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The importance of shale caprock damage for well integrity

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ABSTRACT

Well integrity is crucially dependent on the bonding quality between cement and rock. Several studies have been made of this in the past, but none have taken into account that the drilled rock can be fractured and damaged during drilling. Especially a caprock fractured in the near-well zone can jeopardize well integrity. In this paper we have investigated the effect of shale caprock damage on the quality of well cement bonding to shale. Both intact and fractured rock has been cemented under realistic conditions, and the degree of the bonding (e.g. contact surface between the shale and cement) has been studied by X-ray computed tomography (CT) scanning. It was found that in the shale samples with fractured borehole, partial cement slurry penetration into the fracture network resulted in larger volume of leakage pathways than in the intact shale samples. The leakage potential through each of the samples was estimated based on connected cracks found by numerical calculations from three-dimensional (3D) reconstruction of CT data.

1. Introduction

A well is constructed by drilling through subsurface rock formations and using drilling mud to hold back pressure and transport cuttings to surface (Fig. 1a). The mud weight is increased as the pore pressure in the formation increases during drilling, and at a certain depth it is necessary to cement in place a casing string to stabilize the hole (Fig. 1b). A smaller drill bit is thereafter chosen, and drilling continues through the cemented casing. The final well construction ends up as a “telescopic” structure of multiple nested casing pipes that are cemented in place through the drilled rock formation (Fig. 1c). When the productive life of such a well is over, it is permanently plugged by placing cement plugs within the casing, or as a formation-to-formation plug (Fig. 1d). The drilling, construction and abandonment of wells is performed in the same way whether the well is to be used for oil/gas extraction, geothermal heat extraction or subsurface storage of gases such as CO_2.

Well integrity means to avoid leakage through wells, and since they can never be removed but only plugged, it has an *eternal* perspective. Well barriers consist of well barrier elements, and among the most important of these are drilled rock, annular cement and casing steel. Failure of any of these individual materials (including interfaces between them) can lead to leakage. The bonding quality of cement to rock and steel is thus of crucial importance for long-term well integrity.

Bonding of well cement to rock and steel in petroleum wells has been investigated for more than half a century. The first comprehensive studies were done in the 1960s (Evans and Carter, 1962; Carter and Evans, 1964; Peterson, 1963). These authors performed experiments to map how several factors influenced cement bonding, such as slurry composition, surface roughness of casing or borehole, rock type and mud/filter cake at the interface. Measurements of shear bond strength and hydraulic bond strength revealed that mud/filter cake at interfaces greatly reduced bonding, and that rough surfaces gave the strongest cement bonding. These early studies were later continued under more relevant conditions for petroleum wells (Carpenter et al., 1992; Ladva et al., 2005; Buzzi et al., 2007). Some more recent studies have focused on advanced experimental methods for measuring the degree of bonding (e.g. bonded surface area versus debonded surface area) between cement and rock/steel (Opedal et al., 2014; Torsæter et al., 2015; De Andrade et al., 2015; De Andrade et al., 2016). These studies have given more information on the geometry and size of the potential leakage paths along cement/steel and cement/rock interfaces.

The effect of damage or fractures in caprock on potential leakage along the cement/caprock interface is a relatively new topic. To the best of our knowledge, there are only a few publications that are related to CO_2 leakage at cement-shale interface, where at least one of these contained some type of damage. Wigand et al. (Wigand et al., 2009) studied diffusion of brine and supercritical (SC) CO_2 through powdered shale into a cement core with a pre-existing fracture in a core flooding setup. The setup was such that first the brine and subsequently $SCCO_2$ mixture passed first through the powdered shale layer and then entered into the cement. During $SCCO_2$ injection at reservoir conditions, calcium carbonate precipitation was observed in the fracture, which led to fracture opening and increase of the relative permeability along the

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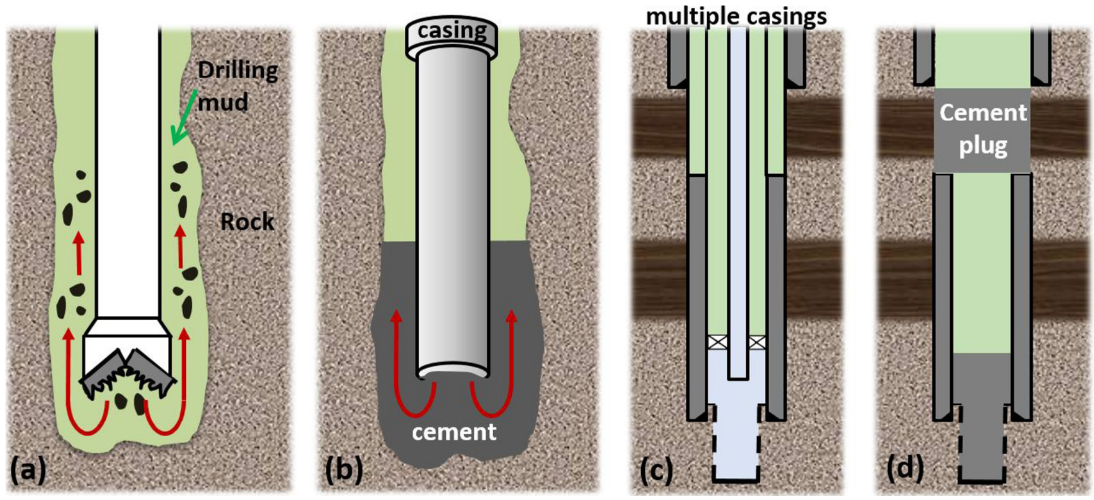

