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The role of geological barriers in achieving robust well integrity

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Abstract

Wells play a key role in the reduction of greenhouse gas emissions. They are not only a critical element in ensuring the permanent trapping of carbon dioxide (CO_2) in deep subsurface permeable formations, but they are also being recognized as an important source of natural gas emissions.

The goal of well integrity is to minimize fluid migration from permeable formations through the use of barriers. Traditionally natural and man-made barriers have been regarded as separate and independent components: once the original impermeable layers such as shale or halite have been pierced by drilling, isolation must be restored by installing steel pipe and annular cement.

However this picture has been blurred by the growing recognition that a particular class of rocks can prevent and control fluid leaks through a well's life, including the hundreds of years after abandonment. Creeping formations such as halides, mudstones and possibly ice can seal uncemented sections and large defects in the cement sheath. More importantly, the radial stress they exert reduces debonding and restores integrity once the cause of a microannulus has been eliminated; this makes the geological barriers self-healing, or robust.

If creeping formations are to become a fundamental element in well design and evaluation, they need to be properly understood and modeled. From an engineering point of view, the identification and characterization of geological barriers should provide four sets of constitutive properties:
- The ultimate radial stress exerted by the formation, as well as its anisotropy (i.e its variation around the casing circumference).

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- Mechanical properties of the formation to estimate leakage rates if the closure stress has been overcome and a microannulus is formed.
- A time scale over which the creep deformation can seal a given defect, or an uncemented section of the annulus.
- The type and extent of geochemical reactions, if any, between the formation and the leaking fluid.

This paper reviews the limited available evidence on the role and characteristic of geological barriers and adds new examples that have arisen from the study of well integrity at the basin scale. A simple model captures the essential characteristics of the formations' behavior and allows identifying the key parameters that control the beneficial aspect of formation creep on well integrity. For a cross-section at a given depth, we model the well system (casing/cement / formation and the potential defects at the interfaces) under plane-strain condition. Modeling formation creep using viscoelasticity, we obtain the time of closure of a given set of defects between the formation and the steel casing. In the absence of defects, or when the defects have already been closed, we also obtain the time evolution of the radial stress clamping the interface. The intensity of such a normal compressive stress clamping the interfaces is the key parameter controlling the occurrence of micro-annulus induced by subsequent fluid injection, such as CO_2 injection, natural gas storage or reservoir stimulation.

We use both an analytical approach in the simplest case of an isotropic far-field stress and a boundary integral equations method in the Laplace domain to handle more complex configurations. Our method is notably agnostic with respect to the viscoelastic constitutive law chosen to model the geological formation time-dependent behavior. We further discuss the impact of the choice of the type of constitutive law on the obtained results.

Lastly, we discuss how the controlling parameters of the problem (in-situ stress, creep formation properties) can be measured or estimated from geophysical logs, geological and geomechanical information as well as active well tests. Our analysis aims at assessing the state of the art in the design and evaluation of geological barriers from a well integrity perspective. We also highlight the remaining questions to be answered by research.

Nomenclature

β_1	closure stress gradient expressed as equivalent density (kg m^{-3})
ε	strain
η	viscosity (Pa s)
κ	function of the accumulated plastic deformation
λ	plastic proportionality parameter (Pa)
ν	Poisson's ratio
ρ	density (kg m^{-3})
$\boldsymbol{\sigma}$	stress (Pa)
τ	time constant (s)
$\mathbf{D}$	compliance tensor (Pa^{-1})
E	Young's modulus (Pa)
G	shear modulus (Pa)
$\mathbf{J}$	creep kernel
K	bulk modulus (Pa)
p	pressure (Pa)
q	plastic potential function
s	Laplace space parameter
t, t'	time (s)
z	depth (vertical coordinate, pointing downwards, m)

1. Introduction

1.1. Well leaks

The long-term integrity of storage sites has always been a major concern for carbon dioxide (CO_2) geological storage (e.g. [1]). Lately the perception of well integrity risk has evolved into a nuanced appreciation of different classes of events: following [2] we can identify blowouts during drilling and intervention, as well as acute and chronic leaks during operation and following abandonment. Blowouts are low-probability events that involve uncontrolled flow of formation fluids (CO_2 and hydrocarbons, but also brine) through steel pipes and the borehole. Those conduits are built to offer low resistance to flow, so the consequences can be severe: for instance, according to [3], the Aliso Canyon gas storage well near Los Angeles (US-CA) had a maximum flow rate of just over 0.5 million tons per year (Mt y^{-1}).

