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Advanced cement integrity evaluation of an old well in the Rousse field

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Abstract

The Rousse field, located in the Lacq basin in the southwest of France, is a site for a pilot carbon dioxide (CO_2) storage project operated by Total. Since 2010, CO_2 has been injected into a depleted gas field at a depth of 4.5 km through RSE-1, a 45-year old production well converted to an injection well.

Older wells are commonly recognized as the most likely pathway for CO_2 to migrate from the injection zone to other zones or to the surface. A number of factors could increase the potential risk for these wells: completions and production history may have created defects in the sealing elements (cement, steel and elastomers); the history itself may not be known in sufficient detail to estimate a reliable risk figure and finally the injected or produced fluids may have corroded the structure

Old wells, whether they are converted to injectors or are in the path of the injection pressure field, could require renewed evaluation and preventive repairs as part of the field-level containment management plan, if their integrity assessment request so.

As part of the due diligence process, advanced cement and steel evaluation logging tools were run in the RSE-1 well to investigate the bottom kilometer of the two kilometer-thick caprock. The 3D integrity map produced by the acoustic logging tools was analyzed for the presence of connected defects (pathways) that could lead to unwanted CO_2 migration. The logs were also compared to the original 40 year old low-resolution sonic log to assess the extent of degradation, if any.

A particular issue for wells drilled before the 1990's, when technological advances almost eliminated the problem, is that of mud channels left behind during the cement placement process. These defects present the highest risk because of their relatively large flow area. Since the well was completed in 1967, special attention was paid to the occurrence, connectivity and extent of channels. Even though imaging of the cemented annulus revealed an eccentered casing, almost lying on the rock face, and an oval borehole, the few mud pockets trapped between casing and rock were confirmed to be intermittent, with good cement providing hydraulic isolation between them. The comparison of the through-casing caliper to the formation sonic log enabled identification of borehole breakouts, caused by stress

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anisotropy, as the reason for the ovalization of the borehole section. Casing-cement bonding was confirmed to be excellent (it actually improved compared to the original log), and model-based inversion of imaging data suggests that cement-formation bond is also good.

Defect-oriented analysis of the logs thus confirmed that RSE-1 provided containment across the caprock and was suitable for conversion to a CO_2 injector without any repair or improvement work.

Keywords: wellbore integrity; cement evaluation; storage containment; leakage risk assessment assessment; injector well conversion; leakage pathways; wireline logging; zonal isolation; pilot project

1. Introduction

1.1. Lacq CCS pilot project

In the Lacq basin, in the south-west of France, Total has been operating a pilot Carbon Capture and Storage (CCS) project since January 2010.

The carbon dioxide (CO_2) is produced at a rate of around 60,000 tons per year from a revamped 30 MWth boiler which runs on natural gas from the Lacq field and has been converted to oxyfuel combustion. Once compressed and dehydrated, the flue gas is transported by pipeline for 29 km to Rousse, a small satellite depleted gas field, for injection into the RSE-1 well. The project has been extended in November 2011 and is now scheduled to last until July 2013, when the original injection target of 120,000 tons of CO_2 will have been reached.

The pilot project has four main objectives:

- Design, build and operate an integrated CCS chain.
- Evaluate the performance and costs of oxyfuel boilers for steam production, with a goal of scaling up the one installed in Lacq by a factor ten.
- Develop and apply geological storage qualification methodologies.
- Develop, adapt and apply monitoring technologies and methodologies suitable for large-scale onshore storage projects.

1.2. RSE-1 well

The Rousse reservoir is intersected by a single production well and, as part of the overall site qualification process, its suitability for conversion to injector had to be assessed.

Above the Mano dolomite reservoir, the >2 km long clay and marl Upper Cretaceous flysch sequence acts as a competent caprock separating the storage horizon from the Tertiary aquifers. The RSE-1 well architecture follows the geology: the 13⅜” surface casing isolates the Tertiary and two casing strings (the 9⅝” and 7”) are set in the caprock with the 7” casing shoe reaching 4,539 m measured depth (MD), 3 m above the reservoir. A final 5” liner is run to 4,737.5 m and perforated between 4,540 and 4,566 m, at the top of the injection interval.

