Characterization of cement from a well at Teapot Dome Oil Field: Implications for geological sequestration

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Abstract

Wellbores represent the weakest link in terms of CO2 storage permanence. As a result, special attention to the numerous existing wells that perforate storage formations is needed. The pre-injection condition of the cement can influence the rate (and type) of alteration by the injected CO2 plume. The condition of the existing well cement depends on a variety of factors including wellbore/formation and wellbore/brine interactions as well as the composition and type of cement placed in the well (i.e. type of admixtures used, water/solids ratio, sulfate resistant mixes, etc.). In this paper, the details of recovering wellbore cement from an older well to determine pre-injection seal integrity are described. Petrographical and chemical analyses are presented for samples of cement that were retrieved from a 19-year-old well at Teapot Dome in Wyoming. Examination revealed that the retrieved cement had altered as a result of original slurry composition and with respect to the local downhole wellbore environment. Although samples were obtained from a single well, significant differences were observed in their alteration and condition. Sulfate attack resulted in abundant ettringite formation in a cement sample taken adjacent to the Wall Creek sandstone (3060 ft), while cement taken adjacent to the Tensleep formation (5478 ft) was decalcified and enriched in magnesium, owing to reaction of calcium hydroxide in the cement with the dolomite formation.

1. Introduction

A potentially important strategy for reducing carbon dioxide in the atmosphere is to capture CO2 and inject it into the subsurface. Exhausted petroleum reservoirs provide particularly attractive sites for geosequestration of CO2, because their geology is well characterized and a good seal (cap rock) is present. However, the cap rock is penetrated by wells that were lined and then plugged with cement when they were abandoned. Well cement could be attacked by the carbonic acid created when injected CO2 mixes with the brine in the formation (Bachu and Celia, 2009). Considerable research is currently addressing the kinetics of acid attack on cement (Scherer et al., 2005; Duguid, 2006, 2010; Rimmele et al., 2008; Kutchko et al., 2008), and the rate of dispersal of CO2 should leaks occur (Nordbotten et al., 2005; Gaus et al., 2008; Oldenburg et al., 2009; Viswanathan et al., 2008). Previous samples recovered from existing wells are limited to those already exposed to CO2 over extended periods of time (Carey et al., 2007; Crow et al., 2010). Little is known about the pre-injection condition of the well cement in those studies and how that may have contributed to their alteration. These studies required interpretation of both the effects the CO2 and long-term aging within the wellbore environment. The rate and mechanism of cement alteration will depend on its pre-injection condition. The purpose of this study was to describe the procedure employed to recover cement from an existing well and present a characterization of that recovered cement.

2. The well

The Rocky Mountain Oilfield Testing Center (RMOTC) in Caspar, Wyoming, is a testing site for oil field technology that resides within the Naval Petroleum Reserve No. 3 (NPR-3), the Teapot Dome Oil Field, near Casper, Wyoming. Teapot Dome produces from 600 wells in nine geological formations. The well chosen for sampling in the present study was #43 Tpx-10, which has a pay zone in the Tensleep formation. A stratigraphic column of Teapot Dome...
at well Tpx-10 is presented in Fig. 1, which shows the Tensleep extending from about 5525 to 5845 ft (1680–1780 m) below the surface.

2.1. Reservoir characterization

Cement was recovered adjacent to the Tensleep and 2nd Wall Creek Formations. The Tensleep reservoir pressure and temperature are reported as 16.2 MPa and 88 °C, respectively (Friedman and Stamp, 2006). Over 1.8 million barrels have been produced to date (Friedman and Stamp, 2006). Tensleep contains a network of fractures and faults that impact both performance and reservoir flow (Friedman and Stamp, 2006). The 2nd Wall Creek Formation was subjected to a waterflood and produced gas re-injection in 1979. The waterflood was discontinued in 1992 and the reservoir currently exists in a pressure-depleted state. The northern part of the reservoir is separated from the south by a sealing fault (Stamp, 2010).

