

FINAL TRIAS REPORT

1. *Project Title*
Chemically and Electrically Coupled Transport in Clayey Soils and Sediments, Part 2
(Field experiments and Numerical Modeling).
2. *TRIAS number*
835.80.032
3. *Research Period*
September 10, 2001 to September 10, 2005
4. *Names of the researchers*
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5. *Summary*

Research objectives. The main objective of the work was to provide insight in the occurrence and significance of osmotic phenomena in clayey sediments under *in-situ* conditions in the field. Specific aims were quantification of semi-permeable membrane properties of clays and assessment of the magnitude of osmotically-induced pressures and flows that might be generated within these sediments. To this aim osmosis field experiments were conducted and numerical modeling was performed.

Background. Osmotic phenomena occur in porous media that function as semipermeable membranes. Semi-permeability refers to relative restriction or hindrance of transport of solutes through the membrane relative to passage of the solvent, in our case water. The restricted passage of solutes causes two processes:

- (a) fluid flow through the membrane in response to a concentration gradient, which is known as chemical osmosis and
- (b) filtration or salt sieving when the fluid is forced through the membrane by a hydraulic gradient, which is called ultrafiltration or hyperfiltration.

These two processes can occur individually or in combination. A number of laboratory studies have demonstrated that clays and shales exhibit membrane properties. Chemical osmosis and ultrafiltration have also been suggested to occur in sedimentary basins where they are thought to be responsible for the generation of anomalously high pore pressures and high salinities. Direct evidence for membrane behavior of natural clays from field measurements has only been obtained for the Cretaceous-age Pierre Shale in South Dakota, USA, and more recently, at the final stage of this PhD-study, for the Jurassic-age Opalinus Clay in Switzerland. Apart from chemically coupled flow and transport, electrical effects can also cause osmotic phenomena. The latter electrical coupling effects were addressed in to the two partner PhD-projects that were carried out in the Geochemistry Group (Katja Heister; Part I) and in the Environmental Hydrogeology Group (Sam Bader; Part 3) of Utrecht University. The present project focused solely on chemical coupling to keep the already complex field experiments manageable and

because the modeling framework for electrical coupling was only developed at a very late stage of the three-tier research program.

Methods. For the present research, *in-situ* experiments were conducted in unconsolidated Calais Clay, found at shallow depth in the central part of the Netherlands, and in highly consolidated Boom Clay, in Belgium. For the measurements in the Calais Clay, a special piezometer was developed that can be filled with different aqueous solutions, shut-in (closed off from the atmosphere) and in which fluid pressure and electrical conductivity, EC, can be monitored (Figure 1).

