Turbidites Characterization from Seismic Stratigraphy Analysis: Application to the Netherlands Offshore F3 Block*

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Abstract

The generation of geological models (stratigraphic, structural and paleo-environmental) that allow the localization of sand bodies such as turbidites and submarine channels is nowadays one of the most useful tools used by geoscientists for the generation of new drilling opportunities to increase production. Now, using methods such as sequence stratigraphy, geometrical and stratigraphic seismic attributes linked to well log and core information define the basis for the interpretation of both lithostratigraphy and chronostratigraphy of sand bodies. Similarly, these models allow the interpreter to reconstruct the depositional environment and deformation history. This article shows the chronostratigraphic stages proposed for the Netherlands Offshore F3 Block which are based on the termination of reflectors and seismic facies. Also, a set of system tracts such as TST, HST, FSST and LST were identified corresponding to the transgression and regression phases in the basin. The available dataset provided the information to identify the geometry and changes in the sedimentation patterns of the stratigraphic sequences from the Miocene to the present, defining a 3D model of the sedimentological and structural architecture of this area. Last but not least, based on the stratigraphic model previously defined, a 3D model of the main sand bodies derived from submarine channels and fluvio-deltaic setting was generated.

Introduction

Sequence stratigraphy is considered a revolutionary paradigm in the field of sedimentary geology (Catuneanu, 2006). From the beginning, this discipline generated controversy and long arguments among geoscientist trying to define the conceptual basis of this technique. In this context, throughout history several models have been proposed in an effort to best explain and reconstruct the depositional environment of an area of interest (Donovan, 2001), as it is shown in Figure 1. Now, the different point of view of the authors listed in Figure 1 generated variations on the original depositional sequence model theme proposed by Vail (1977), which resulted in several publications of slightly modified versions (Figure 2). For this particular application the sequence model found under the Depositional Sequence IV in Figure 2 will be followed to generate all the sequence stratigraphic analysis and to build system tracts model.

Extended exploratory projects have remarkably improved the understanding of offshore basins such as the North Sea (Back et al., 2011), which have been explored over the past few decades in order to find the most profitable plays. Recently, many techniques for both geophysical and geological interpretation of seismic and well log data have been generated (Chopra, 2008; Catuneanu, 2006.), which have allowed geoscientist the identification of key features that can lead to the discovery of new fields. Now, by using these techniques both seismic and well log information can be converted to the basic input data to generate a reliable geological model of the subsurface. Nevertheless, despite all the information that can be obtained by using these interpretation techniques, using them separately diminish their potential. Rather than using them separately, it is recommended to combine them with classical methods of geological interpretation such as core analysis, outcrop analogs and regional geological knowledge (Brouwer, 2008).

The scope of this article is to show how the integration of different advanced techniques of geological and geophysical data interpretation led to the generation of a robust sequence stratigraphy model that accounts for the characterization of the turbidites found in the F3 Block North Sea prograding Tertiary delta complex.

Data and Methodology

The principal data of this study is a high-quality 3D PSTM from the block F3, located in the North Sea Offshore of Netherlands (Figure 3, left) presenting relevant large-scale sigmoidal bedding. The dataset consists of seven wells with the right well logs for the application, core and cuttings description, time to depth tables for the seismic well tie process and the seismic volume mentioned before (Figure 3, right). Figure 4 shows the workflow applied to the dataset to get the final model. All steps and partial results are illustrated and briefly described in the following sections. It is worth mentioning that both the seismic survey and well information in the interval related to this study do not have any importance for hydrocarbon exploration. Nevertheless, this methodology may be applied to an analog survey that shows similar geological features where it might be suitable for play definition.

Regional Geological Setting

The study area is located in the North Sea in part of the offshore of Netherlands (Figure 5). The basic structural framework of the North Sea is mainly the result of extensional tectonics due to a failed rifting during the Latest Jurassic and Earliest Cretaceous and are fundamental to the understanding of oil and gas traps in the North Sea (Brooks, 1987; Pegrum, 1990). According to these events, the geological setting is subdivided into three parts with respect to the main episode of rifting (Gautier, 2005). The first episode marked is by events and processes prior to rifting (pre-rift). Those events and processes that took place during the rifting event are called syn-rift and the depositional processes and structural events subsequent to the Late Jurassic/Earliest Cretaceous are considered post-rift.

Rifting in the North Sea had largely ceased by the end of Early Cretaceous time (Ziegler, 1990). Steep geothermal gradients associated with the extensional tectonics decayed, and the regional pattern became one of gradual cooling and associated subsidence, especially near the axis of the abandoned rift where post-rift sediments accumulated to their greatest thickness. Late Cretaceous to Earliest Paleocene post-rift rocks are dominated by fine-grained pelagic carbonates (chalks) (Hancock, 1975). The Tertiary sedimentary sequences are mainly marine mudstones with locally significant submarine fans. Fans deposited during the Paleocene and Eocene are particularly significant (Reynolds, 1994).

Subsidence and sedimentation have continued in many areas throughout the Tertiary and Quaternary. The great isostatic differences resulting from erosion of uplifted blocks and accompanying rapid sedimentation in sub-basins and half-graben probably initiated salt tectonics in the Central Graben (Bain, 1993).

Well Logs Interpretation

Following the workflow illustrated in Figure 4, the processing of data was started with well log data interpretation. Figure 6 illustrates the available well log and sample (core and cuttings) description for one of the correlation wells. This information was used along with the implementation of methodologies such as Vshale interpretation and neural net classification to obtain a 1D facies model that best described the stratigraphic column analyzed in the study area. By using neural networks one can associate as many well log properties as there are available, thus finding clusters of points in a crossplot that share similar ranges of the rock properties used as input data. Therefore, one of the clusters defined during the application of neural network in classification mode would represent a specific rock type with a given range of porosity, shale fraction, resistivity, density, P-wave and S-wave velocity, photoelectric factor, etc. Using this methodology for rock type classification would let the interpreter differentiate an unconsolidated sandstone from a low porosity sandstone, which is crucial when performing reservoir characterization. Additionally, the classification of different types of claystone may also be performed by applying neural networks in classification mode. However, it is highly recommended to use stratigraphic columns generated from the description of core and cuttings samples as input data to calibrate all of the interpretations of litho-types made from neural networks or any other methodology.

Figure 7 shows the resulting crossplot of the facies modeling and Figure 8 is a corresponding profile for one of the correlation wells calibrated with the litho-types found in the stratigraphic study performed in that well. Once the 1D facies model was defined, sedimentary environment interpretations from Electrofacies and seismic-well tie processes were performed in order to have all of the possible information from the wells to calibrate the 3D geological model.

