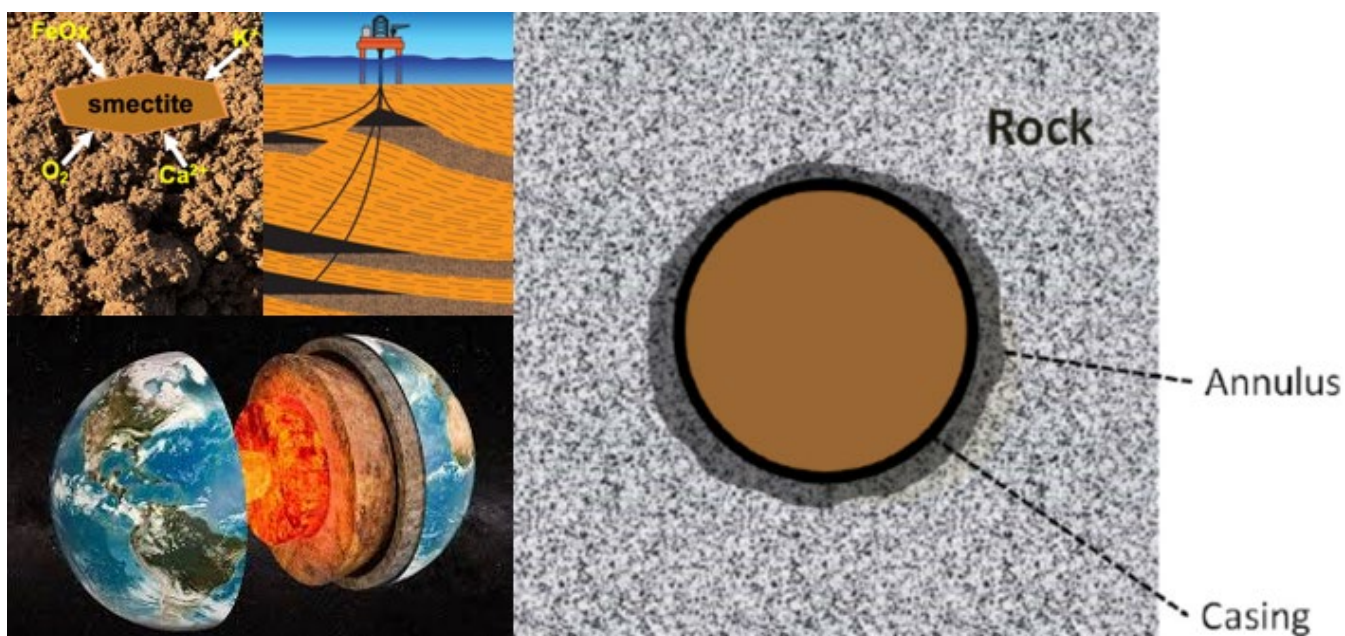




Knowledge Acquisition for Qualification and  
Use of Creeping Shale as a Well Barrier  
Element on the Norwegian Shelf



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## **1 Executive Summary**

Havtil initiated this knowledge gathering to document the status of the qualification and use of creeping shale as a well barrier element (WBE) and to contribute to transfer of experience and learning across the industry. Creeping shale as a WBE has been used on the NCS since 2006 and its minimum functional and performance requirements in permanent plugging and abandonment (PP&A) are described in NOROK D-010 rev5/2021 EAC (Element Acceptance Criteria) table 52.

In the early 2000s, Operators on the NCS made observations that indicated creep of certain shale formations had occurred in older wells. Ultrasonic logging of these wells indicated good bonding between material behind the casing and the casing above the documented top of cement (ToC) compared with the original well documentation and well design. This led to investigations and research into understanding the behaviour of creeping shales with a view to assess whether they could be used as an acceptable well barrier element (WBE) in PP&A. The potential to use creeping shale as a barrier in well construction has also been recognised and work has been done on development and use of this application.

The industry has initiated a series of Joint Industry Projects (JIPs) on research specifically focussed on the use of creeping shale as a well barrier element. Several papers have been published in established journals and there has been an active process for transfer of experience and learning with respect to qualification and use of creeping shale in forums for PP&A and well integrity. Further research and development of more specific functional and performance requirements are anticipated.

Reflekt has discussed the qualification and use of creeping shale as a WBE with four Operators and three of these are using creeping shale as a WBE. The Operators have different strategies for the application of creeping shale determined by their experience related to smectite and shale content in geological layers in their fields, and their future requirements with respect to ongoing validation of pressure integrity tests and corresponding verification by bond logs. The Operators' strategies and experience determine their approach with respect to development and continuous improvement of requirements for qualification of creeping shale as a WBE and development of best practices, guidelines and procedures.

PP&A of wells on the NCS will require significant resources over a long period of time. The use of creeping shale provided by natural sealing elements in the overburden or geology in the respective wells, can be an effective and cost-efficient methodology to provide an acceptable well barrier element in the casing annulus in the future, and further research and development is anticipated.

## **2 Introduction**

Reflekt has been requested by the Norwegian Ocean Industry Authority (Havtil) to gather knowledge and experience on the development, qualification and use of creeping shale as a well barrier element on the NCS. To this end, Reflekt has carried out discussions with Operators, research institutions and service providers of technology related to the application of creeping shale and verification of well barriers. Creeping shale as a WBE is primarily used for permanent plugging of the annulus between the production casing and the formation. Havtil's intention is that this report can facilitate experience transfer and learning and to this end contribute to further development of the methodology and associated technology.

### 3 Abbreviations and Definitions

| ABBREVIATION | FULL DESCRIPTION                                         |
|--------------|----------------------------------------------------------|
| AI           | Artificial Intelligence                                  |
| ECP          | External casing Packer                                   |
| GEA          | Greater Ekofisk Area                                     |
| GSL          | Geologically Similar Layers                              |
| Havtil       | Norwegian Ocean Industry Authority (Havindustritilsynet) |
| IP           | Intellectual Property                                    |
| JIP          | Joint Industry Project                                   |
| LWD          | Logging While Drilling                                   |
| NCS          | Norwegian Continental Shelf                              |
| OBM          | Oil Based Mud                                            |
| PP&A         | Permanent Plug and Abandonment                           |
| PUC          | Pontifical Catholic University of Rio de Janeiro         |
| PWC          | Perforate, Wash and Cement                               |
| ToC          | Top of Cement                                            |
| WBE          | Well barrier element                                     |
| WBM          | Water-based mud                                          |
| XLOT         | Extended leak off test                                   |

| DEFINITION               | DESCRIPTION                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Creeping shale           | <p>Low permeability shale formations which are sufficiently mobile to allow rapid closure of cracks. Typical formation characteristics: low permeability, ductile, high smectite and clay content or salt, low content of cementing materials (quartz, carbonates etc), low friction angle, low cohesion, and low unconfined compressive strength (UCS).</p> <p>This is definition is based on the definition for creeping formation used in NORSOK D-010 Rev. 5 2021</p>                                                                                         |
| Differential leak test   | A leak test in a downhole environment where the tubular is perforated both above and below a potential isolating zone in the tubular annulus and pressured up using downhole packers (or similar) to determine whether the zone can hold a given pressure either from above or below.                                                                                                                                                                                                                                                                             |
| Extended Leak off test   | A test to determine the minimum in-situ formation stress. The test propagates a fracture into the formation and establishes the fracture closure pressure. NORSOK D-010 Rev. 5 2021                                                                                                                                                                                                                                                                                                                                                                               |
| Formation Integrity test | A test to confirm that the formation is capable of withstanding the maximum possible pressure. Adapted from NORSOK D-010 Rev5 2021                                                                                                                                                                                                                                                                                                                                                                                                                                |
| Qualification            | <p>Where the petroleum activities entail use of new technology or new methods, criteria shall be drawn up for development, testing and use so that the requirements for health, safety and the environment are fulfilled. The criteria shall be representative for the relevant conditions of use, and the technology or methods shall be adapted to already accepted solutions.</p> <p>The qualification or testing shall demonstrate that applicable requirements can be fulfilled using the relevant new technology or methods. Facilities Regulations § 9</p> |
| Smectite                 | Smectite clays are swelling clays that contain an interlayer space which can expand by the absorption of a suitable solvent, for example water.                                                                                                                                                                                                                                                                                                                                                                                                                   |
| Track record             | <p>A documented record of consistent operational achievements and performance matching or exceeding expectations.</p> <p>In the context of creeping shale, a track record is qualified by a minimum of three (3) successful operations, using the same conditions/parameter set. NORSOK D-010 Rev. 5 2021 – formation integrity tests</p>                                                                                                                                                                                                                         |

| DEFINITION | DESCRIPTION                                                                                                                                                                                                                    |
|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|            | It should be noted that the term ‘track record’ is not used in EAC Table 52, however the description in D. (4) clearly indicates the intention of establishing a track record including how many formation tests are required. |

#### 4 Methodology for review

The initial assignment with Havtil included interviews with three Operators in the information gathering, (AkerBP, ConocoPhillips and Equinor). Meetings were held to describe the process and to obtain an overview of the qualification and use of creeping shale in the Operators’ activities. Follow-up meetings were arranged to discuss strategy, development and application of creeping shale as a WBE. Reflekt used a checklist with four main themes and specific questions within these themes:

- Qualification of the methodology related to the use of creeping shale as a WBE
- Assessment of formations and geological layers that may be suitable for this purpose.
- WBE design, execution and verification
- Learning and experience transfer

The information gathering was extended to a fourth operator, Vår Energi, and a meeting was organised to cover the above themes. The objective here was to understand how an operator relatively new to the use of creeping shale approached the challenges associated with qualifying creeping shale as a WBE.

