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Rock physics and geomechanics in the study of reservoirs and repositories

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Abstract: Reservoir management for hydrocarbon extraction and repositories design for radioactive waste storage are two different areas in which rock physics and geomechanics provide valuable information. Although the targets and objectives are different, similar approaches and common attributes exist in both fields: safety assessment, short- to long-term prediction, integration of various scales of investigation, and remote monitoring, among others. Nevertheless, there are also important differences: reservoirs at depth are investigated through remote geophysical studies, well-logging and/or core samples retrieval, whereas direct access to repositories is possible through excavation in the host formation in which underground research laboratories can be constructed. We review a number of studies focusing on geomechanics and rock physics applied to the characterization of reservoirs and repositories, including laboratory experiments and predictive models, at different scales.

Reservoir management and assessment of repository performance require the integration of different fields in Earth sciences, including geochemistry, geophysics, structural geology, and, in the case of interest here, rock physics and geomechanics. We present recent advances in the studies of reservoirs and repositories with the aim of emphasizing how rock physics and geomechanics help to obtain a better insight into important issues linked to reservoir management for exploitation of natural resources, and to repository safety assessment for hazardous waste storage in the geological environment.

In the area of reservoir management, the importance of geomechanics in problems such as wellbore stability, hydraulic fracturing and subsidence is well known. Recently, there has been a growing interest in the development of a link between fluid flow simulators and geomechanical models. Several approaches have been proposed to incorporate the correct physics and to account for physical phenomena usually neglected in reservoir simulation. New techniques developed in laboratory studies provide relevant data for this integration. The approaches differ in the degree of coupling. The stronger the coupling, the more computationally demanding the simulation. Numerical experiments showed that coupling is of interest for poorly consolidated reservoirs such as chalk reservoirs. In other cases, one may wonder whether a more accurate modelling of production processes justifies the required computation cost. Complementary sensitivity studies have to be performed to better estimate the conditions in which the coupling is worthwhile.

In the area of underground waste storage, the key issue is to design a repository as safe as possible for human activity and for the environment at the near surface, on time scales of the order of hundreds of years. This challenging task requires us to identify favourable geological targets for the storage, and to develop extensive scientific research in different fields, so as to obtain eventually a predictive model of the repository evolution over large time scales, when high-level radioactive waste packages will be stored underground. Input for these predictive models can only be obtained by thorough experimental research, at different scales (Fig. 1). For that purpose, underground research laboratories (URL) have been constructed in possible host formations in several countries. Two main options are considered. The 'soft rock' option consists in storing the radioactive packages at depth in weak rocks such as shales, taking advantage of the retention capacity of clays and the creep capability of the soft rocks. In the 'hard rock' option the repository is implemented in low-permeability rocks with a high mechanical strength, such as crystalline rocks.

Whereas the targets are geologically very different (for reservoir rocks, large porosity and permeability are desirable; for waste storage, low permeability and large retention capacity are

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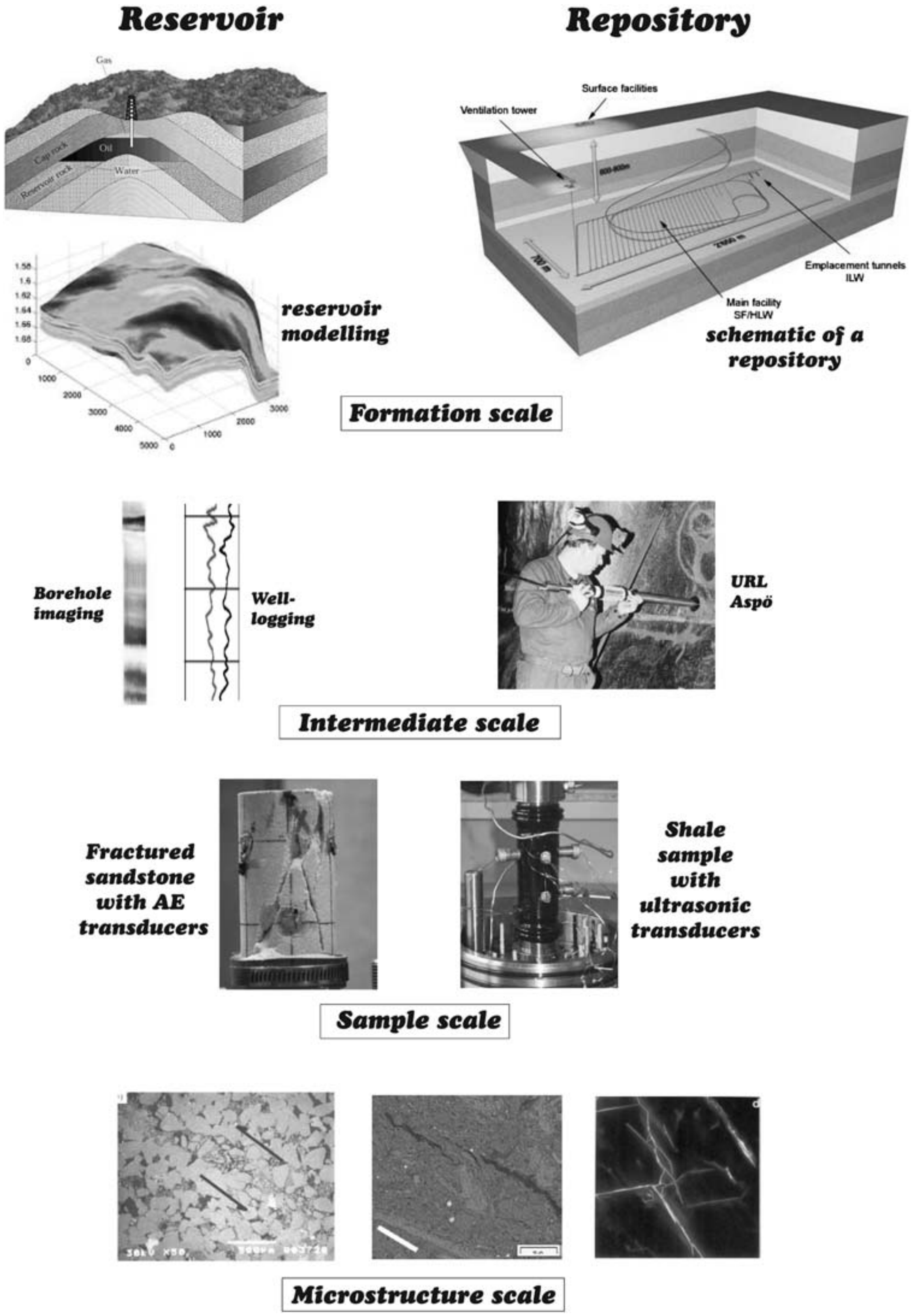

