Static and dynamic elastic behaviour of siliciclastic reservoir rocks

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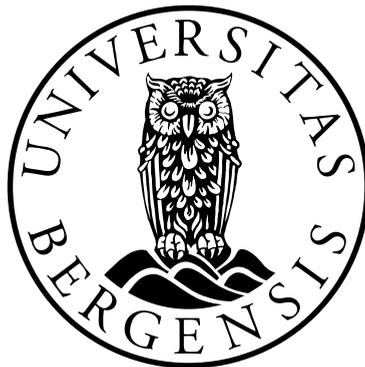
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Abstract

Siliciclastic rocks are composed of a wide range of minerals; including quartz, feldspar, clay minerals, calcite to name the most common; and various textural properties such as grain size (sorting), shape, orientation and packing. However, most of the rock physics models used to reproduce their elastic behaviour make use of severe idealizations of those rock properties, such as assuming single mineralogy, spherical, uniform grain sizes and shapes, or by representing the pore space by an ellipsoid characterized by one aspect ratio only. Even when those models may have considerable success modelling clean, well sorted siliciclastic rocks; their application faces considerable challenges in the modelling of heterogeneous sedimentary rocks. The objective of this thesis was to develop strategies to parameterize existing models from geologically controlled observations, with the aim of extending their application to wider ranges of composition and textural properties. The study used mainly existing laboratory data, which provided extensive information about composition and texture of the analyzed samples. It was found that a quantitative comparison between the results of various rock physics model is essential when making diagnostics about rock microstructure from elastic measurements. We were able to calculate percolation limits of clay-bearing rocks through an analogy between the critical porosity concept, as used in rock physics, and the liquid limit of clay powders in clay and soil science. Scanning electron microscope (SEM) images of clay-water composites showed that the large scale (>0.1 μm) pore space of kaolinite samples had more elongated and oriented pores (smaller aspect ratios) than smectite samples. However, we needed to include smaller aspect ratio pores, which exist at the scale of the individual clay platelets, to reproduce the observed elastic measurements. We observed a significant correlation between pressure sensitivity, in terms of velocity and attenuation, and the abundance/lack of quartz mineral in siliciclastic rocks. Therefore, by associating the content of secondary minerals to the amount of crack-like pores we modelled the pressure variations of velocity and attenuation using a visco-elastic theory. In addition, we found that pores at different scales such as equant, elongated and cracks-like require different relaxation time constant to honour the observed attenuation values.

Preface

This thesis is submitted in partial fulfilment of the requirements for the degree of philosophiae doctor (PhD) in petroleum geosciences at the Department of Earth Science, University of Bergen. This research was funded by the Norwegian Research Council (NFR) through the Petromaks program (program for optimal management of petroleum resources) under the scope of the project entitled "Reservoir Monitoring and Dynamic Reservoir Characterization with Production, Seismic and Electromagnetic Data". The principal supervisor was Professor Tor Arne Johansen at the University of Bergen. Co-supervisors were Dr. Kyle T. Spikes at University of Texas at Austin, and Adjunct Professor Philippe Doyen at University of Bergen.

The structure of this thesis follows the recommended outline for doctoral dissertations in natural science, in which the main body consists of scientific articles submitted, or in preparation to be submitted, to relevant peer-reviewed scientific journals. The articles are preceded by an introduction (Chapter 1) to the geological context of this study. Chapter 2 reviews the main findings presented in each one of the scientific papers. The overall conclusions of the project are summarized in Chapter 3. Afterwards, 4 scientific articles constituting the main outcome of this project are given as an appendix.

I would like to thank everyone who has helped me to finish this dissertation. In particular, I express my gratitude to my supervisors Tor Arne Johansen, Kyle Spikes and Philippe Doyen for their continuous support and guidance during this work. I am greatly indebted to the University of Bergen, NFR and my supervisor Tor Arne Johansen for providing me with the invaluable opportunity of pursuing doctoral studies. Special thanks go to Aart-Jan van Wijngaarden, Arild Buland, and Alexander Olsen at Statoil for granting the leave to complete the PhD studies. I feel privileged to have collaborated with: Erling Jensen and Remy Agersborg at University of Bergen and Nazmul Mondol at University of Oslo.

