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Chemical & Biological Hazards Programme

Commissioned Report CR/06/243N

BRITISH GEOLOGICAL SURVEY

CHEMICAL & BIOLOGICAL HAZARDS PROGRAMME
COMMISSIONED REPORT CR/06/243N

Gas transport processes in argillaceous rocks within the EDZ: BGS contribution to NF-PRO WP4.4.1

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Keyworth, Nottingham British Geological Survey 2006

Keywords

Argillaceous rocks; nuclear waste disposal; two-phase flow; gas transport; EDZ; self-healing; self-sealing.

Front cover

Cover picture details, delete if no cover picture.

Bibliographical reference

CUSS, RJ, REEVES, NOY, DJ, AND HJ, HARRINGTON, JF. 2006. Gas transport processes in argillaceous rocks within the EDZ: BGS contribution to NF-PRO WP4.4.1. *British Geological Survey Commissioned Report*, CR/06/243N. 30pp.

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Contents

FIGURES

TABLES

Summary

This report outlines the contribution made by BGS to the NF-PRO (Key processes in the Near Field) project; part of the *EC Euratom Research and training Programme on Nuclear Energy.* BGS was asked to contribute to Work Package 4.4.1 examining EDZ Characterisation and Evolution. This work package included a state-of-the-art report on the gas flow properties within the Engineered Damaged/Disturbed Zone (EDZ), BGS was requested to contribute to the chapters on clay (this report) and crystalline rock (Reeves *et al.*, 2006). This work was co-funded by United Kingdom Nirex Limited (Nirex).

1 Introduction

The NF-PRO (Key processes in the Near Field) project is part of the *EC Euratom Research and training Programme on Nuclear Energy (call 2003).* BGS is contributing to Work Package 4.4.1 examining EDZ Characterisation and Evolution.

The construction of a tunnel in any type of rock results in the creation of new free surfaces and therefore leads to a redistribution of stresses resulting in a damaged or disturbed zone around the opening (EDZ). The size and the properties of this zone depend on the state of stress, the pore water pressure and the hydro-mechanical properties of the rock (as well as the excavation methods, including the size and shape of the excavation; not considered in this study).

The most important change in the EDZ compared to that of the intact rock is the creation of discontinuities, which could result in an interconnected fracture network and an increase in hydraulic conductivity. This could lead to preferential flow along emplacement tunnels, access tunnels (e.g. ramps) or shafts to the biosphere. In the preliminary French Safety Analyses (dossier (Anon) 2001) for instance, treatment of scenarios considering an early seal failure, highlighted the hydraulic role of the damaged zone as a potential radionuclide transport path. Therefore, the presence of an EDZ represents an important issue in repository performance and safety assessment.

After opening, the region of rock immediately surrounding the emplacement tunnels will become partially de-saturated as a result of evaporation due to ventilation during the construction and operation phase. Desaturation can directly influence the behaviour of the rock (creation of suction pressure, stiffening of clay etc.) and time dependent processes (e.g. creep) could enhance and/or create micro- and macro-scale fractures in the EDZ.

In case of rocks with significant time dependent deformation, it is expected that the EDZ will change its properties with time after emplacement of the waste canister and the start of re-saturation due to creep, swelling and/or EDZ re-excavation. This process which is sometimes described as "self-healing" or "self-sealing" of the EDZ could lead to a partial, or even complete, closure of open fractures and discontinuities during the transient period (re-saturation, thermal period) of the repository and its long-term evolution. Therefore, these processes are very important for the understanding of the role of the EDZ in repository performance and safety assessment.

In addition to its hydraulic significance, the role of the EDZ in gas transport needs to be investigated. Repositories of some types of infrastructure and wastes could generate significant gas overpressures in the repository (if the gas cannot be released through the intact host rock or along tunnels). The EDZ could become a transport path for gas and act as a vent, limiting the gas overpressure in the repository. Processes including diffusive or advective transport of gas, 2-phase flow mechanisms, pathway dilation and creation of micro- or macro-fractures need to be investigated.

Work Package 4.4 of NF-PRO (Near Field Processes) concerns the migration of gas through the EDZ. The material contained within this report was submitted to partners in Nagra and GRS towards a report on gas transport processes within clays, shales, mudstones and crystalline rocks. The material within this report is complemented by material supplied by Nagra on the background science and the behaviour of the Opalinus clay and from GRS on salt characteristics. This report covers the aspects of gas transport in clay-rich rocks; transport within crystalline rocks is covered in an accompanying report (CR/06/244).

2 Basic concepts of gas and fluid transport in argillaceous formations

This section outlines the basic concepts of fluid, gas, and two-phase flow in argillaceous rocks.

2.1 GAS AND FLUID TRANSPORT MECHANISMS

This section on gas and transport mechanisms is split into sections on material properties (such as porosity), hydraulic properties (fluid flow), diffusion mechanisms (gas flow), two phase flow (mixed gas and fluid flow) and flow associated with fractures. Within this section the basics are introduced for gas and fluid flow, as well as concepts for matrix flow and fracture transmissivity.

2.1.1 Material properties

2.1.1.1 POROSITY

The total matrix porosity of a clay may be considered as the sum of the porosity associated with each of the size classes: **micropores** (<2 nm), **mesopores** (2-50 nm) and **macropores** (>50 nm). At modest levels of compaction, the primary particles in a natural clay may be arranged in aggregates. In most mudrocks, the platy clay minerals are strongly aligned in a plane that is normal to the direction of the maximum compaction stress. **Interparticle** or **intergranular** porosity usually dominates the pore space of such materials, and is controlled by the packing and orientation of the clay mineral flakes in the matrix. The fabric often appears to have little vertical interconnected porosity due to overlapping of the particles. Some of the water in a compact mudrock may also reside in microcracks or microfissures. It is difficult to characterise these features in the laboratory and their contribution to total porosity under field conditions remains unclear.

Effective, **flowing** and **kinetic porosity** are used synonymously to describe that part of the total porosity that is available for fluid flow. In mudrocks, it seems likely that most of the pores are actually interconnected, but many of the interparticle spaces are so small that viscous drag, surface adsorption and other effects render the water in these voids effectively immobile.

In very compact argillaceous rocks, much of the water present is adsorbed on the internal and external surfaces of clay minerals, and will be so strongly adsorbed that it may not be able to participate in **advective** transport under normally encountered pressure gradients. However deep burial and diagenetic alteration will tend to make these rocks brittle and susceptible to fracturing. Flow may therefore be focused along fractures. Under these circumstances, the true flowing porosity of the rock could be very low.

Since most of the pores in a mudrock are slot-shaped, it is probably more meaningful to think about the distribution of interparticle water-film thicknesses, rather than the distribution of pore sizes. The average thickness of a water-film in a compact, water-saturated clay may be roughly estimated from the fractional gravimetric water content and specific surface, by assuming that the water is distributed evenly over all the available mineral surface area. These thin films of water are generally from 4 to 40 molecular layers thick. About half the pore space in most clay soils occurs in slot-like pores, with a thickness between clay platelets of 10 nm or less. The pore apertures of recent sediments recovered from the floor of the Pacific Ocean are mostly less than 5 nm. The average pore aperture in source-rock shale at a depth of burial of approximately 2 km is around 1 nm. The trend of decreasing water-film thickness with depth of burial is very obvious and can be explained by the balance of forces across these thin films.

2.1.1.2 TORTUOSITY

For an actual porous medium, the interconnected void spaces can be regarded as a number of tortuous pore channels. The tortuosity (τ) is defined as the average ratio of the microscopic path length (L) to the macroscopic path length (x) in the medium, or

$$\tau = \frac{L}{x} \geq 1 \qquad \text{(Eq.2.1)}$$

Calculations are fairly insensitive to τ and, in the absence of experimental data, this parameter is usually taken as $\sqrt{2}$ (= 1.41). However, it has been suggested that clay mineral orientation and the overlapping of clay platelets in compact clays might lead to a tortuosity that is substantially larger than this value (Olsen, 1962).

2.1.2 Hydraulic properties

2.1.2.1 PERMEABILITY

The intrinsic permeability, k (m^2), is considered to be a property of the geological medium, and is not affected by the nature and properties of the fluid/gas. Darcy's law relates flow through a medium to the hydraulic gradient, and can be expressed in one-dimensional form as

$$\overline{q} = -\frac{k}{\mu}\left(\nabla p - \rho \overline{g}\right) \qquad \text{(Eq.2.2)}$$

where $\overline{q}$ is the Darcy velocity, specific discharge, or rate of transmission of the fluid/gas through the medium ($m.s^{-1}$), k is the permeability of the medium (m^2), μ is the viscosity of the liquid (Pa.s), ρ is the fluid density ($kg.m^{-3}$), $\overline{g}$ is the acceleration due to gravity ($m.s^{-2}$) and ∇p is the pressure gradient (Apted *et al.*, 1995). One Darcy is defined as the permeability of a medium for which a flow of 1 cm^3s^{-1} is obtained through a section of 1 cm^2, for a fluid of viscosity 1 cP, and a pressure gradient of $1 atm.cm^{-1}$, or 760 mm Hg cm^{-1} (de Marsily, 1986). One Darcy is equivalent to 9.87×10^{-13} m^2.

