From 3D Photogrammetric Outcrop Models to Reservoir Models: An Integrated Modelling Workflow*

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Abstract

In recent years, the interest for digital outcrop models (DOM) in reservoir analogue studies has constantly increased. Photogrammetry has been successfully tested and then optimized by IFPEN to fit with the inherent constraints of field acquisition. The 3D geomodels that are reconstructed can be used at the reservoir scale, in order to compare the outcrop information with subsurface models: the detailed facies models of the outcrops are transferred into petrophysical and petro- acoustic models, which are used to test different scenarios of seismic (1D convolution or full wave modelling) and fluid flow modelling (well test or full field reservoir simulation). The detailed 3D models are also used to test new techniques of reservoir modelling, based either on geostatistical approaches or on deterministic (process-based) simulation techniques.

Introduction

3D technologies are now widely used in geosciences to reconstruct outcrops in 3D. The technology used for 3D reconstruction is usually based on Lidar (Laser Imaging, Detection and Ranging), which provides very precise models. Such datasets offer the possibility of building well-constrained outcrop analogue models for reservoir study purposes (Hodgetts, 2013) or for the survey of natural hazards (Jaboyedoff et al., 2012).

Photogrammetry is an alternate methodology, the principles of which are based on determining the geometric properties of an object from photographic pictures of this object taken from different angles. Outcrop data acquisition using terrestrial or airborne photo capture is easy (Figure 1), and this methodology allows 3D outcrop models to be constructed with many advantages such as fast acquisition (a few minutes to a few hours), with moderate processing time (depending on the size of the area of interest), integration of field data and 3D outcrop data into the reservoir modelling tools.

Whatever the method, the advantages of digital outcrop models are numerous, as already highlighted by Hodgetts (2013), McCaffrey et al. (2005) and Pringle et al. (2006): collection of data from otherwise inaccessible areas, access to different angles of view, increase of the possible measurements, attribute analysis, fast data collection and of course training and communication.

One important area of applications of such models and of their interpretations is reservoir modelling, and specially geostatistical approaches (Fabuel-Perez et al., 2010; Rarity et al., 2007), because the outcrop models can provide realistic values for parameters (variograms, probability laws, objects statistics, etc.) or training images for multipoint statistics. Outcrop data can also be used as a basis for synthetic seismic and fluid flow modelling or to provide large and robust datasets for DFN modelling, for example.

Workflow

This article proposes a workflow (Figure 2) where 3D geocellular models are built by integrating all sources of information from the outcrops (surface picking, sedimentological sections, structural and sedimentary dips, on- and behind-the-outcrop coring and logging when available).

Data Acquisition

The realisation of a DOM using the photogrammetric method involves the acquisition of the following dataset:

- The most accurate geolocalisation of the picture shooting points.
- Several couples of images of the same object, shot from different viewpoints, with a good overlap between continuous pictures.

IFPEN tested both classical ground acquisition and aerial acquisition with a SUAV (Small Unmanned Air Vehicle) in this case study. These two acquisition techniques are complementary, and the pictures can be mixed together in order to construct the whole outcrop in 3D, taking advantage of a complete view (aerial acquisition) and a very high resolution (ground acquisition).

3D Model Construction

The 3D model is reconstructed thanks to an algorithm that manages almost everything in the computation process. This algorithm automatically detects the identical pixels in the various pictures from the same part of the outcrops, but taken at different referenced locations, and reconstructs the 3D shape of the outcrop. The calculation time depends on the number of pictures, but a few hours are usually needed for models that require about 200 pictures. The model resolution depends on three factors: the pixel size, the focal length, and the distance to the object.

3D Model Interpretation

The main purpose of a DOM acquisition is the possibility to interpret the modelled outcrop. To reach this goal, IFPEN has designed a software which enables all the field measurements and interpretations to be integrated in the DOM.

This software allows horizon picking (bedding, faults, fractures) as well as property painting (facies, petrophysics,…) and measurement of geo-bodies (size, dips…), which can be exported as constraints in modelling tools.

From 3D Outcrop to Reservoir Model

A reservoir model was thus constructed by using all the geological features interpreted on the 3D outcrop, calibrated on the dataset directly observed and measured on the real outcrop.

