UNIVERSIDADE
EDUARDO
MONDLANE

ACADEMIC MASTER´S IN PETROLEUM ENGINEERING

SEISMIC STRATIGRAPHY CHARACTERIZATION AND DEPOSITIONAL ENVIRONMENT OF ONSHORE NORTHERN OF THE BUZI BLOCK, MOZAMBIQUE BASIN

A Dissertation by

Osvaldo Henrique Cabral

Maputo

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Supervisior
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Maputo

2025

DECLARATION OF DOCUMENT ORIGINALITY

"I declare that this dissertation has never been submitted to obtain any degree or in any other context and is the result of my own individual work. This dissertation is presented in partial fulfillment of the requirements for the degree of Academic Master`s in Petroleum Engineering from the Eduardo Mondlane University".

Submitted by:

Osvaldo Henrique Cabral

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ABSTRACT

This research applies seismic stratigraphy characterization to identify the depositional environments in the northern Buzi Block into the Sedimentary Mozambique Basin. The study aims to enhance the understanding of onshore reservoirs in the Mozambique Basin and their hydrocarbon potential through detailed seismic and well log analyses.

The study integrates the results of seismic interpretation, analyses of seismic reflection patterns, seismic attribute extraction, and well log motif analyses to classify lithology and identify depositional environments. Seismic data were integrated with checkshot/VSP data to ensure accurate seismic-to-well ties. Cross-validation between seismic facies, seismic attributes, and lithology classifications ensured data consistency and quality. Petrel version 2016 and ArcGIS software were employed for data processing, analysis, and visualization.

This work identifies diverse depositional environments from the Sena to Cheringoma formations, spanning floodplains to marine and deltaic settings. The Sena Formation demonstrates reservoir potential, while chaotic eastern sediments from Sena Formation suggest low hydrocarbon trap potential. A fault associated high amplitude anomaly in the Domo Formation highlights its prospect as a hydrocarbon trap. The Lower Grudja Formation presents cyclic coarsening-upward sequences, indicating strong reservoir potential and clear evidence of shallow marine environments (deltaic or shoreface). In contrast, the Upper Grudja Formation reflects stable sedimentation with potential for hydrocarbon traps reservoir presence, as indicated by the presence of seismic reflectors with high amplitudes.

RESUMO

Esta pesquisa aplica a caracterização sismo-estratigrafia para identificar os ambientes deposicionais na parte norte do bloco de Buzi, Bacia Sedimentar de Moçambique. O estudo tem como objectivo aprimorar a compreensão das características dos reservatórios e seu potencial para acumulação de hidrocarbonetos, através de análises detalhadas de dados sísmicos 2D e informação de diagrafias de furos.

A pesquisa integrou os resultados da interpretação sísmica, análise de padrões de reflexões sísmicas, extração de atributos sísmicos RMS e análise de padrões de diagrafias de furos para classificação litológica e identificação de ambientes deposicionais. Os dados sísmicos foram integrados com dados de checkshot/VSP para garantir a correcta calibração dos dados sísmicos e de furos. Para este propósito foram usados softwares Petrel versão 2016 e ArcGIS para o processamento, análise e visualização dos dados.

O estudo identifica diversos ambientes deposicionais desde a Formação de Sena até Cheringoma, abrangendo planícies de inundação, bem como ambientes marinhos e deltáicos. A Formação Sena demonstra potencial como reservatório, enquanto os sedimentos caóticos a Este (E) da Formação Sena indicam baixa probabilidade de armadilhas para hidrocarbonetos. A anomalia de amplitude associada a falha na Formação Domo destaca o seu potencial como armadilha para hidrocarbonetos. A Formação do Grudja Inferior apresenta sequências ciclicas de *coarsening upward*, indicando forte potencial como reservatório e evidência inequívoca de ambientes marinho de águas rasas (deltáico ou *shoreface*), enquanto a Formação Grudja Superior reflete sedimentação estável com potencial para presença de reservatório para hidrocarbonetos reflectido pela presença de reflectores sísmicos com fortes amplitudes.

DEDICATION

"This research work is dedicated to my beloved parents, to my mother, for her unconditional love, constant encouragement, and unwavering presence, and to my father, in memory, whose example, sacrifices, and values continue to inspire every step of my journey. Their support has been the foundation of my aspirations, guiding me through the challenges and achievements of academic life. With a heart full of gratitude, I dedicate this work to them as a testament to the profound impact they have had on my life and as a symbol of my enduring love and appreciation."

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation	Description
AI	``Acoustic Impedance´´
ASL	``Above Sea Level´´
BHPL	``Buzi Hydrocarbon Pte Ltd´´
CDP	``Commom Depth Point´´
C.I	``Contour Interval´´
CNC	``Carbonate Porosity Log´´
CNL	``Neutron Porosity Log´´
DT	``Sonic Log´´
ECL	``Exploration Consultants Ltd´´
ENH	``Empresa Nacional de Hidrocarbonetos´´
FLNG	``Float Liquified Natural Gas´´
FTD	``Final Total Depth´´
GIIP	``Gas Initially In Place´´.
GIS	``Geographic Information System´´
GR	``Gamma Ray Log´´
INP	``Instituto Nacional de Petróleo´´
KB	``Kelly Bush´´
LNG	``Liquified Natural Gas´´
m	``Meter´´
m SSTVD	``Meter Sub-Sea True Vertical Depth´´
MD	``Measured Depth´´
MDRKB	``Measured Depth Below Rotary Kelly Bush´´
MIREME	``Ministério dos Recursos Minerais & Energia´´
NPHI	``Neutron Porosity´´
ms	``Milliseconds´´
P&A	``Plug and Abandonment´´
PSTM	``Post Stack Time Migrate´´
P	``Primary´´
DEN/RHOB	``Bulk Density Log´´
RMS	``Root Mean Square´´
s	``Second´´
S	``Secondary´´
SCH	``Scmittar´´
SP	``Spontaneous Potential´´
Sqk	``Square Kilometer´´
tcf	``Trillion of Cubic Feet´´
twt	``Two Way Travel time´´
VSP	``Vertical Seismic Profile´´

KEY WORDS

This study aims to comprehensively analyze the seismic stratigraphy and depositional environment of the Buzi block, specifically focusing on the northern onshore region within the Mozambique Basin, by utilizing seismic data. The research seeks to characterize the geological architecture and understand the environmental conditions under which sedimentary rocks were deposited in this area. The findings are expected to provide valuable insights into the region's geological history and hydrocarbon potential, contributing to the knowledge base for exploration and resource evaluation endeavors.

Key Words: Buzi Seismic Analysis, Mozambique Basin.

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CHAPTER I
INTRODUCTION

1.1 Introduction

Mozambique's hydrocarbon exploration, rooted in a century-old legacy, has recently undergone a transformative resurgence. The Mozambique Basin, marked by onshore exploration activities in 1904, witnessed a pivotal phase between 1961 and 1967 when the international oil company (Gulf Coast) identified substantial hydrocarbon reserves at Pande, Buzi, and Temane in the Mozambique Basin (ECL., 2000). This era confirmed the presence of significant resources, identifying eight coursing-upwards sandstone horizons in the Lower Grudja formation (G6 to G11 and G11A to G12) (Salman & Abdula, 1996).

Despite historical challenges in the energy sector, Mozambique has seen a remarkable turnaround. With two large Sedimentary Basins of natural gas, the country has become the focus of an intensive exploration campaign.

Over the past decade, discoveries in Area 1 and Area 4, in the Rovuma Basin, have unveiled gas reservoirs estimated at 150 trillion cubic feet (tcf), making Mozambique one of the most prolific exploration areas globally (Mahumane G., 2012). The basins feature complex geological formations like extensional faults, compressional structures, and deep-water submarine fans (Mahanjane & Franke, 2014).

Beyond geological significance, the discoveries in the Rovuma Basin hold transformative economic potential. The estimated 150 tcf of natural gas could contribute billions of dollars to Mozambique's economy, positioning the country to become the world's third-largest producer and exporter of Liquefied Natural Gas (Eni, 2022).

The Buzi Block, located onshore in the northern part of the Mozambique Basin, represents a relatively underexplored region with growing interest due to its geological complexity and potential hydrocarbon resources. Characterizing its depositional environments requires a detailed geoscientific investigation that combines seismic stratigraphy, structural interpretation, and petrophysical analysis. Understanding the subsurface depositional environments is fundamental for successful hydrocarbon exploration and reservoir characterization.

1.2 Research Problem

The central research problem revolves around the need to enhance our understanding of the geological characteristics and depositional environment of the northern part of the Buzi Block in the Mozambique Basin to understand the hydrocarbon potential of the region. This region holds significant hydrocarbon potential, making it a prime target for exploration and production activities. However, despite its geological importance, there are notable gaps in our knowledge regarding the depositional environment.

Existing studies may have provided some insights into the geological features and depositional environments of the region. However, these studies often lack a comprehensive analysis that integrates advanced seismic and well log data interpretation techniques. As a result, our understanding of the complex geological processes and structures in the area remains limited.

1.3 Research Objectives

The main objective is to analyze seismic and log data to characterize and interpret depositional environments in the onshore northern Buzi block in the Mozambique Basin.

The specific objectives are:

- To analyze seismic facies patterns to identify depositional sequences, structural trends, and sedimentary features.
- To utilize Root Mean Square (RMS) seismic attribute analyses to enhance understanding of depositional environments.
- To identify dominant log motifs in well log data and correlating them with depositional environments and sedimentary processes.

1.4 Motivation, Contribution, Significance

The motivation, contribution, and significance of this thesis lie in its potential to advance our understanding of the geological characteristics and depositional history of the northern part of the Buzi Block in the Mozambique Basin. Here is a detailed elaboration on each aspect:

Motivation:

Exploration Potential: The Mozambique Basin is known for its hydrocarbon potential, and the northern part of the Buzi block represents an area of particular interest for exploration activities. Understanding the geological features and depositional environments in this region is crucial for identifying prospective hydrocarbon reservoirs.

Knowledge Gap: Despite previous geological studies in the area, there may still be gaps in our understanding of the subsurface geology and sedimentary processes. This thesis aims to address these gaps by conducting a detailed analysis using advanced seismic and well log data interpretation techniques.

Contribution:

The thesis will contribute into the geological characteristics, depositional sequences, and structural trends within the study area. By analyzing seismic facies patterns, RMS seismic attributes, and dominant log motifs, the research will provide a comprehensive understanding of the subsurface reservoirs.