Brine taken from the Tensleep location had a pH of 7.93 with total dissolved solids (TDS) at 3220 mg/L, rich in sulfate (887 mg/L) and chloride (870 mg/L). Bicarbonate levels were measured at 148 mg/L. Brine in the 2nd Wall Creek had an average pH of 8.2 in the southern portion of the reservoir and an average pH of 7.9 in the northern portion. Measurements taken between 1969 and 1996 showed sulfate concentrations ranging from 0.00 mg/L to over 10,500 mg/L. Detailed compositions of the brines are given in Tables 1 and 2.

2.2. Cementing

Well #43 Tpx-10 was cemented in February, 1985. A 7 in. (17.8 cm) K-55 steel casing was set at 5643.3 ft (1719 m); a float collar was set one joint up from the guide shoe and a stage tool
Table 2
Composition of formation water in the 2nd Wall Creek Formation.

<table>
<thead>
<tr>
<th>Year collected</th>
<th>Reservoir location</th>
<th>pH</th>
<th>Cations (mg/L)</th>
<th>TDS</th>
<th>Sulfate</th>
<th>Chloride</th>
<th>Sodium</th>
<th>Bicarbonate</th>
<th>Carbonate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969</td>
<td>South</td>
<td>8.0</td>
<td>16,578.0</td>
<td>10518.0</td>
<td>230.0</td>
<td>4963.0</td>
<td>952.0</td>
<td>0.0</td>
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</tr>
<tr>
<td>1979</td>
<td>South</td>
<td>8.3</td>
<td>12,848.0</td>
<td>0.0</td>
<td>6200.0</td>
<td>5028.0</td>
<td>2966.0</td>
<td>156.0</td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>South</td>
<td>8.4</td>
<td>13,787.0</td>
<td>0.0</td>
<td>6500.0</td>
<td>5448.0</td>
<td>3074.0</td>
<td>228.0</td>
<td></td>
</tr>
<tr>
<td>ave</td>
<td></td>
<td>8.2</td>
<td>14,404.3</td>
<td>3506.0</td>
<td>4310.0</td>
<td>5146.3</td>
<td>2240.7</td>
<td>128.0</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td></td>
<td>0.2</td>
<td>1940.1</td>
<td>6072.6</td>
<td>3536.6</td>
<td>263.3</td>
<td>1131.9</td>
<td>116.6</td>
<td></td>
</tr>
<tr>
<td>1977</td>
<td>North</td>
<td>8.3</td>
<td>14,720.0</td>
<td>150.0</td>
<td>5900.0</td>
<td>5874.0</td>
<td>4892.0</td>
<td>300.0</td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>North</td>
<td>8.2</td>
<td>13,491.0</td>
<td>0.0</td>
<td>6400.0</td>
<td>5320.0</td>
<td>2989.0</td>
<td>204.0</td>
<td></td>
</tr>
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<td>1979</td>
<td>North</td>
<td>8.0</td>
<td>13,806.0</td>
<td>45.0</td>
<td>6350.0</td>
<td>5458.0</td>
<td>3758.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>1987</td>
<td>North</td>
<td>7.3</td>
<td>13,744.0</td>
<td>9.5</td>
<td>4461.5</td>
<td>4610.1</td>
<td>4636.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>North</td>
<td>7.6</td>
<td>15,100.0</td>
<td>6.9</td>
<td>7260.0</td>
<td>5650.0</td>
<td>2501.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>ave</td>
<td></td>
<td>7.9</td>
<td>14,172.2</td>
<td>42.3</td>
<td>6074.3</td>
<td>5382.4</td>
<td>3755.2</td>
<td>100.8</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td></td>
<td>0.4</td>
<td>696.8</td>
<td>62.7</td>
<td>1027.1</td>
<td>479.4</td>
<td>1028.1</td>
<td>142.1</td>
<td></td>
</tr>
</tbody>
</table>