Conversely, leaks during and after well operation must generally bypass significant lengths of annular cement, an effective hindrance that reduces the potential flow rate: on a well we studied, the gas leak rate never exceeded 0.5 t y^{-1} over many years. Small leaks, for which [4] proposes a threshold of 100 t y^{-1}, do not in general represent an actual safety risk; they may nonetheless be an important source of methane (CH_4) emissions, as a growing body of evidence suggests. Kang [5] measured CH_4 leaks from a series of abandoned wells, finding rates in the range 10^{-6}-0.72 t y^{-1}. Frankenberg et al. [6] computed CH_4 emission rates for all sources in a 3,200 km^2 area using airborne infrared absorption spectroscopy; their attention was focused on standard fugitive emissions that take place downstream from the wellhead, but they caught two plumes originating at well pads, with inferred flow rates of 170 and 4,700 t y^{-1} (the detection threshold was around 18 t y^{-1}); interestingly, both Frankenberg et al. [6] and Loizzo et al. [4] find that the leak distribution has a long tail, implying that few sources account for a large share of total emissions.

Even though small, chronic leaks are not a showstopper, they may soon become an important issue for the oil & gas industry, and may impact acceptance of CO_2 geological storage.

1.2. The concept of barrier

The standard NORSOK D-010 [7] defines well integrity as the "application of […] solutions to reduce risk of uncontrolled release of […] fluids throughout the life cycle of a well". It can therefore be seen as a subset of asset integrity, i.e. the ability of an asset to perform its function effectively, efficiently and safely – in the case of a well, that implies without leaks.

NORSOK D-010 [7] also played a leading role in spreading the use of the term barrier in the context of well integrity. "Barrier" is a powerful metaphor in risk management: rather intuitively, it denotes any measure that protects possible targets from damage by hazards. When the hazard is a formation or well fluid, such as CO_2 or CH_4, then the barrier, like a dyke, will prevent it from migrating vertically or will reduce the unwanted flow rate, i.e. mitigate the leak's consequences.

Strictly speaking, a barrier is a system of different barrier elements that extend horizontally and may comprise natural elements (caprock), cement, sections of steel pipe and sealing elements (valves or packers); in the following we will however be dropping the "element" qualifier and refer to them as barriers.

A barrier is robust whenever a failure, a leak in this context, does not compromise any residual ability to control flow; in some cases the barrier may even regain its original integrity whenever the cause of failure is removed. Steel casing is not robust: holes will erode and corrode at a relatively high rate, leaving little residual hydraulic resistance; cement's ability to control vertical flow, on the other hand, does not degrade appreciably when exposed to hydrocarbon or brine flow, and may even heal under certain conditions when CO_2 is leaking (as proposed by [8]). This is especially true when considering aging defects that appear during well operation or after abandonment: work by Lecampion et al. [9] and Dusseault et al. [10] suggest that debonding at cement interfaces is responsible for these aging integrity failure, and the resulting microannulus typically has high hydraulic resistivity and low reactivity.

When designing a well, the borehole is assumed to be static. Any creeping formation, be it mudstones or halites, is only considered a drilling hazard, since it can lead to the drill string or the casing getting stuck while tripping in or out of the hole. There is substantial evidence that creep can actually provide a robust barrier, by gripping directly the casing or, indirectly, the annular cement. In the following we will be reviewing this phenomenon and showing how it can be understood and harnessed to provide and engineered barrier.

2. Results

2.1. Evidence of creep

The first methodical investigation of a specific geological barrier and its use in designing abandonment (the last step in a well lifecycle) was carried out by Williams et al. [11]. The authors proposed a process to qualify a mudstone formation offshore Norway, the Hordaland Green Clay; the aim of "qualification" is to show that the barrier element prevents fluid migration up to a certain maximum working pressure.

Their analysis is based on the effect the clay layer has on acoustic cement evaluation logs, and on pressure tests carried out above the failure limit. Their results show that creep, viscoplastic and/or viscoelastic, is likely to be the main physical phenomenon that causes the partial bond observed on logs instead of structural failure or expansion, whether thermal or physicochemical (osmosis). We can make two observations on the data presented by [11].

First, log response is not what would be expected from a solid shear-bonded to the casing, but it is rather typical of previously debonded annular material that regains contact because of normal stresses. This is to be expected since drilling fluids were filling the annular space at first, only to be removed by the creeping clay. Arguably logs are only needed to distinguish between liquid and solid since a creeping formation is not subject to defects that compromise its integrity, and its mechanical properties don't need to be measured after placement but can be determined through open-hole logs. It would nonetheless be interesting to study quantitatively how ultrasonic log response compares to the density and wavespeeds of the creeping formation, and whether bedding, cracks and stress anisotropy affect logs' readings.
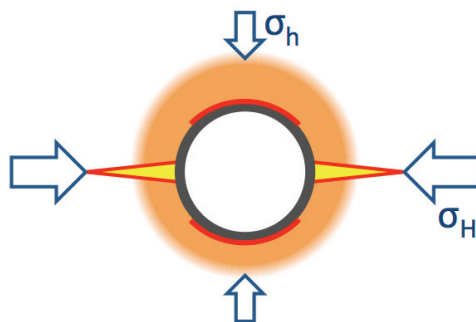

Fig. 1. Schematic of possible natural barrier failure modes: vertical fractures are drawn in yellow and partial debonding at the casing interface in red.