The matrix permeability of natural clay media ranges from around 10^{-17} m^2 for a glacial till (close to surface), through 10^{-19} m^2 for a typical overconsolidated clay, to around 10^{-22} m^2 for a shale. The Kozeny-Carman equation provides an indication and an explanation of the sensitivity of permeability to some important material properties. For small porosity values, permeability is predicted to vary with the cube of porosity, explaining the dramatic decrease in flow rates as sediments become more compacted. The equation also predicts that permeability will vary with the reciprocal of the square of the specific surface, providing a possible explanation for the very low hydraulic conductivity of a smectite-rich clay (e.g. bentonite), with high specific surface, when contrasted with a kaolinite-rich clay having a similar total porosity.

Many of the concepts of fluid flow in soils and rocks stem from the theory of laminar flow in capillaries. The single capillary is the basic building block of so-called capillary-bundle models of single and two-phase flow in porous media (Dullien, 1979; Scheidegger, 1974).

2.1.2.2 SCALE EFFECT

Scale-effects may have a strong influence on the permeability values obtained for many clays and mudrocks, with laboratory tests frequently giving values which are substantially lower than medium and large-scale field values. This is closely linked to the issue of fracture flow in clays. Scale-effects may be less important in some of the more plastic clays. Matrix permeability is often found to vary in different directions. The preferred orientation of clay minerals and the laminated fabric of many mudrocks are likely to the main factors governing hydraulic anisotropy, but there is a possibility that microfracture alignment in some materials also influences the direction of fluid flow.

2.1.2.3 NON-DARCY FLOW

According to Darcy's law, the flux of groundwater in a porous medium is linearly proportional to the hydraulic potential gradient. Clay minerals exhibit complex interactions with both water and solutes, and there are good reasons to suspect anomalies in flow behaviour as aqueous solutions move through the sub-microscopic flow channels of compact clays or mudrocks. Non-Darcy flow through clays has been widely reported.

2.1.2.4 COUPLED FLOW

A coupled flow process is one in which flow of any kind (e.g. fluid, solute, heat, electrical current) is driven by the gradient of a potential that is not usually associated with that flow or, more specifically, the flow depends on a non-conjugate thermodynamic force. These processes are often collectively known as Onsagerian coupled flow processes. There seems little doubt that most, if not all, of these processes can operate in compact clays especially in the presence of large gradients of solute concentration or temperature.

2.1.3 Solute transport mechanisms

2.1.3.1 DIFFUSION

Given the general importance of diffusion as a transport mechanism in the unfractured and generally more plastic argillaceous rocks, the factors affecting the diffusion coefficients of various chemical species in the clay environment are of particular interest. In one-dimensional form, Fick's first law can be written as

$$J_D = -D(\nabla C) \qquad \text{(Eq.2.3)}$$

where J_D is the flux of solutes (mol.m^{-2}.s^{-1}), D is the diffusion coefficient (m^2.s^{-1}) and ∇C is the concentration gradient.

The diffusion of one chemical species at low chemical concentration into another is known as **tracer diffusion**. The limiting value of the tracer diffusion coefficient at infinite dilution can be predicted theoretically. The term self-diffusion is understood to mean the diffusion of a molecule or ion within a system comprising the same molecules or ions, where no distinction is made between isotopes (e.g. water in water, HTO in water). Self-diffusion is essentially Brownian motion.

Chemical species diffusing through the solution-filled pore spaces of a rock encounter an irregular network of pore channels, and frequently collide with the walls of these channels. Diffusion through this porous space is slower than it would be in the absence of the mineral framework. Based on these simple concepts of the diffusional process, the physical characteristics of the rock responsible for slowing down molecular diffusion are generally considered to be the porosity itself, the pore size distribution (represented by a constrictivity term) and the tortuosity (τ) of the diffusional path.

Research on compact clays suggests that only a fraction of the total porosity is available for diffusive transport (Horseman *et al.*, 1996). The mechanism of electrostatic repulsion can cause negatively charged ions to be excluded from the narrower interparticle spaces of the clay by negative surface charges (anion exclusion). Size-exclusion may also be important. This has prompted the use of a diffusion accessible porosity term in transport modelling.

Both the diffusion accessible porosity and the retardation factor depend on chemical characteristics of the diffusing species (size, charge, etc.) and on the surface chemistry of the pores. In theory, the geometry factor should be a function of the porous medium and should be independent of the diffusing species, but because of the complexity of the interactions between ions and negatively charged mineral surfaces in the narrow interparticle spaces of a compact clay, it is doubtful whether this simple picture is actually born-out in practice.

2.1.3.2 ADVECTION

Although diffusion is expected to be the most important solute transport mechanism in clays in most cases, advection can become significant when fractures and microfissures are present. The conventional advection-dispersion model combines the principal mechanisms of advection, dispersion, and sorption. Dispersion represents the combined effects of mechanical mixing and Fickian diffusion. It is a complex and poorly understood process.

2.1.3.3 DISPERSION

Qualitatively, mechanical dispersion and diffusion have similar effects and dispersion is usually modelled using a diffusion-like term, with the dispersive flux taken to be proportional to the concentration gradient. Mechanical dispersion is quantified by a parameter known as the dispersion length. It is observed that this parameter is related to the length scale of the heterogeneities in a porous medium, and increases for long distance solute transport because the heterogeneities affecting the process become larger. The relative importance of advective and diffusive processes can be assessed using the Peclet number.

2.1.4 Two phase flow

If gas is generated faster than it can be dissolved and advected and/or diffused away from the source zone then it will form a separate phase. Transport of the gas will then be affected by its interaction with the aqueous phase. A generalisation of the single-phase Darcy's law is usually assumed with the form

$$\overline{q}_f = -\frac{kk_{rf}\left(S_f\right)}{\mu_f}\left(\nabla p - \rho\overline{g}\right): \qquad f = w,g \qquad \text{(Eq.2.4)}$$

where f is the phase, water (w) or gas (g), k_{rf} is the relative permeability of phase f, and S_f is the saturation of phase f, or fraction of the pore space occupied by the phase, $\overline{q}$ is the Darcy velocity and $\overline{g}$ is the acceleration due to gravity ($m.s^{-2}$). Gas and water pressures are related by the capillary pressure, p_c, which is a function of the gas saturation:

$$p_g - p_w = p_c\left(S_g\right) \qquad \text{(Eq.2.5)}$$

Gas and water saturations are related by

$$S_g + S_w = 1 \qquad \text{(Eq.2.6)}$$

The functional dependencies of k_{rf} and p_c on the phase saturations cannot in general be determined from first principles and many parameterised functions have been introduced in the literature. Amongst those most commonly applied to granular porous media are the Brooks-Corey (Brooks and Corey, 1964) and the van Genuchten (van Genuchten, 1980, Luckner *et al.*, 1989) functions which are described in more detail below. It should be noted, however, that all such functions are necessarily approximations and ideally explicit data for permeability verses saturation etc. for specific rocks should be used where possible.

The full transport equations are obtained by combining the above flow law equations with continuity equations for fluid and solid components. The formulation is completed with additional constitutive relations that describe the compressibility of solid and fluid phases, usually combined with an assumption that solid phase displacements are small.

2.1.4.1 Brooks-Corey functions

The Brooks-Corey relative permeability for the aqueous phase is defined in terms of an effective saturation, S_e, given by

$$S_e = \frac{S_w - S_{wr}}{1 - S_{wr} - S_{gr}} \tag{Eq.2.7}$$

where S_{wr} is the residual water saturation, below which the water is immobile, and S_{gr} is the residual gas saturation. The aqueous phase relative permeability is then given by

$$k_{rw} = S_e^{(2+3m)/m} \tag{Eq.2.8}$$

where m is a fitting parameter, which may be set to $m = 2$ to give the simpler equations of Corey (1954). The gas phase relative permeability is given by

$$k_{rg} = (1 - S_e)^2 \left(1 - S_e^{(2+m)/m}\right) \tag{Eq.2.9}$$

The dependence of the capillary pressure on the effective water saturation is given by

$$p_c = \frac{p_d}{S_e^{1/m}} \tag{Eq.2.10}$$

where p_d is the air entry pressure.