Surface model and reservoir geometry were constructed from polylines directly digitized on the 3D outcrop, which separate the different units to be simulated with ad-hoc simulation parameters. These polylines were exported in a geomodelling tool and were used to build the surface model. The properties (mainly facies) the model is filled with derive directly from the outcrop interpretation and logging on the field. Facies were directly painted on the 3D outcrop model, and exported as properties in the gridded model.

Case Study

In deep offshore clastic environments, turbidite systems can constitute productive oil and gas reservoirs. In these reservoirs the description of small-scale heterogeneities is important to improve reservoir simulation and hydrocarbon production because they can have a major impact on the fluid flow behaviour (permeability barriers). Unfortunately these heterogeneities are usually below seismic resolution and difficult to reconstruct deterministically because of the limited number of wells in deep offshore. Analogue outcrops are used to better characterize these heterogeneities; synthetic seismic and fluid flow modelling of these outcrops gives a better understanding of the link between interpreted seismic data and sedimentological bodies and enables us to identify the impact of the heterogeneities on the fluid recovery.

A modelling workflow was designed from 3D outcrop modelling to reservoir modelling, including geostatistical modelling, seismic modelling and fluid flow simulations. We illustrate this workflow on a well known turbidite reservoir analogue in Northern Spain (the Ainsa-1 quarry outcrop).

The Ainsa-1 Quarry Outcrop (Spain)

The Ainsa turbidite system is located in the South-central Pyrenean foreland basin in North- Eastern Spain and has been studied since 1977. Published studies have presented seismic model- ling works and interpretation based on a description of the Ainsa-2 channel outcrop and has compared the simulated synthetic seismic images with real seismic traces of offshore Angola turbidite systems (Bakke et al., 2008). The Ainsa-1 outcrop has been used to test various techniques of facies modelling and their impact on recovery efficiency (Falivene et al., 2006), but until now there has been no published integrated study linking facies, petrophysics, seismic and fluid flow modelling.

To build our geological model, we used a recently published characterization study of the Ainsa-1 quarry outcrop (Arbués et al., 2007). The study area is a section up to 42 m thick, 750 m wide and oriented 160°-340° N, oblique to the mean paleoflow estimated around 290° N. The (x,y,z) size of the modelling area is 960 m by 1050 m by 50 m.

Surface Modelling

The Ainsa-1 turbidite system is subdivided into three cycles of channel-complex development and abandonment (C1, C2 and C3). Channel complexes are composed of closely stacked channel forms several tens of meters thick. Based on geological interpretation of both the field observations and the photogrammetric model, the outcrop section was divided into six sedimentary zones by seven bounding horizons. The generated zones are: channel-form set C1, which is located at the lowest part of the outcrop, the middle, lower and upper packages of channel-form C2.1, channel- form C2.2 and channel-form set C3.

The bounding horizons were directly picked on the 3D outcrop photogrammetric model as polylines (Figure 3) that were imported into the SKUA™ geomodelling tool (Figure 4). The horizon surfaces were reconstructed in SKUA™ using these polylines and structural dips measured both on the field and on the photogrammetric model.

A modelling grid was defined for each sedimentary zone by considering the nature of its bounding horizons (erosive or concordant top and bottom).

Facies Modelling

Using the Arbués et al. (2007) classification, five different lithofacies were discriminated:

- gravelly mudstone debrite (1, blue),
- sandy conglomerate (2, red),
- mudstone-clast conglomerate (3, orange),
- thick-bedded sandstone (4, yellow) and
- heterolithics (5, green) i.e. alternating cm-thick mudstone and sandstone beds.

The facies of the sedimentological sections measured on the field were directly painted on the 3D outcrop photogrammetric model at their exact locations (Figure 5). Each point set of the sedimentological section was imported with its facies code in the SKUA™ grid and used as a constraint to populate the grid using geostatistical techniques (Truncated Gaussian). The modelling result can be displayed on the outcrop face in order to check the quality of the reconstruction (Figure 6).

This facies modelling was also done in the PET- REL™ and CobraFlow™ geomodellers using the Sequential Indicator Simulation method in order to compare the two geomodelling approaches (Figure 7).

Seismic Modelling

The 3D facies model was transferred into a petrophysical model by assigning, to each facies, velocity, density and Ip and Is impedance values derived from deep offshore fields (Table 1).