Second, the authors mention formation stress requirements, suggesting that pressure should be less than the minimum horizontal stress (σ_h) in order to prevent failure. There is no mention of a specific failure mode, but one suspects that propagation of a horizontal fracture in the formation is implied. In reality, as discussed below, it is likely that the formation debonds from the casing as soon as fluid pressure overcomes the closure stress at the interface, propagating a fracture-like microannulus between casing and rock according to a mechanism described by Lecampion et al. [9] and outlined in Fig. 1. This failure mode does not depend on rock cohesion or toughness, whatever little role they may play in practice in delaying fracture propagation, and would imply that the geologic barrier is indeed robust and self-healing: once the fluid pressure decreases to below the closure pressure bond is regained. It would be easy to determine the exact failure mode, either form cement evaluation log response

(especially in case of stress anisotropy) and from interference pressure testing, using gauges located above and below the formation being studied.

The research described in [11] has spawned further activity in Norway. The fourth revision of NORSOK D-010 [7], issued in 2013, contains creeping formation as a new well barrier element in addition to in-situ formation: the former guarantees <u>annular</u> isolation, whereas the latter prevents vertical fluid migration outside the borehole, and has to be backed up by cement that fills the space between rock and steel casing. The criteria used for qualifying the barrier are somewhat arbitrary: two independent logging measurements with azimuthal resolution are required, with response criteria set before the log, backed by two pressure testing protocols (integrity testing across the formation, and testing to failure at the bottom of it). It is not clear what exact criteria should be used to declare the logs successful, or why azimuthal resolution is required: would tools that provide an indication of azimuthal variation (such as multiple-receiver low-frequency cement bond logging, CBL, tools) acceptable or only measurements with truly independent azimuthal readings? It is expected that as experience and confidence accumulate, qualification criteria more closely related to the mechanical behavior of geomaterials will emerge.

The addition of creeping formations to the list of acceptable annular barriers also fostered the start of a joint industry project coordinated by Sintef, an independent Norwegian research organization, on shales as abandonment barriers (see [12] for a review of results).

Of course the notion of geological barriers and appreciation of their role in ensuring well integrity goes beyond the groundbreaking study in [11]. Clark et al. [13] describe a borehole-closure experiment they conducted in Orange County, Texas, near the Louisiana border. A 27 m section of shale at a depth of 865 m and with a borehole diameter of 280 mm was allowed to creep and seal the annular space around tubing with an outer diameter of 2⅞ in (73 mm). The closure process was passively monitored by observing pressure above and below the shale interval, and the newly created seal was later pressure tested.

Nicot [14], while studying leaks (indeed, their rarity) from wells in Texas, builds on the experiment reported in [13] to suggest that "natural barriers", such as heaving (creeping) shales or sink zones "might retard or prevent a leak".

Other formations that exhibit a marked creeping tendency are halites; to which rock salt (halite) belong. The ability to seal shafts and behave as a robust, self-healing barrier has been studied in Germany as an alternative seal for radioactive waste repositories (see [15] for some of the result of the research program). The concept has been taken up again by Hou et al. [16] who proposed a large scale test in the Altmark gas field in Germany within the framework of the German research project CLEAN. Unfortunately the planned experiment could not be carried out.

2.2. Creep in the Paris Basin

During an integrity assessment of oil wells in the Paris Basin, France (a project described in [17]), we came across multiple evidence of creep, especially across the Gault Clay. This is a formation of Lower Cretaceous age that overlies the fresh-water aquifers of the Albian-Neocomian at a depth of around 800 m. Other clay intervals across the Lower Cretaceous and Upper Jurassic also exhibit creep behavior, and thus act as an effective barrier that protects the strategic drinking water resource; the Gault Clay however is the topmost member of the sequence and at least part of it is below the intermediate casing shoe, meaning that evidence from logs and annular pressure testing (when pressure is applied from surface) provide information about this interval in particular.

Suggestions that the Gault Clay creeps came from drilling and even milling operations, when the formation required constant reaming to prevent the drilling string from getting stuck; this observation is of course not conclusive since hole stability problems can in theory also be caused by mechanical failure or swelling, if the drilling fluid is not sufficiently inhibited.

Intriguing evidence came from two cement bond logs acquired 21 years apart. As shown in Fig. 2(a), the original log (in blue) behaves as expected: low bond index (BI), very close to the 0% value characteristic of a liquid annular material, then a reasonably quick transition to the higher values characteristic of cement. The second log (in red) shows almost the opposite behavior: now most of the 73 m between the previous casing shoe and the top of cement show signs of a bonded solid in the annular space. Right at the top of the open-hole section the BI values approach 80%, and would thus be considered competent cement. Significantly, the BI drops suddenly as the logging tool

enters the intermediate casing, supporting the hypothesis that the CBL response is caused by something in the borehole (as opposed to, for instance, drilling mud settling or late setting of cement).