2.1.4.2 van Genuchten functions

The aqueous and gas phase relative permeabilities are given by

$$k_{rw} = S_e^{\eta} \left[1 - \left(1 - S_e^{1/n}\right)^n\right]^2 \tag{Eq.2.11}$$

and

$$k_{rg} = (1 - S_e)^{\varsigma} \left[1 - S_e^{1/n}\right]^{2n} \tag{Eq.2.12}$$

where S_e is given by Eq.2.7, n is a parameter related to the pore-size distribution of the porous medium and η and ζ are pore connectivity parameters, often taken to be equal to 0.5. The capillary pressure function is given by

$$p_c = \frac{1}{\alpha} \left(1 - S_e^{-1/n}\right)^{(1-n)} \tag{Eq.2.13}$$

where α is the reciprocal of the air entry pressure. An important difference between the Brooks-Corey and van Genuchten models is that in the latter the capillary pressure goes to zero as saturation approaches unity. It may be noted that neither of these models include any hysteretic effects, but other authors have suggested modifications to accommodate this (e.g. Parker and Lenhard, 1987).

The above formulations for two-phase flow were originally developed for and applied to granular porous rocks for which they have been found to provide good approximations of the processes involved. When flow takes place in clay formations there are a number of processes involved that are not taken into account in the above formulation. Firstly, the pore water in clays may interact strongly with the clay minerals causing both non-Darcy flows and thermodynamic coupled flows, either of which may affect single or two phase transport. Secondly, the clay skeleton tends to be weak and pore water or gas pressures may lead to significant deformations that may exhibit non-linear and visco-plastic behaviour. In the extreme case the deformations may lead to fracturing of the clay fabric and the formation of discrete flow channels. The above formulations consider only a compressibility term which is only adequate for small elastic deformations. Under such conditions the applicability of two-phase flow theory to adequately describe gas flow in compact clay-rich media is highly questionable (Harrington and Horseman, 1999).

2.1.5 Flow associated with fractures

Relationships of flow given above assume flow through the matrix of the rock. Of significant importance in the EDZ is the flow of fluids and gas through the fractured network surrounding the tunnel repository. Flow is facilitated at a potentially faster rate than through the matrix and can be viewed as a short-circuit in the system.

2.1.5.1 HAGEN-POISEUILLE EQUATION FOR FLOW IN A CAPILLARY TUBE

The Hagen-Poiseuille law concerns laminar stationary flow of an incompressible uniform viscous liquid through a cylindrical tube with a constant circular cross-section. For water flow in a capillary tube, the relationship is:

$$Q = \frac{\pi(p_1 - p_2).a^4}{8l\eta} \qquad \text{(Eq.2.14)}$$

where Q is laminar stationary flow, p_1 and p_2 are the pressures at either end of the capillary, a is the internal radius of the capillary, l is the total length of the capillary, and η is the dynamic fluid viscosity.

The compressibility of a gas is so large that it must be taken into account. The volume of gas entering the capillary is not the same as the volume leaving it, as p_1 and p_2 are not equal. It is the mass of gas crossing every section of the tube that must be constant under steady state conditions. Therefore for the case of gas flow in a capillary tube:

$$Q_1 p_1 = Q_2 p_2 = \frac{\pi a^4}{16l\eta}\left(p_1^2 - p_2^2\right) \qquad \text{(Eq.2.15)}$$

2.1.5.2 FRACTURING AND OVER-PRESSURE

Over-pressure is a condition where the pore fluid pressure is higher than it would be within the rock-mass for the given stress-regime, i.e. pressure at given depth greater than predicted for hydrostatic conditions. There are several ways in which over-pressure can occur within the EDZ. Naturally the host rock may be over-pressured due to its burial history. The construction of the tunnel results in a significant change in the in situ stress regime in a very short period of time. Construction usually occurs at a rate whereby pore fluid within the rock cannot drain sufficiently fast enough due to the low intrinsic permeability of argillaceous rocks. This results in undrained loading. The pores of the rock reduce due to the increased load in the EDZ, but pore fluid is not able to escape. This results in a rapid increase in pore-pressure, lowering effective stress and in some cases making stress negative. Over longer time-periods, excess pore pressure may also be created through gas generation during disposal or through creep deformation.

Hydraulic fracturing (tension fracturing) can occur:

- Naturally, due to the tectonic regime and changes in the effective stress conditions (hydrofractures)
- Artificially, due to drilling activities (drilling-induced tensile fractures)
- Artificially, generated around a tunnel or borehole due to the *in situ* stress.

Hydrofractures may be large features, or a linked, permeable, dilatant fracture network. These changes may be induced by the development of disequilibria pore pressure conditions or by changes in the tectonic load. For example, a reduction in the minimum compressive stress (σ_3), induced by extension during regional uplift, may result in the formation of dilatant shear fractures. Hydrofractures occur under conditions of low differential stress when pore fluid pressure reduces the minimum effective horizontal stress below zero to a stress level that exceeds the tensile strength of the rock.

In extensional basins, where the minimum compressive stress (σ_3) is significantly less than the maximum compressive stress (σ_1), hydrofractures are invariably vertical to semi-vertical in orientation and form perpendicular to σ_3. For hydrofractures to develop in preference to shear fractures, the following conditions must be satisfied:

$$u_f = \sigma_3 + T_0 \quad \text{and} \quad \sigma_1 - \sigma_3 < 4T_0 \qquad \text{(Eq.2.16)}$$

where u_f is pore fluid pressure required to initiate hydrofracture, σ_1 and σ_3 are maximum and minimum horizontal stresses respectively and T_0 is the tensile strength of the rock (Hubbert and Rubey, 1959; Sibson, 1995). These conditions can occur in highly overpressured systems undergoing continual subsidence, or during exhumation when rapid denudation, without re-equilibration of overpressure, results in tensile failure. This can also be the result of fluid overpressure created within a repository during the long-term storage of waste as the canister undergoes breakdown and/or a bentonite buffer undergoes swelling, creating an internal pressure upon a tunnel lining.

According to the 'classic theory' of hydrofracture [Jaeger and Cook, 1969], a tensile fracture will develop and propagate when the tensile stress acting in a direction tangential to the surface of a hole is equal to the tensile strength, *T*, of the clay. Using linear elastic stress analysis, the fracturing pressure, p, of the clay around a borehole is given by

$$\mathrm{p} > 3\sigma_3 + \mathrm{T} - \sigma_1 \qquad \text{(Eq.2.17)}$$

Brittle shale will increase its permeability by developing dilatant fractures, whereas ductile shale is able to undergo plastic deformation without increasing permeability (it will contain non-dilatant, sealing fractures). The tendency to dilate will be a function of the mechanical properties of the rock, effective pressure and shear zone geometry. At a given effective pressure, a stronger (overconsolidated or cemented) rock is more likely to dilate than a weaker one.

2.2 MECHANICAL CONCEPTS

2.2.1 Dilatancy and the dilatancy boundary

Figure 2-1 shows the consequence of mechanical deformation on porosity and permeability as applied to the critical state soil mechanics (CSSM) approach (Schofield and Wroth, 1968; Atkinson and Bransby, 1978; Wood, 1990). The CSSM has been successfully applied to argillaceous rocks (Adams and Wulfsohn, 1997; Cotecchia and Chandler, 2000; Kirby, 1994; Kirby and O'Sullivan, 1997, Maatouk *et al.*, 1995; Petley, 1999; Wheeler and Sivakumar, 1995), as well as other rock types (e.g. Cuss *et al.*, 2003), through the simple modification in the low stress regime. This approach can be useful in describing the volume, and hence porosity, variation during deformation by a simple differential stress. It is possible to extend this approach into the more complex true-triaxial stress space, see Cuss and Horseman, 2004; Horseman *et al.*, 2005.