Then a zero offset P_reflectivity cube (Figure 8) was calculated from these assigned impedances and various synthetic seismic cubes were obtained after1D convolution of the reflectivity with different Ricker wavelets (50, 80 and 100 Hz). These data and a set of seismic attributes, such as impedances estimated by stratigraphic inversion, were used in order to improve the seismic interpretation of such turbidite channels in the subsurface (Jardin et al., 2010).

More advanced seismic modelling techniques such as 3D full wave modelling can also be used to obtain more realistic results taking into account the 3D effects (Bourgeois et al., 2004).

Fluid Flow Modelling

The 3D facies model was converted into a petrophysical model by assigning porosity and permeability parameters to each facies (Table 1). An initial oil saturation of 0.2 was imposed for each facies.

The two-phase fluid flow simulation was achieved using an injection production in a quarter five-spot configuration, using PumaFlow™ (Figure 9). The producer and injector wells are located in opposite corners of the Ainsa-1 reservoir model. The water/oil rates are maintained constant.

Conclusion

In this article, we have presented an integrated reservoir characterization and modelling approach for the study of outcrop reservoir analogues. Based on 3D photogrammetric data and sedimentological sections, the workflow comprises the same steps as a subsurface reservoir study: horizon picking, facies interpretation, reservoir grid building, geostatistical modelling of reservoir properties, synthetic seismic modelling, and fluid- flow simulation. 3D Digital Outcrop Models are a precious input for subsurface reservoir characterization and modelling. DOM can also be of the highest interest in methodological studies on property modelling. Last, but not least, DOM provide valuable realistic material for teaching geosciences. All steps require several industrial or prototype software. Further work will concentrate on this aspect for a fully integrated workflow.

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Figure 1. Photogrammetry acquisition devices.

