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Advanced Method of Controlled Core Scratching as a Source of Geomechanical Data

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Abstract

The established practice of geomechanical testing includes the procedures of core sampling and marking, as well as core plug drilling out and testing. The key challenge is that a selection of core plugs is physically or economically limited. The classical core analysis offers a limited and discrete data set. Along with that, the tests carried out on a set of core plugs are dependent upon the core quality and the accuracy of selection of the core plugs sharing identical properties. These constraints impair accuracy and reliability of geomechanical models.

This paper describes controlled core scratching (CST) as a method of geomechanical testing of full-size cores. Physically, the CST method is based on resistance measurements of the of full-size cores to scratching. Depending on the cutter penetration depth and the core sample scratching rate, the force characterizes unconfined compressive strength (UCS) and/or fracture resistance of the rock.

The principal CST advantage is that it provides accurate and diverse continuous geomechanical rock properties. The application of the CST method enhances comprehensive core analysis accuracy, synthetic physical & mechanical parameters reliability and, therefore, geomechanical modeling precision. In practice, the CST method applied in conjunction with the classical geomechnical core analysis enhances the quality of drilling, completion, frac'ing, and field development support in general.

This paper presents a comparative study of geomechanical models that incorporate synthetic curves for unconfined compressive strength (UCS), Brazilian tensile strength (BTS) and cohesion strength (CS), derived from the CST and well logging data, using a well that is drilled through halocarbonates and clastics as an example. The comparative study of the CST-based and log-based geomechanical models demonstrated that the CST-based model outputs robust correlations and detailed distinctive curves of physical & mechanical properties and clear stratification boundaries.

Introduction

It becomes more and more topical in the petroleum industry to develop and implement digital geomechanical reservoir models based on spatial distribution of physical & mechanical properties and stress of the rock. The application of such models helps solve a wide range of applied tasks throughout the well life cycle, including the drilling, casing, and completion design (Toropetsky K.V., Kayurov N.K. et al., 2016).

The spatial distribution of physical rock properties builds upon the following data types:

- lab-based core analysis;
- well logging;
- mud logging while drilling;
- land and borehole seismic and electrical exploration (SE and EE) results.

The established lab-based core analysis practice involves core recovery from the wells, core marking, and core plug sampling and analysis. However, a significant disadvantage of this approach is a limited nature both of the cores recovered from wells and of core plug collections available for analysis due to the core quality and time and money considerations (Toropetsky K.V., Ulyanov V.N. et al., 2016). Therefore, the actual core analysis practice limits the accuracy and reliability of the geomechanical models that can be based on this data.

So, a standard well cored for 270 meters, with core plugs sampled every 10 cm, will require a set of 2,700 core plugs, which is very time- and money-consuming. Besides, the production of core plugs requires high-quality original cores (free of discontinuities and sufficiently homogeneous by volume), which does not often happens in reality. Besides, regularly spaced core sampling makes the original cores unfit for further testing and the samples undergo destructive testing. Finally, visual core selection, with a focus on core plug producibility, gives no reasons to believe that the resultant core plug collection is representative and fully descriptive of the stress-strain behaviour of the original cores, because there is no way to compare the properties of the sampled core plugs against the unsampled sections. Moreover, there is no way to guarantee that the resultant core plug collection is representative of the entire diversity of the original core properties. It should be noted that the most challenging intervals, which are poorly consolidated or fractured rocks, requiring a detailed analysis of their stress-strain behavior, turn out unavailable for the study because it is not possible to produce core plugs of acceptable quality out of them.

This paper suggests complementing the routine stress-strain behavior analysis, carried out on core plug collections, with controlled core scratching (CST) of full-size cores, which will give very detailed curves of physical & mechanical rock properties (Germay C. et al., 2014). Physically, the CST method implies the measurement of the full-size core resistance to scratching. Subject to the scratching modes that are characterized by a cutter penetration depth and the sample scratching rate, this force defines the unconfined compressive strength (UCS) and/or the fracture toughness (K_{IC}) of the rock under analysis (Lin J.-S. et al., 2013).

This paper presents a comparative study of the geomechanical models which include synthetic curves for unconfined compressive strength (UCS), Brazilian tensile strength (BTS) and cohesion strength (CS), derived from the CST on full-size cores and the log data, using the well that is drilled through halocarbonates and clastics as an example (a field in Eastern Siberia).