at 3965 ft (1208 m). In the first stage, a “lead” mix with a density of 14.3 lb/gal (1715 kg/m³) containing 50% Class G cement and 50% Pozmix® (pozzolanic fly ash, Halliburton), 2% benonite, and 7% Calseal® (ground rubber and polymer, Henry Co.) was introduced through the float collar. This was followed by a “tail” mix with a density of 15.9 lb/gal (1907 kg/m³) containing Class G cement mixed at a water/cement ratio 0.44 using formation water; 10% NaCl (per weight of formation water) was added to improve the strength and reduce shrinkage of the cement. Additionally, Flocele® (3/8 in. (∼1 cm) cellophane flakes intended to prevent water loss into the formation, Halliburton) was added at a ratio of 0.25 lb per 94 lb sack of cement (0.265 wt%).

The cementing record indicates problems with circulation during the first stage (cemented with partial returns), which may mean that the Tensleep formation is naturally fractured; this might have resulted in the lead cement not being completely displaced by the tail cement. The second stage cementing, through the stage tool at 3965 ft, used a mix identical to the lead cement; the records indicate good circulation in this step.

The cumulative production of this well was about 74,000 barrels of oil (Schulte, 2000). The pressure in the well at the level of the Tensleep formation has remained near 16.2 MPa (2350 psi), owing to strong bottom water drive. There is no indication of sustained casing pressure in this well. If pressure had been detected, a remedial cementing job would have been required (Stamp, 2010), but no such work was done.

3. Retrieval and optical microscopy of bulk samples

Sidewall cores were retrieved from well NPR-3 43 TPX-10 at RMOTC on 18 August 18, 2004, using a sidewall coring tool developed by Schlumberger. The tool, which is about 20 ft (∼6 m) long, is shown in Fig. 2. Most of the length contains control equipment; a pressure shoe moves out from the tool when the drill is opposite the target site, to hold the tool against the casing. The drill rotates 90° into a horizontal position and moves into contact with the casing; after it drills to its full extension (1 7/8 in., 47 mm), it tilts down again and the sample falls into the recipient below. The drill bits are ∼1 in. (25 mm) in diameter and have diamond-coated teeth (see Fig. 3). They survive one use, because this type of bit is not intended for cutting steel.

3.1. Core 1 (Sample 1)

The first core was taken at a depth of 3060 ft (933.3 m) in a band of dense limestone (to avoid the need to reseal the hole with cement). The drilling went perfectly: the drill penetrated slowly through the steel, which is ∼0.31 in. (7.9 mm) thick, then rapidly passed through the cement. When the tool was raised out of the hole, the sample was retrieved from the container on the bottom; the rate of rise of the tool was 5000 ft/h (1525 m/h). As shown in Fig. 4, the core broke into two pieces, but the piece on the right is firmly attached to the steel casing (bright area at lower end). There

![Fig. 2.](A) Sidewall coring tool (total length ∼20 ft) consists of control electronics, pressure shoe that moves out and pushes the tool against the casing, motor and (B) drill bit (which turn horizontal before drilling, then tip back before retrieval), and sample catcher (to hold sample when it falls from the bit).
3.2. Core 2 (Sample 2)

The second core was taken at a depth of 5477 ft (1670.5 m), in the cap rock about 6–10 ft (2–3 m) above the producing zone of this well. The tool jammed when approaching the full thickness of the steel casing (perhaps because of an annular gap behind the steel), so it had to be moved back and forth to cut through the casing. The withdrawal rate of the tool for this and the subsequent cores was 20,000 ft/h (6100 m/h). This time, none of the steel was retrieved, and there were only fragments of cap rock, along with fine debris. Sample 2 consisted only of some small fragments of cap rock.