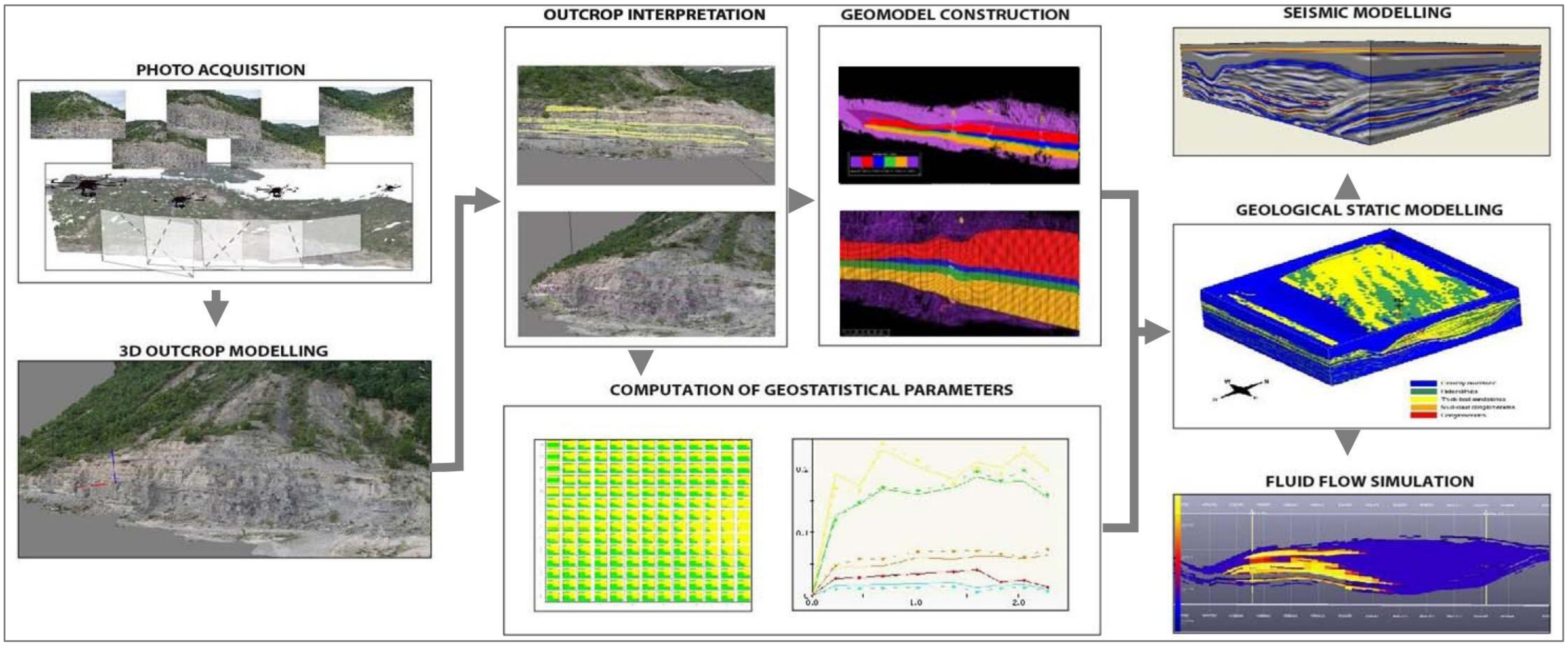

Figure 2. Description of the workflow.

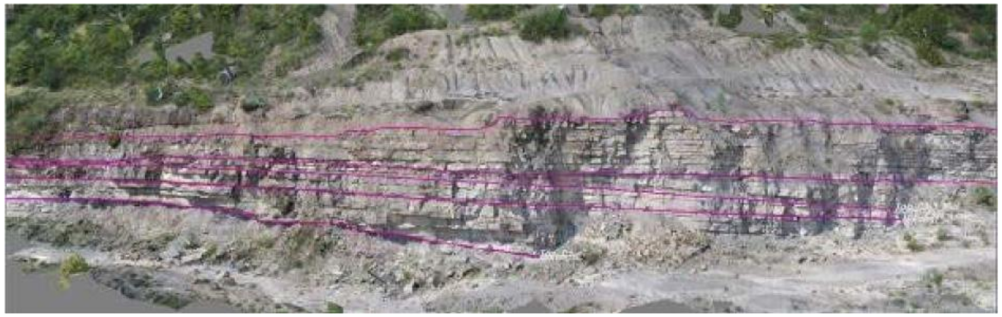

Figure 3. Horizon picking on the 3D image.

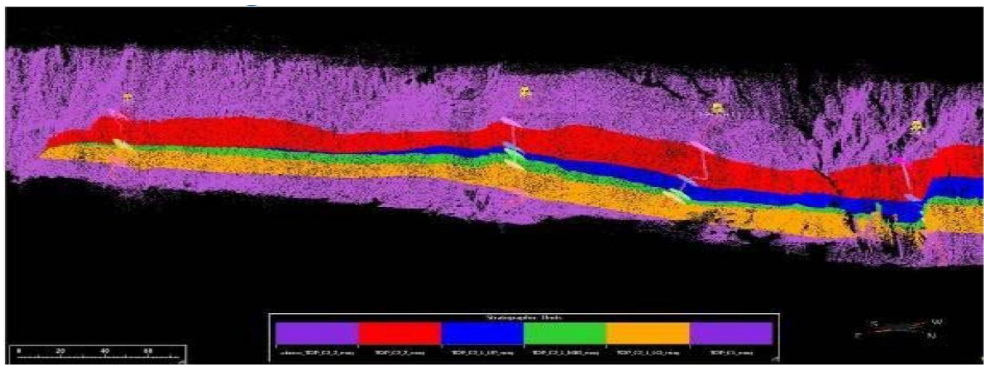

Figure 4. Sedimentary zones in SKUA™.

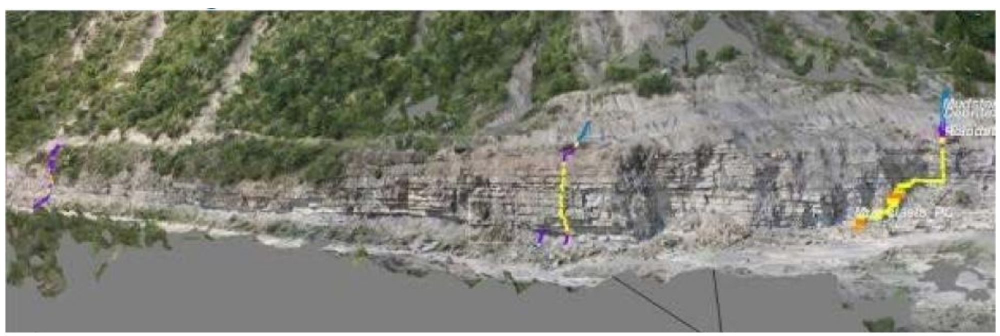

Figure 5. Sedimentological sections.