My colleagues both past and present, office mates and friends at the Department of Earth Science are deeply indebted for helped me enjoying everyday life. You have simply made this time enjoyable and worthy. In particular, special thanks go to the Grosfeld-Plivelic family for being my adoptive family in these remote northern lands.

I would like to finalize with a personal note. My family has always been there for me, no matter how far I decided to go. This dissertation is dedicated to my mother, Lydia, whose values and integrity have inspired each one of my steps.

Bernardo Moyano

Bergen, April 2013

List of papers

Paper 1:   Moyano B., Jensen E.H. and Johansen T.A. Improved quantitative calibration of rock physics models. *Petroleum Geoscience, November 2011, v. 17, p. 345-354.*

Paper 2:   Moyano B., Spikes K.T., Johansen T.A., Mondol N.H. Modeling compaction effects on the elastic properties of clay-water composites. *Geophysics, vol. 77, No. 5, p. D171-D183 (Sep-Oct. 2012).*

Paper 3:   Moyano B., Johansen T.A., Agersborg R. and Spikes K.T. Diagnostics of seismic time lapse effects of sandstones: Based on laboratory data. *Submitted to Geophysics, 2013.*

Paper 4:   Moyano B., Jensen E.H. and Johansen T.A. Spatial constrained inverse rock physics modelling. *In preparation to be submitted to Geophysical Prospecting, 2013.*

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" There is no book so bad but it has something good in it"

From "The ingenious gentleman Don Quixote of La Mancha"

Miguel de Cervantes Saavedra

(1547 - 1616)

1 Introduction

The elastic properties of clean siliciclastic rocks are often well characterized by theoretical models used in the analysis of log and laboratory data. The term clean is often used to refer to quartz dominated and well sorted sandstones. Compositional and textural heterogeneities present in natural rocks affect their physical response and add considerable uncertainty to the results. These small scale heterogeneities can arise from their composition, with clay minerals as common source of anomalies, and from variations in texture such as grain size (sorting), grain shapes, packing, cement presence and other similar features. Experimental laboratory studies (Han et al., 1986) have demonstrated a significant dependency of P-wave velocity, and to lesser degree S-wave velocity, on porosity. The scatter along the velocity-porosity relations has been attributed to clay content (Han et al., 1986; Klimentos and McCann, 1990; Yin, 1992). A group of authors (Avseth et al., 2005; Avseth et al., 2010) have proposed combinations of heuristic, theoretical and empirical models to distinguish between (steep) diagenetic and (flatter) depositional trends in the velocity-porosity space. Despite a great deal of studies on the elastic signature of heterogeneous sandstones, the relative importance of the distinctive rock textural properties controlling their response are still not completely understood. In the following sections, a brief description of heterogeneous reservoirs is presented along with experimental details of laboratory datasets used in this study. Additionally, the main objectives of the thesis work are presented, and the most relevant findings of each scientific paper are reviewed.

1.1 Heterogeneous reservoirs

Sandstones are composed of various minerals, with quartz, feldespar, and clay-minerals as the most abundant. They possess a wide range of textural properties such as different grain shapes, sizes and orientation. In this thesis well sorted quartz-dominated sandstones are refereed as "clean" sandstones, whereas poorly sorted multi-mineralic formations are mentioned as "heterogeneous sandstones". In the study of heterogeneous reservoirs is important to identify and understand which are the critical factors affecting their geophysical properties and, in particular, their elastic properties. The elastic properties of the mineral constituents and its textural characteristics may have an impact on the effective properties of the rock. Moreover, the complexity in composition and texture is also manifested in the topology of the pore space.

