Integrated workflow for rotary sidewall cores orientation: best practices and examples from planning to execution

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Abstract. Over the last five years, the acquisition of rotary sidewall cores has become increasingly important in the O&G business. It is a matter of fact that the current tendency is to prefer them as a replacement to bottom hole cores, essentially for rig time related cost saving. This fact leads to force their use also for those types of characterisation usually reserved to larger size samples so, by consequence, some specific issues associated to their small size and to the lack of knowledge of *in situ* orientation have to be faced. For several applications such as geomechanics (whose experimental analysis require vertical plugs), petrophysics (permeability anisotropy, natural fracture orientation) and sedimentology, the original orientation, or its *a posteriori* identification, is mandatory in order to correctly measure properties relevant for reservoir management and studies. The full orientation of rotary sidewall cores requires to acquire or compute three couples of spatial information: high-side and low-side, wellbore end and formation end, trend and plunge of the samples. A dedicated workflow to *a posteriori* reconstruction of the orientation of large size rotary sidewall cores has been developed by means of the integration of multiple scale imaging techniques: images from logs and sidewall core are integrated through commercial software usually adopted for dip analysis. This approach has been successfully applied to several sidewall cores gathered in different geological environments. Currently, new coring and conveyance technologies allowing a predetermined sidewall cores orientation are emerging, increasing the reliability of the orientation workflow. Therefore, different scenarios of log planning strategy, operational solutions and post-coring analysis can be expected, depending on the confidence in the geological-structural interpretation and on the complexity of the technical environment. In all cases, it is extremely important to plan specific data acquisition and handling operations from wellsite to laboratory; including formalized minimum requirements and dedicated procedures, in order to maximize the quality of the subsequent laboratory analyses.

1 Introduction

The recovery of bottom hole cores (BHC) has always been a significant component of worldwide drilling costs. Over recent years, however, the general trend has become to acquire an increasing number of large size rotary sidewall cores (RSWC) instead, trying to find a balance between reducing costs and ensuring the acquisition of enough material for laboratory analyses. Unfortunately, RSWCs are not currently suitable for several types of characterization usually reserved for larger size samples, since they recover a much lower amount of material than BHCs and their original *in situ* orientation is unknown. The first drawback makes the overall quality of the acquired RSWCs extremely important (in order to maximize the data obtainable from most types of experimental analyses). Moreover, several applications require also the knowledge, or the *a posteriori* identification, of the original orientation of the recovered plug. For example, in petroleum-related experimental geomechanics, this requirement arises from the need to simulate in the laboratory the stress and deformation boundary conditions observable in a reservoir; similarly, the sedimentology can base its studies on oriented thin sections [1]. Furthermore, reservoir characterization often requires oriented permeability measurements [1] or the evaluation of natural fracture distribution also in terms of their spatial orientation [2, 3, 4]. A complete reconstruction of the *in situ* orientation of a RSWC requires the determination of the following parameters (see Fig. 1 below):

- trend and plunge, which are function of the borehole orientation (hole azimuth and deviation) and of the RSWC azimuth;
- wellbore end and formation end, corresponding to the two opposite sides of the RSWC facing the wellbore and the formation respectively;
- high side and low side, which are the geometrical intersection of the RSWC with the vertical plane.

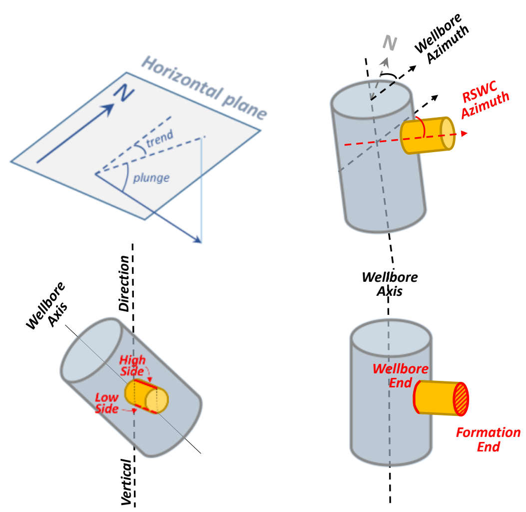

Fig. 1. Reference nomenclature for RSWC goniometry.

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Some of the above parameters, such as the borehole orientation, are generally known or acquired during the operation of coring and logging. The azimuth of the RSWC is not usually recorded during coring operations, unless specific conveyance methods (i.e. tool taxi) are adopted or a dedicated image log is run after coring. Wellbore and formation ends are generally easily identifiable since the most common commercial tools for RSWC acquisition store the samples in the core container with the same side-up (Fig. 2).