Controlled Core Scratching Method

The authentic controlled core scratching methodology serves to determine micro-hardness (i.e. resistance to scratching in the surface layer) of the materials by indentation with a load on the indenter of max. 2 N (Parshev S.N. et al., 2004). However, since 1992, efforts have been taken to adjust this methodology for determining rock strength (Almenara R. et al., 1992; Suarez-Rivera R. et al., 2002) and to apply the method for estimating the ultimate strength, which is devoid of these disadvantages.

In order to determine the resistance to scratching, an apparatus that features isokinetic (constant-rate) scratching of full-size core samples (a diameter of 60 to 100 mm), up to one meter long, with a penetration depth of 200 μm at a rate of 100 mm/min, was used. These testing parameters were selected to execute ductile rather than brittle rupture of all rock types in the cross-section under analysis.

There are two known methods of material rupture during the scratch testing: ductile and brittle (Richard T., 1999). Ductile rupture occurs at shallow cutter setting depths [depending on the rock type, the upper depth limit ranges from ~ 0.5 mm to 2 mm] (Richard T., 1999) and it characterizes the material strength. In this test mode, the rock is ruptured into the particles with a size of 10-100 μm (i.e. into the grains that compose the rock; the intergranular contacts are ruptured). Penetrating deeper than the scratching depth limit triggers brittle rupture, with a fracture running across the scratching direction, followed by the chip-off of macroscopic rock fragments, which size is roughly the scratching depth (Gamwo I.K. et al., 2010; Dagrain F., 2001).

The most general formula that defines the forces at CST with the compressive strength is as follows:

$$\mathbf{UCS} = \mathbf{k} \cdot (\mathbf{Ft} - \boldsymbol{\mu} \cdot \mathbf{Fn}) / (\mathbf{w} \cdot (\mathbf{d} - \boldsymbol{\alpha} \cdot \mathbf{Fn})),$$

where:

Ft is the horizontal force component, N;
Fn is the vertical force component, N;
μ is the cutter-on-rock friction coefficient, dimensionless;
w is the a cutter width, mm;
d is the a cutter penetration depth at Fn = 0, mm;
α is the vertical stiffness of the measurement system, N/mm;
k is the proportionality constant, dimensionless.

The controlled core scratching testing (CST) includes four principal process stages:

1. Fixing a full-size core sample in the cartridge. This procedure neutralizes the impact of the apparatus clearances and of the imperfect core condition on the test results. The cartridge accessories help align individual fragments relative to one another and rigidly fix them.
2. Surface grinding to a common plane. This procedure serves to remove macroscopic surface defects (deviation along the depth of max 1.0 mm), such as tapers, potholes, superficial cracks etc.
3. Flattening to the cutter. The flattening is intended to remove microscopic heterogeneity (deviation along the depth of max 10 μm) of the core surface that appeared while grinding.
4. Controlled scratching. Measuring the components of the force on the cutter that scratches the core sample at a constant advance rate and at a specified cutter setting depth.

Figure 1 provides photographs of the full-size core fixed in the coreholder at different test stages.

Figure 1—The full-size core at different test stages: top - after grinding, bottom - after a measuring cutter run

Geomechanical Modeling

The first stage of geomechanical modeling was building a correlation between the force on the cutter and the unconfined compressive strength (UCS). The CST method was used to analyze 1.5 m of the full-size core. In order to determine UCS, seven core plugs, bored out of the interval under analysis perpendicular to the bedding, were analyzed. The results are given in Figures 2a and 2b.