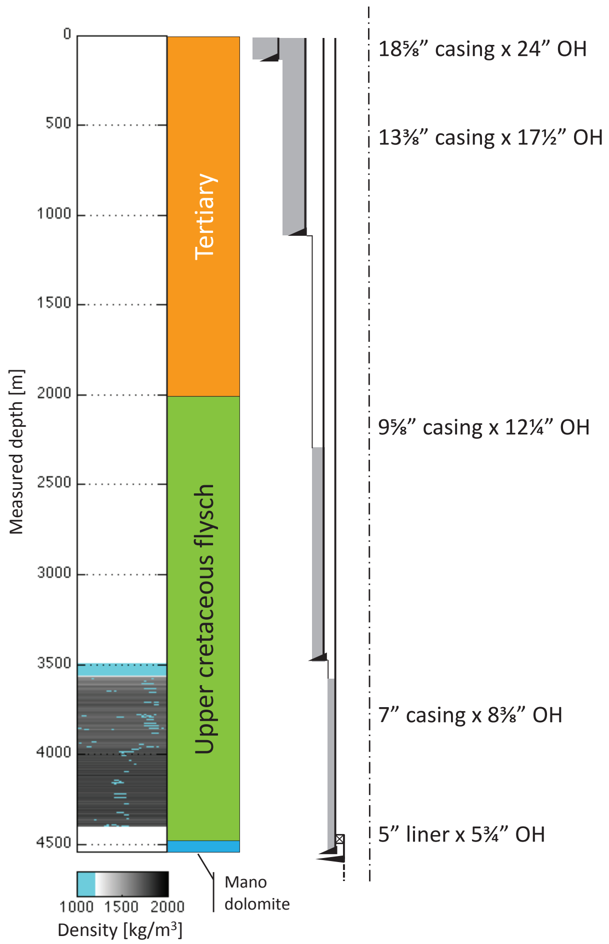

Fig. 1. RSE-1 schematic with casing section positions and general stratigraphy. The column to the left shows the extent of the Isolation Scanner log and is color- coded according to the inverted cement density.

The primary cement barrier fills the annulus between 7" casing and 8⅜" open hole up to a depth of 3,569 m, 103 m below the 9⅝" casing shoe; the upper annulus is in direct hydraulic connection with the wellhead. The well was drilled in 1967 and very little information was left about the design and execution of the cement job, other than that 6 centralizers were used between the 7" and 9⅝" casings and that 1,960 kg/m^3 density Diamantite cement was pumped. Research later revealed that Diamantite was a proprietary type of cement commercialized by Lafarge in the 1960's and roughly equivalent to API class B.

The original log data set included gamma ray, one-arm caliper and compressional sonic wavespeed for the 8⅜" hole section, and a Cement Bond Log (CBL) for the 7" casing cement. On 2009 Feb 22 a new combination log was run to characterize the conditions of the casing, cement and caprock from 3,500 to 4,405 m; the logging string comprised Isolation Scanner* cement evaluation service, Sonic Scanner* acoustic scanning platform and an accelerometer sub to align the logs with the vertical direction (the well has a maximum deviation of 12º).

Nomenclature

BI	Bond Index, dimensionless
E	Cement Bond Log signal amplitude at the 3 feet receiver, mV
Z	acoustic impedance, product of density and compressional wavespeed, MRayl
α	attenuation, dB/m
r	reflection coefficient, dimensionless
s	extensional wave path length along the casing, m

2. Leakage pathways

A barrier, such as the 7” casing cement, is a physical mechanism that prevents a hazard, in this case CO_2 from the reservoir, from coming in contact with a target, either fresh water aquifers or the atmosphere. Cement sheaths are very thin, a few millimeters at their narrowest, and very long, of the order of a kilometer. This means that failure along the well axis requires extensive, vertically connected defects. In addition to the defects, a leakage “pathway” will also need a source of high-pressure fluid and a sink, i.e. a target of any other permeable formation. Following [1], pathways will be classified in four categories, ranked by increasing hydraulic resistance:

1. Low top of cement, either by faulty design or execution. This is a trivial defect, but probably the leading cause of major annular leaks.
2. Mud channels, i.e. sections of the annulus where the drilling mud has not been replaced by cement during the placement process.
3. Chimneys: these are relatively frequent, very thin features resembling vertical cracks, likely caused by pressured formation fluids (gas or brine) breaking through cement during the setting process.
4. Microannuli, i.e. debonding between cement and rock or cement and casing; these are mechanical defects that appear after cement has set.