Fig. 1. (a) A drill bit piercing through rock and cuttings transported to surface by circulating drilling mud. (b) Steel casing pipe cemented in place in the borehole. (c) Well consisting of multiple casings ready for production. (d) Well after abandonment.

fracture with time. The cement reacted with the $SCCO_2$-brine system (e.g. carbonation occurred), whereas no significant reaction with brine or $SCCO_2$ occurred at the cement-shale interface. The shale also reacted with the $SCCO_2$-brine system, but there was no interaction with the cement. A similar experimental setup was used by Walsh et al. (Walsh et al., 2014a; Walsh et al., 2014b) to observe cement alteration at cement-caprock interface during CO_2-brine flooding. In this case, the cores consisted of semi-cylinders of cement and caprock, where cement had a fabricated pattern at the interface, whereas the caprock surface toward cement was smooth. However, the focus of these reports was cement carbonation and degradation, and not interaction with the caprock – which was used only as an impermeable barrier against the cement.

Jung et al. (Jung et al., 2014) studied cement alteration along defected cement-basalt caprock interfaces under CO_2 storage conditions. Basalt semi-cylinders were placed in a plastic mold and surrounded by cement slurry, which was then cured. Artificial fractures were then introduced by compressive loading in one sample, while the others remained intact. The samples were reacted with $SCCO_2$-brine mixture in batch under static conditions in three pressure vessels. In addition, computational fluid dynamics (CFD) analysis was performed, using X-ray micro-tomography (μ-CT) datasets as input for fracture patterns, to reveal detailed flow characteristics through the fractures and to calculate the flow rate under a given pressure difference across the specimen. Cement carbonation and calcium carbonate precipitation was observed in all samples. In the pre-fractured sample, the fractures within the cement matrix filled with calcium carbonate, but no extensive calcium carbonate precipitation was observed within the fracture at the cement-basalt interface. On the other hand, in the intact samples, calcium carbonate precipitated in the debonded volume at the cement-basalt interface. CFD modelling indicated decrease of permeability although fractures opened upon calcium carbonate precipitation and cement dissolution. However, for large fracture aperture, as in the pre-fractured sample, debonded cement-basalt interface remained vulnerable during CO_2 leakage. Lorek et al. (Lorek et al., 2016) used similar experimental setup as described by Jung et al. (Jung et al., 2014), but the cores consisted of semi-cylinders of different rock types against which cement slurry was cured. Upon exposure of the cement-shale (slate) sample to CO_2-brine under static conditions, the shale fractured already during the first 30 days and this process progressed during the entire exposure duration. At the end of the exposure (200 days), it was observed that the cement and the shale had debonded and calcium carbonate precipitated at the cement surface. There was a calcite enriched zone in the shale at the interface as well, which was followed by a highly porous zone in the shale. Lorek et al. (Lorek et al., 2016) concluded that the effect of CO_2 exposure on the integrity of the cement-rock interface was strongly dependent on the rock lithology. These two studies (Jung et al., 2014; Lorek et al., 2016) indicate that sealing of the debonded cement-caprock interface upon CO_2 exposure can be dependent on many parameters

The rock surfaces applied in the studies discussed above were all smooth, laboratory prepared rock surfaces. This is unrealistic with respect to a real downhole borehole surface. The rock can be damaged by the drill bit during drilling, or later as a result of impact and smearing from the rotating drillstring and stabilizer. Since it is of outmost importance for well integrity that the cement-caprock bond is tight, the sealing ability of cement towards realistic shale interfaces is especially interesting to study. Drilling-induced borehole damage in shales has been studied previously in the laboratory (Gabrielsen et al., 2011). It was found that the type and amount of drilling-induced damage is strongly dependent on the bedding orientation with respect to drilling. Laboratory studies have also revealed that small shale fragments are smeared back onto the borehole wall during drilling, giving rise to a perturbed shale zone near the hole (Torsæter et al., 2014). A field study of a 55-year old well from SACROC field in Texas has also indicated that the shale zone is indeed fragmented prior to cement placement (Carey et al., 2007). A sidewall cores consisting of casing, cement and shale caprock were studied, and a fragmented shale zone at the caprock-cement interface was observed (Carey et al., 2007). On the other hand, in another field study, in this case of a natural CO_2 producer, it was observed that cement was well bonded to the formation (Crow et al., 2010). To the best of our knowledge, there are just a few field studies published on cement-formation bonding, which is not sufficient to reach consistent conclusions.

The scope of our work is to investigate experimentally how cement bonds to shale borehole with more realistic interfaces, and to simulate leakage through such pathways at the cement-shale interface. The objective of this publication was to focus on the *placement of cement* slurry in down-scaled hollow shale cylinders. More specifically, the aim was to observe how cement was able to provide a seal in the borehole, but also its ability to penetrate complex fractures and repair a damaged caprock. This was performed by using smooth and non-fractured samples (best-case scenario) as a reference for comparing to samples with a high level of damage (worst-case scenario).