Fig. 1. Synthetic figure showing the different scales that studies in geomechanics and rock physics for reservoir and repository characterization have to deal with. Formation scale: on the left, typical reservoir geometry in an anticline (http://www.maverickenergy.com/oilgas.htm) with an example of a reservoir geomechanical simulation (Fornel *et al.* 2007); on the right, a schematic illustration of a repository in a sedimentary formation (http://www.grimsel.com/general/bg_geoldisp.htm). Intermediate scale: for reservoirs, this scale corresponds to borehole

required), there are common interests for the geomechanics and rock physics community to work on these topics. The first one is obviously to characterize the permeability of the formations, which in one case should be high, and in the other case low. Mechanical stability is also needed in both cases, for drilling the borehole into the reservoir, and for the shaft and tunnels in the repository. Studies in geomechanics and rock physics should also be predictive over different time scales, to forecast the evolution in terms of production rate and storage capacity for reservoirs, and in terms of safety assessment for repositories. The scale effect has also to be considered constantly: properties defined at the micro- or sample scale have to be extrapolated (or upscaled) to the formation scale (Guéguen *et al.* 2006). In this regard, underground research laboratories give the opportunity for researchers to work at an intermediate scale, that of the tunnels in which the packages will be stored, a possibility that does not exist for reservoir studies. Finally, there is the need for monitoring the sites (reservoirs or repositories), to anticipate any problem that might occur during production or operation.

Below, we present some recent advances in the area of geomechanics and rock physics applied first to reservoir characterization, and second to repositories in different geological environments.

Reservoir studies for hydrocarbon recovery

Over the past decade, reservoir geomechanics has emerged as a necessary integral part of reservoir simulation studies to better develop and manage oil reservoirs. First, withdrawing or injecting fluid from into the reservoir causes a change in pore pressure, which results in a change in the 3D effective stress state. The stress path followed by the reservoir governs the evolution of the effective stress state; that is, the change in deviatoric stresses, which produces rock deformation and permeability changes. Second, one of the most challenging fields in reservoir engineering is the integration of all available data for the characterization of reservoirs and the reduction of uncertainties in oil and gas production. These data traditionally include such factors as production history, water cuts and gas/oil ratio. Since the late 1990s, they also consist of 4D seismic data; that is, repeated 3D seismic acquisitions. Four-dimensional seismic data are potentially a powerful tool for monitoring fluid movements throughout the reservoir. The integration of 4D seismic data into reservoir modelling clearly depends on the link between transport and elastic properties. Below, we discuss the issues related to the interplay between geomechanics and flow simulation in produced reservoirs.

Geomechanical effects in produced reservoirs

To date, in conventional flow simulators, the pore volume variation only depends on the pore pressure variation through a pore volume compressibility coefficient (Geertsma 1957). According to this approach, stress changes and strain resulting from reservoir production are not explicitly computed and the pore volume change is directly related to the pressure change through the rock compressibility, which is the only mechanical property considered in conventional reservoir simulations. The use of such a rock compressibility factor implicitly supposes that the stress path followed by the reservoir is known *a priori* and constant during reservoir production. On the other hand, reservoir permeability is unaffected by pore pressure changes. In addition, conventional flow simulators do not account for the interactions between the reservoir and the surrounding regions, such as overburden, underburden and sideburden. Therefore, these simulators are restricted to reservoirs with competent rocks and laterally uniform rock properties: they do not apply to reservoirs where stresses change. However, during reservoir production, many mechanisms generating variations in pressure, saturation and temperature are likely to induce stress changes. The geomechanical contribution is particularly significant for poorly compacted reservoirs and highly compacted rock formations.

