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COMMITTEE ON RADIOACTIVE WASTE MANAGEMENT

Co-ordinating Group on Site Evaluation and Design of Experiments for Radioactive Waste Disposal (SEDE)

Working Group on Measurement and Physical Understanding of Groundwater Flow through Argillaceous Media (the "Clay Club")

Detection of Structural and Sedimentary Heterogeneities and Discontinuities within Argillaceous Formations

Synthesis and Compilation of Abstracts
"Clay Club" Topical Session
Brussels, Belgium, 3 June 1998

The present document has been drafted by the Secretariat with the help of Professor N. Vandenberghe (KUL, Belgium) and Mr. P. Manfroy (ONDRAF/NIRAS, Belgium) who co-chaired the Topical Session, and of M. Thury (Nagra, Switzerland), the Clay Club Chairman

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PART A

SYNTHESIS

Detection of Structural and Sedimentary Heterogeneities and Discontinuities within Argillaceous Formations

Synthesis of the Clay Club Topical Session

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1. Introduction

The Topical Session on the *Detection of Sedimentary and Structural Heterogeneities and Discontinuities within Argillaceous Formations* was organised in the framework of the 8th meeting of the NEA Working Group on Measurement and Physical Understanding of Groundwater Flow Through Argillaceous Media (informally named the "Clay Club"). The session was held in Brussels (Belgium) on 3rd June 1998 at the invitation of the Belgian Organisation for Radioactive Waste and Fissile Materials (ONDRAF/NIRAS) and the Nuclear Energy Research Centre (SCK/CEN).

Several national waste management organisations, regulatory authorities, geological surveys and service companies linked with the oil industry were represented, as was the academic community (26 participants from 9 OECD Member countries and the EC).

The Topical Session was principally aimed at exchanging information on:

- the recent developments, within national waste management programmes and in the oil-exploration industry, in the detection of intra-formational heterogeneities;
- the integration of the various scales of observation and of the various disciplines that are involved in these observations;
- the genetic understanding of the heterogeneities and discontinuities.

It was not intended to cover all programmes active in clays or all observations and methods. However, the geological settings covered in the presentations concerned the whole range of argillaceous media (from soft, plastic clays with high water content to indurated claystones with low to very low water content) currently studied with respect to deep disposal of radioactive waste. The session was introduced by a keynote presentation, given by Professor N. Vandenberghe (KUL, Belgium), on the various intra-formational discontinuities that can be encountered at different scales in argillaceous media. The aim of this keynote was to provide the audience with a common background on the types of features of interest. Test cases from different programmes were then presented and discussed. The last presentation dealt with recent technical developments in borehole geophysical logging and testing tools and their applications to argillaceous formations.

The current synthesis is aimed at briefly reflecting the material that was presented at the Topical Session and providing an overview of its main outcomes. It is however not intended to provide a comprehensive *résumé* of the presentations and discussions. The abstracts of the presentations are compiled, without further elaboration from the Secretariat, in the second part of the document. Annex 1 gives the list of participants to the Topical Session.

The NEA wishes to express its gratitude to:

- the Belgian Organisation for Radioactive Waste and Fissile Materials (ONDRAF/NIRAS) and the Nuclear Energy Research Centre (SCK/CEN) which hosted the Topical Session;
- Professor N. Vandenberghe (KUL, Belgium) and P. Manfroy (ONDRAF/NIRAS, Belgium) who co-chaired the Topical Session;
- the speakers for their interesting and stimulating presentations; and
- the participants for their constructive contribution.

2. Types and Scales of Discontinuities

As clays are very fine grained and deposited in quiet waters without currents, such deposits are reputed to be necessarily homogeneous. **Vandenberghe** (KUL, Belgium) reviewed, on the basis of numerous examples from the Belgian Tertiary sedimentary sequence, the different reasons why clay deposits seldom correspond to such an idealised situation. Among these reasons are:

- the nature of the sedimentary environment that may lead e.g. to lateral facies changes in tidal environments, sorting due to storm-induced wave effects in sediments deposited below the wave base, slumps on instable slopes;
- the occurrence of other sediment types above clay that may create density instabilities and diapirism;
- the diagenetic mineral growth that is, in clays, a very active geochemical and biogeochemical process (e.g. precipitation of pyrite, redistribution of carbonates into nodules);
- the structural deformations that can affect, at different scales, a clay deposit. Among these deformations are the large-scale extensional faults that may result from the important volumetric change in the course of the diagenesis, and the meso- and small-scale discontinuities related to the development of the bedding-parallel orientation during compaction;
- the periodically changing climatic conditions which may affect the sediment properties (e.g. granulometry sorting, variation in mineralogical supply).

On 4th June, Professor Vandenberghe conducted a visit to the Kruibeke clay pit (N Belgium) that provided field examples of some of the topics discussed in his presentation.

Later in the session, **Beaudoin** (ENSMP, France) presented observations from the Vocontian basin (SE France) supporting early faulting and fracturing in marly formations. In the Aptian-Albian “Blue marls”, the presence of centimetric- to metric-thick sand sills and dykes records an early, synsedimentary fracturation episode (*per descensum* hydraulic injection and/or turbiditic currents). In the Domerian marls, one can observe two families of carbonate nodule-beds drawing a double stratification, without apparent faults. One family is parallel to the general bedding, the other records synsedimentary faults that affected the Domerian formation. The double anisotropy, bedding (gravity) and oblique fractures (tectonics), acted as a control to the migration and chemical re-deposition of calcite into nodules.

3. <u>Surface and Borehole Geophysiscal Methods</u>

Wouters (ONDRAF/NIRAS, Belgium) summarised the approach followed for the geophysical characterisation of the argillaceous rocks that are potentially considered as host formations for waste repository in Belgium; i.e. the Boom Clay (Rupelian) under the nuclear zone of Mol-Dessel, and the Ypresian Clays on the site of the Doel nuclear power plant. He reported mainly on the multidisciplinary dataset collected for Boom Clay that is currently being processed and interpreted with a view to produce an integrated seismics, wireline logging and core interpretation. The geometry (including the large-scale discontinuities) of the Boom Clay and surrounding formations has been successfully studied by various reflection seismic campaigns. The seismic inversion of the testline shot in 1991 showed some impedance variations within the Boom Clay itself and demonstrated the interest of high-resolution reflection seismic for detecting intra-formational stratigraphic variations. High-resolution logging tools (e.g. induction imager, resistivity micro-imager) have allowed the visualisation of the decimetric clay/silt alternation within the Boom Clay[1]. The nuclear magnetic resonance data seems very promising in defining hydrogeological sub-units within a tight formation, and is particularly useful for focusing more detailed hydrogeological testing[2].