Seismic Image Conditioning and Input Data for Sequence Stratigraphic Interpretation

Right after performing the seismic-well tie process, the interpretation of the 3D seismic data started by conditioning the seismic image. This process included relative dip reflector interpretation and the enhancement of both reflectors continuity and faults. Based on the reflector dip attribute called Dip Steering (which was calculated using Opendtect) a set of about 1400 horizons were tracked which follow nicely the reflectors and therefore represent time lines that will be used in the following steps. It is worth mentioning that these horizons are truncated if they approach each other up to a certain distance defined by the interpreter, therefore making even easier the interpretation of stratigraphic features such as subaerial unconformities.

This 3D horizons framework along with time attributes such as the variation of thickness calculated from the horizons framework allows the assessment definition of time attributes of bounding surfaces. Using the 3D horizons framework and the bounding surfaces defined from this last dataset a Wheeler diagram was then built, which led to the interpretation of the system tracts. In this context, both the conditioned seismic data and the 3D horizons framework were flattened using the Wheeler transform, in which time slices are equivalent to chrono-stratigraphic horizons. In these time slices it is possible to interpret the paleo-geomorphology of the entire seismic volume and identify stratigraphic features

such as erosional events, non-depositional hiatuses (De Bruin et al., 2006), submarine channels, debris flows and most importantly turbidites. Figure 9 illustrates the conditioned seismic image and the corresponding 3D horizons framework for an Inline of the seismic survey. One may see on this Inline the prograding delta deposited during the Late Miocene and Pliocene (Archard, 1987), which is nicely followed by the horizons framework generated in this study.

Sequence Stratigraphic Interpretation

In this context, based on the horizons framework and the reflectors terminations associated with them a complete set of stratigraphic surfaces was defined which were later used to interpret the systems tracts (Figure 10). From Figure 10 it can be seen from bottom to top that the segment bounded by the light blue and the first light green surface shows retrograding para-sequence which can also be seen in the Wheeler domain (Figure 11). Based on the para-sequences, reflectors terminations and Electrofacies defined in the correlation wells, this interval was interpreted as a Transgressive System Tract [TST] (Figure 12) and therefore the light green surface represents the end of the transgression and so a maximum flooding surface [MFS]. The next package corresponds to a set of very steep prograding clinoforms that downlap the maximum flooding surface and present the typical toplap reflectors terminations of a normal regression of the coastline preceded by a transgression. According to the para-sequences and all the features listed before, this package is interpreted as a Highstand System Tract [HST] (Figure 12). This package is bounded at the bottom by the maximum flooding surface and at the top by both the subaerial unconformity [SU] and the basal surface of forced regression [BSFR] (Figure 10 and Figure 12).

Going forward, the following package is characterized by offlap reflectors terminations of a prograding set of clinoforms overlying the concave up BSFR. One can see that the clinoforms that overly the BSFR have a clear trend of decreasing height seaward and are commonly found as products of the early stages of a forced regression of the coastline. These prograding clinoforms are then overlaid by a set of reflectors with onlap termination, which are one of the particular products of the late stage of a forced regression of the coastline. This package was interpreted as a Falling Stage System Tract [FSST] and is bounded at the bottom by the BSFR and at the top by the last part of the SU and the Correlative Conformity [CC] (Figure 12).

The next package consists of a set of reflectors that exhibit prograding and aggrading para-sequences, which combined result in a normal regression of the coastline that according to the Depositional Sequence IV proposed by Hunt and Tucker (1992, 1995) is characteristic of a Lowstand System Tract [LST]. This fact is an indicator of two important changes in the base level which are the end of base level fall and the beginning of the base level rise. During the early stages of base level rise the accommodation space is utterly consumed by the sedimentation rate thus creating a regression of the coastline and aggradation of fluvial and nearshore facies.

Now, in this particular case the LST is not followed by a transgression as in a normal base-level cycle. It can be seen in the Wheeler domain (Figure 11) that the clinoforms start prograding again instead of retrograding and attached to the surface that indicates the onset of progradation of the clinoforms one can find truncation and offlap reflectors terminations, which means that the base-level is falling again. This package was interpreted as a FSST based on the characterization mentioned before followed by a normal regression marked by a LST (Figure 11 and Figure 12). The last package interpreted in this section corresponds to a retrograding set with onlap reflectors terminations and a particular convex shape. Based on the description previously listed this package was interpreted as a TST.

Turbidites Geobodies Extraction

Based on not only the 3D horizons framework generated from the seismic data but also the 3D systems tracts interpreted, it was possible to extract the geobodies that represent the turbidite deposits that were generated during the FSST and subsequently preserved (Catuneanu, 2006). The main turbidites geobodies interpreted were found right after the last prograding off-lapping lobe where, according to Catuneanu (2006), it is most likely to find high density turbidite deposits associated with mounded geometries. Figure 13 illustrates the two horizons used to extract one of the geobodies interpreted as a turbidite. The main input used to interpret all of the 3D model of the turbidite (Figure 14) were the 3D horizons framework, a thickness attribute estimated from the 3D horizons framework and the geometric attributes estimated during the seismic image conditioning phase. This particular turbidite corresponds to a high density turbidite deposit (Catuneanu, 2006) which most distal package was drilled by some of the correlation wells as it can be observed in Figure 15 where the gamma ray log clearly decreases once it reaches the top of the turbidite body.

It is then concluded that the distal portion of this turbidite has a lower sand-to-mud ratio, whereas the proximal portion has a higher sand-to-mud ratio. This conclusion is of paramount importance when designing an exploration strategy, since this body is overlying a MFS, which might represent a potential source rock and it is overlain by the late stage of a FSST that might have generated a potential seal layer. This interpretation has significant impact when defining a new play in a basin that is just being explored.

Conclusions

The definition of a 1D litho-types model using neural networks has proven to be a suitable method which has to be calibrated using core descriptions and sedimentological models built for the interval of interest. The generation of a 3D horizons framework based on the reflector dip is of paramount importance for seismic stratigraphy analysis, since it provides the main input data for the Wheeler transform.

Defining stratigraphic features such as reflectors terminations, boundary surfaces and electrofacies allows one to accurately interpret the depositional environment of an interval. The integrated interpretation of geological information (seismic, well log, drilling core and regional geology) presented in this article shows the relevance of using different sources of information to utterly understand the area of interest and properly define exploration strategies.