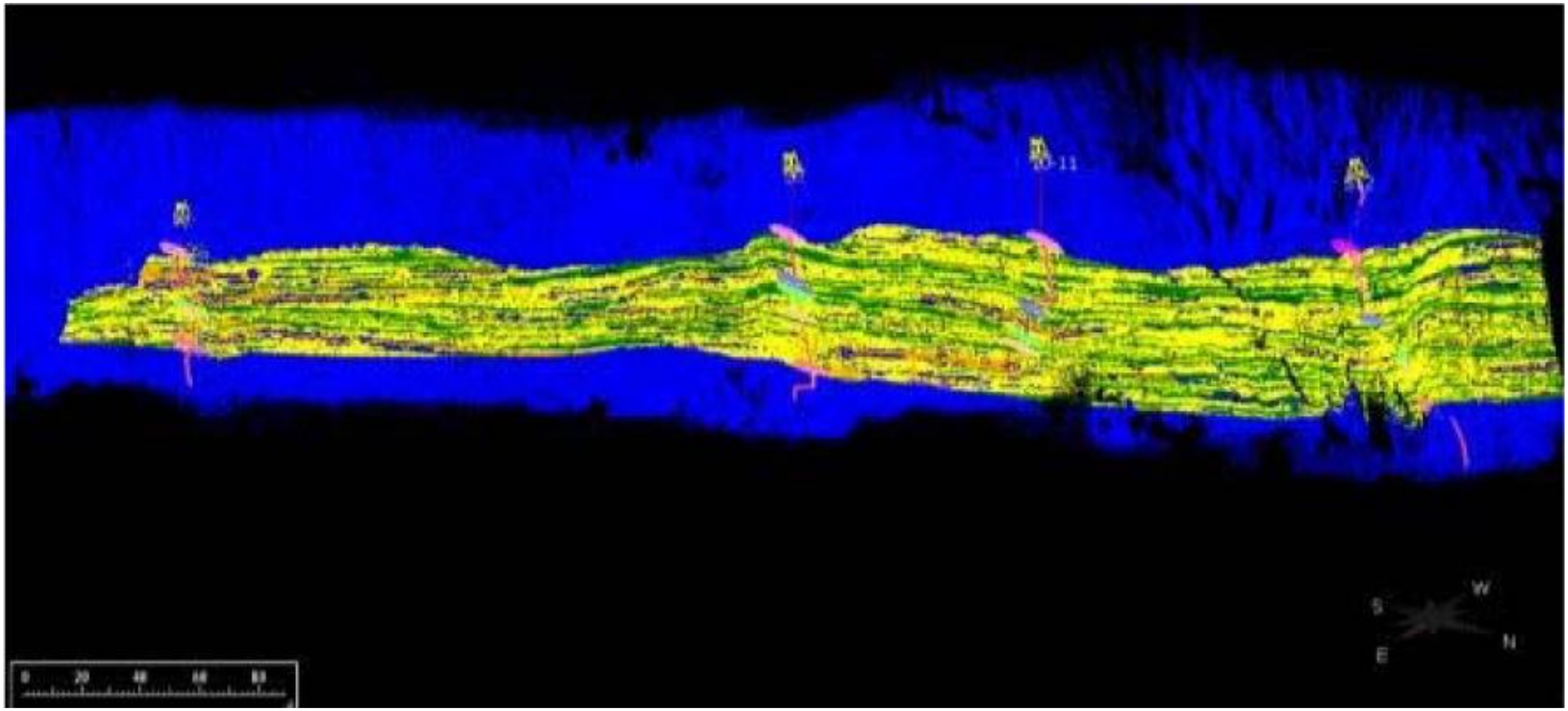

Figure 6. Simulation of the facies distribution in SKUA™.

