INTRODUCTION

Disposal of high-level and/or long-lived radioactive waste in engineered facilities, or repositories, located underground in suitable geological formations, is being widely investigated world wide as a long-term management solution. This is in order to protect humans and the environment both now and in the future. From a quantitative point of view, a repository is said to be safe if it meets the relevant safety standards, such as internationally recommended or specified by the responsible national regulatory authorities. In recent years the scope of the safety assessment has broadened to include the collation of a broader range of evidence and arguments that complement and support the reliability of the results of quantitative analyses. The broader term "post-closure safety case", or simply "safety case",[1] is used to refer to these studies. It has also become evident that repository development will involve a number of step by step stages punctuated by interdependent decisions-making on whether and how to move from one stage to the subsequent one. These decisions require a clear and traceable presentation of technical and robust arguments that will help in giving confidence in the feasibility and safety of a proposed concept. The depth of understanding and technical information available to support decisions will increase from step to step. The safety case is a key input to support that decision to move to the next stage in repository development. It reflects the state and results of the research and development (R&D) undertaken at a certain stage, and supports decisions concerning future R&D efforts.

Potential geological host formations (and their surroundings) are chosen in particular for their long-term stability, their ability to accommodate the waste disposal facility, to prevent or to attenuate potential release of radioactivity, their buffering capacity vis-à-vis external and internal perturbations. Natural hazards are also considered in the site location choice for a potential disposal facility. It is recognised that no natural system is in equilibrium; the concept of "geosphere stability" does not therefore imply that steady state conditions are prevailing over very long periods of time. However, changes occur in many systems to an extent and at such rate that their effects would not compromise deep disposal safety.

Site characterisation and evaluation are important for determining the site suitability and the long-term safety of geological repositories of long-lived radioactive waste. Two previous NEA workshops already took into consideration "geosphere stability". The first one was held in Helsinki, September 1991 on "Long-term observation of the geological environment". It dealt particularly with the needs and techniques for long-term observations of the geological environment. At the workshop, it was considered that long-term observation programmes form an integral and crucial part of site qualification and confirmation for deep repositories in view of building confidence in geological performance models. The second workshop was held in Paris in 1994, and highlighted the "Characterisation of long-term geological changes for disposal sites". This workshop clearly noticed that scientific information concerning the long-term geological evolution is needed for several purposes such as disposal designs, safety assessments, confidence building and siting programmes.

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1. "The safety case is an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the geological disposal facility" [see NEA, (2004), *Post-closure Safety Case for Geological Repositories – Nature and Purpose*].

Since then, through various initiatives, national safety assessments have been compared and studies have evolved towards providing an important basis for decision making related to geological disposal. That evolution has taken place through heightened incorporation of site characterisation data made possible by a real progress in site understanding and by an increasing depth of understanding of both technical and non-technical issues.

With regards to the long timescales involved in the concept of geological disposal, the relevance of various natural processes and events depends on the time frame to be considered. With respect to the lessons learnt from a previous NEA workshop,[2] the main concern is on features, events and processes (FEPs) over a period of about one million years – the order of magnitude of the time needed for radioactivity to decay to levels comparable to uranium ores is about a few hundred thousands years. Repositories are typically sited in stable geological environments in which key characteristics that provide safety are unlikely to change significantly in the course of time. However, over long enough timescales, even the most stable geological environments are subject to perturbing events and changes. Arguments for safety can be developed to build confidence in the overall safety case and an acknowledgement of the limits of predictability of the system will be important for credibility.

With respect to the geosphere stability, it is necessary to develop arguments for the reliance that can be placed on key safety functions. This applies in particular to the maintenance of the long-term containment capability of the geosphere and/or the maintenance of favourable mechanical or chemical conditions in and around the engineered barrier system. In building in an overall safety case, it is therefore important to assess:

- the features, events and processes that could impact the evolution of the geosphere;
- the long-term stability of the favourable conditions displayed by the host formation;
- the buffering capacity of the formation vis-à-vis perturbations.

The key issue is to evaluate the resilience of the main safety functions of the geosphere (often relying upon flow and transport properties) to natural perturbations. Thus phenomenological evidence of persistence of those functions in past episodes of climatic changes, seismic activity, diagenetic evolution, burial/uplift, etc should enhance confidence in geosphere stability.

To provide national waste management organisations and the scientific community at large with an overview on that subject of geosphere stability, the NEA Integration Group for the Safety Case (IGSC) launched a series of workshop dealing with this issue for various host rock types (i.e. crystalline rocks, argillaceous media and evaporites). The first workshop of the series dealt with argillaceous formations. It was hosted by GRS, (Gesellschaft für Anlagen und Reaktorsicherheit) in Braunschweig, Germany, on 9-11 December 2003. The workshop was organised under the auspices of the IGSC Working Group on the Characterisation, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations (referred to as "Clay Club").

Due to the multidisciplinary aspect of the IGSC initiative, the Earth Science community was solicited to give its views about the scientific and operational bases for the assessment of geosphere stability. Therefore the workshop brought together scientists from academic institutions, engineers from various research institutions or companies, consultants, regulatory authorities and national waste management organisations. One should note that the workshop did not aim to present details about all relevant disciplines but rather establish bridges between these disciplines and between the various communities.

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2. NEA (2002), *The Handling of Timescales in Assessing Post-closure Safety of Deep Geological Repositories*, Workshop Proceedings, Paris, 16-18 April 2001.

SCOPE AND OBJECTIVE OF THE WORKSHOP

Among the favourable properties often quoted to support the choice of argillaceous media as a host formation for disposing of high-level and/or long-life radioactive waste are:

- Ability to self-seal fractures and discontinuities.
- Diffusion-controlled transport of solute.
- High sorption capacity.
- Geochemical conditions that favour low radionuclide solubilities, high sorption of migrating species and low degradation of engineered barrier system (EBS).
- High geochemical and mechanical buffering capacity, which is often considered as a means to maintain favourable properties over a long period of time.

The workshop focused on clay specific issues and considered the whole spectrum of argillaceous media envisaged as host formations, i.e. from poorly indurated, soft clays to hard, potentially fractured clays. In particular it addressed:

- The multiple lines of evidences to support the stability/buffering/robustness of the clays over long timescales.
- The resilience of the favourable properties of clays to natural perturbations; tested against, experiences on changes or alteration in response to diagenesis and geological history (tectonic, thermal loading, water expulsion, organic matter degradation, etc.), and may be quite reactive to external and internal perturbations (such as oxidation or thermal load).

A further important objective was to evaluate the extent to which there is confidence about the required level of stability, whether it is known what evidence to look for, and if there are adequate tools to carry out long-term investigations.

The workshop focused mostly on natural events. As a consequence, some repository-induced effects (e.g. radiolysis, and migration of alkaline plumes) were excluded from the remit of this workshop.