3.3. Core 3 (Sample 3)

The third core was taken just below the second, at 5478.5 ft (1671 m), in an attempt to get cement from the cap rock zone. The drilling proceeded much as in core #2, in that the bit jammed as it reached the outer surface of the steel. The sample was slightly smaller than #2; again, no steel was retrieved. A portion of a core of cement almost an inch (2.5 cm) long was recovered. The flat side of the core has circular grooves that may have formed when the cement spun against the casing or the formation during drilling. A fragment of cap rock was retrieved with a film on the surface that appears to be cement.
Table 3
Brief description of cores obtained from well #43 Tpx-10 at Teapot Dome Oil Field.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Depth (ft)</th>
<th>Thin section ID</th>
<th>Adjacent formation</th>
<th>Description</th>
<th>Cement description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>3060</td>
<td>TPD 1a and TPD 1b</td>
<td>Frontier—2nd Wall Creek</td>
<td>Cement recovered</td>
<td>Sulfate attack of cement, porous paste, Class C fly ash observed</td>
</tr>
<tr>
<td>Sample 2</td>
<td>5477</td>
<td>TPD 2</td>
<td>Tensleep—dolomitic caprock</td>
<td>Small fragments of caprock recovered—no cement recovered</td>
<td>No cement recovered</td>
</tr>
<tr>
<td>Sample 3</td>
<td>5478.5</td>
<td>TPD 3a and TPD 3b</td>
<td>Tensleep—dolomitic caprock</td>
<td>Cement and caprock recovered</td>
<td>Dedolomitization of cement observed no cement recovered</td>
</tr>
<tr>
<td>Sample 6</td>
<td>5496</td>
<td></td>
<td>Tensleep—dolomitic caprock</td>
<td>Casing recovered—no cement observed</td>
<td>No cement recovered</td>
</tr>
<tr>
<td>Sample 7</td>
<td>3846</td>
<td></td>
<td>Thermopolis Shale(?)</td>
<td>Pieces of formation and fine debris recovered—no cement recovered</td>
<td>No cement recovered</td>
</tr>
</tbody>
</table>

3.4. Core 4

The fourth core was taken from the “pay zone”, where the casing had been perforated to permit extraction of oil, at 5488 ft (1674 m). The bit slowed as it approached the outer surface of the casing, then jumped about an inch, apparently because there was a gap behind the casing. The bit then stopped, so it had to be worked back and forth extensively. There was no sample retrieved here, but we did collect some fine debris, in case it might be cement.

3.5. Core 5

The fifth core was again taken from the perforated zone, at 5494 ft (1675.7 m), and ran into problems similar to #4. No sample was obtained. The tool was apparently malfunctioning, so it was replaced with a spare.

3.6. Core 6

A new tool was installed, and a sixth core was taken at 5496 ft (1676.3). This tool went through the steel at about half the rate of the others, so it took ~20 min to penetrate the casing. The drill seemed to move smoothly through the cement, with only one jam that required retracting the drill. Unfortunately, the only sample retrieved was a piece of casing; no cement was evident. Circular grooves on the surface presumably resulted from spinning of the steel against something hard during drilling. It is unlikely that the cement could have scratched the steel, so it was probably the formation; this may mean that there was no cement in that location.

3.7. Core 7 (Sample 7)

The seventh and last test was taken at 3846 ft (1173 m). The drill went smoothly through the steel and well into the cement before jamming—possibly in the formation rock. It was necessary to pull back the drill and re-enter the formation, after which the progress was very slow. The operator pulled the bit back a few more times before finishing, but we expected a good result. Again, however, only pieces of the formation and fine debris were recovered.

Several factors might have contributed to the low rate of retrieval of cement. The experiment required the same tool to cut through steel, concrete, and stone, which normally would require different bits. A set of experimental bits was designed for this purpose, and each sample was taken with a different type. Probably

Fig. 7. Scanning electron microscope (SEM) backscattered electron (BSE) image of Sample 1 (thin section TPD 1a) showing highly porous cement, abundant amounts of ettringite and fly ash. Former cement grains have also been decalcified. The region of cement represented in this image was typical of both TPD 1a and TPD 1b.
Fig. 8. BSE images of Sample 1 (thin section TPD 1a) with energy dispersive spectrum (EDS) showing deposits of ettringite. The morphology and EDS spectrum is typical for ettringite in cement.