Defects 1 to 3 happen during the cement placement and setting process, before the well is commissioned and are thus independent of the operating conditions to which cement is exposed.

Excluding faulty design, when hazard or target formations are not correctly identified or not enough cement is pumped to fill over-gauge boreholes, insufficient cement coverage is mostly caused by losses during cementing. Since the mid 1980’s ([2]) cement placement simulators have enabled accurate predictions of dynamic pressures downhole, thereby reducing the occurrence of this type of defect.

Prevention of mud channels is another example of successful technological innovation in the oilfield: their role and causes have been described since at least 1940 ([7]); field studies, lab experiments and numerical simulations carried out in the 1970s and 80s helped identify and elucidate dominant factors and allowed the deployment of effective, reproducible practices at the beginning of the 1990’s ([8], also refer to [9] for a thorough description of mud removal best practices). The spread of solutions to the mud channel problem had a noticeable and lasting effect on cement failures worldwide: a thorough analysis of well leaks in Alberta described in [10] finds an important and steady decline in well leaks starting around 1995, which was likely caused by a reduction in this type of defects. The downside of this timeline means that wells drilled before 1990 (such as RSE-1) are at greater risk of channels and that particular attention should be taken to assess their presence and vertical connectivity.

Unlike channels, microannuli are mechanical defects that can happen at any time during the life of a well. Why and how they happen is still the subject of research ([3], [4]), although as early as 1966 their occurrence has been correlated to high-pressure operations, such as fracturing and fluid injection ([5]). Recent modeling and lab experiments ([3], [6]) seem to confirm the early insight and suggest that microannulus propagation along the well axis is akin to hydraulic fracturing: annular overpressure debonds either cement interface and the resulting gap propagates vertically, sustained by density differences or lower pressure (or temperature) in the casing.

Microannuli are not the only possible mechanical failure in cement: radial or shear cracks are bound to happen under certain conditions (e.g. overheated steam production in geothermal wells), but cement log analysis suggests that these types of cement sheath damage are either very infrequent or spatially localized, requiring one of the four pathways listed above to achieve vertical connectivity.

Failure of set cement, whether by debonding or by cracks developing in the matrix, depends on the stresses to which the annulus is subjected (i.e. the well operating conditions) as well as on the thermal, elastic and failure behavior of the material itself. It is therefore necessary to characterize the actual properties and geometry of annular materials, as well as the defects affecting them, to be able to assess the risk of operational, as opposed to construction, failures. This in turn relies on quantitative log analysis.

3. Logging tools and pathways

3.1. CBL and Sonic Scanner

The basic physics of the CBL measurement is deceptively simple: an extensional wave is excited in the casing at a frequency around 25 kHz that radiates energy overwhelmingly through shear coupling, i.e. it is strongly attenuated only if in the annulus there is some solid material that is well-bonded to the casing.

Quantitative CBL interpretation relies on the fact that the apparent attenuation (α_{app}) of the first waveform peak is proportional to the fraction of the circumference bonded to a solid – called the Bond Index (BI) – and, to a lesser extent, to the strength of the solid itself ([11]). This dependency is formalized in Eq. 1, where α is either the measured or apparent attenuation (in dB/m), E is the amplitude, measured at 3 feet from the transmitter, and s the wave path length in the casing.

$$\alpha_{app} = -\frac{20\log_{10}\left(E/E_{FP}\right)}{s} + \alpha_{FP} \qquad BI \equiv \frac{\alpha - \alpha_{FP}}{\alpha_{FB} - \alpha_{FP}} \tag{1}$$

For the BI to be properly calculated, one thus needs three parameters: the free-pipe amplitude (E_{FP}), i.e. the amplitude of the first waveform peak when the casing is surrounded by fluid on both sides and which should be measured directly in the well or, at worst, calibrated in the lab; the free-pipe attenuation (α_{FP}), which can be obtained from correlations; and the fully-bonded attenuation (α_{FB}), i.e. the attenuation of an extensional wave when the cement pumped in the well is fully bonded to the casing. This latter parameter can be obtained through a mixture of models and correlations or measured directly in the well, if an undisputed reference section is available. Of course, direct measurement of attenuation obviates the need for a reliable free-pipe amplitude and for knowledge of logging fluid properties (which determine s), thus reducing the BI error.