The findings of this thesis can aid in reservoir characterization efforts, helping to identify potential hydrocarbon-bearing zones, delineate reservoir compartments, and improve reservoir modeling accuracy. This information is essential for optimizing hydrocarbon exploration and production strategies in the Mozambique Basin.

Significance:

The research outcomes have direct relevance to the oil and gas industry, particularly companies involved in exploration and production activities in the Mozambique Basin. The insights gained from this thesis can guide decision-making processes related to well placement, drilling operations, and reservoir development.

The thesis contributes to the body of scientific knowledge in the field of geology and petroleum engineering. It provides a case study of depositional environments and sedimentary processes in a relatively unmature area, contributing to the advancement of geological understanding and research methodologies.

1.5 Research Questions

The research questions for this study are:

What are the seismics facies pattern of the northern part of the Buzi block in the Mozambique Basin?

How can RMS seismic attribute analysis be utilized to enhance the understanding of depositional environments in the study area?

What are the dominant log motifs observed in well log data, and how do they provide insights into the depositional environments and sedimentary processes within subsurface reservoirs?

1.6 Hypothesis

Hypothesis for Research Question 1:

Null Hypothesis: There is no significant variation in seismic facies patterns within the northern part of the Buzi block in the Mozambique Basin.

Alternative Hypothesis: Seismic facies patterns within the northern part of the Buzi block exhibit distinct variations, reflecting different depositional sequences, structural trends, and sedimentary features.

Hypothesis for Research Question 2:

Null Hypothesis: Root Mean Square (RMS) seismic attribute analysis does not significantly contribute to the understanding of depositional environments in the study area.

Alternative Hypothesis: RMS seismic attribute analysis provides valuable insights into the depositional environments in the study area by revealing characteristic patterns that correlate with specific depositional processes and environments.

Hypothesis for Research Question 3:

Null Hypothesis: There is no dominant log motifs observed in well log data from the northern part of the Buzi block in the Mozambique Basin.

Alternative Hypothesis: Dominant log motifs are evident in well log data from the northern part of the Buzi block, providing insights into the depositional environments and sedimentary processes within subsurface reservoirs.

1.7 Summary

This research addresses the need to enhance our understanding of the geological characteristics and depositional history of the northern part of the Buzi block in the Mozambique Basin. Despite its significant hydrocarbon potential, there are notable knowledge gaps regarding the hydrocarbon reservoirs in this area. The research aims to comprehensively analyze seismic facies patterns, utilize RMS seismic attribute analysis, and identify dominant log motifs in well log data to provide insights into the depositional environments and sedimentary processes within subsurface reservoirs. Through a detailed investigation, the research seeks to contribute new insights into the geological characteristics, depositional sequences, and structural trends of the study area. The outcomes of this study are expected to have significant implications for hydrocarbon exploration and production activities in the Mozambique Basin, ultimately contributing to the advancement of scientific knowledge in the field of geology and petroleum engineering.

CHAPTER II

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Introduction

The scarcity of geological knowledge and data on Mozambique Sedimentary Basin poses a significant challenge locally and globally. Despite recent efforts to publish scientific articles in petroleum geosciences, these contributions remain limited compared to the broader scope of knowledge needed for assessing the hydrocarbon potential of the Mozambique Basin, especially in specific study areas.

This gap underscores the urgent need for more extensive research and exploration initiatives. While existing scientific literature provides valuable understanding, comprehensive efforts are essential to fill data deficiencies and enhance understanding of the region's geological characteristics and hydrocarbon potential. The study area within the Mozambique Basin, particularly in the northern part of the Buzi block, represents a critical focus for such initiatives.

2.2 Synthesis of Recent and Relevant Research

The more recent and relevant references in the list represent advancements in sedimentary geology and hydrocarbon exploration, leveraging modern techniques and methodologies to address contemporary challenges in the field.

Song et al. (2023) explores state-of-the-art techniques for log motif identification and their significance in understanding depositional environments and sedimentary processes. Their research involves the development of automated algorithms or machine learning approaches to analyze large volumes of well log data and extract full patterns.

Haldar (2020) explores cutting-edge seismic attribute analysis methods, such as RMS analysis, and their applications in reservoir characterization and hydrocarbon exploration. It provides insights into how these advanced techniques can enhance our understanding of subsurface geological structures and improve reservoir delineation.

The field of sedimentary geology and hydrocarbon exploration has seen a significant evolution in methodologies over the years, beginning with Selley's foundational work in 1978.

Selley established the basis for interpreting sedimentary environments through log motifs, showing how variations in log shapes could reveal depositional settings like barrier bars and submarine fans. Cant's 1992 study built on this foundation by categorizing log trends and linking them to specific depositional environments, such as aeolian sands and carbonate reefs, thus refining practical log analysis. In 1999, Posamentier and Allen advanced the field by introducing systematic approaches to interpreting wireline logs, emphasizing the importance of recognizing patterns like boxcar and funnel shapes to reveal depositional processes. The focus shifted in 2005 with Chow, Ching, and Fuh's exploration of gamma-ray (GR) readings, adding detail to log interpretation by showing how GR variations reflect different lithological characteristics and sedimentary facies. By 2010, Tokhmchi and colleagues addressed the challenges of unconventional reservoirs, such as shale and tight gas formations, using advanced seismic attribute analysis techniques to propose innovative solutions for complex reservoir characterization. Li and colleagues, in 2017, further advanced seismic analysis by integrating multiple attributes to enhance reservoir characterization and identify subtle features. In 2016, both Nazeer, Abbasi, Solangi, and Lyu et al. contributed to the evolution of log motif analysis, with Nazeer providing in-depth interpretations of log shapes and Lyu focusing on improved log motif identification for reservoir characterization. Haldar (2020), study marked a significant leap with advanced seismic attribute analysis techniques, such as RMS analysis, enhancing the understanding of subsurface geological structures. Finally, in 2023, Song et al introduced cutting-edge techniques using automated algorithms and machine learning for log motif identification, representing the integration of modern computational techniques into sedimentary geology and reflecting the latest advancements in the field. This chronological progression highlights a continuous refinement and enhancement of methods, from basic log interpretations to sophisticated computational approaches, improving our understanding of subsurface geology and hydrocarbon exploration.

2.3 Literature Supporting the Research Problem and Research

The field of sedimentary geology and hydrocarbon exploration has evolved significantly through a series of key studies over the decades. In 1982, Anderson et al. pioneered seismic attribute analysis techniques essential for identifying subsurface structures and potential reservoirs. Building on this foundation, Posamentier and James (1993) introduced a framework for understanding depositional sequences, crucial for interpreting sedimentary strata and predicting reservoir quality. Perini and Batist (1994) enhanced this by correlating well log data with lithofacies, improving reservoir characterization. Pirini et al (1996), furthered understanding of sedimentary processes in fluvial systems, shaping interpretations of depositional environments. Salman and Abdula (1996), advanced basin analysis and petroleum system modeling, offering predictive tools for assessing reservoirs. Posamentier and Allen (1999), expanded sequence stratigraphy with a hierarchical framework, refining reservoir characterization methods. In 2014, Schlumberger's industry-focused research applied these advancements to practical exploration and production strategies. Recent advancements by Li et al. (2020) and Haldar (2020) introduced novel seismic attribute analysis methods, such as RMS analysis, enhancing the ability to interpret complex subsurface structures and optimize exploration strategies. This progression highlights the continuous refinement of techniques and integration of practical applications, leading to a more comprehensive understanding of subsurface geology and improved hydrocarbon exploration methods.

2.4 Theoretical Framework

Seismic facies analysis attempts to formalize seismic stratigraphy ideas by extracting all the relevant information from the seismic data. These include the external shape of the seismic sequence and the relationship of the internal reflections to the boundaries to assign which kind of geological environment the rocks have been formed. Seismic facies also used to predict lithology distribution (Catuneanu O, 2009).

Seismic Reflection Characteristics

Seismic reflection characteristics infer many of the geological interpretations, such as bedding patterns, depositional processes, erosion and paleontography, fluid contacts, and bed thickness. These facies parameters include amplitude, frequency, and interval velocity from (Van Wagover, 1990).

Reflection Amplitude

Seismic amplitude is a measure of the strength of reflected signals. Variations in amplitude can indicate changes in rock properties, such as porosity or fluid content. Bright spots or flat spots in seismic data are often associated with hydrocarbon-bearing formations. Relates to the impedance contrast between beds and provides information about bed spacing, tuning thickness, and to some extent fluid content.

Reflection Frequency

Frequency analysis involves studying the number of wave cycles within a seismic signal. Changes in frequency can be indicative of different lithologies or geological features, contributing to the interpretation of subsurface stratigraphy.

Interval Velocity

Interval velocity is the velocity of seismic waves through a specific rock interval. Variations in interval velocity can provide information about the physical properties of subsurface formations.

By integrating these parameters, seismic facies analysis allows geoscientists to characterize subsurface environments and make informed interpretations about the geological features present. This comprehensive approach aids in identifying potential hydrocarbon reservoirs, mapping structural complexities, and understanding the overall geological history of a given region. Several challenges are faced to unravel details of this complexity from the techniques used, acquisition parameters (sampling interval) that have an impact on the vertical resolution of the seismic data, not allowing smaller structures to be visualized within the resolution limits of the available used tools. However, for the seismic response to be useful in delineating the reservoir extension, sand pathways and reservoir properties.

The description of internal units' geometry of the sequence stratigraphic is a tool to know the cyclic nature of stratigraphic successions and the use of the chronostratigraphic framework to enhance lithological prediction (Posamentier & James, 1993). In addition, this approach involves the identification of reflection terminations indicative of stratigraphic discontinuities, the description of reflection geometries between discontinuity surfaces, and mapping of the amplitude, continuity, and frequency of reflections, all on seismic reflection profiles. Integration of these observations into seismic facies maps provided the basis for interpretation of depositional environment and lithology (Ponsamentier, 2005).

Reflection terminations, configurations, and geometry, as well as the outer shape of seismic units, are crucial elements in seismic interpretation and provide valuable information about subsurface geological features. The following concepts, modified from Mitchum et al (1977a, b), outline key aspects **(Figure 1 e Figure 2**).

1. **Reflection Terminations**

Conformable Terminations: Represented by continuous and parallel reflections, indicating uninterrupted sedimentation with no significant breaks in deposition.

