ARGILLICEOUS GEOLOGICAL BARRIERS, - MULTI-DISCIPLINARY VIEW

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ABSTRACT

The multi-disciplinary approach utilises the experience and methods of other geo-engineering fields (mining, tunnelling, waste's disposal, petroleum-engineering, subsurface water management) in relation with argilliceous barriers. One extend the information sources. One provides upgraded methods for site investigation/assessment. One allows to derive more generalised conclusions on the general barrier features and on the principles of assessment.

In spite of the strongly different rock-features of the argilliceous formations (e.g. weak, high porosity clay, versus hard, over-consolidated, low-porosity claystone) some essential barrier properties are common ones: low water conductivity, dominance of migration in pollution transfer, good adsorption properties, self-remediation of the confinement. The earthquakes and new faulting do not damage the essential barrier properties of deeply buried thick layers. The translation along faults modify the aquifer and barrier properties of the fault in the boundary areas. This modification can be neglected in thick barrier and aquifer formations.

The multidisciplinary overview have displayed some common principles for risk assessment e. g :

- --The integrated utilisation of site tests and analogous experience are proposed.
- --The risk assessment should consider all potential risks basing on pessimistic scenarios. During operation the human safety in the man made cavities should be ensured. During the post closure period the long term safety of inhabitants and the environment are the deterministic requirements.
- -- The hidrofracturing, is a frequent way failure in the zones of modified rock stress around human-made openings an around the abandoned zones. The conservative criterion against the hydrofracture $p_w < p_{sh} = \sigma_{min}$ serves as a multipurpose safety-criterion. One can be determined either directly from shut-in pressure measurements or from experience of similar geological/mining conditions. The fulfilling of this criterion
  - -- provides safety for caving,
  - -- preserves the virgin properties of the confinement against the migration/seepage of the pollutants,

-- serves as one of the safety criteria for sealing the repositories in argilliceous hostel rocks.

Special aspects for mining and tunnelling:

-- The clay breccia (e.g. in fault zone or re-consolidated broken clay in the goafs) has two-faced -feature: In one side it is low conductive as an intact clay. In other side the quick loading causes quick decreasing its inner friction due to undrained stress. Displacements along clay breccia-filled faults, clay inflows often occurred.

-- The piping in open fissures or in hydrofracture-caused channels is a site specific barrier-aquifer interaction. Site- and/or analogous experience need for risk-assessment.. The piping may allow unlimited inflow from large aquifers (lakes, sea, flooded old workings). This risk must be excluded by proper barrier thickness/stress.

Some specific conclusion for mined disposal of hazardous (nuclear and toxic) wastes are also introduced:

-- The medium-hard and hard argilliceous host rocks promise appropriate environment for deep repositories.

-- There are no reasonable safety arguments against the potential suitability of argilliceous formations for mined disposal of toxic an-organic wastes. The retrievability of the buried wastes can also be preserved.

MULTI-DISCIPLINATY VIEW IN GEOSCIENCES

However many specific fields of the geo-sciences & geo-engineering have its special goals, and views, the virgin- and human-induced processes of the Earth are governed by the same laws. The Nature as a "black-box" system provides information on their features, on its governing laws in forms of responses to different natural and human-induced impacts. The responses of the same (or similar) natural environment due to different natural- or human-induced impacts provide useful information for many site and task specific studies.

Ancient origin - actual efforts

The view of the nature as a whole originated in the Ancient Age. However the diversification of the sciences, and the practical applications divided the specialists, the greatest scientists of the modern nuclear- and solar physics were/are searching the general laws of the Universe.

The universities represented the institutional-spiritual continuity of multi-disciplinary view from the Ancient age, during Medieval Age up to now. Many "multi-disciplinary disciplines" (e.g. system research) and the applications of same mathematical methods/models (game-theory, catastrophe-theory, neural-network modelling) in many disciplines originated in the modern academic research.

Special geographical, economic, political, cultural conditions ("high density" of educated heads in a small developed area where everybody know each others, open society, continuous communication channels with the World) provided/provide good climate for multi disciplinary view (e.g. the Ancient Athens, the Medieval Venice, the area of Belgium and Netherlands during the last five centuries, and actually Slovenia as well.)

The needs of the different fields of modern geo-engineering also formed many institutional and spontaneous ways for exchange of information and for multi disciplinary team-work:

--multi-disciplinary task-force commissions, working teams (e.g. for managing geo-accidents),

--long-term giant projects (e.g. for nuclear waste's disposal)

--specialised contractors, consultants dealing in more fields of geo-engineering,

--professionals moving from the descending professional fields (e.g. mining) to other fields,

The Clay Club of OECD-NEA is focusing to the argilliceous barriers for radwaste's disposal.

The INTERNET and other new tools/information sources multiply and extend the potential information sources and communication channels, even for home PC users.

The author was/is an in-door/out-door member of almost all actual types of the multi disciplinary teamwork. However the author is also learning to apply the INTERNET, this paper summarises his personal experience on multi-disciplinary approach from the "Pre-INTERNET Age".