(*Continued*) studies using Formation Microscanner imaging or well-logging tools; for repositories, this scale corresponds to underground research laboratories where scientists have direct access to the host formation for instrumentation (http://www.skb.se/default2____16762.aspx). *Sample scale*: concerns laboratory experiments on rock cores retrieved from boreholes or from URLs. On the left, fractured Bentheim sandstone sample (height 80 mm) with acoustic emission (AE) sensors located at the surface, after a mechanical test; on the right, experimental device for loading a COX argillite sample in a triaxial setup (Sarout 2006) with ultrasonic transducers mounted on the sample surface through a Neoprene sleeve. Microstructure scale: this is the scale of grains, pores and cracks. On the left, scanning electron micrograph of a shear band in Berea sandstone (scale bar represents 500 μm); in the middle, scanning electron micrograph of crack patterns in a COX argillite sample after triaxial mechanical testing (scale bar represents 100 μm); on the right, confocal microscopy image of cracks in a granite from Spain (courtesy B. Menéndez & J. Sarout).

Poorly compacted reservoirs. Typical poorly compacted reservoirs consist of chalks and unconsolidated sands. As the reservoir is produced, the pore pressure diminishes, leading to an increase in the effective stress. It triggers grain-scale deformation processes (e.g. Bernabé & Evans 2007) causing elastic (recoverable) and inelastic (permanent) reservoir strain. The increase in the effective stress can be sufficient to enhance reservoir compaction.

Compaction generates an increase in pore pressure (Charlez 1997), which enhances fluid production. For instance, for the Bachaquero field in Venezuela, half of the production was driven by compaction (Merle *et al.* 1976). Depending on rock properties, compaction can propagate to the surrounding sideburden and overburden (Segall 1989). Contraction in the vertical direction is accommodated by subsidence of the free surface. Subsidence can vary from a few centimetres to a few metres. Contraction in the horizontal direction is resisted by the surrounding rock, which is pulled towards the reservoir. Compaction has been recorded in a number of notable case histories. For example, the Wilmington field, located in California, experienced a maximal subsidence of about 9 m as a result of production over 20 years. Horizontal displacements as large as about 4 m were also recorded (Allen 1968). Another example is the Ekofisk field in the North Sea, where a sea-floor subsidence of 42 cm per year was reached in 1990 (Sylte *et al.* 1999). Another consequence of compaction is well failure. At the Belridge diatomite field, California, nearly 1000 wells have experienced severe casing damage during the past 20 years of production.

As stated above, compaction contributes to improve production by squeezing oil from the rock into the borehole. It is also the basis of a contrary effect. Compaction decreases reservoir porosity (Weng *et al.* 2005), thereby reducing reservoir permeability (Wong *et al.* 1997; Ostermeier 2001), and ultimately production.

In addition, recent field and laboratory studies suggest that the overall picture can be much more complicated than simple, uniform compaction. Thin, natural tabular zones of compaction in certain types of sandstone, called compaction bands, were observed in outcrop by Mollema & Antonellini (1996) and Sternlof *et al.* (2005). Similar features were also noticed around boreholes (Haimson 2001). Because of the much reduced porosity in the compaction bands, these structures are potentially important as permeability barriers in reservoirs (Sternlof *et al.* 2006). To avoid the conditions leading to the formation of compaction bands, which can produce destructive compartmentalization of reservoirs, one has to better understand how the occurrence of localized zones of compaction is related to the stress state and the constitutive properties of the rock. Development of this phenomenon has been investigated in the laboratory, primarily in sandstones with porosities ranging from 13% to 28% (DiGiovanni *et al.* 2000; Olsson & Holcomb 2000; Klein *et al.* 2001; Fortin *et al.* 2006). The data show that localized failure in compactant rock is commonly associated with stress states in the transitional regime from brittle faulting to cataclastic flow (Wong *et al.* 2001), with the mode of localization associated with a broad spectrum of complexity (Baud *et al.* 2004; Ngwenya *et al.* 2003). Simultaneous measurements of stress, strain, acoustic emission locations and permeability during experiments on sandstone samples revealed an up to two-orders-of-magnitude decrease in permeability in the compacted zone (Holcomb & Olsson 2003; Vajdova *et al.* 2004). Theoretical modelling (Katsman *et al.* 2005; Katsman & Aharonov 2006) and microstructural studies (Louis *et al.* 2007) suggest that grain-scale homogeneity played a major role in the development of discrete compaction bands. Rudnicki (2007) has proposed a theoretical model for the propagation of compaction bands. Haimson & Lee (2004) focused on boreholes in Mansfield sandstone, which fail by developing fracture-like breakouts. The Mansfield sandstone contains mainly quartz grains (90%) held together primarily by spot-sutured contacts. Haimson & Lee (2004) observed that the failure mechanism was the removal by the circulating drilling fluid of mainly intact grains loosened during the formation of the compaction band. They concluded that the initial porosity, type of cementation, mineral homogeneity, grain strength, and sphericity appear to be major factors in the formation of compaction bands. Haimson & Klaetsch (2007) performed miniature drilling in St. Peter sandstone samples. They showed that compaction bands precede slot-shaped breakouts, which are formed by flushing off grains from within these bands.