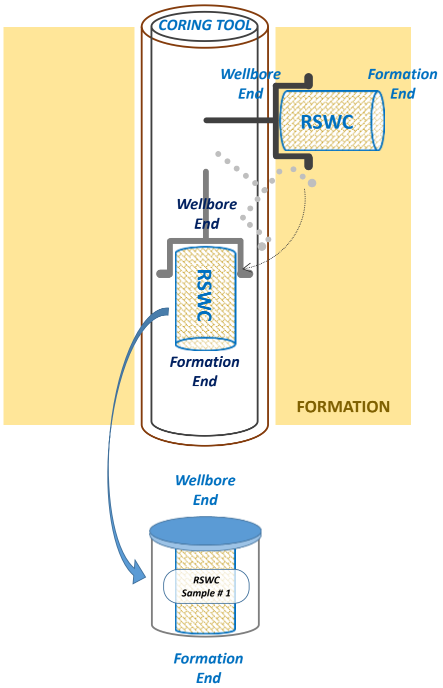

Fig. 2. Recovery of a RSWC.

When RSWC quality is high, this information can also be inferred by inspecting the RSWC: the wellbore end is the borehole wall and it is concave (and usually shows a more polished surface, Fig. 3a), while the formation end can show an indentation generated by the breaking of the RSWC (Fig. 3b) [2, 3].

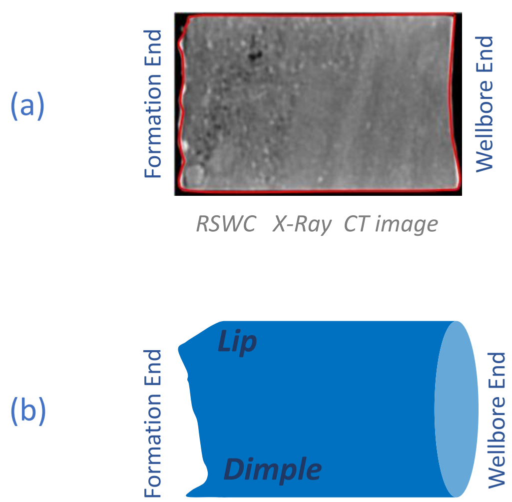

Fig. 3. RSWC characteristics helpful for orientation.

The high/low sides of the RSWC are never recorded during coring. In some cases, where the RSWC quality is particularly good and recovery procedures are known, at least the direction in which the RSWC has been broken by tilting, which corresponds to wellbore axis, can be inferred from the first inspection of the core (lip/dimple in Fig 3b and Fig. 6) [2, 3].

Therefore, to provide an accurate *a posteriori* reconstruction of the parameters describing the *in situ* orientation of RSWCs, a workflow mainly based on laboratory X-Ray CT scans and wellbore log images has been developed by integrating all the available wellsite and laboratory data.

Regardless of the adopted procedure, the *a posteriori* orientation of a RSWC is not a straightforward task and, to maximize the probability of success of this operation, it is extremely important to accurately track all the required data and to preserve the quality of the RSWC along all its lifetime. So, all the recovery, data acquisition and handling operations from wellsite to laboratory have to be specifically planned. In the following paragraphs, the identified minimum operative requirements will be formalized and dedicated procedures will be suggested in order to maximize the accuracy of the orientation process and, by consequence, the quality of the subsequent laboratory analyses. Indeed, orientation is particularly important for some petrophysical properties that strongly depend on the measurement direction (e.g. to validate permeability in anisotropic geological environments).

2 Minimum requirements and procedures for coring

2.1 Job planning and execution

Whenever the orientation of the RSWC is required for the subsequent studies, careful planning of the acquisition operations must be put in place and all relevant information and best practices gathered in a dedicated coring protocol to guarantee the reliability of the dataset required by the orientation procedure. This paragraph dictates the specific requirements that must be followed throughout the coring operations, namely: a) purpose of core acquisition and formation characteristics, b) selection of core samples, c) log acquisition and correlation plan, d) rotary sidewall coring operational procedures, e) wellsite handling of core samples.

a) The objectives of the acquisition must clearly state that the core orientation is requested based on the core analysis purposes. Furthermore, the lithological and sedimentological formation characteristics significant to the acquisition have to be highlighted. The Uniaxial Compressive Strength (UCS) computation from sonic Δt (using the appropriate algorithm calibrated on nearby wells or analogues) has to be provided in order to properly plan the operations.

b) The criteria for selecting number and depth of the sampling points must be defined taking into account the expected quality in terms of size and shape, always in connection with the requirements for the laboratory analyses. The sequence and priority of sampling points have to be considered; extra cores must be planned when targeting thin beds or bed boundaries, since depth accuracy issues are emphasized.

c) The log suite suggested to support the orientation of the RSWC would better include two image log runs, before and after the coring operation.