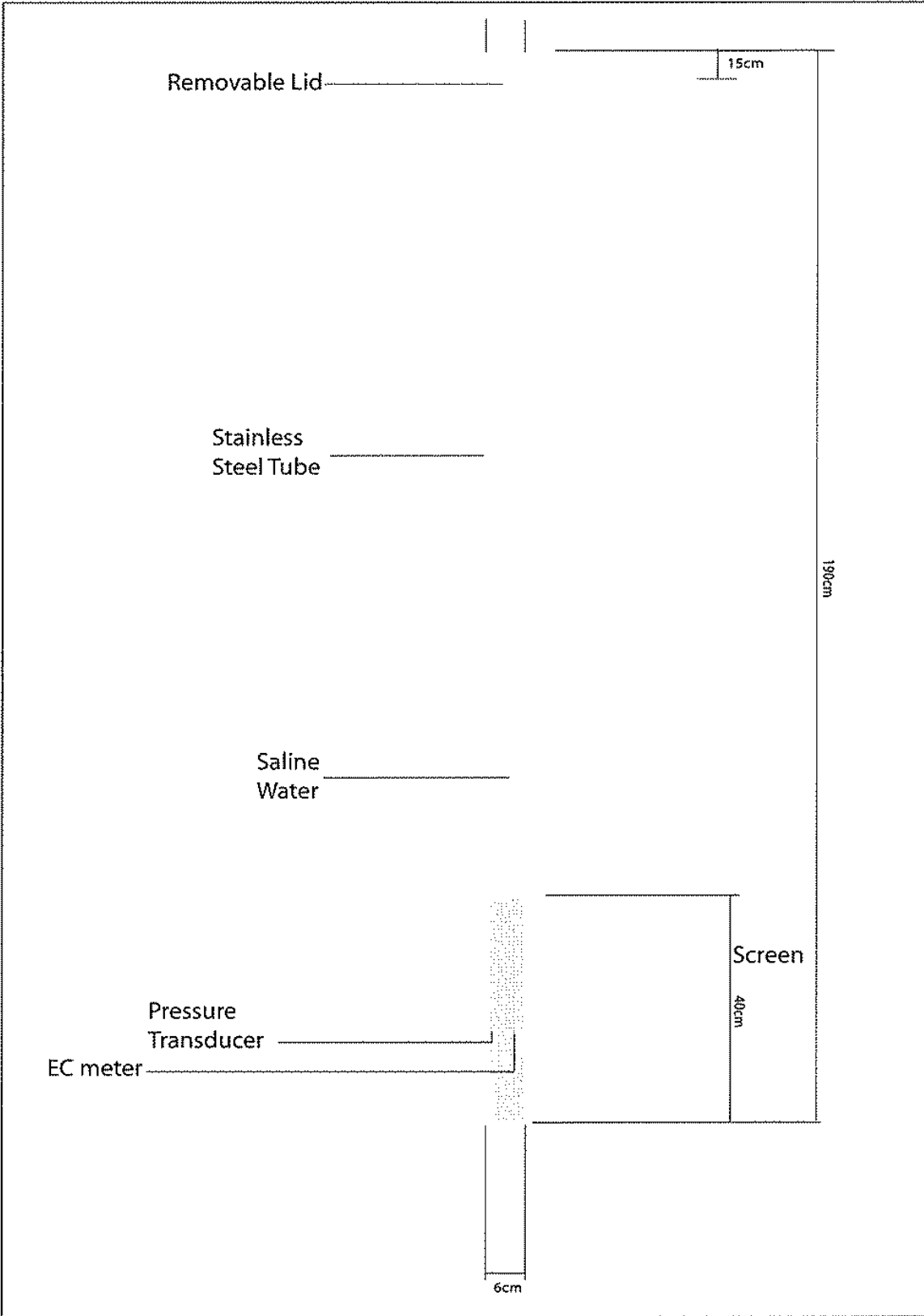


Figure 1. Newly developed piezometer for in-situ testing in shallow clays

The instrument was designed based on a review of existing hydraulic testing, pore pressure measurement and pore water sampling methodologies and on explorative calculations carried out with a numerical model that incorporates osmotic phenomena. Experiments consisted of the recording of water pressure and EC responses for tests in which water with different solution concentrations were used in the instrument, including a pore-water duplicate. Additionally, a BAT-probe was used, an existing instrument that is particularly suited to conduct permeability and pore pressure measurements in low-permeability sediments (Figure 2).