Highly compacted reservoirs. Highly compacted reservoirs include fractured and faulted reservoirs. The main geomechanical effects for these reservoirs is not compaction, but fracturing and changes in fracture conductivities. These effects are related to thermo-poroelastic changes (Guttierrez & Makurat 1997). They can be observed around water injectors, because of the injection of cold water. They also appear around fractures and fault planes: because of the high stiffness of the matrix, strains are localized on fractures and alter their hydraulic conductivities. As a result, preferential flow paths can be created and change production (Heffer *et al.* 1994; Koutsabeloulis *et al.* 1994).

Coupling between flow simulators and geomechanical models

As mentioned above, for both weakly compacted reservoirs and highly compacted fractured reservoirs, the expected deformation can strongly influence permeability. To account for the geomechanical effects generated by stress changes in and around reservoirs, the fluid flow problem has to be solved in association with a geomechanical model, which accurately predicts the evolution of stress-dependent parameters through time.

Over the past decade, studies focused on the coupling of flow simulators with geomechanical models (Gutierrez & Makurat 1997). However, theoretical and practical difficulties have prevented coupled approaches from being used routinely in simulation studies. Some of these challenges are the complex mechanical behaviour of geomaterials, the strong interplay between mechanical and flow problems, and the fact that reservoir models become very computationally intensive.

As mentioned by numerous researchers, the coupling occurs in various forms, which are listed below. Each coupling technique has its own advantages and disadvantages. Further information has been given by Longuemare *et al.* (2002), Tran *et al.* (2005) and Jeannin *et al.* (2006).

Partial coupling. Partial coupling means that the stress and flow equations are separately solved from two distinct simulators, but intermediate results are passed between the two simulators. Basically, the pore pressure and temperature increments calculated by the flow simulator are given to the geomechanical simulator, which computes the corresponding changes in stresses. These are used to update the permeability values provided to the flow simulator. Partial coupling often uses the finite-difference method for fluid flow simulators and the finite-element method for geomechanical simulators.

Partial coupling may be explicit or iterative. If the information obtained from the geomechanical simulator is not sent back to the flow simulator, the coupling is explicit. If the information is passed back and forth until convergence, the coupling is iterative. Because of its reduced computing cost, explicit coupling is often preferred (e.g. Settari & Mourits 1998). It can be applied to gas reservoirs without significant error, as gas compressibility usually dominates rock compressibility. In such a case, the mass balance is mainly controlled by gas pressure rather than stresses. Iterative coupling requires more CPU time. The computation needed to achieve an iterative-coupled simulation is around 200 times longer than a conventional reservoir simulation (Samier *et al.* 2006). This approach is preferred when the reservoir behaviour is sensitive to compressibility.

Full coupling. Full coupling is more rigorous: it involves the simultaneous solution of stress and flow equations in the same simulator (e.g. Stone *et al.* 2000), and anisotropy and nonlinearity must be handled. The full coupling usually gives good solutions, but may be extensively CPU-time consuming, especially when dealing with steam-assisted gravity drainage (SAGD) in reservoirs with nonlinear behaviours. Its feasibility and accuracy have yet to be proved for large-scale reservoirs.

Partial iterative and full coupling methods are equally recommended when rock compressibility affects the material balance. Two examples are liquid-filled reservoirs with compaction and subsidence problems and reservoirs with highly nonlinear geomaterials. The iterative coupling approach is considered to be the most flexible, as it can be used without substantial code modifications.

Numerical experiments. The results of a few numerical experiments carried out to investigate the influence of the geomechanical flow simulation coupling are reported in the literature. Jin *et al.* (2000) considered a typical North Sea reservoir. They ran reservoir simulations first with only the flow simulator and second with a flow simulator partially coupled to a geomechanical model. They observed that the evolution of the stress state significantly affects the oil production profile. Longuemare *et al.* (2002) used a partial coupling method to investigate the sensitivity of a highly heterogeneous and compartmentalized limestone reservoir to stress. They showed that the perturbation of the reservoir equilibrium leads to progressive strain localization on a limited number of faults. Samier *et al.* (2006) also carried out a comparative study for two field cases: a large North Sea chalk reservoir and a North Sea HP–HT gas reservoir in a faulted geometry. Samier *et al.* performed different simulations with an increasing coupling. For the chalk reservoir, the results leave no doubt about the importance of using a flow simulator with a geomechanical coupling. The difference in hydrocarbon production and reservoir pressure can reach 25%. For the HP–HT faulted reservoir, the difference in gas and oil production is less than 5% and 1%, respectively. The geomechanical analysis stressed that the three major faults in the central area are not reactivated by the depletion.