- The image log acquired before coring is aimed at defining the formation texture and structure; therefore high resolution image tools are needed where complex and not homogeneous geological environments are expected in order to correctly plan the RSWC coring points; a full coverage image log is not mandatory. The complete logging suite will also allow basic lithological and petrophysical characterization.
- The image log run after coring has the main target to define the correct depth of sampling points and, moreover, the azimuth of the RSWC. Thus, a full coverage view of the borehole wall is needed, since it ensures the location of the holes left by cutting the RSWC. High resolution image logs are not necessary, provided that the quality is enough to clearly identify the coring points.

The two previous targets can be reached by combining image logging while drilling (LWD) and/or wireline (WL) in the safest and most cost effective ways:

- Image log acquisition before the RSWC performed in LWD mode, using either low resolution (e.g. density azimuthal imaging) or high resolution (e.g. resistivity) tools depending on the geological environment complexity; then a WL image acquisition after coring, even with low resolution tools (e.g. ultrasonic).
- WL image log acquisition before and after coring, choosing high resolution tools for the first run when the geology is complex and low resolution otherwise.
- Regardless of whether the image log acquisition before coring is planned in LWD or WL mode, it can be provided in LWD mode after coring if a wiper trip is needed.

d) Depending on the available tool, dedicated coring and breaking procedures to maximize the RSWC recovery and quality must be selected on the based on the formation characteristics and the well environment (mud type, overbalance, solids content etc.). Recommendations must be detailed and strictly followed for approaching each station, by reducing the speed and according to the well depth, to minimize both the cable stretch and creep; finally, a dedicated tripping out procedure must be pursued according to the formation petrophysical and lithological characteristics and well environment conditions.

e) All wellsite surface procedures are aimed at minimizing damage during handling and shipping to the laboratories. Particular care is needed to preserve the RSWC order of collection within the container and its formation end/wellbore end orientation. The documentation must include for future reference a close-up picture of each core in the container before its removal (Fig. 4) This is crucial when no core separators are used due to tool design and/or well deviation [5].

Care is recommended when wiping off the samples and packing them in the transportable jars with the wellbore end facing up. Additional wrapping of the sample is required with plastic or aluminium foil on which red and black parallel lines should be marked to preserve the correct sequence and top/bottom ends of the samples (red on the left, facing the core from wellbore end towards formation end) (Fig. 5). Shock adsorbing materials to stabilize the RSWC inside the containers are always suggested to preserve the sample integrity.

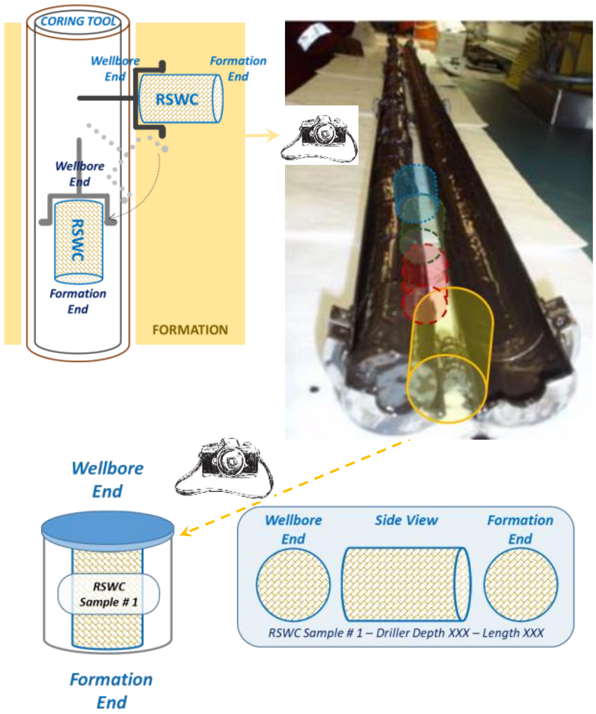

Fig. 4. Suggested pictures to be acquired on site.