Multi-disciplinary approach in geo-engineering, and benefits

The site measurements produce samples on the features of the geological environment, and short-time human induced impacts (tests) into a limited area. This information is usually insufficient for forecasting long-term processes in larger area. Experience of similar geological sites under similar human induced impacts are also utilised. Some features cannot be tested by boreholes. (e.g. The study on the post failure features requires the experience from similar sites under similar impacts.)

The multi-disciplinary approach is an extension of the utilisation of analogies in two respects:

1. *Other human-induced processes* and natural impacts into the similar geological environment are also considered/analysed for utilisation. The extended information bases (with quite small additional costs) provides two types of benefits. Expensive site tests can be substituted partly by more reliable direct experience. This approach cut costs/time of site studies. More generalised conclusions can be derived, that are valid for more fields.
2. *The similarity between the tasks* allow *to utilise the methods from other geo-engineering areas*. One provides also two types of benefits.. The selection of appropriate testing-, risk-assessment methods for the actual project is based on more information. Ones improve the reliability of the actual site-characterisation. The larger information bases allow to derive generalised conclusions on principles for site assessment and on the process control.

This multi-disciplinary approach should integrate non homogenous information of different fields. This task is quite similar to the puzzle-in game.

Geo-engineering areas as information sources

This summary is a *personal view* on the existing practice, on the further possibilities with special regard to the *argilliceous barriers*. This is based on the personal experience/practice of the author.

The geological history is the most important information source both on the actual properties of the rocks both on their responses to different quick and long term impacts (consolidation, erosion, folding, tectonic displacement fracturing due to over-pressurised fluids, heat impact, chemical impacts). The status of the geological formations without human induced impacts (called: virgin conditions) provide essential information on the long term barrier properties, on longevity of sealing, Some virgin features and emissions can be studied on the surface, More other features should be studied inside the rock under human impacted conditions (boring, mining, tunnelling).

The mining was the first mayor human impact inside the earth crush. Quite different geological environments have been tested for decades/centuries long period. This experience displays very similar features of the similar geological formations at different continents. These similarities allowed to implement empirically based risk-assessment methods far away from its birthplace (e.g. the evaluation methods of the British land subsidence engineering). The long life mining openings tested the long term stability. The abandonment of mineral extraction cavities provoked large displacements/failures in the overburden rocks. The failure processes can be studied under different rock/water/mining conditions. The mining and its abandonment have drained underground and surface aquifers at a large area. After the abandonment the rebuilding of the aquifer pressure can be studied in a human impacted geological environment. This drainage and rebuilding as a large scale & long term pumping rebuilding test provided information both on aquifer and barrier properties (clay, salt, vulcanite, granites). The barrier properties are tested under strong displacements and under earthquake impacts as well. *There are a lot of information on the mining/abandonment induced response on the geological environment, however the overwhelming volume of the historic data relate only to qualitative features. Quantitative parameters, time-plots are also available on the last decades.* The number hydrodynamic test results inflow-data provides a lot of analogous information on aquifer properties for water supply and for random estimation of fissured barriers. The next chapters refer to some case examples on utilising the experience of mine water engineering in other geo engineering areas [e.g. Kesserü, 1991, 1993, 1995, 1997: Kesserü-Majoros 1996]. The abandonment of mining also formed fluid/solid waste repositories in underground and waste relicts (e.g. heap leach piles) on the surface. These are also large scale & long term tests on impacts of waste's, however the in-place stabilisation of giant heap leach and mine debris piles require different approach, than the industrial wastes' disposal [Hutchison-Ellison 1992; Caldwell 1993; Lendvai-Csővári-Csicsák 1996]. The mineral processing has been the origin of many waste's treatment technologies.

The tunnelling and constructing long-life underground spaces select the most suitable rock condition for these spaces. One do not provide many information on rock failure and on extreme water drainage. The most frequent lining method (NAT) requires to develop and apply up to date test methods for controlling the rock deformation. This practice provides in-situ rock-deformation parameters along the whole length of the tunnel. The tunnelling have provided important information on potential barrier rocks for radwaste's disposal. The Scandinavian tunnelling and space technologies in granite (including TBM-bored tunnels) provided essential information on barrier properties of the granite. [Morfeld 1992]. The Grimsel international test site is a task specific bypass of the Grimsel granite tunnel [NAGRA 1996]. Radwaste-oriented clay studies were realised at some Italian tunnels [Gera, Chiatone 1990]. International clay test site is planned in Mt. Terri motorway tunnel (CH)[Neerdael-Wemare-Thury-Gautschi 1996].