- **Concordance**

Unconformable Terminations: Signify a break in the sedimentary sequence, often caused by erosion or non-deposition. This is observed as a discordant relationship between older and younger strata.

- **Downlap Terminations:** Characterized by seaward progradation of sedimentary packages, creating downlapping patterns in seismic reflections.
- **Toplap:** Reflector termination at an overlying surface or upper boundary.
- **Onlap Terminations:** Younger sediments progressively cover an older surface, resulting in overlapping reflections.
- **Offlap:** Reflector termination at an overlying surface or upper boundary.
- **Erosional Terminations:** Erosion removes part of the sedimentary sequence, leading to a distinct boundary in seismic reflections.

2. **Reflection Configurations and Geometry**

The configuration of seismic reflections refers to their spatial arrangement. Understanding the geometry and arrangement of reflections helps in identifying structural features and stratigraphic relationships in the subsurface.

Continuous, Parallel Reflectors: Indicate conformable deposition with minimal structural disturbances.

Anticlinal Folds: Upward-arching strata due to tectonic compression, creating distinctive geometry in seismic reflections.

Synclinal Folds: Downward-folding strata resulting from tectonic forces, visible in seismic reflections.

Faults: Discontinuities in seismic reflections caused by the displacement of geological units along fault lines.

Draping Over Structure: Sediments that conformably cover underlying structures, creating a draped appearance in seismic reflections.

3. **Outer Shape of Seismic Units**

Wedge-shaped Deposition: Seaward thickening of sedimentary units, forming a wedge shape in seismic reflections.

Draped Over Structure: Sediments conformably covering underlying structures, creating an outer draped shape in seismic data.

Sedimentary Lobes: Fan-shaped bodies of sediment deposited by underwater currents or rivers, visible in seismic reflections.

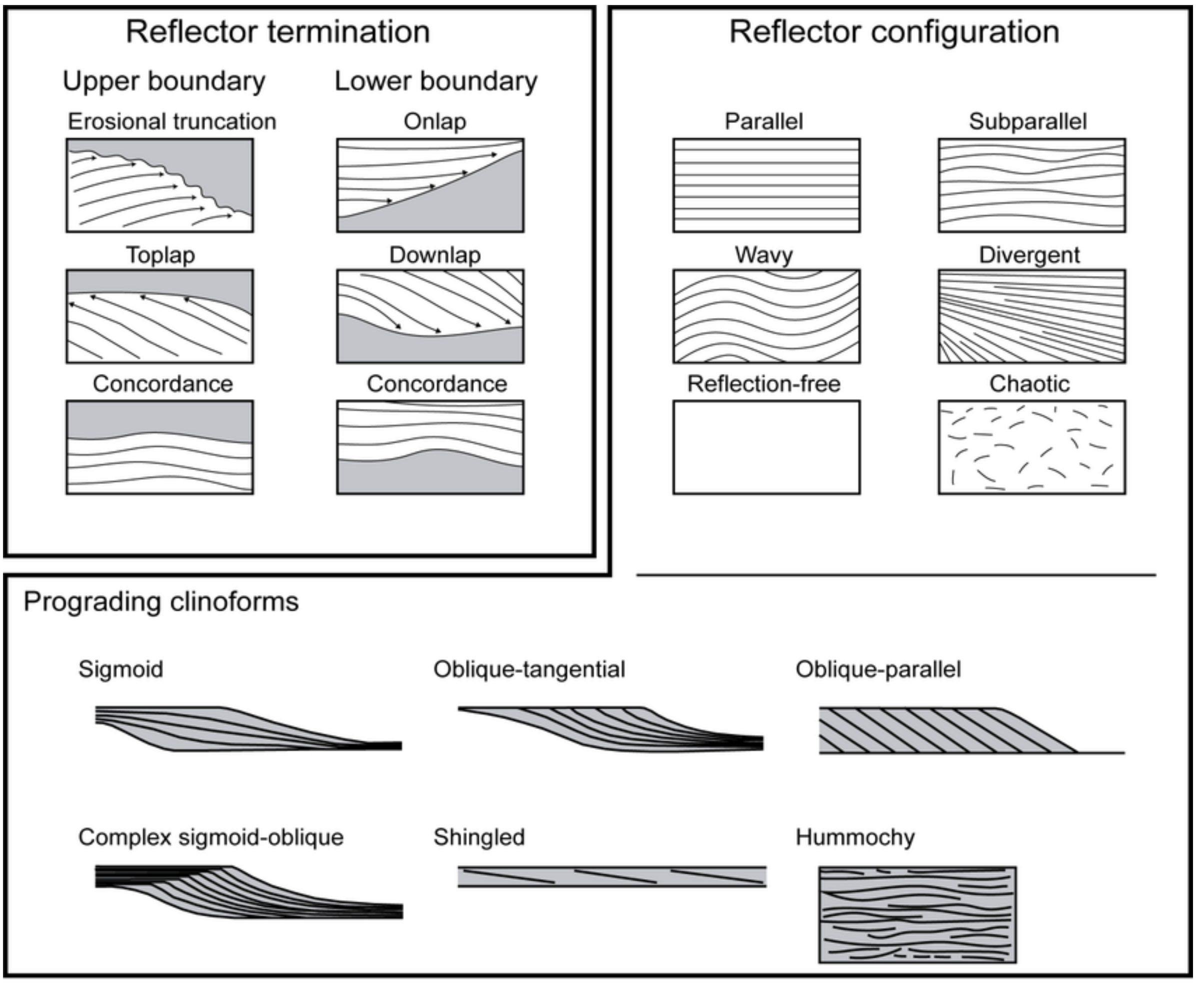


Figure 1 Reflector terminations and configurations, Modified from Mitchum et al. (1977a, b).

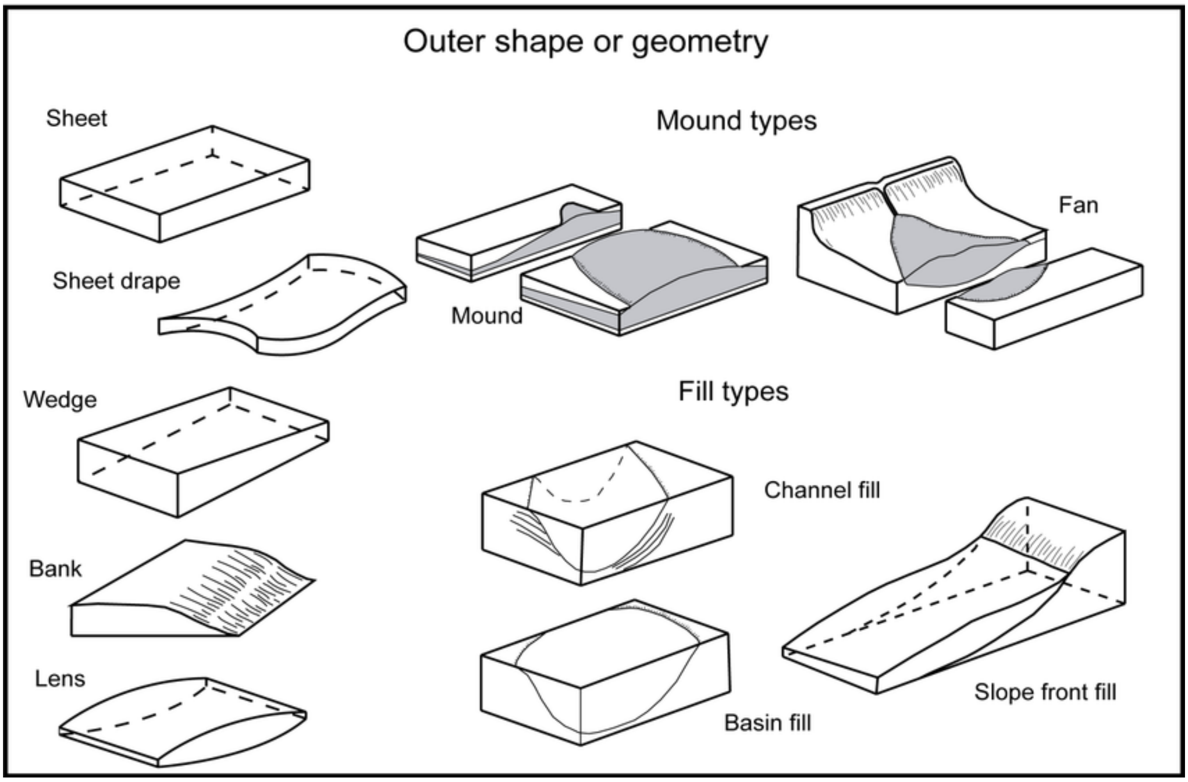


Figure 2: Outer shape of seismic units. Modified from Mitchum et al. (1977a, b).

2.5 Relevance of the Theoretical Framework

According to (Mondol, 2010), the seismic source at any point on Earth generates four (4) types of seismic waves: compressional (P-wave), shear (S-wave), Rayleigh (ground roll) and Love, that travel through the layers (**Figure 3**). Each layer will have a specific density and velocity. Rayleigh and Love waves are surface waves and propagate approximately parallel to the Earth's surface.

The fundamental principle of seismic surveying is to initiate a seismic pulse at or near the earth's surface and record the amplitudes and travel times of waves returning to the surface after being reflected or refracted from the interface or interfaces of one or more layers of rock (Selley & Sonnenberg, 2015), this principle base on the Snell's law, the law describes the changes in the direction of a wavefront as it travels in media of different velocities. If the seismic wave is incident at an angle, both reflected and refracted P and S waves will be generated at an interface between two media, as shown by Snell law in (**Equation 1**):

$$\sin \theta 1 / \sin \theta 2 = v_2 / v_1 \qquad \textbf{(Equation 1)}.$$

Where: v_1 and v_2 are the velocities of the first and second media, **sinθ1** and **sinθ2** are the sines of the incidence and refracted angles, and **θ3** is the reflected angle.