With respect to the order of magnitude of the time needed for HLW radioactivity to decay to levels comparable to uranium ores, the workshop main focus is on features, events and processes over a period of about one million years. This is in line with the conclusions of a previous NEA initiative related to the handling of timescale in assessing a post-closure safety.[3]

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3. NEA (2002), *The Handling of Timescales in Assessing Post-closure Safety of Deep Geological Repositories*, Workshop Proceedings, Paris, 16-18 April 2001.

The synthesis aims at summarising the oral and poster presentations given at the workshop as well as presenting the outcomes of the workshop discussions. It does not aim at providing a detailed overview of the state of the art in all the geoscientific disciplines that were touched upon during the workshop. Rather it focuses on providing, to the extent possible, some insights for supporting arguments to build confidence in the stability of the geosphere for deep repositories, notably through answering the key questions that were set up in advance by the workshop Scientific Programme Committee.

The synthesis is completed by a compilation of extended abstracts (Appendix A). The list of participants is given in Appendix B.

Fifty-eight persons from the academic community, research and development institutions, national waste management organisations and regulatory authorities from eleven NEA member countries attended the workshop.

SYNTHESIS OF THE WORKSHOP

The workshop was divided into four sessions and a poster session. The first and second plenary sessions concerned respectively the fundamental requirements for the deep disposal and the scientific understanding about natural endogenic and exogenic processes that could affect the geosphere properties. The third and fourth sessions focused on more specific processes with regards to the stability and buffering capacity of argillaceous formations.

Session I – General Framework: Argillaceous Media as Host Formations

The main issues that were discussed were:

- *"What are the main functions/roles of the geosphere for disposal at different timescales (especially for argillaceous media)?"*
- *"What kind of assumptions relating to argillaceous geosphere are commonly made in safety cases?"*
- *"What are* the regulatory expectations concerning the confidence in geosphere stability?"

Ph. Lalieux, ONDRAF/NIRAS, Belgium, gave an overview of the expected roles of argillaceous media as host formations and the important aspects to consider in geological disposal safety cases. Disposal in a geological formation aims at protecting humans and the environment from the radionuclides in high-level and/or long-lived radioactive waste by isolating the waste by means of a multi-barrier system, that consists of an engineered barrier system (EBS) and a natural barrier (host formation and its surrounding geological setting).

The long-term safety is achieved through the fulfilment of a series of safety functions by multi components of the disposal system and among various time frames. The main safety functions of the host formation are: (i) to isolate the repository from human activities and from external phenomena; (ii) to provide a favourable chemical and physical environment to the engineered barriers; (iii) to act as a barrier to radionuclide release and migration toward the biosphere; and thus (iv) to attenuate the impacts of the repository. The most challenging aspect is the long timescale involved which is much greater than applies to any common human engineered structures. Quantitative assessments are made typically over one million years compared with the fifty years for civil engineering. One million years corresponds to the time at which the radio-toxicity index declines to be about five times the natural radioactivity of a typical host formation.

In case of disposal of HLW in clay, the host formation can be considered as the main barrier and so stability is one of the key characteristics of the site selection. Some favourable characteristics of the host formations to be investigated are: low hydraulic conductivity and gradients, extent and thickness continuity, high sorption capacity and generally long-term stability of those characteristics. It must be remarked that the long-term performance of the clay formation may overshadow the performances of other components of the disposal system like the EBS.

The geosphere stability issue is managed in performance assessment through the construction of one or more scenarios reflecting the likely or possible evolution of relevant features, events and processes. However, it makes an important contribution to the overall safety case if a convincing argument can be made for the long-term retention of safety functions derived from the geosphere characteristics. To improve the quality of assessments and to strengthen the confidence of stakeholders including regulators, approaches that are considered in those assessments should be in agreement with most recent developments and findings of Earth scientists.

As an illustration, the Boom Clay case was presented in particular as a practical application of what "safety functions" and "favourable characteristics" mean. In the Belgian HLW reference case, the quantitative safety assessment assumes that the EBS (with the exception of the waste matrices) does not fulfil any safety function after the thermal period. The latter has duration of a few hundreds of years for vitrified HLW and a few thousands of years for spent fuel. After this thermal period, performances of the waste forms (i.e. their resistance to lixiviation) barely influence the estimated doses as the latter are mostly controlled by the performances of the host formation. Therefore, the maintenance through time of diffusion-controlled transport (i.e. low hydraulic conductivity and low hydraulic gradients), reducing geochemical conditions and high sorption capacity is of key significance in building confidence in the safety case. The normal evolution scenario used for performance assessment considers a steady state geosphere regarding the diffusion and sorption processes. Additionally, various separate altered geosphere scenarios are or will be considered such as periglacial conditions, denudation, faulting. These scenarios are based on current geological knowledge but do not consider probabilities of occurrence of those events. They cannot be considered as representative of an evolving geosphere but rather as illustrations of various end stages of geological events.

J.-Y. Boisson, IRSN, France provided the French regulator's point of view concerning the handling of geosphere stability, which is addressed through qualitative requirements regarding site properties. He emphasised the safety recommendations as depending on the stage of the development of the disposal project. In particular, considerations of the geosphere stability might be different for the site selection stage and for subsequent stages. The French Basic Safety Rule III.2f (BFS III.2.f) distinguishes the essential criteria from important technical criteria to be fulfilled by selected sites. The long-term stability of the site and its hydrogeology characteristics are considered in the BFS III.2.f as essential criteria whereas important criteria concern thermal, mechanical and geochemical properties, and minimum depth requirement. In addition, no natural resource should be of interest in the area. After the site selection phase, the subsequent steps should confirm the favourable characteristics of a selected site and assess the potential disturbances by the engineered barrier and site development to the host formation capabilities. The overall objective of that step by step approach, which consists of site selection, feasibility studies, and design options, is to propose at least one technically conceivable disposal design for the protection of human health and the environment.

Session II – Examples of Key Exogenic and Endogenic Processes Affecting the Geosphere

This Session aimed to give an overview of the state of the art of the knowledge on key processes and events that could affect the geosphere properties. A wide range of events and processes were presented: climate, geomorphology, seismicity and faulting, basin geological history and diagenesis.

The key questions to be addressed were:

- *"What are the predominant processes for natural and anthropogenic evolutions?"*

- *"What kinds of predictions over long timescales are recommended and what are the related uncertainties?"*

- *"What predominant predictions could be provided for crustal movement and seismicity?"*

- *"Are the diagenetic processes in a subsiding basin continuous or not in particular regarding THMC mechanisms? What are the potential consequences on the geosphere at repository depths of these processes e.g. ice loading, saline water intrusion, oxygenated water intrusion, crustal movement, and seismicity?"*

V. Masson-Delmotte, CEA, France gave an overview of the understanding of past, present and future climate processes. Although short-term climate (40-1 500 years) behaviour seems rather chaotic, it is possible to understand and predict long-term climate characteristics and their general evolutions. Direct records of atmospheric parameters are very recent, but ice cores provide records for up to the last 800 000 years. Climate forcing and feedback have diverse time and spatial scales and volcanism may affect climate over a few years. Earth's orbital parameters induces climate cycles of 100 000 years. The natural variability is mainly characterised by glacial-interglacial cycles that are governed by astronomical parameters. Rapid events may be of importance such as growth or decay of ice sheets modifying the ocean circulation over tens to hundreds of years at a hemispheric scale level. Anthropogenic greenhouse effects and aerosols undoubtedly influenced the climate/over the last century.