The cemented interval BI has meanwhile dropped to around 20%, suggesting that cement is now debonded from the casing. This is because the CBL measurement is primarily sensitive to shear bonding, much less so to the mechanical properties of annular materials: BI is therefore significantly reduced, but does not quite reach the values characteristic of liquids.
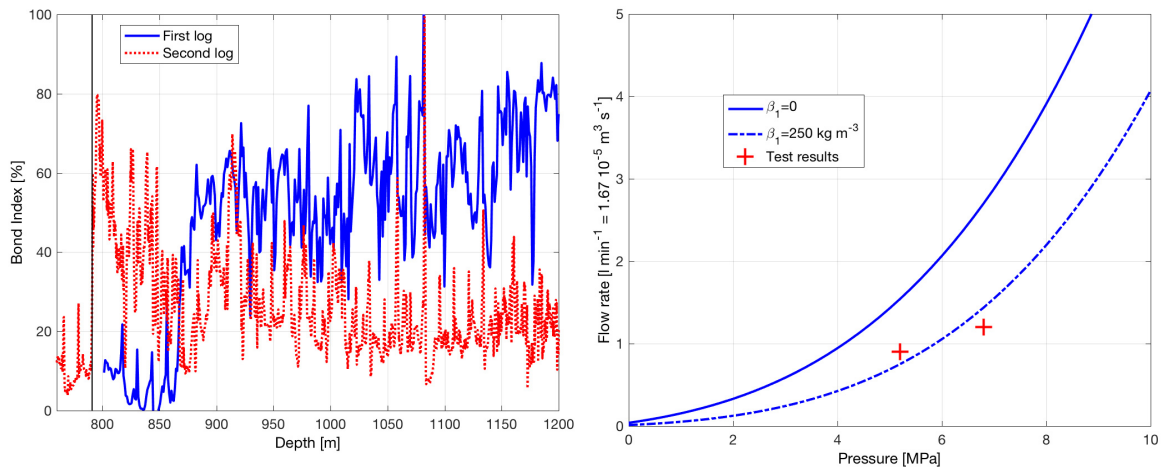

Fig. 2. (a) comparison of two cement bond logs (CBL) acquired 21 years apart. The black vertical line denotes the previous casing shoe depth. The y-axis shows the "bond index", a measure of the fraction of the casing circumference that is well bonded to cement; this is proportional to the logarithm of a specific peak in the sound wave recorded by the logging tool. (b) pressure test results from Table 1 compared to microannulus models that use different values of the closure stress gradient β_1 (expressed as equivalent density ρ, so that p=ρgz), according to [9].

Table 1. Pressure-flow rate relation measured during annular testing.

Surface pressure (MPa)	Flow rate ($m^3 s^{-1}$)
5.2	1.5 10^{-5}
6.8	2.0 10^{-5}

An explanation for this change can be found in the annular pressure, which was increased to 9.1 MPa before the second log (on another well in the field 10.1 MPa were reached). This value is much higher than the ~3 MPa estimated fracture pressure (its actual value is unknown because no leak-off test had been carried out in the field), and suggests that no horizontal fracture opened at the shoe to relieve the annulus, a scenario commonly used to calculate the maximum allowable annulus surface pressure (MAASP). What seems to have happened is that the bond between casing and cement, and casing and Gault Clay above 860 m, failed and a microannulus – i.e. an azimuthal interface fracture – opened up instead. Interestingly, bond was regained across the Gault Clay and possibly around 915 m, showing that creeping shales are robust barriers.

Annulus testing in a separate well also provided useful data about the relation between pressure and flow rate, reported in Table 1. As Fig. 2(b) shows, the large relative uncertainty in measuring small flow rates in the field does not allow us to detect non-linearity in the relationship, or the existence of a pressure cut-off value. The test suggests however that the microannulus closure stress gradient $\beta_1 \cong 250$ kg m^{-3}, when we express it as equivalent density.

There are only a few references that provide estimates of minimum and maximum horizontal stresses, σ_h and σ_H, in the Paris Basin: [18] reports almost constant $\sigma_h \cong 12$ MPa across the Callovo-Oxfordian argillite, a clay layer of Jurassic origin which is found at similar depths as the Gault Clay in the wells we studied. The paper also reports substantial horizontal stress anisotropy, with $\sigma_H \cong 14$ MPa; stress variation around the borehole would slightly

complicate microannulus modeling, although this step is not warranted by the paucity and uncertainty of available data. The value of σ_h would result in an apparent closure gradient (in excess of annular fluid hydrostatic) of $\beta_1 \cong 530$ kg m^{-3} at 800 m.

Analysis of further logs, some of them acquired by ultrasonic imaging tools that build a map of annular acoustic impedance (the product of density times compressional wavespeed, whose unit in the International System is the Rayleigh, or Rayl), confirmed that all shales intervals seem to exhibit a degree of creep, and that the behavior seems stronger above 70 GAPI. Above 100 GAPI the pipe seems fully bonded to a material close to the original undisturbed shale, with an acoustic impedance of around 3.5-5 MRayl.