Extensional attenuation therefore provides a simple and robust measure of the fraction of cement bonding to the casing, which is very useful to properly detect and characterize microannuli, as well as very large mud channels. On the other hand, the CBL amplitude's dependency on cement mechanical properties is very limited, making the use of CBL alone problematic for a proper analysis of cement and its defects.

In addition to the BI, a CBL routinely records the full wavetrain at 5 feet, which is displayed as a Variable Density Log. On this map, arrivals of compressional and shear head waves that propagate in the formation can be qualitatively followed, and their energy provides some information about the quality of cement-formation bonding, since it affects acoustic coupling. Unfortunately many other variables also contribute to the formation arrival strength, such as mechanical properties' contrast and cement-casing bonding, making clear-cut identification, much less quantification, of an external microannulus very difficult.

Real attenuation measurements with Sonic Scanner can be taken between two eight-receiver stations at 3 and 5 feet from the transmitters, which enable the measurement to be compensated for pressure and temperature effects on transducers; the effect of tool eccentering with respect to the casing axis is also greatly reduced. Using Sonic Scanner in RSE-1 allowed the ability to obtain, through the casing, formation compressional and shear wavespeeds as well as shear anisotropy, which was in turn used to determine maximum horizontal stress (or fracture plane) direction ([12]). Having Sonic Scanner in the tool string for geomechanical logging had the positive effect of providing high-quality cement data.

3.2. Isolation Scanner

Isolation Scanner operates at much higher frequency than the CBL, around 300 kHz, and relies on a rotating head with four transducers that provide two independent measurements ([13]) with an azimuthal resolution of around 1 inch (2.54 cm):

- A pulse-echo normal-incidence measurement, already used by the USI* ultrasonic imager, from which an elegant algorithm extracts casing thickness and annular material acoustic impedance (the product of density and compressional wavespeed).
- A pitch-catch measurement where two receivers 10 cm apart record the arrival of casing flexural waves excited by the transmitter. The advantage of this new measurement physics is that it delivers compact wave packets from the casing and the cement-formation interface (and from any other reflectors in between). The casing arrivals are used to compute the flexural wave attenuation, which crucially doesn't only depend on cement acoustic impedance and is thus almost independent from the pulse-echo measurement.

The two measurements' partial independence allows a better classification of the annular material, determining whether it is a solid, a liquid or a gas, with the results being displayed in a Solid Liquid Gas map. It is therefore possible to characterize narrow mud channels and chimneys; features even smaller than the ultrasonic beam width can also be identified from characteristic interference patterns in the full flexural waveform.

The waveforms recorded by both sets of transducers are stored and can be later analyzed to provide data about the position and reflectivity of the cement-formation interface up to several centimeters into the annulus. Research is ongoing to use this wealth of information to identify and characterize cement-formation microannuli.

3.3. Key log parameters

Accurate log calibration is required to ensure that measured properties can be compared to models and lab experiments; calibration is thus a pre-requisite for quantitative interpretation and for solving inverse problems, e.g. obtaining microannulus thickness.

The most important calibration factors are the acoustic impedance of the logging fluid (ZMUD) and the flexural attenuation offset (UFAO). The particular algorithm used to invert the pulse-echo measurement results in cement acoustic impedance errors five times greater than the original errors on ZMUD. Part of the challenge in selecting the correct values is that ZMUD is greater or equal than the actual fluid acoustic impedance, with the constant difference accounting for transducer response.

The best way to determine ZMUD and UFAO is by iterating with a goal of obtaining annular material properties consistent with the expected values. The resulting parameter list for RSE-1 is summarized in Table 1.

Fig. 2 shows how using these parameters the three different tools are in overall agreement when it comes to the amount of solid coverage of the casing.

Table 1. Calibration parameters used for the quantitative evaluation of RSE-1 cement logs.