In terms of composition, clay-minerals are probably the components with the most anomalous properties in silicicastic rocks. The elastic properties of clay minerals are not

completely understood and direct measurements are challenging due to their reduced size compared to the other minerals. Published values differ considerably and a general consensus does not exist. Some values for the elastic properties of the most abundant minerals, extracted from the literature (Mavko et al., 2009), are presented in Figure 1. It is noticeable that Poisson's ratio (or Vp/Vs ratio) can be useful to distinguish between a clean (quartz-dominated) and heterogeneous formations. It is also clear from Figure 1 that a small amount of clay mineral can have significant impact on the effective properties of the rock.
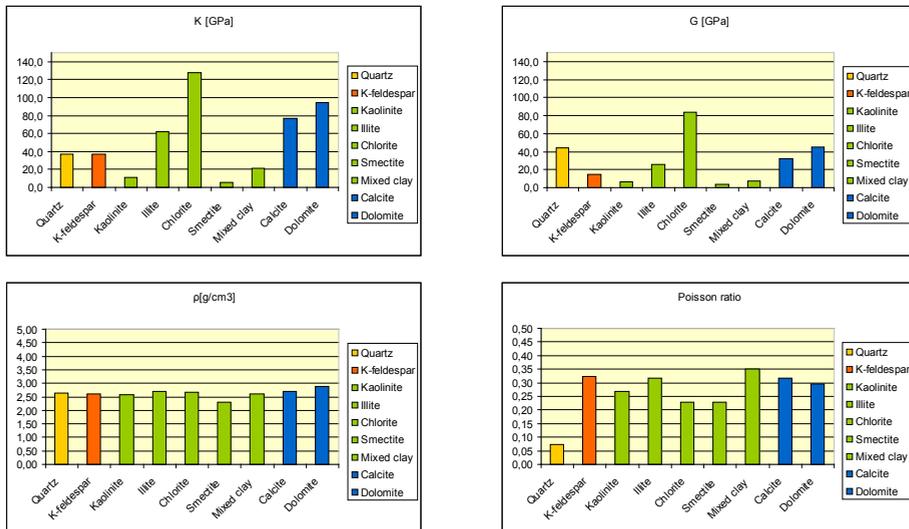

Figure 1 Elastic moduli of common minerals in siliciclastic rocks as reported in *The Rock-Physics Handbook*, (Mavko et al., 2009). Original references: Quartz from Carmichael (1989), K-feldspar from Woeber *et al.* (1963), Kaolinite and Smectite from Vanorio *et al.* (2003), Illite and Chlorite from Wang *et al.* (2001), mixed clay from Tosaya (1982), Calcite from Simmons (1965), Dolomite from Humbert and Plicque (1972).

Two important aspects of the siliciclastic sediments are their sedimentary structures and textures (Tucker, 1991). They are closely related to the depositional processes but they are also severely influenced by post-depositional and diagenetic processes. The texture of modern sediments is often studied to infer the depositional process that gave origin to them. These studies consider features such as:

- Grain size (sorting)

- Grain morphology (shape, sphericity)

- Fabric, described by grain orientation and packing.

These texture characteristics are described by parameters with qualitative character but sometimes they can be described in a semi-quantitative way. For instance, sorting is a quasi-quantitative parameter describing the spread (standard deviation) of the grain size distribution. Sorting also indicates the effectiveness of the depositional medium to separate grains of various sizes. Based on their textural attributes, sediments can be considered in terms of it textural maturity (Tucker, 1991). Texturally immature sediments are characterized by abundant matrix (clay rich), poor sorting and angular grains; mature sediments have little matrix, moderate to good sorting and subrounded-to-rounded grains (Tucker, 1991). In the most developed case, texturally supermature sediments have no matrix, very good sorting and well rounded grains. This is related to the energy level of the depositional process. Minimal current activity will generate texturally immature sediments, whereas highly energetic systems tend to produce texturally mature sediments. For instance, many immature deposits can be found in glacial or fluvial systems, where in turns supermature deposits are often associated with aeolians, beach and shallow marine environments. Interestingly, porosity and permeability increase with increasing textural maturity because the presence or lack of fine grained material (matrix) controls the available space for fluid and fluid flow (Tucker, 1991).