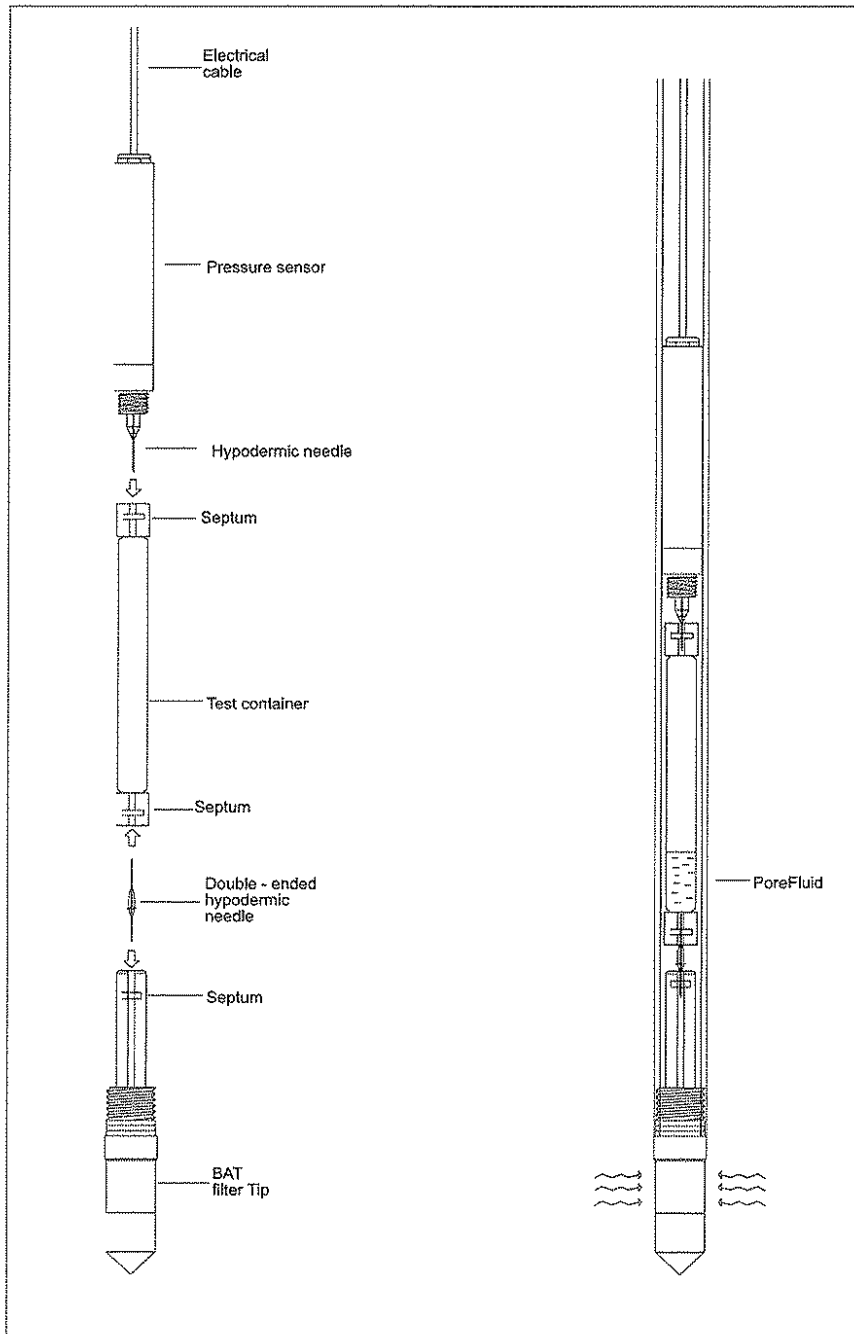


Figure 2. BAT probe. Left: disassembled instrument. Right: inflow test configuration.

For the present study the ceramic filter of the BAT-probe was pre-saturated with different aqueous solutions and the pore pressure response monitored. The experiments on the Boom Clay were carried out in the Underground Research Laboratory (URL) of the Research Center for Nuclear Energy (SCK-CEN) in Mol, Belgium, using existing shut-in piezometers that allowed fluid exchange. In collaboration with the other project partners, notably Sam Bader (Part 3), a numerical model for chemically and electrically coupled flow and transport was developed. Major contributions were made in developing the appropriate set of model equations and in testing of the model in various applications. The model, without the electrical coupling, has been used in the present project in

- (a) explorative calculations for the field experiments;
- (b) analysis and modeling of the experimental results of the field experiments;
- (c) studies of an existing laboratory osmosis test and the existing field experiment in the Pierre Shale; and
- (d) a study of the role of osmosis in the generation of overpressures found in the Triassic-age Dunbarton Basin, in the eastern US.

Results. For the Calais Clay no significant differences in pressure response between saline and pore-water duplicate tests were observed for the specially-designed piezometer, which suggests that the Calais Clay does not exhibit significant semipermeability, a result which is consistent with laboratory measurements on this clay carried out in Katja Heister's project (Part 1). For the BAT-probe, pressure responses were recorded that are suggestive of osmotic behavior. However, we have not been able to explain the response characteristics in sufficient detail to ascertain the osmotic origin of the measurements and rule out contributions from other effects. For the Boom Clay, two tests were conducted. Both tests yielded osmotically-induced pressures up to 0.2 bar for the employed aqueous solutions (Figure 3).

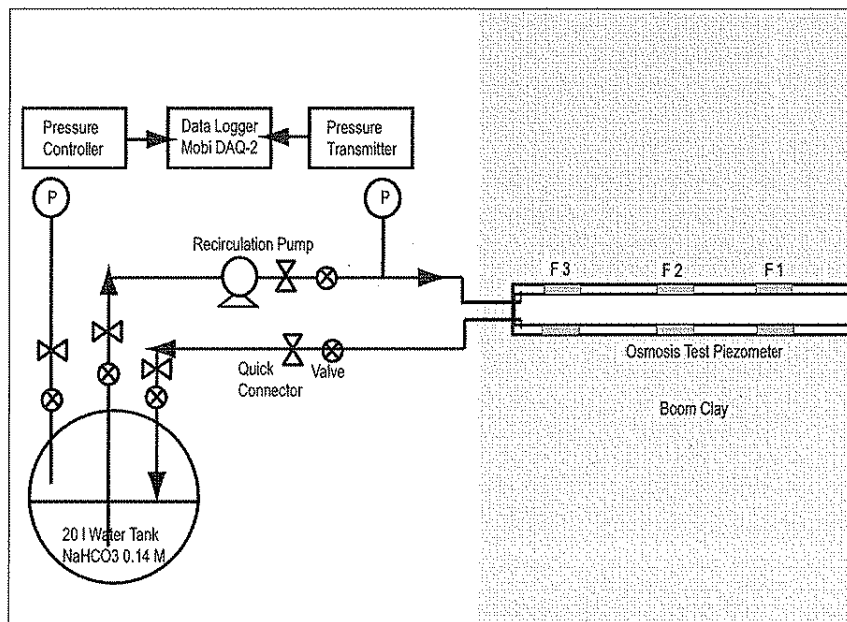


Figure 3. System used for testing the Boom Clay. Experiments were carried out in Filter 3.