Application to 4D seismic data

An example is the integration of 4D seismic data in reservoir models. Four-dimensional seismic data result from the interpretation of repeated seismic surveys over a producing hydrocarbon field. They are used to identify changes in reservoir parameters such as pore pressure, saturation and temperature. To date, the integration of 4D seismic data into reservoir models involves iterative workflows (Landa & Horne 1997; Gosselin *et al.* 2000; Kretz *et al.* 2004; Fornel *et al.* 2007). Briefly, an initial reservoir model is proposed and a flow simulation is performed. The computed pore pressures and saturations are then provided to a petro-elastic model usually built from quantitative relationships, most of them being empirical, to link elastic properties of rocks to pore space, pore fluid, fluid saturation, pore pressure, and rock composition (Mavko *et al.* 1998). In this regard, the theory of poroelasticity provides the right framework to address these problems: Blöcher *et al.* (2007) thoroughly investigated the poroelastic response of Bentheim sandstone samples in undrained conditions and compared their experimental results with finite-elements calculations using detailed information on the rock microstructure. Microtomography techniques have become very powerful in imaging the 3D geometry of porous rocks, from which poroelastic properties can be derived (Arns *et al.* 2002). The petro-elastic model allows for calculating seismic velocities, impedances and time-shifts. The following step consists in comparing the computed seismic answers with the 4D seismic data to be reproduced. Then, the initial model is modified to better match the reference data and the whole process is repeated until 4D seismic data as well as production data are reasonably matched (Le Ravalec-Dupin 2005). In this special case, the coupling is very loose, which means that the computed pore volume changes are derived from pore pressure changes, not stress changes. To our knowledge, the porosity provided to the petro-elastic model is usually the porosity at time zero. In other words, compressibility effects are disregarded, although they are integrated in the flow simulation. In addition, the flow simulation is limited to the reservoir: the overburden and sideburden are not considered. However, as shown by Vidal-Gilbert & Tisseau (2006), the decrease of layer thickness as a result of compaction and the increase in effective stresses result in higher seismic velocities within the reservoir. The seismic travel time is then reduced across the reservoir layer. Above the reservoir, the overburden is stretched and the decrease in effective stresses leads to lower seismic velocities and to an increase in the seismic travel time across the overburden. Therefore, the time-shifts observed at the reservoir base or top are also affected by the overburden. In their preliminary study, Vidal-Gilbert & Tisseau (2006) concluded that the integration of geomechanical modelling to compute time-lapse seismic velocities and time-shifts shows a moderate effect of the reservoir and the surrounding formations. A careful sensitivity study should be performed to estimate what geomechanical modelling can provide to seismic monitoring.

In addition, including the overburden, sideburden and underburden in the modelling means that additional data have to be collected to feed the coupled simulators, which may be a challenging task. Also, as far as fluid production is the main focus, the relationship between permeability and stress should be the key point of the coupling between flow simulation and geomechanics. However, it is neglected in most coupled reservoir simulations. In some flow simulators, an empirical relation between permeability and pressure can be defined. These relations are generally derived from permeability measurements at various pressures during depletion tests, although uniaxial strain paths are not necessarily representative of the stress state in the reservoir. On the other hand, there is no standard method for determining the changes of fracture conductivities of initially sealing faults. These problems should motivate further laboratory and modelling studies.

Repository studies for radioactive waste storage

The management of radioactive waste is of crucial importance for industrial countries. Underground storage is one of the options on which researchers in many countries are currently working. The principle is to place the waste packages at depth in structures excavated in geological formations known to be impervious to water. The depth at which such structures would be excavated should be at least of the order of 500 m to prevent any disturbance at the Earth's surface and any human intrusion. A geological repository is always based on the concept of multiple barriers that prevent, on different time scales, water coming in contact with the hazardous waste, which would lead to hydrodynamic dispersion into the geological environment. The barriers include the waste packages, the engineered barrier (i.e. the filling material placed between the waste and the rock in the excavated structures) and finally the geological barrier (i.e. the host rock itself) (Schmitz *et al.* 2007). The safety of a repository is assessed by taking all of these barriers into account: they should guarantee that the radioactivity cannot escape for at least several centuries. Eventually, on a longer time scale, fluids present in the host formation will reach and corrode the packages, and from that time on the radionuclides still present will slowly be released into the geological medium. The retention quality of the geological barrier is then crucial, to delay the migration of radioactive substances and to limit its extension in space. The choice of the host formation is of prime importance, and many countries have put considerable effort and money into studies to find the best location for radioactive waste repositories. To achieve that goal, characterizing the rock properties from cores retrieved from boreholes or at outcrops is far from sufficient. It is necessary to combine scientific investigations at different scales: at the field scale with studies using preferentially geophysical techniques to characterize the extent and potential of the storage area, and at the sample scale to estimate accurately the host-rock properties. However, it is mostly useful to work at an intermediate scale, that of the underground research laboratory (URL) in which real size experiments in galleries and tunnels excavated in the host rock can be run *in situ*, on the host rock as well as on the engineered barriers (Plötze *et al.* 2007). Several URLs are currently operating around the world, in different geological environments: the Meuse Haute-Marne URL in the Callovian–Oxfordian argillite formation (France), the Mont Terri project in the Opalinus clay formation (Switzerland), the Aspö Hard Rock Laboratory in igneous rocks (Sweden), the Lac du Bonnet laboratory in a granite (Canada) and the Yucca Mountain project in ash-flow tuffs (USA), among others. Only one site is in operation, the WIPP site in the USA, where radioactive wastes are stored at about 700 m below the surface in a salt formation. The questions to be addressed when a repository site has to be designed are numerous: Which geological environment is the more relevant? What would be the environmental impact on a long time scale? What kind of technology will be used to store the packages? Will the repository be designed to be reversible (i.e. will there be the possibility to retrieve the packages back to the surface if new technologies for managing radioactive wastes exist at a future date) or not? Which methods will be used for monitoring the site before, during and after operation? To answer these questions, it is necessary to integrate information from many fields in Earth sciences, including geochemistry, geophysics, hydrogeology, structural geology, and of course geomechanics and rock physics. Geomechanical studies are aimed to assess the mechanical stability of the repository in the excavation phase, during operation and in the post-closure period, whereas rock physics studies aim to characterize the physical properties of the host formation as well as those of the surrounding geological formations, with emphasis on properties related to fluid transfer.