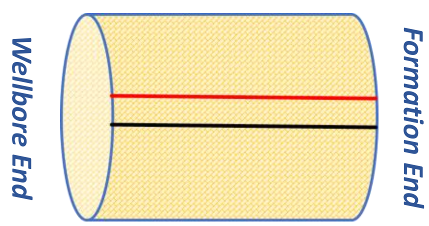

Fig. 5. Marking of RSWC packing to track formation/wellbore ends.

2.2 Laboratory processing of samples

The procedures to be observed when receiving and handling sidewall cores are analogous to those adopted for bottom hole cores: it is mandatory to treat them with great care in order to avoid mechanical shock; to protect them from extreme temperatures, humidity and dehydration and to limit as much as possible the use of fresh water to clean them. Labelling and marking require even greater attention. In fact, it is extremely important to preserve the proper sequence and core orientation ensuring that individual samples are not out of order or turned upside down.

More in detail, specific actions have to be performed in terms of: a) wellsite data retrieval; b) visual inspection of the core and RSWC labelling and marking; c) RSWC photos; d) X-Ray CT scan.

a) Generally speaking, all the coring-related well site data should be retrieved. In particular, the following cannot be neglected: coring parameters (weight on bit, rate of penetration, coring time, etc.); sample description, included its quality (intact, fractured, broken, crumbled, etc.); effective length and diameter of each recovered sample; trace of the wellbore/formation ends of the sample, according to the established conventions (see Fig. 5).

b) It is mandatory to preserve the correct sequence of the samples and their orientation, properly labelling and marking each RSWC. This implies the validation of the collected field data through a visual inspection of the core and, when possible, the data integration through the determination of the direction in which each RSWC has been broken by tilting, which corresponds to wellbore axis (Fig. 6).

The red and black parallel lines drawn at wellsite on the external surface of the wrapping must be transferred onto the RSWC sample. Moreover, to provide a further reference for the subsequent operations, it is recommended to draw the double line along the upper side with respect to the determined tilting direction, if previously identified.

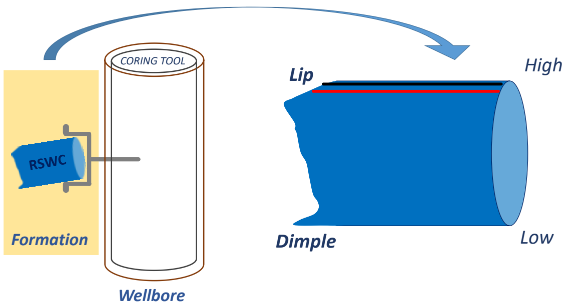

Fig. 6. Marking of RSWC to track the identified formation and wellbore ends

c) A complete set of RSWC photos (Fig. 7) should be acquired. Wellbore end, formation end and side views must be photographed, taking care to correctly mark the references. A comparison with the wellsite photos is also recommended to confirm the RSWC ends identification (see Fig. 4).

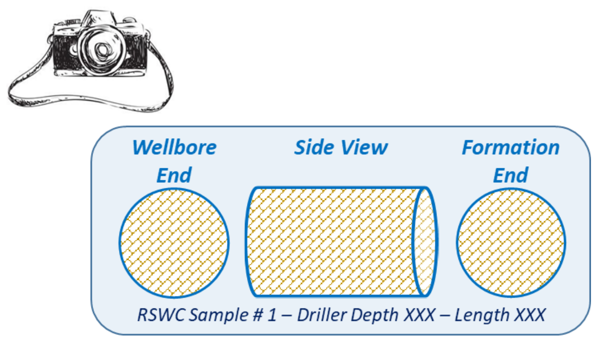

Fig. 7. Suggested views for RSWC photos at the laboratory.

d) A 3D X-Ray Computed Tomography of the sidewall core must be acquired at the maximum feasible resolution (the typical resolution of a medical CT scanner, 250 µm, is assumed satisfactory in most of the cases) A 2D 360° unrolled image must be extracted from the acquired volume, by following the maximum possible circumference, compatibly with the surface roughness. This picture is the main input for the goniometry procedure described in section 3. Moreover, it is mandatory that the position of the starting point of the unrolled images be recorded and recoverable on the sample. This starting point position (left border of the 2D image) should be measured as the angle from the line representing the side corresponding to the tilting direction, if its estimate has been possible. A corresponding reference notch or sign must be created on the RSWC.