The inferred membrane efficiency for the Boom Clay is rather high (up to 41%). These values are of key importance for SCK-CEN because the Belgian government has obliged this organization to assess the relevance of osmotic phenomena for the safe storage of nuclear

waste in the Boom Clay. A more extensive assessment through more extensive model calculations will be conducted in collaboration with the VUA following on the present project. The negligible membrane efficiency for the Calais Clay is attributed to a low degree of compaction of the clay and to a dominance of calcium rather than sodium ions on the exchange complex of the surface of clay particles. The modeling tool that was developed in the collaborative effort may also be considered, in part, a result of the present study. With the model, high membrane efficiencies were also inferred for the Pierre shale and for shales in the Dunbarton basin in the US. Moreover, the modeling provided strong evidence for an osmotic origin of high fluid pressures in the Dunbarton basin.

6. Popular Summary in *Dutch*

Achtergrond. Een opvallende eigenschap van kleien is hun lage doorlatendheid. Transport van water en opgeloste stoffen in klei-rijke sedimenten verloopt in de regel langzaam. Van deze eigenschap wordt dankbaar gebruik gemaakt bij de inzet van kleien als afscheidende laag bij vuilstorten. Daarnaast worden kleilagen recentelijk ook in beschouwing genomen als opslagmedium voor ondergrondse berging van radioactief afval. De langzame processen die optreden in kleien zorgen ervoor dat de huidige verdeling van het zoutgehalte van het grondwater in kleien vaak kustlijnverschuivingen en andere veranderingen in het oppervlaktemilieus weerspiegelen uit een ver geologisch verleden. De verdeling van zoutgehalte en specifieke opgeloste stoffen kan gebruikt worden om het verleden te reconstrueren. Voor al deze toepassingen is het belangrijk om de transportprocessen van water en opgeloste stoffen in en door klei-rijke milieus goed te begrijpen en te kunnen voorspellen.

In de klassieke benadering vormen ruimtelijke verschillen in stijghoogte de drijvende kracht achter grondwaterstroming. Voor het transport van opgeloste stoffen worden traditioneel twee fundamentele processen onderscheiden: advectie en moleculaire diffusie. Advectie beschrijft het meegevoerd worden van opgeloste stoffen met het stromende grondwater; diffusie is transport dat ontstaat door de willekeurige bewegingen van individuele moleculen die samenhangen met hun kinetische energie. Diffusief transport kan worden berekend uit ruimtelijke verschillen in de concentratie van opgeloste stoffen. Uit laboratoriumstudies is echter bekend dat dichte kleien zich kunnen gedragen als semi-permeabel membraan. Dat betekent dat in deze kleien ruimtelijke verschillen in concentratie stroming van water veroorzaken; een verschijnsel dat wordt aangeduid met de term chemische osmose. Semi-permeabiliteit uit zich ook in het verschijnsel van ultrafiltratie dat kan worden beschreven als het uitzeven van opgeloste stoffen wanneer zout water door een membraan wordt geperst. Dit laatste proces kan worden gezien als een belemmerde vorm van advectie.

Het membraangedrag van kleien en de daaraan gekoppelde osmotische verschijnselen hangen sterk samen met de negatieve elektrische oppervlaktelading van kleideeltjes die het transport van ionen in het water belemmeren. Dit gedrag wordt sterker naarmate de klei meer is samengedrukt en de ruimte tussen de kleideeltjes kleiner is. Een ideaal membraan is volledig impermeabel voor opgeloste stoffen. Niet ideale, of lekkende membranen laten beperkt transport van opgeloste stoffen toe. Laboratorium studies hebben herhaaldelijk aangetoond dat natuurlijke en industriële kleien zich kunnen gedragen als semi-permeabel membraan.