The petroleum engineering represents the *high-tech* in geophysical testing, boring, well-testing/stimulation and in process simulation in reservoirs. Ones spread out to other geo-engineering areas. The geo-chemical and molecular interactions between the reservoir rock and the formation fluids are deeply studied and utilised for production. The existence of pressurised formation-liquids (hydrocarbons, carbon dioxide etc.) inside the geological formations under many geological impacts (earthquake, faulting etc.) provide direct information on the long term barrier properties of different caprock-formations. The geo-chemical and barrier experience have not been transferred widely into other geo-engineering fields. *The overwhelming part of measured, observed data on the features and responses of reservoirs and barriers are in closed files.*

The underground water resource's engineering has been the birthplace of geo-hydraulics from the first application of the Darcy's Law to the random approach in the geo-hydraulics. The quantitative (engineering) view of hydrogeology has been based both on traditional geological approach of hydrogeology and on quantitative models/measurements of geo-hydraulics/surface-hydrology [e.g. Todd 1959, 1980]. The drainage of underground aquifers (for water supply, for mining), and the hydrocarbon-production also mobilise the pore fluids of the argilliceous barriers. This process were/are studied for estimating the land subsidence and/or fluid resources., however it is an important marker of seepage in very low conductive argilliceous barriers.

The final disposal of dangerous wastes in shallow and mined/bored geological repositories is a valuable information source, however one represent two types of problem approach.

The actual practice and policy of toxic wastes accept only the surface disposal facilities on clay outcrops. Engineered barriers; (geo-materials, geo-membranes, and concrete lining are also applied). Bottom-lateral drains for collecting and treatment of leakage are also serving as standby observation and barrier. The site selection focus to the water conductivity/migration/adsorption properties of the bottom clay and of the engineered barriers. A lot of site measurements are available on the water conductivity of clays and on its migration/adsorption/ion-exchange properties in relation with different toxic elements and with different geo-chemical environment, However the results relate to shallow conditions (low rock stress/water-pressure), many results of these studies can also be transposed on behalf of studying deeper buried similar clays as well.

The siting for final disposal of nuclear waste's also focus to deeper barrier formations, because the mined/bored deep disposal facilities are accepted for the long lived high level wastes. Some West European countries prefer the deep disposal for short lived and medium wastes as well. This field represents the actual "high tech" of geo engineering. Multi disciplinary international teams operate in the frame of giant projects. The idea on final disposal in geological formations are based on geological analogies. The international consensus on the potential the hostel rock-types (salt, granite, vulcanite-tuffs, argilliceous rocks) is based on mining and tunnelling experience. In the first period of studies the most developed methods and top professionals of other geo-engineering areas has been collected. Almost all fields of geo-sciences contribute the studies. *This field have already produced important results for other geo-engineering areas as well:*

- The assessment of the hostel rocks for geologically long periods required to study geological analogies (e.g. on seepage, on nuclide migration, on thermal and on geo-chemical impacts etc.)
- The potential hostel rock types are studied in underground test sites called underground laboratories (URL). However the studied area is quite small in comparison with mined areas and tunnel lines the studies provide essential information in more aspects:
  - -- The programs of investigations are excellent case examples of multi-disciplinary approach and of multi-disciplinary teamwork.
  - -- The QA/QC is a deeply implemented in the practice.
  - -- "High-tech" testing methods are applied, that ones provide data of high accuracy. In situ parameters and information on very low conductive rocks are available (e.g. on migration, on seepage) that ones are not available from other geo-engineering activities.
- This field has the most developed ethic & professional view, and methodology for risk assessment/process control.
  - -- According to the ethic principles of the OECD-NEA commission we must not leave uncontrolled situation and one way decision routes for the next generation.
  - -- The risk assessment must consider the pessimistic scenarios, "all site and waste-specific aspects, the longevity of engineered barriers, during an extreme long period (e.g. 1 million years [Cantion 1996] for high level, long lived waste's disposal).

BARRIER FEATURES OF THE ARGILLICEOUS GEOLOGICAL FORMATIONS

The multi-disciplinary view of geological barriers is based on the principle and practice summarised in the last chapter. The compact presentation refers to the applications in all important geo-engineering fields. This approach allows to point out some common- and field-specific principles.

Utilisation of geological barriers and relating requirements

The barrier features of geological formations are important for more geo-engineering aspects:

-- safety of human life and activity (mining/tunnelling) against aquifers and surface water bodies,

-- impact of mining/tunnelling and of abandonment into aquifers and surface water bodies,

-- water resources' management (resource's estimation, risk of pollution etc.),

-- assessment on pollution of the underground environment due to surface human activities,

--.disposal of fluid/solid wastes in geological formations.

The requirements on the barrier features and the longevity depend on the task and on the conditions.

The safety of human life/health and of mining/tunnelling operations require prevention against unforeseen water induced events, and to limit the water inflows according to the sensitivity of the technology and of the capability of water/sediment delivery-pumping system. This requirement means the safety against the failure of the barrier *during the operational period.* [Kesserü-Schmieder and others 1974, Kesserü 1996].

The safety of the environment (including subsurface aquifers, and surface water bodies) against surface/subsurface human impacts require long term barrier properties. The barrier should prevent against the failure of the barrier, and one should limit the pollutant-migration within the permitted limit for properly long period.

The safety of final disposal of wastes in geological formations requires to fulfil the exposure-limits on behalf of the safety of many generations of human population. The integrated effects of the waste form & encapsulation, the engineered & geological barriers can be taken into account within the life-time of the engineered barrier [IAEA 1995] For geologically long period the geological barrier is the only prevention. The assessment of the geological barrier should evaluate the pollutant transfer in the intact barrier and the safety against the failure of the geological barrier due to human and geological impacts for a geologically long period [IAEA 1995 Morfeld-Langer 1989]. If the storage cavities situate inside the barrier rock the stability of the cavities during the operational period, and the long term stability of the filled cavities (waste's retrievability) are also important aspects.