Similarly, the compositional maturity of the sediments can be assessed by the abundance of labile and unstable grains, rock fragments and minerals such as feldspar. The level of compositional maturation increases with increasing stable minerals such as quartz and decreasing feldspar and rock fragments. A rock composed almost exclusively of quartz and no feldspar is denoted as supermature (Tucker, 1991).

1.2   Sand-clay arrangements

The elastic properties of heterogeneous reservoirs are affected by the content of clay, and how the clay-minerals geometrically distribute within the quartz grains. Clay minerals are constituted by plate-like particles with different elastic properties; they may have intrinsic anisotropy and amount of electrically bounded water. According to the clay-sand arrangement, three clay distributions are often recognized: dispersed (pore-filling), structural and laminated clays (Figure 2). Structural and laminated clays are originated during deposition, whereas dispersed clay can be post-depositional, generated by alteration of pre-existing minerals, as feldspars for example. Therefore, modelling their elastic signature has a predictive potential, for instance, in estimating how the properties of a specific reservoir change with burial depth, utilizing various clay models (e.g. a disperse clay model, or the character of clay-rich depositional facies, using laminar or structural models).
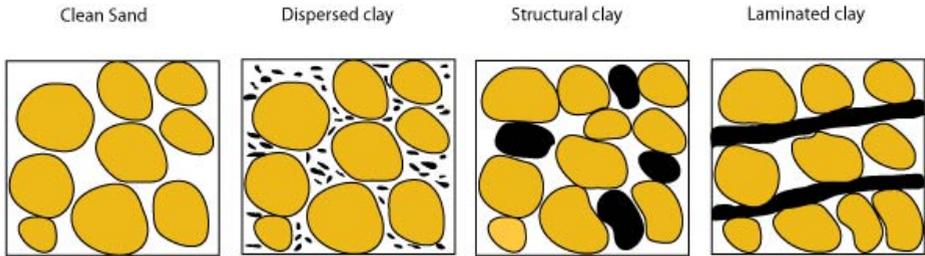
Figure 2 Various clay-sand distributions in siliciclastic rocks. From left to right: clean sand, dispersed clay, structural clay and laminated clay.

The laminated case refers to thin beds of clay minerals (or shale) alternated between clean sand beds. These laminations prevent vertical communication and consequently they reduce effective porosity and permeability. The properties of the laminations can be assumed to be similar to the embedding shales, due to their similar geological and burial history (Serra O. and Serra L., 2004). In the dispersed case, the clay minerals distribute filling up pore space or coating sand grains. Essentially, dispersed clay reduces porosity linearly with increasing volume of clay. Permeability and fluid mobility is also reduced. The structural clay corresponds to the case when clay minerals form bundles or clusters that are part of the frame of the rock. A propagating wave through the rock would see its velocity reduced due to the intrinsic velocity difference between quartz and clay minerals. The different clay-sand arrangements are often associated with different rock physics models, which, accordingly, predict somewhat different elasticity effects conducted by the occurrence of the clay (Minear John W., 1982; Xu and White, 1995; Sams and Andrea, 2001; Dvorkin and Gutierrez, 2001; Avseth et al., 2010).

