Advanced rock-physics diagnostic analysis: A new method for cement quantification

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Abstract

Rock-physics diagnostic (RPD) analysis is widely used to describe the functional relationship between seismic velocity and porosity, which is consistent with local geology, for example, characterizing diagenetic pore-filling cement and contact cements. Rock-physics studies indicate that quantitative cement substitution is as important as fluid substitution in understanding the difference between the hydrocarbon effect and the cementation effect from seismic data. Cement quantification is also important in understanding the fluid flow and mechanical strength of reservoir rocks. A new method quantifies the amount of contact and pore-filling cement by using RPD analysis. This cement-quantification method combines soft-sand, stiff-sand, and intermediate stiff-sand models and is a physical-based approach to quantify the amount of contact and pore-filling cement. By using these rock-physics models, one can examine the relationship between elastic properties and porosity in laboratory data and can link rock-physics properties to diagenesis to quantify the amount of cement. Pore-filling berthierine cements determined from thin-section analyses agree well with pore-filling cement determined from RPD analysis. The amount of contact cements determined from RPD analysis also agrees well with the amount of quartz cement determined from thin-section analyses. This new approach can be used to quantify the amount of pore-filling and contact cement from seismic properties.

Introduction

Cementation is an important stage of the diagenetic process in rocks. It involves the solution and precipitation of minerals. Depending on how cement is distributed, it can be classified into two groups: contact cement and pore-filling cement (Figure 1). Both types of cement lead to a decrease in the pore volume of the rocks. The sensitivity of the seismic response to hydrocarbon in reservoir rocks is highly affected by reservoir diagenesis, and it is important to include these diagenetic factors in rock-physics analysis.

A schematic rock-physics template provides a simple way to visualize the effect of cementation (Figure 2). Initially, we assume that the models were generated for clean, unconsolidated sand and shale. For rocks with higher porosity containing lower levels of pore-filling minerals, fluid sensitivity is higher. In contrast, in rocks with lower porosity in which more pore-filling minerals are present, the sensitivity to fluid is lower. However, fluid sensitivity can decrease dramatically with the presence of contact cement (Figure 2).

Avseth et al. (2005) show that the initial cement drastically changes the AVO signatures of the reservoir and reduces pressure and fluid sensitivity in sandstones. In a case example from the North Sea, Avseth et al. (2005) demonstrate how cementation affects AVO anomalies associated with two adjacent hydrocarbon discoveries.

Hossain et al. (2012) demonstrate that brine-bearing weakly cemented sand can have similar AVO responses to oil-bearing cemented sand. This implies that cementation quantification is important when one observes the transition from unconsolidated to cemented intervals in terms of rock-physics properties.