Unfortunately, without access to density, porosity or spectral gamma ray logs that were not acquired so far above the reservoir intervals, we cannot try and guess the mineralogical composition of the Gault Clay. Nonetheless [19] reports that the clay facies, also present in Southern England, is predominantly composed by kaolinite, illite and smectite (montmorillonite), which are not distributed uniformly or randomly. Nicot [14] quotes a source providing a long list of creeping shales that contain smectite, and in fact the mineral has lower stiffness and pronounced (visco)plastic behavior because of its high water content, which allows clay platelets to slide past each other. In another unpublished study, we have indeed observed a creeping marl with an approximate clay composition of 75:25 smectite and illite.

The conclusion of the Paris Basin analysis was that creeping shale layers in the Lower Cretaceous and Upper Jurassic provide a mechanically weak yet very effective annular barrier that will reseal the annulus even after multiple "failures" through debonding at the casing interface. The strategic deep fresh-water aquifers, which are only ~600 m shallower than an overpressured, brine-bearing limestone aquifer (the Dogger) are thus protected against contamination, that may not only arise from oil production but also from low-enthalpy geothermal energy generation and from deep water wells that have been drilled for the past 175 years.

2.3. Modeling viscoelastic creep

We have developed two semi-analytical solutions in order to address two key problem already mentioned in the introduction:

- How much time is required for a viscoelastic formation to creep back and close a microannulus (interface defects) of given size?
- What is the time evolution of the compressive normal stress acting at the casing/cement interface in the case of a viscoelastic creeping formation?

We assume the rock to behave viscoelastically: i.e. its elastic properties depend on time and the complete stress/strain history (see Fig.3 for two simple examples of viscoelastic constitutive models).

Assuming a viscoelastic behavior for the rock formation allows using the so-called viscoelastic-elastic correspondence principle [20]. After performing a Laplace transform on the original viscoelastic problem (i.e. switching the time dependence to the Laplace space parameter (s), one obtains an equivalent elastic problem where the elastic properties of the medium are only s-dependent. Example of a Laplace-transformed constitutive law is also displayed in Fig. 3. In principle, any viscoelastic model that can be described in differential form (as combination of spring and dashpot) can be used. In others words, these viscoelastic solutions are constitutive model-agnostic.

Knowing the corresponding elastic solution in the Laplace domain, the time-domain solution can be obtained by applying the inverse Laplace transform. Although, an analytical solution in the time-domain may be obtained for simple loading case and simple rheological models, in most cases, a numerical inverse Laplace algorithm must be carried out to obtain time-domain results (i.e. using for example Stehfest algorithm, see [21]).

We have solved two distinct plane-strain problems relevant to the configuration depicted in Fig. 1. The first problem consists in the case of a wellbore drilled in a viscoelastic rock under constant internal pressure and constant bi-axial far-field stresses (i.e. representing the two horizontal in-situ stresses). The time evolution of the radial displacement of the wellbore wall obtained can answer our first question: namely, how long does it takes to close a

microannulus under a particular set of conditions (rock properties, far-field stress, micro-annulus pressure and micro-annulus size).

For the second problem, we consider a bi-material case: rock formation (plus cement modeled with the same properties than the rock for simplicity) and a steel casing. Similarly to the previous problem, the inside of the wellbore is assumed to be under a constant pressure while bi-axial constant far-field stresses are applied at infinity.

We are here notably interested in the evolution of the normal stresses acting on the interface between the two materials. The magnitude (and azimuthal distribution) of such interface normal stress provides the fluid pressure threshold above which the interface will debond [9].

Example of uniaxial viscoelastic response

Maxwell model

$$\sigma + \frac{\eta}{E}\frac{d\sigma}{dt} = \eta\frac{d\varepsilon}{dt}$$

Burgers model

$$\sigma + \left(\frac{\eta_1}{E_1} + \frac{\eta_1}{E_2} + \frac{\eta_2}{E_2}\right)\frac{d\sigma}{dt} + \frac{\eta_1\eta_2}{E_1E_2}\frac{d^2\sigma}{dt^2} = \eta_1\frac{d\varepsilon}{dt} + \frac{\eta_1\eta_2}{E_2}\frac{d^2\varepsilon}{dt^2}$$

Three dimensional constitutive law in the Laplace domain assuming volumetric elastic behavior

$$\widehat{\sigma}_{ij} = 2\widehat{\mu}(s)\widehat{\epsilon}_{ij} + (K - 2/3\widehat{\mu}(s))\widehat{\epsilon}_{kk}\delta_{ij}$$

Transformed shear modulus:

Maxwell model

$$\widehat{\mu}(s) = \frac{Gs}{s + G/\eta}$$

Burgers model

$$\widehat{\mu}(s) = \frac{G_1 s(s + G_2/\eta_2)}{s^2 + s(G_1/\eta_1 + G_1/\eta_2 + G_2/\eta_2) + G_1 G_2/(\eta_1\eta_2)}$$
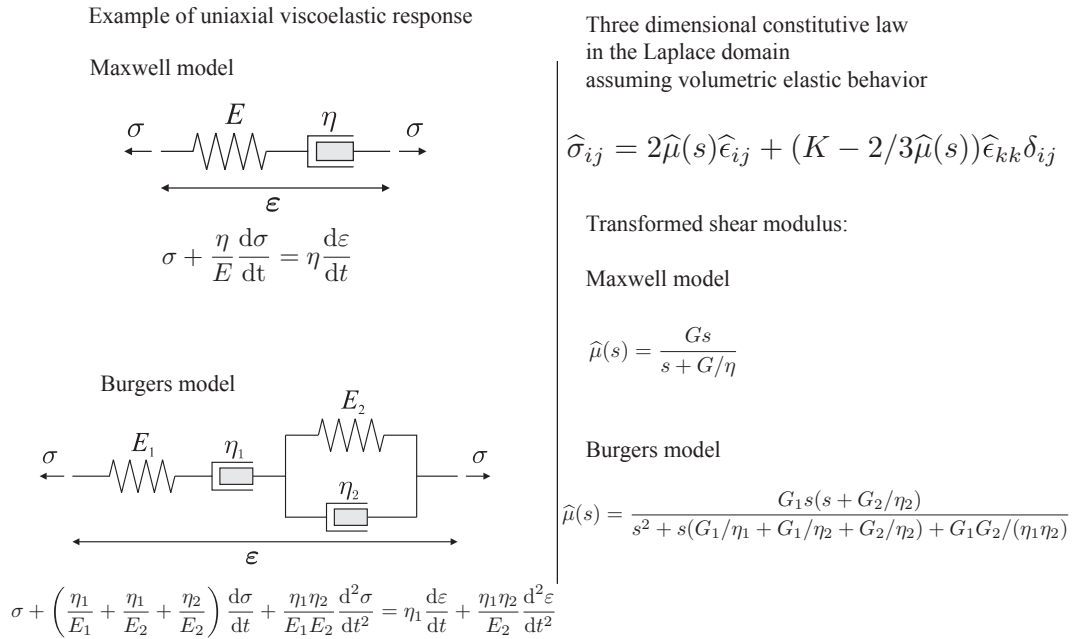
Fig. 3 uniaxial viscoelastic response for Maxwell and Burgers models (left) and three-dimensional constitutive law in the Laplace space (right). The viscoelastic response of most materials (and of all rocks) is associated with shear deformation. The volumetric response is elastic (and the bulk modulus K is time-independent). The Burgers model possesses two time-scales, while the Maxwell model has a single characteristic time-scale.

The details of the solution to these two problems are omitted here for brevity and will be published elsewhere [22]. The solution procedure is based on the integral representation of plane elasticity using complex variables [23,24]. Such an approach is quite general, and would allow extending the solution to a complete tri-material case (rock/cement/casing) with a possible standoff of the casing.

Fig. 4 displays an example for the case of an un-supported wellbore (problem 1) using either Burgers model or Maxwell viscoelastic model. We use constitutive parameters of the Bure Callovo-Oxfordian argillite from [25] (see section 2.2 above) for the Burgers model: K=4,000 MPa, G_1=2,000 MPa G_2=3,000 MPa η_1=10^{10} Pa.s η_2=10^9 Pa.s. We also ensure that the long-term uniaxial creep response is similar for both models (such that Maxwell model parameters are K=4,000 MPa, G=1,200 MPa, η=10^{10} Pa.s). As a result, the radial displacement normalized by the wellbore radius evolves similarly at large times. For illustration, we have performed a computation for hydrostatic far-field stress equal to 20 MPa and a wellbore pressure of 5 MPa. From Fig. 4, it is easy to determine the time needed for a microannulus of a given size to close for this given configuration.

Fig. 5 displays an example of the evolution of the normal stress acting on the interface as function of time. In this illustrative calculation, we have assumed a steel casing with a large thickness (5% of wellbore radius). This plot quantifies the level of fluid pressure that would fail such an interface as a function of time. Due to the non-

hydrostatic far-field stress in that case (σ_{xx}=21 MPa, σ_{yy}=19 MPa), the evolution of the normal stress is non-monotonic with time (at different azimuth). However, the value of normal stress tends to the far-field stresses at large time (azimuth dependent).
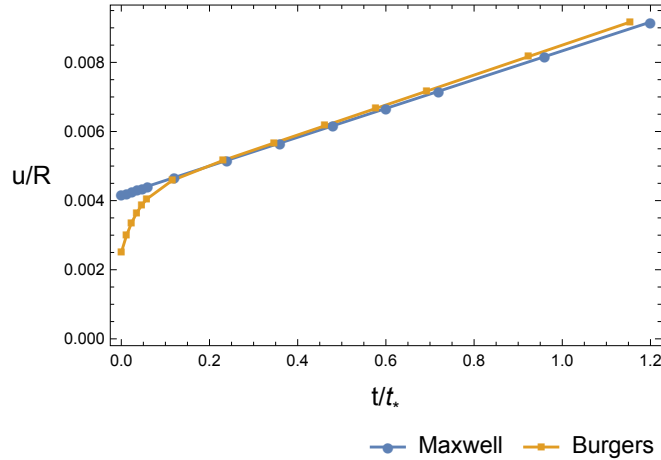