The estimation of the underground water resources need to evaluate the surrounding rocks as barriers against the hydraulic connections with the surface and between the aquifers. The intact conductivity/migration properties have essential importance with special reference to faults.

The overview of the requirements allows some conclusion on the essential barrier properties:

--The necessary information on barrier features/processes *are determined by the requirements.*

--*The mayor part of the requirements are non task specific ones.* The long term barrier properties are important ones in waste disposal and for the long term environmental safety at human impacted (e.g. abandoned mining, industrial areas), however the long term impacts of the short term human activity into the barrier properties should also be specified/considered in the post closure period..

--*The risks for the environment at the abandoned mining/industrial areas due to their surface and underground relicts are often similar ones* (e.g. salt, heavy metal, acid, organic pollutants and their migration in the barriers and aquifers.*). The similarities of the risks and of the tasks allow and require the multi-disciplinary approach..*

Argilliceous formations as "less suitable" objects for similarity based studies

The collective noun: "argilliceous" marks clayey sedimentary rocks of quite different actual *properties (clay, marl,, siltstone, claystone, shale etc.)*, however their primary features have been similar:

The dominant part of the clastic sediment is/has been very small size (<2 μm) hydrous aluminium or magnesium silicates, that ones settled in water. This clay matrix may also includes larger (silt/sand) size mineral (e.g. silica) particles, relicts of micro-fauna and micro-flora etc. [Gillot 1987].

After settling the transported particles and after their primary consolidation the geological processes (diagenesis, loading/de-loading, faulting, folding, weathering, thermal impacts, fissure-filling, metamorphic impacts) transform the original properties (porosity, mineral content, structure, etc.). Zones of special properties were/are also formed (faults, fissures, intrusions/fillings, layered structure etc.) inside, and weathered zone on its surface. These time- and site-dependent processes produced wide variety of argilliceous formations [Gillot 1987, Goodman 1989].

The similarity based considerations, seems to be more uncertain in comparison with other barrier types (e.g. salt, granite). The next subchapters of the paper demonstrate, that some essential barrier properties are similar ones at all kinds of argilliceous formations. All types of argilliceous rocks are very good barriers even for geologically long period.

Essential barrier properties under virgin conditions

A/ Information sources on intact rock properties:

The information *refer to many types of argilliceous formations*, (weak clays, medium claystone, extra-hard (rigid) claystone, marl, shale including folded, faulted structures. Ones originate from:

-- extra accuracy well tests and migration tests in URLs (and in surface based holes),
-- the responses of argilliceous layers in the close vicinity of the drained aquifers,
-- the observation in mine openings and in tunnels under such condition, where the barrier thickness exceed the zone of excavation response around the openings.

B/ Qualitative picture

The buried, low-consolidated weak clays are high-porosity, low-conductive rocks. Ones cannot preserve open fissures faults. The essential inhomogenity/anisotropy of the barrier-properties caused by its stratigraphical features. These rocks are known form URL in Mol, from some reference study sites (in Italy) from mining experience (e.g. Central Europe, China,), from tunnelling (subways).

The clayey shale represents hard fissured rocks of layered structure. This rock type known from mining, tunnelling and from reference sites for radwaste's disposal.

In between the two extreme types many sites of compact, consolidated/over-consolidated medium-hard/hard claystone, marl are known from mining, tunnelling and from borehole exploration & URL-studies in potential hostel formations for geological disposal of radwastes. The single claystone URL operates in Hungary below 1100 m of the surface. The rock is hard, over consolidated low porosity lacoustric clayey siltstone-mudstone of high albite content. The accurate borehole studies in Switzerland relate to Vanginian marl (Wellenberg) and Opalinus clay (Jura-mountains).

The faults are usually filled with in-place milled clayey materials and (by calcite at some sites). Large faulted zones that ones contain hard rock pieces inside of in-place milled fine grained materials have been also intersected. In the claystone closed tensile cracks have been observed in the vicinity of sheared fault zones [e.g. Csicsák 1996] Similar tensile cracks can be observed in the vicinity of all sheared zones of hard rocks. (The analyses of laboratory-shear tests also displayed tensile stress zones near the sheared surface [e.g. Vutukuri 1974])

***C/ Water conductivity** (,observations, tests):*

In weak and medium hard argilliceous formations the mine openings and tunnels *looks dry* even at fissured, faulted, folded zones[Kesserü 1991]. (The visual observations cannot detect very low seepage, that may evaporate from the rock wall.) According to the observations in the Hungarian claystone URL, small droppings occur at some tensile cracks, however a part of the them are not permanent ones [Csicsák 1996].