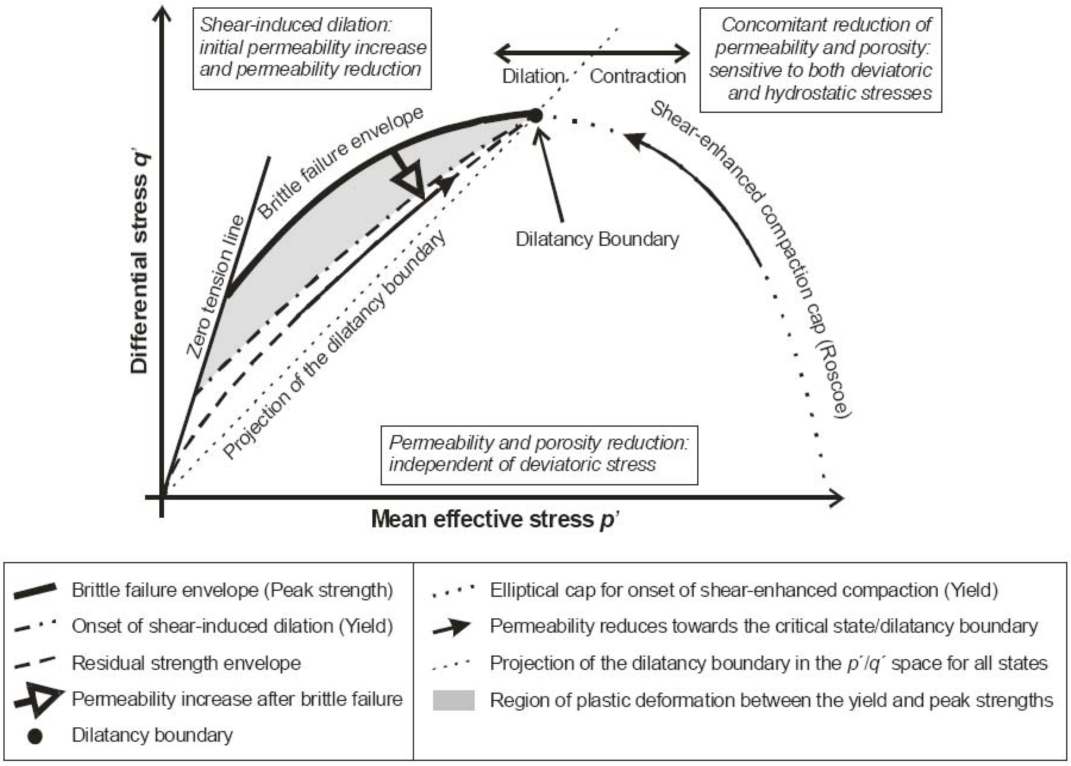

Figure 2-1 – The role of the dilatancy boundary in the sealing of argillaceous rocks.

The CSSM shows that deformation at relatively low mean effective stress is characteristic of shear-enhanced dilation, referred to as the *dry side*. Deformation is concentrated into a shear-band, which appears as a macroscopic fracture. Formation of the fracture results in a significant increase in permeability. At elevated mean effective stresses, deformation is characteristic of shear-enhanced compaction, with damage pervasively distributed throughout the bulk-rock, referred to as the *wet side*. Concomitant reduction of permeability and porosity occurs, which is sensitive to both deviatoric and hydrostatic stresses. In terms of the pure CSSM, the dry side is described by the Hvorslev surface, although in lithified rocks, such as argillaceous ones, deformation occurs at a rupture envelope that has failure at stresses above the Hvorslev. The initiation and formation of a brittle fracture results in the stress-state reducing to the conditions of residual strength, at a stress similar to the Hvorslev. The wet side is described by the Roscoe surface. The point between these conditions is called the critical state, but this is often referred to as the brittle-ductile transition or the dilatancy boundary. The CCSM states that a rock will permanently deform or yield when the stress-state intercepts the yield surface. On both the wet and dry sides, the stress state will progress towards the critical state, where deformation is isovolumetric. During this stress-path, permeability will reduce. On the wet side this permeability reduction will be of the initial permeability, whereas the reduction on the dryside will be from the fracture permeability, which will be greater than the initial.

On the wetside, deformation will result in a reduced permeability and hence increased sealing potential of the host rock. On the dryside, permeability will increase through dilation. The further ‘left’ the stress state of the dilatancy boundary, the greater the enhanced permeability. Thus, the further right of the dilatancy boundary, the more favourable geological disposal becomes.

2.2.2 Macroscopic fracturing

As described for the CSSM, at low effective mean stress regimes, argillaceous rocks deform through the formation of macroscopic fractures. The network of fractures induced through the construction of tunnels has been seen to be complex and can be extensive, especially in highly over-consolidated argillaceous rocks.

Fracture permeability can be seen to be much higher than the bulk permeability of an argillaceous rock; for example Kimmeridge shale has a fracture permeability of 3×10^{-11} m^2 (at 10 MPa normal stress), compared with an intact permeability of 1.1×10^{-19} m^2 (Gutierreza *et al.*, 2000). This study showed that fracture permeability reduced from a k/k_0 value of 1 to 0.1 as normal stress across the fracture increased from 0 to 10 MPa. Shearing of fractures can lead to a reduction in fracture permeability as a fault gouge is formed and clay material gets 'smeared' along the discontinuity. Gutierreza showed that fracture permeability after shearing was about 10^{-6} before shearing commenced.

2.2.3 Plasticity

The CSSM approach enables a prediction of when deformation progresses through elastic (recoverable) deformation to plastic (permanent) deformation. The argillaceous rocks experienced in the various National Programmes can be described as plastic clays. Perfect-plastic behaviour initiates at a critical threshold of yield stress, with permanent strain continuing rapidly and indefinitely at constant effective stress. Generally, rocks are not perfect-plastic materials, with strain-hardening, strain-softening, viscous-behaviour and plastic-brittle behaviour observed after yield.

Several models have been formulated that incorporate plasticity. These are usually based on the Cam-clay family of models, which are synoptic models that define yield surfaces between the critical state, normal consolidation and rebound-reconsolidation lines (Roscoe and Schofield, 1963; Roscoe and Burland, 1968). There are four main ingredients to an elasto-plastic model: 1) elastic properties, 2) yield surface, 3) plastic potential, 4) hardening rule. Plastic potentials describe the dependence of plastic deformation on yield stress-state rather than the route by which stress state is attained (Wood, 1990). Barnichon (2002) outlines the application of the modified Cam-clay models to the excavation of the Test-Drift gallery at Mol.

The consequence of plastic deformation is the modification of the fluid/gas properties within the EDZ. A complex gradient of pore pressure is created within the plastic zone (which may be, or may be not, coincident with the EDZ).

2.2.4 Creep

It is believed that all rocks can exhibit time-dependent deformation, or creep (Horseman *et al.*, 2005). For many rocks this creep is imperceptibly small as to be considered insignificant. However, for materials such as plastic clays, this time dependent deformation can be significant. Time-dependent consolidation can be viewed as a creep phenomena.

Argillaceous rocks can creep by means of a number of processes, such as bulk rock creep, discontinuity creep, secondary consolidation, sloughing, strain-softening, pyrite alteration, gypsum dissolution or hydration, or stress-relief swelling triggered by pore chemistry changes. Argillaceous rock samples deformed in a distributed manner microstructurally show evidence of several deformation mechanisms; including microcrack formation and extension, compaction of void space, and dislocation glide in clays leading to the formation of micro-link bands and associated voids (Ibanez and Kronenberg, 1993).

Several methods exist for the modelling of creep including the Lemaitre model (Boidy *et al.*, 2002), rheological models (Rousset and Bouilleau, 1991), constitutive modelling (Thimus and De Bruyn, 1998), elastoviscous modelling (Yin *et al.*, 2002). It is possible to incorporate creep into the CSSM approach, in its classical form (Leroueil, 1998) or in the extended true-triaxial CSSM (Horseman *et al.*, 2005).

The effect of creep is a modification of the pore and mineral arrangement. For void compaction, this will result in a lowering of effective porosity and permeability. In the case of microcrack formation and extension this will result in an increase in localised permeability. Therefore, creep can have a complex effect on gas migration in the EDZ over considerable time-scales. The most obvious manifestation of creep is in convergence of the tunnel wall after construction.

2.3 SELF-HEALING AND SELF-SEALING

Argillaceous rocks have been proposed for the long-term storage of waste due to their ability to self-seal or self-heal. This simply reflects their ability to close dilatant features (and thereby reduce fluid movement) through a number of processes (outlined above). Self-sealing refers to processes that affect fluid conductivity that are largely mechanical and hydromechanical in origin. Self-healing processes have additional geochemical processes acting and can be viewed as sealing with a loss of memory of the pre-sealing state. This definition (Davies and Bernier, 2004) is not definitive and there are examples that contradict it (Horseman *et al.*, 2005).

Mechanical processes that contribute to self-sealing/healing include changes in the stress-field, movement of porewater, swelling, softening, plastic deformation and creep. Geochemical processes include chemical alterations, transport in aqueous solution and the precipitation of minerals. The stress-state, temperature and chemistry of pore fluids all influence the ability of a rock to self-seal/heal.

2.4 ISSUES OF NOTE OF BASIC CONCEPTS OF GAS AND FLUID TRANSPORT

In order to understand fully the processes that occur in the EDZ, there are a number of additional complexities that require careful consideration and thought. These complexities reflect the complexity of the near field in the tunnel.