For the future, climate models integrate the general atmospheric and ocean circulation models, land, biosphere and ice models as well as CO_2 cycle model and scenarios of human consumption for the next century. The model computations show that, due to anthropogenic releases in the atmosphere, the present interglacial, in the worst case, would span over 200 000 years instead of 50 000 years for an unperturbed natural system. During this longer warm and wet period, the temperature rise is expected to induce the complete melting of ice sheets, a significant sea level rise, variations in land cover and use. Beyond 200 000 years climate variations should be controlled again by orbital forcing, in the absence of any further anthropogenic perturbation.

Progress on modelling capacities are observed and will improve the understanding of climate processes in the future. One of the key parameters that influence the potential consequences of climate changes for repository safety is the water availability for dilution (recharge).

It was noticed during the discussion the potential helpfulness of feedback of the EC BIOCLIM project (report planned in 2004).

F. Schlunegger, University of Bern, Switzerland presented an overview of surface processes shaping the topography of mountainous systems. Three main processes were described and illustrated: hillslope creep, hillslope failure and fluvial processes (incision and sediment transport). Landscape parameters such as roughness or length scale depend on the local dominant erosion process. The fluvial and debris flow dominated systems have rough, highly incised surfaces with dense channel network, whereas areas dominated by hillslope processes have smooth topographies, low relief and greater channel spacing. Geomorphologic processes depend on two main external forcing: climate and tectonics. Climate mainly influences process rates and thus timescale and topographic roughness and length scales. A theoretical approach predicted that warm and humid climate enhances hillslope processes. Further studies are needed to validate this theory in the field. Tectonic uplift increases slopes and generates upward propagating erosion with a recognisable knick-point in the river profiles. In an Alpine study case, erosion rates were determined by measuring sediment load in the river as a proxy to total basin erosion. It illustrated the correlation between erosion and bedrock lithology as well

as with former glacial zones. However, this approach has a strong bias since erosion can be much localized in the basin. Measuring changes in channels or studying aerial photographs may be some alternative tools to determine erosion rates. The discussion raised the representativeness of Alpine features (e.g. "instantaneous" erosion rate) and the way to extend such data and observations outside orogenic areas. Indeed, most – but not all – considered repository sites are in rather flat areas where an overall accumulation of sediments should occur. As many data related to erosion rates are based on observations in orogenic areas, they can only be considered as an upper limit for performances assessment purposes.

The USEPA (United States Environmental Protection Agency) standard definition of 1981 defines an active fault as "any fault that can be shown to have produced an earthquake in the last 10 000 years". The inherent difficulty with respect to this definition might be the issue to associate an earthquake to a given "active" fault. Thus, **R.M.W. Musson, BGS, United Kingdom** argued in favour of a new classification of faults as "inert", "reactivatable" and "controlling" faults. Inert faults are defined as faults that cannot be reactivated, at least in present stress regime. Reactivatable faults can be, or have been reactivated. Controlling faults are the preferential loci for current deformation. The assessment of faulting matters for two types of hazards: rupture and shaking hazards. The rupture hazard is clearly important as it can disrupt the waste area. Rupture features may induce secondary induced hazards such as changes in groundwater flow. The first defence against rupture hazard is obviously siting as a vast majority of earthquakes takes place along pre-existing structures (reactivatable faults). Rupture hazards in argillaceous media have been understudied. In such environments, earthquakes usually occur in the underlying crystalline rock and do not reach the surface. In some cases, argillaceous sediment may inhibit the rupture propagation but may not prevent deformation after the event.

The importance of the shaking hazard is less clear, in particular since it was shown that ground motion decreases rapidly with depth. In addition, the issue of long-term representativity of the current recognised seismicity was also discussed as tectonic processes may change over the periods considered for safety assessment and may exhibit significant heterogeneities. However, significant tectonic changes are most likely to take several million years to develop and are thus not of prime importance. Climate changes and particularly the deglaciation rebound may also affect the seismicity of a given area. Just after ice retreat, deglaciation faulting may be more severe than the one currently registered in Northern latitudes.

Current approaches for estimating seismic parameters and their limits in low seismic areas, such as most of the clay host formations for deep geological repositories, were also presented. Considering the few experiences that exist on the rare seismic events in such settings, both probabilistic and deterministic methods have strong limitations when assessing seismicity over long periods of time. Balance between adequate conservatism and a sense of physical realism is to be sought ideally.

T. Nohara, JNC, Japan presented results on research on fault activity in Japan which represents a high seismic area. Japanese islands are at the margin of the Pacific plate which collides with the Eurasian plate with a convergence velocity of 8 cm/year. It is reasonable to assume that the current tectonic setting will continue for the next hundred thousands of years and so will the associated seismic patterns: interplate earthquakes and inland shallow ones. The latter could be considered as the most dangerous for the underground repository stability. In Japan, scientific studies started in the thirties with active fault mapping. Associated distinctive landscape features can be identified by field studies, aerial maps and geophysical studies. Collected data highlighted regularity of active fault movement over time. Both laboratory and field studies investigated a relationship between the cumulative displacement and the width of the crushed zone which typically ranges from several meters to several hundred meters at most. Deformation occurs on a wider area. The associated effects of

major active faults on a deep geological repository might be insignificant at distances greater than 10 km from the active major fault. This safety distance may be lowered with field study. Measurements at the Kamaishi mine have also clearly demonstrated strong attenuation of ground motion with depth.

F. Schneider, IFP, France introduced the point of view of the petroleum exploration industry which is relevant to geological basin studies. Basin modelling couples several numerical models such as kinematic, deposition and erosion processes, compaction, heat transfer, organic matter maturation and fluid transfer models. Present data and paleodata are crucial to constrain these models; they are used to estimate rock physical properties and geometrical information on the basin. Deposition history is determined from seismic and geological data and then translated into sediment supply rates and subsidence maps in order to be used as input to the 3-D stratigraphic model. This stratigraphic model simulates sediment deposits at the basin scale. A loading path is simulated since present sediment behaviour and properties depend on the burial history and tectonic setting. Constitutive laws of rheology and compaction are then computed to account for the evolution of physical properties through time. Furthermore, the model is able to simulate diagenetic processes and induced changes in hydraulic parameters. As climate and tectonic settings change with time, transient phenomena could occur over long timescales, and, therefore no steady-state should be considered. The major difficulty is to estimate the boundary conditions to apply to the modelled system. At the end, it was recognised that even if sediment history can be characterised in the laboratory, long timescale processes must be addressed by basin modelling. Some natural analogues could be used for a better understanding of the involved processes (e.g. Niger analogues for shale deposits).

