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Use of forward stratigraphic modelling for the detection of sub-seismic scale heterogeneities in shallow marine environments

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Summary

Many stratigraphic features occur at a scale that is at the edge or below vertical seismic resolution. Thus, they cannot be directly observed in the seismic data, while still having an important effect on the fluid flow within the system. The better understanding of these sub-seismic scale features or heterogeneities can help decrease subsurface uncertainty. Here we present a novel method that integrates forward stratigraphic modelling, petrophysics, and geophysics to decipher the seismic imprint of heterogeneities in wave-dominated, shallow marine environments. The proposed three-stepped method starts with defining geology-related input parameters for BarSim, a stratigraphic forward modelling software that produces models that include stratigraphic architecture, grain size distribution, and facies distribution. Then, the geological data is translated, cell by cell, into petrophysical data (density, Vp, and Vs) using emphirical relationships. Finally, the forward seismic modelling is performed by combining a finite difference approach strategy and angle-dependent full wavefield migration to retrieve the angle gathers This method also allows the generation of large amounts of field-independent data suitable for machine learning applications.

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Introduction

The stratigraphic architecture of sedimentary successions depends on the sedimentological processes responsible for the deposition of the sediments and the structural processes that deformed them. Many features of the stratigraphic architecture occur at a scale that is at the edge or below vertical seismic resolution [e.g. Zeng et al. (2013); Jackson et al. (2019)]. Thus, they cannot be directly observed in the seismic data, while still having an important effect on the fluid flow within the system [e.g. Jackson et al. (2009)]. As a consequence, a certain degree of uncertainty is added to the seismic interpretation, hindering the subsurface characterisation workflow. These features, or heterogeneities can be discrete (baffles, barriers) or gradual changes in properties over certain spatial scale. For both cases, their analysis can benefit from the combination of seismic imaging and geologic prior knowledge obtained from modelling of geologic scenarios.

This study focuses on wave-dominated shallow marine systems, a highly variable depositional environment. Here, sub-seismic scale heterogeneities are associated with (1) the generation of erosional surfaces and stacking of contrasting facies, and (2) gradual property changes, including porosity [e.g. Sømme et al. (2008)]. There is a degree of predictability on such heterogeneities, thanks to the sedimentological knowledge on the processes that control their formation. Such knowledge is the basis for Forward Stratigraphic Modelling (FSM) tools, which use the physics behind the sedimentological processes to generate geological models.

The improved method we present is a combination of FSM and forward seismic modelling that will enable us to better interpret seismic data and to decrease subsurface uncertainty by allowing the potential connection between previously unclear features to stratigraphic heterogeneities. Previous work has shown positive results in improving stratigraphic interpretation for deep-water deposits [e.g. Jackson et al. (2019)] and clinoforms [e.g. Zeng et al. (2013)] at sub-seismic scale, based on specific outcrop analogues. Here, we propose a workflow integrating FSM and forward seismic modelling that could help provide a plethora of scenarios that are not analogue-based and that capture the variability of the depositional systems.

Methodology

This three-step methodology allows the generation of seismic data starting from geological data.

Step 1: Generation of geological models using forward stratigraphic modelling (FSM) tools

A series of 2D sections are created using the BarSim forward modelling software (Storms et al. 2002). The aim of creating the models is not to replicate the conditions of any outcrop analogue, but to generate possible and realistic scenarios. BarSim is an open-source, process-based modelling tool that models the long-term evolution and stratigraphic architecture of wave-dominated coastal systems. It is a two dimensional model based on a simple approximation of a cross-shore profile [e.g. Storms et al. (2005)]. BarSim uses highly parameterised physics. The modelling provides a compilation of equidimensional cells with, among other outputs, sedimentological (grain-size, facies) and architectural information at different scales.

Step 2: Translation of the geological output into petrophysical values

The next step is the realistic population of the grid cells from the FSM output with petrophysical parameter values, namely density, P-velocity, and S-velocity values. The empirical equations proposed by Eberhart-Phillips et al. (1989) have been used for obtaining P-velocity and S-velocity:

$$V_p = 5.77 - 6.94\phi - 1.73\sqrt{C} + 0.446\,(P_e - e^{-16.7P_e})$$
$$V_s = 3.70 - 4.94\phi - 1.57\sqrt{C} + 0.361(P_e - e^{-16.7P_e})$$

where ϕ is porosity (unitless), C is clay content (unitless), and P_e is effective pressure (kbar).

The clay content is directly obtained from the grain size distribution from BarSim's output. The effective pressure is user-defined. The porosity is calculated in a three-step process and under the assumption of rounded grains. Firstly, the sorting is calculated as a weighted standard deviation of the grain size distribution and a series of sorting intervals are defined based on Folk and Ward (1957). Secondly, considering the combination of sorting and mean grain size intervals, a value of porosity is assigned to each cell based on the values reported by Beard and Weyl (1973) for unconsolidated mixes. Lastly, a ratio of porosity reduction according to the effective pressure is applied to account for the porosity loss occurred after burial. The porosity value is also used for the calculation of the density, under the assumption of water-saturated porosity and quartz as the solid fraction.