The results obtained in the framework of the Spanish deep disposal programme were presented by **Plaza and Gillot** (Enresa, Spain and CGG, France). This multidisciplinary study (core samples, logging, 2D reflection seismic survey) was conducted on the Miocene San Pedro clay formation. It was aimed at gaining better knowledge of the petrophysical characteristics of the clays and of their distribution, as well as detecting and characterising structural discontinuities. The various members defined according to the spectral gamma ray log can be matched with the seismic facies and followed along the different reflection seismic lines. A inversion study (acoustic impedance variations) allowed the visualisation of small-scale lithological changes and structural discontinuities within the clay formation.

Birkhäuser (Nagra, Switzerland) reported on the first results from the structural interpretation of the 3D seismic imaging of the Opalinus Clay in Northern Switzerland. This survey, together with borehole and *in situ* tests, forms the basis for an evaluation of the suitability of the Opalinus Clay as a host rock for deep disposal of high-level and long-lived waste in Switzerland. The results of this seismic survey are currently being interpreted from a structural point of view with the help of softwares that allow to fully exploit the wealth of information inherent in such a 3D data set (e.g. automatic picking of seismic events, seismic attribute analysis and pattern recognition). From this interpretation it can be concluded

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[1] A poster, that had been prepared for the IHRWM Conference was also displayed, as support to the oral presentation: P. Win et al., Definition of Clay-Silt Sequences Using Wireline Logs, Presented at the IHRWM Conference, Las Vegas, May 1998

[2] See Strobel et al., 1998 and Win et al., 1998 in footnote 3

that e.g. individual intra-formational heterogeneities can be mapped, faults with vertical throws larger than about 10 metres are directly visible from the data, features with vertical dimensions of just a few metres but with a certain lateral extent can be recognised as patterns from the seismic attribute maps. Azimuth attribute maps have also allowed to observe that some tectonic movements at the deeper levels have been absorbed within the relatively ductile Opalinus Clay sequence. When the geophysical logs from the planned calibration borehole are available, the interpretation will be carried further, concentrating on the seismic stratigraphy of the target horizon and lateral extrapolation from the borehole into the investigation area.

Some recently-developed (in the oil and gas industry) high-resolution borehole geophysical logging methods were presented by **Hagood and Crossouard** (Schlumberger, The Netherlands and United Kingdom). Among these tools and methods are:

- the high-resolution electrical imaging of borehole wall and near-invaded zone that allows delineation of very thin beds (effective vertical resolution of 0.5 cm) and vertical facies changes as well as an estimation of fracture density and aperture;
- the combination of gamma ray and elemental spectroscopy, and measurement of photoelectric effect that can help estimate *in situ* geochemistry and derive mineral volumes and cation exchange capacity;
- the nuclear magnetic resonance (NMR) logging that can be used for hydrogeological reconnaissance within low-permeability argillaceous formations. This method is based on the investigation of the reaction of hydrogen nuclei in static and dynamic magnetic fields. Information about pore- and grain-size distribution, porosity, permeability and the state of water in the formation (i.e., clay bound, capillary bound, or free) can be derived.

Examples of recent applications to argillaceous formations (and in particular to the Boom Clay in Belgium[1]) supported this presentation.

[1] Additional information on the nuclear magnetic resonance imaging tool, and the application of wireline logs to argillaceous formations have been distributed to all participants after the Topical Session:

B. Kenvon et al., Nuclear Magnetic Resonance Imagining – Technology for the 21st Century, Oilfield Review, Autumn 1995

R. Kleinberg, Petrophysics of the Nuclear Magnetic Resonance Tools, Schlumberger, July 1996

J. Strobel et al., Groundwater Permeability Correlation in the Boom Clay using Wireline Logs, Presented at the IHRWM Conference, Las Vegas, May 1998

P. Win et al., Definition of Clay-Silt Sequences Using Wireline Logs, Presented at the IHRWM Conference, Las Vegas, May 1998

M. Herron et al., Log Interpretation Parameters Determined from Chemistry, Mineralogy and Nuclear Forward Modelling, Int. Symposium of the Society of Core Analysts, Calgary, Sept. 1997

4. Other Presented Methods and Tools

Mikake (PNC, Japan) reported on the on-going study on the role of heterogeneous hydrological conditions in governing the locations of uranium concentrations at the Tono mine, Central Japan (Tertiary compacted sedimentary sequences overlying Cretaceous granitic basement). The distribution of heterogeneous conductivity fields has been estimated, from geophysical logging results, using fractal theory and successfully compared with the results of long-term piezometric head observations and groundwater flow analysis that have been carried out as part of the Shaft Excavation Effect Experiment. In order to build confidence in the applicability of the model, a comparison of the computed tracer concentration distribution with observations of natural uranium migration profiles is on-going.

The preliminary results of radar investigations carried out at the Tournemire tunnel (S France) were presented by **Boisson** (IPSN, France). Geophysical methods based on the propagation of electromagnetic waves (radar) are not usually used in argillaceous settings (too high absorption). To assess their potentiality to investigate the discontinuities in such geological environments, several tests were performed in the Toarcian Argilite crossed by the Tournemire tunnel. Anomalies in the reflectometry measurements in single boreholes could in some cases be correlated with geology (faults, zones of higher carbonate concentrations). Contrasts in propagation velocities derived from crosshole transmission can be related to the presence of fractured media. Surface reflectometry along the tunnel lining allows a good visualisation of the tunnel structure and the detection of an excavation disturbed zone with open fractures. However, more limited excavation-induced perturbation, observed around a recent gallery, cannot be detected by reflectometry.

5. General Conclusions

From the presented cases and the ensuing discussions, the following conclusions and recommendations can be drawn:

- One of the key outcome of the Topical Session is the confirmation of the ubiquity of intra-formational discontinuities in argillaceous formations and of their highly "relative" character, due to their scale-dependency. Therefore, in order to avoid confusion, the level of homogeneity and/or heterogeneity should always be defined *vis-à-vis* the scope, scale and target of the study. This conclusion is especially valid in the framework of potential repository systems in argillaceous settings, where the assessment and understanding of the impact of discontinuities on groundwater flow and radionuclide transport is of utmost importance.

- Progress in the genetic understanding of the discontinuities was also shown, even if several field observations remain to be fully explained.