Selected References

Archard, G., 1987, Offshore Netherlands single well non-exclusive studies, Report No. 2, The Stratigraphy of the NAM F/2-1 Well.

Back, S., H. Gent, L. Reuning, J. Grötsch, J. Nierderau, and P. Kukla, 2011, 3D seismic geomorphology and sedimentology of the Chalk Group, Southern Danish North Sea: Journal of the Geological Society, London, v. 168, p. 393-405.

Bain, J.S., 1993, Historical overview of exploration of Tertiary plays in the U.K. North Sea, *in* J.R. Parker, ed., Petroleum geology of Northwest Europe, Proceedings of the 4th conference: London, Geological Society, p. 5-14.

Brooks, Jim, and K.W. Glennie, 1987, Petroleum geology of North-West Europe, in two volumes: London, Graham & Trotman, 1219 p.

Brouwer, F., G. Bruin, P. Groot, and D. Connolly, 2008, Interpretation of seismic data in the Wheeler Domain: Integration with well logs, regional geology and analogs: SEG Annual Meeting, Las Vegas.

Catuneanu, O., 2006, Principles of Sequence Stratigraphy, First Edition, Elsevier, Amsterdam, 375 p.

Chopra, S., and K. Marfurt, 2008, Emerging and future trends in seismic attributes: The Leading Edge, v. 27, p. 298-318.

De Bruin, G., H. Ligtenberg, N. Hemstra, and K. Tingdahl, 2006, Synchronized sequence stratigraphic interpretation in the structural and chrono-stratigraphic (Wheeler transformed) domain: EAGE Research workshop, Grenoble.

Gautier, Donald L., 2005, Kimmeridgian shales total petroleum system of the North Sea Graben Province: U.S. Geological Survey Bulletin, 2204-C, 24 p.

Hancock, J.M., and P.A. Scholle, 1975, Chalk of the North Sea, in A.W. Woodland, ed., Petroleum and the continental shelf of Northwest Europe, volume 1, Geology, Barking, Applied Science Publishers, p. 413-427.

Hunt, D., and M.E. Tucker, 1992, Stranded parasequences and the forced regressive wedge systems tract: Deposition during base-level fall: Sedimentary Geology, v. 81, p. 1-9.

Hunt, D., and M.E. Tucker, 1995, Stranded parasequences and the forced regressive wedge systems tract: Deposition during base-level fall, Reply: Sedimentary Geology, v. 95, p. 147-160.

Pegrum, R.M., and A.M. Spencer, 1990, Hydrocarbon plays of the northern North Sea, in Jim Brooks, ed., 1990, Classic petroleum provinces: Geological Society, London, Special Publication 50, p. 441-470.

Reynolds, T., 1994, Quantitative analysis of submarine-fans in the Tertiary of the North Sea Basin: Marine and Petroleum Geology, v. 11, p. 202-207.

Vail, P., and R. Mitchum, 1977, Seismic stratigraphy and global changes of sea level, part 7: Seismic stratigraphic interpretation procedure, in C.E. Payton, ed., Seismic Stratigraphy - Applications to Hydrocarbon Exploration: AAPG Memoir 26, 516 p.

Ziegler, P.A., 1990, Geological atlas of Western and Central Europe (2nd ed.): Shell International Petroleum Maatschappij, 238 p., 52 enclosures.
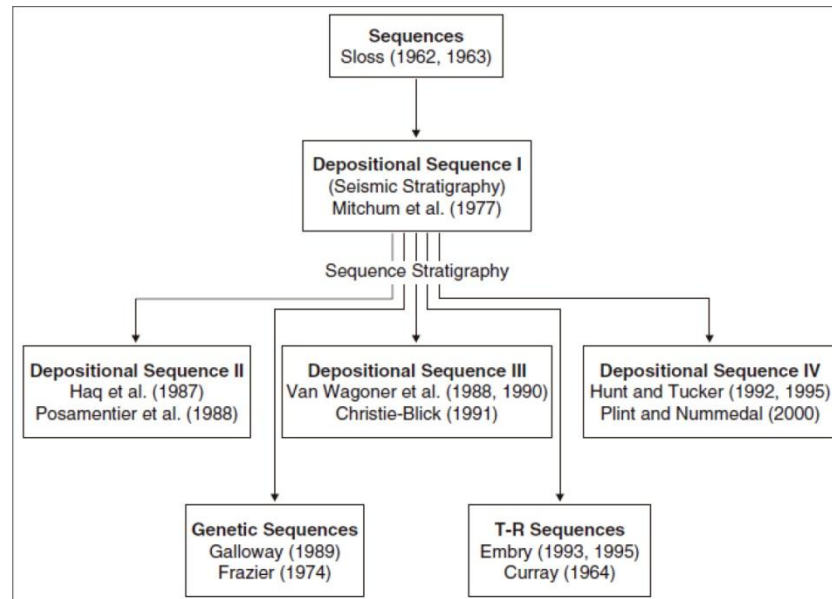
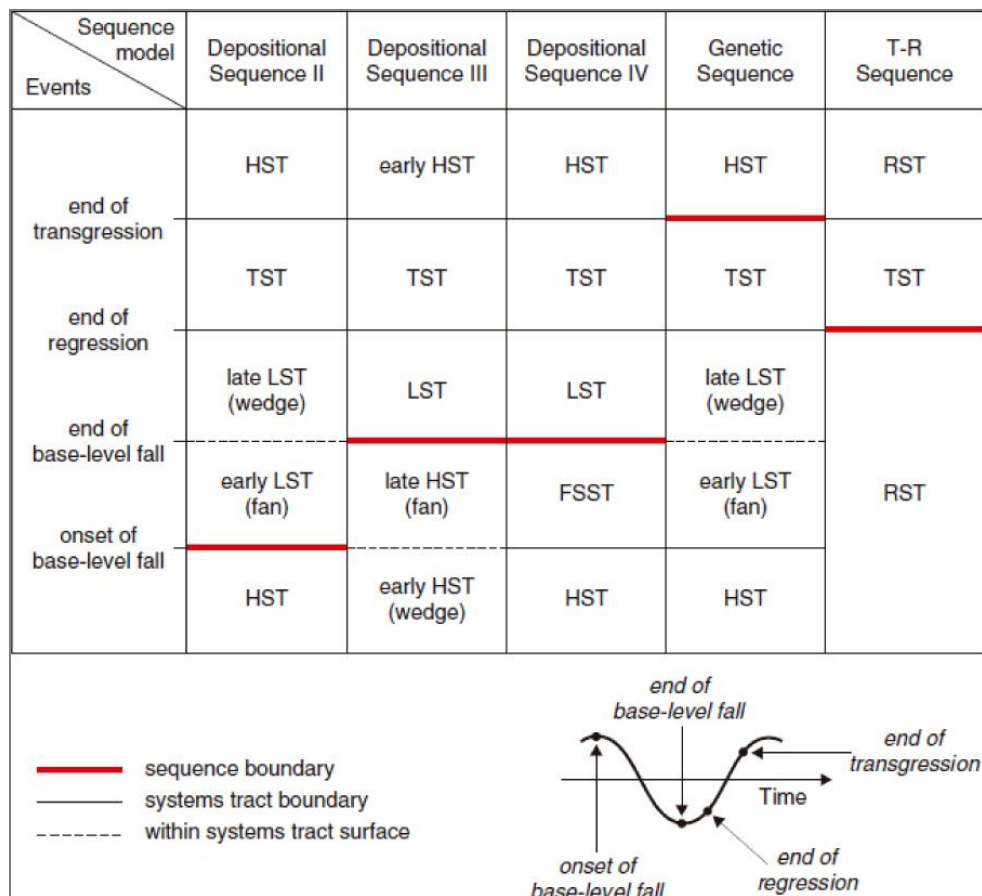Figure 1. Family tree of sequence stratigraphy (modified from Donovan, 2001).