L. Warr, CGS-EOST, France made an overview on diagenetic processes in clays and their forcings. First he noticed that the prediction of diagenetic evolution of argillite is based on the study of natural and experimental system. Processes could be classified in three main categories: the Good, the Bad and the Ugly, respectively precipitation and crystallisation, dissolution, and fracturing and anisotropy. Diagenesis in argillite is controlled by fluid chemistry, rock composition, hydraulic conductivity, temperature, time and stress. However, much more is known on thermodynamic processes than on kinetics. Rates of diagenesis vary greatly in nature. Fast diagenesis occurs in environments subject to weathering, fast hydrothermal, or fracture/fault controlled and spans from years to ten thousand years. Diagenesis due to burial and metamorphism is a slow process occurring over longer timescale (10 000 years to millions of years). Fine-grained mineral reactions are quite well known by applying thermodynamics, but very little is known on the kinetics of reactions in argillaceous media. Standard laboratory methods for monitoring mineral reactions use batch reactors where minerals grow. The main issues of these methods are that they concern closed systems and that sampling induces disturbances of the natural media. A new method was presented using flow-through reactors (wet-cell) in a hot chamber. This open-system method allows better reproduction of rock evolution.

The general discussion closing this session on external processes and their impact on the geosphere pointed out that there is a need to further study the impact of low-level earthquake propagation in clay media. More generally, there seems to be a discrepancy of interests between the academic world and the waste management industry. The first is studying regions where processes are active (mountainous, hydrothermal or fractured areas). In contrast, deep geological repository sites are located in areas that have been selected for their high stability and where such processes are quite slow or neglectable. However, it was stated that the waste management industry should open its facilities and data to academia because they characterise unique sites in very specific media and stable areas.

Session III – Arguments to Support Confidence in the Stability of Clays Considered as Potential Host Formations

This Session focused on arguments in support of the confidence in geosphere stability such as:

- Large-scale geo-tectonic environment and its evolution.
- Burial and temperature history.
- Scientific basis in particular on methods and arguments.
- Paleohydrogeological aspects.
- Future geological evolution, predictability, effects analysis.

P. Hoth, BGR, Germany presented the screening methodology used in Germany for site selection. Characterisation of clay sites started only recently since Germany previously had focused its research on the use of thick salt formations. The first phase involves a mapping of shale formations, an analysis of well files, and an establishment of seismic profiles in order to identify the shale formations that meet the following three thresholds: minimum thickness of formation equal to 100 m, a burial depth of the shale formation below 1 500 m and an upper level of the disposal at more than 300 m deep. Three formations meet these specifications with shale content above 80%: Tertiary, lower Cretaceous and middle to lower Jurassic in Northern and Southern Germany. The second phase comprises a regional characterisation of these sites with well-log analysis. Burial, temperature history, hydrocarbon production, compaction and diagenesis are reconstructed and detailed maps created. Moreover, shale homogeneity and predictability are major issues in the assessment of the host formation. There are addressed in this screening phase with a numerical method developed for well-log correlation. The future third screening phase will select dominant processes and criteria of importance for the site evaluation.

A. Gautschi, Nagra, Switzerland presented lessons learnt from the past studies in order to predict the future evolution and stability of the Opalinus Clay site in the Zürcher Weinland area in NE Switzerland. He focused on the multiple arguments that support the stability of this host formation. The Opalinus Clay formation is 100-125 m thick in 300 m of confining units, surrounded by two aquifers. In order to get the strongest argumentation in the prediction of the future evolution of the Opalinus Clay, the long-term history of the site was reconstructed through the application of a large number of techniques such as apatite fission track analysis, and stratigraphic evidence. In particular, the burial history showed that the site was affected by a maximum temperature of 85°C which corresponds closely to the expected temperature at the vicinity of the waste storage facility. The host formation is a diffusion dominated system and fault activity is low. Furthermore, the facility would be constructed at a sufficient distance from a major fault (Neuhausen fault) which has been inactive for millions years. The erosion rate of the fluvial system was estimated from the difference between the current topography and the reconstructed pre-glacial peneplain. Calculated erosion rates of 0.07 to 0.15mm/year are in line with the Danube terraces dating. In conclusion, predicting the future evolution and stability of a geological system for time-scales up to 1 million year using information from past evolution is an acceptable scientific approach not witchcraft.

J. Brulhet, Andra, France presented a status of the French study on the evolution of the Callovo-Oxfordian Argillite Site in Eastern France. The Callovo-Oxfordian site is a 130 m thick hard argillite layer at 420 m depth and is surrounded by non productive aquifers. The region is tectonically stable, away from ice-sheet development areas. However, the region is subject to moderate erosion:

erosion of the circular sedimentary outcrops and associated incision of valleys. Andra is following a two fold approach. Firstly, the past evolution of the basin is reconstructed in order to better understand the present conditions and the properties of the environmental settings and of the host rock. Secondly, potential external changing conditions are determined and their impacts on the future evolution of the site are assessed. There are three complementary elements to the analysis: (i) field work with a series of conceptual models at various temporal and spatial scales and using acquired data and knowledge; (ii) numerical simulations of the driving forces such as climate or geomorphologic processes; (iii) syntheses work via one conceptual model integrating the whole evolution to ensure the overall consistency of the multidisciplinary studies. An interdisciplinary research group (Bio-geoprospective Group) ensures the overall consistency of these studies. At the scale of interest, climate and geomorphology are considered as the two most important factors. Cold climate has direct effects on the geosphere characteristics through the development of permafrost and of glacio-eustatic fluctuations. Climate change was modelled for the next million years under the BIOCLIM European project. There is little indication of direct changes in the host formation. But, one can expect due to the geomorphologic context, changes in the river network and thus long-term modification of groundwater flow in the surrounding aquifers.

T. Torres, Madrid School of Mines, Spain gave an overview of the Spanish program regarding the evaluation of long-term geological and climatic changes. Two sites were presented: the Priego area and the Baza Basin. Regarding the Tufa deposits in the Priego area of Central Spain, mineralogical and chemical properties were first studied. Secondly, a geochemical model was utilised to better understand the evolution of both mineralogical and chemical properties. A dating method (aminostratigraphy) using amino acid racemisation was applied to ostracod shells of the Tufa at different terrace levels. The estimated incision rate was as high as 100 m/400 Ky. Several analytical analyses were performed on the lacustrine deposits of the Guadix-Baza Basin (AARD dating, paleomagnetism, paleobiology, isotopic analysis, fluid inclusions, and trace elements.) Based on that analysis, it was possible to establish the paleoclimatic and paleoenvironmental reconstruction of the area. T. Torres strengthened the particularity of the Mediterranean settings that are quite different from the North European settings. In particular, glacial and interglacial periods could be described respectively by “cold and humid” and “warm and arid” conditions. In addition, the Padul peat bog in Southern Spain was introduced as a paleoenvironmental record which covers 900 000 to 3 000 years before present.