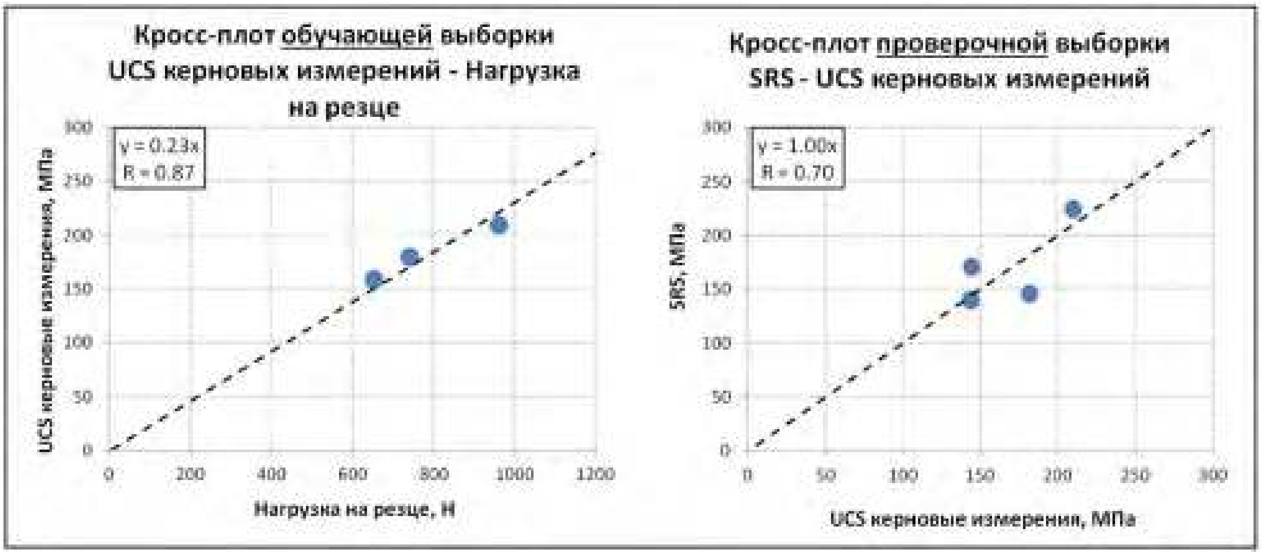

Figure 2—Cross plots: (a) UCS on core plugs – force on the cutter (on a learning set), (b) SRS by a scratch test – UCS on core plugs (on a validation set)

Due to a high level of detail of the CST test results (2 µm/point), the initial resistance-to-scratching curve was statistically processed using the moving average with a window of 60 mm, which is equivalent to averaging over the core plug length, and compared against the learning set of the core plugs. Then they were compared against the samples from the validation set. In order to build CS and BTS curves, the correlations derived from the learning set were also used. A full list of petrophysical functions is given in Table 1.

Analysis of the Results

A comparative analysis of the modeled UCS, BTS and CS parameters, based on the CST and logging results, was performed for the resultant cross-section model. To build log-based synthetics, the correlations derived when studying the properties of an analog field were used. The list of the petrophysical functions used is given in Table 2.

Figures 3 to 5 provide the synthetic logs derived from the equations given in Tables 1 and 2 with the results of the lab-based core analyses for BTS, UCS, and CS, respectively.

Table 1—The list of CST-based petrophysical functions

Model parameter	Function
Tensile strength (Brazilian method)	$TS(SRS)=0.1913\times SRS^{0.8256}$
Cohesion (carbonates)	$CS_{cb}(SRS)=0.4769\times SRS^{0.8277}$
Cohesion (clastics)	$CS_{tr}(SRS)=0.7315\times SRS^{0.7257}$
Unconfined compressive strength (carbonates)	$UCS_{cb}(SRS) = 1.1202\times SRS+54.467$
Unconfined compressive strength (clastics)	$UCS_{tr}(SRS)=9.902\times SRS^{0.628}$

Table 2—The list of log-based petrophysical functions

Model parameter	Function
Tensile Strength (Brazilian method)	$TS = 0.5\times UCS\times \frac{1-\sin(FANG)}{1+\sin(FANG)}$
Cohesion Strength	$CS=0.0521\times UCS^{1.1728}$
Unconfined Compressive Strength (carbonates rocks)	$UCS_{cb}=0.3667\times Edyn^{1.33}+35$
Unconfined Compressive Strength (terrigenous rocks)	$UCS_{tr}=0.4721\times Edyn^{1.5629}-90$