Many of the underlying phenomena which could affect gas and fluid transport are scale dependent, i.e. behaviour observed at different scales, be these microscopic or regional scales, is very different. This can be observed in many different properties, such as permeability, porosity, fracture density, mechanical strength, geochemical potential, etc. Considerable work has been afforded to this problem and many features have been quantified, at least in part. Scale issues should always be considered when interpreting *in situ* or experimental results, as our scale of observation may affect these.

Anisotropy and variability are two very different problems, but have similar consequences in our understanding. Anisotropy is simply the variability of a property, usually expressed as differences in direction. For mechanical anisotropy, we tend to construct stress or strain ellipsoids, based on the structural geology approach. In gas flow problems, we tend to observe considerable anisotropy perpendicular and parallel to bedding, especially in highly indurated argillaceous materials, such as Opalinus clay. This anisotropy is caused by fabric and structure, and may be evident in a number of properties. Variability is simply a description of the range of values a parameter may have in a three-dimensional space. In terms of a parameter such as porosity, we may observe that a rock has a different value when measured on a bulk-rock scale compared with observations at a microstructural scale. We may also note that parameters vary considerably between bands within a given geological sequence and also appreciably within the same band. The parameter may also vary with time. Both anisotropy and variability are complex issues that are often neglected or simplified. Further research is required.

Locality is an issue that requires consideration. The majority of research available is for Opalinus Clay at Mont Terri (Switzerland), Boom Clay at Mol (Belgium), and the Toarcian and Domerian shales at Tournemire (France). Both sites and rock types have specific issues unique to their location, relating to physical and chemical properties, as well as issues related to tunnel construction methods. There are also differences between different concepts of long-term storage that will impact on the type of gases generated. This complexity makes the use of data from different sites difficult to compare and analyse.

3 Gas and fluid related rock properties

3.1 RELEVANT ROCK PROPERTIES

Table 3-1 outlines the parameters important to assessing gas and fluid transport in the EDZ.

	Parameter	**Description or examples**
Structural Data	Discontinuity type	Fissures, Joints, Fractures, Minor shears and slickensides, Bedding plane shears, Faults and major shears, Bedding planes and bedding disturbances, Laminations and fissility
	Discontinuity orientation	Dip and dip direction of the discontinuity
	Discontinuity spacing	Spacing between discontinuities
	Discontinuity persistence	Length of discontinuity
	Discontinuity planarity	Shape of discontinuity surface
	Discontinuity roughness	Nature of discontinuity surface (also referred to as Joint roughness coefficient)
	Discontinuity aperture	Perpendicular distance between walls of discontinuity
	Filling/gouge composition	Material separating walls of discontinuity
	Discontinuity throw	Relative movement along discontinuity
	Discontinuity slip sense	Direction of movement including extension
	Discontinuity relative age	Relative age of the discontinuity, be it pre-tunnelling, result of tunnel face advancement, or late post-boring.
	Seepage	Water flow or free moisture visible in discontinuity
	Weathering	Wall strength
	Tensile strength	Pressure required to induce a hydrofracture
	Normal stress across fracture	The normal stress that is acting across an identified discontinuity
	Shear stress along fracture	The shear stress that is acting along an identified discontinuity
	Tunnel geometry	Measure of tunnel length and diameter
	EDZ thickness	Measure of depth of disturbance into the wall-rock
	Fracture density	Number of fractures per unit volume of rock
	Fracture connectivity	Expression of connection of fracture network
	Facies architecture	This family of parameters describe rock complexity; including heterogeneities, bedding, purity of clay (i.e. does it include silt, nodules, etc)
Hydro Data	Specific storage	The quantity of water that a unit volume of porous rock releases from storage under the effect of a unit decline in hydraulic head.
	Intrinsic permeability	Intrinsic permeability is considered as a property of the geological medium and is not affected by the nature and properties of the fluid.
	Capillary pressure	The difference in the pressure between two immiscible fluid phases separated by a curved meniscus and occupying the pores of a solid rock.
	Diffusivity coefficient	Measure of the diffusion properties of pore fluids
	Total porosity	The total amount of porosity present within a rock. Defined as the ratio of the total pore volume to the bulk volume
	Effective/kinetic porosity	The amount of porosity that is available for fluid flow. This will be less than the total porosity as isolated/disconnected pores are not part of the transport network.
	Bulk volume	Total volume of a block of material.
	Volume of pores	The total volume of the effective pore network.
	Average grain density of mineral solids (ρ_s)	Density of the mineral constituents of a rock.
	Bulk rock dry density (ρ_b)	Density of a unit block of rock after drying.

	Darcy velocity/specific discharge	The volume rate of flow through a porous medium divided by the cross-sectional area normal to the direction of flow.
	Fluid viscosity	The viscosity of the transport fluid or gas.
	Hydraulic radius (R_H)	The radius of a capillary that is able to transmit fluid.
	Tortuosity (τ)	Defined as the average ratio of the microscopic path length to the macroscopic path length in the medium. This is because within an actual porous medium, the interconnected void space can be assumed to be a number of tortuous pore channels.
	Relative permeability	The permeability of a rock, gas, or water with respect to each other when more than two are present
	Wettability	Process when a liquid spreads on (wets) a solid substrate
	Surface tension	The property of the surface between water and gas
	Contact angle	quantitative measure of the wetting of a solid by a liquid. It is the angle formed by the liquid at the three phase boundary where a liquid, gas (or a second immiscible liquid) and solid intersect.
Geomechanical	In situ stress	Cartesian stress orientation: Stress in a geographic sense is denoted σ_h, σ_H, σ_v, stress is usually denoted σ_1, σ_2, σ_3 (where $\sigma_1 > \sigma_2 > \sigma_3$) Polar stress orientation: Stress around a circular opening is denoted radial stress (σ_r) and circumferential/hoop stress (σ_θ)
	Stress (σ)	Deviatoric stress, effective stress, mean stress, octahedral stress, normal stress, shear stress
	Strain (ε, γ)	Change in shape or volume of a body as a result of stress. Defined as the ratio of original length to deformed length.
	k	Ratio of average horizontal to vertical stress
	K_0	Stress path coefficient defined as the constant ratio of change in effective minimum (horizontal) stress to effective maximum (vertical) stress from initial reservoir conditions.
	Pore pressure	The pressure within the fluid contained within the pore network of a porous rock.
	Liquid limit	The water contents at which a material behaves as a liquid.
	Plastic limit	The water contents at which a material exhibits plasticity.
	Plasticity Index (I_p)	Plastic behaviour only occurs within a limited range of water content. The plasticity Index = liquid limit – plastic limit
	Liquidity Index (I_l)	The liquidity index provides a quantitative measure of the current state of soils
	Unconfined compressive strength (q_u)	The strength of a sample of rock at rupture when measured in the standard uniaxial compression strength. It indicated strength at surface with no lateral confinement.
	Modulus of elasticity (E)	Defined as the ratio of the stress applied to a body to the strain produced. This parameter refers to elastic (recoverable) deformation.
	Poisson's ratio (ν)	Defined as the ratio of the lateral strain to the longitudinal strain. This parameter refers to elastic (recoverable) deformation and describes how much axial compression is translated into radial strain.
	Tensile strength	A measure of the resistance that a material offers to tensile stress. It is defined as the stress required to cause rupture.
	Shear strength	The internal resistance of a body to shear stress, typically including a frictional component and cohesion.
	Shear Modulus (G)	Defined as the tangential force per unit area divided by the angular deformation in radians. This parameter refers to elastic (recoverable) deformation
	Friction Angle (ϕ)	Tangent of the coefficient of friction
	Cohesion	Shear strength of a rock not related to interparticle friction.
	Skempton's B parameter	The ratio of the change in porewater pressure for a change in total stress during an undrained test. In an incompressible system B=1
	λ	Critical state parameter: Slope of the straight Normal Consolidated Line when viewed in the void ratio versus log effective stress space.
	M	Critical state parameter: Slope of the critical state line in the effective stress versus differential stress space.
	κ	Critical state parameter: Slope of the straight Rebound-Reconsolidation Line when viewed in the void ratio versus log effective stress space.
	OCR	Over Consolidation Ratio – defined as the ratio of maximum depth of burial to the current in situ depth of burial. An OCR of 1 indicates that a rock is at its maximum depth of burial and is said to be normally consolidated. A sediment that has been buried to depth and has been exhumed to near surface will have a high OCR and is said to be highly over-consolidated (i.e. has consolidation characteristics of a rock of greater depth of burial).