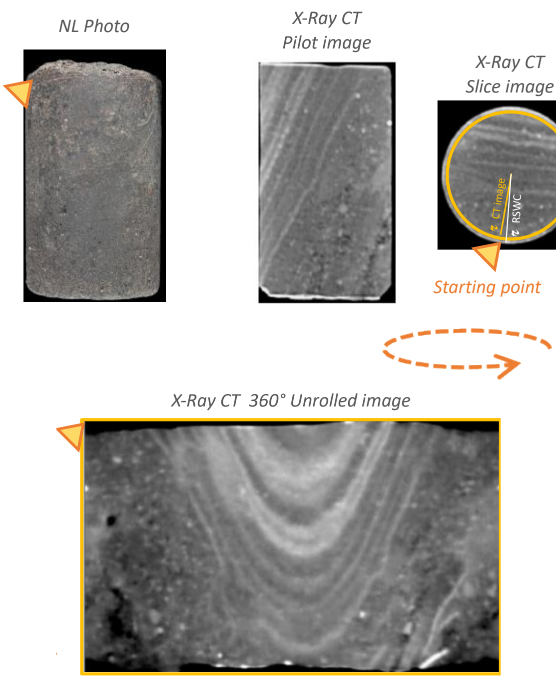

Fig. 8. RSWC Imaging.

3 The sidewall core goniometry procedure

The proposed "Eni SideWall Core Goniometry" (e-SWCG) procedure has been developed in order to provide an exhaustive methodology for the *a posteriori* reconstruction of the original *in situ* orientation of RSWCs. As described in Fig. 1, the determination of three main variables is required: wellbore/formation ends, RSWC azimuth and high/low sides.

The e-SWCG workflow is based on the identification of geological features (layering, fractures, stylolites, etc.) that are recognizable both at the laboratory scale on the X-Ray CT image of a RSWC and at the well scale on the image logs. Since these two scales are very different, to properly apply this procedure, the analysed large size RSWC must honor a diameter as close as possible to the nominal one (1.5") and a minimum length around 1.5". By consequence, lithologies without features detectable at both image scales of resolution or smaller diameter RSWC are not suitable for this approach.

The workflow starts with the 3D X-Ray CT acquisition of the analysed RSWC. Then, a 360° unrolled image is extracted from the volume; this unrolled "sampling" must be obtained at the maximum possible radius able to avoid the external surface roughness (Fig. 9).

The unrolled X-Ray CT image is converted into a digital borehole image format, uploaded onto an image analysis software platform and treated in the same way as an image log with its own deviation coordinates: inclination and azimuth. The top of the unrolled image is assumed to be coincident with the wellbore end of the RSWC.

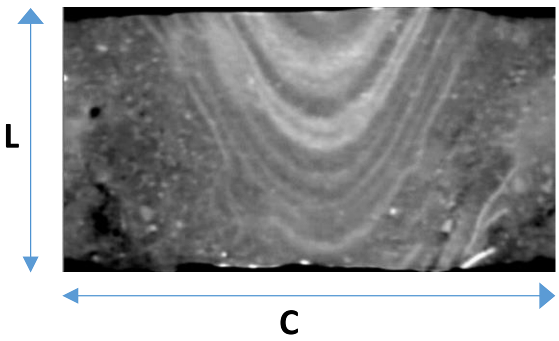

Fig. 9. Unrolled X-Ray CT image of a RSWC, where L is the length and C is the circumference. The actual image diameter is 1.34" (see field case of paragraph 4.2).

Since the commercial software platforms for log analysis usually manage the data loading according to the borehole depth and the sidewall core is oriented at 90° with respect to the well axial direction, the unrolled image has to be loaded assuming the following rules to preserve its correct aspect ratio:

- Top: Core wireline depth – 0.5L;
- Bottom: Core wireline depth + 0.5L;

where L is the length of the RSWC.

Bedding planes, fractures or other geological features must be identified and manually interpreted on both RSWC and log images.

The geological feature visible on the image log is oriented by picking the sinusoid and the corresponding tadpole will be generated (see 4th track on Fig. 11).

This tadpole, which represents a plane specifically oriented in space (true dip), has to be replicated on the RSWC image. The amplitude and offset (apparent dip) of the sinusoid drawn on the core image depend on the three unknown orientation variables.

To obtain the original orientation of the RSWC, the three variables must be tuned until the geological feature visible on the RSWC image matches exactly the sinusoid. The final orientation is best achieved step by step with a trial and error procedure. If the orientation variables are all unknown, it is suggested to start the procedure from the four base cases shown on Fig. 10 and then fine tuning the variables starting from the case that provides the best match.