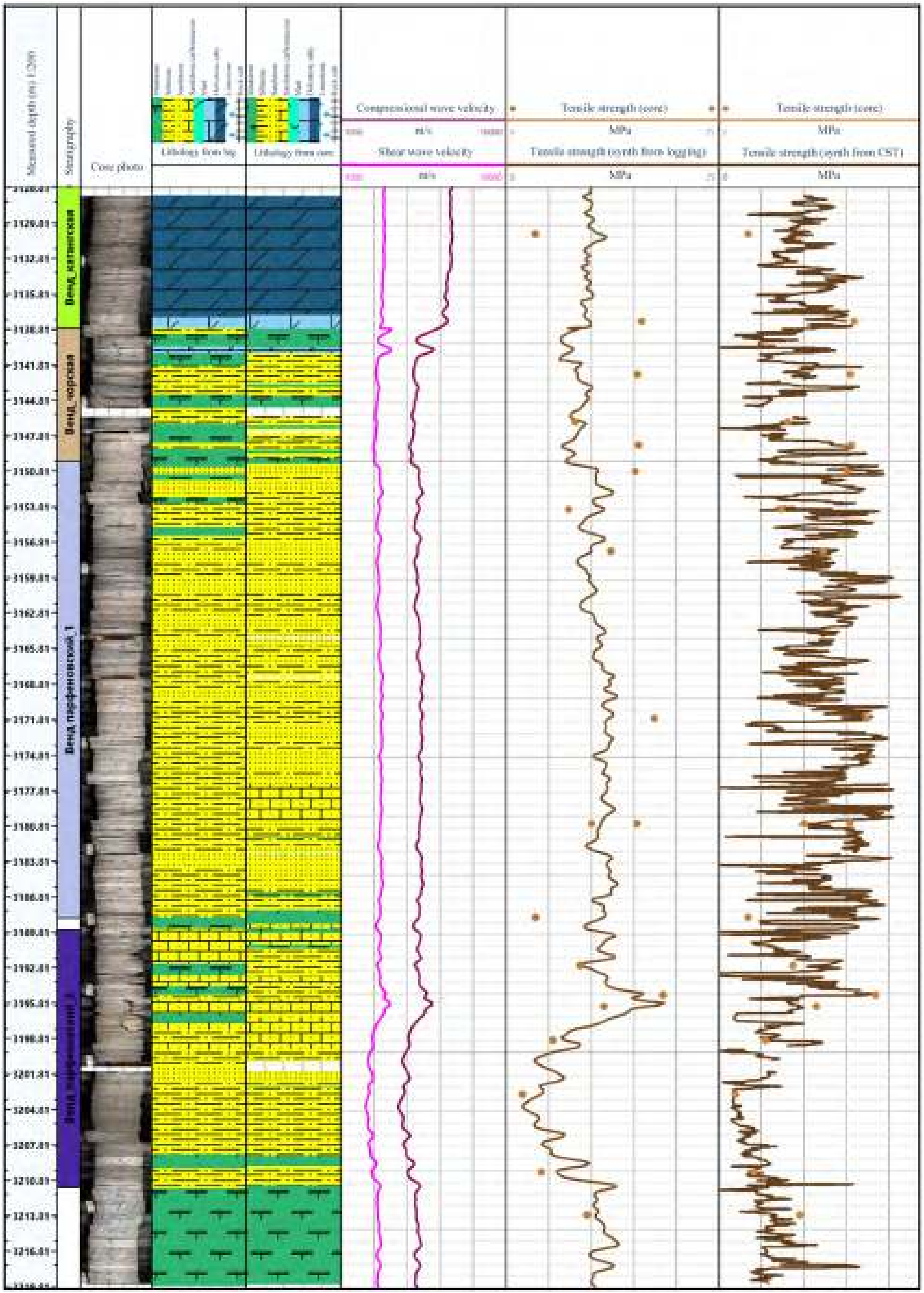

Figure 3—The modeled BTS log, based on the well logs (left) and on the CST results (right)