Repositories in soft rock formations

Shales are good candidates for radioactive waste storage because of their mechanical properties (Naumann *et al.* 2006) and very low permeability (Kwon *et al.* 2004*a*, *b*): several URLs are currently devoted to the study of shaly formations; for example, in France (ANDRA 2005*a*) and Switzerland (Bossart & Thury 2007). The Callovian–Oxfordian (COX) argillite formation is extensively studied in the URL that ANDRA (the French agency for radioactive waste management) is operating in the Meuse Haute-Marne region in France. The COX formation is characterized by a low hydraulic conductivity of the order of 10^{-12} m s^{-1} consistently over the region investigated (Distinguin & Lavanchy 2007), a good homogeneity with virtually no tectonic-induced features such as fractures or joints, and a mineralogical composition that ensures high retention capacity and chemical stability (Gaucher *et al.* 2004). From the mechanical viewpoint, the presence of quartz and carbonates in the rock composition gives the rock a reasonably high mechanical strength (Naumann *et al.* 2007), whereas the clays and especially the swelling properties of smectite make the COX argillite easily deformable with a high potential to creep (Gasc-Barbier *et al.* 2004; Zhang & Rothfuchs 2004; Fabre & Pellet 2006).

The creep capability of shales is a very important property for the evolution of the excavation damaged (or disturbed) zone (EDZ) induced by stress redistribution when galleries or shafts are excavated in the host formation. Indeed, creep will eventually lead to the closure of the excavation-induced fractures in the EDZ, which will help the rock to recover its initial state. This is a very important point, because fractures are highly undesirable in a repository because of their weakening effect on the mechanical stability and most of all their capability to drive fluids much faster than in the pore network of the undisturbed host rock (Bossart *et al.* 2002). Fracture healing or sealing also occurs in hard rocks: Bernabé & Evans (2007) studied the process of fracture closure when pressure solution occurs at asperities. In soft rocks, both *in situ* and laboratory studies show that self-sealing of fractures in the EDZ leads to a significant reduction in the effective hydraulic conductivity with time, thus reducing the potential flow along excavated structures at depth (Blümling *et al.* 2007). Corkum & Martin (2007) have shown that the mechanical behaviour of the EDZ in the Opalinus clay is not linear elastic because of the presence of strong diagenetic bonds locking elastic strain energy into the rock microstructure, leading to low mechanical strength. Bossart *et al.* (2006) pointed out that there are still a number of open questions related to the evolution of the EDZ, which need to be addressed by conducting careful experiments like those in progress at Mont Terri. One of these experiments has been described by Damaj *et al.* (2007), who showed that the evolution of the EDZ can be surveyed by means of seismic velocity measurements using a multiple array of sensors combined with tomography techniques to image the disturbed zone. Other key experiments needed for progress have been outlined by Bossart (2007), head of the Mont Terri Rock Laboratory project. Dedecker *et al.* (2007) developed a numerical model (AC/DC; Adaptive Continuum/Discontinuum Code) to predict the variation of permeability close to an excavation in the COX argillite after a few years of its opening: those workers showed that the permeability variations are low, even in the worst scenario that they considered.

Another key issue with the EDZ in repositories is the saturation problem. When drifts or shafts are excavated in a repository, dewatering takes place on the rock wall and the fluid saturation decreases. The effect of excavation on the thermo-hydro-mechanical behaviour of a geological barrier has been studied by Gatmiri & Hoor (2007) using a fully coupled formulation for an unsaturated porous medium subjected to heating in radioactive waste repositories. Rock physical properties and especially mechanical properties are strongly affected by variations in fluid saturation (Mavko *et al.* 1998). An increase in strength and failure strain is generally observed when the saturation decreases (Zhang & Rothfuchs 2004) because most mechanical changes occur along the interlayer space in clays, making the rock softer when saturation increases (Valès *et al.* 2004). Variations in the water content of shales induced by excavation or by heating is also important because it can induce mineralogical transformations, which can be monitored by magnetic measurements (Aubourg pers. comm.).