Indirect evidences are available, that gradient-induced seepage exists even in very low conductive clays, in the vicinity of the drained sand aquifers, however this seepage must be very low. The case example relates to a Pliocene lignite-bearing sand/clay formation. The drained sand aquifers are inter-bedded by (1-20m thick) clay layers. The dominant part of land subsidence originate from clays [Kesserü 1971]. The water head time plots and the land subsidence time-plots and their time derivative curves are presented in [Jambrich 1995]. *Three years delay between the maximums of derivative-curves demonstrate the existence of seepage in clays and the dominant role of the compaction in clays in causing land subsidence.*

The seepage features depend on the rock properties:

The high porosity clays operate as anisotropic, matrix-porosity systems. Under high hydraulic gradient, the Darcy's law is valid. [Canniére-Put-Neerdael 1994].

The shale is regarded as fissured system. The shale at Reskajaege Quarry (U.K) served as reference test site for hydrodynamic testing of fissured, low-permeable hostel rocks.

The seepage feature of medium-hard mudstone/marl formations pores and fissures are to be considered. The role of fissures depend on the rock properties and on rock stress conditions. In cases of plastic deformation of the fissure-surfaces, the fissure conductivity can be neglected [Kesserü 1985]. The tensile cracks in the hard beds of the claystone (around the Hungarian URL remained open). The 100-150 days long pressure build-up curves [Csicsák 1996] refer to cylindrical flow pattern.

The results of the *sensitive permeability measurements* varied among 10^{-9} -10^{-12} m/s. [Canniére-Put-Neerdael 1994; Csicsák 1996] Differences between the vertical and parallel direction to layering have also been detected at Mol site. Under hard rock conditions the tensile cracks at the vicinity of faults produced higher permeability values: in magnitude of 10^{-8} m/s [Lendvai Csõvári-Csicsák 1996].

The long-term pore pressure measurements have detected a high water pressure anomaly inside the marl barrier, that has been interpreted as a relict of the pore water pressure *due to the glacial cover in Pleistocene.* [Vinard-Blümlig 1994]. This observation demonstrate the low permeability of the folded marl formation.

The observations and test-results on water seepage allow one non-site specific conclusion with comments.

Wide variety of argilliceous formations (including folded structures, sheared fault zones) display very low conductivity, however direct evidences are available, that slow water seepage does exist. This feature seems to be a general feature of all argilliceous formations. The existence of pressurised hydrocarbon deposits below folded argilliceous caprock formations supports this statement.

The low water conductivity of the sheared faults inside the medium hard and hard argilliceous formation surely is caused by the in-place milled clayey fillings [Kesserü-Majoros 1996]. The strongly impacted large fault zones contain even larger hard rock pieces inside the fine grained milled clayey matrix. This is similar to clay filled conglomerates, that are usually low conductive ones [Hámos-Máthé-Majoros 1996]. These zones looks also dry [Csicsák 1996]

The argilliceous formations impacts the permeability of the nearest aquifers as well:

-- The clayey material from the loose argilliceous cover seals partly the fissured bottom aquifer (e.g. paleokarst). The shallow areas of other covered fissured rocks (granite) may also be impacted. This impact may be important both for aquifer- and barrier-uses of fissured rocks.
-- Inside the sandy-clayey formations the rock-particle transfer along the sheared zones of the faults produces a mixed feature of the shear zones. These mixed fault zones are less conductive inside the sandy aquifers This is important in two practical aspects: These fault-zones forms barriers, however the displacement along fault is less, than the aquifer-thickness. The modified granulometric feature of these fault zones strongly increased the risk due to silt inflow [Kesserü 1965; Szepessy 1982].

B/ Migration:

However the low conductivity of many argilliceous faulted, or folded formation seems to be a general feature, the pollutant can also be transferred by migration of the ions in the water, that may exceeds the speed of water seepage. Some geological information and site test are available:

The geological analogies on the migration of nuclides through argilliceous barriers are studied in the frame of "analogous project" for geological disposal of radwastes at Cigar Lake (CDN) and at Oklo open pit (Gabon). Both observation relate to Palaeozoic barriers. The migration of uranium oxide at and the plutonium of natural reactors inside the Oklo enriched uranium bearing formation were quite small.

Near the surface many migration/percolation tests have been made with different toxic ions [e.g. Bertocci-Focardi and others 1993]. These tests have demonstrated the good adsorption/ion exchange properties of clays for many toxic elements and nuclides under proper pH-environment, however the adsorption/ion exchange capability of the barrier is not unlimited.

The single deep long-term site test on migration of nuclides is actually on way in the national/international clay URL in Mol (Belgium). The test-results have demonstrated, that the molecule-migration is the dominant way of nuclide's transfer [Put-De Preter 1996].

C/ Virgin rock stress and pore water pressure

The rock stress and the pore fluid pressure belong to the barrier features for more reasons:

- The water conducting features depend on the effective rock stress, this dependence is deterministic for unconsolidated clays [Gillot 1987] and for the fissure-conductivity in weak and medium hard clays [Kesserü 1985].
- The stability of openings (tunnels waste storage chambers) and the not-protecting zones around the openings depend on the rock properties and on the stress & fluid pressure conditions. The pore fluid pressure can only be neglected in very low porosity (claystone, marl) formations. The fluid pressure in fissures is deterministic for all conditions.