To the density, *Vp* and *Vs* maps, overburden layers and a water layer are added. The user defines the thickness of the layers and the petrophysical parameters to populate them. The user has to remember to adjust the value of the effective pressure that is used to calculate the velocities and densities in accordance to the added overburden.

Step 3: Generation of angle gathers by the application of forward seismic modelling tools

In this stage, simplified geologic models were created by sampling the actual models from steps 1 and 2. The simplified models can imitate reality while preserving the important aspects of the system while being simple enough for a computer to produce the desired answers. Subsequently, the finite difference approach strategy was deployed (Kelley et al, 1976). Afterwards, an angle-dependent full wavefield migration was deployed to retrieve the angle gathers (Fomel, 2011).

Example

For this example, the starting input parameters for the FSM are the sediment supply and relative sea level curve depicted in Figure 1, modelling time of 35000 years, four grain size classes (5, 50, 125, and 250 µm) with a proportion of 25% each, and a grid size of 2 x 2 m.

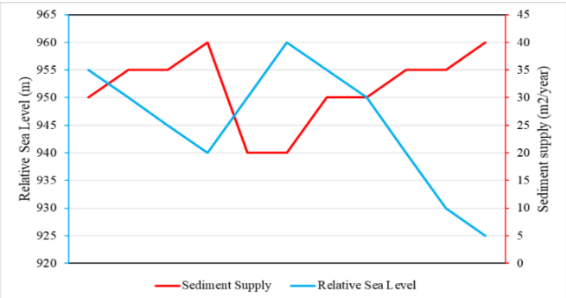

Figure 1 *Figure 1 shows the input values of the FSM tool BarSim for the relative sea level position and the sediment supply throughout the modelling time.*

From these input parameters, BarSim generates the mean grain size map (Fig. 2A), the facies distribution (Fig. 2B). From here, clay content and porosity values are obtained following the described methodology. Then, the petrophysical parameters can be calculated cell by cell, in particular density (Fig. 3A), P-velocity (Fig. 3C), and S-velocity (Fig. 3D). For comparison, the resulting density map for a model that only considers the facies distribution (Fig. 2B) is also included. The final step of the petrophysical translation includes the addition of a water layer and the overburden, both user-defined, to create the final input of the forward seismic modelling (Fig. 3E). From the velocity map depicted in Figure 3C, a simplified velocity model is created (Fig. 4A). After applying the finite difference and the angle-dependent full wave-field migration, the seismic response of the subsurface is obtained (Fig. 4B). Finally angle gathers are obtained in the Radon domain (Fig. 4C).

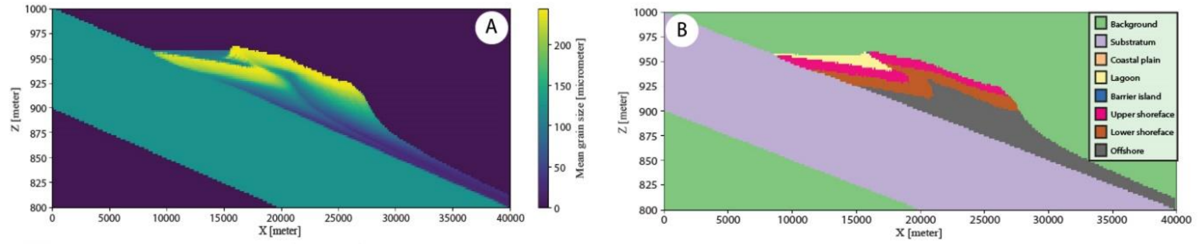

Figure 2 *Outputs from BarSim code for the input parameters in Figure 1. A.- Mean grain size (μm). B.- Facies.*