The e-SWCG procedure allows the unique determination of the vertical direction along the RSWC, which is an essential input for the subsequent studies. On the other hand, an ambiguity of 180° persists on azimuth and high/low sides: in fact, two opposite choices of azimuth and wellbore/formation end of the RSWC can both honor the image log evidence. This ambiguity can be removed, as previously outlined, by providing additional information through one of the following actions:

- by observing the azimuth on an image log acquired after the coring, or
- by adopting coring tools allowing the user to define in advance the azimuth, or
- by identifying the high side from the RSWC topology, but only in vertical wells, or
- by recognizing the wellbore end by inspecting the physical RSWC, the RSWC pictures or the RSWC CT Scan images.

Once the match is achieved on the images, the final step consists of physically orienting the sample.The obtained inclination of the unrolled image coincides with the true inclination of the RSWC and the lateral shift (expressed as angle) of the unrolled image corresponds to the rotation to be applied to the RSWC initially positioned with the reference line up. This information should be provided to core analysts in order to reproduce the true orientation of the RSWC in laboratory before going ahead with analysis.

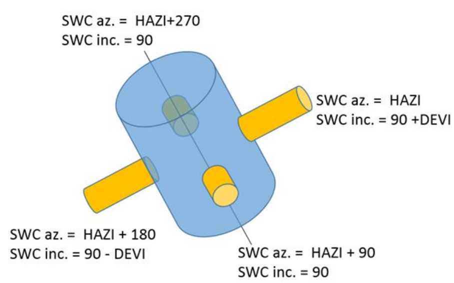

Fig. 10. Possible orientations of a RSWC with respect to a deviated well: blue cylinder represents the borehole and the 4 orange cylinders represent the RSWC in 4 base cases of the

possible orientations: 2 cases on the plane of the borehole direction and another 2 orthogonal to the previous ones.

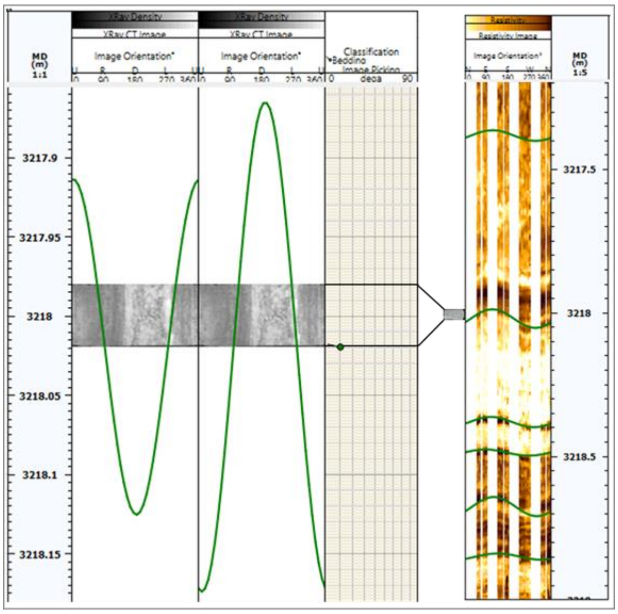

Fig. 11. Green sinusoids represent the bed boundary picked on the image log but show different attitudes because the orientation of the RSWC images are offset by 90° from each other.

4 Case histories

The two field applications of the e-SWCG procedure presented in this section are related to wells that are very different in terms of lithology, borehole environment and, more importantly, *a priori* knowledge of the RSWC orientation. In the first case, all the variables were unknown, while in the second the RSWC azimuth was predefined using a specific conveyance method (tool taxi). Both case histories successfully provided the correct parameters to orient the physical rock samples.

4.1 Carbonate reservoir

The first case is related to a sub-vertical deepwater well crossing Cretaceous to Miocene carbonate shelf and reef build-ups. WL resistivity images at very high vertical resolution were acquired in a 12.25” borehole with water based mud (Fig. 13). On the RSWC, a lamination pattern is visible at low angle with respect to the core axis (Fig. 14). On the image logs, many bed boundaries are well recognisable at the surrounding depth of the SWC, the sequence being well laminated and the borehole imaging at very high resolution (Fig. 13). The bed boundary closest to the RSWC depth has an attitude of 10° dipping toward W. The exercise of orientation of this RSWC is to match the lamination of the RSWC with the sinusoid from the image log interpretation.

Fig. 12. Side view in white light photo of carbonate RSWC (wellbore end on the right side).