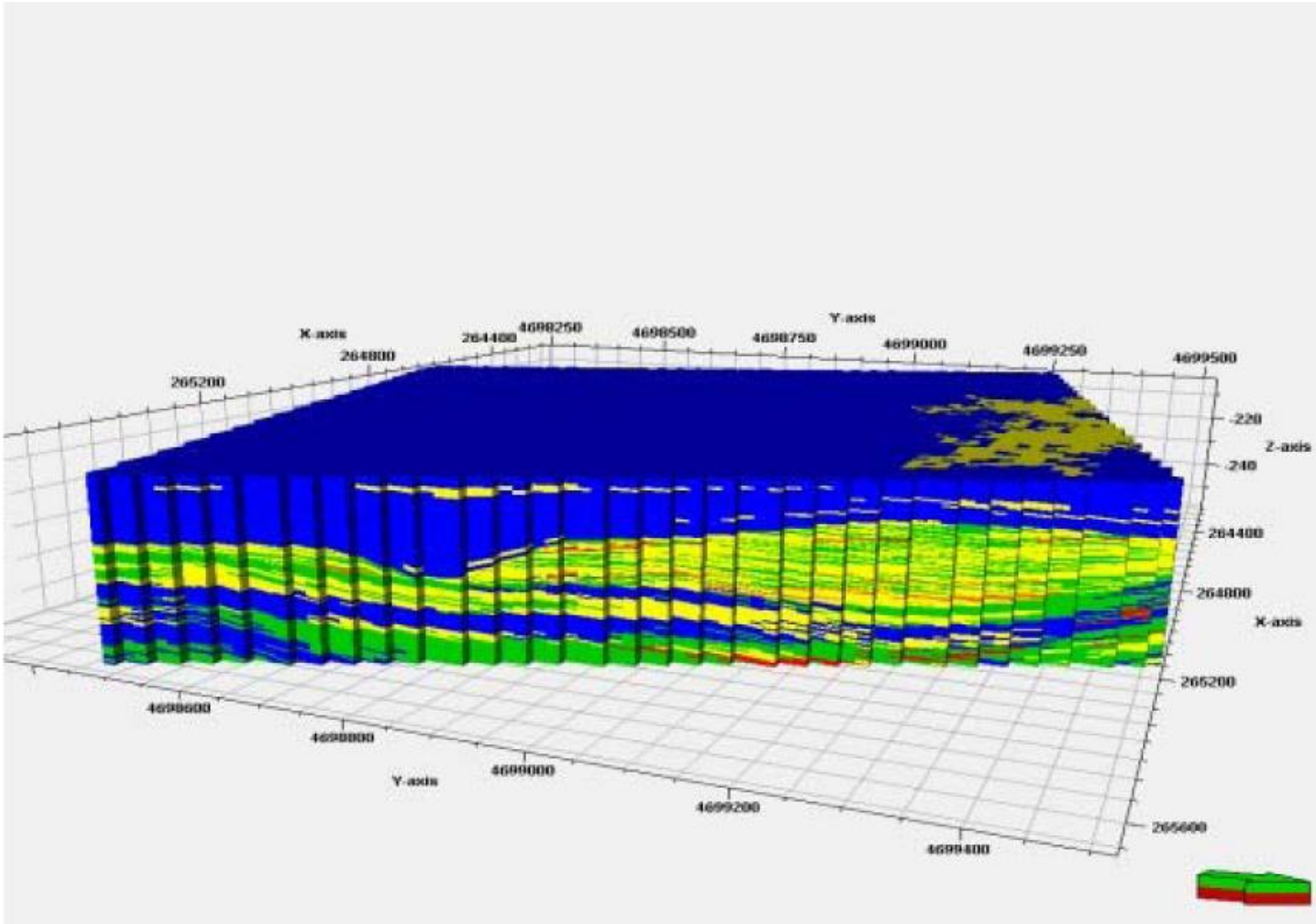

Figure 7. PETREL™ 3D facies model.