4. Petrographic and scanning electron microscopy of thin sections

Six thin sections were examined using a polarizing petrographic microscope and a scanning electron microscope (SEM) equipped with a backscattered electron (BSE) image detector and energy dispersive spectroscopy (EDS) (see Table 3). Petrographic light microscopy (PLM) allows for the identification of phases and constituents based on their optical properties whereas SEM-BSE provides visual information based on gray-scale intensity difference between the densities of the phases. Analysis of thin sections using both PLM and SEM-EDS provides detailed macro- to microscopic information about mineralogical, chemical, and microstructural features. The following provides a more detailed description of each thin section.

Sample 1: Thin section #TPD 1a and TPD 1b. Examination with SEM and PLM revealed that the microstructure of the cement in Sample 1 (thin sections TPD 1a and TPD 1b) was highly porous and lacking in calcium hydroxide and calcium carbonates (Fig. 7). In addition, large quantities of ettringite (calcium sulfoaluminate, \( \text{Ca}_6[(\text{Al,Fe})(\text{OH})_6]_2(\text{SO}_4)_3 \cdot 26\text{H}_2\text{O} )\) were observed throughout these cement samples (Fig. 8). The C–S–H appeared well-crystalline in several regions (Fig. 9). Ettringite amounts and porosity appeared abnormally high for a 19-year-old (unaltered) Class G cement with fly ash.

All the thin-sectioned cement samples contained large quantities of calcium-rich fly ash consistent with Class C fly ash (Fig. 10). Class C fly ash is a high-CaO ash produced as a result of burning lignite or sub-bituminous coal that produces spherical particles. Class C fly ash is not truly considered a pozzolan since it has cementitious properties of its own without the need for calcium hydroxide. The initial hydration products of Class C fly ash include ettringite (Manz, 1999; Taylor, 1997). It was determined by SEM-EDS that the fly ash consisted primarily of calcium-rich spheres associated with lesser amounts of aluminum and minor amounts of magnesium and silicon. The fly ash contained well-defined hydration rings indicating that it was undergoing hydration. Polymer flakes (possibly Calseal®) were observed in Sample TPD 1b.

Sample 2: Thin section #TPD 2. This sample was composed entirely of dolomite. Both very fine-grained and large crystals were observed. No cement was observed.

Sample 3: Thin section #TPD 3a and TPD 3b. There was no observable difference between subsamples TPD 3a and 3b. This sample appeared to contain less fly ash than the other thin sections. Calcite crystals were observed growing on the outer edge of the cement face (Fig. 11). Polymer flakes (possibly Calseal®) were observed in the matrix of the cement. Sample 3 consisted of both dolomite and cement. According to SEM-EDS and PLM, the...
cement paste was depleted in elemental calcium, lacked calcium hydroxide, contained calcium-rich fly ash, and contained appreciable amounts of magnesium. Magnesium-enrichment of the cement paste was observed using SEM-EDS. Magnesium silicate phases appeared throughout the cement, including as pseudomorphs of former cement grains (Fig. 12). A band of calcite was located at the cement/dolomite formation interface (Fig. 11); nevertheless, the interface between the dolomite/calcite and cement appeared visibly tight.

Thin section #TPD 7 was composed entirely of sandstone, not cement.