Parameter	Tool	Value	Unit
Free pipe amplitude (E_{FP})	CBL (1967)	18.0	mV
Free-pipe attenuation (α_{FP})	Sonic Scanner	2.7	dB/m
Fully-bonded attenuation (α_{FP}), above 3 980 m	Sonic Scanner	22.4	dB/m
Acoustic impedance of logging fluid (ZMUD)	Isolation Scanner	2.0	MRayl
Flexural attenuation offset (UFAO)	Isolation Scanner	-9.0	dB/m

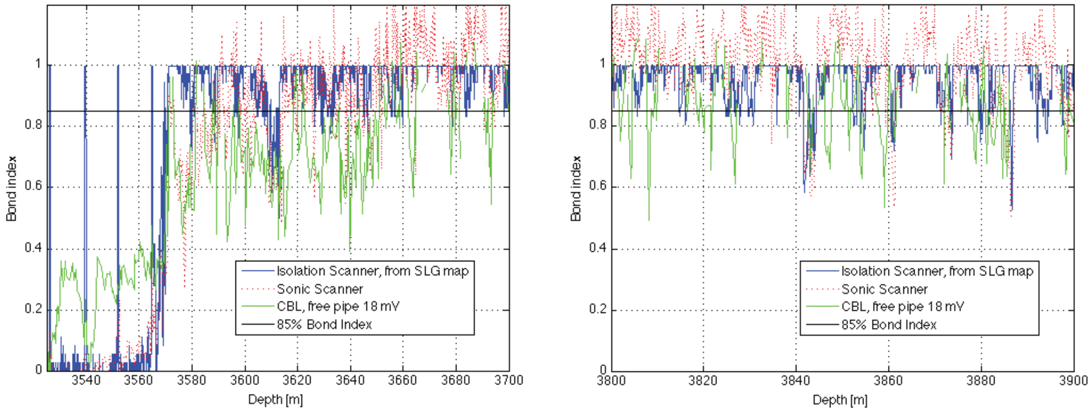

Fig. 2. Bond Index computed from Isolation Scanner ultrasonic measurements by averaging the solid portion of the Solid Liquid Gas map at each depth compared with the corresponding indices for the original CBL and the Sonic Scanner: (a) section around the top of cement and (b) 100-meter section below. Bond Index values above 1 are of course artifacts caused by low signal amplitudes, either because of higher-than-expected cement mechanical properties, or because of destructive interference from the formation signal.

Interestingly, the Bond Index seems to improve between the 1967 and the 2009 logs, especially close to the top of cement. This is most likely caused by slightly contaminated cement not being fully set at the time of the first CBL. It certainly underlines that there has been no degradation, either in cement mechanical properties or in casing-cement bond during the 42 years of well operation.

4. Mud channels

Fig. 3 shows that intermittent pockets of fluid are present across the whole cement sheath; they affect the low side of the hole below ~3,980 m and quickly turn to the side wall, 90º-120º away from the bottom, above that depth. Detection of the cement-formation interface echo in the flexural waveforms confirms that the fluid pockets are always associated with the narrow side of the annulus.

Careful extraction of the fast shear (hence the maximum horizontal stress) direction from Sonic Scanner data, coupled with an analysis of the formation arrivals on Isolation Scanner data ([12]) reveals that the borehole is highly elliptical in places, and that the over-gauge sections seen by the original 1967 open-hole caliper log were caused by the single arm of the tool following the major axis of the ellipsis. In fact, break-outs aligned with the minimum horizontal stress direction are rather like side-lobes on a circular hole instead of the hole being elliptical. Fig. 4 suggests a possible borehole shape consistent with the measured annulus width across the upper cement section.

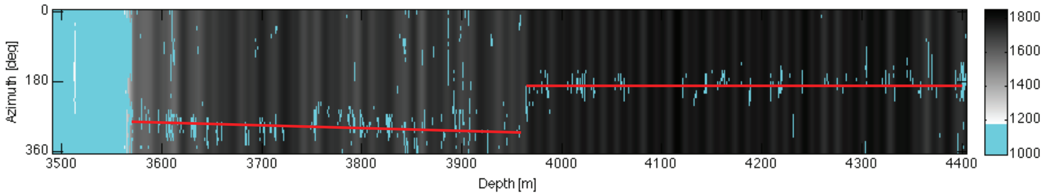

Fig. 3. Solid Liquid Gas map obtained from acoustic impedance and flexural attenuation, with the solid part color-coded according to the average density at each depth (low-pass filtered at 15 m). Red lines show the changing azimuth of the intermittent channel. The map is oriented so that the low side of the hole is at its centre.