Reflekt had meetings with two research institutions that are actively carrying out research into the use of creeping shale as a barrier element, SINTEF and Pontifical Catholic University of Rio de Janeiro (PUC) Rio/Techgraf in Brazil.

Reflekt also had meetings with service providers of technology relevant to the verification and testing of WBE where creeping shale is used.

A key element in the information gathering is how the Operators interpreted and applied the requirements in the Facilities Regulations § 9 on *Qualification and use of new technology and new methods*. This includes formal processes for qualification of technology, and development of best practices/guidelines that meet the intention of the regulation and the current best practice in NORSOK D-010.

#### 5 History of creeping shale as a WBE on the NCS

Permanent plugging and abandonment (PP&A) of wells on the NCS shall ensure there is no flow of hydrocarbons to the surface from the hydrocarbon bearing zones. These zones may be the reservoir that has been exploited or hydrocarbons trapped in the formations above the reservoir. A key factor in successful PP&A is the isolation of the annuli between the casing and the formation. Traditionally this has been done by cement, either through verification of existing isolation by casing cement, through section milling or perforate, wash and cement (PWC), and verification of the WBE in accordance with NORSOK D-010.

Some formations have properties that are suitable as an acceptable barrier material, and a WBE can be created between the formation and the casing. Evidence that some formations creep into

the outside of the casing and create a seal that prevents hydrocarbon flow has been demonstrated. These formations are ductile enough to move under the shearing stresses present and have very low permeability. There are indications that the mechanical properties lead to an improvement in the sealing capacity over time.

In the early 2000s observations in wells in Norway (NCS) indicated creeping shales were present behind casing and above TOC as mentioned previously.

A timeline for the use of creeping shale by the Operators interviewed is shown in figure 5.1.

| Early 2000s                                 | 2005                                             | 2006                           | Early 2010s                                  | 2013 /2014                              | 2015                            | 2016                        | 2020                                         | 2021                                |
|---------------------------------------------|--------------------------------------------------|--------------------------------|----------------------------------------------|-----------------------------------------|---------------------------------|-----------------------------|----------------------------------------------|-------------------------------------|
|                                             | Norsk Hydro                                      | Statoil                        | Conoco Phillips /BP Norge                    | NORSOK D-010 Rev4                       | BP Norge /AkerBP                | Equinor                     | NORSOK D-010 Rev5                            | Vår Energi                          |
| Observations of bond in uncemented sections | Systematic logging and testing of creeping shale | Use of creeping shale as a WBE | Potential for use of creeping shale as a WBE | Use of creeping shale as a WBE included | Use in PP&A of Valhall DP wells | Use in PP&A of Huldra wells | EAC Table 52 and acceptance criteria revised | Use in PP&A of wells in Balder area |

Figure 5.1 Timeline for development of creeping shale as WBE on the NCS

Note that this timeline does not include all their applications on the NCS.

Bond logging of these casing annuli in several wells showed that bonding between the formation and the casing was present in areas above the original top of cement where bonding was not observed in the original logs, see figure 5.2.

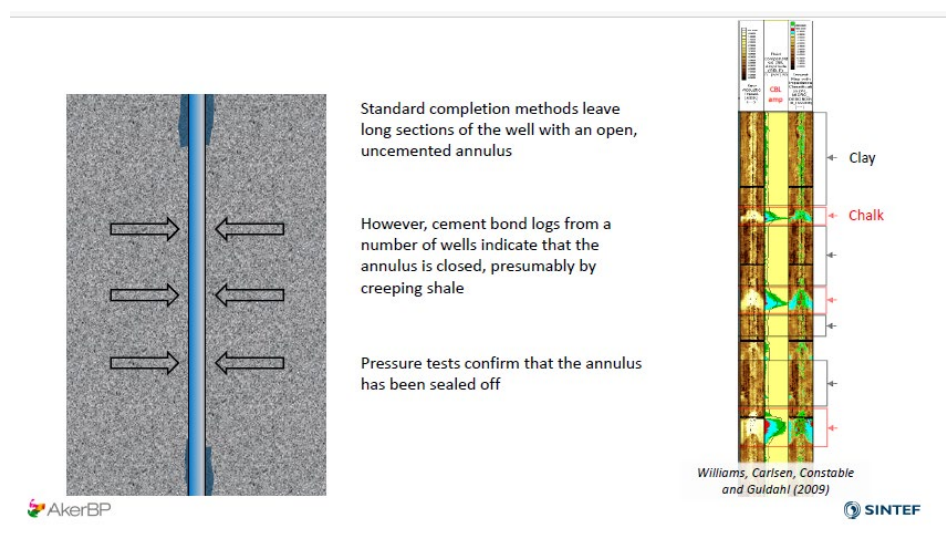


Figure 5.2. Typical indication of creeping shale closing open uncemented annulus<sup>11</sup>

Further work characterised the formations that were likely to creep regarding material and physical properties. These were mainly related to the presence of smectite in the shale formation that gave it the required ductility.

Creeping shale has been used as a WBE from 2006<sup>1,2</sup>.

The type of creep envisaged occurred naturally through pressure reduction in the annuli during the well operation.

In NORSOK D-010, Rev. 3, 2004, creeping shales were not explicitly recognized as a WBE<sup>3</sup>.

The focus was on mechanical barriers such as annular or casing cement.

Individual Operators carried out their own assessments on identification of suitable formations including the understanding of the required material and physical properties. Studies were initiated to characterize these formations in the laboratory followed by field testing.

The Operators developed procedures for the initial testing and verification of WBEs where creeping shale was part of the barrier envelope.

Operators using or considering the use of creeping shale as a WBE developed best practices or guidelines to describe the application of the barrier and the verification of the barrier integrity, see figure 5.3.

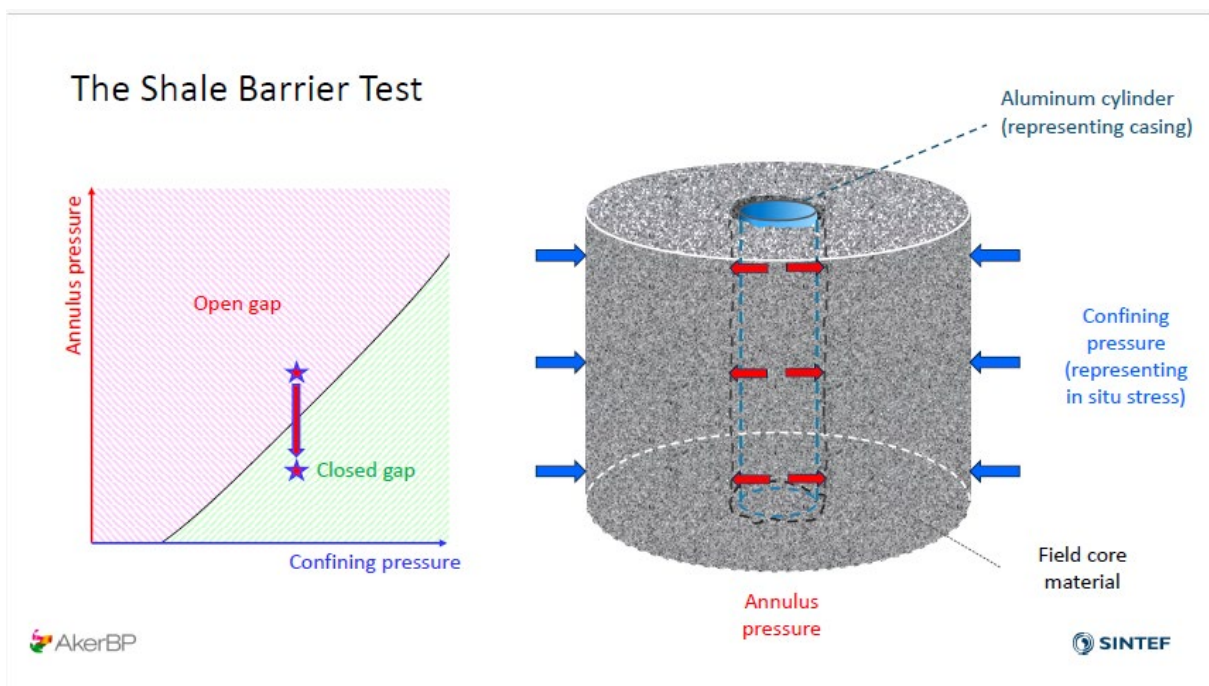


Figure 5.3 The key factors in the testing of creeping shale barrier elements

A key element in the barrier verification was the demonstration of a 'track record' for extended leak off tests (XLOT) and/or formation integrity tests verified against bond logging with barrier quality.

The use of creeping shale as a WBE was first described in NORSOK D-010 version rev4 in 2013<sup>4,5</sup>.

- Shale formation was recognized as a WBE in permanent well abandonment (PP&A) cases.

- It was described as a formation with sufficient long-term sealing capability (e.g., salt, plastic clay) that could close off the wellbore annulus through its own plastic deformation.
- Specific requirements were outlined, including documentation of formation properties, verification of its long-term sealing ability, and consideration of wellbore geometry and conditions.

From 2015 a series of Joint Industry Projects (JIP) were initiated with SINTEF to study creeping shale see the timeline in figure 5.4. Appendix 1 has more detailed information on these JIPs.