Session IV: Reaction of Argillaceous Media vis-à-vis Natural Perturbations and Geosphere Evolution (Buffering)

The key questions to be addressed were:

- *“What is the stability of key transport processes and parameters (diffusion, ...)?”*
- *“What kind of analogues should be used to support confidence (e.g. other types of formations and coming from other industry, e.g. the oil industry)?”*
- *“What kind of arguments could support the THMC buffering or absence of buffering? (NB repository-induced effects are excluded)”.*

Four main topics were considered:

- Hydro-mechanical (HM) aspects.

- Long-term efficiency of diffusion.
- Chemical buffering/mineralogical processes.
- Organic matter evolution.

S.T. Horseman, BGS, United Kingdom made a state-of-the-art presentation on the understanding of self-healing properties of clay rich rocks. The term "self-healing" is regularly cited as the primary mechanism which should reduce mass transfer (water, radionuclides and gas) in natural fractures and in the excavation damage zone (EDZ). Self-healing could result from mechanical processes (change in the stress tensor), hydro-mechanical processes (change in the water content leading to swelling), geochemical processes (alteration, mineralisation) or combined processes. These processes tend to reduce the fracture openings, or fracture porosity. S. Horseman developed his presentation on the basis of: (i) the experiments performed on EDZ in Underground Research Laboratories such as Mol (Belgium) and Mont Terri (Switzerland) and on core samples in surface laboratories; (ii) self-healing observations on natural analogues; (iii) soil and rock mechanical concepts and theories (dilatancy, brittle-ductile transition, viscoplasticity, …) explaining the self-healing process. He concluded that the self-healing should lead to a gradual decrease of mass transfer. Nevertheless, the long-term geochemical evolution of the damaged rock and its effect on the transport properties of the EDZ remain to be elucidated. Clay properties favouring self-healing are usually drawbacks for engineering purposes since it is considered to be difficult to drill in such media.

P. Marshall, Nagra, Switzerland reported results on studies regarding the impact of geological evolution on long-term safety of a potential HLW repository in the Zürcher Weinland (NE Switzerland). The geological evolution comprises erosion, uplift and climate changes. The main perspective was the impact of these processes on the hydrogeology of the site: vertical gradient modifications induced by changes in recharge and discharge areas, permeability enhancement of Opalinus Clay due to uplift, expulsion of contaminated pore water from the disposal area as a result of ice loading. With regards to the latter, the speaker presented a complete modelling of the ice-loading effect. In this study, the host rock and the repository architecture were taken into account. Overpressure created at the repository level by the ice loading and the pore water expulsion towards the surface was computed. Based on this modelling and on geological observations, erosion and other geomorphologic processes will not enhance vertical gradients between layers because topography is flat. Uplift is not expected to enhance permeability of the Opalinus Clay over the next million years. Ice cover does not change the diffusion dominated transport regime. P. Marshall concluded that safety functions are met for the Opalinus Clay sites.

M. Mazurek, University of Bern, Switzerland analysed natural conservative tracer (Cl) concentrations in several clay formations (Belgium, France, Switzerland, United Kingdom, and Canada). As the speaker said: "these profiles help to understand the long-term evolution of this type of formation because they represent long-term and large-scale natural experiments that can be used for the up scaling of laboratory data in space and time". Considering such diverse formations as the silt layer at Marcoule (France), the Opalinus Clay at Mont Terri and Benken (Switzerland) and the Boom Clay at Mol (Belgium) he interpreted most of the tracer profiles (Cl, ^{3}H and ^{18}O) as diffusion profiles. Diffusion process took place generally for periods spanning from 100 000 years up to several millions of years. The lack of information in paleo-hydrogeology is the limiting factor in interpretation. Nevertheless, these profiles tend to show the efficiency of diffusion over a very long period of time.

Martin Mazurek's presentation was followed by a series of four presentations dedicated to the buffering capacity of clay rocks. As C. Beaucaire said: "*The long-term performance of nuclear waste repository is strongly dependant on the chemical properties of the host rock. The host rock establishes*

the chemical environment that determines such important performance attributes as radionuclide solubilities from the waste and the transport rates from the repository to the accessible environment. Clay-rich rocks are especially favourable host rocks because they provide a strong buffering capacity to resist chemical changes prompted internally either by reactions of the waste itself and emplacement materials, or externally by changes in the hydrologic system surrounding the host rock."

C. Beaucaire,[4] **IRSN, France** focused her presentation on the ability of a clay rock to provide pCO_2 and redox buffering and to resist external chemical changes. C. Beaucaire pointed out the buffering capacity as a measure of the system ability to resist to changes in its intensive properties which are chemical potentials of system components such as pH, pCO_2, pE, solute concentrations. Temperature and pressure can be considered as external boundary conditions. CO_2 and O_2 may be supplied externally directly from the atmosphere during the operational phase or after its closing. According to the existing literature, C. Beaucaire showed that clay rocks have a high buffering capacity, due to mineralogical buffers, for CO_2, mainly carbonate and alumino-silicate minerals, and for O_2, reduced phases such as pyrite, siderite and organic C. Thus, they are not changed rapidly in response to external chemical changes.

Then, **É. Gaucher, BRGM, France** brought some key elements that support the understanding of the argillaceous media stability. As an example, he reminded that argillaceous formations can be stable over very long periods of time, from 150 million years, regarding the Callovo-Oxfordian formation, up to 420 million years for the Silurian formation of the Arabic platform. É. Gaucher highlighted three key arguments that support a better understanding of the geochemical stability of this type of rocks: (i) favourable liquid/solid ratio (very fine granulometry) allowing very strong buffering effects through low porosity, low permeability and long water residence time); (ii) progress in the understanding of clay thermodynamics and clay stability (illite and smectite), auto-regulation of carbonate system by mineralogy (cf. Beaucaire's presentation). He concluded that clays appear to be geochemically stable if temperature and pressure do not evolve significantly over a long time period.

The two following presentations were given by **J.-C. Parneix, ERM, France**. The first one focused on natural analogues studies as arguments to support the understanding of the impact of temperature on clay geochemistry. Studies of natural analogues allowed measurement of the mineralogical transformations (smectite illitisation) with temperature and provide therefore the possibility to develop and validate coupled thermo-geochemical models. At the present time the main mineral reactions involving clays are understood and evaluated and the corresponding kinetics have been partly determined. A time vs. temperature diagram of clay mineral stability was proposed. However, the impact on the rock physical properties is poorly known and should be studied in the future. As an echo to this recommendation, the second presentation showed how to determine two- and three-dimensional micro-structures of a clay matrix. The Scanning Electron Microscope (SEM) and the Electron Probe Micro Analyser (EPMA) techniques provide the means to experimentally establish the pore and mineral spatial distribution. Based on that distribution, the inference and modelling of transport properties are on going and first, interesting results have been obtained.