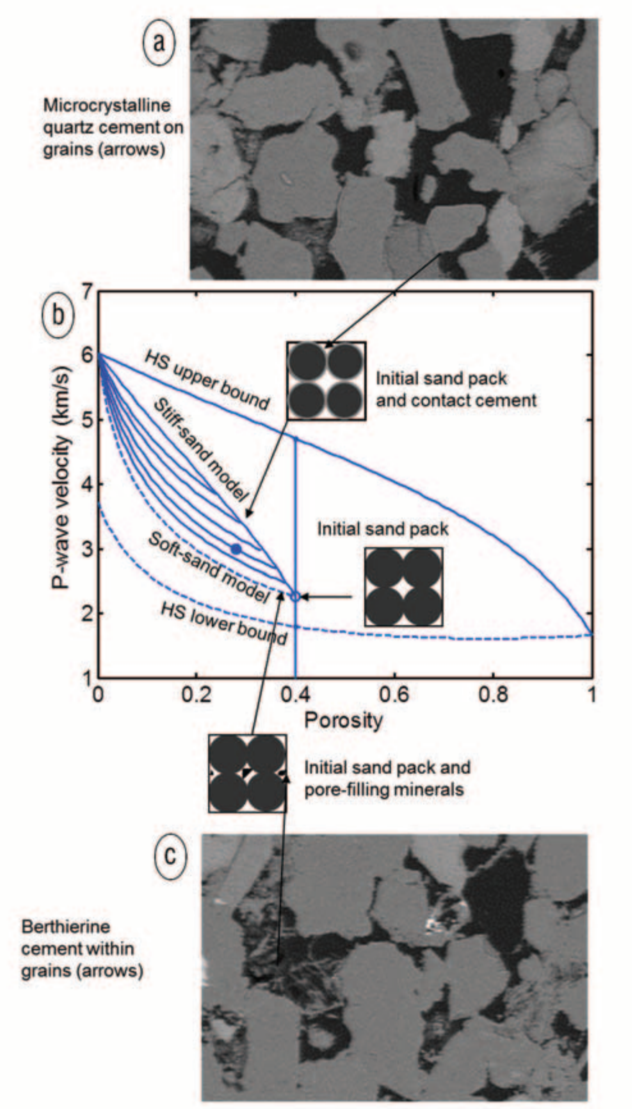

Figure 1. (a) Backscattered electron (BSE) images of microcrystalline quartz-cemented greensand. (b) Soft-sand model (modified Hashin-Shtrikman lower bound) and stiff-sand model (modified Hashin-Shtrikman upper bound). The curves between bounds are the intermediate stiff-sand model, which uses the soft-sand model equation with increasing coordination number. (c) BSE image of berthierine-cemented greensand.

These two examples imply that rock-physics diagnostics can be applied at the seismic scale in addition to the log scale. Take into account that cementation of the rock improves the ability to identify pore fluids from seismic. Therefore, quantitative cement substitution is as important as fluid substitution in understanding the difference between fluid effects and other lithologic effects in seismic data.

Cement quantification is also important in understanding fluid flow in reservoirs. For high-porosity sandstones, permeability depends not only on porosity but also on cementation in pore spaces. Permeability is affected mostly by the part of the pore-filling cement that is deposited away from grain contacts and that blocks the pore space (Dvorkin and Brevik, 1999). However, Hossain et al. (2011b) show that small amounts of microcrystalline quartz cement on the surface of grains can significantly reduce the permeability of reservoir rocks. If the amount of contact and pore-filling cement can be quantified, the results can be used to infer which effect on fluid flow is larger.

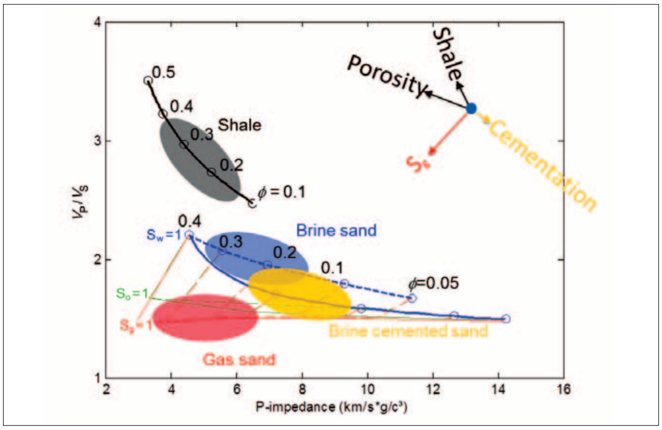

Figure 2. Schematic outline of a rock-physics template illustrating the effect of cementation. Gas-saturated sand is normally well separated from brine-saturated sand in the rock-physics crossplot of V_P/V_S *versus acoustic impedance. The effect of cement will reduce the fluid sensitivity and will move brine-sand data toward the oil-sand model.*

Cement quantification also can be important in understanding resistivity in reservoirs. Laboratory-measured resistivity increases with increased pore-filling berthierine cementation (Hossain et al., 2012). In addition, quantitative analysis of cement volume can be used as a potential tool for determining the mechanical strength of reservoir rock. Intuitively, the larger the amount of contact cement, the stronger the rock at the same porosity (Al-Tahini et al., 2007).