Doelstelling en aanpak. Het doel van ons onderzoek was om meer duidelijkheid te verkrijgen omtrent het vóórkomen en de relevantie van osmotisch gedrag van kleirijke sedimenten onder *in-situ* omstandigheden in het veld. Daartoe hebben we veldexperimenten uitgevoerd om membraaneigenschappen te kwantificeren en is procesmodellering gebruikt om bestaande en nieuwe metingen te interpreteren en om voorspellingen te doen.

Veldexperimenten. Veldmetingen zijn uitgevoerd aan "Calais klei" in centraal Nederland en aan Boomse klei in noord België. De Calais klei is een Holocene, estuariene, ongeconsolideerde, plastische klei die zich op geringe diepte onder het maaiveld bevindt, terwijl de Boomse klei een sterk geconsolideerde, mariene, doch zoete klei is waarbij metingen tevens zijn verricht in een ondergronds laboratorium op ca. 220 meter onder maaiveld. De experimenten betroffen registratie van veranderingen in waterdruk en zoutgehalten in van de atmosfeer afgesloten vloeistofreservoirs die via een filter in contact staan met de klei. Om een osmotisch signaal te krijgen werden de filters gevuld met water met een zoutgehalte dat afwijkt van dat in de klei.

Voor de experimenten in de Calais klei hebben we speciale instrumenten ontworpen en gebruikt. Tevens hebben we gebruik gemaakt van de "BAT probe". een handsonderingsapparaat dat speciaal geschikt is voor grondwaterdruk- en doorlatendheidsmetingen in slechtdoorlatende lagen. De metingen bleken niet eenduidig te interpreteren. Membraangedrag van de Calais klei lijkt echter zeer gering of afwezig.

Twee *in-situ* experimenten aan Boomse klei werden uitgevoerd in het Ondergrondse Onderzoekslaboratorium (URL) van het Studiecentrum voor Kernenergie (SCK-CEN), te Mol, België. De experimenten zijn verricht in het kader van een groter onderzoeksprogramma naar de geschiktheid van de Boomse klei voor ondergrondse opslag van radioactief afval. Interesse van SCK-CEN heeft vooral betrekking op de vraag of osmotisch-gedreven stroming, veroorzaakt door potentiële toekomstige lekkage van grote hoeveelheden nitraat-rijke bitumineus radioactief afval, vloeistofdrukken zou kunnen genereren die de afsluitende eigenschappen van de klei sterk zou kunnen aantasten. Voor de experimenten is gebruik gemaakt van bestaande piëzometers. Analyse en modellering van de experimentele gegevens tonen aan dat de membraaneigenschappen (uitgedrukt in de osmotische efficiëntie, σ) van de Boomse klei sterk aanwezig zijn onder onverstoorte chemische condities ($\sigma = 41\%$ bij 0.014 M NaHCO₃), maar sterk afneemt bij toenemende concentraties ($\sigma = 7\%$ bij 0.14 M NaHCO₃). Deze informatie is van cruciaal belang voor SCK-CEN omdat dit studiecentrum door de Belgische overheid verplicht is om aan te tonen wat de betekenis is van osmotische processen voor de veiligheid van ondergrondse berging van kernafval in de Boomse klei. Dit aspect zal in samenwerking met de VUA middels uitgebreidere modellering in vervolg op dit promotieonderzoek verder worden onderzocht. De geringe semi-permeabiliteit van de Calais klei wordt toegeschreven aan de geringe compactiegraad van deze klei en de grote calciumbezetting van het cation uitwisselingscomplex op het oppervlak van de kleideeltjes in deze klei.

Modellering. Voor de modellering is gebruik gemaakt van een numeriek eindige-elementen model voor het oplossen van gekoppelde partiële differentiaalvergelijkingen. De vergelijkingen beschrijven zowel de bovengenoemde conventionele transportprocessen als de osmotische processen. Daarnaast is in het model de sterke concentratieafhankelijkheid van de osmotische efficiëntie meegenomen. Modellering van data van een bestaand laboratorium osmose experiment met bentoniet laten zien dat het model wel algemene karakteristieken goed simuleert zoals die in het algemeen worden waargenomen in dit type osmose experimenten: een differentiële drukopbouw door osmotisch gedreven watertransport gevolgd door een geleidelijke afname van het drukverschil die wordt veroorzaakt door de geleidelijke afname van de concentratiegradiënt in het membraan door moleculaire diffusie; echter voor het gekozen laboratoriumexperiment bleek het niet mogelijk de experimentele druk- en zoutgehalteverandering gelijktijdig goed te reproduceren. Dit duidt mogelijk op structuurveranderingen in de klei die zijn ontstaan tijdens het experiment en die niet in beschouwing zijn genomen in de numerieke simulaties. Modellering van een negen jaar durend *in-situ* osmose experiment in de Pierre shale in South Dakota in de Verenigde Staten geeft een