1.3   Experimental details of the laboratory dataset used in paper 2

A summary of the experimental set-up of the compaction of clay-water composites used in paper 2 is presented here for completeness (Mondol et al., 2007; Mondol et al., 2008). The saturated composites were compacted by constant rate-of-strain tests in a high-stress oedometer cell. Effective vertical stress varied from 1 to 50 MPa. The tests were in drained conditions and the pore pressure was kept below 10% of the effective vertical stress. Measurements of the vertical strains, throughout linear variable displacements transducers (LVDT), were used to calculate the reduction of porosity and bulk density. The pulse transmission technique was used in the measurement of the velocities. Joint P- and S-wave transducers with a resonant frequency of 500 kHz were used for the velocity measurements. Relative errors in the velocities were estimated as ± 4.7% for the P-wave data and ±3.2% for the S-wave data. The cell size has an area of 20 cm^2 and a height of 30

mm. The initial height of the samples was about 30 mm whereas the final compressed height was between 8-10 mm. In a medium with velocity of 2000 m/s a P-wave propagating with frequency of 500 kHz would have a wavelength of λ = 4.0 mm. This implies that the height of the samples is always 2 to 6 times larger than λ, ensuring full pulse ultrasonic transmission. Moreover, scattering effects from small scale heterogeneities are minimized by a wavelength ∼ 400 times larger than the maximum grain size (10 μm).

1.4   Experimental details of the laboratory dataset used in paper 3

A brief summary of the ultrasonic measurements setup is given for completeness. Details can be found in Han et al. (2011a; 2011b). The ultrasonic reflection technique was developed by Winkler and Plona (1982) and later adapted by Klimentos and McCann (1990) and Best et al. (1994). In this technique a sample is placed between two Perpex buffer rods with a dual P/S wave transducer and receiver located on top of the upper buffer. The travel time difference between ultrasonic pulses reflected from the top and base of a rock sample is recorded. Velocities are calculated combining the travel time difference and the sample thickness. Attenuation is computed from the amplitude decay of equivalent cycle arrivals. The transducer used a pulse with a frequency of 1.0 MHz for the P-wave data and 0.7 MHz for the S-wave data. In this study, the saturated samples were loaded with 65 MPa confining pressure (isotropic) and the ultrasonic measurements were done in unloading cycle steps with constant pore pressure of 5 MPa. The sandstone samples were cylinders 2 cm long with a diameter of 5 cm. The saturating fluid was a brine solution (35 g/l) made of distilled water and sodium chloride. The P/S transducers used in this experiment provided an accuracy of ±0.3% and ±0.2 dB/cm for the velocity and attenuation coefficient measurements, respectively (Han et al., 2011a; Best, 1992).

1.5   Objectives

The main objective of this PhD thesis was to improve the understanding of the elastic signatures of heterogeneous siliciclastic reservoirs. Therefore, a critical task was to develop strategies to quantitatively assess the success of various rock physics models reproducing the elastic response of a given dataset. The study also attempted to identify the most relevant models and their critical parameters accounting for the elastic behaviour of heterogeneous rocks. Special attention was given to the effects of clay minerals on the elastic properties of rocks under increasing stress. Moreover, of particular interest was to be able to parameterize the existing theoretical rock physics models from geological observations in order to extend their use to wider ranges of compositions and textural properties.

2   Main scientific contributions

This section summarizes the main scientific contributions achieved in the four scientific articles which are the core of this thesis. The first paper presents a strategy to quantitatively assess the performance of various rock physics models when reproducing observed data. The second paper consists of modelling of compacting clay-water composites along with estimations of clay minerals elastic properties. The third article is a study of the interrelations between compositional maturity, pore texture, pressure, velocity dispersion and attenuation in clean and heterogeneous siliciclastic reservoirs. The fourth paper proposes a method to constrain predictions made by inverse rock physics modelling with spatial correlations calculated from the predicted parameters. Preliminary results of this work were presented in international conferences in Denver 2010, Vienna 2011 and Copenhagen 2012. In the following the main findings and conclusions of each paper are summarized. The papers in full extension are presented in the appendices I to IV.

2.1   Paper 1: Improved quantitative calibration of rock physics models.

Bernardo Moyano, Erling Hugo Jensen and Tor Arne Johansen.

Petroleum Geoscience, November 2011, v. 17, p. 345-354.