The estimation of cement volume can provide geoscientists with additional rock-physics parameters that contain useful extra information about reservoir properties. However, the amount of cement is not easily quantified from conventional petrophysical logs. Nevertheless, if cement can be observed within thin-section analysis, then we can estimate the amount of cement from seismic properties via rock-physics relations.

The objective of this study is to offer a new method to quantify the amount of pore-filling and contact cement by analyzing velocity data via rock-physics diagnostic (RPD) analysis. We used RPD analysis to quantify the cement volume and compare the results with the cement volume determined from thin-section analysis to validate the approach. Furthermore, we used laboratory-measured velocity data from quartz-cemented sandstones to quantify the amount of contact cement

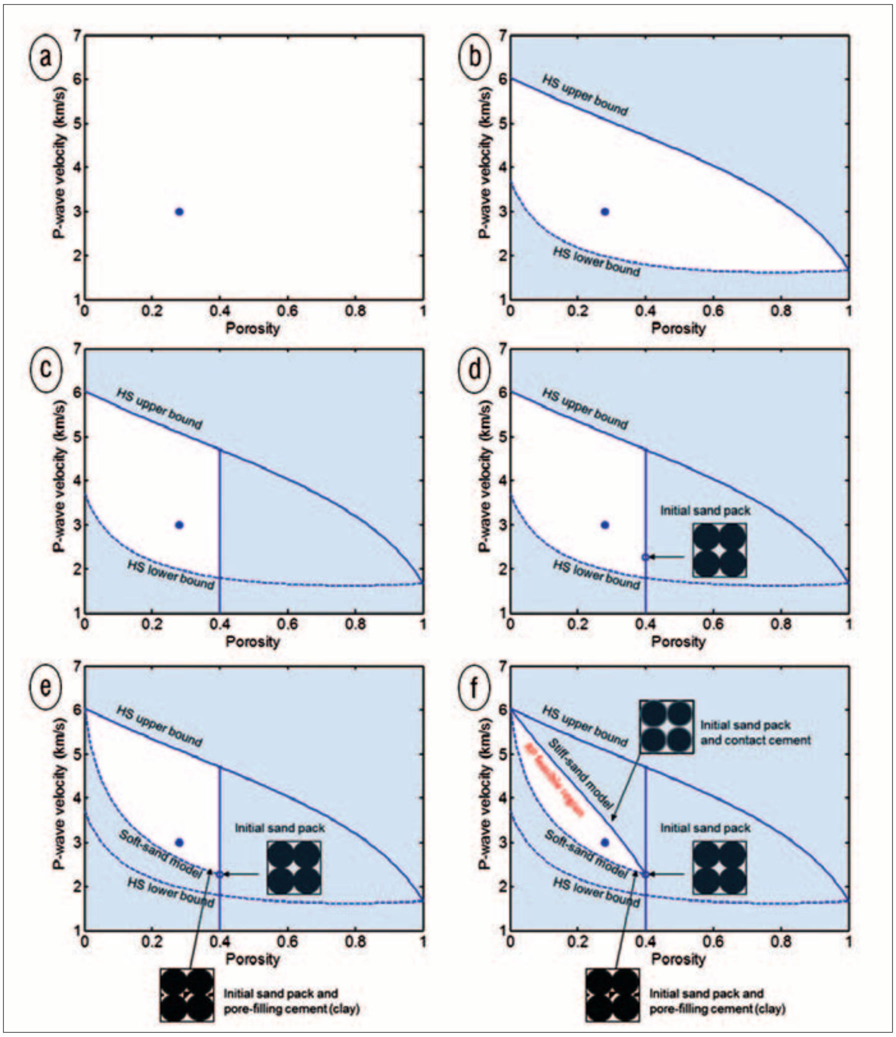

Figure 3. Method to define the rock-physics feasible region (RPFR) for measured data. (a) Insert the measured porosity-velocity crossplot. (b) Apply Hashin-Strikman (HS) upper and lower bounds. (c) Define the critical porosity. (d) Calculate initial sand-pack velocity using the Hertz-Mindlin contact model (fluid substitution is required for fluid-saturated rock). (e) Modify the HS lower bound based on soft-sand model theory. (f) Modify the HS upper bound based on stiff-sand model theory. The rock-physics feasible region is then smaller than the area of HS bounds.