waarde van de osmotische efficiëntie $\sigma = 21\%$ voor het totale zoutgehalte van 3.5 g/l dat lokaal aanwezig is in deze schalie. De niet-stationaire modellering leverde tevens waarden voor de intrinsieke doorlatendheid, specifieke berging en de diffusie coëfficiënt die realistisch zijn voor de Pierre shale. De resultaten van modellering van de experimenten aan de Boomse klei zijn boven reeds weergegeven. Tenslotte is het model gebruikt om de bijdrage van osmose aan gemeten hoge poriewaterdrukken in het Dunbarton bekken in de Verenigde Staten te onderzoeken. In de literatuur worden voor klei-rijke formaties van Trias ouderdom waarin zich water met een hoog zoutgehalte bevindt, stijghoogten gerapporteerd voor twee putten (192 en 140 m boven zeeniveau) die veel hoger zijn dan de daarbovengelegen lokale grondwaterspiegel (58 m boven zeeniveau) in de kustvlakte. Eerder is op basis van een eenvoudige berekening van osmotische drukken voor de betreffende zoutgehalten voorgesteld dat osmose verantwoordelijk is voor de hoge vloeistofdrukken in het bekken en dat de kleien zich gedragen als een ideaal membraan. Toepassing van het eindige-elementen model geeft aan dat de efficiënties voor de hoogste en laagste gemeten concentraties respectievelijk 0.9897 en 0.9950 bedragen en dat de grootte van de gemeten stijghoogten goed kan worden gereproduceerd. De modellering laat verder zien dat de overdrukken grotendeels bewaard kunnen blijven in het bekken over een periode van 200 miljoen jaar, wat ongeveer overeenkomt met de ouderdom van het bekken.

Conclusies. We concluderen dat osmotisch gedrag van klei-rijke sedimenten onder *in-situ* omstandigheden duidelijk aanwezig is bij sterk gecompacteerd kleien zoals de Boomse klei en de Pierre shale en dat de membraaneigenschappen goed kunnen worden gekwantificeerd middels *in-situ* meettechnieken. Deze eigenschappen zijn van essentieel belang voor organisaties die tot taak hebben om de veiligheid van ondergrondse opslag van nucleair afval te onderzoeken. De membraaneigenschappen spelen tevens een cruciale rol bij vloeistofstroming en drukopbouw in sedimentaire bekken. Osmotische eigenschappen van de weinig geconsolideerde Calais klei lijken zeer gering of afwezig. Metingen aan andere kleien zijn nodig om vast te stellen of dit resultaat van toepassing is op ondiepe, weinig geconsolideerde kleien in het algemeen. Meer kennis is vereist van de invloed van reactieve chemische processen in kleien op de membraaneigenschappen om nauwkeurigere voorspellingen te kunnen doen van osmotische processen.

7. Impact and relevance of the project for soil protection

The results of this study demonstrate that osmotic phenomena do occur in within highly consolidated clays such as the Boom Clay, the Pierre Shale and deeply buried shales in sedimentary basins and that the membrane properties of these clays can be measured using *in-situ* techniques. These findings will contribute to improved assessment of the suitability of such clays to serve as host-rocks for storage of nuclear waste and evaluation of emissions of contaminants from sludge depots and through clay liners at waste dumps. Moreover, the results also provide essential information to evaluate the significance of the membrane properties of these clays for sea-water intrusion in coastal areas where such consolidated clays occur at relatively shallow depths. Both the modeling capability and the measurement techniques that have been developed and tested in the project will prove to be valuable tools in future soil and subsurface protection studies that require evaluation of contributions of osmotic transport phenomena.

8. Presentations.

First National Scientific Symposium "Bodem Diep" in Zeist, The Netherlands, June 2002. (Oral)

International Meeting: Clays in natural and engineered barriers for radioactive waste confinement, Reims France. December 2002. (Poster)

Working visit to the US Geological Survey in Reston, VA, USA, February 2003 (Oral)

Second National Scientific Symposium "Bodem Diep" in Zeist. The Netherlands, June 2003. (Poster)

Second International Meeting Using Natural and Engineered Clay-based Barriers for the Containment of Radioactive Waste", Tours, March 2005. (Poster)

UCG colloquium, Utrecht University, 28 February 2005. (Oral)

The 13th International Clay Conference, Tokyo Japan, August 2005. (Poster)