The measurement-results originate from oil fields, from URLs and from mines in grained sedimentary rock environment:

The virgin rock stress field of the *young sedimentary basins* are usually quasi-homogenous. The ratio of vertical/horizontal stress components vary among 1,2-0,8 [Grauls 1996; De Bruyn 1995]. The pore fluid pressure measurements usually relate to the reservoir rocks. Linear increasing trends are detected. [Gao-Ding and others 1996], however between the Pliocene and Miocene series of the Pannonian Basin pressure jumps were often detected by oil wells. Under virgin conditions the pore pressure of the argilliceous interbeddings are assumed as quasi-equal with the reservoir pressures.

Characteristic horizontal stress anisotropies has been detected in horizontal directions inside the Carboniferous coal bearing (argilliceous-aleurolite-sandstone) series in UK, USA, in Australia and at Tokyo bay in sandstone-argilliceous series [Oki-Higara 1988], however jumps of stress directions and values have not been detected. The observations, measurements at the Hungarian claystone URL (below 1100 m the surface) characteristic differences between the vertical and horizontal component have not been detected [Kovács 1996]. The quasi homogeneous virgin stress field can be interpreted by two assumptions: The 600-800 m thick claystone formation is a part of a Mesozoic isle, that one is surrounded by deep Neogene sedimentary basins. That basins surely means homogenous lateral boundary stresses. The clay breccia of the main faults has less friction angle than the hostel rock. The translations along these faults may allow to -decrease/eliminate the deviator stress due to lateral loading. These conditions differ from the Carboniferous coal bearing formations, where more hundred meter thick clayey formations do not situate.

D/ Impacts of local paleo failures

The argilliceous caprocks of the aquifers often serves as geological barriers either against the inflows from the aquifer or against the human induced pollution of the aquifer from the surface some special paleo-failures may had damaged the caprock. The geologically long re-consolidation and diagenesis either remedied the "wounds", or ones remained up to now. Each type of damages require site and task specific studies. Some types of local paleo failures are listed here:

-- The paleo-collapse of karstic caves in the bedrock caused sinkholes in the caprock. The considerations on the actual barrier features can be based on modern sinkhole observations and on the similarities with undermined barriers after a long reconsolidating. The operations over the karstified bedrock sometimes intersected paleo-sinkholes. The impacts of cave collapses below the thick, weak argilliceous barriers depend on the thickness of the barrier. The risk assessment can also utilise the similarity to the undermining. [Kesserü 1997]. The impact of a paleo-collapse below a caprock that one were hard even at the time of the collapse is quite uncertain.

-- According to the modern observations: the sedimentation cannot seal the giant springs, or ones will be sealed later. The former channels remained as sand filled shafts intersecting partly/fully the barrier layer. These types of paleo-wounds usually remained up to now. The risk assessment need paleo-hydrogeological considerations.

-- The relicts of paleo-hydrofractures in the caprocks of paleo-sandy aquifers are sand filled hydrofractures, intersecting partly/fully the argilliceous caprocks. [Siegentahler 1987]. The should also be regarded as actual local damages.

BARRIER-EVALUATION AND PROCESS CONTROL

The barrier evaluation and process control in the barrier is an inserted item of the complex risk assessment and process control. The barrier-expert should be a team-member.

The human impacts have to be considered in all cases of risk assessment. The risks due to geological impacts in the future are to be considered under special circumstances (e.g. sinkhole risk) or for special tasks (e.g. final disposal of long lived wastes inside the barrier formation)

Human-induced impacts

General considerations:

The analysing the interaction of the barrier and the forming/abandoning of man-made cavities requires general and task-specific considerations.

The operational and the post closure status should be analysed for all cases. The abandonment impact is usually stronger. During the operational period the human and operational safety inside the cavities is the dominating criterion. In the post closure status the long term safety of the human being and of the natural environment provide the essential requirements for barrier-assessment.

The interaction-analyses of the geological environment and the man-made cavities should pay special attention to the water inside and outside the barrier formation. Under specified circumstances the presence of the water outside the barrier can cause more types of dramatic barrier-failures.

The failures intersecting the barrier eliminate/damage the confinement against pollutant migration, however its capability to moderate the water through-flow may remain acceptable for the safety of the human live and of the operations. The essential ways of barrier-failures due to forming and abandonment of man-made cavities are as follows:

-- *Forming open fissures* and subsequent piping, if the zone of open fissures intersect the barrier. The extension of the zone of fissures depends on the rock conditions and on the caving/lining and abandonment conditions/technologies. The calculations on the extension of open fissures should be supported by site measurements. *The zone of open fissures do not provides any barrier effect.*