to compare with the amount of quartz cement determined from thin-section analysis. Achieving this objective will allow us to understand the effect cementation has on seismic properties, fluid flow, and mechanical strength of rocks. Without quantifying and understanding these cementation effects, we might not be able to forecast the pore fluid in cemented reservoir rocks.

Method for cement quantification

We combined three rock-physics models — the soft-sand model, stiff-sand model (Mavko et al., 2009) and intermediate stiff-sand model (Mavko et al., 2009; Hossain et al., 2011a) — to determine the amount of cement. However, before quantifying any amount of cement, it is important to perform rock-physics diagnostic analysis. To provide proper RPD analysis, we introduce a concept termed *rock-physics feasible region* (RPFR). The objective of the RPFR is to define the smallest area or smallest bounds required to visualize the physical properties of rocks.

Figure 3 demonstrates the concept of the RPFR. Initially, a porosity-velocity crossplot is populated with data to define the RPFR (Figure 3a). Second, Hashin-Shtrikman (HS) upper and lower bounds between fluid and rock solid are applied to check the quality of measured data (Figure 3b). In the HS bounds, the elastic moduli at the zero-porosity end-member are defined by the elastic moduli of the minerals.

Even though the Hashin-Shtrikman bounds represent the narrowest bounds in theory, the physical properties of rock still cannot be described by those bounds without introducing a geometric parameter. By defining the critical porosity or initial sand-pack porosity of this sample, the area of these bounds can be decreased further (Figure 3c). At critical porosity, the rocks are not in suspension anymore; therefore, their elastic properties should be higher than the HS lower bound suggests. The effective moduli of the initial sand pack are computed by the Hertz-Mindlin contact theory (Figure 3d). The Hertz-Mindlin contact model is used routinely to calculate the dry-pack modulus, so a fluid-substitution method is required for fluid-saturated rock.

After this, the soft-sand (Figure 3e) and stiff-sand (Figure 3f) theories can be applied to define the RPFR. The soft-sand model assumes that porosity reduces from the initial sand-pack value because of the deposition of solid matter away from grain contacts. The soft-sand model line is represented by the modified lower Hashin-Shtrikman bound (Mavko et al., 2009) and connects the sand-pack porosity end point and the pure mineral end point.

The lower Hashin-Shtrikman bound, which is an isostress model for suspensions, is always the elastically softest way to mix multiple mineral phases. The porosity reduction between these points will result in a gradual stiffening of the rock because smaller grains fill the pore space between larger grains.

A counterpart to the soft-sand model is the stiff-sand model, which assumes that porosity reduces from the initial sand-pack value because of deposition of cement at grain contacts. The stiff-sand model line is represented by the modified upper Hashin-Shtrikman bound (Mavko et al., 2009) and connects the initial sand-pack porosity end point and the pure mineral end point.

