán J D G, Ramos-Tejada M M, Arroyo1 F J, González-Caballero F, 2000. Rheological and Electrokinetic Properties of Sodium Montmorillonite Suspensions I. Rheological Properties and Interparticle Energy of Interaction. Journal of Colloid and Interface Science Volume 229, Issue 1, p. 107–117.

Emerson W W, Bakker A C, 1973. The comparative effects of exchangeable calcium, magnesium, and sodium on some physical properties of red-brown earth subsoils. II. The spontaneous dispersion of aggregates in water. Australian Journal of Soil Research 11(2), p. 151–157.

Felhendler R, Shainberg I, Frenkel H, 1974. Dispersion and hydraulic conductivity of soils in mixed solution. Trans. 10th Int. Cong. Soil Sci. Moscow, Vol: 1, Nauka, Moscow, p. 103–112.

Frenkel H, Goertzen J O, Rhoades J D, 1978. Effects of Clay Type and Content, Exchangeable Sodium Percentage, and Electrolyte Concentration on Clay Dispersion and Soil Hydraulic Conductivity. Soil Science Society of America Journal 42: p. 32–39.

Gardiner M P, Grindrod P, Moulin V, 2001. The role of colloids in the transport of radionuclides from a radioactive waste repository: implication on safety assessment, Final Project Report EUR-19781.

Ghezzehei T A, Or D, 2000. Dynamics of soil aggregate coalescence governed by capillary and rheological processes. Water Resources Research, Volume 36, Issue 2, p. 367–380.

Grindrod P, Peletier M, Takase H, 1999. Mechanical interaction between swelling compacted clay and fractured rock, and the leaching of clay colloids. Engineering Geology, Volume 54, Issues 1–2, p. 159–165.

Grolimund D, Elimelech M, Borkovec M, Barmettler K, Kretzschmar R, Sticher H, 1998. Transport of in-situ mobilized colloidal particles in a natural porous media. Environmental Science and Technology, 32, p. 3562–3569.

Hajra M G, Reddi L N, Glasgow L A, Xiao M, Lee I M, 2002. Effects of Ionic Strength on Fine Particle Clogging of Soil Filters. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 128, Issue 8, p. 631–639.

Herbert H J, Kasbohm J, Moog H C, Henning K H, 2004. Long-term behaviour of the Wyoming bentonite MX-80 in high saline solutions. Applied Clay Science, Volume 26, Issues 1–4, p. 275–291.

Huertas F J, Cuadros J, Huertas F, Linares J, 2000. Experimental study of the hydrothermal formation of smectite in the beidellite-saponite series. American Journal of Science, vol. 300, p. 504–527.

Janek M, Lagaly G, 2001. Proton saturation and rheological properties of smectite dispersions. Applied Clay Science Volume 19, Issues 1–6, p. 121–130.

Kaufhold S, Dohrmann R, 2008. Detachment of colloidal particles from bentonites in water. Applied Clay Science Volume 39, Issues 1–2, p. 50–59.

Keren R, Ben-Hur M, 2003. Interaction effects of clay swelling and dispersion and CaCO3 content on saturated hydraulic conductivity. Australian Journal of Soil Research 41(5), p. 979–989.

Keren R, Singer M J, 1988. Effect of Low Electrolyte Concentration on Hydraulic Conductivity of Sodium/Calcium-Montmorillonite-Sand System. Soil Science Society of America Journal 52: p. 368–373.

Kersting A B, Efurd D W, Finnegan D L, Rokop D J, Smith D K, Thompson J L, 1999. Migration of plutonium in ground water at the Nevada Test Site. Nature 397, p. 56–59.

Kia S F, Fogler H S, Reed M G, 1987. Effect of pH on colloidally induced fines migration. Journal of colloid and interface science, 118:11, p. 158–168.

Kretzschmar R, Borkovec M, Grolimund D, Elimelech M, 1999. Mobile subsurface colloids and their role in contaminant transport. Advances in agronomy, vol. 66, p. 121–193.

Kurosawa S, Kato H, Ueta S, Yokoyama K, Fujihara H, 1999. Erosion properties and dispersion-flocculation behavior of bentonite particles. Materials Research Society Symposium Proceedings 679, (8).

Lagaly G, Ziesmer S, 2003. Colloid chemistry of clay minerals: the coagulation of montmorillonite dispersions. Advances in Colloid and Interface Science, Volumes 100–102, p. 105–128.

Luckham P F, Rossi S, 1999. The colloidal and rheological properties of bentonite suspensions. Advances in Colloid and Interface Science Vol. 82, Issues 1-3, p. 43–92.

Missana T, Alonso Ú, Turrero M J, 2003. Generation and stability of bentonite colloids at the bentonite/granite interface of a deep geological radioactive waste repository. Journal of Contaminant Hydrology Volume 61, Issues 1–4, p. 17–31.

Nuttal H E, Long R L, 1993. Mobility of radioactive colloidal particles in groundwater. Radioactive Waste Management and the Nuclear Fuel Cycle 17 3–4, p. 237–251.

Ouhadi V R, Yong R N, Sedighi M, 2006. Influence of heavy metal contaminants at variable pH regimes on rheological behaviour of bentonite. Applied Clay Science, Vol. 32, Issues 3–4, p. 217–231.

Penner D, Lagaly G, 2001. Influence of anions on the rheological properties of clay mineral dispersions. Applied Clay Science, Volume 19, Issues 1–6, p. 131–142.

Permien T, Lagaly G, 1994. The rheological and colloidal properties of bentonite dispersions in the presence of organic compounds; I, Flow behaviour of sodium-bentonite in water-alcohol. Clay Minerals; Vol. 29; No. 5; p. 751–760.

Pupisky H, Shainberg I, 1979. Salt Effects on the Hydraulic Conductivity of a Sandy Soil. Soil Science Society of America Journal, 43: p. 429–433.

Pusch R, 1983. Borehole Sealing for Underground Waste Storage. Journal of Geotechnical Engineering Vol. 109, No. 1, p. 113–119.

Pusch R, 1999. Experience from preparation and investigation of clay microstructure. Engineering Geology Volume 54, Issues 1–2, p. 187–194.

Pusch R, Madsen F T, 1995. Aspects on the illitization of the Kinnekulle bentonites. Clays and Clay Minerals; v. 43; no. 3; p. 261–270.

Quirk J P, 2001. The significance of the threshold and turbidity concentrations in relation to sodicity and microstructure. Australian Journal of Soil Research, 39, p. 1185–1217.

Quirk J P, Schofield R K, 1955. The effect of electrolyte concentration on soil permeability. Journal of Soil Science 6: p. 163–178.

Shainberg I, Letey J, 1984. Response of Soils to Sodic and Saline Conditions. University of California, Division of Agriculture and Natural Resources, 57 pp.

Shainberg I, Levy G J, 1992. Physico-chemical effects of salts upon infiltration and water movement in soils. Interacting Processes in Soil Science, Lewis Publishers.

Sumner M E, 1993. Sodic soils – New perspectives. Australian Journal of Soil Research 31(6), p. 683–750.

Tombácz E, Szekeres M, 2004. Colloidal behavior of aqueous montmorillonite suspensions: the specific role of pH in the presence of indifferent electrolytes. Applied Clay Science Volume 27, Issues 1–2, p. 75–94.

Villar M V, 2006. Infiltration tests on a granite/bentonite mixture: Influence of water salinity. Applied Clay Science Volume 31, Issues 1–2, p. 96–109.

Yong R N, Warkentin P B, 1975. Soil Properties and Behaviour, Elsevier, 449 pp.