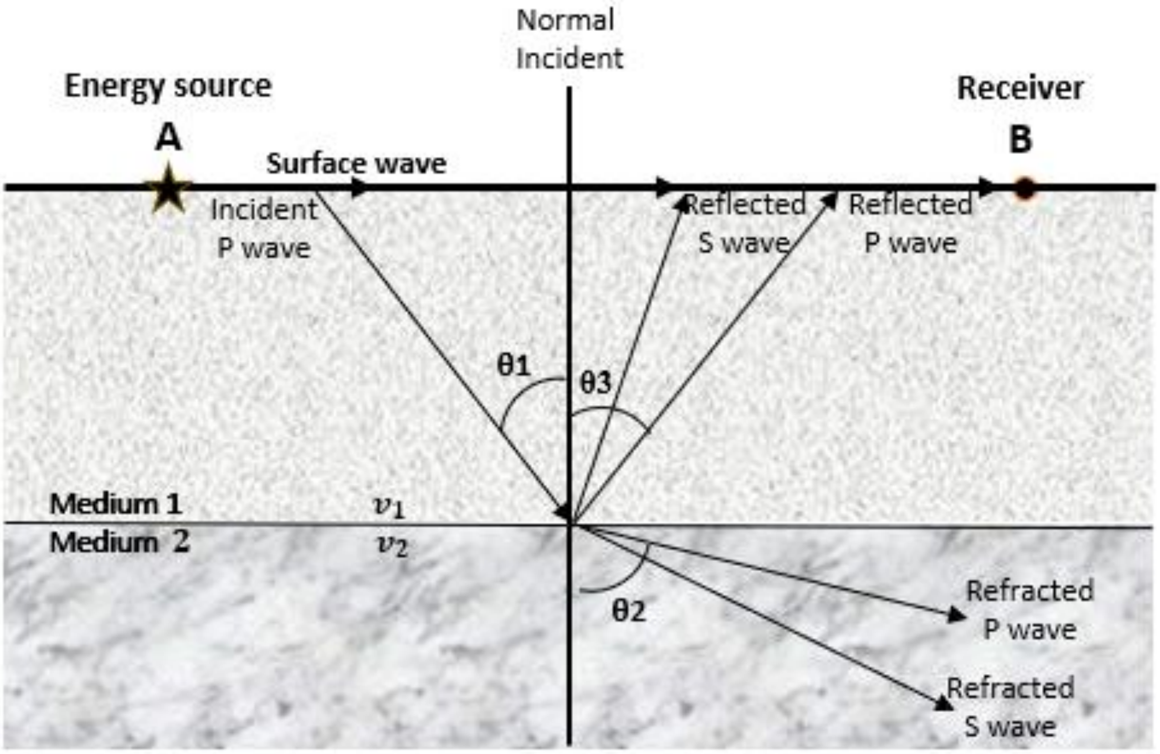


Figure 3. Cross-section illustrating various seismic wave paths modified from (Selley & Sonnenberg, 2015).

Seismic Sequence Analysis

Seismic sequence analysis involves identification of major reflection “packages” that can be delineated by recognizing surfaces of discontinuity. Discontinuities may thus be recognized by interpreting systematic patterns of reflection terminations along the discontinuity surfaces.

Seismic facies analysis plays a pivotal role in understanding the vertical arrangement of facies and their lateral movement through time in terms of Walther's Law. This approach, as outlined by Miall, (1999), involves the interpretation of sedimentary facies, which are lithostratigraphic bodies characterized by distinct lithological or fossil features, reflecting specific depositional origins. These sedimentary facies are part of larger depositional systems, comprising groups of facies linked by common processes and environments.

Each stratigraphic unit within the identified sequences exhibits unique geometry and seismic facies, or distinct variations in facies characteristics. These features are discerned based on acoustic properties such as frequency and amplitude, serving as proxies for different depositional environments. For instance, high-frequency, low-amplitude reflections may indicate shallow marine or fluvial environments, while low-frequency, high-amplitude reflections could signify deeper marine or deltaic settings (Pirini, Missiaen, Ori, & Batist, 1996)

Over time, depositional systems in a basin evolve, with abandoned systems becoming buried and potentially transforming into reservoir rocks. By combining seismic with well data, it becomes feasible to comprehend the depositional system sufficiently, allowing predictions of distribution and quality in unexplored areas (Bacon, Simm, & Redshaw, 2003).

A key concept in seismic facies analysis is the application of sequence stratigraphy, which is based on recognizing unconformity-bound, relatively conformable stratigraphic packages known as sequences. According to McLaughlin Jr (2005), sequence stratigraphy provides a framework for understanding the evolution and infill architecture of sedimentary basins. This methodology enhances predictive exploration of natural resources by emphasizing changes in depositional trends such as progradation, retrogradation, aggradation, and erosion.

The fundamental principle guiding sequence stratigraphy is the balance between accommodation space (space available for sediments to fill) and sediment supply. Changes in this balance over time result in distinct stratal stacking patterns, providing valuable insights into the history of sedimentary basins (Neto & Catuneanu, 2012). The recognition of sequences and their internal characteristics aids in deciphering the geological history of an area, facilitating more informed decisions in resource exploration.

According to (Posamentier & James, 1993) there are two different approaches to stratigraphy, Lithostratigraphy and Sequence Stratigraphy or Chronostratigraphy. Lithostratigraphy defines rock units based on the physical characteristics of the rocks, while sequence stratigraphy defines rock units based on chronostratigraphy and focuses on the importance of surfaces separating major sedimentary successions (**Figure 4**).

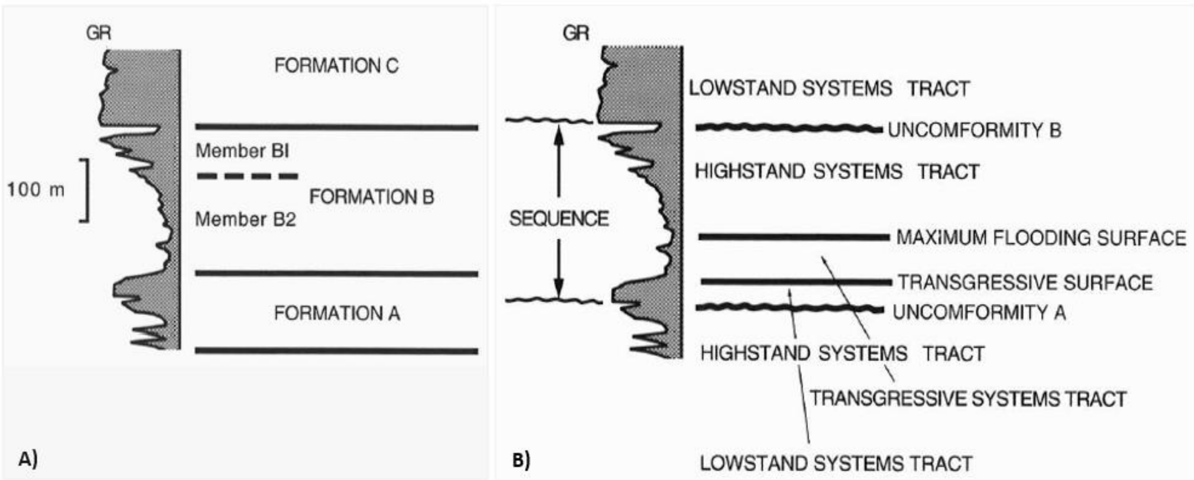


Figure 4. Two different approaches of "classical" stratigraphy, i.e., **A**) lithostratigraphy, and B) sequence stratigraphy or chronostratigraphy. (Posamentier & Allen, 1999).

<u>Seismic Attribute Analysis</u>

Seismic attributes play a crucial role in reservoir characterization, offering valuable insights into structural, stratigraphic, and petrophysical aspects of subsurface formations. These attributes are special measures derived from seismic data, capturing kinematic, dynamic, geometric, or statistical characteristics (Oumarou, 2021). In recent years, their application in reservoir characterization has significantly improved the understanding of reservoir properties.

Seismic attribute analysis involves the study of various wave characteristics, including shape, polarity, continuity, dip, frequency, phase, and amplitude. These attributes provide information related to the structure, stratigraphy, and reservoir properties of the subsurface. The analysis aids in indicating the thickness and nature of sand bed contacts, contributing to predictions of geometry and internal reservoir characteristic (Selley & Sonnenberg, 2015).

A fundamental seismic attribute is amplitude, typically reported as the maximum (positive or negative) amplitude along a picked horizon. There is a well-established correlation between amplitude and formation properties, such as porosity and saturation. Specifically, higher amplitudes in seismic data often indicate increased porosity or fluid saturation within the reservoir (Li & Wong, 2008), as illustrated in **Figure 5**.

Classification of Seismic Attributes

(Taner, Schuelke, O'Doherty, & Baysal, 1994), were the first to introduce a coherent classification for seismic attributes, creating two main categories: geometrical and physical. Geometrical attributes enhance features like dip, azimuth, and continuity, while physical attributes are related to subsurface properties and are 29 in total, linked to lithology. These attributes are derived from amplitude, frequency, and phase components of the seismic trace. Additionally, the attributes can be divided into pre-stack and post-stack, depending on the data processing stage from which they are derived.

(Chen & Sidney, 1997) classification divides attributes in two main groups: one based on wave kinematic/dynamics, and the second group based on geologic reservoir features and further sub-divisions depend on where the attribute is extracted and on the expected output.

Brown (2001) later proposed to classify attributes using a tree structure with branches for time, amplitude, frequency, and attenuation, with each branch being further divided in pre-stack and post-stack attributes. Time attributes provide information about structural geology while amplitude attribute give information on stratigraphy and reservoir properties.

Surface Attributes

A surface attribute is the value of an attribute relative to a single horizon and an interval window, between two horizons or within a constant time window. It can be computed in *Petrel* using the "*Surface Attributes*" processes under "*Geophysics*". Petrel 2008.1 has fifty surface attributes divided into four areas depending on the applied algorithm: *Amplitude*; *Statistical*; *Signal Shape* and *Measurable Interval*. In *Petrel,* surface attributes can only be computed in surfaces built from horizon interpretation.

In this research, RMS amplitude attributes were utilized to generate amplitude maps along the interpreted horizons, enabling the mapping of sand distributions (Brown, 2001). Seismic attribute analysis plays a crucial role in reservoir characterization, as it enhances the interpretation of subsurface features and aids in identifying potential hydrocarbon reservoirs. By integrating various seismic attributes, researchers gain a comprehensive understanding of reservoir characteristics, allowing for more accurate assessments of resource potential.