J. Samper, University of Coruña, Spain gave an oral overview on the Spanish "reference" clay and the associated research programme with an emphasis on clay geochemical characterisation and determination of the buffering capacity. This "reference" formation is located in a lacustrine-continental sedimentary basin deposited during the Oligo-Miocene period. The clay layer is surrounded by two aquifers with a marly gypsum semi-impervious layer between the clay and the upper aquifer. The potential burial depth lies between 82 metres and 600 metres. The clay mineralogy

4. C. Beaucaire is currently working for the CEA, France.

is a mixture of smectite and illite. J. Samper presented the geochemical modelling of hydrochemical experiments performed on drill core samples. Then, he introduced some results of the preliminary paleogeochemical modelling to assess the geochemical stability of the host rock. This modelling was performed with the geochemical code CORE. A preliminary sensitivity analysis has been performed with respect to the direction and magnitude of the vertical water fluxes across the clay layer in order to fit the tracer concentrations, mainly the chloride. Results show a good agreement with tracer data with an upward flow of 2 metres per million years. Extensive future work is planned in particular on the automatic calibration of tracer profiles taking into account reactive chemical species, isotopic data, etc.

R. Michels, ERM, France summarised the results on the nature and reactivity of organic matter in the Callovo-Oxfordian of the Bure site. As the speaker quoted: "Especially in the case of argillaceous sediments, known for their proneness to organic matter, the study of fossil organic matter is able to unravel a large amount of information concerning the geological history (depositional conditions and preservation, paleoenvironmental, and burial, thermal history) as well as the future evolution (effects of induced thermal perturbation, oxidative alteration, biodegradation)". The results of the extensive characterisation of the organic matter in the site (chemistry, thermal maturation, etc.) were presented. R. Michels concluded that "the organic matter will not react further in terms of geological thermal reactivity within the next million years unless the basin subsides or the heat flux increases significantly".

B. Beaudoin, École des Mines, France presented a summary of the work in progress on the fracturing and associated carbonate transfer in shaly-marly blocks. This work has been performed within the MINANDRA partnership between Paris School of Mines and Andra. At the present time; two main processes are studied in the field on two large outcrops located in the South East of France. B. Beaudoin showed some examples of early fracturation at different scales and explained the evidence of presence of carbonate nodules as an indicator of carbonate transfer. The validated methods will be applied to the Andra URL at the Bure site in France. B. Beaudoin discussed the difficulty to link and extrapolated results from experiments on samples, localised field observations to formation behaviour at depth. Field and samples work are complementary in view of bringing multiple arguments to build confidence in the performance of a formation.

A. Bauer, FZK, Germany focused his oral presentation on the preliminary results on the evolution of clays in basic solutions. Basic solutions may be generated by interaction of pore-water with concrete. The potential negative impact of such solutions on clay mineralogy is one of the main issues to be considered. Smectite in an alkaline solution may lead to illitisation and collapsed layers. A. Bauer presented results of observations that were carried out on the geochemical evolution of clay samples from the Bure site and the Opalinus Clay. Clays have been in contact with highly alkaline synthetic solutions in laboratory batch experiments. No visible effect on the Bure and the Opalinus Clays was observed even after one-year experiment. Natural organic substances in potential clay host were characterised using a Scanning Transmission X-ray Microscopy (STXM). Natural organic matter still covered clay edge Si, Al functional groups after 1 year in SYF (closed system), indicating the passivation of the reactive sites. Organic matters from various origins are connected to different clay phases. This result was not expected for diagenetically overprinted sediments. The released humic and fulvic acid is related to the sources and type of argillites respectively smectite and illite/calcite.

The issue of linking the microscopic tests and observations to the formation level was debated at the end of this session. It was noted that the diffusion coefficients that are measured in samples and at the formation level at the Mont Terri site were of the same order of magnitude. Moreover, microscale studies and in particular the ones on organic matter were recognised as being useful in validating the macroscale (formation scale) approach as it was shown during the experiments made on the Boom Clay site.

Gas migration was considered as a key issue and so studies have to be continued. Natural analogue studies were viewed as potential arguments to support the process understanding and it was so suggested to go further on that topic when developing multiple lines of evidence on the performance of a site in a safety case.

No agreement was achieved on the pertinence of coupling geomechanical and geochemical models. In a Japanese unlined mudrock tunnel, oxidation by diffusion of O_2 leads to softening of the clays. These effects are rock dependent and might be negligible for other sites. Furthermore, very few studies have been conducted on the permafrost effects on clay rocks.

POSTER SESSION

The Poster Session dealt with additional case studies and with more specific technical details.

G. Kosakowski, PSI, Switzerland, presented some numerical investigations on the influence of glacial loading on radionuclide transport in the Opalinus Clay. His poster illustrated the more general presentation of P. Marshall (Session IV). Kosakowski presented a rather complete modelling study of the influence of consolidation flow due to successive glaciations on radionuclide transport in the repository architecture and in the Opalinus Clay. He highlighted that the overpressure created at the repository level by the ice loading increases the release of pore water towards the surface and therefore enhances radionuclide transport.

A. Dierckx, ONDRAF/NIRAS, Belgium, showed the burial histories of the Boom Clay and the Ypresian Clay, which is an alternative potential host rock. They concluded that the area of the HADES Underground Research Facility was relatively tectonically stable for the past 50 millions years.

M. Van Geet, SCK•CEN, Belgium, presented the work performed on the characterisation of organic matter in the Boom Clay. The organic matter contained in the Boom Clay (5% of its weight) may act as complexant for radionuclides. Van Geet concluded that the organic matter is very immature and could evolve in the future, and therefore it should be taken in consideration for the performance assessment.

J. Brulhet, Andra, France, presented a deterministic method to compute seismic ground motion. This method simultaneously treats both epistemic and random uncertainties. The first ones, being associated with the present knowledge about the geological structures and their deformation modes, are propagated using a logic tree. A Monte Carlo technique is used to simulate the latter, which are associated with the input parameters of spectra (magnitude, depth and attenuation law) in the context of deterministic seismic hazard assessment.

J. Ďúran, VUJE, Slovak Republic, gave a summary of the on-going site selection process in Slovakia for nuclear spent fuel disposal. The process which started in 1996 selected initially 15 areas. At the present time, four areas in granite and two in clay remain. The final selection is expected in 2010.

F. Claret, FZK – INE, Germany reported some experiments on the characterisation and quantification of humic and fulvic acids released by the Bure and Opalinus Clays in highly alkaline solutions. This poster related to part of the work programme presented by A. Bauer (Session IV). Colloids may play an important role in radionuclide transport due to their high complexation characteristics. The author observed the complexation of these acids with Cm^{3+} ions. They conclude that radionuclide migration in clay under cement dissolution conditions may be enhanced.