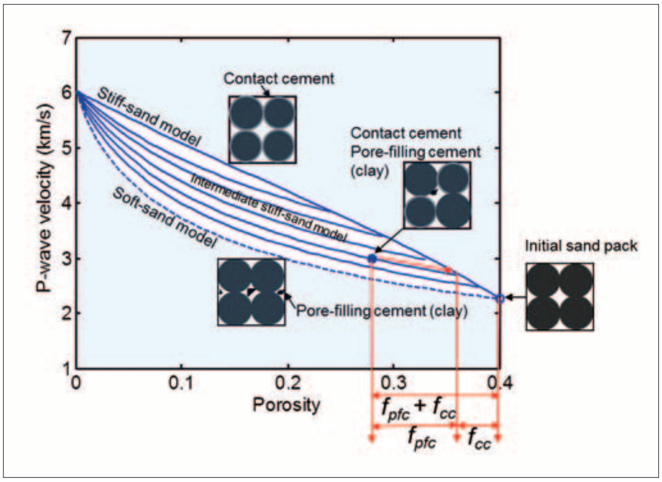

Figure 4. *Method for contact (f_{cc}) and pore-filling cement (f_{pfc}) quantification. The stiff-sand model explains the theoretically stiffest way to add cement with initial sand pack, whereas the soft-sand model explains the theoretically softest way to add pore-filling minerals. The intermediate stiff-sand model describes both initial-contact cementation and noncontact cement.*

As for the soft-sand model, the initial sand-pack modulus of the stiff-sand model is determined by the Hertz-Mindlin theory (Mavko et al., 2009), whereas the mineral end point is defined by the elastic moduli of the minerals.

The area defined by the RPFR is much smaller than the area of HS bounds. Measured data inside the RPFR can easily be identified based on bounds of this feasible region without further interpretation. As long as these measured data lie between the lower bound of the feasible region (soft-sand model) and the upper bound of the feasible region (stiff-sand model), the measured data are influenced by pore-filling minerals and contact cement.

This diagnostic can be described using the intermediate stiff-sand model, which fills the interval between the stiff-sand and soft-sand models (Mavko et al., 2009; Hossain et al., 2011a). The intermediate model uses the functional form of the soft-sand model, but the high-porosity end point is situated on the stiff-sand model curve (Figure 3).

The easiest way to generate such curves is by simply increasing the coordination number of the Hertz-Mindlin theory in the soft-sand model (Mavko et al., 2009). The stiff-sand model explains the theoretically stiffest way to add cement with initial sand pack, whereas the soft-sand model explains the theoretically softest way to add pore-filling minerals. However, rocks with little initial contact cement are not well described by either the stiff-sand or soft-sand model. In this case, the intermediate stiff-sand model can be used because it takes into account the initial cementation effect. Therefore, according to theory, the intermediate stiff-sand model describes both initial contact cementation and noncontact cement (Hossain et al., 2011a).

To determine the amount of cement from sonic and porosity information, we use a method assuming that a high-porosity sandstone has an idealized texture, comprising a basic framework of a random pack of identical spherical grains at critical porosity. Because of the diagenesis, the grains are enveloped by a layer of contact cement and pore-filling cement deposited within the pore space away from grain contact. Therefore, changes in porosity away from the critical porosity are caused by diagenetic processes. In the absence of mechanical compaction and abnormal pressure, this diagenetic process can be attributed to pore filling (pore-filling cementation) and contact minerals (contact cement).

In the second step, let us take a data point in the velocity-porosity plane that can be modeled with an intermediate stiff-sand model. If the data fit with the intermediate stiff-sand model, then it describes the presence of contact and noncontact cement that contribute to the stiffness of rock and porosity reduction. A contact-cement trajectory is drawn along the intermediate stiff-sand model to the stiff-sand model line (Figure 4). The intercept between intermediate stiff-sand model and stiff-sand model describes the initial contact cement point of these data. The porosity difference between critical porosity and porosity at the initial contact cement is assumed to be the porosity change resulting from the contact cement (f_{cc}). Finally, the amount of pore-filling cement (f_{pfc}) is calculated by subtracting the amount of contact cement from the total diagenetic cementation.

Cement quantification from laboratory and log data

Figure 5a shows modeling of glauconite-bearing greensand from the North Sea where the Hertz-Mindlin contact model for two types of grains was used to calculate the initial sand-pack modulus for a soft-sand and a stiff-sand model. Detailed descriptions of these samples can be found in Hossain et al. (2011a).