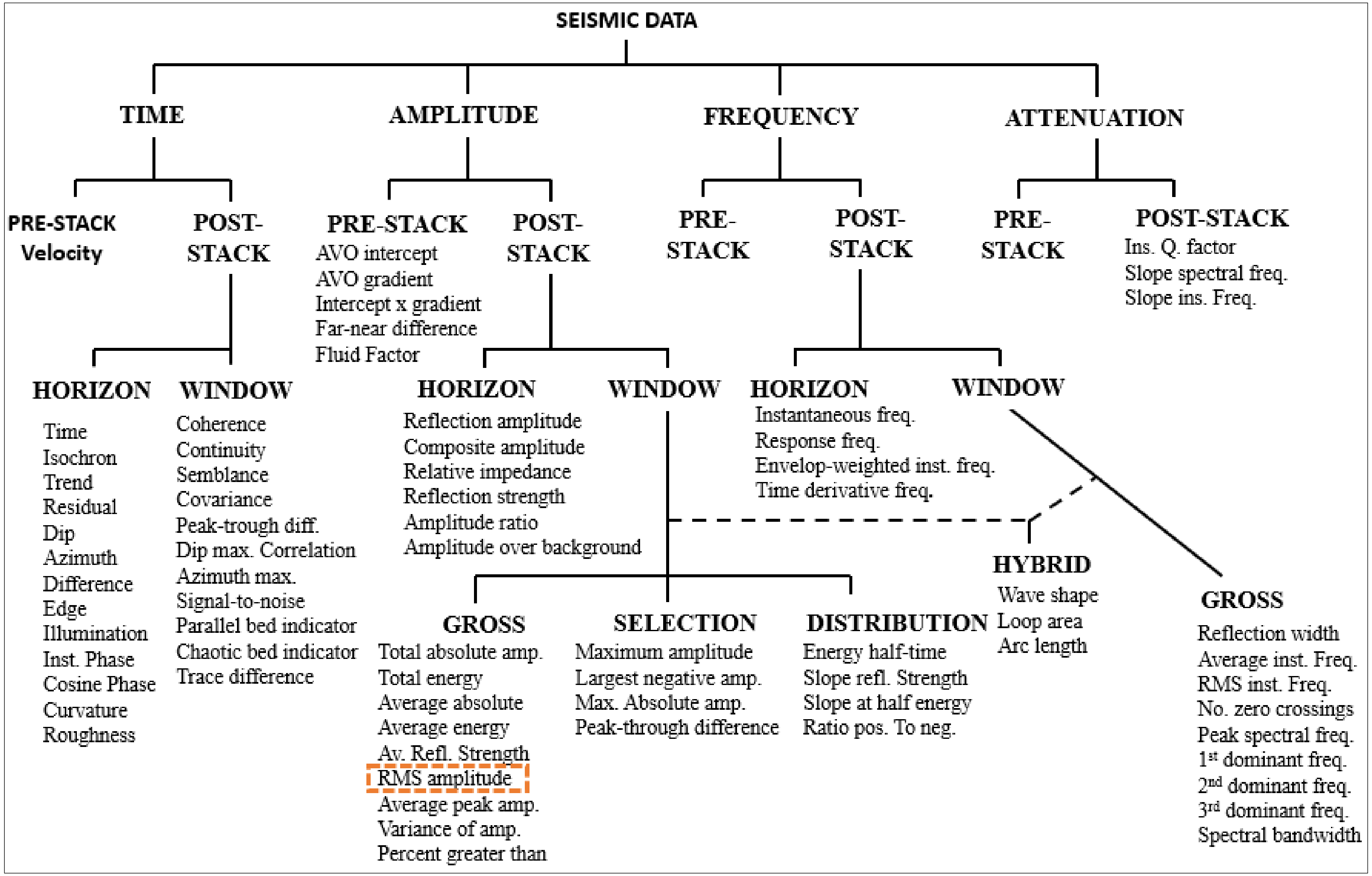


Figure 5. Classification scheme of seismic attributes, from basis seismic information of time, amplitude, frequency an attenuation (Brown, 2001)

Well Logs

Conventional well logs

There are nine conventional logs widely used for formation evaluation, comprising three lithology logs Caliper (CAL), Natural Gamma Ray (GR), Spontaneous Potential (SP), three porosity logs, Bulk Density (DEN, RHOB), Neutron Porosity (CNL, CNC, NPHI), Sonic Interval Transit Time (AC, DT)), and three resistivity logs (Micro, Shallow, Deep) (Zhang, Jin, Jiang, Wang, & Jia, 2015). These logs provide critical data for characterizing subsurface formations, identifying lithological properties, estimating porosity, and assessing fluid types, all of which are essential for effective geological interpretation and reservoir evaluation in oil and gas exploration (Nabawy, Rochette, & Géraud, 2010).

The Caliper (CAL) Log measures the borehole diameter and is commonly used to identify lithology, assess borehole shape and size, and recognize fractures and borehole breakouts. This data is essential for understanding subsurface conditions and ensuring accurate interpretation during formation evaluation (Lai, et al., 2024). Regarding (Glover, 2001) lithologies encountered in drilling vary based on the borehole diameter and formation permeability. Consolidated formations, such as sandstones and shales, are stable and non-permeable. Larger borehole diameter, like salt and brittle shales formations, can be weak or soluble, leading to instability. Smaller hole diameter, such as swelling shales and permeable sandstones formations, can cause issues like swelling and mudcake development.

Advanced well logs

Gamma Ray Logging

The GR log measures the natural radioactive elements in the rocks, specifically uranium, thorium, and potassium (Gamal, El-Araby, El-Barkooky, & Hassan, 2022). The GR log is considered the primary lithology identification log for sedimentary rock formation; shales can be easily detected by their high GR readings (Han, et al., 2022)

A rough estimation of clay volumes (Vcl) can be calculated using GR reading. By setting sand point, minimum GR reading (γmin) which indicates 100 % sand content, and shale point, maximum GR reading (γmax), which indicates 100 % shale content, GR index (I_{GR}) can be calculated by linear scaling, (Ellis & Singer, 2010):

$$I_{GR} = \frac{\gamma_{\log} - \gamma_{min}}{\gamma_{max} - \gamma_{min}} \quad \textbf{(Equation 2)}$$

Poupon and Gaymard (1970) proposed that shale volume is equal with IGR. Beside linear scaling, there are several different approaches that consider the effect of clay distribution in the reservoir rock, clay mineral, and clay bound. This method is visualized in **Figure 6**.

Gamma-ray (GR) logs are valuable tools for identifying shale and differentiating rock types, but they have limitations. While GR fluctuations indicate changes in mineralogy, they can be affected by various factors, leading to potential misinterpretation. Accurate analysis requires complementary data, such as mud logs and borehole conditions (like caliper logs and bit size), as well as additional wireline logs, including spontaneous potential (SP) and sonic logs (Nazeer, Abbasi, & Solangi, 2016).

A significant limitation of standard GR logs is their inability to distinguish between different radioactive minerals contributing to the gamma response. This lack of differentiation poses challenges when assessing clay content in reservoirs where clay may be kaolin (potassium-free and non-radioactive) or where other radioactive minerals, such as mica, glauconite, zircon, monazite, or uranium associated with organic matter, are present (Selley & Sonnenberg, 2015).

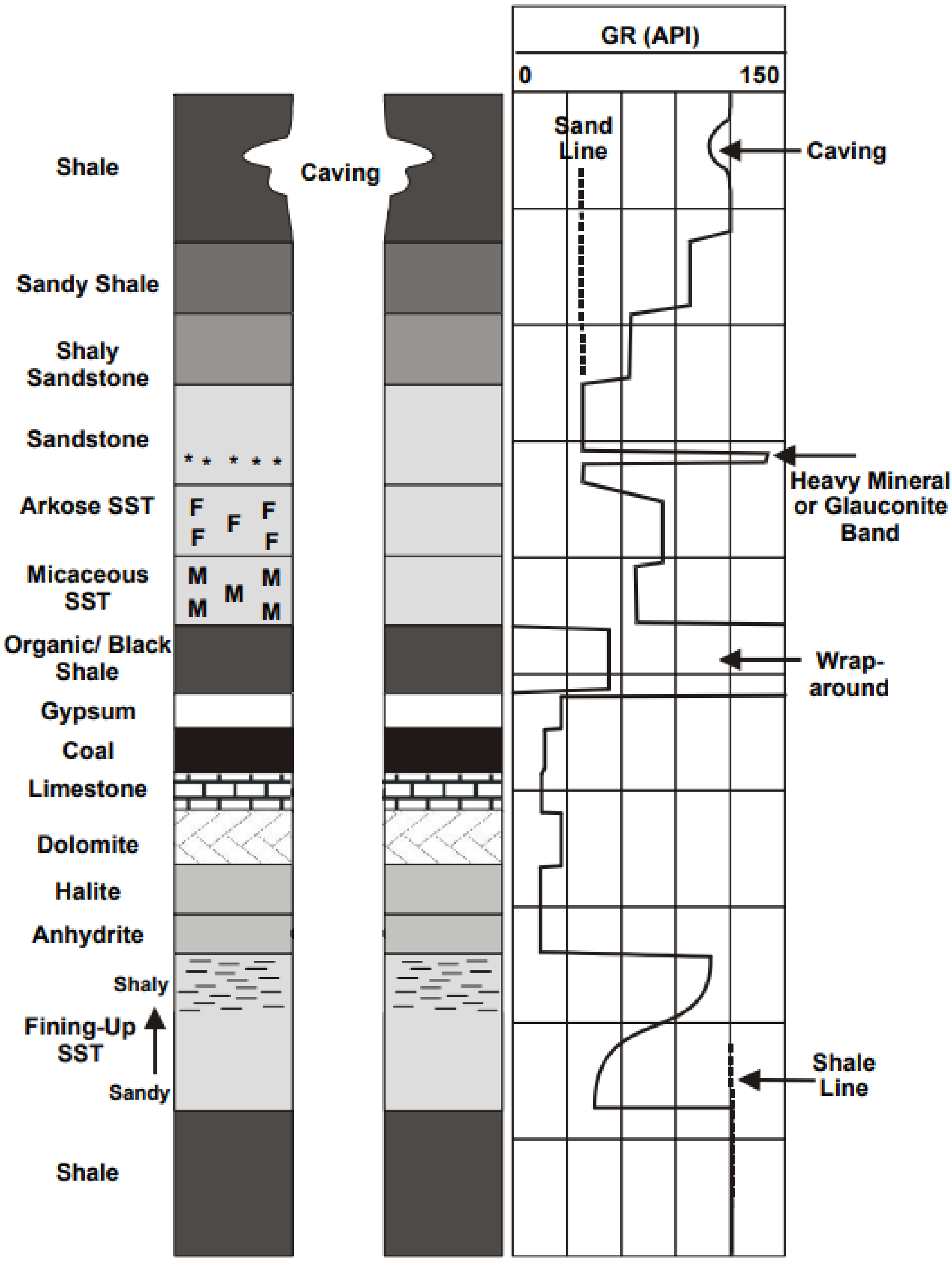


Figure 6. Effect of different lithologies on the gamma ray log (Glover, 2001).