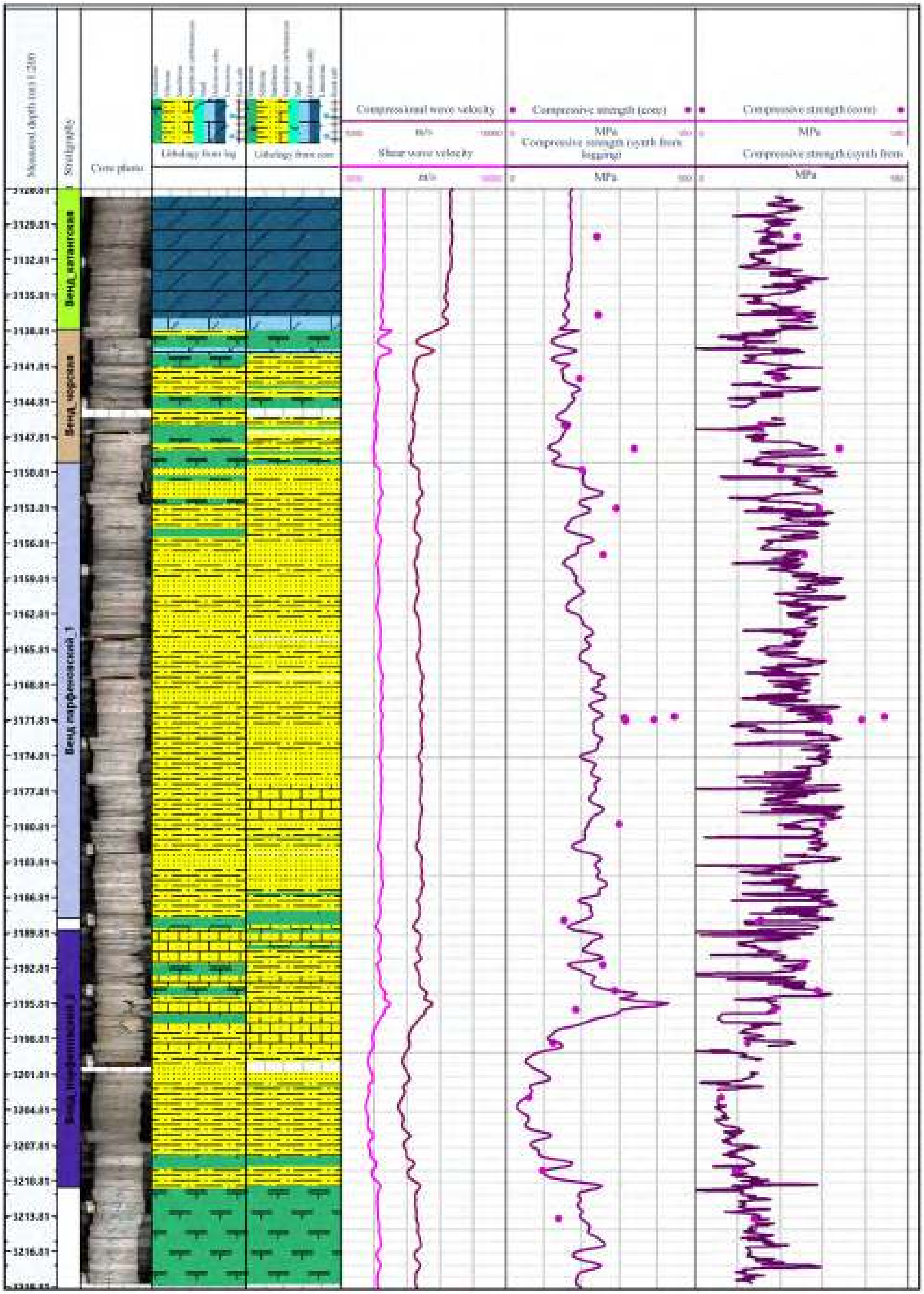

Figure 4—The modeled UCS log, based on the well logs (left) and on the CST results (right)