In this paper we applied the inverse rock physics modelling (IRPM) strategy as a calibration tool of various rock physics models to a given dataset. In the IRPM the rock physics transforms are reformulated so that the input data are seismic observables (P- and S-wave velocities, impedances, density) and the output data are reservoir parameters such as porosity, lithology and fluid saturation (PLF). We illustrated the advantages of using the IRPM and its quantitative character with two cases. The first case compared the calibration to a laboratory dataset, of a model for dispersed clay against a model for structural clay. The second case evaluated three models against a large dataset of laboratory measurements in sandstones. The main conclusions are summarized below:

- A straight forward calibration of a rock physics model in a given cross plot domain, for example velocity-porosity, may not be sufficient to evaluate the success of the model.

- The IRPM strategy provides a way to assess the model capability of honouring up to three seismic observables, such as P- and S-wave velocities and density, simultaneously. In addition, the model predictions of PLF reservoir parameters can

be quantitatively compared by the evaluation. This provides a more robust analysis for addressing the suitability of a given model than any specific cross-plot domain.

- The IRPM strategy can also be used to obtain a sensitivity analysis of a particular rock physics model to its input parameters.

2.2 Paper 2: Modeling compaction effects on the elastic properties of clay-water composites.

Bernardo Moyano, Kyle T. Spikes, Tor Arne Johansen and Nazmul Haque Mondol.

Geophysics, vol. 77, No. 5, p. D171-D183 (Sep-Oct. 2012).

In this paper we modelled the elastic properties of a set of clay-water composites under mechanical compaction. The samples were composed of pure kaolinite, smectite and mixtures of them. We used differential effective medium theory (DEM), analysis of pores topology on SEM images together with estimations of critical porosity of the mono-mineralic composites, to reproduce the elastic measurements. The results of this study are summarized as follow:

- The monomineralic smectite sample contained randomly oriented pores with larger aspect ratios (α) than the pure kaolinite sample, which showed smaller aspect ratios with a noticeable preferential orientation. This was revealed by image analysis of SEM images from the compressed samples.

- DEM simulation with single pore shapes indicated that the bulk and shear moduli are controlled by different parts of the aspect ratio spectrum. The bulk modulus is controlled by fairly rounded pores (large α), whereas the shear modulus is more sensitive to elongated pores (small α). This suggested that the elasticity of the studied clay-water composites and probably of clay-bearing rocks is affected by pores at two different scales; i.e. large scale pores (interaggregate) visible with SEM images, and smaller pores similar in size and shape to the individual clay platelets.

- We found an analogy between the critical porosity concept, as used in the rock physics context, and the liquid limit (LL) of clay powders used in clay and soil science. This provided a way to estimate critical porosity from laboratory measurements of the liquid limit for different clay minerals. We used measurements of the liquid limit of the studied clay powders to calculate the critical porosity for kaolinite and smectite and the mixture of the two.

- The integration of the critical porosities, elastic properties of the critical phase, bimodal aspect ratio pore space and differential effective medium theory

reproduced well the observed elastic behaviour of the composites under compaction.

- Additionally, the modelling provided robust estimates of the elastic properties of smectite and kaolinite.

2.3 Paper 3: Diagnostics of seismic time lapse effects of sandstones: Based on laboratory data.

Bernardo Moyano, Tor Arne Johansen, Remy Agersborg, Kyle T. Spikes.

Submitted to Geophysics, 2013.

In this study we evaluated P- and S-wave velocity dispersion, attenuation, pressure and fluid effects for a set of siliciclastic rock samples. The dataset, extracted from literature, consisted of 63 samples of clean to highly heterogeneous sandstones on which velocity and attenuation measurements were collected at various pressure conditions. A visco-elastic rock physics model was used to consistently model the velocity and attenuation data. The main conclusions of this paper are summarized below:

- We observed that the sensitivity of velocity and attenuation to pressure variation in heterogeneous sandstones is larger than that seen for clean sandstones. This suggests that, for similar porosity and burial conditions, time-lapse pressure effects associated with the production of hydrocarbons are likely to be larger in heterogeneous reservoirs than in clean reservoirs.