Spontaneous Potential Log

SP log is firstly treated as a porosity indicator, and now is for identification of permeable zones indicating the amount of clay in the reservoir, determining the water flooding zone and calculating the formation water resistivity or even indicating depositional environment (Ellis, D. V; Singer, J. M., 2007). The SP represents the natural potential difference between the trajectory of the wellbore and the ground SP has a good effect in identifying sandstone with developed pores and mudstone (Lyu, Zeng, Liu, Liu, & Zu, 2016). Tight rocks such as calcareous mudstone and shale often have higher electrical resistance than mudstone. However, SP is also affected by the type of reservoir fluid, salinity, and saturation.

Neutron Log

The neutron log, as its name suggests, is produced by a device that bombards the formation with neutrons from an Americium beryllium or other radioactive source. Neutron bombardment causes rocks to emit gamma rays (GR) in proportion to their hydrogen content (Selley & Sonnenberg, 2015).

The neutron logs are used for porosity calculation, which assumes that the contribution of elements other than hydrogen is negligible. The second use of neutron logs is lithology determination. The source of a hydrogen atom is not only from fluids occupying the pore space, but it can be originated from bound water molecules in shales, crystallized water in evaporites, or hydrated minerals in igneous and metamorphic rocks (Glover, 2001).

The apparent porosity of shale is varying, but it is usually higher than the apparent porosity identified in carbonate and sandstone rocks. This high porosity reading by neutron tool is caused by the effect of hydrogen contained in the bound water in shale. However, shale identification by using neutron log requires extra concern due to the effect of hydrocarbon gas which may be present and disturbs the log (Corina, 2016).

Electrical Log (Resistivity)

The main use of the electrical tools is to calculate the water saturation of a reservoir formation, and hence the STOOIP. The electrical tools also have a number of qualitative uses, principle of which are (i) indications of lithology, (ii) facies and electro-facies analysis, (iii) correlation, (iv) determination of overpressure, (iv) determination of shale porosity, (v) indications of compaction, and investigation of source rocks.

Density Log

This is the third type of radioactivity tool that employs gamma radiation to measure formation density. It emits gamma radiation into the formation and records the amount that returns. The tool automatically corrects for borehole diameter and mud cake thickness effects. The corrected gamma radiation reading correlates with the electron density of the formation's atoms, which, in turn, is directly linked to the bulk density of the formation. Bulk density, a key parameter influenced by lithology and porosity, plays a crucial role in reservoir characterization and resource estimation. Porosity, a measure of pore space within the rock, can be calculated using established Equation 3, such as the one proposed by Selley and Sonnenberg (2015). This tool provides valuable information into formation properties, aiding in geological and reservoir assessments crucial for hydrocarbon exploration and production endeavors. The porosity can be computed using the equation below (**Equation 3**).

$$\emptyset = \frac{\sigma_{ma} - \rho_b}{\rho_{ma} - \rho_f} \qquad \textbf{(Equation 3).}$$

where σ_{ma} is the density of the dry rock ρ_b is the bulk density recorded by the log, and ρ_f is the density of the fluid, all given in g/cm^3.

The density log alone is not ideal for lithological identification because different rocks, such as shales, sandstones, and limestones, have overlapping density ranges due to varying mineral compositions and porosities (**Figure 7**). However, when combined with the neutron log, which measures hydrogen content and provides porosity information, the two logs offer a more accurate method for identifying lithologies. The neutron-density crossplot enhances rock differentiation, making the combined logs a powerful tool for subsurface geological interpretation (Glover, 2025).

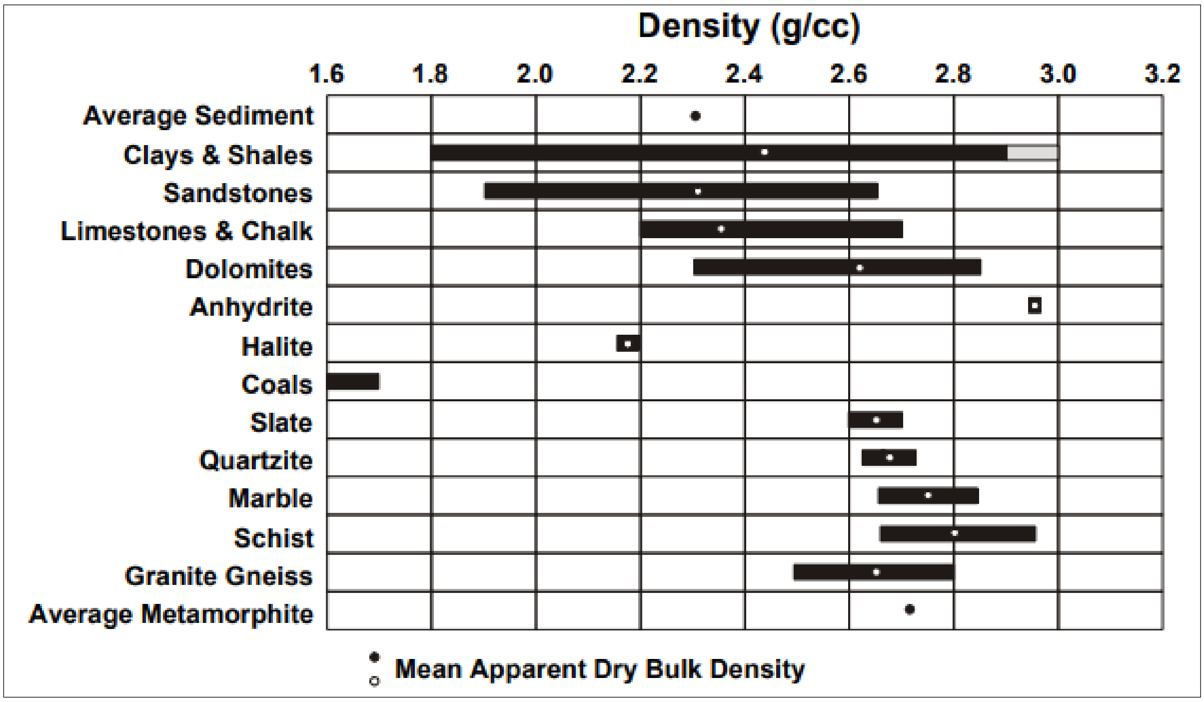


Figure 7. Density ranges of common lithologies (Glover, 2001).

Acoustic or Sonic Log

The acoustic or sonic log is the least accurate log of the three used for porosity estimation because it is highly affected by lithology (Selley & Sonnenberg, 2015). The interval transit time (Δt), (**Equation 4**) which is measured in microseconds per foot, can then be used to calculate porosity according to the Equation 4 (Wyllie, 1956).

$$\emptyset = \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \qquad \textbf{(Equation 4)}$$

where Δt_{log} is the interval transit time recorded on the log, Δt_{ma} is the velocity of the rock at $\emptyset = 0$, and Δt_f is the velocity of the pore fluid.

The sonic method, while considered the least accurate of the three porosity logs due to its susceptibility to lithology effects, holds significant value in lithology identification and well-to-well correlation. Its sensitivity to lithology variations makes it a valuable tool for distinguishing between different rock types and formations (Selley & Sonnenberg, 2015). Consequently, it is widely employed in the oil and gas industry for lithological characterization and correlation purposes.

Log Motifs

When working with subsurface information in the absence of core or nearby outcrop data, the interpreter commonly must make do with wireline logs for the detailed analysis of depositional environments. As discussed above the interpretation of depositional environments from well logs in the absence of cores is somewhat speculative.

In siliciclastic deposits, these well-log signatures often signal a gradual shift toward higher-energy environments, categorized simply as boxcar shape, funnel shape, bell shape, symmetrical or bow shape and serrated/irregular shape (Posamentier & Allen, 1999).

Boxcar shape

This type of log shape is characterized by sharp boundaries at the upper and bottom boundaries with relatively consistent gamma log readings which indicate consistent lithology. In the simple words cylindrical/boxcar trends shows uniform lithology overall (Nazeer, Abbasi, & Solangi, 2016).

(Cant, 1992) defined boxcar trend as clean trend and considered aeolian (sand dunes), fluvial channels, carbonate shelf (thick carbonate), reef, submarine canyon fill as suitable environment of boxcar shape. (Selley R. , 1978), considered (a) tidal sands, (b) grain flow fill and (c) prograding delta distributaries channels as favorable sedimentary environment for funnel shape environment in clastic.

Funnel shape

In the funnel shape, GR values decrease upward consistently from maximum value of log reading in trend, or may decrease relatively from maximum values, indicating decrease of shale content, forming coarsening upward trend overall. The funnel motif indicates coarsening or cleaning upwards of thick sediments with rapid deposition in clastic (Chow, Ching, & Fuh, 2005).

Bell shape

In the bell shape, GR values increase upward consistently from minimum value of log reading in trend, or may increases relatively from minimum values, indicating increasing shale content, forming fining upward trend (Nazeer, Abbasi, & Solangi, 2016).

The bell-shaped successions are usually indicative of a transgressive sand, tidal channel, or deep tidal channel and fluvial or deltaic channel. Fluvial point bar, tidal point bar, deep sea channels, braided streams, detail distributaries, proximal deep-sea setting are associated with bell shape in literature (Nazeer, Abbasi, & Solangi, 2016). The bell-shaped successions with carbonaceous detritus are deposited in environments of fluvial or deltaic channels (Selley R. , 1978).

Symmetrical shape

This shape is formed as gradual cleaning upward sequence which changes from its maximum value with dirtying-up trend of similar grain size without sharp breaks. The opposite of this, the trend is right bow shape (Nazeer, Abbasi, & Solangi, 2016).

Serrated/saw tooth shape

Serrated shaped GR log motifs is consisted of fluctuated GR reading with high and low values over very short interval of vertical well profile. Such trends show variation of lithology in laminated beds, beds of shale and sand. Such trend may represent the slope deposits and sometime called as turbidities (Nazeer, Abbasi, & Solangi, 2016).