-- *Spontaneous hydro-fracturing* (re-opening existing joints faults bedding-planes) occur inside the zone of modified rock stress if the water-pressure exceeds the "fissure reopening pressure" [Kesserü 1984, 1991]. The subsequent piping may enlarge the hydrofrac-channels. In the overwhelming part of the practical cases, the risk due to hydrofracturing is the deterministic one, because the zone of the modified stress is more extended than the zone of open fissures. The conservative safety criterion substitutes the "fissure reopening pressure" with the "shut in pressure": $p_w < p_{sh} = \sigma_{min}$ One is smaller value, and one can be measured directly in boreholes. Under virgin fluid-pressure & rock-stress conditions (that ones represent a quasi-equilibrium state of earth), the hydrofracture-risk-does not exist. This simple stress criterion can be discovered behind the site- and task-specific empirical criteria on safe thickness of the mining impacted argilliceous/aleurolite geological barriers [Kesserü 1984 1991, 1995]. These empirical criteria can also be utilised under appropriate circumstances. This way of failure have been detected at more geo-engineering fields as well [Sherard 1987, Siegentahler 1987, Kogan 1987]. If the confinement should prevent against the pollutant transfer, the risk of piping must be excluded. If the barrier serves only for limiting the water inflow, the final stage of piping and the aquifer properties should also be considered.

-- The result of piping depend on the barrier and aquifer properties. The risk of piping and the final stage of piping cannot be determined by site-borehole-tests. Experience are necessary from sites under similar conditions (of barrier and aquifer properties and the man made impacts) [Kesserü-Schmieder and others 1974]:
  - Under hard/medium-hard rock conditions the piping of open/reopened joints/bedding planes usually are strongly limited The barrier moderates the inflow.
  - The loose zone of fault-fillings inside the hard, medium hard rocks are usually impacted by piping, however, the hard boundaries limits the piping. (The site-specific averaged value of the channels of piping was equivalent with 4 cm hole diameter in the Eocene bottom barrier of Tatabánya-Dorog coal-field against the karstified limestone)
  - Inside the weak clay barriers two impacts may cause unlimited piping; the de-flocculation of Na-montmorillonite [Sherard 1975] and the erosion due to the solids from loose sandy aquifer [Kesserü-Schmieder and others 1974].

  The risk of unlimited piping is allowed only under very exceptional cases (e.g. the conductivity of the aquifer is low)

The secondary risks are caused by the water-infiltration/intrusion inside the human-impacted zone of the barrier: [Kesserü 1985, 1995].

- The pressurised water inside the reopened joints, bedding planes modify the rock stress conditions, that one may cause secondary rock failure and lining failure as well. The closing of water filled bed-separation zones may causes similar impacts [Kesserü 1991, 1995].
- The pressurised water inside the joint system of the modified rock stress zone may causes quick decreasing the inner friction of the jointed rock zone. Wet clay intrusions occurred in roadways [Kesserü 1985].
- The quick loading into the jointed, water-filled clay causes undrained stress conditions, (quick wet clay inflows have often occurred). [Kesserü 1985].

Geological risks

The intact and human-impacted barriers may also be impacted by geological impacts as well. The essential risks are discussed here:

Earthquakes

The direct mining experience on the safe thickness of the argilliceous-aleurolite bottom barriers from quiet and from earthquake impacted regions did not display any difference [Kesserü 1993]. The impacts of the earthquake into the shallow barriers are well known (changes of location and flow rate of springs, open fissures on the surface etc.). These differences can be derived from the safety criterion against hidrofracturing. Under the depth of mining and under quasi-virgin stress conditions 5-10 m changes of water head do not impact the safe ratio of $p_w < p_{sh} = \sigma_{min.}$ In shallow depth the same water level change can cause hydrofractures [Kesserü 1993].

New faulting

Actual low and quick faulting activities have been observed at many areas of the Globe. The rate of the quick faulting is in the magnitude of cm-meter/month. Direct experience on the impacts of forming new faults and on new translation along old faults inside the argilliceous barriers are not available. A lot of experience are available on similar type and rate of displacements (along faults and on forming new sheared displacements) inside the bottom barriers of surface water bodies and underground aquifers due to undermining. In spite of the strong displacements the appropriate thickness of the faulted, shear-failure-impacted overburden barrier prevents against any visually detectable through-flow from the undermined water bodies (lakes, sea etc.). Under appropriate stress conditions the faults, and the new sheared failures remain closed even in harder argilliceous formations. This is due to the in-place milled clayey filling of the faults. Under virgin rock stress conditions of the thick deeply-buried argilliceous barriers the new displacements along the old faults and the sheared new displacements are assumed to produce closed features [Kesserü 1993, 1995].

Collapses of natural caves below the barrier

The risk of further collapses of natural (e.g. karstic) caves are also potential risk sources even for the overburden barrier and for the infrastructure on the surface. The damages of the overburden barrier may open new pathways for pollution from the surface. If the realistic estimations are available on the forms/sizes of the cavities, "the analogy of undermining" provides bases for risk assessment both on the confinement and on surface's subsidence [Kesserü 1997].

Task-specific aspects

The specific aspects originates from the field/task specific requirements (summarised before) on the capability of the barrier and from the special features of the caving-abandonment responses.

Tunnelling and long-life mine drifts/shafts

The operational status of tunnels/long-life mine drifts, means limited (0,3-5 m) fissured zone around the openings, and amore larger zone (5-20 m) of modified rock stress conditions. (In this zone closed fissures/joints and deformations without fissures occur.)