- A full battery of geophysical tools (to be used from the surface, in boreholes or from underground excavations) and interpretation methods currently provide access to the internal structure of the clay formations and have proven to be highly valuable for potential repository site evaluation. These tools cover the whole scale range: from regional structures to mineralogical variations and clay/water interactions.

- Contrasts in acoustic impedance within argillaceous formations are strong enough to allow the successful use of modern interpretation methods that can provide access to the internal structure of the clay formations: 3D seismic attribute analysis (that provides e.g. dip and azimuth of seismic events) and seismic inversion (that allows e.g. log/seismic correlation, stratigraphic modelling, extrapolation/interpolation of petrophysical parameters between boreholes).

- Evidences of “absorption” of tectonic movement in clay sequences were presented (Boom Clay, Opalinus Clay).

- Among the most successful recent developments in the logging tools is the high-resolution electrical imaging of borehole wall that could visualise very thin beds and help define fracture properties. The recently-developed logging tools based on the nuclear magnetic resonance are very promising as they provide access to the clay-water interactions and they could help assess hydrogeological properties of tight formations.

- Further calibration is however needed to fully adapt these new geophysical tools and interpretations methods to repository-relevant rocks and depths. Indeed they have been developed and tested by the oil and gas industry, i.e. at great depths into highly compacted rocks, with possible overpressurised fluids. This calibration should also help understand the limitations of these measurement tools and interpretation methods. Collaboration with the oil industry on these matters is thus important.

- The need for calibration was also mentioned for the comparison of geomechanical data acquired in laboratory and derived from geophysical measurements, due to the difference in the physics of the measurements.

- Further developments (notably in the interpretation methods) are needed for the application of radar techniques to argillaceous settings.

- Overall, the Topical Session demonstrated the increased integration of various types of geoscientific data (e.g. geophysical measurements, core information, genetic understanding) that is needed and currently carried out within national disposal programme to fully comprehend the internal structure of argillaceous formations. This multidisciplinary integration is of utmost importance for confidence building in the geoscientific base for disposal.

PART B

COMPILATION OF ABSTRACTS

Types of Intra-Formational Discontinuities at Various Scales in Argillaceous Media

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Abstract

Intra-formational discontinuities in clay formations refer to the heterogeneity in clay formations. Heterogeneity of a sediment is a scale dependent phenomenon. Indeed, at the mineral and pore level very few sediment bodies if any can be considered as homogeneous because the mineral grains and the pores which make up the sediment differ quite commonly in mineralogy, in size and in shape. In addition quite often the sediment is disturbed by bioturbation, a process which renders the sediment more homogeneous or more heterogeneous dependent on the initial structure of the clay and on the scale of observation.

Nevertheless, macroscopically geologists and material scientists may consider sediment bodies as homogeneous when no obvious discontinuities occur in the samples, leading to the assumption that the properties of all these samples will also be similar. In such case also the anisotropy in a sample may be constant for all samples. As clays are very fine grained and deposited in quiet waters without currents such deposits are reputed to be necessarily homogeneous, in contrast to sandy deposits which have been subjected to high energetic currents, capable of sorting and structuring the sediment. Clay deposits however seldom correspond to such an idealised situation, and that for several reasons.

First, the sedimentary environment of clays is not always limited to below wave base and sedimentation on instable slopes may occur. Secondly the occurrence of other sediment types above a clay may lead to density instabilities. Thirdly heterogeneities may form during diagenetic mineral growth. Fourthly structural deformations of different scales can affect a clay deposit. And fiftly when a deposit reaches a certain thickness i.e. time, it can be predicted that the deposit will have formed under periodically changing climatic conditions some of which undoubtedly will affect the sediment properties.

I. Sedimentary structures in a clay deposit

1. Tidally deposited clays.

Clay deposits may be laterally heterogeneous especially when they are formed in a tidal environment. This is easily understood for a tidal flat deposit (e.g. the Wadden Sea) with many creeks and eventually deep channels between barrier island. In a tidal environment clay deposits may be ripped up and eroded by strong currents (e.g. the Egem Sands, Ypresian). When clays are exposed above water mud cracks can develop.

2. Inner shelf deposits.

Even if a clay deposit is formed well below wave base on the inner shelf, depending on the sedimentation rate versus the occurrence of large storms, it can be expected to see the presence of winnowed horizons (storm layers) and even the development of regionally widespread horizons consisting of flat gullies of sorted sediment as described in the basal silty clay layers of the Boom Clay (Vandenberghe 1978, photo 8 & 9). In very near shore clay deposits even gutter gullies may be found (Belsele-Waas member of the Boom Clay).

3. Instability of the sediment.

Clay sediments deposited on slopes may become unstable and form internally deformed slumps. Eventually mudlayers may turn into a convoluted layer if triggered e.g. by quakes (e.g. Ordovician Coticula layers).

II. Density instabilities

1. Synsedimentary origin.

Density differences and rheological behaviour differences between consecutively deposited lithologies are the causes of boundary effects in the top of clay layers such as flame structures, sand balls in clay layers, small scale mud volcanoes, several of which are generally termed load cast phenomena.

A special boundary instability leading to a wavy contact can sometimes be observed between sand and clayey layers (sandy and clayey Oorderen Sands boundary, Lillo Formation, Neogene) the origin of which is not well understood.

2. Diapirism of penecontemporaneous sedimentary origin.

Originally diapirism was thought to be restricted to salt deposits because of their exceptionally small density and their easy flow capacity. Clays however are known these days to form diapirs at depth if their density remained somewhat low and especially if squeezed in anticlinal structures.

However diapirism has been reported also at shallow depths. Mud lumps e.g. are systematically reported off shore in the Mississippi delta area as they form a threat to the navigation. Mud lumps are diapirs that form as a reaction to sandbars prograding over the mud deposits (Morgan et al., 1968). In the Namurian deltaic front deposits at the Namur Citadelle plastic shale deformation structures have been interpreted as fossil diapirs which originated when the sediment was buried only a few tens of meters at maximum. In the same location other deformation structures also involved plastic clays squeezed between sand bodies upon Namurian tectonic compression (Vandenberghe and Bouckaert, 1984).

In the Boom Clay the first diapir was described as a curiosum at the construction site of the Scheldt tunnel in Antwerp (Laga, 1966). Later seismic work in the Scheldt itself (Wartel, 1980; Schittekat et al., 1983) showed several diapiric uprises of the Boom Clay in the upper about twenty meters when the river eroded down into the clay top. Apparently the local erosion of clay was sufficiently lowering the vertical stress on these overconsolidated clays, estimated at about 75 meter in Antwerp (Schittekat et al., 1983), to have the horizontal stresses squeezing the clay upwards. Diapirs outside the Scheldt valley where never observed. Such an origin of diapirs in eroded valleys remembers the uprising of clays under river valleys described as cambering structures.