Events \ Sequence model	Depositional Sequence II	Depositional Sequence III	Depositional Sequence IV	Genetic Sequence	T-R Sequence
	HST	early HST	HST	HST	RST
end of transgression					
	TST	TST	TST	TST	TST
end of regression					
	late LST (wedge)	LST	LST	late LST (wedge)	
end of base-level fall					RST
	early LST (fan)	late HST (fan)	FSST	early LST (fan)	
onset of base-level fall					
	HST	early HST (wedge)	HST	HST	

sequence boundary
systems tract boundary
within systems tract surface

end of base-level fall
end of transgression
Time
onset of base-level fall
end of regression

Figure 2. Timing of system tracts and sequence boundaries for the sequence models currently in use (modified from Catuneanu, 2002).
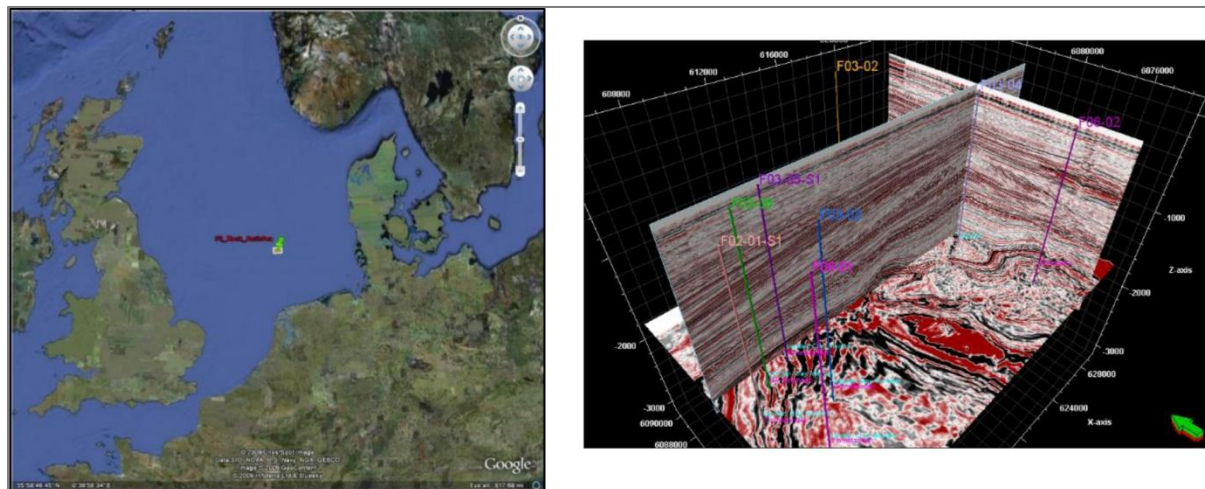
Figure 3. Location satellite image of the F3 Block seismic survey (left) and location of the seven correlation wells in the 3D seismic survey.
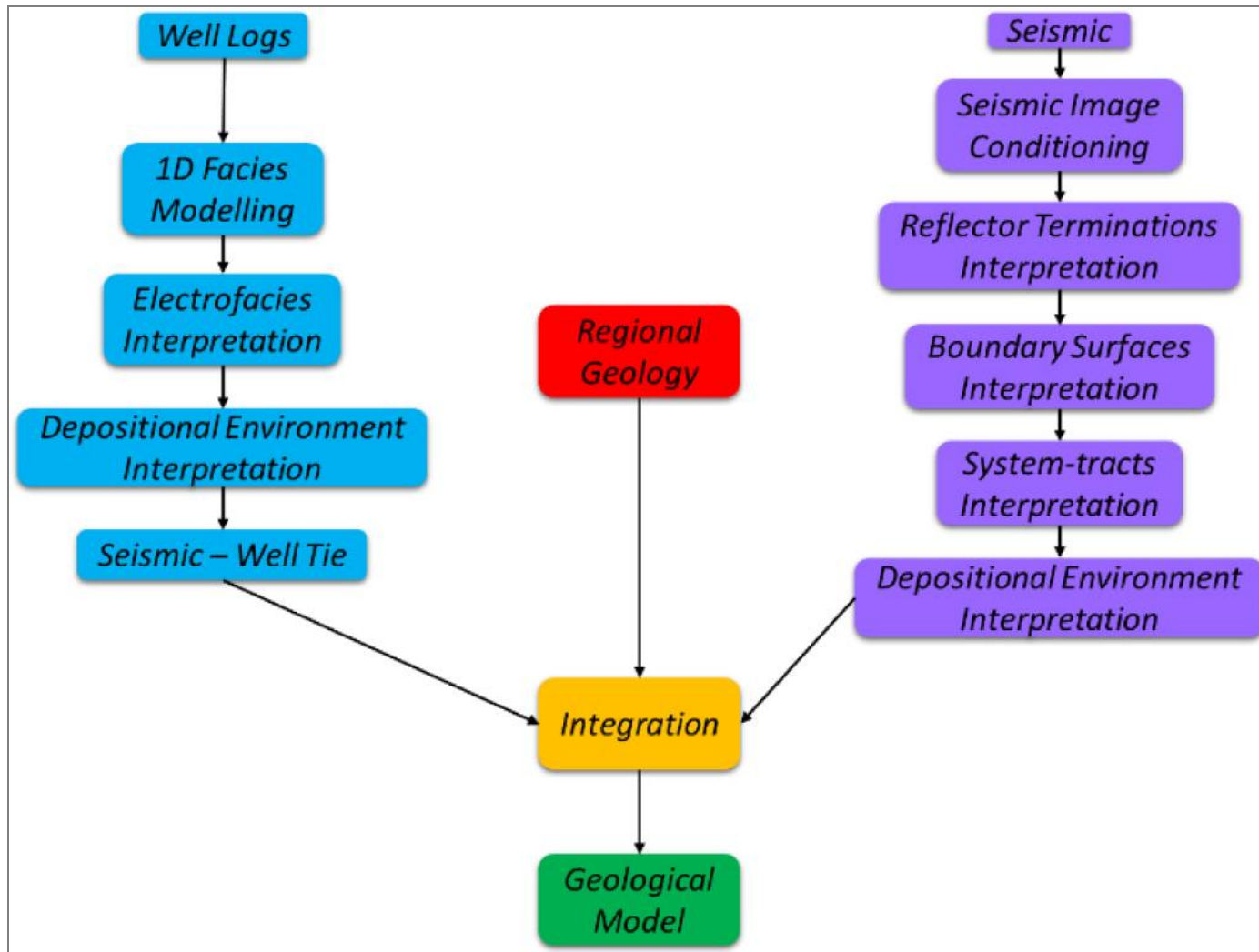
Figure 4. Workflow applied to transform petrophysical and geophysical information into a 3D geological model.
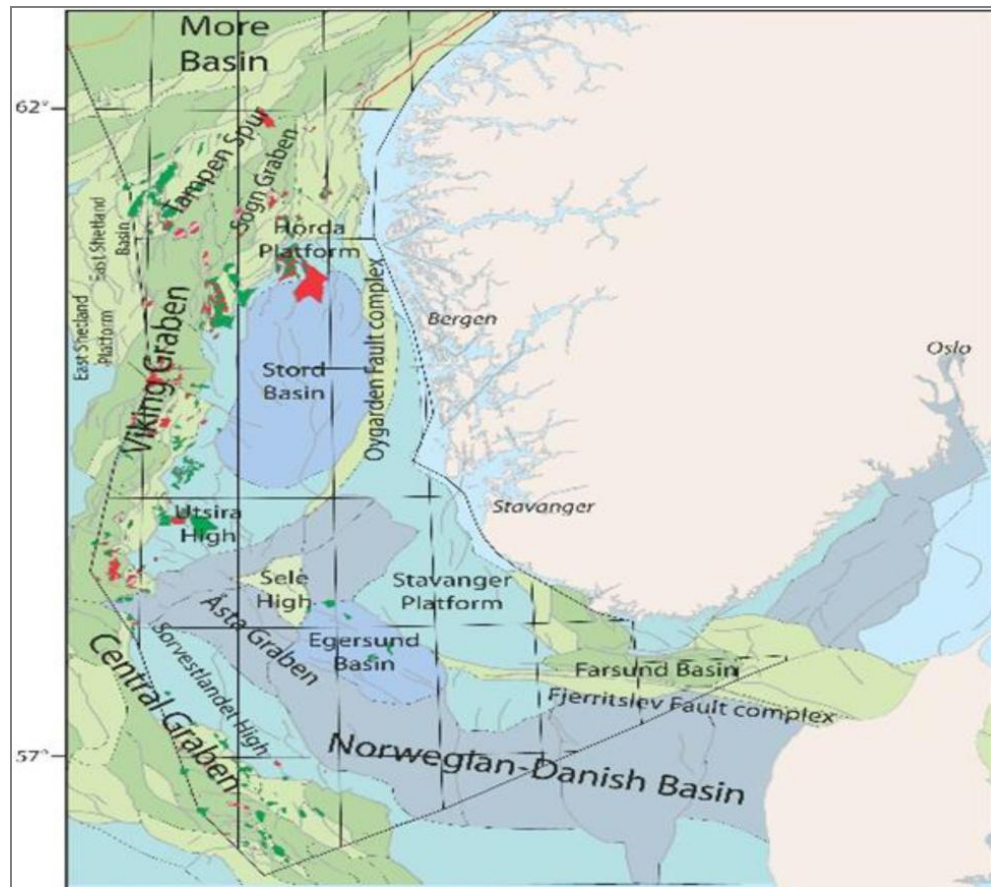
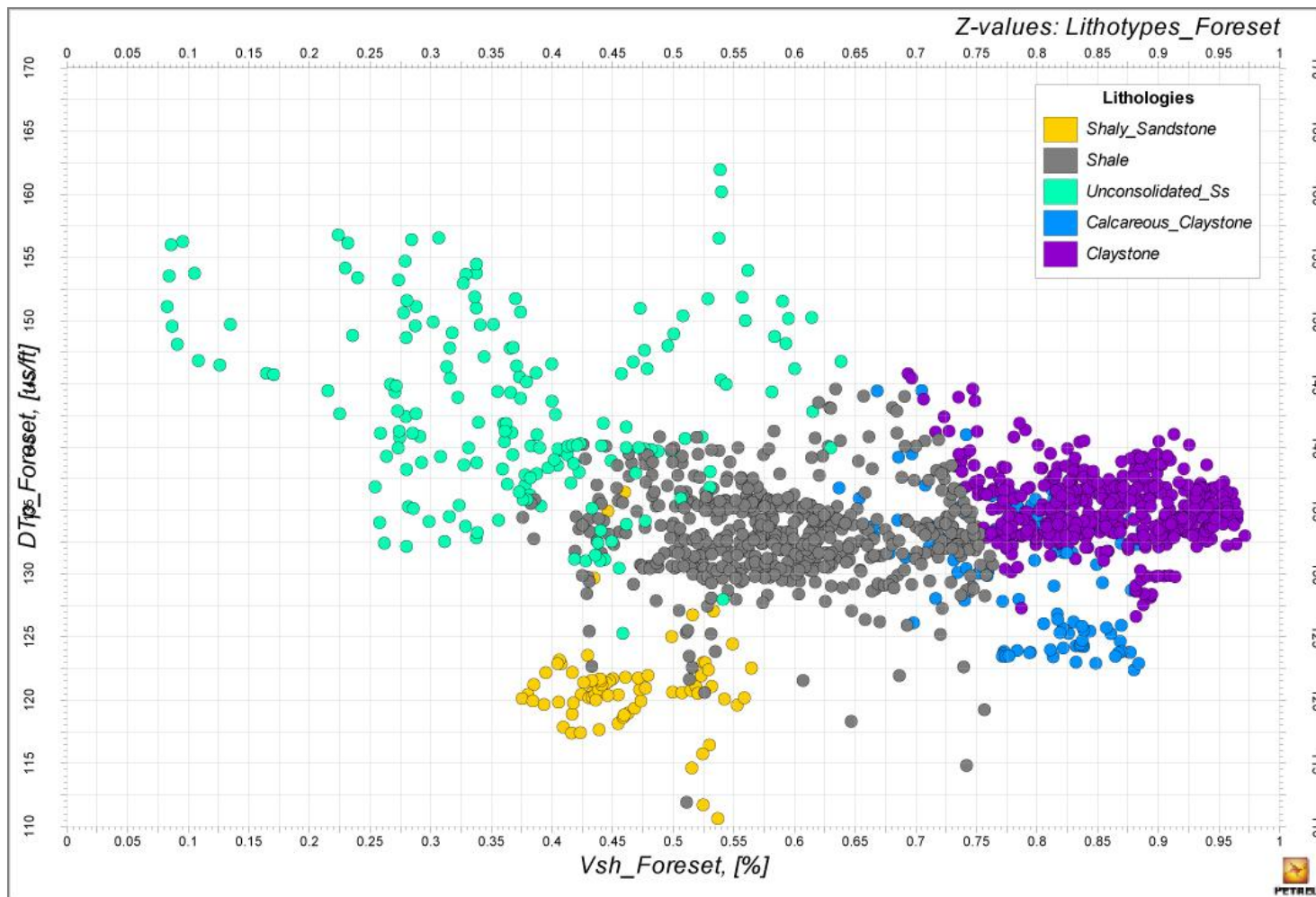Figure 5. Regional context of the study area. Modified from Halland, 2014.