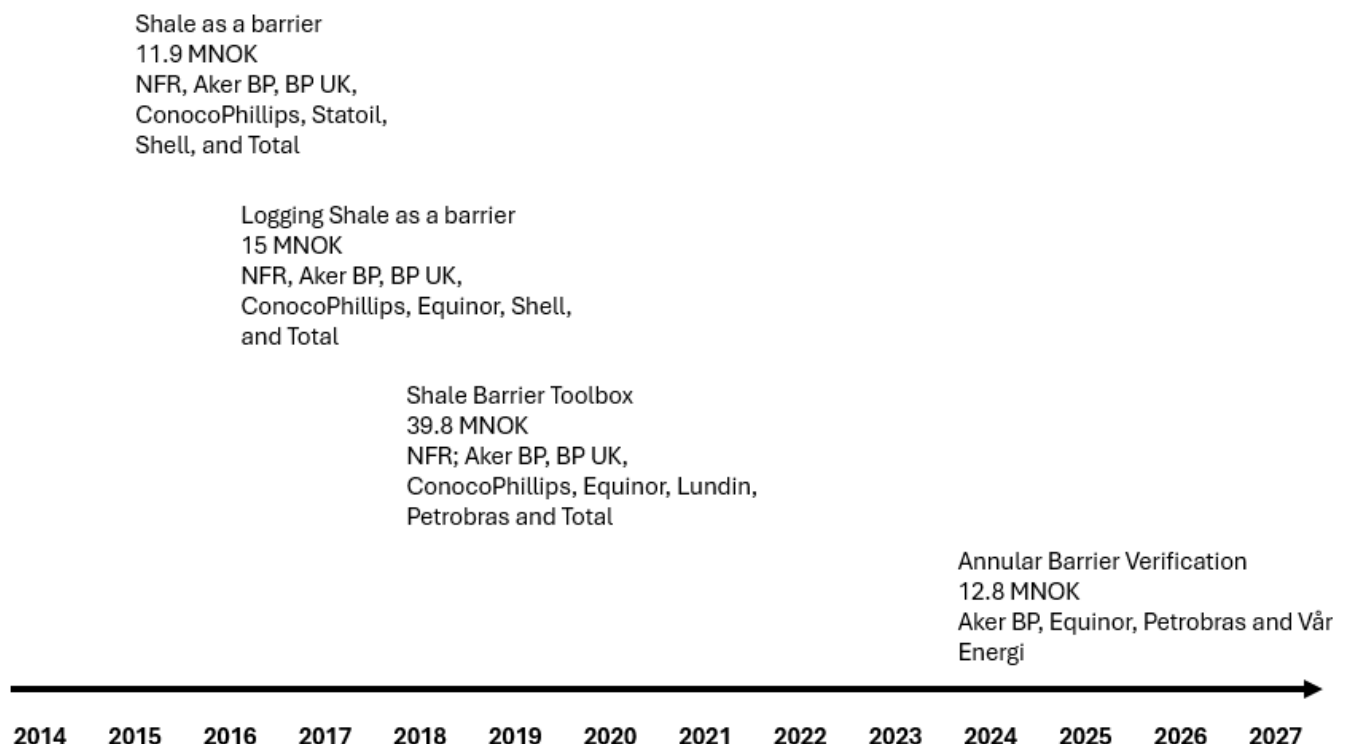


Figure 5.4 Timeline of Joint Industry Projects related to creeping shale

During this period some of the Operators carried out their own studies of shale formations and developed or further developed their own best practices and guidelines for the application, mainly related to PP&A and slot recovery.

### Minimum depth of integrity

These also include an assessment of the minimum depth at which the creeping shale can be qualified as a WBE. Some formations may have the appropriate material and physical properties, however, will not have the required formation integrity for the maximum pressure it can be exposed to. Geomechanical forces as a result of well direction and inclination are an important factor here.

One Operator developed a process for the use of creeping shale as a WBE in well construction. Another Operator developed a process for the use of creeping shale in establishing wells barriers in complex situations where a standard practice had not succeeded in establishing a verifiable barrier.

NORSOK D-010 rev5 was published in 2020 including the section on Plug and Abandonment in Chapter 10 (formerly Chapter 9)<sup>6</sup>. EAC Table 52, which covers creeping shale was revised, including the acceptance criteria.

### **Development of technology**

The use of creeping shale as a WBE has led to development of technology and methodologies for qualification and verification, in particular for acoustic logging and formation integrity testing.

Acoustic logging tools are used to measure the quality of the bonding between the formation and the casing, and tools and interpretation techniques have improved significantly, including techniques that distinguish the materials behind the casing.

Tools used to leak test the formation to verify the formation integrity and establish the required 'track record', have been developed to meet the requirements for testing creeping shales. These tools can be used for extended leak off tests and differential leak tests.

### **Other areas**

There is also ongoing work in the use of Logging While Drilling (LWD) information, cuttings analyses and core samples to characterize formations and determine if they have the right material and physical properties for creeping shale. This can be an important area for the planning of PP&A and well construction.

Oil and Gas UK (OEUK) has issued Guidelines on the use of Barrier Materials in Well Decommissioning, and these guidelines contain information on how creeping shale can be used as a WBE<sup>7</sup>.

Creeping shale as a WBE has been the subject of master studies at academic institutions in Norway, and these provide useful background information on both the history and application<sup>8</sup>.

## **6 Operator Experience**

Reflekt has gathered information and experience on creeping shale from four Operators currently working on the NCS. The Operators have different strategies for the qualification and use of creeping shale as a WBE, dependent on their experience, and current and future requirements. These strategies have influenced technological development, including verification of the WBEs for further use, and the drive for experience transfer/knowledge sharing and learning.

### **6.1 ConocoPhillips**

#### **6.1.1 History of Creeping shale in Greater Ekofisk Area (GEA)**

In the early 2010s, ConocoPhillips identified access to the annulus to establish a cross-sectional barrier as a key challenge to improving efficiency in PP&A.

Remediation was normally achieved by section milling, which is a time consuming and extensive drilling operation.

Two methodologies were at this time identified that could make a significant difference:

- Perforate, Wash and Cement (PWC) and
- Creeping shale.

ConocoPhillips reviewed information on the use of creeping formation as a WBE from published articles and through industry well forums and networks and started work on the potential for application in the Greater Ekofisk area (GEA) in 2013<sup>9,10</sup>.

As of 2014 COP started to differentiate between:

- **Naturally occurring formation creep.** This occurs when an envelope of mineralogy and lithology, depth, temperature, geology, fluids and casing design allows or does not prevent the creep process
- **Activated formation creep.** This is when there is an action to initiate or accelerate a creeping process. COP identified pressure, temperature, shear forces and formation fatigue as potential mechanisms that may be relevant and secured an IP for same (2014) 2015.

License to use COP IP was given to the participants in the JIP (and a service provider) at no cost with the intention of ensuring the technology was made available for industry wide application.

ConocoPhillips participated in the first JIPs on creeping shale (2015). Before the startup of JIP, ConocoPhillips did not observe significant bonding in wells above top of cement (ToC), and this led to a perception that the formations in the GEA did not have the required properties as creeping shale, '*our shales don't creep*' (and hence the initiative to activate creep)<sup>11</sup>.

In 2016, ConocoPhillips logged a well that showed significant bonding over ToC and this led to a study on why this well was seemingly different from the others.

This particular well was drilled with water-based mud (WBM), and this allowed the pressure in the annulus to relieve as the formation began to creep, and enabling the creep to continue to provide a bond with the casing. The pressure reduction is due to the water in the mud being able to migrate into the formation as the formation creeps. ConocoPhillips now had undisputable evidence that creeping formations were present in the Ekofisk area and had the potential for use as a WBE. This information was consistent with other Operators' experience with these formations.

ConocoPhillips had previously concluded that the reasons for lack of creep in the formations were due to the Ekofisk well design, using external casing packers (ECP's) and the use of oil-based mud (OBM) during drilling. The oil in the mud does not migrate due to capillary pressure effects. This experience provided valuable information about casing design and drilling fluid selection and their influence on promoting or preventing formation creeps.

A trapped volume (liner hanger/external casing packer/other) combined with OBM appeared to have prevented the pressure reduction required to initiate the formation creep.

### 6.1.2 Best practice

ConocoPhillips developed a 'best practice' that described how to identify, test and document creeping shale as a barrier for PP&A operations. This best practice includes how to establish a track record using XLOT and log bonding quality. This practice was applied in the PP&A campaign on Ekofisk Alpha concluded in 2016. It is noted that the Lower Hordaland and Rogaland formations, where other Operators are using creeping shale as a WBE, are below the production packer for wells in the GEA. ConocoPhillips does not have a great deal of data from the potentially creeping shales below the normal production packer depth.

### 6.1.3 Geologically Similar Layers

ConocoPhillips carried out further work on the determination of Geologically Similar Layers (GSL) that was intended to characterize formations across the Ekofisk area and determine their suitability as a creeping shale with potential as a barrier material. The intention was to show that the formation material and physical properties were not significantly different across the area. This led to development of internal recommendations for requirements for creeping shale as a WBE in PP&A.

Studies carried out by ConocoPhillips have reached similar conclusions to work carried out by SINTEF as part of the JIP work. ConocoPhillips has also been active in sharing their experience with creeping shale both in industry forums, e.g. P&A Forum and through published papers<sup>9,10</sup>.