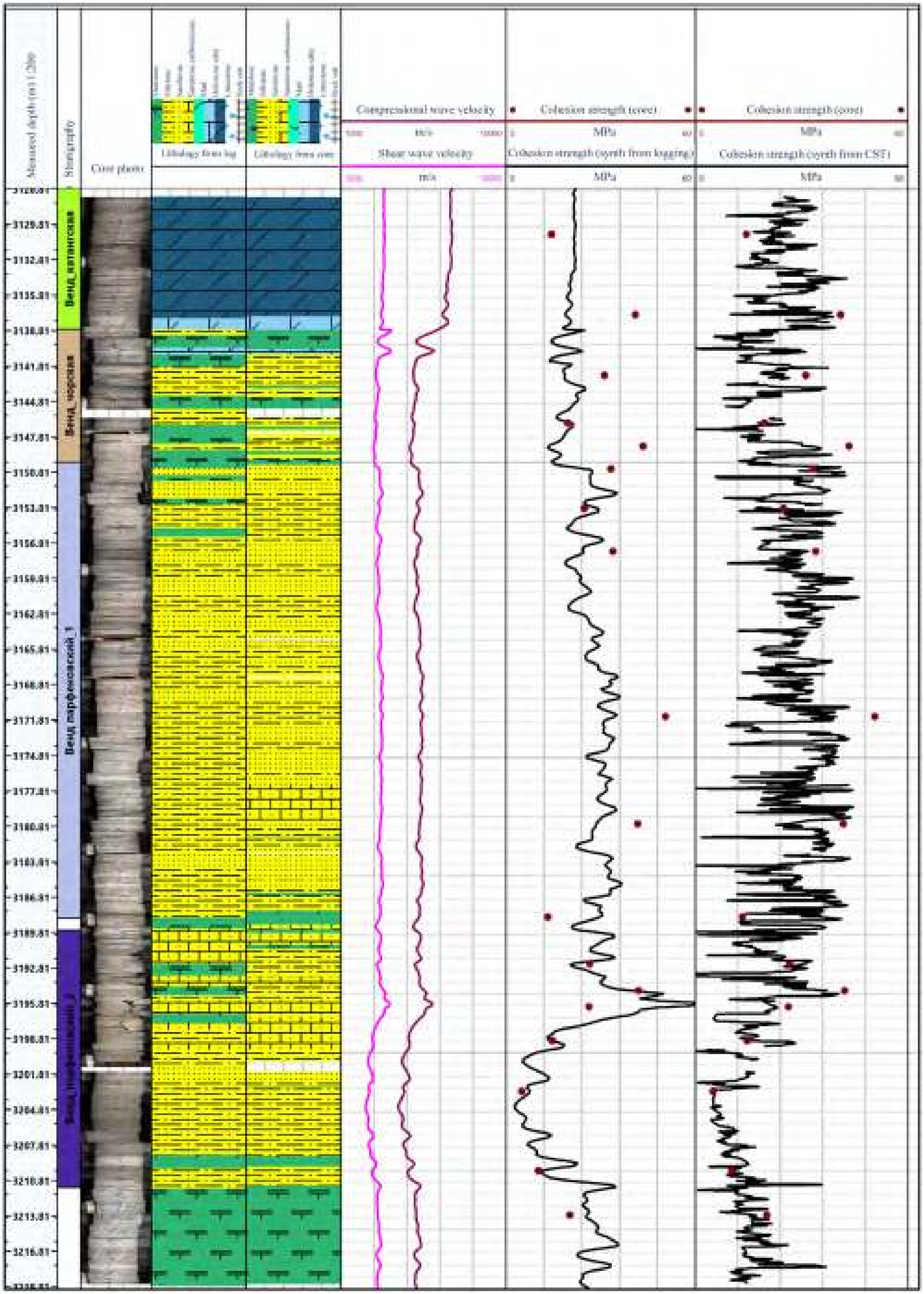

Figure 5—The modeled cohesion strength log, based on the well logs (left) and on the CST results (right)

The logs presented above clearly demonstrate that even the averaged resistance-to-scratching curve with a 60 mm window provides a much more detailed characterization of the cross-section than the geomechanical models based on the well log interpretation data, which level of detail is limited by the influence of the host rock while logging.

Also, the variations that are not present in the log-based synthetic curves can be observed on the CST-based synthetic curves of mechanical parameters. Besides, the CST-based model largely correlates with the lab-based core analysis results. The correlation reliability coefficients R^2 for each of the parameters and models are given in Table 3.

Table 3—The correlation reliability coefficients R^2 for the geomechanical model parameters

Parameter	R^2 Log-based model	R^2 CST-based model
Tensile Strength (Brazilian method)	0.49	0.65
Cohesion Strength (carbonates rocks)	0.83	0.81
Cohesion Strength (terrigenous rocks)	0.83	0.86
Unconfined Compressive Strength (carbonates rocks)	0.71	0.80
Unconfined Compressive Strength (terrigenous rocks)	0.47	0.82

Conclusions

The following advantages of the CST shall be mentioned:

- Defining the rock stress-strain behavior with a level of detail that largely surpasses the capability of the existing lab-based core analysis practices;
- Not as time-consuming as the established lab-based core analysis process;
- Applicable to cores of any quality level, irrespective of their continuity and/or homogeneity by volume;
- Providing a detailed and representative mechanical stratification of the original cores, irrespective of their quality and/or properties;
- Having the lowest damaging impact on the core under analysis;
- Giving information about the rock, irrespective of its properties; it could also give an opportunity to analyze poorly consolidated rocks.

The above-mentioned advantages can increase the correlation reliability coefficient for the synthetic physical & mechanical parameters and core analysis results. As regards the well in question, the application of the CST-based model demonstrated an increase in the correlation reliability coefficient R^2 from 0.62 to 0.79.

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