I. Szűcs, MECSEKÉRC, Hungary, presented the results of the investigation programme – the so-called Short-term Programme, till 1999 – of Boda Claystone Formation, which is the potential host rock for HLW and SF disposal in Hungary. The poster illustrated the geological properties of BCF, the explorations in the former underground research laboratory, and listed the mineralogical and

hydrogeological properties of the Boda Claystone. Furthermore, long term safety issues and the geotechnical suitability were highlighted. In the final conclusion it was mentioned, that after 1999 there were not carried out further explorations, but an overall and countrywide site screening was completed. Based on the results of the screening and the SPT a new site characterisation process started in 2003.

H.-J. Herbert, GRS mbH, Germany, investigated mineralogical and chemical changes of bentonites in a natural analogue study and in laboratory experiments where bentonite samples were in contact with high saline solutions. Their purpose was to study the impact of the solid/liquid ratio on the stability of bentonites. The idea was that open geological media are characterised by low ratio (flow of large water volume over geological times) and that bentonites used as technical barriers in salt formations are characterised by high ratio (closed media with very little water volume available). Bentonites are not stable within a high saline environment, neither in an open system nor in a closed system. Important mineralogical transformations were observed.

C.L. Zhang, GRS mbH, Germany, presented their experimental results on the hydromechanical behaviour of the Callovo-Oxfordian argillite core samples. These experiments have been performed in the framework of the MODEX-REP project which aims to investigate the hydro-mechanical response of the argillite to shaft sinking. The short-term mechanical behaviour of the argillite was investigated by means of uniaxial and triaxial compression tests. The long-term behaviour was studied by uniaxial creep and relaxation tests. Some influence factors such as material anisotropy, scale effect, water content and sample origin were also examined. With respect to the short-term mechanical behaviour scale and anisotropy effects were observed. Concerning the long-term behaviour the authors concluded that no lower creep limit, no significant scale effect and no significant anisotropy effect on the pure creep behaviour for the argillite were found. The long-term mechanical behaviour of the investigated region of the argillaceous formation was relatively homogeneous.

I. Kolaříková, Faculty of Sciences, Charles University, Czech Republic, reported experimental work performed regarding the impact of heating on the physical and chemical properties of bentonite from the Rokle deposit which may be used as a backfill material. Their results showed that thermal effects strongly affect the bentonite material, i.e. decrease in rehydration ability, decrease in cation exchange capacity and increase of specific surface area with temperature increase.

CONCLUSION

The key findings as summarised below were drawn during the five sessions.

Impact of exogenic perturbations (climate change and erosion)

One thousand years seems to be the predictability limitation of current climate models. It is however possible to understand and predict general long-term climate evolutions. Worst case modelling of climate change due to anthropogenic releases shows that the present interglacial would span over 200 000 years (with complete melting of ice sheets). Beyond 200 000 years climate variations should be controlled again by orbital forcing in the absence of any further anthropogenic perturbation. The key parameter that influences the prediction outcome is the water availability for dilution (recharge).

Most – but not all – considered repository sites are in rather flat areas where an overall accumulation of sediments should occur. As many data related to erosion rates are based on observations in orogenic areas, they can only be considered as upper limit for performance assessment purposes.

Impact of endogenic perturbations (seismicity)

Uncertainties exist in defining active faults and predicting magnitude and lifetime. Current concepts in hazard analysis originating in the context of active tectonic environments may not be readily applicable to low and moderate seismicity areas where most repositories are planned. Novel methods are being developed for assessing hazards at surface and at depth. Nevertheless, a consensus exists that hazard is low in low seismic areas and that a strong attenuation of ground motion occurs with depth. For high seismic areas, as in Japan, the attenuation related to depth and to distance in relation to the fault locations needs to be considered in siting.

One needs to differentiate shaking hazard to repository in operation (i.e. open or partially open underground infrastructures – with operational lifetime rather similar to classical nuclear facilities) and to disposal facilities after backfilling and closure. There is also a need to provide perspectives to the seismicity studies by a better definition of the period over which the engineered barrier system (EBS) integrity has to be maintained.

Geological evolution of clay formations

Basin modelling for predictive purpose is still in its infancy. Clay diagenesis is very slow and might not be relevant over periods smaller than one million years.

Self-sealing

Field observations provide evidence on the positive influence of this key process that should reduce the mass transfer of a potential opened fracture. Self sealing is reasonably understood from the hydro-mechanical point of view, but the influence of geochemical mechanisms less well.

Efficiency of transport processes over geological times

Diffusion in clay formations should be the main transport mechanism over very long timescales. That is supported by the current results of the analysis of tracer profiles in various argillaceous formations which relate to the last 10^5-10^6 years.

Geochemical buffering and organic matter

Given the generally long residence times, the chemical composition of pore waters in clay-rich formations is controlled by equilibria with mineral phases, such as carbonates and silicates, and ion-exchange reactions with clay minerals. The generally reducing conditions are strongly buffered by pyrite, siderite and/or organic matter. Therefore, clay-rich rocks are especially favourable host rocks because they provide a strong buffering capacity to resist chemical changes prompted either internally or externally. Expected natural geosphere evolution at repository sites should not induce drastic changes in organic matter behaviour. However, chemical (oxidation) and thermal perturbations induced by the construction and operation of the disposal facilities will affect organic matters (e.g. CO_2 production).

Studies on potential host formations and/or sites for HLW repositories have led to the following general conclusions:

a) It is expected that the ground surface of repository areas may experience some important changes due to climate and erosion, but that changes will decrease with depth. More generally, any hydraulic, mechanical or chemical perturbations should be buffered by the clay formation properties. There is little indication of direct impact of these surface changes on the host clay transport properties at depth. Outside the argillaceous host formations, radionuclide pathways towards the biosphere may however be affected by surface changes notably through a modification of the hydrogeological and geochemical boundary conditions in the surroundings.

b) Predicting the overall geological evolution of a given site and its environment over periods of time of relevance for long-term safety assessment (i.e. few hundred thousands years to one million years) seems feasible based on the current understanding and a combination of geocientific-arguments.

c) A large spectrum of geoscientific arguments in support of the long-term stability of host formations is being used by waste management agencies when building their safety cases for long-lived geological repositories in argillaceous formations. In most case, multiple lines of arguments covering various spatial (site to basin) and temporal scales are utilised. Furthermore, comparison with much less favourable geological situations and scoping calculations notably help testing the robustness of the proposed repository systems.

d) There is a need for waste management agencies to better harmonise and justify the potential multiple arguments in support to the geosphere stability. Indeed, there is an apparent lack of consistency when comparing the various sites and therefore the corresponding sets of arguments. One should foster a better justification of why an argument is used or is valid for a site or a host formation and not in another case.

e) The need to provide a comprehensive "history" of the host formation was emphasised in view of presenting multiple line of evidence of the capacity of the host formation to fulfill the safety functions. This contributes to building confidence when presenting a safety case. The petroleum industry already has important experiences on this matter, and this should be further used.

f) An additional important issue concerns the self-sealing process, as the EDZ remains, in stable conditions, the only potential pathway for significant water, gas and radionuclide transfer. It was confirmed that the coupling between hydraulics, mechanics and geochemistry need to be further investigated, both experimentally and theoretically. The two ongoing projects EC SELFRAC and the Clay Club self healing initiative are considered as relevant steps to better understand the driving processes in EDZ generation and evolution.