The rock-physics models shown in Figure 5a for laboratory data imply that we can define the two main diagenetic phases in the greensand: silica cementation and berthierine cementation, as illustrated in Figure 6a. The silica cement appears in the form of microcrystalline quartz, with crystals about 2 m in diameter, probably formed as an opal rim on the surface of the grains (Figure 1a). Microcrystalline quartz

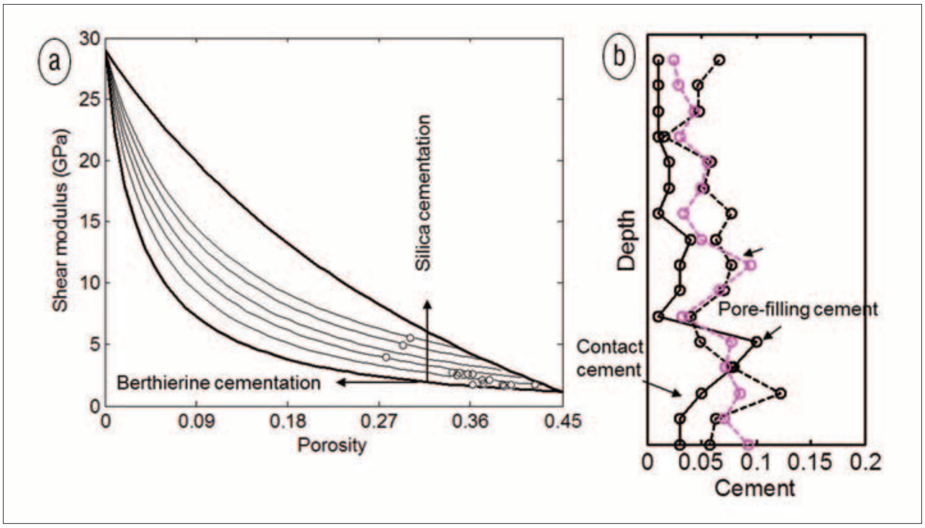

Figure 5. (a) Modeling of laboratory-measured greensand samples for shear modulus. Model curves represent the soft-sand (lower), intermediate stiff-sand (middle), ands stiff-sand (upper) models (Hossain et al., 2011a). (b) Volumetric contact and noncontact cement quantification from RPD analysis. The amount of noncontact cement (black dashed curve) quantification from RPD correlates well with the amount of pore-filling berthierine cement (Hossain et al., 2011b) quantification from image analysis of thin sections (pink curve).