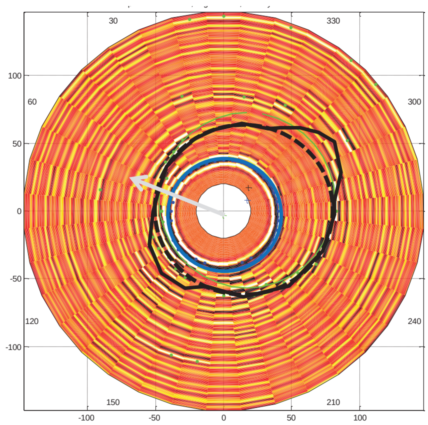

Fig. 4.36 flexural waveforms acquired at 3,803 m and displayed as a radar plot. The casing arrival is highlighted by a blue line and the formation arrival by a black circle with possible breakouts sketched. This suggests how the narrow side of the annulus (gray arrow) may not be aligned with the low side of the hole.

Break-outs explain why the narrow side of the annulus is not necessarily found at the bottom of the hole, especially since well deviation is small (less than 12º).

No centralizers were installed on the casing in the open hole section, resulting in the pipe lying close to the borehole wall with only the connection collars providing a measure of standoff at every pipe joint. The casing is therefore very eccentered: 79% of the narrow side of the annulus is less than 10 mm thick across the lower cement section (below 3,980 m), and 90% of the upper section is less than 5 mm thick. This is very small compared with 17.5 mm nominal annular thickness.

With such an asymmetric annulus it is not surprising that mud removal was ineffective, and that mud was left along the narrow section. However, the ultrasonic and sonic tools seem to agree that the channel is discontinuous, with well-cemented section separating isolated mud pockets. The issue with very narrow cement layers is that both the acoustic impedance and flexural attenuation measurements can become polluted by formation reflections and be potentially unreliable – even though the Solid Liquid Gas map makes partially up for the limitations of the individual measurements because of their different response to thin cement sheaths.

An independent confirmation that solid material is interrupting the mud channel comes from an “interferometric” approach: with thin cement sheaths, the pulse-echo inversion algorithm reads the equivalent acoustic impedance of the layered medium formed by cement and formation (to be exact, it reads the real part of the complex impedance that matches the reflection coefficient of the layered medium at the casing resonant frequency); with increasing cement thickness, the equivalent impedance oscillates between a minimum value $Z_{eq}=Z_{cmt}^2/Z_{form}$ and a maximum $Z_{eq}=Z_{form}$. The goal is to distinguish between the two cases of cement (Z_{cmt}=7-8 MRayl) and mud (Z_{cmt}=2 MRayl), which result in minimum impedances, respectively, of 3 and 0.3 MRayl, a difference large enough to be easily detectable. [14] shows that the minimum apparent acoustic impedance along the narrow side of the annulus is consistent with cement, rather than mud, across a number of casing joints and validates the estimate of the Solid Liquid Gas map. The length of well-cemented sections can then be compared to the minimum required to guarantee zonal isolation, 3 m for 7” casing according to the industry standard ([15]): 15% of well-cemented sections are longer than the threshold below 3,980, and 8% above.

The presence of a narrow intermittent mud channel poses a challenge to CBL-type logs: the good agreement with ultrasonic logs displayed in Fig. 2 depends crucially on a reliable value chosen for fully-bonded attenuation; in this case it was computed from the cement properties inverted from the ultrasonic measurements. If only sonic logs are available, bootstrapping accurate calibration parameters becomes a hard task, especially since Bond Index values >85% are considered as well cemented (to account for local variation in cement properties and uncertainties in calibration factors). The ability of sonic tools alone to detect narrow channels and chimneys is therefore very limited.

5. Casing-cement microannulus

Identifying a gas-filled casing-cement microannulus is easy: even micron-size gas layers outside of the casing, because of acoustic impedances of the order of 0.1 MRayl, reflect the totality of the acoustic energy and show up as uniform gas on ultrasonic acoustic impedance maps.

Fluid-filled microannuli are slightly harder to detect by ultrasonic tools alone, since they tend to “dampen” the readings of acoustic impedance and flexural attenuation (albeit in different ways) resulting in what appears to be weaker cement. Nevertheless, those microannuli are extremely easy to spot by comparing Bond Indices generated from ultrasonic and sonic tools: the sonic tool will show values close, yet noticeably higher than free pipe (BI~0.2), whereas the ultrasonic readings will be consistent with cement. As a consequence, if the ultrasonic BI is much higher than its sonic counterpart, a fluid-filled microannulus is the most probable explanation.