	YSR	Yield Stress Ratio - defined as the ratio of the current partially saturated yield stress to the mean net stress, and therefore varies with depth. The yield stress increases with suction, giving high *YSR* values close to ground surface.
	Dilatancy boundary/critical state/brittle-ductile transition	Stress-state between the conditions where deformation is brittle (dilatant) and ductile (compressive). Deformation at this state is isovolumetric.
	Void ratio	Ratio of the volume of void space to that of solid material in a sediment.
	P-wave sonic velocity	Seismic wave velocity that involves particle motion of alternating compression and expansion in the direction of propagation (Primary or Push wave).
	Specific volume	The volume of a substance per unit mass. The reciprocal of density.
	Lode angle	The third invariant of stress.
	Bulk modulus (K)	Defined as the ratio of the pressure on a body to its fractional decrease in volume. This parameter refers to elastic (recoverable) deformation.
	Creep law	Creep is the time-dependent deformation of rock. There are many creep models that are used to describe time-dependency. Each of these models have several parameters, some of which have physical basis while others are purely empirical.
	Anisotropy	Many of the mechanical and hydraulic parameters listed in this table are directional and have strong anisotropy. For a thorough understanding, each parameter should be quantified for anisotropy.
	f P	Effect of confining pressure on porosity, permeability, strength
	f T	Effect of temperature on porosity, permeability, strength
	f Chemistry	Effect of fluid composition on permeability, strength
	$f\ \dot{\varepsilon}$	Effect of strain rate on strength, permeability
	f Shear	Effect of shearing on permeability
	f Swell	Effect of swelling on all responses
	Temperature	Temperature of the system.
	Coefficient of friction (μ)	Friction is the force that resists the motion of one surface relative to another with which it is in contact.
	Effective pressure coefficient (χ)	Description of whether a rock perfectly obeys the law of effective stress, which states that effective stress = total stress – pore pressure. Perfect conditions occur for $\chi = 1$.

Table 3-1 - Parameters important to assessing gas and fluid transport in the EDZ

4 In-situ and laboratory characterisation methods

In order to understand fully the processes that occur in the EDZ, it is necessary to conduct many experiments on both 'intact' material and that within the EDZ of URLs. These experiments can be *in situ* tests, measuring conditions at the test site, or laboratory, where small samples of rock can be investigated in a highly controlled manner.

4.1 PERMEABILITY TESTS

A number of techniques have been developed to examine the transport characteristics (e.g. intrinsic permeability, capillary pressure, relative permeability, dilatancy and pathway flow) of natural and synthetic materials. The choice of test methodology depends on the type of material under investigation and the parameters required for a particular study. The main laboratory and field techniques are based on simple principles where the injection permeant is held at a constant pressure, injected at a constant flow rate or increased to an elevated pressure and then allowed to decay. A laboratory or field study can often employ one or more of these techniques to fully quantify the transport characteristics of a particular material or formation.

4.1.1 Laboratory permeability tests

In **constant pressure gas testing**, the injection pressure of the permeant is raised in a series of steps until gas entry occurs. Subsequent steps in gas pressure are used to define the gas permeability function. In **constant flow rate tests**, the gas permeant is pumped into the upstream reservoir of the injection system, gradually raising its pressure until it overcomes the resistance for flow within the laboratory specimen. Once gas movement within a specimen occurs, flow rate into the injection system can be varied to examine the transport characteristics of the material, thereby defining the permeability function. In **pressure decay tests**, the gas pressure is increased rapidly to a value exceeding that of sum of capillary entry and porewater pressures, so that gas flow begins at the start of the test. Pressure in the injection system is then allowed to decay with time. The shape and asymptote of the pressure decay curve can be analysed to yield both permeability and capillary pressure data. The **pore-pressure oscillation technique** (Kranz *et al*., 1990; Fischer, 1992; Fischer and Paterson, 1992) relies on the generation of a sinusoidally varying pressure pulse in the upstream pore fluid reservoir by means of a computer-controlled servosystem. Transference of this pressure wave through a porous sample results in amplitude attenuation and phase shift when measured in the downstream reservoir, from which specimen permeability can be calculated. Tests can be conducted with different upstream pressure amplitudes, typically 1 MPa, and with varying periods, usually between 100 and 2000 seconds.

Constant pressure and constant flow rate tests result in a progressive desaturation of the material as gas pressure and saturation increases (i.e. a drainage response). In contrast, pressure decay tests result in a progressive reduction in gas saturation as gas pressure decreases (i.e. an imbibition response). The hysteresis between these two types of behaviour and the time dependency of some of the processes under investigation may result in a range of values depending on the test methodology selected. A comparative study of the different testing techniques has yet to be undertaken. However, given the unique physico-chemical properties of mudrocks and diversity and complexity of their behaviour, a rigorous and complete appraisal may take considerable time.

Either way, the selection of test methodology and subsequent design of the experimental programme should be appropriate for the formation under investigation in order to provide quantify data suitable for the purposes of the study. In designing a test programme, care should be taken to minimise perturbations (both chemical and physical) to the material under examination, for example, caused during installation of field equipment or sampling and specimen manufacture. When determining intrinsic permeability in chemically reactive formations such as clays, mudrocks and shales, drill fluids and aqueous permeaments should be matched, where appropriate, to the properties of the interstitial fluid. Laboratory and field tests should be performed under representative conditions, with the test procedure carefully designed to prevent inducing a material response which is non-representative of the natural behaviour.

Laboratory tests can have the addition of axial load in order to ascertain the changes in transport properties during deformation. This allows transport properties to be mapped onto mechanical frameworks, such as the critical state model. The laboratory allows researchers to isolate the environmental parameters, such as pore pressure, confining pressure, axial stress, temperature, pore fluid chemistry, etc, to describe fully the effect of each.

4.1.2 In situ permeability testing

Packer tests consist of one or more ‘packers’ that are inflated along a section of borehole. The pore-pressure can be varied between the ‘packers’ thereby defining the transport characteristics within the isolated interval of rock. This allows variations in transport properties to be determined through the EDZ.

Injection tests are conducted with the injection of a gas or other fluid at specific pressure ‘steps’ up and/or down an appropriate pressure range. The behaviour of the system to these tests can render useful information on the rock and fracture behaviour. **Discharge tests** are carried out in boreholes with flowing conditions. The natural formation pressure response is monitored after the equilibrated shut-in is allowed to decay with respect to time. **Shut-In recovery tests** are often run immediately following a Discharge test. The build-up in pressure over time is monitored to provide information on the transport characteristics of the formation.

A **slug test** essentially consists of measuring the recovery of head in a well after a near-instantaneous change in head at that well or in a nearby observation well. In the standard configuration, a slug test begins with a sudden change in water level in a well. This can be done, for example, by rapidly introducing an object ("slug") or equivalent volume of water into the well (or removing the same), causing an abrupt increase (or decrease) in water level. The system is monitored as it returns to equilibrium after the gradient imposed by the sudden change in head.

Pump tests may be conducted to determine (i) the performance characteristics of a well and (ii) the hydraulic parameters of the EDZ. The latter is to provide data for transmissivity, hydraulic conductivity and storage coefficient. A pumping test consists of pumping a well at a certain rate and recording the drawdown in the pumping well and in nearby observation wells at specific times. This can be done either by constant-rate tests or step-drawdown tests. In the constant-rate test, the well is pumped for a significant length of time at one rate, whereas in a step-drawdown test the well is pumped at successively greater discharges for relatively short periods.

A **drawdown test** is one in which the rate is held approximately constant while the well pressure is measured. The well pressure generally falls over time. The rate at which the pressure changes depends on reservoir and fluid properties, reservoir boundaries, and drive mechanisms. Thus, the pressure response can be used to estimate these parameters.

It is hard to maintain a constant rate on a flowing well, but it is easy to keep a well at a rate of zero. We can run a pressure transient test by monitoring the pressure after any sort of rate change; changing the rate to zero has lots of advantages. In a **buildup test**, we simply shut the well in (usually at the surface, but it may be downhole) and monitor the pressure buildup using pressure gauges.

Sometimes we are concerned about large-scale property trends. We can monitor the pressure changes at one well (the “observation” well) due to flow rate changes at another (the “active” well). This can give improved estimates of directional permeability in the EDZ.

4.1.3 Microstructural and macrostructural studies

Microstructural studies are an important part of both *in situ* and laboratory experiments. It is possible to inject resin into the wall rock of the EDZ and to obtain material for the preparation of microstructural analysis. It is relatively straightforward to inject resin into a laboratory sample through vacuum injection. In both cases, this analysis aims to examine clay fabric, porosity, mineralogy and fracturing changes between intact and deformed samples. This analysis allows a thorough understanding of the underlying processes that occur within the EDZ.

Macrostructural studies are also an important part of our analysis and offer insight into the processes that occur within the EDZ. These studies are conducted by mapping observed fractures in the tunnel wall. It is common for new tunnels to be built off main tunnels within a URL or waste storage facility. These ‘new’ features allow ‘older’ features to be described as they get exposed.