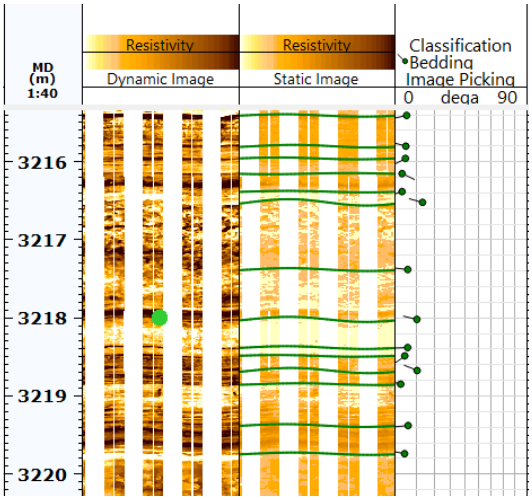

Fig. 13. Image logs and picking in the interval surrounding the carbonate RSWC.

For this RSWC, all three orientation variables, defined in paragraph 1, are unknown because the RSWC azimuth was neither measured nor imposed a priori. For this reason, the search for the match was started by trying the 4 RSWC azimuths corresponding to the 4 base cases of Fig.10 and selecting the case with the closest match.
Then, the one in which the best-fitting feature has an orientation as close as possible to the sinusoid was selected. To improve the match quality, fine tuning was also performed by applying a further rotation of 25° to the RSWC image and the final match was obtained (Fig. 14).

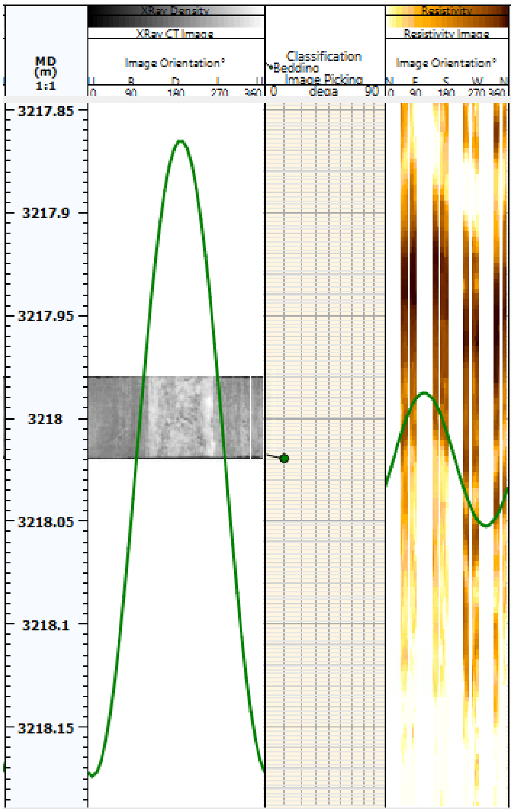

Fig. 14. Final match of carbonate sample.

4.2 Clastic reservoir with conveyance tool

The second case was an offshore 40 slanted well drilled through a Pliocene deltaic to turbiditic siliciclastic sequence where several RSWCs were cut inside the sandstones. The 12.25" phase in the reservoir section was drilled using oil based mud and the available image log was Density LWD with low vertical resolution. One of the RSWCs was taken in a portion of rock where laminations are well visible at the image log scale. On visual inspection, the core sample is apparently homogeneous without sedimentary laminae (Fig. 15), whereas the X-Ray CT shows that it is actually well laminated, with the layering displaying a high angle with respect to the RSWC axis (Fig. 9). Fig. 16 shows the LWD density image including the bedding interpretation. At the RSWC depth, the bedding inclination is between 10° to 20°. dipping toward NNW.

Fig. 15. Side view in white light photo of siliciclastic RSWC (wellbore end on the left side) .

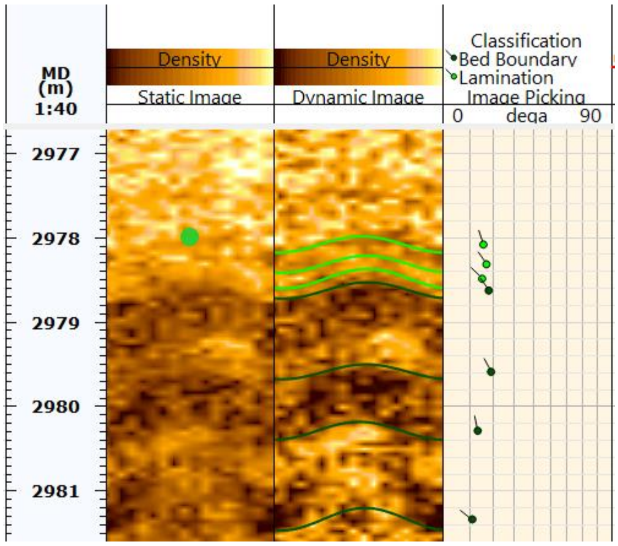

Fig. 16. Image logs and picking in the interval surrounding the siliciclastic RSWC.