9. Publications

Garavito, A.M., S. Bader, H. Kooi, K. Richter and T.J.S. Keijzer (2002). Numerical modelling of chemical osmosis and ultrafiltration across clay membranes. In: S.M. Hassanizadeh et al. (Editors). *Computational Methods in Water Resources. Developments in Water Science*, **47**, 647-653. (refereed)

Garavito A.M. (2002) Chemical Osmosis in Clay Soils and Sediments. Overview. In proceedings of the 1st National Scientific Soil Symposium Bodem Diep, June 2002, Zeist, The Netherlands (non-refereed)

Kooi, H., A.M. Garavito and S. Bader (2003) Numerical modelling of chemical osmosis and ultrafiltration across clay formations. *Journal of Geochemical Exploration*, **78-79**, 333-336. (refereed)

Garavito, A.M., H. Kooi and C.E. Neuzil (2005) Numerical Modeling of a Longterm *In-Situ* Chemical Osmosis Experiment in the Pierre Shale, South Dakota. *Advances in Water Resources*, in press. (refereed)

Bader, S., and H. Kooi (2005) Modelling of solute and water transport in semipermeable clay membranes: comparison with experiments. *Advances in Water Resources*, in press. (refereed)

Garavito, A.M., P. De Canniere and H. Kooi (submitted) *In Situ* Chemical Osmosis Experiment in the Boom Clay at the Underground Research Laboratory (URL) in Mol Belgium. *Applied Clay Sciences* [vol. 29] or "*Physics and Chemistry of the Earth*" [vol. **28**]. (refereed)

Garavito, A.M. (2005) Chemical osmosis in clayey sediments; field experiments and numerical modeling. PhD-thesis, Vrije Universiteit, Amsterdam (under review).

10. Patents / Professional Products

None

11. Discussion of objectives

a. To what extent have original objectives been realized?

The original objectives as formulated in the project proposal consisted of two parts:

- (1) to provide evidence for and to quantify membrane properties of clayey sediments;
- (2) to assess the role of membrane properties in transport of solutes and water in groundwater systems

Objective (1) has been met. This applies in particular to the Boom Clay. For the Calais Clay quantitative information on membrane properties was also obtained; however, for this clay the evidence proved negative in the sense that no osmotic behavior was observed. Membrane properties were further quantified for the Pierre Shale and, to some extent, for shales in the Dunbarton Basin, albeit for experimental and observational data obtained by others. More *in-situ* tests of shallow clays, including tests in other clays such as harbor sludge, were envisaged at the start of the project, but these were not realized. The reason for this is that the development of instrumentation and testing procedures for the *in-situ* tests proved more problematic and time-consuming than anticipated. Apart from the above field testing and modelling, identification of membrane properties was also planned to occur through screening of data bases for pressure or concentration anomalies that might be related to osmosis. This approach was abandoned early in the project because such anomalies were not likely to be apparent and detectable.

Objective (2) has been met to a minor extent. The idea was to address this issue through modelling of relevant and realistic conditions in groundwater systems and comparing simulations in which membrane properties are either ignored or incorporated. This has only been done for a deep sedimentary basin. The results highlight the importance of osmotic behavior in generating high fluid pressures in this basin and in maintaining these pressures for geologically significant periods of time (> 100 kyr).

b. Did the project include non-scientific objectives?

No

c. Did the project's aims include expanding the scientific network?

Expansion of the international network of contacts was not an explicit aim of the project. However, important contacts were definitely established. A key new contact was established through a cooperative agreement with the Studiecentrum voor Kernenergie (SCK-CEN), Mol, Belgium, with specific reference to dr. Pierre de Cannierre. In addition, key interaction and cooperation was established with dr. Chris Neuzil of the United States Geological Survey (USGS).

12. Do the results obtained match the original objectives?

The results match satisfactorily with the objectives. Evidence of osmotic behavior was provided and semi-permeable characteristics of highly compacted clayey sediments have been quantified. However, for shallow clay layers with a lower degree of compaction proof for osmotic properties has not been rendered yet. Clarification of this issue is still needed. For a wide variety of practical problems negligence of semi-permeability of clays may not be appropriate. Although the role of osmosis in solute and water transport in groundwater systems was not evaluated it was clearly shown that pressure and salinity anomalies occurring within deep clayey sediments can be explained by osmosis. Furthermore it has been shown that the osmotically-induced pressures can be maintained within these environments over geologically significant period of time.

13. Integration with other projects

The project was part of a larger, collaborative research effort involving two other PhD projects that were carried out in the Geochemistry Group (Katja Heister; Part 1) and in the Environmental Hydrogeology Group (Sam Bader; Part 3) of Utrecht University.