Figure 6. Well log and stratigraphic analysis from core and cuttings samples for one of the correlation wells.
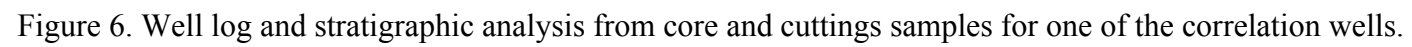
Figure 7. Final crossplot for the facies modeling, applying neural networks and Vshale.
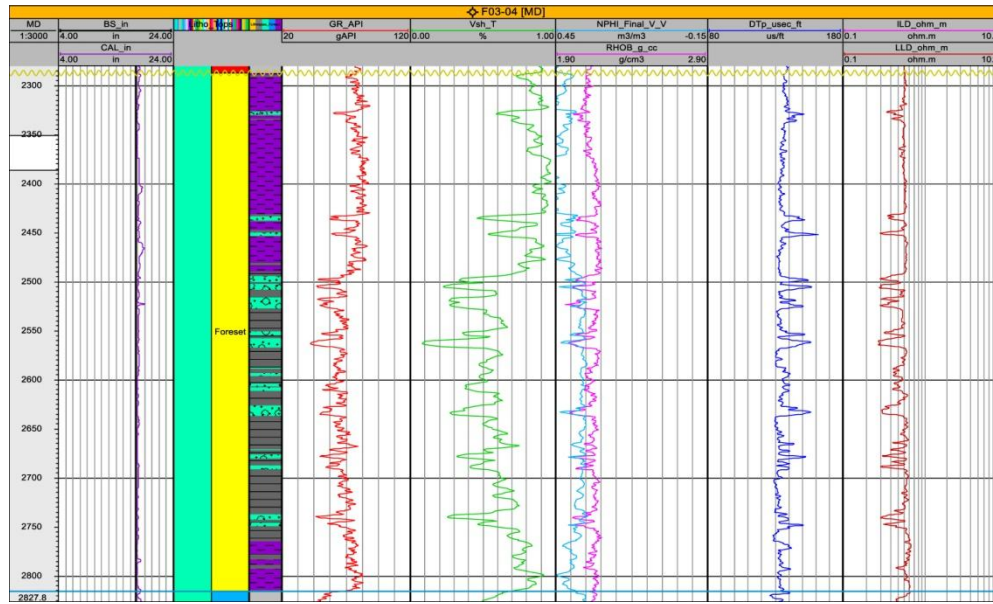
Figure 8. 1D Facies model for one of the correlation wells obtained applying neural networks and Vshale.
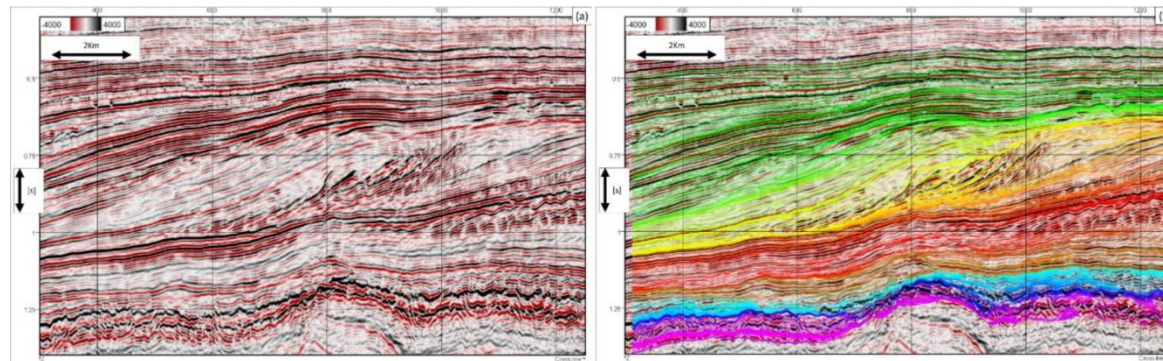
Figure 9. (a) Conditioned seismic image, and (b) its corresponding horizons framework defined from the Dip-Steering attribute.