### 6.1.4 The future use of Creeping shale

There is currently no active use of creeping shale as a WBE in fields on the NCS operated by ConocoPhillips. The rationale behind this:

- Modern wells are drilled with liner design and OBM that results in a 'trapped volume' which has proven to be an effective showstopper for naturally occurring formation creep in the GEA.
- A diminishing number of wells are drilled with WBM, hence diminishing value and short horizon of technique
- ConocoPhillips PWC improvement project has been successful, and the operation has become a routine activity for PP&A. In addition to the efficiency in the field it simplifies planning/programs, logistics, contingencies not to mention budgeting<sup>12</sup>

ConocoPhillips does, however, design the PWC operation to allow naturally occurring creep in suitable formations to provide additional assurance on the long-term integrity of the tested barriers.

Since ConocoPhillips has no plans to use creeping shale as a barrier in the near future, they are not participating in the current JIP on Annular Barrier Verification. ConocoPhillips are monitoring the development of technologies that may change their current strategy on the use of creeping formation and one area that is particularly important is the development of dual string logging tools.

## 6.2 AkerBP

### 6.2.1 History

The potential for creeping shale as a WBE was first considered by BP Norge in 2008 and a project was started with an initial view to assessing formations in the Valhall area where there were several challenges with the drilling and completion and PP&A of wells on the Valhall field. Physical and material properties were studied and shales that could be described as 'creeping shale' were identified.

Norske Shell, a partner in the Valhall field at that time, shared their experience with creeping shale on Brent in 2015 as part of the first industry JIP. Logging of wells in the Valhall area that indicated good bonding between formation and casing above the documented top of cement (ToC). This provided an indication that the formation was behaving as predicted and proved the potential of the application.

BP Norge developed a systematic method for using creeping shale as a barrier in PP&A. This method was used for the PP&A of Valhall DP wells in 2015<sup>13</sup>. AkerBP followed up the work carried out by BP Norge and conducted laboratory research, numerical modelling, risk assessment and collated experience from operational applications.

AkerBP has used creeping shale as a WBE in several fields on the NCS and sees major potential for both PP&A and also in the future, well construction. They have developed guidelines for use of creeping shale as a barrier and have carried out an extensive qualification process on the application of creeping shale as a WBE for both PP&A and well construction.

### **6.2.2 Formal qualification process**

In 2021 AkerBP carried out a formal technology qualification process<sup>14</sup>. The purpose of the process was to:

- Document the totality of the qualification program and its activities for using shale as a barrier.
- Systematically capture the qualification activities according to DNV-RP-A203 and AkerBP TQ work process.
- Describe the implementation process and current status and practice of use of shale as a barrier by AkerBP.

The qualification process was facilitated by DNV and research personnel from SINTEF participated. Requirements in the UK Oil & Gas Guidelines on qualification of materials for suspension and abandonment of wells were considered. The process documented the use of creeping shale and the limitations to its application, threats and mitigations measures<sup>15</sup>.

The use of creeping shale as a barrier in well construction has been extended to other fields on the NCS, including Ula and Ivar Åsen.

### **6.2.3 Best Practice**

The method mentioned above became AkerBPs guideline for using creeping shale as a WBE. The guideline includes the requirements for documentation that the formations in question have the appropriate material and physical properties to be suitable as a barrier material. The guideline distinguishes between well construction and PP&A.

AkerBP has established requirements for design, construction and verification equivalent to NORSOK D-010 EAC Table 52 for application of creeping shale as a WBE to well construction. The requirements for PP&A in the guideline are in accordance with the NORSOK D-010 requirements.

The guideline describes a workflow for application and a verification process for WBEs and establishing a track record to ensure there is correlation between bond quality from logging response and extended leak off testing (XLOT) and differential leak testing.

The interval required for verification of the WBE with regard to formation integrity is also specified. Quality requirements for logging, including tools and interpretation, are also covered. The guideline is intended to inform personnel on how creeping shale barriers work and their potential application.

AkerBP has carried out logging of well sections to document the change in bond logging responses over time<sup>16</sup>.

This work provides assurance that the integrity of a WBE based on creeping shale improves over time. See figure 6.1.

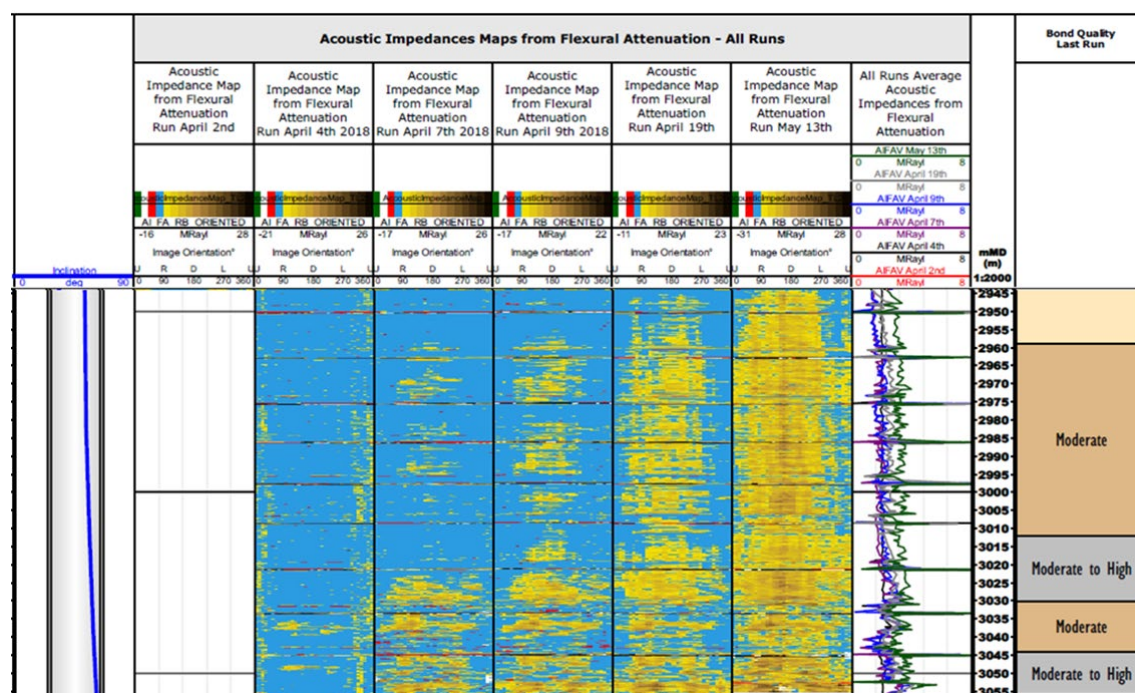


Figure 6.1 Time-lapse data of how the shale bond behind the liner is developing over a 45-day period.

BP Norge and then AkerBP have participated in the four JIPs related to creeping shale and described in Appendix 1. They have also been active participants in discussions on creeping shale in the Offshore Norge P&A Forum (PAF) and are supporting work at the University of Texas in Austin<sup>17</sup>. AkerBP is actively promoting learning and experience transfer on the use of creeping shale and published several papers and made presentations at well forums including at the P&A forums and seminars<sup>18,19,20</sup>.

#### 6.2.4 Technology development

AkerBP has worked closely with suppliers on the development of logging tools, and the interpretation of logging responses. A key factor for this work has been how to identify material behind casing, e.g. hydrocarbon, water, cement, formation, with a high degree of confidence. This is an important factor in the planning of P&A and well construction. AkerBP regards this as an important focus area for industry.

AkerBP is currently working with suppliers on tools to heat up formations with a view to stimulating/activating creep<sup>21</sup>. Heating could accelerate the shale barrier development primarily and may also activate shales that would not creep enough. Work at University of Texas at Austin also indicates that heating the shale can recover the integrity of degraded cement, but that usage will need more work to mature for use in the field.

AkerBP is aware of the experimental work carried out by SINTEF where 'rebound' was identified for artificial activating creep. AkerBP and SINTEF have also co-authored a paper on their work with rebound. The paper refers to field experience with the Valhall field and the likely duration of the 'rebound' effect. The paper highlights the requirement to carry out bonding logs at least 48 hours after the heat source is removed. Reference to SINTEF section for description of rebound. AkerBP intends to carry out a separate qualification process for the use of methods to stimulate creep.

#### **6.2.5 Future use and focus areas**

AkerBP sees a significant potential in creeping shale as a well barrier material and has actively promoted the advantages in material characteristics over conventional cement. These advantages include low permeability of the creeping shale, the improvement in barrier quality over time and a single interface between the casing and the formation, compared to two interfaces in a conventional cement application.

AkerBP is actively pursuing establishing an industry standard for creeping shale as a WBE in well construction. AkerBP also has a focus on the qualifying short intervals of creeping shale accumulated over a longer section. AkerBP is collaborating with other Operators to initiate a process to revise NORSOK D-010 to cover these two issues.

### **6.3 Equinor**

#### **6.3.1 History**

Equinor has had experience with creeping shale as a WBE since the early 2000s and from several fields/areas<sup>1,2</sup>. Norsk Hydro carried out systematic logging and testing of creeping shale prior to 2005. Creeping shale as a WBE has been used in Equinor since 2006, including the PP&A of wells in the Huldra field in 2016<sup>22</sup>. Statoil carried out further studies on creeping shales from 2008, and several articles were published with their experience. Statoil contributed to the revision of NORSOK D-010 in 2013 that established requirements for using creeping shale as a WBE in PP&A applications.

#### **6.3.2 Best practice**

Equinor has developed a best practice for how creeping shale as a WBE can be used for the PP&A of wells. This best practice is in accordance with NORSOK D-010 and includes how a formation is identified and characterized to demonstrate that it has the required physical and material properties to be suitable as a WBE.