- The dataset studied showed that Vp/Vs ratio is significantly correlated (inversely) with the content of quartz in comparison with all other petrophysical parameters.

- To mimic the observed pressure sensitivities of the velocity and attenuation using the visco-elastic model it was necessary to incorporate an amount of compliant pores proportional to the volume fraction of secondary minerals. Different pore sizes required different relaxation time constants to reproduce the observed velocity and attenuation data.

2.4 Paper 4: Spatial constrained inverse rock physics modelling.

Bernardo Moyano, Erling Hugo Jensen, Tor Arne Johansen.

In preparation to be submitted to Geophysical Prospecting, 2013.

In this paper we used spatial correlations present in predicted reservoir parameters, namely porosity, lithology and fluid saturation (PLF), to constrain the range of possible solutions provided by an inverse rock physics modelling procedure (IRPM). The workflow was applied to log data from the Glitne field in the North Sea. The main results of the study were:

- Spatial correlations along the depth axis can be used to constrain the range of solutions of the inverse rock physic modelling strategy. Hard data, provided from observations or a more restricted modelling, can further constrain the solutions range.

- Interrelations between the PLF parameters mean that reducing the range of solutions for one of them imply a reduction of solutions for the other parameters.

- Porosity showed larger spatial correlation than lithology and saturation. Hence, the range of possible solutions was mostly reduced by the saturation and lithology spatial constrains.

- The final model predictions compared well with the observed log data.

3 Conclusions

The overall objective of this thesis was to identify rock physics modelling strategies to consistently reproduce the elastic signature of heterogeneous reservoirs. During the study we compared models based on different arrangement of clay and quartz grains, such as pore-filling, laminated and structural clay. Even when pore-filling clay significantly affect porosity, we noticed that its effect on the elastic properties is substantial only at low clay concentration, for instance for the Yin's dataset (Yin, 1992) at clay content less than 10 %. When clay content exceed this value, it tends to disturb the rock frame, reduces its elastic properties and the effect becomes structural. The quantitative calibration performed by inverse rock physic modelling (IRPM) in paper 1 revealed the ambiguity of a diagnostic of rock microstructure when the rock physics model calibration is limited to a cross plot space of two arbitrary parameters. Moreover, it also emphasizes the need of a quantitative approach in cases when several models seem equally plausible. In the context of seismic inversion, where reservoir parameters such porosity, lithology and fluid saturation are estimated from seismic data, the IRPM strategy has the advantage that it attempts to honour the three seismic parameters (e.g. P- and S-wave velocity and density) simultaneously. Thus, through the intersection between iso-surfaces in the constraint cubes, it can reveal inconsistencies between the model predictions of P-wave and S-wave velocities or density.

The study of compacting clay-water composites, along with the analysis of pores textures on SEM images, suggested that kaolinite-rich rocks can be more anisotropic than smectite-rich rocks. The modelling also showed that a bimodal pore shape distribution may be necessary to reproduce consistently the bulk and shear signature of clay-bearing rocks. In addition, a method to estimate the critical porosity of clay mineral powders and their mixtures was found by an analogy with the liquid limit concept used in clay and soil science. This approach is relevant for the understanding of the elastic behaviour of unconsolidated clay-bearing rocks.

Finally, with the use of inclusions of various shapes and scales (i.e. equant, elongated and crack-like) into a visco-elastic model, we demonstrated that the velocity and attenuation responses of a wide range of heterogeneous sandstones can be well modelled. The model accounts for pressure and frequency dependency together with fluid effects. The study highlighted the critical role of compositional maturity, namely quartz abundance, in the rock texture and consequently in the pressure and fluid time-lapse signatures of siliciclastic reservoirs.

"Organizing libraries is a silent way of exerting the art of criticism."

Jorge Luis Borges.

Argentine writer (1899 - 1986)

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