Fig. 4. evolution of radial displacement (u_{rr}, where the r-axis points away from the borehole) scaled by wellbore radius as function of dimensionless time t/t* for Burgers and Maxwell models, a hydrostatic far-field stress of 20 MPa and a wellbore pressure of 5 MPa. Note that the characteristic time-scale t* is equal to $(G_2\eta_1+G_1(\eta_1+\eta_2))/(G_1G_2)$ and (η/G) for Burgers and Maxwell respectively.
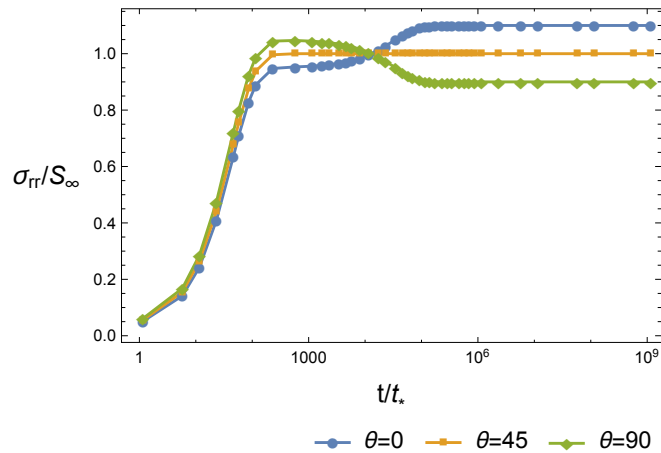

Fig. 5. evolution of the normal stress at the casing/cement interface (scaled by the far-field mean stress – here equal to 20 MPa) as function of dimensionless time for Burgers model (same constitutive parameters than previously). A difference of 2 MPa between the far-field horizontal stresses engenders a non-monotonic response with stress relaxation at large time following early-time creep. As in Fig. 4, the r-axis points away from the borehole.

    The modeling strategy described above applies to viscoelastic problems. However laboratory experiments have demonstrated that formation creep is in large part caused by viscoplastic deformation, which is a fundamentally different phenomenon: viscoplasticity is dissipative, the deformation is permanent when stress is relieved and (in many formulation) only starts accumulating once a yield surface is reached, and is mostly non-linear with respect to stress.

    When looking at the behavior of a creeping formation on a monotonic loading path, nonetheless, a sometimes-complex viscoelastic law can be fitted to the actual viscoelastic response. Further analysis is needed to verify the

predictive power of viscoelasticity in case of repeated debonding, even though the small deformations involved should not cause overdue concern.

3. Discussion

3.1. Engineering geological barriers

Natural barriers cannot be designed as such, but wells can be engineered to take advantage of them. In theory, once the formation's behavior is well characterized there is no additional need for pressure testing or geophysical logging to qualify individual barriers, except for a run-of-the-mill gamma ray log to confirm the exact position and extent of the formation in a particular well; in this sense, a creeping shale should not be different than a caprock, i.e. in-situ formation in NORSOK D-010 [7].

So what would it take to understand sufficiently well a creeping formation to include it in the well design? To answer the question we will focus on shales, since they are more widespread than halides and thus potentially more useful. There are in fact three separate questions:

- How do we recognize a creeping formation?
- What is the safe operating envelope of the barrier element, and what leak rate should be expected in case of failure?
- How long does it take for the formation to grip the casing or cement, and gain (or recover) bond?

Any sedimentary formation with a clay matrix predominantly composed by smectite is a good candidate for natural barrier. Signs of sloughing shales during drilling are an excellent indicator of this phenomenon, but a series of geophysical investigations, provided by logging while drilling or wireline logging, are recommended at the initial characterization stage. Four-arm calipers will help recognize creep directly, as well as stress anisotropy. Density, neutron porosity and possibly spectral gamma ray will clarify the mineralogical composition; these logs are routinely acquired as part of a triple combo (together with sonic wavespeed) and automatic processing to identify facies and extract petrophysical and mineralogical properties is widespread.

Cement evaluation logs, especially the CBL, which is very sensitive to shear bond, are very effective in identifying creeping shales; in fact, they measure precisely the ultimate effect of creep: annulus bridging by a natural barrier. The drawback is that there should be two distinct measures: one log soon after cementing and another one approximately a week later to distinguish between cement and creeping shale. An ultrasonic log some days after cementing can be used alone to identify the formation, if properly calibrated and interpreted; at any rate, running a log after such a delay requires planning and may only be feasible for deeper hole sections, where drilling can be long.