There is also description of how formation testing and verification should be carried out and how a track record of XLOT against log response is established. Equinor has established an overburden competence group that provides expert advice to the business assets on the use of creeping shale.

#### **6.3.3 Future use and strategies**

Equinor does not use creeping shale as a WBE in the planning of new wells and well construction. Equinor has however developed a process for how creeping shale can be verified as a WBE in complex well integrity situations where conventional methods have failed to establish an acceptable WBE. These complex well integrity situations are documented as deviations and approved in accordance with the Equinor management system.

Equinor participated/are participating in the four JIPs on creeping shale facilitated by SINTEF, see Appendix 1.

Equinor is working with other Operators on short barrier plugs as part of the barrier capacity project<sup>23</sup>. Equinor is also working with suppliers on the development of dual string logging technologies<sup>24</sup>.

#### 6.4 Vår Energi

Vår Energi has used creeping shale as a WBE in wells in the Balder area. The process used by Vår Energi is based on NORSOK D-010 requirements as described in EAC Table 52 – Creeping formation. Vår Energi has internal competence in well integrity, log interpretation and formation assessment to ensure the NORSOK D-010 criteria are achieved for all wells.

Vår Energi has carried out extensive work to identify which formations show the best attributes and composition to creep and to function as a WBE. Vår Energi has established acceptance criteria for the verification of WBEs.

Extended leak-off tests were carried out on three wells in the Balder area to validate the bond logging response and establish a track record for subsequent wells in the area. All creeping shale barriers are logged and must have the required response as determined by the track record to be verified as a barrier. Bond logs must show a bond equivalent to this response over at least 30 m interval for a single section in order to be approved.

Vår Energi recognizes the potential for creeping shale as a WBE and the potential for application on other fields on the NCS. Vår Energi is participating in the latest JIP and is actively promoting learning and experience transfer.

#### 6.5 Summary of Operator experience

A summary comparing the Operator experience and future requirements is shown in the table in figure 6.2.

| Creeping formation - comparison of selected operators |        |            |                |            |
|-------------------------------------------------------|--------|------------|----------------|------------|
|                                                       | AkerBP | Equinor    | ConocoPhillips | Vår Energi |
| PP&A                                                  | ✓      | ✓          | ✓              | ✓          |
| Well construction                                     | ✓      | X          | X              | X          |
| Formal qualification (DnV-RP-A203)                    | ✓      | X          | X              | X          |
| Qualified through experience (NORSOK D-010)           | ✓      | ✓          | ✓              | ✓          |
| Characterised creeping formations                     | ✓      | ✓          | ✓              | ✓          |
| Track record                                          | ✓      | ✓          | ✓              | ✓          |
| Best practice                                         | ✓      | ✓          | ✓              | ✓          |
| Example fields                                        | Hod    | Kvitebjørn | Ekofisk A      | Ringhorne  |
| Future plans PP&A                                     | ✓      | ✓          | X              | ✓          |
| Future plans Well Construction                        | ✓      | X          | X              | X          |

Figure 6.2 Comparison of Operator experience and future requirements

### 7 Research on creeping shale

Research on creeping shale as a WBE is ongoing at SINTEF, Pontifical Catholic University of Rio de Janeiro, and the University of Texas at Austin.

As part of this knowledge gathering SINTEF and Pontifical Catholic University of Rio de Janeiro, provided an overview of their ongoing research projects.

## 7.1 SINTEF

Creeping shale and verification of barriers has been the subject of a series of research projects at SINTEF. The drivers for these research projects are potential cost savings associated with using creeping shale as a WBE and avoiding expensive section milling operations, see figure 7.1.

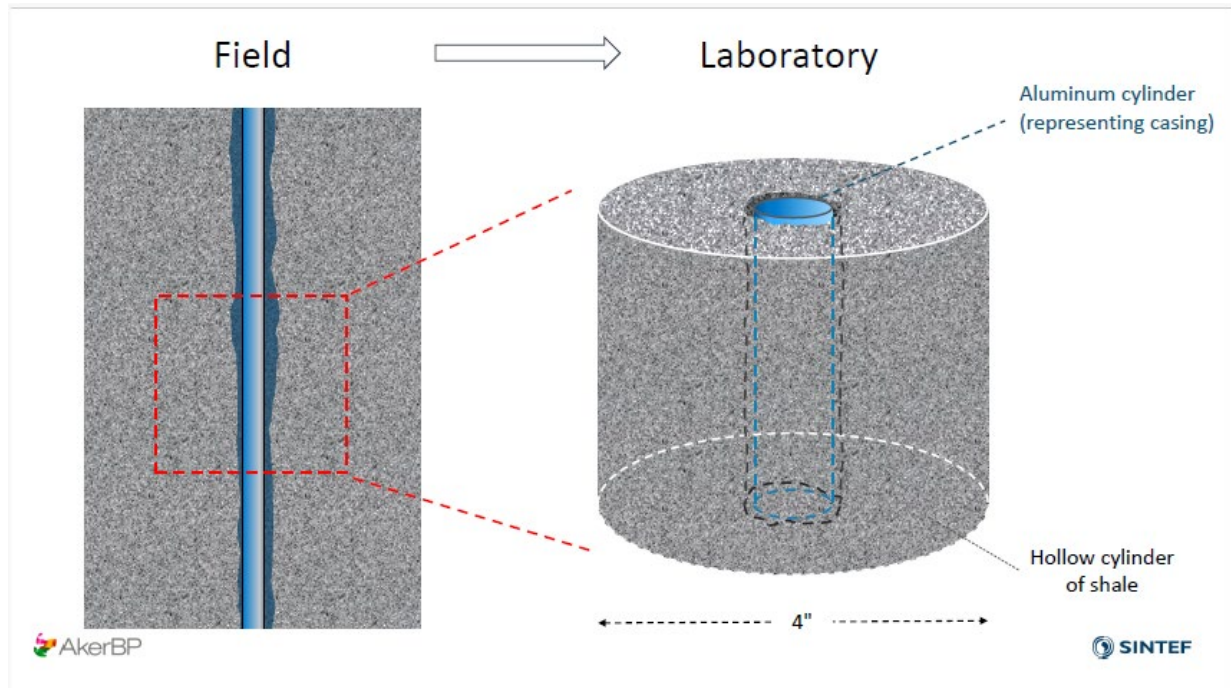


Figure 7.1 Creeping shale laboratory modelling of field conditions<sup>13</sup>

SINTEF started their research work on this topic in 2015, and they have facilitated four JIPs with participation from Norwegian and international Operators<sup>25,26</sup>. The fourth JIP is due to be completed in 2027. Information on the JIPs including the objectives for each project, is contained in Appendix 1 of this report. SINTEF has established a significant competence in this area through laboratory testing, numerical models and several years of experience. This work has contributed to understanding both characteristics and geological history and their importance in assessing their potential as creeping shale and hence suitable as a WBE.

SINTEF has constructed test equipment, designed testing procedures, and carried out laboratory tests to determine the material and physical properties that define a geological formation that is suitable as a WBE, see figure 7.2<sup>27</sup>.

## Around a borehole....

Basic question:

Some holes in the ground stay open,  
others collapse.

Why?

$$\text{Net closure stress} = \text{In situ stress} - \text{Annulus pressure}$$

Figure 7.2 Key factors in the determination of suitable formations

The annulus closure resulting from creeping shale depends on the balance between in situ stress, annulus pressure and rock properties. This is also an important factor in achieving a verifiable barrier and not collapsing the casing. Tests have been carried out on both the creep characteristics and on the integrity of the resulting formation/casing see figure 7.3.

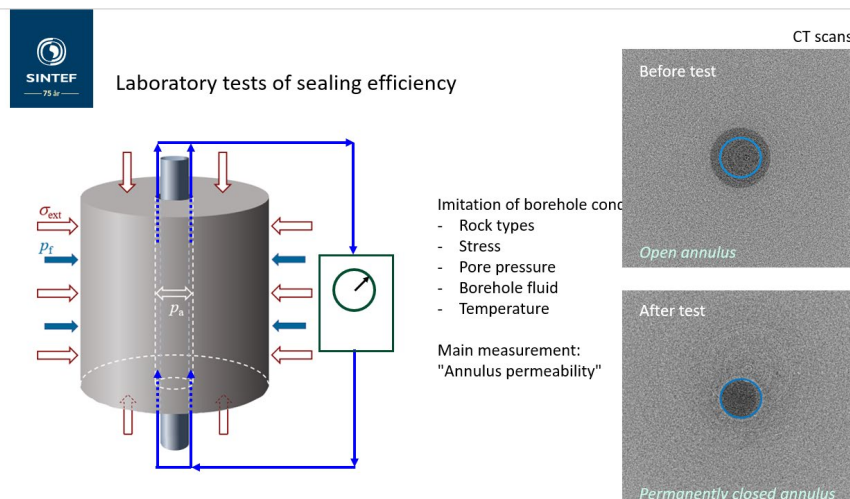


Figure 7.3 Laboratory testing of creeping shale

One of the key results from the laboratory work is the observation that the sealing efficiency of a creeping shale barrier improves with time. This is also observed in the field and has been confirmed in time-lapse logging carried out by AkerBP.

SINTEF, in cooperation with the University of Minnesota, has developed a set of creep models for borehole geometry<sup>28</sup>. The models are intended to identify the impact of various rock properties, and hence to determine whether a formation is acceptable as a WBE and whether there is a high probability of casing failure due to collapse. Casing failure due to collapse where the in-situ stress exceeds the casing collapse rating. Stress anisotropy is included in the modelling and hence the inclination and direction of the well is also accounted for.