4.1. Thin section discussion

The cement from the two different sections (depths) of the wellbore was significantly different in microstructure and mineralogy from each other. They were also different from the expected initial state of a Class G cement mix with fly ash. Sample 1 (thin sections TPD 1a, TPD 1b) was taken adjacent to the Upper Cretaceous Wall Creek (Frontier) Sandstone (3060 ft) whereas Sample 3 (thin sections TPD 3a, 3b) was taken adjacent to the Tensleep formation dolomites (5478.5 ft) (see Fig. 1). The cement from the Wall Creek sandstone appears to have undergone a form of sulfate attack while the samples retrieved from the Tensleep location consisted of cement that had undergone decalcification and magnesium-enrichment likely a result of “dedolomitization”. It appears that a variety of influences including the initial composition and location (placement) of wellbore cement altered the cement mineralogy and microstructure over time. These observations highlight the need to understand influences such as rock/brine/cement interactions and the role of admixtures.

Sulfate attack consists of a series of chemical reactions between sulfate ions and various components of hardened cement caused by exposure to sulfates originating from internal or external sources (Skalny and Thaulow, 2002). Typically, sulfate ions penetrating the cement paste will react with the calcium and aluminum compounds to form calcium-alumino-sulfates (ettringite) (Glasser et al., 2008). Based on the distribution and abundance of ettringite, it appears that the cement underwent a form of sulfate attack likely due to contact with a sulfate-rich brine (see Table 1). Solutions rich in calcium sulfate attack the alumina-bearing hydration products and/or unhydrated tricalcium aluminate to form ettringite.

The presence of fly ash (~50% by PLM estimate) indicates that this is the “lead” cement mix, rather than the “tail” mix. The “lead” cement did not use formation water in the mix as did the “tail” cement (and the “tail” cement did not use fly ash). Lost circulation problems, as indicated in the cementing record, likely resulted in the recovery of the “lead” cement where “tail” cement was expected.

The Class C fly ash likely contributed to the large amounts of ettringite and the lack of calcium hydroxide observed. Fly ash will react with portlandite and aluminate to form ettringite. In addition, the addition of Class C fly ash is known to decrease the sulfate resistance of cement (Neville, 2004; Monteiro and Kurtis, 2003). The exposure of a brine rich in sodium sulfates to cement containing Class C fly ash has been shown to cause a rapid reaction with both aluminate and calcium hydroxide to form large amounts of ettringite (Taylor, 1997). In oilwell cements, the tricalcium aluminate (C₃A) is present in trace amounts or is absent altogether (Meller et al., 2004). Therefore, the primary aluminum source for ettringite formation was likely the fly ash.

The formation of ettringite after the cement has hardened is particularly destructive. Under ambient conditions, sulfate attack of hardened cement causes strength loss, cracking, and disintegration of the cement and is known to lead to decalcification and destruction of the C–S–H (Taylor, 1997). This is consistent with the microscopic and elemental observations of Sample 1. However, the wellbore environment is significantly different (increased temperatures, pressures, and confining stresses) than ambient conditions. The wellbore environment will affect the solubility, stability, and crystallization pressure effects of ettringite. The mechanism and nature of sulfate attack in well cement requires further study.

Ettringite will decompose where the pH of the cement pore water is less than ~11.5 (Neville, 2004). Therefore, the presence of ettringite is a good indication that the pH of the cement pore water remained above ~11.5. However, if CO₂ was to penetrate the cement, the pore water pH would effectively be lowered causing the decomposition of the ettringite. It is unknown at this time if this process would be beneficial (i.e. forming calcium carbonates) or harmful (leaching of calcium compounds). The mechanical effects...
of ettringite formation in wellbore cement are also unknown and require further study.

Cement using fly ash admixtures and similar in density to Sample 1 have been studied in previous laboratory experiments (Kutchko et al., 2009). These laboratory samples did not exhibit the porosity or alteration observed in the wellbore samples. A Class G cement simulating the “tail” cement was prepared and cured under in situ reservoir conditions. The cement was mixed using a solution identical to the formation water, and included the extra 10% NaCl and polymer flakes as specified in the cementing record. Upon initial examination there was no evidence of ettringite formation or excessive porosity. However, this may simply be a time dependent result.