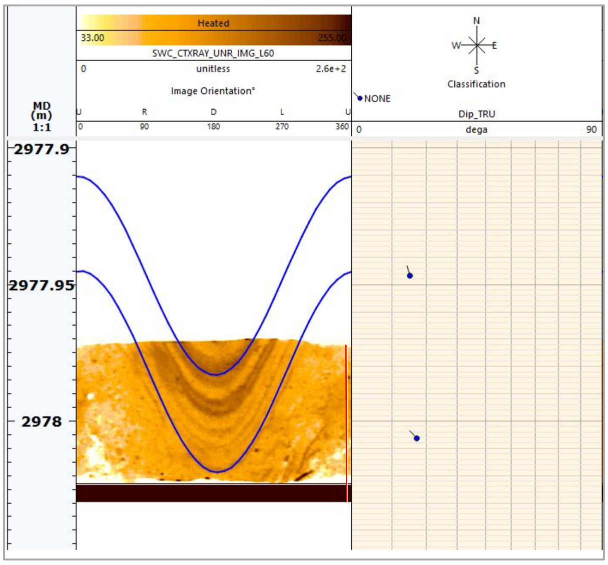

Fig. 17. Final match of clastic sample.

The RSWC azimuth and inclination are known because the coring tool was run with the tool taxi and the RSWC was taken in the lower side of the borehole. The wellbore end information was preserved during the wellsite recovery from the core barrel. The only unknown variables are the high and low sides of the RSWC. The match between sinusoids and laminations was achieved by choosing the right angular offset of the RSWC, which means a 10° lateral shift on the RSWC image. The position of the reference line can be used to orient the real sample (Fig. 17).

5 Conclusions

The original *in situ* orientation of RSWC is a fundamental input for obtaining reliable results from geological studies and for the proper execution of experimental analyses. The e-SWCG procedure presented in this paper can deliver a complete *a posteriori* goniometry of the RSWC, provided that an appropriate core and log acquisition program has been planned, as well as correct handling operations at wellsite in order to obtain and accurately track all the data needed for the orientation procedure. Moreover, the overall quality of the acquired RSWC is extremely important to maximize the data that can be recovered through experimental analyses and studies from an inherently more limited amount of material with respect to BHC. The presented case studies highlight the possibility of applying the orientation procedure in different geological contexts. Particularly, the case history on carbonates shows the reliability of the procedure even with limited data. On the other hand, the example related to a clastic reservoir emphasizes the advantages of using coring tools providing greater control on RSWC positioning.

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This paper is dedicated to the memory of our dear colleague and friend Sandro Atzei, who recently passed away.

References

1. D.K.T. Hansen, M.B. Enderlin, “Petrophysical significance of oriented sidewall cores for improved reservoir characterization”, in Worthington, P.P., and Longeron, D., eds., *Advances in core evaluation II - reservoir appraisal*, p. 135-144 (Gordon and Breach Science Publishers, 1991)
2. B. A. Hardage, E. Doherty, S.E. Laubach, F. T. Hentz, “Secondary Natural Gas Recovery in the Appalachian Basin: Application of Advanced Technologies in a Field Demonstration Site, Henderson Dome, Western Pennsylvania”, PhD Thesis Bureau of Economic Geology The University of Texas at Austin Austin, TX (1998).
3. S.E. Laubach, E. Doherty, “Oriented Drilled Sidewall Cores for Natural Fracture Evaluation”, *SPE Annual Technical Conference and Exhibition*, (SPE56801, 1999).
4. J.F.W. Gale, L.A Gomez, “Late opening-mode fractures in karst-brecciated dolostones of the Lower Ordovician Ellenburger Group, west Texas: Recognition, characterization, and implications for fluid flow”, AAPG Bullettin, **91**, 7, p. 1005-1023 (2007).
5. V. Torlov, C. Bonavides, A. Belowi, “Data Driven Assessment of Rotary Sidewall Coring Performance”, *SPE Annual Technical Conference and Exhibition*, (SPE187107-MS, 2017).