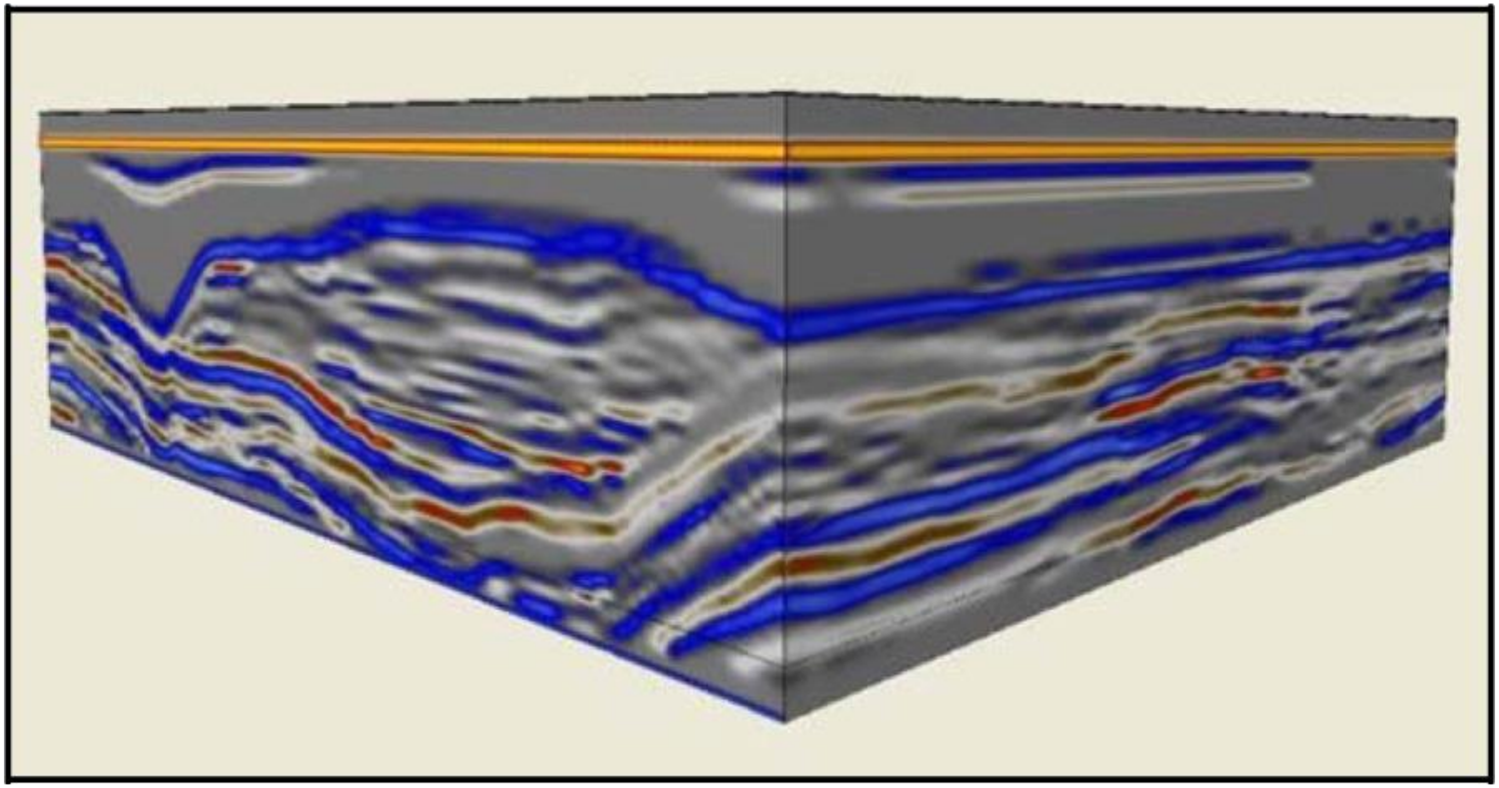

Figure 8. 3D reflectivity cube.