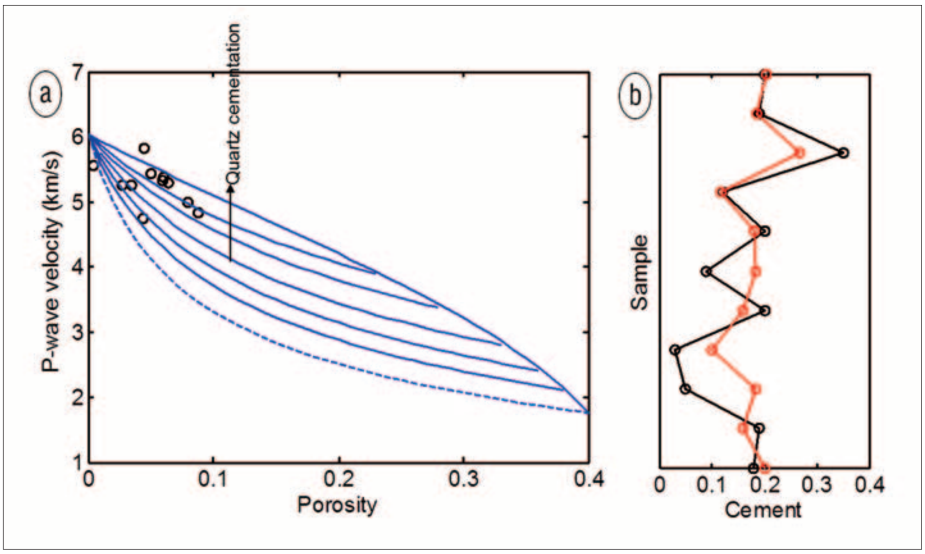

Figure 6. (a) Modeling of laboratory-measured sandstone samples from Saudi Arabia (Al-Tahini et al., 2007). Model curves represent the soft-sand (lower), intermediate stiff-sand (middle), and stiff-sand (upper) models. (b) Volumetric contact cement quantification from RPD analysis (black line). The amount of quartz cement quantification from thin-section analysis (red curve) from Al-Tahini et al. (2007) correlates well with the amount of contact cement determined from RPD analysis (black curve).

coating on detrital grains is located at the grain contacts. As a result, this quartz cement acts to stiffen the rock (Stokkendal et al., 2009). Hence, the presence of microcrystalline quartz cement should have a major effect on the elastic properties of greensand and a weaker effect on porosity.

The pore-filling berthierine cement is oriented randomly and precipitates in the pores between large grains (Figure 1c). These pore-filling minerals have small effect on the elastic modulus but a large effect on porosity. Hence, porosity in greensands decreases from initial quartz-glauconite pack porosity because of the increasing amount of pore-filling and contact cement. This behavior is described adequately by the intermediate stiff-sand model.

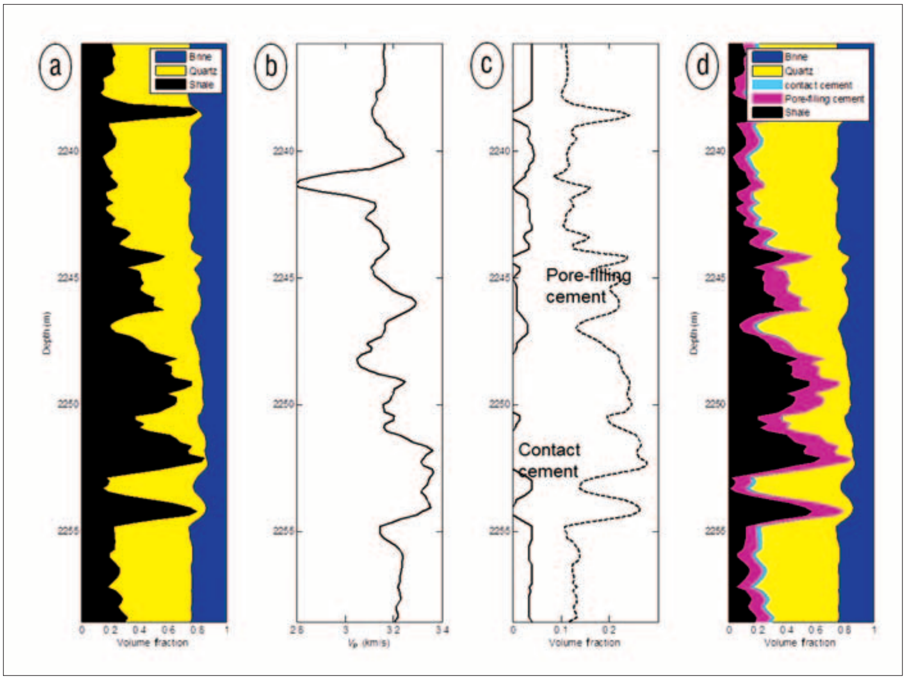

__Figure 7.__ (a) Volume fraction of rocks obtained from petrophysical well-logging analysis, (b) P-wave velocity, (c) contact and pore-filling cement quantification from RPD analysis, and (d) reevaluation of petrophysical analysis after quantitative RPD analysis.