Diapirs in muds can nowadays be observed in marine deposits both in the compressive regimes of subduction settings and in passive margin settings in front of large delta’s (e.g. Niger delta).

III. Diagenetic heterogeneities

The diagenesis of muds into clays is a geochemical and biogeochemical very active process. Especially the reduction of the sediment with the associated ubiquitous pyrite formation in marine clays and the biochemically influenced carbonate diagenesis and redistribution into nodules should be reported. Pyrite can be present as thin mineralised worm tracks, as pyritized molluscs, as fist large concretions or as layers of concretions. Carbonate nodules can reach diameters of more than a meter and display typical septaria cracks with minerals deposited on the septae walls. Also larger phosphate nodules are commonly found in clay deposits. Obviously oxidation can change the properties of the clays as well known in the red pottery business.

IV Structural deformation in clays

1. Large scale faults

Obviously clay deposits can be cross-cut by faults as it is the case with any rock type. Faults influence the geometry and the permeability of the clay mass. Clays can also be deformed both in a plastic and in a brittle way by glacial loading.

In thick clay deposits polygonal patterns of extensional faults are detected by seismic reconnaissance surveys (Cartwright and Lonergan, 1986). They are layer bound and occur also in relatively young deposits. The faults are listric in shape. The volume gain through extensional faulting is probably compensating for the important fluid losses during the early diagenesis. The fault throws are estimated up to 80 m and polygone diameters are in the order of a few hundred meter. This can be the reason that faults are seldom seen in clay pits. In the Ypresian clay deposits in Belgium similar faulting was observed both offshore and on land (Henriet et al., 1989; Henriet and Batist, 1996). Clay breccia observed in a borehole may be related to the faulting. The role of the faults themselves in the dewatering processing is debatable.

A particular flat-lying fault was observed in the Boom Clay. Its origin is not understood but might eventually be linked with the diapirs in the Scheldt valley which are less than a kilometer away from the fault location.

2. Meso scale discontinuities

Upon compaction clays develop a bedding-parallel preferred orientation leading to a cleavage when the clays are decompacted artificially or by erosion. The quality of this cleavage depends on the precise lithological composition. When clays approach the plasticity limit during the compaction the stress field imposed by burial, by eventual regional tectonic deformation or by simple uplift creates jointing planes in otherwise plastic clays. This can commonly be seen in clay pits. Such cleavages and joints are the explanation for the curious existence of water pits dug into the top of clay layers which make up the regional geological substrate close to the surface and for the observation of pollutant seepage through clay layers into groundwater reservoirs.

3. Small scale discontinuities

Typically in stiff overconsolidated clays small slickensides fissures are present. They typically range in the centimetre scale. They form especially if the clay is very pure and probably in the latest phase of the clay evolution. They may represent the pathway for fluids in pure clays.

4. Erosional truncation of clay

A classical example is the incision in which later the Diest Sands are deposited (top Miocene). It certainly influences a regional hydrogeology model and caused disturbances in the Boom Clay exposed at the valley flank (Vandenberghe and Vandenberghe, 1980).

V. The sedimentary sequence documented in the clay deposit

As the climate is evolving at different scales ranging from the seasonal scale, over the Milankovitch periodicities to third order type sequence periodicities controlled by glacio-eustacy (sensu Vail) and to even lower frequency periods, it can be predicted that if climate influences the sedimentary record in anyway this should be detected also in clay deposits. A clay deposit indeed generally represents a fairly long time span compared to equal thicknesses of a sand deposit.

The Boom Clay is an example by excellence to demonstrate such climatically driven cyclicity (Vandenberghe et al., 1997). Milankovitch driven periodicities in grain size and in organic matter distribution can be seen. Organic matter and grain size are related through a model of sea-level variation in response to climate change. Two third order sequences driven by glacio-eustacy are expressed by the grain-size variations. Carbonate layers are formed periodically but are not related to the above cited climate cycles. Tectonics control the bed thickness but the sediment supply is apparently also influenced by a long duration eccentricity cycle. At the level of the chemistry and the detailed mineralogy of the deposit even intermediate climate driven cycles can be observed. In particular in clay deposits such climatic cycles can be expected to occur over a wide area.

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Geophysical Prospection of Tertiary Clays in Belgium Methods For Detecting Heterogeneities

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The Belgian nuclear repository programme is in the process of characterising the host capacities of Tertiary clay layers. Two clay layers are considered as potential host rocks for deep burial of long-lived high-level waste. The Boom Clay has been studied for more than 25 years. The research activities are concentrated in the nuclear zone of Mol-Dessel, where an underground experimental facility was built at a depth of 225m. Some years ago, the study of the Ypresian Clays was started and a first drilling campaign on the site of the Doel nuclear plant was performed.

To qualify as a potential host rock, the clay layer has to meet certain qualifications : it must have a minimum depth and a minimum thickness and be as homogeneous as possible. The latter not only on a small scale (grainsize differences, mineralogical variations, diagenesis), but also on a large scale (faults, unconformities, facies). These features can be detected by various geophysical methods : reflection high resolution seismics for large-scale heterogeneities, wireline logging for small-scale heterogeneities. These homo-heterogeneities on both scales play a key role in the safety assessment methods.

I. Available geophysical data on the Boom Clay in Mol-Dessel

Apart from the underground research laboratory on the SCK-CEN site in the nuclear zone of Mol-Dessel, we dispose of several logged wells and seismic data. Geophysical exploration started in the mid-seventies with the drilling of the SCK-15 well. Wireline logging included a gamma ray (GR), long & short normal resistivity logs, a spontaneous potential and a density log. Soon after this drilling a seismic campaign was conducted in the same area. This campaign (3D-78 seismic campaign) was characterised by a special acquisition set-up, a precursor of the later three-dimensional set-ups. A seismic testline was shot in 1991 to determine the best parameters for a two-dimensional high resolution seismic campaign. The drilling of the DESSEL-1 well started in October 1993. An extensive logging programme was run including an Array Induction Imager Tool, a Fullbore Formation MicroImager, a Dipole Shear Sonic Imager tool and a P& S wave VSP. Moreover, 24 pre-tests were run with the Single Probe Modular Formation Dynamic Tester in order to obtain in situ permeability values. Early 1996, preparations started for the 2D HR seismic campaign in the nuclear zone of Mol-Dessel and its vicinity. The total campaign is composed of 13 lines with a total length of 64.67 km. Where possible, explosives were used as seismic source. Lines on roadtracks and in build-up areas were shot by vibroseis. Soon after the end of the 96-ON seismic campaign, the MOL-1 well was drilled on the intersection of two seismic lines. This partly cored well was logged with a complete set of high resolution logging tools, including a VSP. Some special advanced tools such as the Nuclear Magnetic Resonance and Epithermal Neutron Porosity were used to assess grain size, pore distribution and groundwater mobility.