More generally, there seems to be a discrepancy of interests between the academic world and the waste management industry. The first is studying regions where processes are active. In contrast, deep geological repository sites are located in areas that have been selected for their high stability and where such processes are quite slow or negligible. The challenge that has to be faced is thus bilateral, i.e. from academic to waste management, transferring knowledge from active areas towards more stable settings, and conversely, generating interest in the academic world for further confirming stability arguments. In this framework, bridging the gaps between the academic community and the waste management community should be set as a key objective of the IGSC initiative on geosphere stability.

The workshop undoubtedly helped to build confidence in the overall long-term stability of argillaceous formations that are considered as potential host for long-lived deep disposal facilities.

TABLE OF CONTENTS

Introduction 9

Scope and Objective of the Workshop 11

Synthesis of the Workshop 13

Poster Session 25

Conclusion 27

COMPILATION OF PAPERS

SESSION I
GENERAL FRAMEWORK: ARGILLACEOUS MEDIA AS HOST FORMATIONS

Functions of Argillaceous Media in Deep Geological Disposal and Their Handling in a Safety Case
J. Marivoet, S. Voinis, Ph. Lalieux and P. De Preter 33

Regulatory Expectations Concerning the Geosphere Characterisation for Disposal in Argillaceous Formations
G. Bruno, J.-Y. Boisson and F. Besnus 41

SESSION II
EXOGENIC AND ENDOGENIC PROCESSES

An Overview of Climate Change
V. Masson-Delmotte and D. Paillard 47

Surface Erosion in Orogenic Systems
F. Schlunegger 55

Faulting and Hazard in Low Seismicity Areas
R.M.W. Musson 61

Research of Fault Activity in Japan
T. Nohara, N. Nakatsuka and S. Takeda 67

Geological Evolution of Clay Sediments: The Petroleum Exploration Vision
F. Schneider 75

Predicting the Diagenetic Evolution of Argillite Repositories Based on the Study of Natural and Experimental Systems
L. Warr, N. Clauer and N. Liewig 83

SESSION III

ARGUMENTS TO SUPPORT CONFIDENCE IN THE STABILITY OF CLAYS CONSIDERED AS POTENTIAL HOST FORMATIONS

Screening Methodology for Site Selection of a Nuclear Waste Repository in Shale Formations in Germany
P. Hoth, P. Krull and H. Wirth 91

The Geological Evolution of Opalinus Clay in the Zürcher Weinland Area (NE Switzerland): Learning from the Past to Predict Future Evolution and Stability
A. Gautschi and M. Mazurek 99

The Evolution of the Callovo-Oxfordian Argillite Site, Eastern France
J. Brulhet 103

Evaluation of Long-term Geological and Climatic Changes in the Spanish Programme
T. Torres and J. Eugenio Ortíz, A. Cortés and A. Delgado 109

SESSION IV

REACTION OF ARGILLACEOUS MEDIA VIS-À-VIS NATURAL PERTURBATIONS AND GEOSPHERE EVOLUTION (BUFFERING)

Clay Club Initiative: Self-healing of Fractures in Clay-rich Host Rocks
S.T. Horseman, R.J. Cuss and H.J. Reeves 117

Hydro-mechanical Aspects: Glacial Loading/Erosion – The Opalinus Clay Study
P. Marschall, T. Küpfer and U. Kuhlmann 135

Geochemical Stability of Clay-rich Rock Formations: Evidence Based on Natural Tracer Profiles
M. Mazurek, T. Gimmi, H.N. Waber and A. Gautschi 139

Chemical Buffering Capacity of Clay Rock
C. Beaucaire, F.J. Pearson and A. Gautschi 147

Some Elements of Understanding of Argillaceous Media Stability
É. Gaucher 155

Chemical Buffering/Mineralogical Aspects: Mineralogical Stability
S. Sammartino, A. Bouchet, J.-C. Parneix, D. Prêt and A. Meunier 159

Nature and Reactivity of Organic Matter in Argillaceous Formations: Example of the Callovo-Oxfordian of Bure (France)
R. Michels, M. Elie, P. Faure, V. Huault, L. Martinez, D. Bartier, S. Fleck and Y. Hautevelle 165

Early Fracturation in Argillaceous Massifs and Related Carbonate Transfer
B. Beaudoin, J. Brulhet, S. Dennebouy, O. Parize and A. Trouiller 169

POSTER SESSION

Numerical Investigations About the Influence of Glacial Loading on the Transport of Radionuclides in the Opalinus Clay
G. Kosakowski 177

Burial History of Two Potential Clay Host Formations in Belgium
J. Mertens, L. Wouters and Ph. Van Marcke 183

Presence and Evolution of Natural Organic Matter in the Boom Clay
M. Van Geet, I. Deniau, C. Largeau, C. Bruggeman, A. Maes and A. Dierckx 187

Uncertainty Propagation in a Deterministic Seismic Hazard Assessment
C. Martin, R. Secanell, P. Combes and J. Brulhet 193

Geological Disposal of Spent Nuclear Fuel in Clay Host Formation in Slovakia
S. Prváková, M. Pospíšil and J. Ďúran 199

Characteristic Properties and CM(III) Complexation of Humic and Fulvic Acids from Callovo-Oxfordian and Opalinus Clay
F. Claret, T. Schäfer, T. Rabung, A. Bauer, M. Wolf, G. Buckau and T. Fanghänel 203

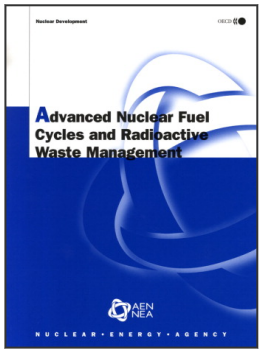
Confinement Performance of Boda Claystone Formation, Hungary
I. Szűcs, J. Csicsák, Á. Óvári, L. Kovács, and Z. Nagy 209

Mineralogical Behaviour of Bentonites in Open and Closed Systems
H.-J. Herbert and J. Kasbohm 225

Experimental Study of the Hydromechanical Behaviour of the Callovo-Oxfordian Argillites
C.L. Zhang and T. Rothfuchs 229

Changes in X-ray Patterns, Rehydratation, Ability, Cation Exchange Capacity and Specific Surface Area of Bentonites from Rokle Due to the Experimental Heating
I. Kolaříková, R. Hanus, E. Jelínek and R. Přikryl 231

List of Participants 235



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