The serrated sandstone log motif is another electrofacies element that can be observed in a broad variety of depositional environments, ranging from fluvial to deep marine. This pattern is indicative of a heterogenous lithofacies, at least at the scale of wireline-log data. A heterogenous succession implies deposition under the influence of rapidly alternating high and low energy such that when environmental energy is high, sand is deposited (if available), and when energy is low, mud or silt is deposited (Posamentier & Allen, 1999).

The **Figure 8,** displays five primary types of log curves, each corresponding to specific sedimentological environments and their characteristic grain size profiles. These log curves demonstrate a direct correlation between facies types and various other log shapes, reflecting sedimentological relationships within the studied environments (**Table 1**).

Table 1. Shows five major types of log curves, sediment supply, GR log profile behavior, and possible depositional environments, modified from (Selley R., 1978).

Log Motif	Cylindrical/box	Funnel shape	Bell shape	Symmetrical	Serrated/saw
Sediment Supply	Aggradation	Progradation	Retrogradation	Prograding & Retrograding	Aggrading
Characteristic	Sharp top and base with consistent trend	Abrupt top with coarsening upward trend	Abrupt base with fining upward trend	Ideally rounded base and top	Irregular pattern/spikes of GR log
Grain size	Relative consistent lithology	Grain size Increases	Grain size decreases	Cleaning upward trend changes into dirtying up sequence from top	Inter-bedded shales and Sands
Depositional Environment	Aeolian (sand dunes), fluvial channels, carbonate shelf (thick carbonate), reef' submarine canyon fill, tidal sands, prograding delta distributaries	Crevasse splay, river mouth bar, delta front. shore face, submarine fan lobe	Fluvial point bar, tidal point bar, deltaic distributaries, proximal deep sea, setting	Sandy offshore bar, Transgressive shelf sands and mixed tidal flats environment	Fluvial flood plain, mixed tidal flat, debris flow and canyon fill

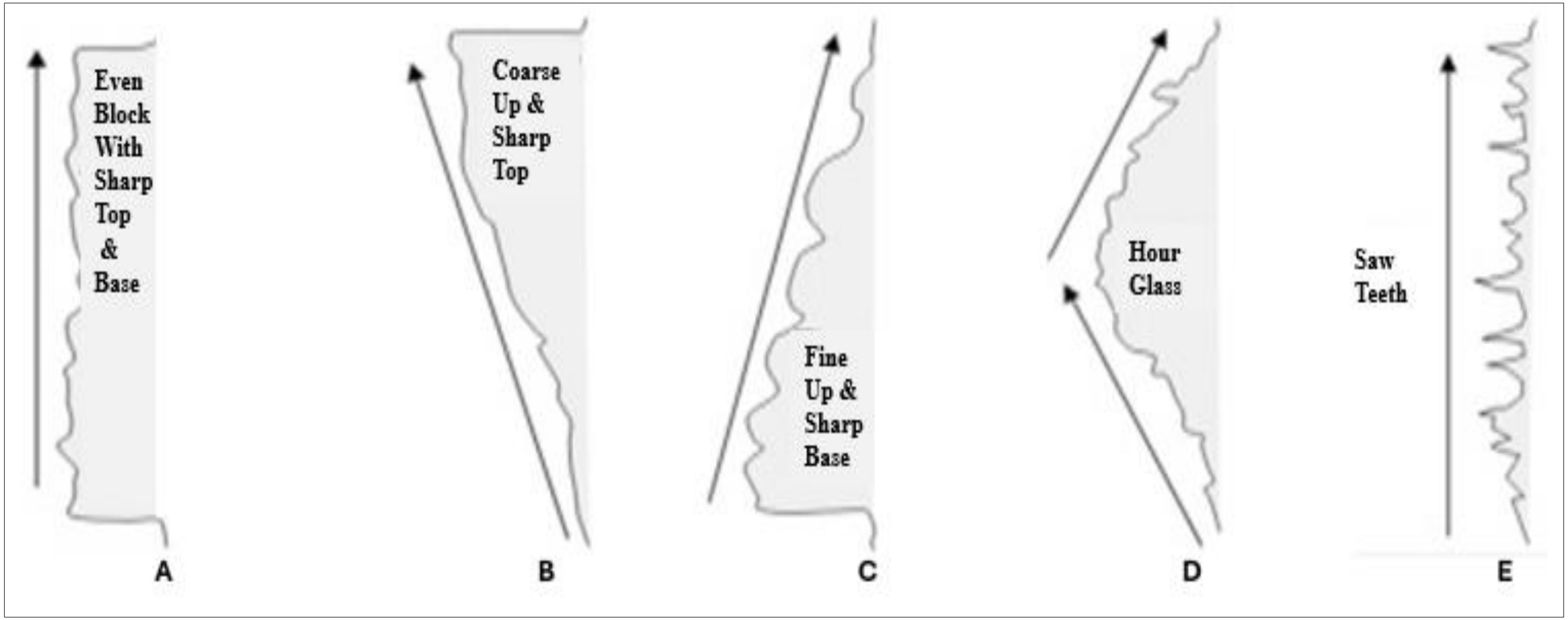


Figure 8. Shows five major types of log curves: A-Cylindrical/box; B-Funnel shape; C-Bell shape; D- Symmetrical & C-Serrated/saw. Vertical profiles of grain size in specific environments modified from Selley (1978) and Nazeer, Abbasi, and Solangi (2016).

2.6 Summary

Seismic facies description and the interpretation of seismic reflectors are integral components of subsurface characterization in the field of geology and geophysics. By analyzing the patterns and attributes of seismic reflections, geoscientists can infer valuable information about lithology, sedimentary environments, and depositional processes. This understanding allows for the reconstruction of subsurface, identification of depositional systems such as fluvial, marine, or deltaic, and assessment of the interplay between factors like accommodation space and sediment supply through time. Such insights not only contribute to our scientific comprehension of sedimentary basins but also have practical applications in the exploration and exploitation of natural resources, particularly hydrocarbons.

Seismic attribute analysis further enhances reservoir characterization by providing detailed information about subsurface properties and structures. By analyzing attributes such as amplitude, frequency, and continuity of seismic reflections, delineate reservoir boundaries, identify structural traps, and assess reservoir quality. The integration of various seismic attributes offers a holistic understanding of reservoir architecture, facilitating more informed decision-making in exploration and development activities.

In the realm of well logging, lithology identification remains a fundamental task. Well logs, which record various properties of subsurface formations, serve as invaluable tools for characterizing reservoir facies and deciphering depositional environments. By analyzing log responses to different lithologies, geologists can infer lithology variations within the reservoir and assess their impact on reservoir properties such as porosity and permeability. This detailed understanding of lithology is essential for optimizing reservoir development strategies and maximizing hydrocarbon recovery.

CHAPTER III

RESEARCH METHODS AND STRATEGIES

3.1 Introduction

The research methods and strategies focus on achieving seismic stratigraphy characterization and understanding depositional environments in the onshore northern part of the Buzi Block. The methodology includes seismic interpretation, analysis of seismic reflection patterns, extraction of RMS seismic attributes, classification of lithology, and analysis of log motifs. These methods are integrated to identify and characterize depositional environments within the study area.

3.2 Alignment of Methods and Strategies to the Research Study

This work will use the workflow used for similar work in the oil and gas industry, which will consist firstly in review literature related to the regional geology of the Mozambique basin and geo-tectonic framework of the Buzi area, understanding of the hydrocarbon prospectivity in Mozambique basin.

The subsequent step is the use of the Petrel software to project setup where will be applied the following workflow (**Figure 9**).

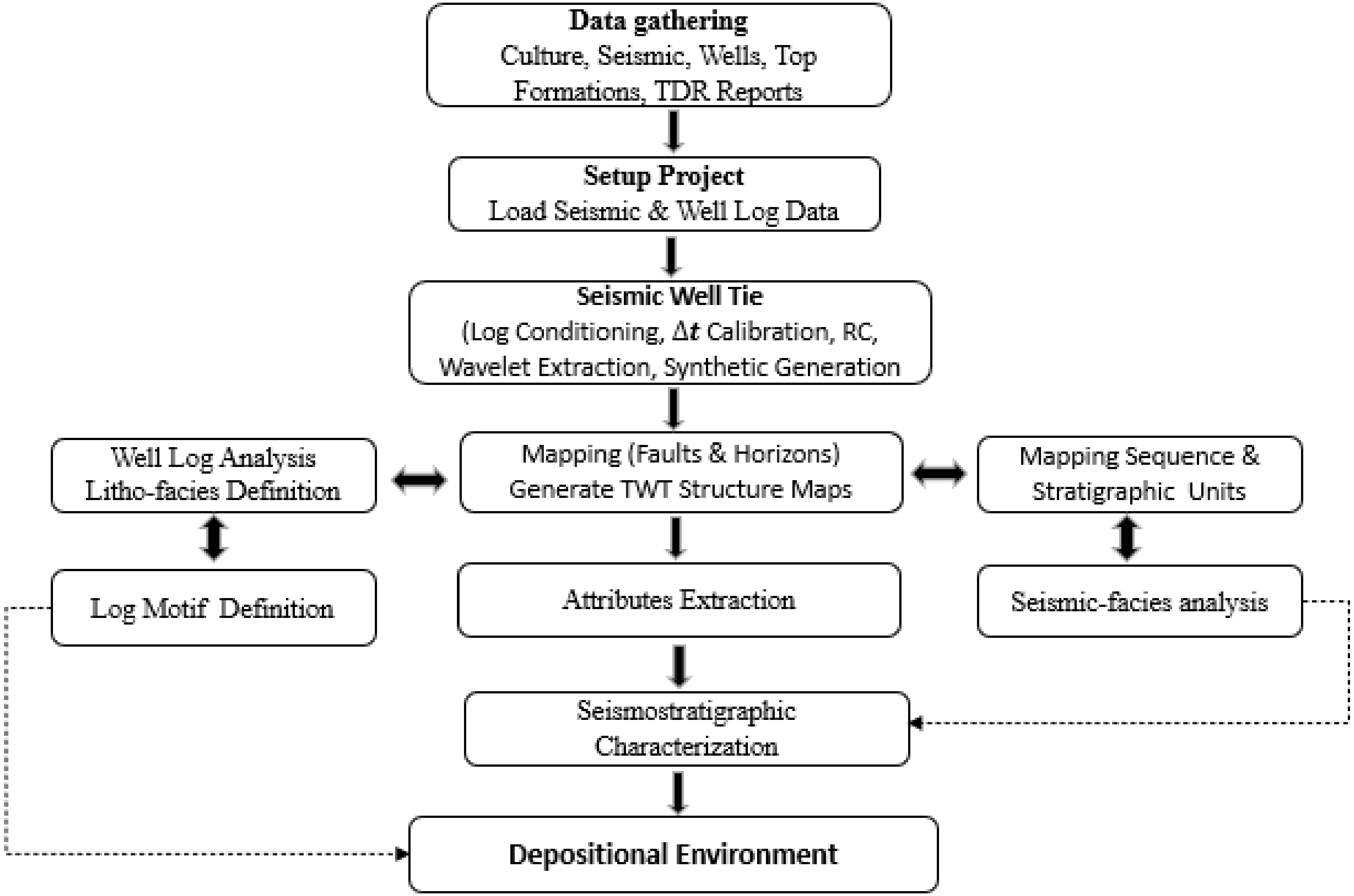


Figure 9. Workflow for seismic stratigraphy characterization and depositional environment definition.