II. Available geophysical data on the Ypresian Clay in Doel

The drilling campaign in Doel was finished at the beginning of May 98. Several piezometers were placed above and below the Ypresian Clays in order to monitor the waterlevels in the different waterbearing strata. The Ypresian Clays were cored and samples were sent to several laboratoria to determine their mineralogical, geomechanical, hydraulic and geochemical characteristics. One of the wells was logged with high resolution logging tools such as AIT, DSI, FMI and CMR. In-situ permeability tests were performed at different levels using the pressure pulse method.

III. Small-scale heterogeneities

The heterogeneous character of the Boom Clay is clearly visible in outcrop: the alternating clay/silt beds can be counted and followed from one pit to the other. Certain distinct layers, e.g. the doublelayer, the pink layer and the septaria layers, are used as stratigraphic markers. It has long been known that the resistivity measurements were the instrument to correlate the Boom Clay from one well to the other. The much higher resolution of recently developed tools such as the azimuthal laterolog (HALS), the array induction imager (AIT), the microspherically focused log (MSFL) and last but not least the fullbore formation micro-imager (FMI) show details and variations on a decimetre scale (Win *et al*., 1998). The clay/silt alternation is beautifully visualised by the FMI, and even allows numbering of the distinct layers in accordance with the outcrop. The permeability curve obtained from the CMR data reflects the presence of six subtle hydrogeologic units that correspond with recognised stratigraphic and geomechanical subdivisions of the formation (Strobel *et al*., 1998). The continuous porosity distribution provided by the CMR log is particularly useful for focusing more detailed hydrologic testing like pressure pulse tests or permeability measurements in laboratories.

IV. Large-scale heterogeneities

The geological map clearly shows many faults to the east of the nuclear zone of Mol-Dessel. Some of these faults, belonging to the Roermond Graben, were still active during early Quaternary times. The Poppel Fault, located 6 km from the SCK-CEN site, has a throw of approximately 80 m at the top of the Boom Clay. The purpose of the 3D-78 and 96-ON seismic campaigns was to accurately define the geometric and lithological properties of the subsurface and of the Boom Clay in particular.

Stratigraphic inversion of seismic profiles can be used to detect stratigraphic variations and structural discontinuities. Although no sonic log was available, the inversion of testline 91-ON-01 shows some impedance variations within the Boom Clay.

V. Future work

Many high-quality data were gathered, and are waiting to be processed, interpreted and summarised into a final study integrating seismics, wireline logging and core analysis. The only way to improve our understanding of the underground and especially of fine-grained sediments, is total integration of different state-of-the-art technologies.

Identification and Correlation of Structural and Sedimentological Discontinuities in Clays using High Resolution Seismic

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This multi disciplinary study conducted in the area of the Miocene Clays enables us to gain better knowledge of the petrophysical characteristics of the clays. This presentation integrates data (core samples, logging, seismic), laboratory studies such as Xray clay analysis, and high resolution seismic acquisition. The Clay formation was divided into members according to the spectral gamma ray log which matches the seismic facies correlated in the first borehole. These members and units were followed along the different seismic lines. An impedance change makes it possible to visualise and appreciate the small changes in lithology and the position of structural discontinuities within the Clay formation. Those powerful tools provide a very efficient solution for a three-dimensional understanding of the Clay formation and the identification of interesting areas with a minimum boreholes. 3D seismic acquisition would be the next step.

I. Presentation steps

- Geological-structural context (regional)
- Geological-structural and geometrical characteristics of the Clay Formation
- Sequence or phases of studies conducted in the area
- Identification and correlation of discontinuities in boreholes
- Seismic reflection survey
- Results and conclusions

3D Seismic Imaging of the Opalinus Clay in Northern Switzerland First Results from the Structural Geological Interpretation

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In 1991 Nagra carried out a programme of regional investigations of the Opalinus Clay formation in Northern Switzerland, in order to delineate a potential future siting area for high-level radioactive waste disposal. The investigations centred on a 2D seismic field campaign. Results showed the Opalinus Clay to be generally well suited for surface exploration and the region of the Zürcher Weinland in particular to be a location where this formation is at a suitable depth for repository construction (400 to 900 metres below ground surface). In this region, the Opalinus Clay is also sufficiently thick (generally 100 metres) and near horizontally bedded with only slight tectonic overprinting. Based on these purely geological selection criteria, priority for further local investigations of the Opalinus Clay was assigned to the Zürcher Weinland as the best prospect for further site evaluation studies.

The programme for local investigations of the Opalinus Clay in the Zürcher Weinland was drawn up in 1995. It comprised a 50 km^2 3D seismic campaign and an exploratory borehole for calibration of the seismic results and for performing downhole hydrogeological and geochemical tests. Together with the comprehensive in situ tests being performed in the Opalinus Clay of the Mont Terri motorway tunnel in the Jura mountains, these investigations will form the basis for a conclusive evaluation of the suitability of this formation as a host rock for deep disposal of HLW/TRU in Switzerland.

The aim of the 3D seismic campaign was to obtain a detailed understanding of the structural and sedimentary setting of the Opalinus Clay formation throughout the investigation area, to detect intra-formational structural and sedimentary heterogeneities and to allow for lateral extrapolation of geological information from the calibration borehole planned at Benken.

The field campaign was specially designed to meet the high resolution aimed for at the relatively shallow target depth, taking into account the difficult field operational conditions (densely populated, agricultural area). Acquisition was completed at the end of March 1997, producing a continuous data set throughout the investigation area, with a 15x15 metres bin spacing and a 12 fold stacking multiplicity at target level. The data, in the meantime, have been processed successfully, confirming the superior quality compared to the existing 2D reflection seismic measurements in the area. The useful frequency bandwidth ranges from 10 to 90 Hz. The vertical resolution at target level is 12 to 15 metres for a quarter of a wavelength. The entire Mesozoic sequence and the upper Permo-Carboniferous below is well imaged, allowing detailed structural analysis and investigations of seismic stratigraphy.