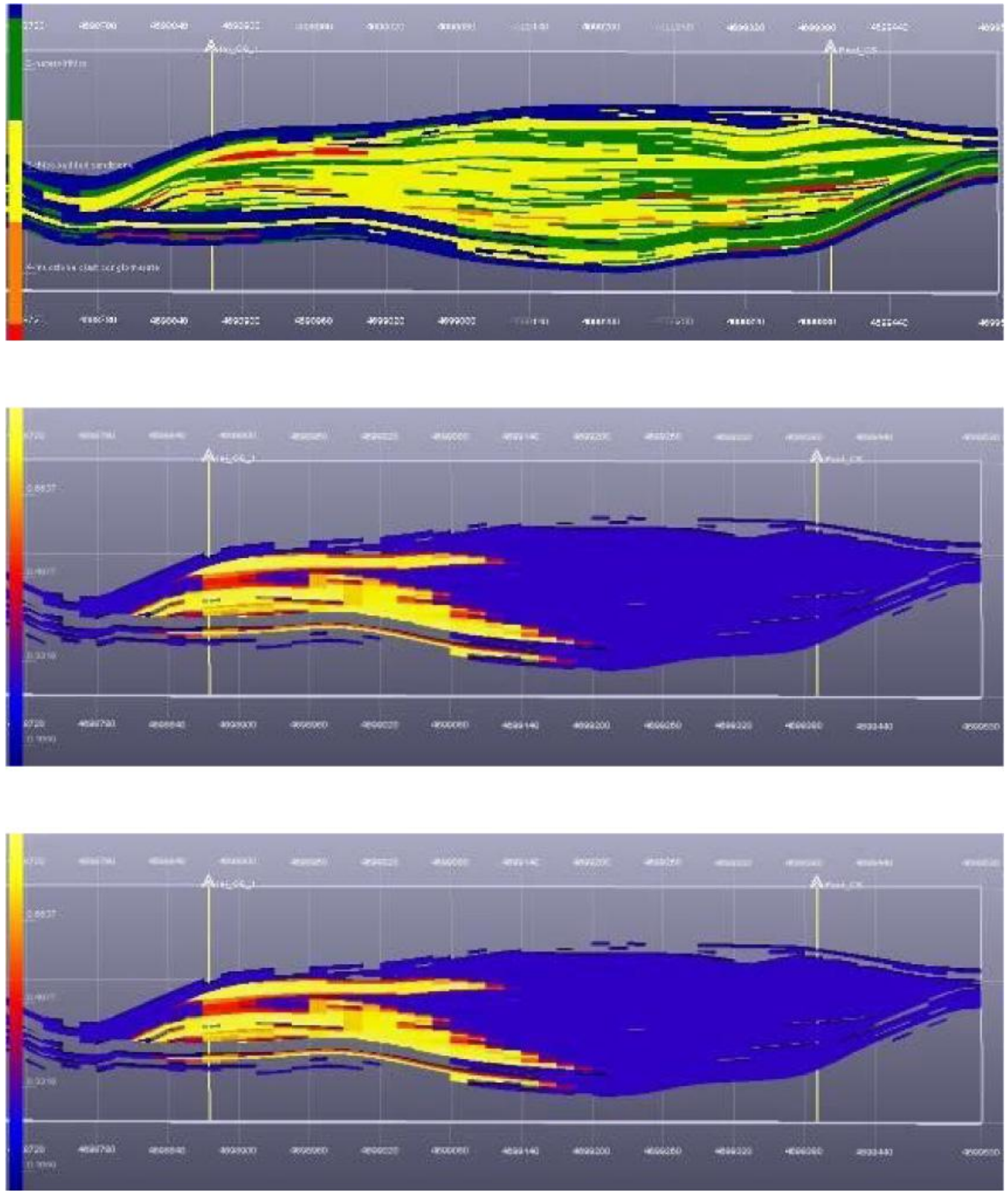

Figure 9. Fluid flow simulation results. Top: facies in CobraFlow™; Middle: after 2 years of water in jection in PumaFlow™; Bottom: after 3.5 years (water breakthrough at the producer well).

Code	Facies	Vp (m/s)	Vs (m/s)	RHOB (g/cm3)	Ip (g/cm3 m/s)	Is (g/cm3 m/s)	PHI (%)	Kh (mD)	Kv (mD)
1	Gravelly mudstone debrite	2350	1000	2.28	5358	2280	0	0	0
2	Heterolithics	2240	1030	2.16	4838	2225	5	40	0.04
3	Thick-bedded sandstone	2200	1100	2.07	4554	2277	30	2000	200
4	Mudstone-clast conglomerate	2480	1300	2.3	5704	2990	15	500	50
5	Sandy conglomerate	2400	1300	2.2	5280	2860	25	2000	200

Table 1. Petrophysical and acoustic parameters attributed to each sedimentological facies.