A common feature in shales is their anisotropy, the origin of which is linked to the depositional conditions of the sediments and the foliated nature of clays. Consequently, most of the physical properties of shales are known to be anisotropic, but the intensity of the anisotropy depends on the rock property. Naumann *et al.* (2007) measured in laboratory experiments the mechanical strength of Opalinus clay samples cored parallel, perpendicular or at 45° to the bedding, and found that the mechanical strength is significantly higher when the loading direction is parallel to the bedding. It is therefore important to have a good knowledge of the orientation of *in situ* stresses in repositories: Martin & Lanyon (2003) showed that this is especially difficult to achieve in weak rocks such as shales. The long-term deformation estimated in creep experiments by Naumann *et al.* (2007) also showed a strong anisotropy, with larger time-dependent strain observed for the samples loaded perpendicular to the bedding plane, in agreement with the results of Zhang & Rothfuchs (2004) on the COX argillite. Valès *et al.* (2004) showed that the failure mode in Tournemire shale samples depends on the core sample orientation with respect to bedding, but also on the water saturation of the samples. Shales are also well known to be anisotropic with respect to permeability, and it is important to keep this in mind when evaluating the kinetics of fluid and ion transfer in shaly formations. Whereas permeability and hydraulic diffusivity are intrinsically low in shales (Revil *et al.* 2005), the anisotropy of transport properties can be very high: for example, Zhang & Rothfuchs (2004) reported that in the COX argillite the permeability in a direction parallel to bedding is about one order of magnitude higher than that perpendicular to bedding and decreases strongly with increasing water content. The low permeability of shales combined with a high anisotropy and a strong dependence on water content makes it difficult to estimate the mechanical properties and poroelastic parameters of shales in the laboratory (Bemer *et al.* 2004). The elastic anisotropy of shales (Sayers 1994) can also be estimated through the measurement of seismic-wave velocities (Sarout *et al.* 2007). David *et al.* (2007) measured a 20% anisotropy for P-wave velocity in the COX argillite, with a minimum velocity oriented in the direction perpendicular to bedding. Robion *et al.* (2007) showed that the anisotropy of P-wave velocity correlates very well with the anisotropy of magnetic susceptibility (although the latter is less intense) and that it changes when temperature increases. Esteban *et al.* (2006, 2007) have also studied the anisotropy of magnetic susceptibility in the COX argillite, and related the orientation of the eigenvectors of the susceptibility tensor to microstructural observations and pore-size distributions using mercury porosimetry applied to oriented samples. Sarout *et al.* (2007) extended the study of elastic anisotropy with the measurement of S-wave velocity, and their study of seismic velocity evolution with increasing effective stress revealed the interplay between damage and variation of water saturation in the COX argillite samples tested in triaxial experiments. A similar study has been conducted by Popp & Salzer (2007) using a multi-anvil apparatus, to define the dilatancy boundary for the Opalinus clay formation. A theoretical model for the anisotropy of seismic-wave velocity for a cracked solid with an anisotropic crack distribution has been proposed by Wong & Zhu (2007). The characterization of the anisotropy of physical properties is of great importance for monitoring purposes (Stenhouse & Savage 2004), because large errors can be introduced if it is considered that the rock behaves as an isotropic medium, which is generally far from the reality in shaly formations.

Repositories in hard rock formations

Hard rock formations are potentially good candidates for radioactive waste storage for several reasons: a very low water content (a typical porosity for a granite is of the order of 0.5%), a high mechanical strength, and a high thermal conductivity, which helps in dissipating heat generated by the packages (ANDRA 2005*b*). Special attention has to be paid to the presence of fractures at all scales in crystalline rocks, as fractures in hard rocks would behave as potential sites for retention of radionuclides, or alternately as preferential paths for the radionuclides to migrate out of the repository. Several URLs are operationg in hard rocks: the Aspö Hard Rock Laboratory in Sweden, the Grimsel Underground Testing Facility in Switzerland, and the Lac du Bonnet Laboratory in Canada are good examples. As is the case for URLs in soft rocks discussed above, one has also to deal with the presence of an excavation damage zone in tunnels drilled into hard rock formations. Tsang *et al.* (2007) presented the results of a fully coupled hydromechanical model to understand anomalies in fluid pressure observed during the excavation of the FEBEX (Full-Scale Engineered Barriers Experiment) tunnel in the Grimsel test site (Switzerland): they argued that the fractures created during excavation are strongly affected by the local stress field, which is different from the regional stress field. The FEBEX tunnel experiment was aimed at monitoring continuously the engineered barrier (bentonite) and the surrounding rock during heating–cooling cycles: it was part of the DECOVALEX international programme, the objective of which was to operate a number of full-scale experiments in different URLs (Tsang *et al.* 2005). The formation and/or propagation of fractures in hard rocks during the excavation phase and/or the operating phase in a repository can be monitored by means of acoustic emissions, a technique that was first applied to laboratory studies (e.g. Chang & Lee 2004; Lei *et al.* 2004) and extended to full-scale studies in tunnels or drifts (e.g. Young & Collins 2001; Reyes-Montes *et al.* 2005). Research projects in the Aspö Hard Rock Laboratory have focused, among other aspects, on the estimation of the regional stress field in the surrounding rock from *in situ* measurements (Ask 2006*a*, *b*) and on the development of a real-size prototype of radwaste deposition holes including copper canisters with heaters, bentonite buffers and backfilled deposition tunnels closed by concrete plugs (Johannesson *et al.* 2007). In the latter experiment, a continuous monitoring of temperature and water inflow was conducted, which showed that the system was still drained after several months of operation with water pressure slowly building up in the tunnel. Indeed, fluid circulation is generally enhanced when fractures are present in hard rocks where permeability is intrinsically low: the EDZ provides theoretically possible pathways for fluids to migrate along the tunnels. However, fractures need to be well connected and form a percolating network for fluid or radionuclides to migrate over long distances.