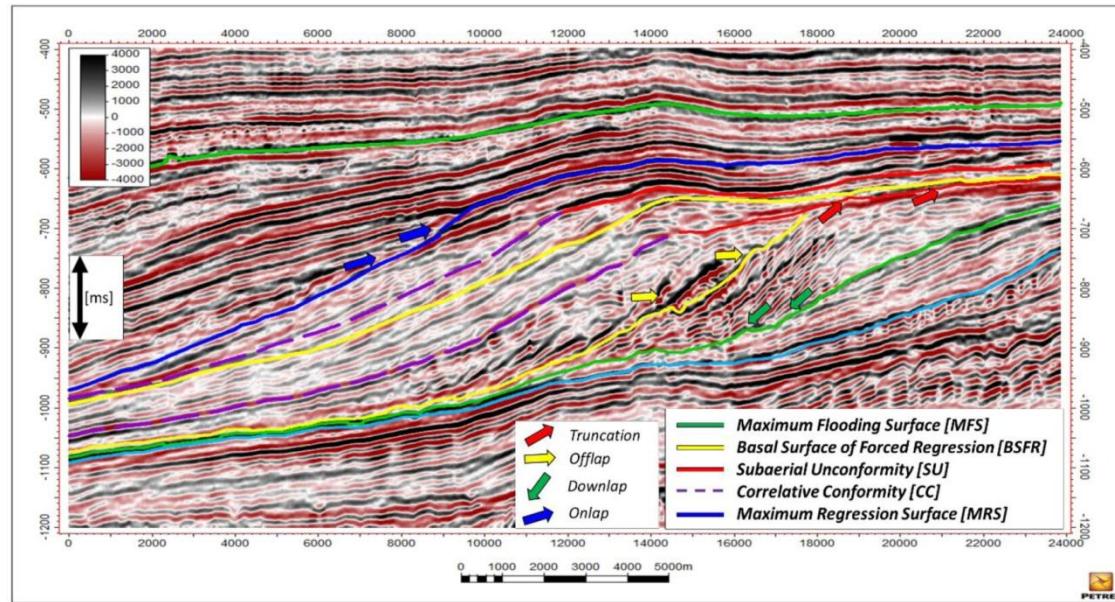
Figure 10. Stratigraphic surfaces associated to reflectors terminations.
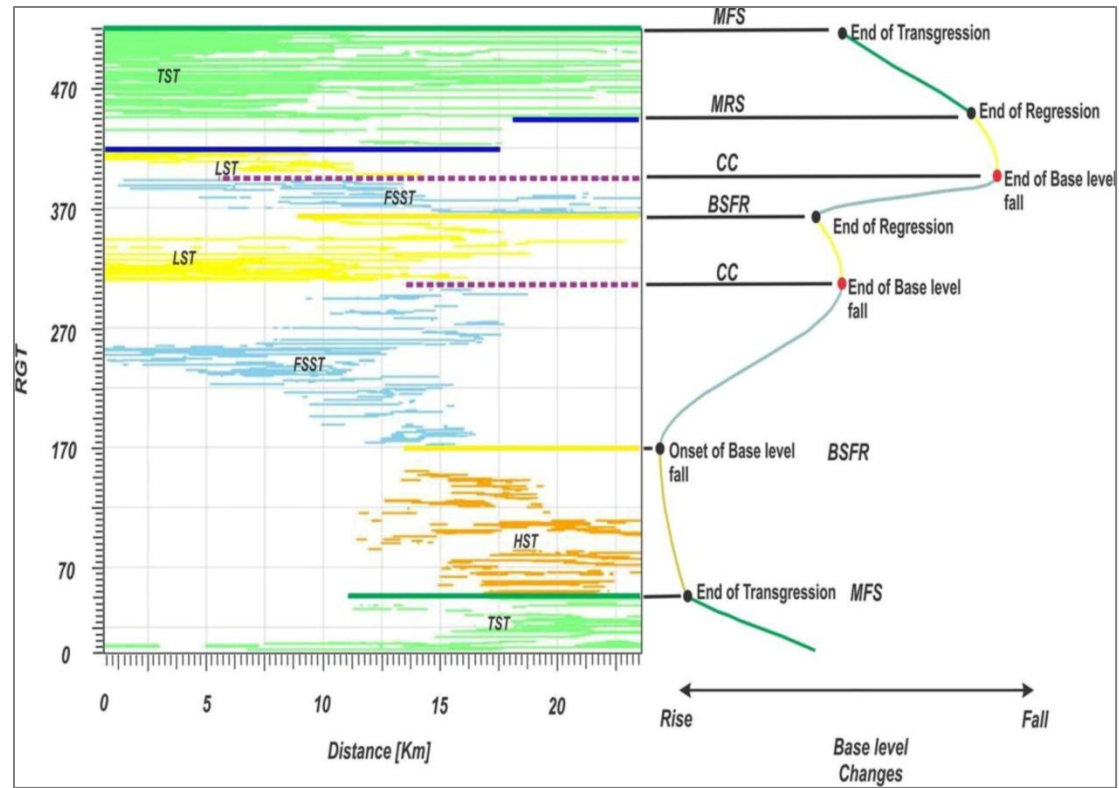
Figure 11. Wheeler domain along with the system tract interpretation and the base level change curve. RGT means "Relative Geologic Time.
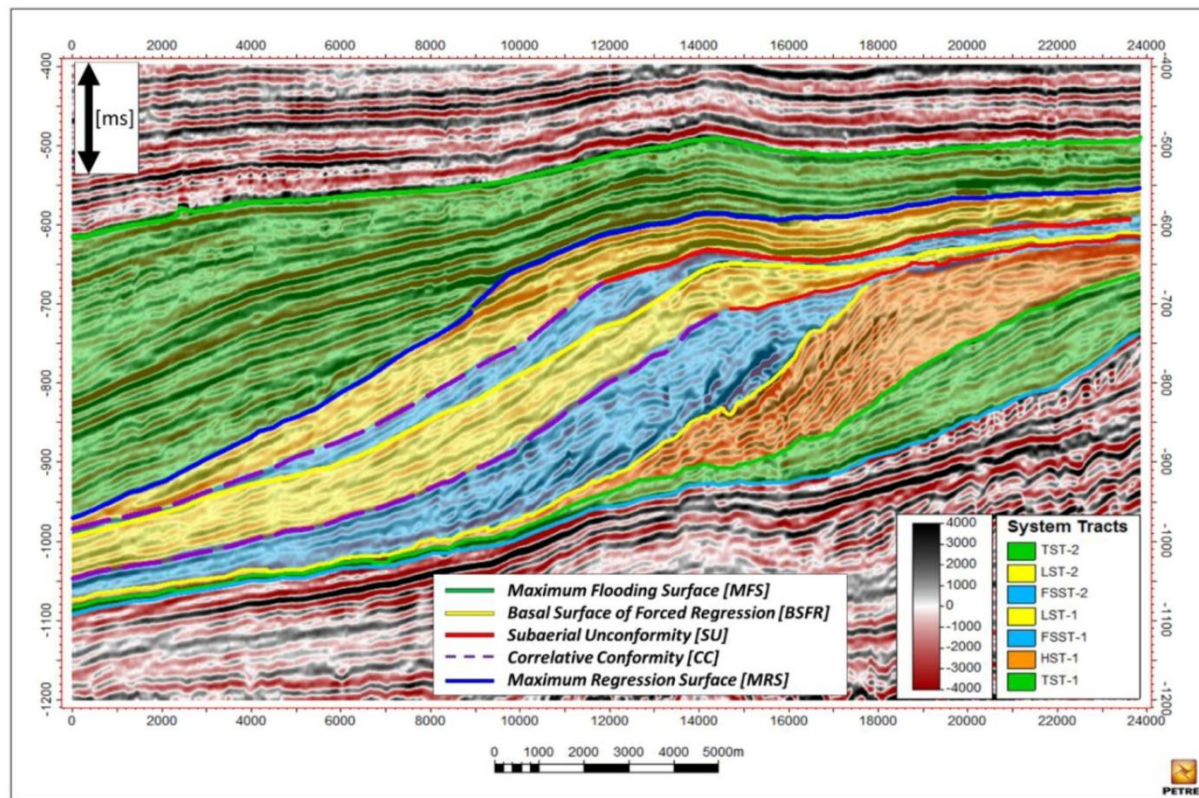
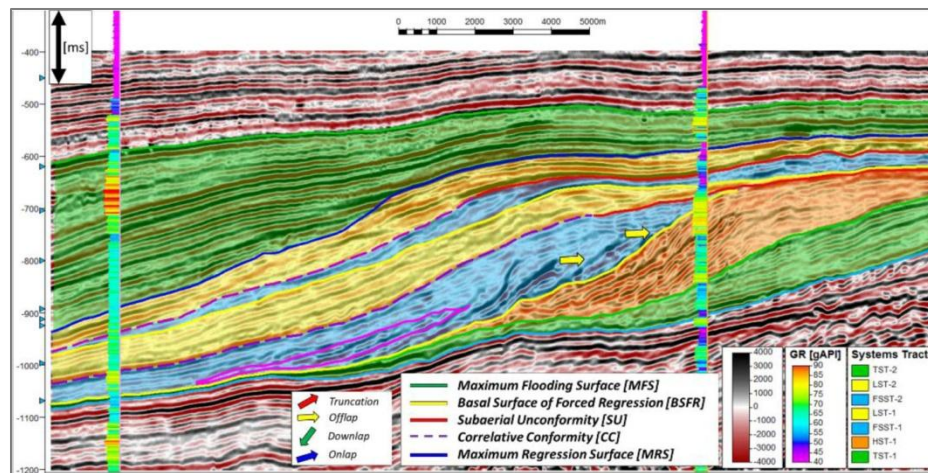Figure 12. Systems tracts interpreted for the interval of interest.