Sample 3 highlights the importance of the cement/formation rock interface. Dolomite is known to react with portlandite in cement, in a reaction referred to as “dedolomitization”, producing both calcite and brucite as follows (Taylor, 1997; Gali et al., 2001):

\[
\text{CaMg(CO}_3\text{)}_2(s) + \text{Ca(OH)}_2(s) = 2\text{CaCO}_3(s) + \text{Mg(OH)}_2(s)
\]  

Although the reactions involved are not well understood (Neville, 2004), this process is known to dissolve dolomite, precipitate calcite, and release magnesium into solution (Taylor, 1997; Ayora et al., 1998). The formation of calcite at the dolomite/cement interface was likely a result of this process (Fig. 11). The magnesium-enrichment of the cement gives evidence for the transport of magnesium through the pore structure of the cement. The decalcified cement paste with the large calcite crystals on the edge of the cement would indicate that calcium was also transported through the matrix. A typical interaction of magnesium with...
in magnesium. Mg(OH)\textsubscript{2} will also react with and decompose C–S–H

SEM-EDS indicated that the hydration rims of fly ash were enriched in the grain due to incomplete hydration (Brown and Doerr, 2000).

Tates in unhydrated cement grains because the local pH is elevated. The cement grain has decalcified and altered to magnesium silicate.

Fig. 12. BSE-EDS images of Sample 3 (thin section TPD 3b) showing (A) magnesium silicate phases deposited in the cement and (B) pseudomorph of a former cement grain. The cement grain has decalcified and altered to magnesium silicate.

cement is shown as the base-exchange reaction (Brown and Doerr, 2000): 

\[
\text{Mg}^{2+} + \text{Ca(OH)}_{2} = \text{Mg(OH)}_{2} + \text{Ca}^{2+}
\] (2)

Within the cement, unhydrated cement grains have been decalcified and converted to a magnesium silicate (Fig. 12). It has been shown that magnesium can replace calcium in former cement grains (Neville, 2004; Brown and Doerr, 2000). Mg(OH)\textsubscript{2} precipitates in unhydrated cement grains because the local pH is elevated in the grain due to incomplete hydration (Brown and Doerr, 2000). SEM-EDS indicated that the hydration rims of fly ash were enriched in magnesium. Mg(OH)\textsubscript{2} will also react with and decompose C–S–H and interact with the silicate hydrate formed from C–S–H decomposition. Under ambient conditions, this process is known to result in the formation of magnesium silicate hydrates lacking cohesive properties (Neville, 2004). It is unknown what implications this would have on the integrity of the cement with regard to CO\textsubscript{2} injection. These observations highlight the need for further wellbore integrity studies.

5. Conclusions

Attempts to retrieve cores from a 19-year-old well at Teapot Dome yielded two samples of cement. Sample 1 experienced sulfate attack, apparently a result of the original cement design reacting with the downhole formation solution. This resulted in the formation of abundant ettringite and porosity. Sample 3, in contact with a dolomitic (Tensleep) formation, showed calcium loss and magnesium-enrichment, owing to reaction of dolomite with calcium hydroxide in the cement. These results indicate that significant modification of the well cement can be expected in older wells, and this should be taken into account in modeling of the chemical durability of cements exposed to geosequestered CO\textsubscript{2}. It is unknown how these significant alterations will ultimately affect the integrity of the cement under CO\textsubscript{2} injection scenarios. As a result, the authors strongly recommend further experimental studies, additional well cement retrieval, and modeling in order to address the implications of pre-injection altered cements in aging wellbores.

Acknowledgments

The cement sampling project was sponsored by the Dept. of Energy, Cooperative Research and Development Agreement No. 2004-051. We are indebted to Steve Hardy, RMOTC Field Engineer, for details regarding the cementing of well #43 Tpx-10, and to Vicky Stamp, RMOTC Project Engineer, for coordinating the project. We thank the Schlumberger crew for designing and operating the coring tool. Andrew Duguid was supported by the Carbon Mitigation Initiative at Princeton University, sponsored by BP and Ford Motor Company.

References


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