Results of all three projects were, amongst others, integrated in a numerical model for chemically and electrically coupled flow and transport. This was intended in the original project proposal. The current project has been particularly useful in evaluating the chemical coupling component in the model through applications of the model to existing and newly obtained experimental data. Integration further occurred through collaborative work on both the Calais Clay and the Boom Clay via laboratory measurements (Heister), field measurements (Garavito) and modelling (Bader).

14. Directions for further research

- Although only marginally successful, the experimental work carried out in this project on the Calais Clay has provided guidelines and methods that will be of great value for future field testing of osmotic properties of the shallow subsurface. These include suggestions for how to avoid problems with air entrapment and methods that reduce ambiguity in interpretation of experimental results that can arise due to clay heterogeneity and differences in timing of tests involving use of saline waters or pore water duplicates.
- Our modeling indicates that existing models should be further developed in such a way that the cation exchange capacity of the clay is taken into account and that the dependence of the thickness of the water film on the concentration is also included.
- Now that the modeling infrastructure has been largely developed, the importance of osmotic effects in groundwater systems can start to be more fully assessed by comparison of modeling scenarios in which osmosis is taken into account and neglected, respectively. This applies in particular to settings where strongly consolidated clays are present. More constraints on *in-situ* osmotic properties of less consolidated clays are still required before similar assessments can be conducted for other settings where such clays are present.
- At the URL additional testing with NaNO₃ solutions should be carried out to evaluate the osmotic effect induced by the salts released by medium level bituminized waste.
- Field experimental work should be extended to include measurements of electrical coupling phenomena.

15. Importance of results for other's research

As mentioned in several sections above, the results of this research highlight the importance of osmotic effects occurring in deep clayey sediments. These results are therefore of importance for fluid flow and solute transport in groundwater studies and for basin analysis and reservoir engineering applications in the oil industry. Similarly, the results are relevant for hydrogeological coastal research in which low permeability clay layers separate coastal aquifers containing water of different chemical compositions. More practical cases in which osmosis may be of importance relate to waste containment application, such as waste dump sites and radioactive repositories that use clays as impermeable barriers.

16. Gaps or obstacles

A key obstacle in applying the results found in the research project relates to the fact that the evidence for osmotic processes operating within shallow poorly compacted clay layers is still inconclusive. Evidence provided in this research clearly demonstrated that for highly consolidated clay layers osmosis is important. Many of the implications of osmotic behavior and

their application to practical cases (i.e. cases mentioned in section 15 deal with shallow clay formations).

Another obstacle is the fact that osmotic phenomena cannot presently be modelled using existing groundwater flow and solute transport codes. Incorporation of these processes in widely used existing groundwater codes (MT3D/SEAWAT-MODFLOW; Sutra etc) is not just a matter of plugging in an extra module. Solving the often strongly non-linear set of equations requires special controls on time-stepping and grid spacing as well as controls for a consistent set of initial conditions. The constraints may often render user-defined problems unsolvable. For instance, using efficient numerical transport schemes such as MOC will likely often lead to erroneous results or may lose its efficiency altogether. Defining proper constraints and controls for a general purpose groundwater code, its testing, rendering them "fool proof", and training of users will take a very long time and will form an obstacle to routine evaluation of these processes.

17. New questions generated

Within this research new questions have been generated and some issues remain unresolved. The main questions have been already named throughout this report especially in section 14. They can be summarized as follows:

- a. Is osmotic behavior important in shallow unconsolidated clay layers?
- b. What is the role of osmosis in solute and water transport in groundwater systems?
- c. How do chemical reactions in groundwater and interactions with the surface of clay particles influence the membrane behaviour of clayey sediments and can these effects be incorporated in numerical models?

18. Links to projects outside TRIAS

In the course of the project, an important link was established with the research program of SCK-CEN in Mol, Belgium. In the research program, the compatibility of Boom Clay is investigated with large amounts of nitrate-bearing bituminised radioactive waste produced by the former Eurochemic fuel processing plant at Dessel. Collaborative research was started to assess the role of osmotic behavior of the Boom Clay.

19. Impact on society

As mentioned in section 7, the results of this project are relevant for soil protection. The impact on society will, therefore, be rather indirect and will be established only gradually through improved assessment of problems related to waste containment, sea-water intrusion, and hydrocarbon exploration and production.

20. Dissemination of the results besides the scientific channels

At the subproject level the results were transmitted only via the scientific channel. At the project level a workshop for the potential model users in the Netherlands "Modelleren : Verpakt bedrog of waardevol instrument" was organized by SKB.

21. New position of the researcher

The researcher has not found a new position yet.