Part of the SINTEF research project is to assess how to initiate creep. The main methods to achieve this are: annulus pressure drop, heating and chemical exposure.

Annulus pressure drop, and to some extent heating, enhances the stress conditions that initiate creep:

- heating can accelerate the creep process,
- chemical exposure may modify the rock properties.

A key observation from the testing is the behaviour of the formation after the process to stimulate creep has been completed.

### 7.1.1 Rebound effect

SINTEF has shown that a shale that has been activated by any of these methods may suffer a 'rebound effect'. The rebound effect can be described as the process where the initial sealing efficiency achieved decreases when the ambient conditions return to normal. See figure 7.4.

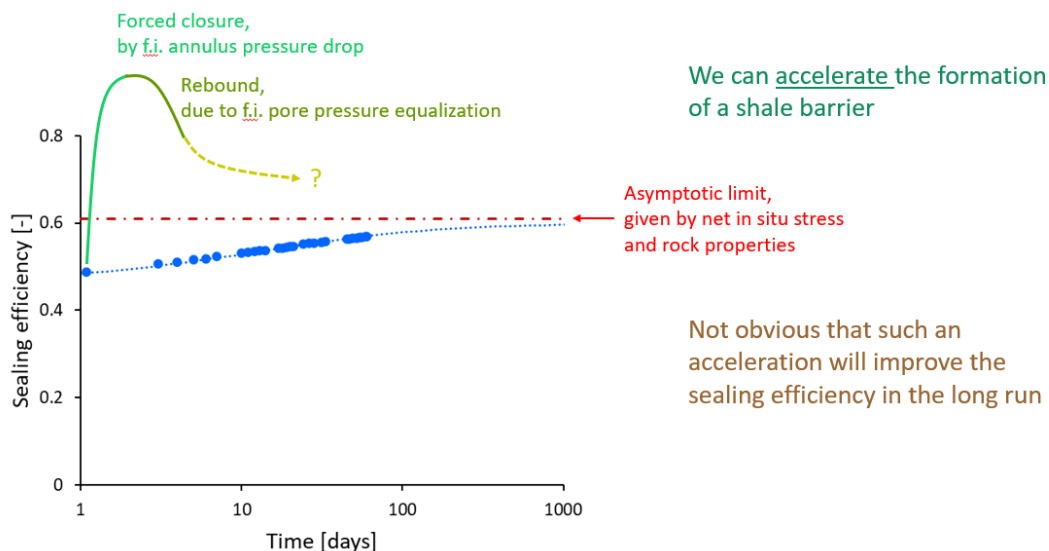


Figure 7.4 The rebound effect from accelerating creep

The methods and procedures used for verification of WBEs in the field have also been subject to evaluation in these projects, with the intension to reduce ambiguity and uncertainties with regard to use of creeping shale as a WBE.

These studies are relevant for both shale barriers and cement barriers.

In addition to the facilitation of JIPs, SINTEF has published several papers on creeping shale as a WBE and is active in learning and experience transfer.

## 7.2 Techgraf PUC-RIO

The use of formations as a WBE in Brazil has mainly been related to PP&A of pre-salt (below salt) wells where salt is the applicable formation. Techgraf PUC were unaware of any wells that have shale as a WBE in Brazil. Some wells have been drilled post-salt (above salt) reservoirs and creeping shale may be applicable in the PP&A in these wells. PP&A is currently a focus area in Brazil.

Salt has been used as a barrier material. It is more impermeable than shales, is more homogenous, and can be hundreds of meters thick. It also creeps faster than shales. There are no regulations against using shale as a WBE, but shales are not considered as straightforward as salt. Currently there is little data regarding creep in the Brazilian shales.

Techgraf is a research, development and innovation facility connected to the Pontifical Catholic University of Rio de Janeiro. Techgraf PUC-RIO are currently engaged in a project in collaboration with Petrobras, Project **Shale As Barrier** (SABAR), 2023 - 2026.

It is noted that Petrobras is a participant in the ongoing JIP project facilitated by SINTEF. The main objective of the project is to develop strategies for prediction, identification and evaluation of geological barriers along shale intervals to simplify well plug and abandonment (P&A). The project is investigating three main areas:

- Formation interval detection and assessment of the properties of the formation,
- Bonding log interpretation
- Well closure simulation and verification of sealing efficiency

The project is developing qualitative criteria for physical and mechanical properties of formations that may be suitable for use as a well barrier material. The work includes mineralogical studies, creep simulations, characterization of shale swelling and an assessment of thermal effects.

Techgraf intends to develop a web application that can be used to collate and correlate information, including from well logging, that will be included in Petrobras well management system.

## 8 Technology related to qualification and use of creeping shale

Four companies were interviewed on their technologies related to the development and use of creeping shale and testing of the WBE integrity:

- **SLB** provided information on ultrasonic logging tools, and interpretation.
- **Archer** provided information on formation testing and verification.
- **Physiq** provided information on the potential use of Logging while Drilling (LWD) to characterize formations.
- **Stag Geological Services** provided information on modelling of geomechanical forces in a well to predict the pressure that shale will start to creep.

### 8.1 Formation Bond Logging

Cement bond logging (CBL) is used to verify the integrity of cement behind casing and the ToC. The logging tools use ultrasonic waves to measure the bonding between the casing and the cement.

The logging technology has been continually developed from the monopole acoustic tools used in the 1960s. Ultrasonic Imaging Tools (USIT) were developed in the late 1970s early 1980s and commercially deployed in the 1980s. These acoustic tools can be used to assess the quality of the bonding between the casing and creeping shale that is required to verify the integrity of WBEs, see figure 8.1. Further development of both the logging tools and the interpretation of response has been an important factor in the assessment of formations for their potential as a WBE and in the verification of the integrity of the barrier installed<sup>16</sup>.

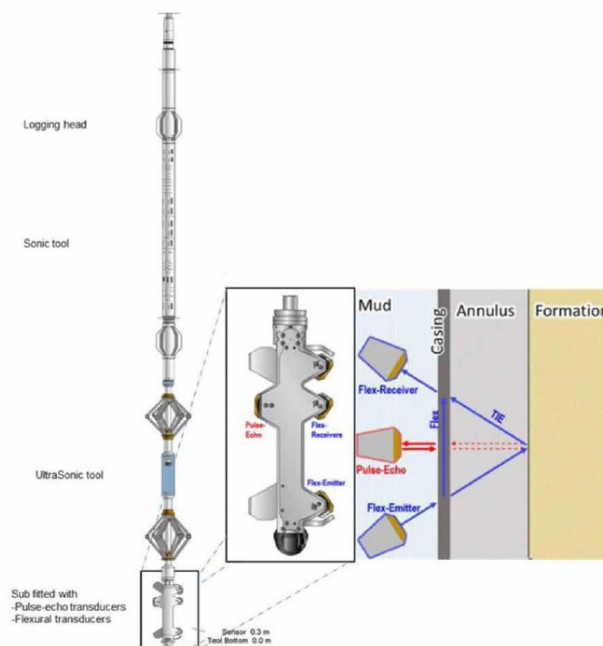


Figure 8.1 Toolstring used for logging

In 2012/2013 observation from bond logging in older wells indicated that there had been a change in the logging response in the areas above the documented top of cement (ToC). The responses indicated that formations had filled the annular space behind casing and where good quality bonding was now observed. SLB in collaboration with Operators carried out work on the interpretation of the logs and the correlation with other logging responses, e.g. gamma ray response, casing ovality. This correlation is important for the identification of formations that have the appropriate properties as a well barrier material. SLB is also collaborating with Operators on the development of logging tools and interpretation for verification of WBEs. SLB has participated in writing papers on the verification of barriers comprising creeping shale.

SLB is developing dual-string logging technology that could provide the industry with valuable information for the planning of PP&A<sup>24</sup>. SLB has also developed logging interpretation techniques that distinguish material behind the casing, e.g. gas, liquid, formation, hard cement, barite etc.

It is noted that there are other companies that supply logging tools for well operations on the NCS.

## 8.2 Formation Integrity Testing

Extended leak off tests (XLOT) and downhole leak tests on potential annulus barrier formations can be performed using downhole packers or similar to isolate perforations in the casing often in combination with downhole pressure and temperature sensors. These tests are required to establish a track record for testing the integrity of creeping shale barriers and compared with a corresponding bonding log. Figure 8.2. shows how perforations can be isolated with packers to enable data gathering on formations and/or potential downhole barriers.

Archer supplies equipment that can be used to carry out integrity testing on formations including extended leak off tests (XLOT) and differential leak testing. These tests are required to establish a track record for bond quality for the testing of the integrity of creeping shale barriers. The way the differential leak test works is described in figure 8.2.