Since mid April, the 3D seismic data have been loaded onto a PC-based seismic workstation for structural interpretation. Early in 1999, when the geophysical logs from the planned calibration borehole are available, the interpretation will be carried further, concentrating on the seismic stratigraphy of the target horizon and lateral extrapolation from the borehole into the investigation area.

The current structural interpretation focuses on making maximum use of the modern tools available to fully exploit the wealth of information inherent in such a three dimensional data set. The particular tools used so far are:

- interactive three dimensional evaluation of structural details (on profiles in all directions, time slices and by means of horizon flattening)
- automatic picking of seismic events, to take advantage of the 2 milliseconds accuracy of the sampling interval
- seismic attribute analysis (e.g. envelope; inst. phase; dip and azimuth)
- pattern recognition from attribute maps of the different seismic horizons

First results from this interpretation confirm that all targets set during planning have been met.

The main achievements are:

1. Throughout the investigation area, there is detailed seismic control of the geology above, below and within the Opalinus Clay sequence.
2. Individual intra-formational heterogeneities can be mapped and set in relation to the tectonic framework of the investigation area.
3. Faults with vertical throws larger than about 10 metres, regardless of their spatial orientation, are directly visible from the data.
4. Faults and other features with vertical dimensions of just a few metres but with a certain lateral extent can be recognised as patterns from the different seismic attribute maps.
5. Pattern recognition also helps to define the fault patterns in zones of reduced data quality.

Comparing the azimuth attribute maps of the interpreted levels, a general change in fault pattern from the horizons above the Opalinus Clay to the ones directly below can be recognised. Analysing the Opalinus Clay sequence at such locations, it can be observed that some tectonic movements at the deeper levels have been absorbed within the relatively ductile Opalinus Clay sequence. This seems to explain why hardly any faults, cutting through the Opalinus Clay sequence, can be observed within the investigation area.

The ongoing interpretation tends to confirm the existing view that the Zürcher Weinland contains the largest extent of an Opalinus Clay sequence which is minimally disturbed by tectonic movements, with blocks extending over several square kilometres without major faulting at this level.

The 3D seismic technique has, in this case, proven to be a highly valuable tool for deep disposal site evaluation in sedimentary rock sequences with sufficiently good acoustic impedance contrasts.

Groundwater Flow of Heterogeneous Conductivity Field in Sedimentary Rocks, Tono Mine, Central Japan

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In compacted sedimentary rocks, hydraulic properties can be characterised with heterogeneity of sedimentary sequences or materials consisted in the formations. Estimation of the heterogeneous hydraulic properties are of prime interest in order to build a confidence of the model of the groundwater flow in compacted sedimentary rocks. In particular, the existence of the continuous high conductivity zone can be characterised as the flow-zone of the groundwater and be expected, so it is important to estimate heterogeneous hydraulic properties.

I. Geological setting

The geology of Tono mine is composed of Tertiary sedimentary sequences and Cretaceous granitic basement. The uranium, which is heterogeneously distributed within the sedimentary layers, is thought to have migrated from a source region to the west of the granite through the weathered granite layer and into sedimentary rocks, as geochemical and climatic conditions altered over time. This study focuses on the role of heterogeneous hydrological conditions in governing the locations of uranium concentrations.

II. Methodology

We discuss heterogeneous conductivity field based on the results of long-term piezometric head observations and groundwater flow analysis that have been made as part of the Shaft Excavation Effect Experiment conducted or carried out at Tono mine, central Japan. And we considered that it is possible to estimate the distribution of hydraulic conductivity using fractal theory, and carried out that the simulation with the results of uranium migration at Tono mine in order to build the confidence of the applicability of the model.

III. Conclusion

It is possible to understand heterogeneous hydraulic properties in compact sedimentary rocks by estimating of the distribution of hydraulic conductivity using fractal theory.

Early Fractures Record in Argillaceous Formations: Sedimentary Dykes and Nodules

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Abstract

SE of France, the Vocontian basin gives the possibility to observe in detail, on continuous outcrops, the different marly formations of the thick Mesozoic marine succession. Two formations will be presented here :

- the Aptian - Albian "Blue marls" (in which is located the Bagnols-sur-Cèze ANDRA project),
- the Domerian marls.

It is now well known that the architecture, morphology and sedimentation of the basin were controlled or at least influenced by synsedimentary deformations at different scales : unconformities, synsedimentary folds and faults, differential subsidence were described in many places and times. But two phenomena in relation with early faulting and fracturing are certainly under-estimated, but exceptionally represented in three outcrops :

- sandy dykes and sills in the Blue Marls (Bevons and Rosans),
- carbonate nodules drawing a double stratification in the Domerian marls (Clue du Vançon).

I. Sedimentary (sandy) dykes and sills

Around Bevons (04), and specially in Le Puy hill, the well stratified Albian and Aptian marls and limestones alternation is cut by sandy bodies. The majority are perpendicular to oblique with regard to stratification, and appear as sandstone dykes ; the others, sub-parallel to bedding, may be named sandy sills.

Near Saint André de Rosans, the major part of the injected sand is found as sedimentary sills which follow nearly the bedding of the Clansayesian level (Uppermost Aptian).

These dykes are from 1 cm to 1 m thick, up to 250 m of penetration in the marly massif, and some may be mapped on some km. The sills are from 1 cm to some meters thick, and some have also been followed on some km.

The field observations demonstrate that the injection of the sandy material took place early, *per descensum* : the sandy network is present below the feeding sandstone channels, in direct connection, and the post-injection compaction rate of the host sediment (recorded by the dykes) show a progressive decrease down-series: at time of injection, the upper sediment was almost not compacted, near the sea-floor, when compaction was very advanced 400 m deeper.

That spectacular hydraulic injection by the sandy (turbiditic) sediment records the early fracturation state : the distribution and orientation of the numerous dykes reveal the role of both synsedimentary faults and slope morphology.

II. Carbonate nodules drawing a double stratification

The Clue du Vançon outcrop, near Authon, offers an unique opportunity to observe and analyse "double stratification": two families of "nodule-beds" cut each other at high angle, without any fault, or fold, or slump structure ... . In each family, individual nodules are up to 20-30 cm thick, and some decimetres up to one meter long. One family is parallel to the general bedding, the other is made of alignments of nodules gathered in parallel and more or less equidistant planes : that second family is clearly parallel to synsedimentary faults which affect the Domerian formations.