The during the operational period the barrier should prevent against uncontrolled inflows

-- In cases of unlimited piping-risk the barrier should be sized against hydrofracturing.
-- If direct or analogous experience are available on the limits of piping, the necessary barrier conditions can be determined on the bases of the allowable water inflow.

The post-closure (abandoned) status of the tunnels/drifts usually means flooded conditions. In one side the water pressure support the cavities. In other hand the water may modify the rock properties. Site-specific analyses are required. The low water pressure or the water pressure drop often caused cave collapses. Both stable and collapsed caves should be regarded as potential/existing polluted water stores.

Chambers/repositories for final disposal of wastes.

The chambers for final disposal of wastes are sized/lined for long term stability.. The safety during the pre-closure state is usually not questionable.

The long-term safety for the post closure status require appropriate virgin barrier, appropriate seals seal at the human-impacted zones and safety against geological (earthquake faulting) risks.

-- The appropriate thickness of virgin barrier also provides appropriate safety against earthquake and faulting risk as discussed before
-- The repository-seal should perform equivalent properties with the virgin barrier. In argilliceous hostel rocks the shaft/tunnel/chamber seals need watertight concrete bulkheads, Appropriate rock stress conditions should also be performed in the excavation-impacted zone around the bulkhead, that prevents against hydrofracturing. The mining experience (including the author's method [Kesserü 1991) may provide a good starting position for developing long life shaft/access-chamber seals in argilliceous environment.

Forming and abandonment of mineral extraction cavities

However a wide variety of methods are applied for (partial/total) extraction and for its abandonment (with or without back-filling), the site-specific and general barrier evaluation methods are available for almost all cases. The general method is based on the safety-criterion against hidrofracture [Kesserü 1995].

The abandonment of the large extraction cavities usually causes more extended and more stronger impacts into the barrier, than the supported part of the extraction cavities. After the abandonment a re-consolidation process starts, that one restore partly the confinement properties of the argilliceous barriers.

For the operational-period the maximal extension of the changed zone should be taken into account for the assessment of human safety. The risk assessment should consider the hydrofracture risk and the secondary risks as well [Kesserü 1985, 1995].

For the post closure period the safety of the environment should be ensured. The long-term confinement against the pollution from the flooded mining cavities is the deterministic requirement. The assessment can take into account the decreased extension of the modified zone. Only that zones of the barrier can produce appropriate confinement against the pollutant-migration where open fissures and the hydrofraturing risk do not exist.

CONCLUSIONS

The multi-disciplinary approach utilises the experience and methods of other geo-engineering fields (mining, tunnelling, waste's disposal, petroleum-engineering, subsurface water management) in relation with argilliceous barriers. One extend the information sources. One provides upgraded methods for site investigation/assessment. One allows to derive more generalised conclusions on the general barrier features and on the principles of assessment.

In spite of the strongly different rock-features of the argilliceous formations (e.g. weak high porosity clay, versus hard over-consolidated low-porosity claystone) some essential barrier properties are common ones: low water conductivity, dominance of migration in pollution transfer, good adsorption properties, self-remediation of the confinement. The earthquakes and new faulting do not damage the essential barrier properties of deeply buried thick layers. The translation along faults modify the aquifer and barrier properties of the fault in the boundary areas. This modification can be neglected in thick barrier and aquifer formations.

The multidisciplinary overview have displayed some common principles for risk assessment e. g :

--The integrated utilisation of site tests and analogous experience are proposed.

--The risk assessment should consider all potential risks basing on pessimistic scenarios. During the operational period the human safety in the man made cavities should be ensured. During the post-closure period the long term human/environmental safety are the deterministic requirements.

-- The hidrofracturing, is a frequent way failure in the zones of modified rock stress around human-made openings/abandonments. The conservative multipurpose criterion against the hydhydofacture $p_w < p_{sh} = \sigma_{min}$ can be determined either directly from shut-in pressure measurements or from experience of similar geological/mining conditions. The fulfilling of this stress criterion

-- provides safety for caving,

-- preserves the virgin migration/seepage of the confinement against pollutants,

-- serves as one of the safety criteria for sealing the repositories in argilliceous hostel rocks.

Special aspects for mining and tunnelling:

-- The clay breccia (e.g. in fault zone or re-consolidated broken clay in the goafs) has two-faced -feature: In one side it is low conductive as an intact clay. In other side the quick loading causes quick decreasing its inner friction due to undrained stress. Displacements along clay breccia-filled faults, and clay inflows often occurred.

-- The piping in open fissures or in hydrofracture-caused channels is a site specific barrier-aquifer interaction. Site- and/or analogous experience need for risk-assessment.. The piping may allow unlimited inflow from large aquifers (lakes, sea, flooded old workings). This risk must be excluded by proper barrier thickness/stress.

Specific conclusion for mined disposal of hazardous (nuclear and toxic) wastes:

-- The medium-hard and hard argilliceous host rocks promise appropriate environment for deep repositories.

-- There are no reasonable safety arguments against the potential suitability of argilliceous formations for mined disposal of toxic an-organic wastes. The retrievability of the buried wastes can also be preserved.

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