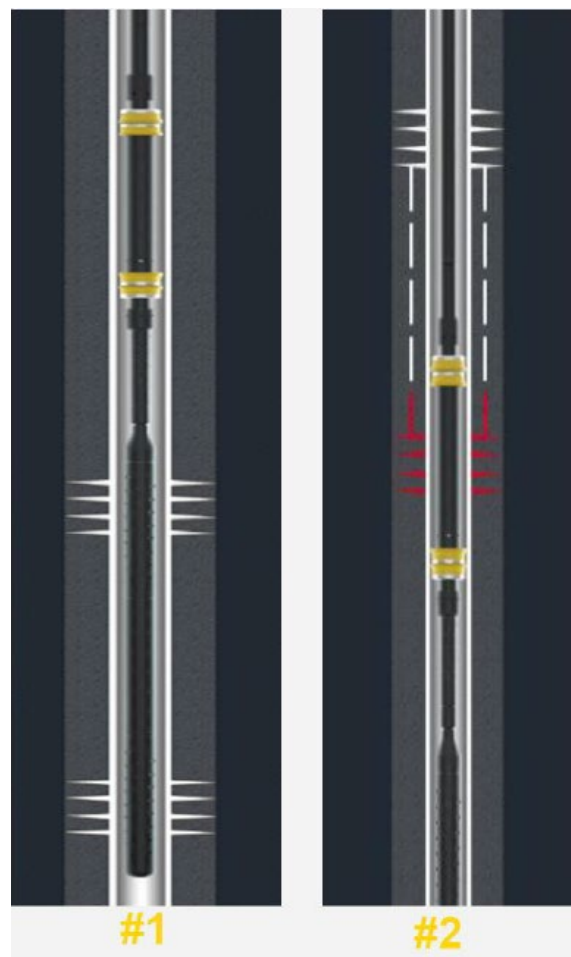


Figure 8.2 steps in a differential leak test of a potential annulus barrier

- The first step is to perforate the top and bottom intervals to establish communication with the formation that has filled the annulus.
- The second step is to isolate the lower perforations and pressure up and monitor for a pressure build up at the upper perforations.

It should be noted that in a differential leak test the distance between the perforated intervals should not exceed 30 meters as required by NORSOK D-010.

The perforation guns, cups and packers can be configured to perform different tasks related to testing WBEs. To increase sensitivity, the volume that is monitored can be minimized by using packers and downhole pressure and temperature sensors.

Archer has carried out work with several Operators on the NCS and has contributed to papers on qualifying creeping shale as a barrier<sup>29</sup>.

### **8.3 Formation Characterization**

The industry is developing methodologies to identify suitable shale barriers and to predict their creep behaviour. This shale barrier information can be incorporated into PP&A risk assessments. The methodologies are validated against multiple data sources, including LWD data, pressure tests, cement bond logs, and analyses of core and cuttings and utilizes AI technology. One company active in this area is Physiq.

The industry is developing models for the determination of local geomechanical stresses in the formation around the well that can be used for the design and testing of WBEs that use creeping shale. This includes assurance that creeping formation has the required integrity at the given depth. Well direction and inclination are important parameters in modelling. One company working in this area is Stag Geological Services.

## **9 Development Areas for Creeping Shale**

This section gives an overview of development and potential development areas regarding creeping shale as a WBE.

### **9.1 Stimulation and Acceleration of Creep**

The industry is currently carrying out work on stimulation and acceleration of creep. The techniques being considered are thermal and chemical and research work is underway to investigate these. Some formations may need to be stimulated to initiate the creep process and hereby form an acceptable WBE. Acceleration of creep can reduce the time between setting the barrier and testing the integrity of the barrier with the obvious cost savings involved. Research work has identified potential challenges including the rebound effect described in section 7.1. Application of stimulation and acceleration will require a formal technology qualification process, development of guideline/best practice and ultimately a detailed description of requirements in NORSOK D-010.

### **9.2 Formation Bond Logging**

There are two areas that are being considered with respect to formation bond logging.

The first is development in ultrasonic logging tools and interpretation will give more reliable information on the material behind the casing as well as more reliable bond assessment.

The second is development in logging while drilling (LWD), including application of artificial intelligence (AI) to interpretation, can provide more reliable information on formation material and physical properties, hence their potential for use as a WBE. LWD with AI may become important for the planning of PP&A and well construction in the future.

### 9.3 Geologically Similar Layers

Most formations extend across field and production license boundaries, and the material and physical properties (lithology) may not vary significantly. The determination and delineation of geologically similar layers is an important factor in the design, installation and testing of WBEs. The aim is to show that the characteristics of the individual formations over a large area do not vary significantly and hence can be defined as 'similar' for the purpose of establishing a track record.

### 9.4 NORSOK D-010

As the industry builds up more experience with creeping shale as a barrier, NORSOK D-010 will need to be updated to keep pace with the development, testing and further use, for example application of geomechanical models in the design of WBEs where creeping shale is used.

One important milestone will be annulus monitoring of creeping shale during a well's lifetime.

## 10 Future Development Areas

There were several points that arose during the interviews that are not just relevant to creeping shale, but have more general application and potential for the industry, in particular for PP&A.

### 10.1 Acceptability of Accumulated Lengths of Formation behind Casing

The normal criteria for the acceptance of a WBE with cement or creeping shale is that there is a continuous permanent seal of at least 30 meters. Ref. NORSOK D-010 EAC Table 22 (Annulus cement), EAC table 52 (creeping formation), EAC table 61 (PWC)<sup>5</sup>.

A project on accumulation of short barrier lengths has been initiated where the potential for using accumulation of shorter intervals is being assessed<sup>17</sup>. This project is relevant for both cement and creeping shale. The intention is that this project will initiate a process on the use of shorter barrier lengths accumulated to provide an acceptable WBE. Research work is also ongoing that can be used to develop the criteria for acceptable verification. This process will, if successful, provide the basis for an update of NORSOK D-010.

### 10.2 Standardisation of Formation Log Interpretation Categories

Several of the contributors suggested an industry initiative to standardize well barrier acceptance criteria for categorisation for formation bond logs with respect to well barrier quality from acoustic logging of well barrier material behind casing.

Development of an industry standard could have benefits with respect to consistency in log interpretations that are used to verify WBEs with cement and creeping shale.

### 10.3 Dual String Logging Systems

Development of a reliable Dual String Logging system offers many advantages to the industry. Information on what is behind casing in different casing strings. Dual string logging using a new approach with CBL/VDL technology could be promising. The sonic scanner gets deeper in from the measuring point and can give a reliable indication of what is behind the second tubular. Interpretation is still being developed to differentiate the responses between cement and formation bonding cement bonding<sup>24</sup>.

Dual string logging can provide valuable information in the following areas.

- Early information of annular barrier status to help P&A planning

- Indications/conformation of annular barriers in wells where barrier status is uncertain in wells not planned for P&A
- Determining annular WBEs in old wells without the use of a rig.
- Rig-less P&A

## 11 Discussion

Operators on the NCS have adopted different approaches to qualification and use of creeping shale, reflecting their operational context and maturity of best practice.

The four Operators involved apply the Well Barrier Element Acceptance criteria in NORSOK D-010, verifying conformity with acceptance criteria through testing, logging, and documentation of track records.

One Operator has conducted a formal technology qualification process (DNV-RP-A203) for both PP&A and well construction applications.

Research and Operator experience confirm that successful application of creeping shale as a WBE depends on identifying formations with appropriate material and mechanical properties, notably high clay and smectite content, ductility, and low permeability.

Studies by SINTEF and PUC-RIO, supported by operator data, have improved understanding of how stress conditions, lithology, and well geometry affect creeping shale behaviour. There is most likely a need for a more systematic formation characterization across fields.

Current work on defining Geologically Similar Layers (GSLs) is promising for transferring track records between areas and will require consistent geological and geomechanical criteria. Future research should focus on integrating laboratory testing, acoustic bond logging, LWD, pressure testing, and modelling data to predict creep performance with greater confidence.

Formation integrity testing and verification methodologies for creeping shale barriers have matured considerably. Operators have developed internal guidelines that align with NORSOK D-010 EAC Table 52, detailing requirements for well barrier length, bond logging acceptance criteria, extended leak-off testing (XLOT), and formation integrity testing.

Time-lapse logging results indicate that creeping shale barrier integrity improves over time, reinforcing confidence in the long-term sealing capacity of ductile formations.

Cooperation with technology suppliers has advanced the development of acoustic logging tools, dual-string logging tools, and geomechanical modelling. Verification using probabilistic and risk-based approaches could potentially allow for the acceptance of accumulated shorter intervals when supported by robust data. Continued collaboration between Operators, service companies, and regulators will be required to define verification standards for these evolving applications.

A consistent finding across all contributors is the strong culture of knowledge sharing in the Norwegian well community. Continued investment in structured information sharing, through common databases, referenced by use of documented track records, and standardized reporting will further strengthen industry competence.

The four Operators have participated in Joint Industry Projects (JIPs) that ensure targeted research and dissemination of results. Industry forums such as Offshore Norge P&A Forum and academic partnerships have been effective channels for experience transfer. This collaborative approach has accelerated learning and enabled alignment between Operators, researchers, and suppliers. It also exemplifies how functional, risk-based regulation can promote innovation while maintaining safety and environmental integrity.

## 12 Acknowledgements

Reflekt would like to thank the companies involved in the knowledge gathering for their cooperation, for making personnel available for discussions and providing relevant information as required. The people involved have shown a thorough knowledge of the subject and have in general displayed enthusiasm and engagement that has made the task an interesting learning experience for Reflekt.