4.1.4 Ventilation test

Ventilation tests offer significant insight into gas transport in the EDZ, including the potential coupling of chemical processes to hydraulic and mechanical processes. These tests aim to estimate the desaturation and resaturation times produced by drift ventilation, the saturated hydraulic conductivity of the rock and the evolution of the EDZ, in terms of changes in hydraulic conductivity and of displacements caused by the generation of cracks on drying.

The ventilation test works by producing air at the required relative humidity and constant temperature. By ventilating a tunnel with air under controlled climatic conditions, the progress of the desaturation/resaturation front and its effects (mechanical, hydraulic and geochemical) can be determined within several short boreholes. This is achieved with sensors for temperature, pore pressure, rock displacement, water potential and water content.

4.1.5 Geophysical methods

There are a range of geophysical methods that offer useful information about the EDZ and aid in our understanding of processes that occur. Geophysical methods can be particularly useful in the fact that most are non-invasive. Most techniques do not require the drilling of boreholes or any disturbance to the EDZ. It can be argued that every borehole drilled through the EDZ will in fact have its own EDZ, which may influence any form of measurement taken within that borehole.

Geophysical techniques can be grouped into sonic, electromagnetic and resistivity based tests. Sonic methods include seismic reflection, seismic refraction, dipole-sonic imaging, borehole televiewer (BHTV), ultrasonic borehole imager (UBI), and acoustic emissions monitoring. Electromagnetic methods include conventional EM tools and ground penetrating radar (GPR). Resistivity methods include electrical tomography, formation micro-imager (FMI), formation micro-scanner (FMS), deep laterolog, shallow laterolog, and micro-spherically focussed log (MSLF). These tools can be used to analyse the walls of boreholes, the wall-rock immediately beside a borehole or tunnel, or can be designed to ‘image’ in 3D the rock between 2 boreholes. No geophysical method has been designed to directly measure mass transport properties. They can however, offer detailed information about many useful properties within the EDZ and from relationship of known parameters can be used to estimate permeability and porosity.

5 Case Studies

5.1 BOOM CLAY – EXPERIENCE OF MOL, BELGIUM

In situ observations of evolving pore fluid pressure in the EDZ at Mol, Belgium, give information on transport properties. Excavation of a gallery induces perturbations of the surrounding in-situ stress field and pore pressure field, combined with the generation of displacements. The construction of the Test-Drift (TD) gallery at Mol in April 1987 allowed transport properties to be monitored over time. The 65 metre long gallery has an approximate excavated radius of 2.40–2.45 m. Instrumentation (tassometers, inclinometers and piezometric filters) was installed in the surrounding clay several months before the excavation started

Pore pressure measurements

One borehole dipping at approximately 22° to the excavation was instrumented with five piezometric filters. The measured pore pressure at the five filters is shown in Figure 5-1 as a function of time (Bonne *et al.*, 1992). The influence of the excavation is marked by a rapid drop in pore pressure (u_w), by an amount which depends on the radial distance from the tunnel wall: the u_w drop ranges from 7.2 bars at a radius of 7.6 m to 10 bars at a radius of 12.1 m. Due to the low hydraulic conductivity of the Boom Clay ($k \approx 4 \times 10^{-12}$ m.s^{-1}), the main part of this pressure drop is induced by the volumetric dilation of the clay skeleton. Based on the absence of volumetric strain in the elastic zone around an excavation these results would suggest a plastic zone extent of at least 12 m around the tunnel. However, a contribution to the pressure drop may also come from the water flow towards the gallery.

While the data shown in Figure 5-1 only report pore pressure and not gas flow properties, these observations give us valuable insight into the changes in fluid flow properties within the EDZ, where taking direct flow properties can be challenging. Figure 5-1 clearly shows that a complex change in physical properties occurs within the EDZ. The change in pore pressure is likely to be accompanied by a change in permeability and porosity.

Modelling of the EDZ system can be used to rationalize in situ observations and offer insight into the processes that are occurring during EDZ development and long term EDZ stability. The excavation of the Test-Drift gallery (Mol) was simulated with three constitutive models (Barnichon, 2002). These models were 1) a modified Cam-clay approach, 2) the bounding surface concept based on a simplified Dafalias–Kaliakin model, and 3) the bounding surface concept based on a generalized Al Tabbaa bubble model.

This modeling allowed radial convergence to be modeled and also showed that the extent of the hydraulic disturbance predicted from the bounding surface models was qualitatively closer to in-situ data than the value predicted from the modified Cam-clay model. It highlighted that the hydraulic disturbance is closely related to the extent of the plastic zone around excavations. It should be noted that the amplitude of the pore pressure disturbance was much lower than that measured in the Test-Drift. This discrepancy may come from 1) water flow that was not taken into account, 2) from clay damage close to the excavation walls that may increase locally the hydraulic conductivity, and/or 3) from the viscous behaviour of the clay host-rock.

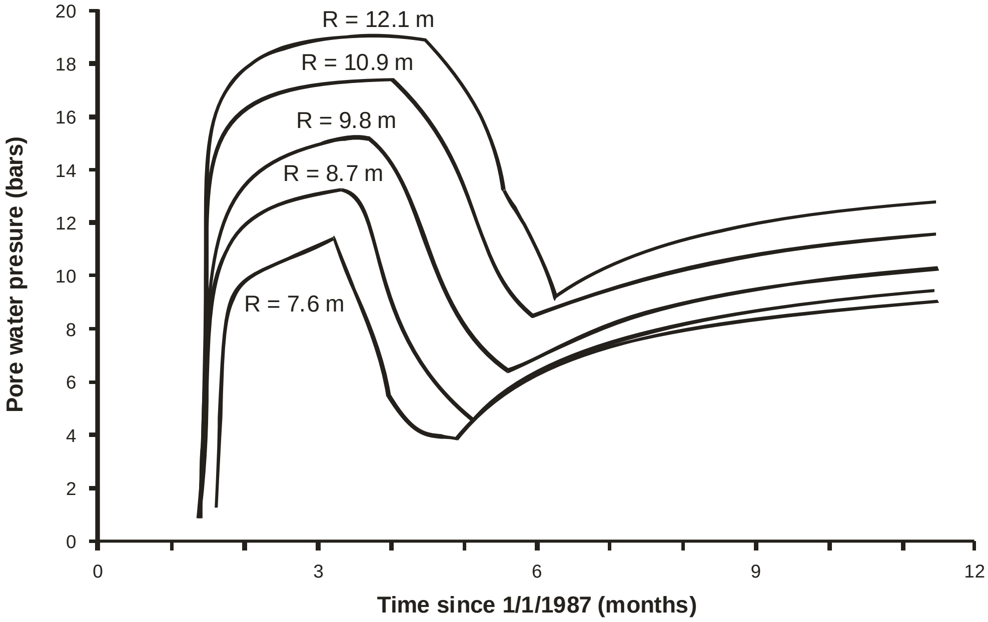

Figure 5-1 – Pore pressure recorded by 5 piezometers during excavation of the Test-Drift gallery in the Boom clay. From Barnichon (2002).

This example highlights the importance and role of the plastic zone in altering the fluid transport properties in the EDZ and near field. Therefore it is not only the creation of new damage in the form of fracturing that plays a role in modifying gas transport.

6 Independent evidence

Considerable information on gas transport in the EDZ can be acquired from a trawl of the available literature for other industries. Of particular interest to the current problem are studies conducted by the hydrocarbons industry, civil engineers and structural geologists.

The gas transport mechanisms in a tunnel wall are a specific problem only really encountered in the nuclear waste disposal industry. Therefore, direct information is not available. Considerable data exist on the permeability characteristics of hydrocarbon reservoir cap-rocks (shale and mudrock), which indicate the likely changes in matrix permeability as a result of a stress change in the EDZ. Several studies have also investigated the modification of fracture permeability of argillaceous rocks. This information can be used to analyse the changes in flow properties expected in the EDZ. Finally in this section, we introduce two concepts from the hydrocarbons/structural geology fields; the concepts of fault valve behaviour and critical stress. These may be important considerations in the EDZ.

The permeability of rocks has been widely reported under hydrostatic stress conditions (e.g. Zoback and Byerlee 1975a; Walsh and Brace 1984; Morrow *et al.*, 1984; David *et al.*, 1994; Dewhurst *et al.*, 1999a; Dewhurst *et al.*, 1999b; Katsube, 2000; Katsube *et al.*, 1996a; Katsube *et al.*, 1998; Kwon *et al.*, 2001; Neuzil *et al.*, 1984) in order to establish the relationship between effective stress and permeability for different rock types. However, in the field, rocks are normally subjected to an inhomogeneous stress-field, where the vertical stress (determined by the weight of the overburden) exceeds the two horizontal stresses (Holt 1990). This has led to investigations of the sensitivity of matrix permeability to non-hydrostatic stress conditions, especially in sandstones (e.g. Keaney *et al.*, 1998; Zhu and Wong, 1994; Zhu and Wong, 1997).