Figure 13. Turbidite geobody (magenta horizons) interpreted at the end of the prograding offlapping lobes inside the *FSST* defined for the study area.
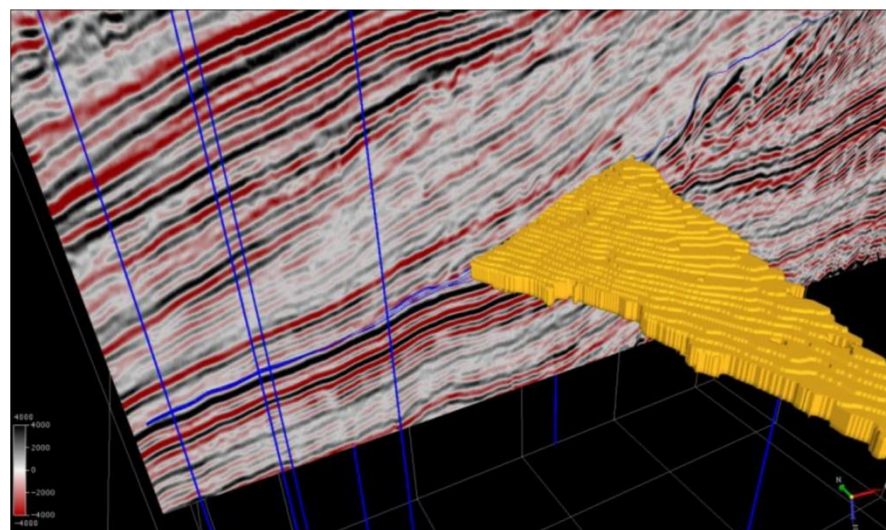