The analysis of carbonate content in both nodules and surrounding marls gives scattered values which testify of important carbonate diagenetic migration : that transfer began early, soon after the first fault activity, in a porous material some tens of meters below sea floor. The double anisotropy, bedding (gravity) and oblique fractures (tectonics), controlled then the migration and chemical re-deposition of calcite.

Such heterogeneities generated later small fractures due to differential compaction between nodules and neighbour marls.

III. Conclusion

These two cases are exceptionally exposed. They testify, mechanically (sandy dykes and sills) or chemically (nodule-beds), of an early fracturation in the marls which is surely more frequent than imagined : their observation and genetic interpretation give some keys to suspect analogous anisotropy and discontinuities in other series.

Preliminary Radar Investigations Into Toarcian Argilites : Tests at IPSN Tournemire Site[1]

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1. RADAR REFLECTOMETRY FROM SINGLE BOREHOLE

1.1 Aim of the tests:

- Check possible depth of investigation
- Detection of abnormal velocities:
  - detection of anomalies (3 to 5 m around borehole)
  - evaluation of structural patterns, presence of fractures
  - zone with different petrophysic characteristics, higher W%, $CaCO_3$% or Clay%

1.2 Means:

- BOREHOLE RADAR RAMAC/LI (ABEM/MALA Geosciences)
  monostatic antenna ∅ (48 mm), central frequency 60 MHz
  + Borehole ID180 (vertical downward), non oriented

- BOREHOLE RADAR SIR 2 (Geophysical Survey Systems, Inc.)
  monostatic antenna ∅ (38 mm), length (1.25 m), central frequency 160 MHz
  + Borehole ID180 (40 m, vertical downward), non oriented
  + Borehole VF1 (40 m, vertical downward), non oriented
  + Borehole ID225 (40 m, 45° downward), oriented

1.3 Results:

- FOR THE BOREHOLE RADAR RAMAC/LI (ABEM/Mala Geosciences, 60 MHz) / ID180
  - No identification of particular dielectric variations within 4 m around ID180
  - Variations of the direct wave (frequency and amplitude) :
    correspond to the "schistes carton" level (-140 m)

[1] Transcription of some of the presented overheads

- FOR THE BOREHOLE RADAR SIR 2 (G.S.S.I. / 160 MHz)

  Borehole ID180 (40 m, vertical downward, non oriented)
  - Zones (-8 m; -15 / -30 m) of high frequency energy : could correspond to high $CaCO_3$ levels (nodules)
  - Low frequency anomalies along the borehole : sub-vertical fissuration with higher W% ?

  Borehole VF1 (40 m, vertical downward, non oriented)
  - Abnormal high frequency zones : carbonated zone at -15.5 to -16.5 m
fracturation at -22 m

  Borehole ID225 (40 m, 45° downward, oriented)
  - Low frequency zone -5 to -8 m : changes in lithology ???
  - High frequency energy zone : ???

- Estimation of electromagnetic waves propagation velocity: 100 000 km/s
- Dielectric permittitivity: about 9

2. RADAR TRANSMISSION BETWEEN BOREHOLES (CROSSHOLE)

2.1 Aim of the tests:

- Check possibility of radar tomography

2.2 Means :

- BOREHOLE RADAR RAMAC/LI (ABEM/MALA Geosciences)
monostatic antenna ∅ (48 mm), length (m), central frequency: 60 MHz

- Between boreholes ID225(emission)/ID180(reception) and ID135(emission)/ID180(reception)

2.3 Results:

- Possible signal identification up to 8 m without specific data processing (12 m after data proc.)
- Low propagation velocities : around 65 000 km/s and High attenuation coefficient
- Between boreholes ID225 (emission) and ID180 (reception) :
important propagation velocities variations :
60 000 km/s (dielectric Cst = 21) at -4 m to 90 000 km (dielectric Cst = 11) at -10 m
- Between boreholes ID135 (emission) and ID180 (reception)
propagation velocities : 100 000 km/s (dielectric Cst = 9) High attenuation coefficient
- Contrast of V between E and W : presence of fractured material
- Vertical anisotropy in the W sector (ID225/ID180)

3. RADAR SURFACE REFLECTOMETRY

3.1 Aim of the tests:

- Possibility of E.D.Z. investigations
- Theoretical depth investigation : 1 to 3 m

3.2 Means:

- RADAR SIR 10 (Geophysical Survey Systems, Inc.) central frequencies : 400 and 900 MHz
- Two 5 m profiles along the tunnel walls
- Two 5 m profiles along the E and W galleries

3.3 Results:

- Traditional radar technique allows (from tunnel) :
    - good visualisation of the tunnel structure
    - detection of important EDZ with open fractures due to excavation
- Traditional radar technique doesn't allow (from galleries) to visualise "recent" EDZ extension

Applications of High-Resolution Borehole Geophysical Logging to Argillaceous Formations Pertinent to Nuclear Repository Siting

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Argillaceous (clay rich) formations are the focus of several international nuclear waste characterisation programmes. An understanding of the physical and chemical properties of this geologic media is of critical importance in these characterisation programmes. These properties govern groundwater, gas and solute movement; properties that are critical for the prediction of radionuclide migration. In the oil and gas industry, the characterisation of argillaceous formations is also of great interest, as they are relevant as nonproducing zones or as seals for oil and gas. Recently-developed high-resolution borehole geophysical logging methods have been successfully applied in this industry to characterise argillaceous formations for geologic, hydrologic, and geomechanical properties. These technologies have been successfully applied in the repository field to quantify hydrologic properties and identify heterogeneities in argillaceous formations, pertinent to characterisation of candidate geologic repository sites.

I. Definition of Thin Beds

There is currently a concerted effort in certain segments of the oil and gas industry to better delineate very thin beds and vertical facies changes in argillaceous formations. This effort has resulted in the development and implementation of several new versions of logging (surveying of drilled well-bores) tools (Win et al, 1998). Their measurements address the following:

a) High-resolution electrical imaging of borehole wall and near-invaded zones. A particular tool of interest is the FMI* Fullbore Formation MicroImager tool, that is capable of distinguishing conductivity anomalies with an effective vertical resolution of 0.2 inches (0.5 cm) with an average depth of investigation of up to 4 inches (10 cm). Depending on borehole conditions, either the HALS* High Resolution Aximuthal Laterolog sonde or the AIT* Array Induction Imager tool will provide a resistivity image reflecting bedding, fluid content and invasion features with a vertical resolution down to 1 foot (30 cm). The Micro

* Trademark of Schlumberger

Cylindrically Focused Log (MCFL) identifies thin invasion features near the borehole down to 0.2 inches (0.5 cm).b) Basic petrophysical properties. The Accelerator Porosity Sonde provides an epithermal neutron porosity and the LDS* LithoDensity Sonde (gamma-gamma tool) provide high-resolution measurements of bulk density, photoelectric absorption and porosity. The LDS provides data with a vertical resolution of 9 inches (23 cm) with a depth of investigation of approximately 2.5 inches (6 cm). The APS provides data at 9 inch (23 cm) vertical resolution with a depth of penetration up to five inches (13 cm).