Over recent decades, a number of laboratory experiments have focused on the interplay between mechanical properties and fluid flow in fractured hard rocks, with emphasis on stress-induced elastic closure (Brown & Scholz 1985), effective aperture in fractures with asperities (Brown 1987), and fracture healing driven by pressure solution (Beeler & Hickman 2004). For a review of these aspects, the reader can refer to Guéguen & Boutéca (2004, chapter 7). Fracture nucleation and propagation in hard rocks can be imaged by means of acoustic emission recording, taking advantage of faster technologies available for signal processing and waveform analysis (Lockner *et al.* 1991; Butt & Calder 1998; Jouniaux *et al.* 2001; Schubnel *et al.* 2006*b*). Stress-induced damage in hard rocks can be estimated indirectly from the variation of elastic-wave velocities (Takemura & Oda 2005), an important point when monitoring issues have to be addressed. Meglis *et al.* (2005) imaged the extension of the EDZ in the Lac du Bonnet URL (Canada) using ultrasonic velocity tomography: variations in velocity, amplitude and anisotropy correlate well with the variations in the local stress tensor, which results in the presence of regions either in tension or in compression in the vicinity of the excavated tunnel wall. In hard rocks, fracture healing is associated with the development of physico-chemical processes such as pressure solution (Yasuhara *et al.* 2004), a mechanism with slower kinetics compared with the development of creep deformation in soft rocks. Jouniaux *et al.* (2001) showed that the presence of healed fractures in a rock mass lowers its mechanical strength and that the acoustic emissions recorded in a triaxial test concentrate along these healed fractures. Kim *et al.* (2007) studied the influence of fracture statistics on the mechanical behaviour of rock masses. At the scale of a fault zone, large variations of physical rock properties are observed in the fault core, the damaged zone and the protolith (Rosener & Géraud 2007). Theoretical models for fracture nucleation and propagation have to take into account the existence of a process zone at the fracture tip (Zang *et al.* 2000), the crack statistics for stress-induced or temperature-induced damage (David *et al.* 1999) and the coalescence mechanisms, which, starting from a diffuse distribution of damage, lead to fracture localization. Recently, numerical models based on particle mechanics, initially developed for granular media (Potyondy & Cundall 2004), have proven to be very useful for modelling mechanical cracking and fracturing processes in granite (Al-Busaidi *et al.* 2005). For such theroretical or numerical models, data are needed on the crack distributions in hard rocks, which can be investigated either by indirect methods (Kachanov 1993; Schubnel *et al.* 2006*a*; Wong & Zhu 2007) or by direct observation using various microscopy techniques (Kranz 1983; Menéndez *et al.* 1999; Liu *et al.* 2006).

Conclusion

Geomechanical modelling for reservoir production enhancement requires the integration of information from studies in rock mechanics and rock physics. Depending on the type of coupling, different levels of complexity exist, involving more or less time-consuming numerical codes. There is still potential for improvement of these models; for example, a key point is to better take into account the relationships between permeability and stress both in the matrix and in fractured reservoirs, for different stress paths. Another key point is to account for the possibility of strain localization in compaction bands, in which case modifications in the fluid flow patterns may occur in the reservoir. Enhancement of reservoir production needs to be further developed for obvious economic reasons, in face of the growing demand on energy resources in industrial and emerging countries.

The repository problem is different in the sense that the key issue is to find a site as safe as possible for storing hazardous waste, and the focus is on environmental rather than economic issues. Research by scientists in many fields is necessary to improve our knowledge of the long-term behaviour of geological formations in which radwastes would be stored. The challenging task is to define scenarios that are as precise as possible for the long-term evolution (typically hundreds of years) of repositories either in soft rock or in the hard rock, from experiments run on short time scales. The accuracy and predictability of models depends on the quality of experimental data obtained at different scales, and the possibility for scientists to work in underground research laboratories is fundamental in this regard. Public acceptance will depend largely on the reliability of the models, on which there is still much work to do. Fortunately, international collaboration is active in making progress on this subject.

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