Figure 14. 3D model of one of the turbidites interpreted in the seismic volume.
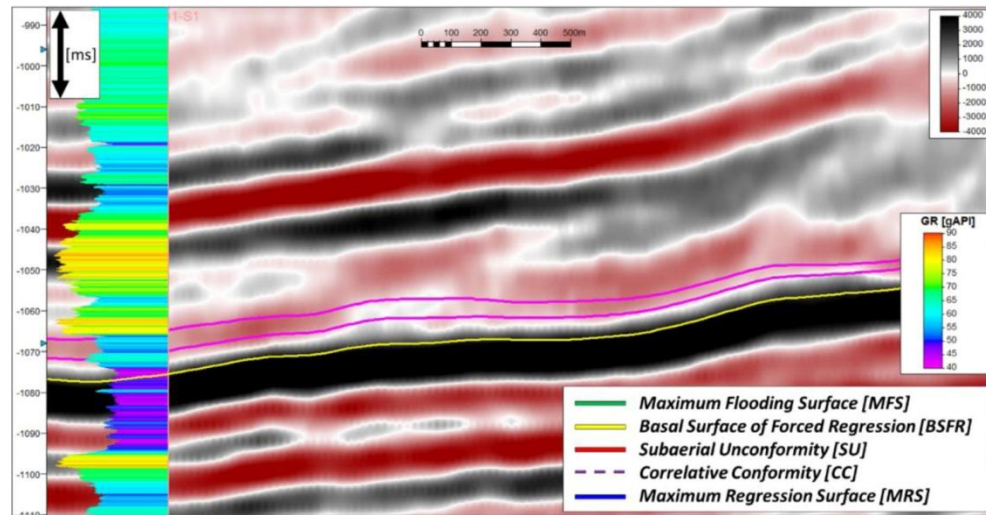
Figure 15. Distal portion of the turbidite geobody (magenta horizons) from the 3D geological model. As it is expected, the Gamma Ray log decreases once it reaches the top of the turbidite interval.