As Fig. 2 shows both Bond Indices are in very good agreement, strongly suggesting that cement is well bonded to the casing. Interestingly this is true also across mud channels, implying that local adhesion or normal stress from the formation (a few Pascals are sufficient to ensure acoustic coupling) are holding cement and casing together, instead of bonding being a side effect of cement contraction during setting.

6. Cement-formation microannulus

Both pulse-echo and flexural waveforms contain information about the reflection coefficients at the cement-formation interface: the former is affected by the real part of the normal reflection coefficient at the resonant frequency of the casing, whereas the latter depends on the complex reflection coefficients at oblique incidence, over the range of frequencies that make up the flexural wave packet. Since the flexural waves have phase velocities in the range 2,700-3,200 m/s, in strong cements (which have compressional wavespeeds of the order of 3,200 m/s) only shear waves can radiate from the casing so the formation echo depends only on shear-shear reflection.

The reflection coefficients in turn depend on the elastic properties of cement and formation and on their bonding: in a gas well such as RSE-1, the two most probable scenarios are reflection at a well-bonded cement-formation interface and a gas microannulus, which is equivalent to reflection at a cement-gas interface.

A cement-gas interface will always result in total reflection. At oblique angles cement-rock can also reflect back all incident energy, making it problematic to distinguish the two scenarios; on the other hand, normal reflection, whose coefficient is defined as $r=(Z_{cmt}-Z_{form})/(Z_{cmt}+Z_{form})$, is slower to "max out" to total reflection when cement is well-bonded to rock, leaving a bigger margin to tell the two cases apart.