II. Geochemistry and Mineralogy

Characterising the geochemistry of an argillaceous formation is relevant to an understanding of the groundwater chemistry, retardation of potentially released radionuclides, reaction to heat, and mechanical stability. The geochemistry of an argillaceous formation can be estimated in-situ with a combination of the HNGS* Hostile Environment Natural Gamma Ray Spectrometry tool, the ECS* Elemental Capture Spectrometry sonde and the LDS Litho-Density tool. The HNGS passively measures the activities of naturally-occurring K, U and Th in the formation, and by itself, can assist in classifying clays. The ECS uses induced capture gamma ray spectroscopy to measure the concentration of specific elements within the formation: Si, Ca, Fe, S, Ti, Gd and calculated Al. Mg can be induced through the analysis by measuring the photoelectric effect (P_e) from the LithoDensity log. The HNGS, ECS, and LDS log results (supported by core chemistry) can be used to calculate the mineral volumes, including those for kaolinite, illite, smectites, feldspar, quartz, and calcite. Resolution of these tools is 12 inches (30 cm). The cation exchange capacity can also be derived from these measurements.

III. Structure and Geomechanics

The nature of fracturing and faulting in argillaceous rock will vary depending on its state of induration, compaction, and the plasticity of the formation. If fractures are present, it is important to provide a full mapping and characterisation to determine if they are natural or induced. It is also important to show with confidence where a formation does not contain fractures, or that fractures have been healed. High resolution measurements of natural and induced fractures and faults can be determined using various logging tools. The FMI tool, mentioned above, can provide a high-resolution image of the borehole wall, and using interactive software, it is possible to determine fracture density and classify and orient planar features picked from its image. The application of the FMI with a resistivity service can permit the estimation of fracture apertures as small as 10 µm. Another tool, the DSI* Dipole Shear Sonic Imager can induce and measure Stonely waveforms, that can be used to identify and determine 2-D orientations of fractures, with a depth of investigation much greater than the FMI (10m). Another acoustic tool, the UBI* Ultrasonic Borehole Imager, can be used to identify fractures at high vertical resolution and with complete 360 degree coverage of a borehole.

These same tools can be used to assess certain geomechanical properties of argillaceous formations. The DSI, in conjunction with a density log, provides a quantitative measure of the dynamic elastic moduli: Poisson’s ratio, Young’s, shear and bulk moduli. The UBI provides a circumferential acoustic caliper measurement that provides orientated images of borehole breakout, from which the

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regional stress system can be inferred. Also, both the FMI and UBI can be used to measure induced microfractures in the borehole wall (i.e., using inflatable packer tools) to infer the regional stresses around the borehole.

IV. Hydraulic properties

Recent advances in logging technology have provided mechanisms to better estimate hydraulic properties continuously in a borehole. Nuclear magnetic resonance (NMR) logging is an innovative technology used in the oil and gas industry to evaluate the economic potential of exploration and production wells, but which can also be used for hydrogeologic reconnaissance within low-permeability argillaceous formations (Strobel et al., 1998). Schlumberger’s version of this tool, the CMR* Combinable Magnetic Resonance tool, is designed to investigate the reaction of hydrogen nuclei in static and dynamic magnetic fields. Based on the number of hydrogen nuclei detected, and the signal decay rate (known as transverse relaxation time), important information about pore size distribution; and the state of water in the formation (i.e., clay bound, capillary bound, or free) can be determined. Distribution of relaxation times can also be converted to pore size distributions which in turn can be related to grain size distribution. Vertical resolution for this tool is 6 inches (15 cm).

Using the CMR porosity and relaxation times, a hydraulic conductivity for the borehole formation can also be determined. Recent work with the Boom Clay in Belgium indicates CMR-derived hydraulic conductivities compare favourably with core-derived hydraulic conductivities (A. Dierckx et al 1998, I. Wemaere 1998) when using a formula equivalent to the Kozeny-Carman equation. Porosity and permeability can also be estimated by using a similar methodology, using as input total porosity and estimates for the mineral fractions, especially clay minerals (derived from the ECS). The resolution of the ECS (every foot) is not as good as the CMR, however, the ECS can be run through open or cased hole, while the CMR is effective only in open hole.

V. Recommendations for borehole geophysical logging programme

For collection of detailed geologic, hydrologic, and geomechanical data for argillaceous formations, it is recommended to implement a logging programme capable of high-resolution in-situ interrogation. A recommended basic programme for logging is shown below. A calibration programme is recommended to accompany the logging programme, requiring comparison of logging data to core-derived measurements; or in some cases comparison to field tests (i.e., hydrologic testing). A well-planned calibration programme not only provides confidence in data from one borehole, but may also allow confidence to replace coring in other, adjacent boreholes.

Bedding definition:	LDS, FMI, resistivity tool
Geochemistry and Mineralogy:	ECS, HNGS
Structure and Geomechanics:	DSI, LDS, UBI, FMI, resistivity tool
Hydraulic Properties:	CMR, LDS, APS, DSI

A complete logging characterisation typically only requires one or two days at the wellsite. Most results are provided at the completion of the logging program.

VI. Future Work

Research on applying borehole geophysical logging tools to characterising low permeability, thin-bedded, sedimentary formations is ongoing. The Schlumberger-Doll Research Laboratory is currently in the process of further investigating the capabilities of CMR and ECS on clays, with the assistance of, and data from, NIRAS-ONDRAF[1] and SCK-CEN[2]. Participation by the Clay Club in the development and application of these, and other tools, to clay-rich formations is welcomed. Future repository-related borehole geophysical logging investigations may also provide opportunity to expand our knowledge on applications of these tools to different types of argillaceous formations.

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[1] Nationale Instelling voor Radioactief Afval en Verrijkte Splijtstoffen-Organisme National des Déchets Radioactifs et des Matières Fissiles Enrichies

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ANNEX 1

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