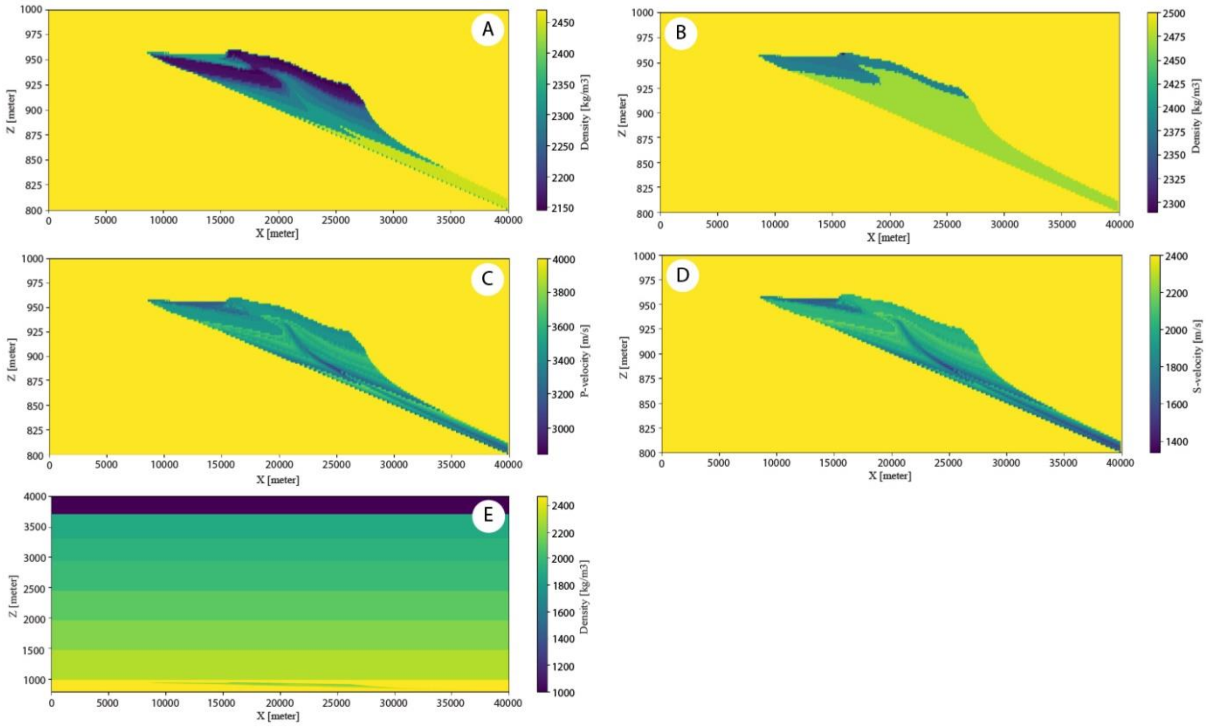

Figure 3 *Petrophysical properties maps resulting from the translation of the geological information in Figure 2. A.-Detailed density map (kg/m3). B.- Density map based on facies distribution, values from Feng et al. (2015). C.- P-velocity (m/s). D.- S-velocity (m/s). E.- Density map including overburden and water layer.*

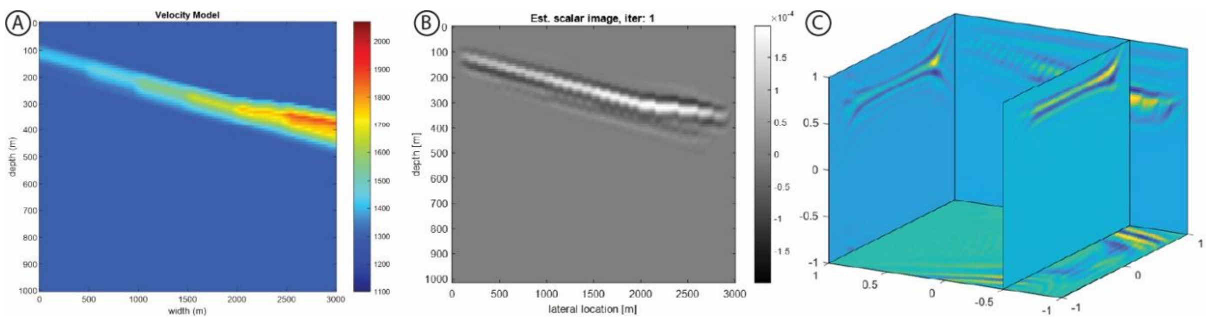

Figure 4 *Geophysical output from the modelling. A.- Simplified velocity model. B.- Subsurface image after deploying the imaging tools. C.- Radon gather information retrieved from Fig. 4B.*

Discussion and Conclusions

FSM allows the generation of realistic and detailed geological models that include stratigraphic heterogeneities at sub-seismic scale. This models are constructed based on the physics that control geological processes, without relying on outcrop analogue data. The present methodology allows to keep the sub-seismic scale heterogeneities in the forward seismic modelling by translating, cell by cell, the geological information into petrophysical properties. Traditionally one value of petrophysical properties has been applied per facies, reducing the amount of detail contained within the facies and ignoring features that might have an impact on the fluid flow.

There are two main benefits. First, the geological modelling is independent of the information gathered from outcrop analogues, making the whole process general and not specific for a certain system. Secondly, large amounts of models and data can be produced, independent from outcrop data, focused on the seismic response of the heterogeneities. This data can be used as input for training of machine learning algorithms and, for the automation of sub-seismic scale heterogeneity detection.

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