Our next step is to quantitatively interpret the amount of contact and pore-filling cement by using RPD. With good local validation of the models, we can quantify the amount of noncontact cement and contact cement from this RPD analysis (Figure 5b). We chose to do this in the shear-modulus-versus-porosity domain to avoid pore-fluid effects.

Having estimated cement volume, we can plot these as logs to be compared with cement quantification from thin-section analysis. Initial observation is that cement volume increases with depth. It is essential to verify this amount of cement prediction from rock-physics relations with thin-section observations. The quantitative amounts of pore-filling cements determined from RPD agree well with the amount of pore-filling berthierine minerals (Hossain et al., 2011b) determined from petrographic thin-section analysis. Hence, this thin-section analysis is consistent with our choice of rock-physics approach to predict the amount of noncontact cement.

In the second example, we analyzed the amount of contact cementation in Jauf and Unayzah sandstone formations of Saudi Arabia. Detailed descriptions of these samples and data can be found in Al-Tahini et al. (2007). Figure 6a shows that the velocities of Jauf and Unayzah samples are highly influenced by the presence of quartz cement and porosity. Velocities increase with the increasing quartz overgrowth. The amounts of quartz cement determined from thin-section analysis correlate well with the amount of contact cement determined from RPD analysis (Figure 6b). Hence, this thin-section analysis is consistent with our choice of rock-physics approach to predict the amount of contact cement.

Applications

Petrophysical well-logging analysis from the North Sea well shows the presence of quartz and shale. However, the analysis does not indicate the amount and type of cement (Figure 7a), even though several authors (e.g., Avseth et al., 2005; Hossain et al., 2011b) have reported the presence of contact and pore-filling cement for sandstone reservoir rocks from the North Sea.

The RPD analysis workflow presented here can be used as a guideline to determine the amount of cement and, from that, to reevaluate the petrophysical well-log analysis. The sand interval in this example can be modeled by rock-physics theory as soft-sand and intermediate stiff-sand. Having estimated cement volume, we plot these as logs (Figure 7c) and recalculate the volume fraction of minerals within the interval (Figure 7d). Now the higher velocities in Figure 7b can be attributed to the presence of cement in the rocks rather than having been caused by higher clay content, as reflected in Figure 7a.

Avseth et al. (2009) use a method to quantify the amount of cements. In their method, contact cement was estimated by interpolating between constant cement volume trends. In contrast, pore-filling cementation in terms of sorting was defined by the observed porosity normalized by the high end-member porosity along the given constant cement trend.

For severe cementation in which diagenetic cement is filling the pore space, the contact cement sand model breaks down, and one should use the stiff-sand model (Avseth et al., 2005). We used the stiff-sand model for contact cement quantification. Therefore, cement quantification based on Avseth et al. (2009) is a method of cement quantification for high-porosity sandstones. In contrast, the method of cement quantification presented in this study is valid for high-porosity and low-porosity sandstones.

Conclusions

Rock-physics diagnostic (RPD) analysis describes functional relationships between seismic velocity and porosity, which are consistent with local geology, e.g., pore-filling and contact cementation. Rock-physics studies indicate that quantitative cement substitution is as important as fluid substitution in understanding the difference between the hydrocarbon effect and the cementation effect on seismic data.

We introduce a new method to quantify the amount of contact and pore-filling cement by using RPD analysis. The new cement-quantification method combines the soft-sand, stiff-sand, and intermediate stiff-sand models and is a physical-based approach to quantify the amount of contact and pore-filling cement. By using these rock-physics models, we examine the relationship between elastic properties and porosity in the laboratory and link rock-physics properties to diagenesis.

Pore-filling berthierine cements determined from thin-section analysis are in good agreement with pore-filling cement determined from RPD analysis. The amount of contact cement determined from RPD analysis also agrees well with the amount of quartz cement determined from thin-section analysis.

Without quantifying and understanding the cementation effects on elastic properties, we could not forecast the correct pore-fluid effect in cemented reservoir rocks from seismic data. TLE

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