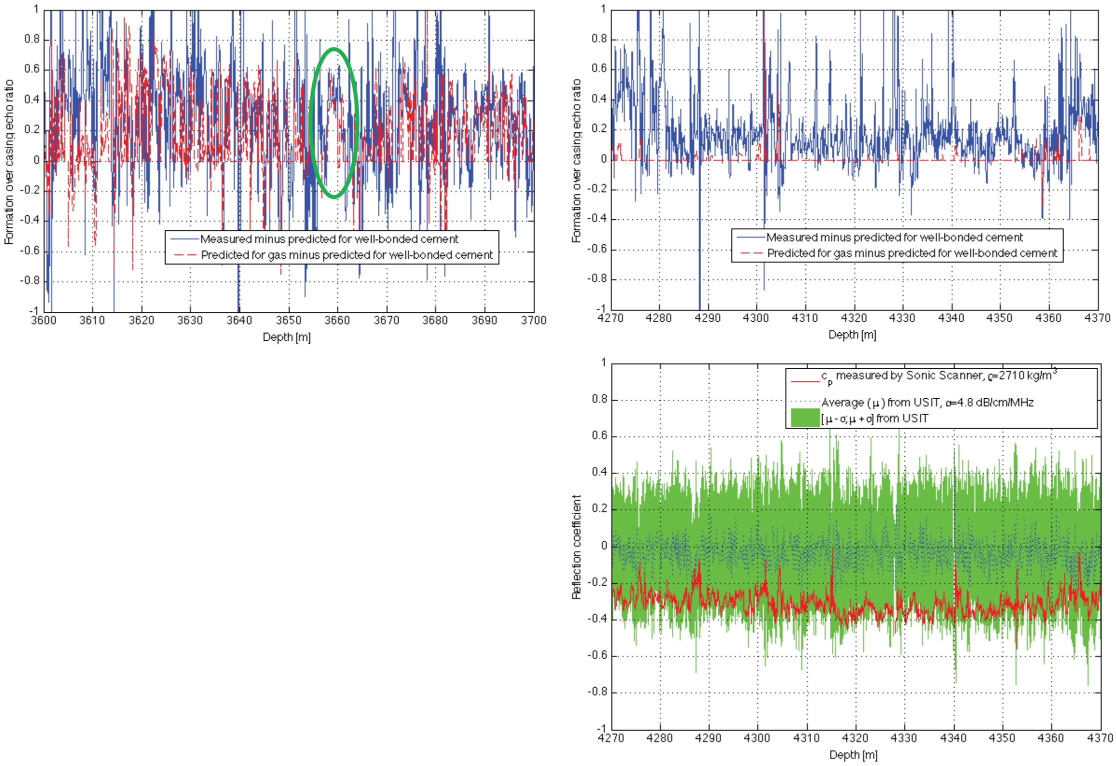

Fig. 5. The upper plots display the measured vs. predicted ratio between the formation echo and the casing echo amplitudes measured across the narrow side of the annulus (where the shear wave in cement is confined to the z-θ plane); the predicted ratio for good cement-formation bonding is subtracted from the measured ratio and from the predicted ratio for a gas microannulus to help distinguish between the two scenarios, when possible. Across the shallower section on the left there is enough difference between rock and gas reflection to verify bonding, whereas across the deeper section on the right the reflection coefficients are the same. The lower plot displays the real (i.e. signed) part of the reflection coefficient obtained from the pulse echo measurement; the average and standard deviation of the 36 reflection coefficients inverted at each depth are plotted together with the predicted reflection coefficient for a cement-rock interface; gas would produce a reflection coefficient of +1. Since no formation density log is available, an average value of 2,710 kg/m^3 was used in all calculations.

The top-right plot of Fig. 5 shows how total oblique reflection across the lower section doesn't allow the flexural wave echo to distinguish between a well-bonded interface and a gas-filled microannulus. Across the same section, reflection coefficients obtained from the pulse-echo measurement clearly support the well-bonded scenario. Higher up, a slightly slower formation results in a usable difference between the predicted responses of good bond and microannulus, and the flexural echo does seem to confirm that cement is well bonded to the formation (see green circle).

7. Cement properties

Ultrasonic measures can be used to estimate annular material properties under the very general assumption that the original fluids were a mixture of mud and cement solid and liquid phases; acoustic impedance and flexural attenuation can thus be related to the fractions of each original fluid. A Bayesian inversion framework described in [15] can then yield the full set of cement properties, as well as error estimates. To reduce the inverse problem error, a sample of points belonging to the same "solid" are used, in this case values of properties are calculated at each depth (the resulting log of cement density is displayed as color scale in Fig. 3).

This model-based inversion allowed the identification of two different cement zones: the upper one with average density 1,730 kg/m^3 down to ~3,980 m, and the lower one with density 1,810 kg/m^3. The consistency of properties across each zone led to the suspicion that a lead and tail slurry had been pumped, instead of a single 1,960 kg/m^3 slurry as the sparse records suggested. In [14] average elastic properties are also computed at each depth and the results are used in CemSTRESS* cement sheath stress analysis software to compute possible mechanical failure conditions. The result suggests that the cement will keep its integrity during CO_2 injection.

8. Conclusions

From the point of view of well containment, Rousse is an ideal candidate for conversion to CO_2 storage: it is a deep reservoir with a very long (>2 km) and strong caprock. The primary cement barrier, isolating the annulus between 7" production casing and 8⅜" hole, is almost 1 km long and accessible to verification logging. Furthermore, the top of cement is in direct hydraulic connection with the wellhead, allowing any annular gas leaks to be immediately detected at surface.

A best-in-class combination of sonic and ultrasonic logging tools able to probe the cement sheath and the near borehole allowed investigating cement conditions and the presence of pathways. The approach is based on identifying and characterizing defects by testing different hypotheses (a method similar to differential diagnosis), and on characterizing geometry and properties of cement to predict its future integrity

An intermittent channel, caused by imperfect mud removal, affects the narrow side of the annulus throughout the length of cement. Mud removal in turn was affected by low centralization and mechanical break-outs, which led to borehole ovalization and larger sections than assumed. In-depth analysis however confirmed that the mud pockets are isolated and that competent cement provides zonal isolation between them.

Casing-cement microannulus was ruled out by a comparison of sonic and ultrasonic measurement and advanced processing of ultrasonic waveforms confirmed good bond at the cement-formation interface too.

Mechanical properties of set cement obtained by Bayesian inversion were used to verify cement integrity when exposed to stresses caused by CO_2 injection.

The study showed that cement-related wellbore containment risks in RSE-1 were minimal, and that the well was an ideal candidate for conversion to CO_2 injector; the experience so far, after 2½ years of injection has borne out the initial assessment.

* Mark of Schlumberger

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