Defining the maximum operating pressure of the natural barrier requires the knowledge of mechanical properties and far-field stresses although, if one ignores the initial transient, viscoelastic and viscoplastic properties can be neglected. The field of geomechanics has developed measurements, protocols and practices to fully characterize the elasticity of rock (including anisotropy and non-linearity) for mechanical applications like: borehole stability – of which creeping formations are indeed a subset – earth deformation, caprock and casing integrity and hydraulic fracturing. Characterizing shale "failure" through debonding may not require extensive laboratory work like core testing: deformations involved in debonding are normally small, and stresses are often well within the material failure envelope. It is thus advisable to extract Young's modulus E and Poisson's ratio ν from the compressional and shear wavespeeds provided by sonic logging tools.

Whereas the logs discussed above are routinely run across reservoir intervals and possibly primary caprock, they are not normally acquired across shallower shale sequences to control costs (not only the direct cost of a log, but also of the time required to run it). A risk-based approach can thus identify promising barrier candidate and focus the characterization effort on them. NORSOK D-010 [7] is rather prescriptive and focused on offshore wells, where drinking water aquifers are not at stake; it is good practice instead to require two independent barriers between any

formation that could be a source of contamination, whether it contains hydrocarbons or over-pressured brine, and an aquifer resource.

Designing for abandonment can also profit from creeping shales. In theory barriers have to be qualified before a well is abandoned, but often it is not possible or practical to run new cement evaluation logs, and any pathway found during evaluation should be repaired too. Robust natural barriers however can be relied on to seal repeatedly and over a very long term, hence the interest raised by [11].

Determining the state of stress can also be a significant endeavor, requiring extended leak-off tests or mini-fracs to find the minimum horizontal stress σ_h. An interesting alternative would be to measure directly the pressure vs. flow rate response of a shale microannulus to infer one, or probably both, horizontal stresses. Ideally the formation should be tested from below, but this would be exceedingly time consuming, requiring the deployment of a test string (that could get stuck in the process) and waiting for the formation to seal against it. Testing the casing in place is potentially attractive, but would not solve the long wait time problem, and cement could not be placed after the annulus has been bridged. A possible solution is to test the barrier from above, as was done with the Gault Clay: uncertainties in the compressibility of the long upper annular section would pollute the data, but it may be possible to extract valuable information, especially if horizontal stresses determine a pressure threshold for flow.

Instrumenting the casing with strain gauges is also an option, as could be monitoring the internal diameter with a high precision measurement (provided the wall thickness is relatively small).

The final set of parameters that is useful for characterizing creeping shales describes the viscous part of deformation. Viscoplasticity relies on complex models: plasticity alone requires a dozen constants, to which it must be added the time constant τ_{vp}. Viscoelasticity instead needs only three parameters: the viscoelastic elastic moduli (E_{ve}/ν_{ve} or K_{ve}/G_{ve}) and the time constant τ_{ve} (there is some evidence that $\nu_{ve} \neq \nu$ but this is generally ignored, so only two parameters are computed). Laboratory testing is possible, but the most effective way to obtain viscoelastic parameters is from repeat cement evaluation logs or pressure testing (as was done by [13]), through the borehole closure time.

Natural barrier qualification would be done only a few times in each field, possibly at the exploration and characterization phase, after which only very limited work on individual wells would be required. Of course, failure to understand the barrier's behavior and to model its mechanical response would leave a degree of uncertainty (and thus risk) and lead to complicated qualification procedures, such as those proposed by NORSOK D-011 [7].

A final observation on reactivity is warranted. The main advantage of a natural barrier is its self-healing ability, either alone or through cement: in the latter case the formation pushes on the cement to reseal a casing-cement microannulus, as has been observed on many logs. Brine or methane flow through a microannulus should not damage shale, whereas CO_2 may have a larger effect because of the increased acidity and the complex reactions with carbonates, if these are present. Salt formations may be dissolved if unsaturated brine or fresh water flows through a microannulus. A bigger issue with CO_2 may come from steel corrosion: for depths higher than a few dozens meters, chemical conditions in the ground are reducing and the main steel degradation mechanism becomes acid corrosion, against which cement provides excellent protection (because of its high pH and low permeability). Flow of wet CO_2, or acid brine, through a microannulus could possibly degrade the casing, although [26] showed that there are a few mechanisms that could plug the pathway and reduce or stop corrosion.

4. Conclusions

Natural barriers are an ideal component of well integrity because of their robustness. Their use in well design, in particular the abandonment phase, relies on proper understanding of their behavior and prediction of their mechanical response. This in turn requires proper risk assessment and planning to ensure effective and efficient data acquisition.

Even though viscoplasticity is the likely cause of formation creep, viscoelasticity can be applied in most situations to simulate borehole closure with time, with the added benefit of simpler model and fast analytical solutions.

At this stage of understanding of natural barriers' characteristics and potential, further research work is warranted. Its goals are: confirming that a microannulus is the mode of failure of creeping formation and that

models based on [9] can predict leak rates; predicting creep parameters from formation petrophysical characteristics; optimizing the determination of stress regimes and sharing the characterization of natural barrier at the basin scale, with the added benefit of increased regulator and public confidence.

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