## 13 References

| Number | Title                                                                                                                                                                                                                                                                                                        |
|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1.     | Williams, Stephen, Truls Carlsen, Kevin Constable, Arne Guldahl: "Identification and Qualification of Shale Annular Barriers Using Wireline Logs during Plug and Abandonment Operations", SPE/IADC 119321, 2009.                                                                                             |
| 2.     | Formation as barrier during P&A, Truls Carlsen, Statoil, Presentation to PAF, 14th June 2012 Stavanger, Norway                                                                                                                                                                                               |
| 3.     | NORSOK D-010 Revision 3, 2004<br>Well Integrity in drilling and well operations                                                                                                                                                                                                                              |
| 4.     | Revision update NORSOK D-010, Rev.4,<br>Terje Løkke-Sørensen, add energy,<br>Well Integrity Workshop (WIF) Workshop 6.6.2012                                                                                                                                                                                 |
| 5.     | NORSOK D-010 Revision 4, June 2013<br>Well Integrity in drilling and well operations                                                                                                                                                                                                                         |
| 6.     | NORSOK D-010:2021 Rev 5.<br>Well Integrity in drilling and well operations                                                                                                                                                                                                                                   |
| 7.     | Offshore Energies UK (OEUK) Guidelines on the Use of Barrier Materials in Well Decommissioning                                                                                                                                                                                                               |
| 8.     | Evaluation of Shale Formations as Barrier Element for Permanent Plug and Abandonment of Wells<br>Kristian Moum Skjerve, NTNU<br>Master of Science Thesis                                                                                                                                                     |
| 9.     | SPE/IADC-204040-MS<br>Identifying Formation Creep – Ultrasonic Bond Logging Field Examples Validated by Full-Scale Reference Barrier Cell Experiments<br>Amit Govil, Schlumberger; Harald Nevoy and Lars Hovda, ConocoPhillips; Guillermo A. Obando Palacio, Schlumberger; Geir Kjeldaas, ConocoPhillips     |
| 10.    | Identifying Formation Creep: Ultrasonic Bond Logging Field Examples<br>Amit Govil*, Schlumberger; Harald Nevøy and Lars Hovda, ConocoPhillips; Guillermo A. Obando Palacio, Schlumberger; and Geir Kjeldaas, ConocoPhillips<br>This is a peer-reviewed reduced size version                                  |
| 11.    | Formation Creep, Observations, Practical implications, Way forward/potential<br>Lars Hovda, ConocoPhillips Wells<br>Bjørn Holien, ConocoPhillips Wells<br>OMAE – Trondheim. 11-6-1 Well Plugging and Abandonment                                                                                             |
| 12.    | Permanent P&A in the Greater Ekofisk Area<br>Plug and Abandonment Seminar - October 20th, 2022<br>Supervisor P&A Engineering<br>Thomas Eide Mæland                                                                                                                                                           |
| 13.    | Implementing a Strategy for Shale as Well Barrier in New Wells,<br>Tron Golder Kristiansen and Laurent Delabroy, Aker BP; Guillermo Andres Obando Palacio and Tonje Winther, Schlumberger; Nils Andre Aarseth, Andreas Bauer, Karstein Hagenes, Anders Lindal, and Pål Tyberø, Aker BP<br>SPE/IADC-204075-MS |
| 14.    | Qualification and Experiences with use of Shale as Well Barriers in New Wells,<br>Tron Golder Kristiansen, Chief Engineer D&W – Rock Mechanics, Aker BP<br>SPE Workshop: Well Integrity in a Changing World 6-7 September 2022                                                                               |
| 15.    | A Unified Model for Shale Barriers<br>Bernt S. Aadnøy, University of Stavanger; Tron G. Kristiansen, Aker BP ASA; Mesfin A. Belayneh, University of Stavanger                                                                                                                                                |

|     |                                                                                                                                                                                                                                                                                                                                                |
|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     | IADC/SPE-212556-MS                                                                                                                                                                                                                                                                                                                             |
| 16. | Time-Lapse Evaluation from Ultrasonic Pulse-Echo and Pitch-Catch Configuration and Sonic Logging Data for Potential Formation Creep and General Annulus Solids Segregation.<br>Guillermo Andres Obando Palacio, Amit Govil, Gaurav Agrawal, and Shilpi Gupta, SLB; Laurent Delabroy and Tron Golder Kristiansen, Aker BP<br>IADC/SPE-212483-MS |
| 17. | Thermal Stimulation of Annular Shale Barriers for Long-Term Well Integrity (IADC/SPE-217694). van Oort, E., Lucas, A., Kverneland, J.O., Godøy, R., Reitan, H., Aldin, M., Thombare, A. (2024). IADC/SPE Drilling Conference and Exhibition.                                                                                                   |
| 18. | Activated creeping shale to remove the open annulus<br>Erling Fjær, SINTEF<br>Tron G. Kristiansen, Aker BP<br>P&A Seminar 2017                                                                                                                                                                                                                 |
| 19. | Activating Shale to Form Well Barriers: Theory and Field Examples<br>Tron Golder Kristiansen, Torill Dyngeland, Sigurd Kinn, Roar Flatebø, and Nils Andre Aarseth, AkerBP,<br>SPE-1911607                                                                                                                                                      |
| 20. | “Why Shale Could be used as a Permanent Well Barrier Element” Tron G. Kristiansen, Geomechanics Advisor, Global Wells Organization, BP P&A Forum 29 October 2015, Stavanger                                                                                                                                                                    |
| 21. | Can Heating Induce Borehole Closure?<br>Xiyang Xie, Jørn F. Stenebråten, Sigurd Bakheim <sup>1</sup> , Alexandre Lavrov, Erling Fjær, SINTEF<br>Tron G. Kristiansen, Andreas Bauer AkerBP<br>Rock Mechanics and Rock Engineering<br><a href="https://doi.org/10.1007/s00603-020-02238-5">https://doi.org/10.1007/s00603-020-02238-5</a>        |
| 22. | Huldra PP&A project<br>- from five to one double barrier –<br>Audun Golberg / Jan Reidar Johnsen, Equinor<br>PAF Seminar, Stavanger – 29.10.2015                                                                                                                                                                                               |
| 23. | Short Barrier plugs – status on the barrier capacity project, Stein Åtland, Equinor<br>Offshore Norge P&A Forum                                                                                                                                                                                                                                |
| 24. | Experience with dual string barrier logging, Eirik Berg Equinor and Amit Govil, Schlumberger<br>Presentation at 10th Norwegian Plug & Abandonment Seminar, October 20, 2022                                                                                                                                                                    |
| 25. | SHALE AS A SEALING BARRIER AROUND DEEP WELLS<br>Erling Fjær, Idar Larsen SINTEF<br>OMAE2018-78749<br>Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering OMAE2018                                                                                                                             |
| 26. | PRESSURE TESTING OF BARRIER INTEGRITY<br>Arne M Raaen and Erling Fjær<br>SINTEF, Trondheim, Norway<br>OMAE2020-18713<br>Proceedings of ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering OMAE2020                                                                                                              |
| 27. | Plug & Abandonment of offshore wells: Ensuring long-term well integrity and cost-efficiency.<br>Torbjørn Vrålstad, Erling Fjær, Thomas Øia, Jan David Ytrehus, SINTEF, Arild Saasen, Mahmoud Khalifeh, University of Stavanger                                                                                                                 |
| 28. | Time-dependent closure of a borehole in a viscoplastic rock                                                                                                                                                                                                                                                                                    |

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|     | <p>Xiyang Xie a, Erling Fjær a,b, Emmanuel Detournay c,*<br/> a NTNU, Trondheim, Norway<br/> b SINTEF Industry, Norway<br/> c University of Minnesota, Department of Civil, Environmental, and Geo- Engineering, Minneapolis, MN, USA</p>                                                                                                |
| 29. | <p>Innovative One Trip System Helps Qualifying Creeping Shale as Permanent Barrier for Plug and Abandonment of Wells on the Gyda Field,</p> <p>Thore Andre Stokkeland, Sindre Opedal Archer, Espen Malde, Per Ove Staveland, Stian Johnsen Dybvik, Yngve Frøyland, John Jacobsen, Thomas Kibsgaard-Vatn, Repsol<br/> SPE - 200755 MS</p> |

## **Appendix 1 Overview of Joint Industry Projects**

### **Shale as a Permanent Barrier after Well Abandonment (2015 – 2018)**

Main objectives:

- to identify the main mechanisms involved when shale is acting as a self-sealing annular barrier around a well
- to establish methods for predicting, and possibly improving, the time dependent efficiency of shale as a self-sealing annular barrier around a well
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Secondary objectives:

- to extend the general understanding of creep in a borehole geometry
- to extend the general competence base, and to train more experts, within plugging and abandonment of wells

### **Logging Shale Barrier before Well Abandonment (2016 – 2019)**

Main objectives:

- to verify the capability of the acoustic cement bond log to identify the material behind the casing.
- to identify acoustic methods to log the sealing capabilities of shale around a casing in lab scale.
- to establish methods for interpreting conventional cement-bond logs with respect to shale barrier identification of shale as a self-sealing annular barrier around a well

Secondary objective:

- to verify the potential of using non-linear acoustic to quantify fracture densities in shale and relate this to seal quality

### **Shale Barrier Toolbox: Designing future wells for efficient completion and simpler P&A (2018 – 2021)**

Main objectives:

- to contribute to reduction of climate gas emissions and environmental impact by providing scientifically based tools for optimizing the use of shale barriers for efficient and permanent sealing of wells
- to establish methods for unambiguous verification of existence and efficiency of shale barriers

Secondary objectives:

- to extend the general understanding of creep and plastic deformation of damaged shales in a generalized borehole geometry, including deviated wells
- to extend the general competence base, and to train more experts, within sealing of operational wells and early planning of plugging and abandonment

### **Annular Barrier Verification at in-situ conditions (2024 – 2027)**

Main objective:

- to establish optimal procedures for testing of outside casing barriers, to bring the leakage detection limit down to an acceptable level.

Secondary objectives:

- to establish models for scaling of parameters important for barrier evaluation from laboratory to field conditions
- laboratory verified new methods for annular barrier testing