The evolution of permeability in rocks under hydrostatic stress conditions has been widely reported. Many researchers have shown that the permeability of shale decreases with externally applied stress (Dewhurst *et al.*, 1999a; Dewhurst *et al.*, 1999b; Katsube, 2000; Katsube *et al.*, 1996a; Katsube *et al.*, 1998; Kwon *et al.*, 2001; Neuzil *et al.*, 1984) and decreased porosity (Dewhurst *et al.*, 1998; Schloemer and Kloss, 1997). A range of non-linear relationships have been proposed between permeability, porosity, and pressure in shale and mudstones, including exponential and power laws between permeability and pressure (Dewhurst *et al.*, 1999a; Katsube *et al.*, 1991).

Heidlund (2003) reviewed published studies of the stress-sensitivity of matrix permeability during triaxial deformation and for various stress-path experiments. This information allows us to map permeability evolution of the initially intact rock onto a theoretical framework, such as the critical state approach. Unfortunately, most of these studies were not conducted on argillaceous material.

6.1 CHANGES IN FRACTURE TRANSMISSIVITY

Gutierreza *et al.* (2000) investigated experimentally the hydromechanical behaviour of an extensional fracture in Kimmeridge Shale under normal and shear loading. It was shown that, at the time it was created, the fracture had about nine orders of magnitude higher permeability than that of the intact shale. Increasing the contact normal stress across the fracture reduced the fracture permeability following an empirical exponential law, as shown in Figure 6-1. However, loading the sample to an effective normal stress twice as much as the intact rock unconfined compressive strength did not completely close the fracture, although it did reduce the permeability by an order of magnitude.

Shearing of the fracture at a constant effective normal stress lower than the unconfined compressive strength of the shale caused dilation of the fracture and an order of magnitude increase in fracture permeability. Shearing at a constant normal stress higher than the unconfined compressive strength of the intact shale caused negative dilation of the fracture and about six orders of magnitude reduction in fracture permeability. The reduced permeability is due to shear-induced gouge formation and transported particles blocking the fracture apertures. However, despite the reduction being close to six orders of magnitude, the fracture permeability was still about three orders of magnitude larger the intact rock permeability.

The ability of rough fractures to retain much of their permeability in the presence of contact stresses across the fracture plane can be attributed to the microscopic structure and roughness of the fracture surfaces. Even in the case of severe loading exceeding the strength of the sediment matrix, it appears that the microscopic asperities at the fracture surface are able to keep open some space and channels along the fracture to allow for fluid flow and to maintain enhanced permeability.

Based on the above results, the current definition of a ‘closed’ fracture as one in which the fracture surfaces come in contact is inadequate. There is, therefore, a need to distinguish between physically or mechanically open/closed fractures and hydraulically open/closed fractures.

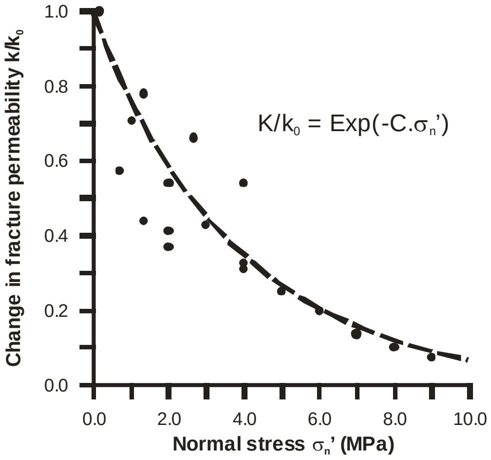

Figure 6-1 – Change in fracture permeability of Kimmeridge Shale with increasing normal effective stress (from Gutierreza *et al.,* 2000).

6.2 THE INFLUENCE OF STRESS ON FAULT/FRACTURE SEALING

The concept of critical stress analysis (Barton *et al*., 1995) is also considered significant. This approach is merely an extension of the idea that fluid-flow properties are related to stress. Any fault, or fracture, will have a three-dimensional spatial orientation at an angle to the three-dimensional stress regime. The interaction of these two three-dimensional systems will result in a component of normal and shear stress along the fault/fracture. Field observations have shown that some fractures along a borehole flow, whereas others do not. The critical stress analysis aims to predict qualitatively those orientations of faulting that will facilitate flow, and hence those that will impede it. These ideas have been widely applied and tested in a number of tectonic settings, including sedimentary reservoir environments, such as the North Sea (Wiprut and Zoback, 2000; Wiprut and Zoback, 2002), Santa Maria Basin (Finkbeiner *et al*., 1997), the Gulf of Mexico (Finkbeiner *et al*., 2001) and the Timor Sea (Castillo *et al*., 2000), and also in crystalline environments (Barton *et al*., 1997; Hickman *et al*., 1997; Ito and Zoback, 2000; Reeves, 2002; Rogers, 2000; Talbot and Sirat, 2001). In the case of the repository, this approach can be used to predict which of the pre-existing faults are likely to seal and which will not.

A more complex approach is needed in order to predict the local stress variations created around the EDZ. Here we observe a complex interaction between the triaxial far-field stresses with those of the localised hoop and radial stresses (a combination of Cartesian and polar stress components). At each point around the tunnel periphery, a different resultant stress direction will act upon the fracture network, which will also tend to be curved in nature.

6.3 THE INFLUENCE OF TIME ON FAULT/FRACTURE SEALING

Faults/fractures tend to be categorised as either sealing or non-sealing. This is an oversimplification, because the combination of lithological and throw variations ensures that the fault rock will be heterogeneous. Faults have been shown to be complex systems, with fault leakage occurring along parts of faults, while other sections seal. As discontinuities tend to follow micro to macro relationships, it is expected that this same variability can be observed along individual fractures. As stress conditions alter over time, a sealing fault may leak. It is therefore vital that these features are not viewed as static over geological or engineering time scales. Pore pressure has been shown to be a vital parameter in achieving sealing or leaking and so pore pressure fluctuations during excavation of an EDZ may result in fault reactivation (fault valve behaviour) and therefore fault leakage.

Fault-valve theory deals with a form of fault reactivation. Faults that act as impermeable seals may behave as fluid-pressure activated valves whenever they transect a suprahydrostatic pressure gradient (Sibson, 1990). The concept of fault valve behaviour may also be fundamental in the long-term performance assessment. The construction of an EDZ will create new fractures; it may also reactivate pre-existing features. Sibson's ideas suggest a fault will seal while the pressure below is low. In the context of hydrocarbons reservoirs, the pore pressure rises as the hydrocarbon column enlarges, and at some threshold this results in fault breach. In the case of a repository there is an evolving pore pressure history as the country rock re-hydrates, the buffer material swells, and possibly gas pressures deriving from the waste itself rise. Thus pore pressures may sufficiently increase to cause the reactivation of tectonic faults and may result in the previously sealed fractures facilitating flow. It is possible that the resultant flow may also promote chemical reactions, which may facilitate self-healing.

Active sealing, where mechanical or diagenetic variations are created within the fault zone itself, are of most interest within the EDZ and performance assessment. Cataclasis, diffusive mass transfer, cementation, and clay smear are fault seal processes that could singly or in combination alter the pore structure and permeability of a discontinuity during and after deformation events within the EDZ. As the seals are created by deformation, their properties primarily depend upon the: 1) host rock lithology; 2) the deformation process; 3) stress conditions, including pore pressure; and 4) degree of cementation and the chemistry of the system.

6.4 BOREHOLE STUDIES

Aoki *et al.* (1993) used constitutive modelling to describe borehole failure in saturated shales. Aoki argued that pervious modelling had been based upon drained conditions, and that the drilling of a borehole through shale is such that the rock behaves as if undrained. This modelling approach shows that the compaction of the rock around the circular opening is anisotropic when experiencing an anisotropic stress-field. This creates regions where pore pressure is significantly greater than others. Induced pore pressure is least in the direction of the least horizontal stress orientation (σ_h), and greatest in the direction of σ_H. The anisotropic pore pressure will influence further deformation, compaction and permeability within the EDZ.

7 Conclusions

This report highlights the significant areas of science surrounding the subject of gas transport in argillaceous rocks within the EDZ. The basic concepts have been introduced, along with the mechanical concepts of the dilatancy boundary and self-healing. An outline of in-situ and laboratory testing is given, along with a case study from the Boom Clay of Mol. This report also covers the wealth of knowledge of argillaceous rocks that is available from the hydrocarbons industry, along with principles/concepts that are both applicable to hydrocarbon reservoirs and the EDZ.

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