3.3 Study Validation

This involves assessing data quality through factors like resolution and consistency. Cross-validation compares results from seismic facies analysis, RMS seismic attribute analysis, lithology classification, and log motif analysis to ensure coherence. Geological calibration aligns interpretations with existing knowledge. Expert review and peer feedback validate interpretations.

3.4 Research Methods

Structural Analysis:

Fault and Tectonic Analysis: Analyzing faulting and tectonic activity within the study area by interpreting seismic data and correlating seismic anomalies with structural features, such as fault-blocks, anticlines, and synclines. This helps in understanding subsurface traps and the geological history of the area.

Structural Mapping: Creating structural maps to highlight key features like fault systems, fold structures, and other tectonic deformations. This information is essential for interpreting sediment deposition and evaluating potential hydrocarbon reservoirs.

RMS Seismic Attribute Analysis: Applying Root Mean Square (RMS) seismic attribute analysis to identify key seismic attributes like amplitude, which help delineate depositional environments and structural features.

Seismic Facies Analysis:

Identification of Seismic Facies: Analyzing seismic reflection patterns to identify different seismic facies within the study area. This helps in distinguishing variations in sedimentary environments, such as marine, deltaic, or fluvial settings.

Well Log Analysis:

Log Motif Interpretation: Analyzing well log data (e.g., gamma ray (GR), logs) to identify typical log motifs (e.g., clean sand, shale, or carbonate intervals) associated with different depositional environments.

Correlation of Seismic Data with Lithology: Using seismic facies to correlate with known well log data, allowing for the identification of the depositional environment and sedimentary processes within each formation.

Sedimentary Environment

Depositional Environment Interpretation: Based on seismic data, well logs, and lithological descriptions, interpreting the depositional environment for each formation (e.g., marine, deltaic, lacustrine). This involves classifying facies sequences and identifying key indicators of sedimentary processes.

3.5 Procedures to Answer Research Questions and Validate Solutions Development of method (model, procedure, experiments, equipment)

The reflection seismic methods make it possible to determine structures and geological surfaces in the subsurface, which allow, with the support of geophysical profiles (which contain lithological and petrophysical information), the construction of detailed geological models.

The workflow, to apply to answer the research questions and validate solutions developed methods in the interpretation of 2D seismic data in the onshore region of the Mozambique basin (Buzi field) (Buzi), will consists of:

(i) Analysis of composite well profiles; (ii) Interpretation of formation tops and lithostratigraphic correlation between wells; (iii) Well-seismic tie, using checkshot/VSP integrating DT and RHOB curves; (iv) Interpretation of the main stratigraphic horizons; (v) Generate of structural contour maps of the main interpreted horizons; (vi) Extract surface attribute (RMS).

Prior to seismic mapping, a critical step involves the seismic well-tie, utilizing check-shot/VSP data. This process ensures a robust correlation between seismic and well data, establishing a reliable relationship. This method is essential for accurate seismic interpretation, particularly when dealing with time-domain data.

The seismic data will be used to map the depositional sequences and to identify and describe the different units that make up each depositional sequence through the different terminations that the seismic facies present. The analysis and extraction of seismic attributes will be carried out to discriminate the geometry of geological bodies and associate them with certain depositional environments.

Log analysis will play a crucial role in defining litho-facies and ultimately establishing log motifs. By examining various well log measurements such as gamma ray, resistivity, neutron, density, and sonic, litho-facies will be characterized based on their distinct log responses. These litho-facies classifications will serve as the foundation for identifying recurring patterns and trends, leading to the establishment of log motifs. Through this approach, the research aims to gain insights into the depositional environments and sedimentary processes within subsurface reservoirs.

3.6 Strategies to address the Research Questions

The strategies employed in this research aim to address the research questions by leveraging advanced analytical techniques and comprehensive data analysis. Here's how each strategy aligns with the research questions:

Seismic Facies Analysis

The strategy consists of analyzing seismic facies patterns to identify depositional sequences, structural trends, and sedimentary features observed in the 2D seismic data.

Addressing Research Question 1: This strategy directly addresses the first research question by examining seismic facies patterns to understand the depositional sequences and structural trends within the study area.

RMS Seismic Attribute Analysis:

Here the strategy consists of utilizing RMS seismic attribute analysis to enhance the understanding of depositional environments.

Addressing Research Question 2: By employing RMS seismic attribute analysis, this strategy aims to provide insights into the depositional environments present in the study area, directly addressing the second research question.

Log Motifs:

The strategy is identifying dominant log motifs in well log data and correlating them with depositional environments and sedimentary processes.

Addressing Research Question 3: The identification of dominant log motifs in well log data allows for the correlation of these motifs with specific depositional environments and sedimentary processes, directly addressing the third research question.

Integration and Interpretation:

Integrate the findings to interpret geological implications and provide recommendations for reservoir characterization and hydrocarbon exploration strategies.

Addressing All Research Questions: This final strategy integrates the findings from seismic facies analysis, RMS seismic attribute analysis, and log motif identification to interpret the geological implications for reservoir characterization and hydrocarbon exploration strategies. It ties together the insights gained from each analytical technique to address the overarching research objectives comprehensively.

3.7 Research Validation

The research validation plan for this thesis involves rigorous steps to ensure the accuracy and reliability of the findings. It includes collecting data, validating analytical methods, cross-validating results, seeking expert review, conducting case studies and continuously improving methodologies.

3.8 Study Limitations

The hydrocarbon exploration activities have been growing in Mozambique in recent years, and there are several companies that scale the country looking to acquire a concession for the exploration of hydrocarbons. Given area of research, however, without looking at detailed geology and geophysics studies, it seeks to know the possible source rock for hydrocarbons.

In this context, these works are sometimes done superficially and in the event of a drilling well being executed and the result is dry well, it ends up compromising the existing hydrocarbon potential in the Mozambique basin, leading the concessionaire to abandon the block without knowing the real block potential.

The biggest limitation to carrying out this project can be associated with the availability of sparse seismic and well data information and considering this factor to achieve the goals set, it involves bringing state institutions that may hold this information to access it. for the research work and to exploit as much as possible the little existing data and to draw analogies to reach the desired results.

It is also important to point out that the major limitation may be associated with the quality and resolution of the 2D seismic data that will be used largely for the study and many of the existing 2D data have a resolution between 20 – 30 meters.

Seismic profiling is a crucial tool in subsurface exploration, particularly in the oil and gas industry. The main distinction between 2D and 3D seismic profiles lies in their acquisition methods, resolution, and application scope. A 2D seismic profile involves collecting seismic data along a single line, generating a vertical cross-section of the Earth's subsurface. This method provides a relatively quick and cost-effective way to understand the regional geology, but its coverage is limited to the area directly beneath the line. As a result, it may miss complex geological structures located between acquisition lines, making it less reliable for detailed reservoir characterization.

In contrast, a 3D seismic profile collects data over an entire surface area using a grid of sources and receivers, creating a three-dimensional volume of seismic information. This approach allows interpreters to analyze the subsurface from multiple angles and with much greater spatial resolution. The increased detail provided by 3D seismic makes it invaluable for accurately mapping reservoir boundaries, faults, and stratigraphic features. However, it comes with higher costs and longer processing times compared to 2D surveys. While 2D seismic is commonly used during early exploration phases for broad geological understanding, 3D seismic is typically employed in later stages for development planning and reservoir management due to its precision and reliability.

The expectation of this work is to develop a project that will help to understand if the wells drilled in study area (Buzi block) are emplaced out of geological structure. and this study project should be used as a reference for future investigations works related with the potential for hydrocarbon occurrence in Mozambique basin and therefore, the use of simplified correlations presented in the proposed work offers a great advantage to optimize activities in Mozambique basin.

The challenge to carrying out this research is associated with the type of seismic data acquired in this block, only 2D seismic data is available in this concession and considering that

Buzi block is a brown field it means that there is a discovery and to mature this kind of field is recommended to acquire and use 3D seismic for interpretation.

To calibration process known as ``seismic well-tie´´ which consist in calibrate seismic data and well data, its need to have all well data information with all conventional logs checkshot and/or vertical seismic profile (VSP), data which represent time and depth relationship and not all well in the study area have this information.

Seismic resolution, crucial in oil and gas exploration, gauges the smallest detectable feature in data. Used widely, seismic data aids subsurface understanding, identifying structures and faults. Vertical resolution, dependent on source signals and earth filtering, impacts depth measurements. Frequency adjustments and filtering enhance vertical resolution in seismic interpretation.

3.9 Summary

The research methods focus on characterizing seismic stratigraphy and understanding depositional environments in the onshore northern Buzi Block. Methodology includes seismic interpretation, analysis of reflection patterns, RMS seismic attribute extraction, lithology classification, and log motif analysis. These methods integrate to identify and characterize depositional environments.

The workflow draws from the oil and gas industry, starting with literature review on regional geology and tectonic framework. Data quality is ensured through resolution and consistency checks, with cross-validation across seismic facies, RMS attributes, and lithology classifications. Seismic well-tie using check-shot/VSP data is critical for accurate interpretation. Seismic data maps depositional sequences and identifies seismic facies terminations. Attributes extracted from seismic data discriminate geological bodies and correlate with depositional environments. Log analysis, incorporating gamma ray, resistivity, neutron, density, and sonic logs, defines litho-facies and establishes log motifs, crucial for understanding subsurface sedimentary processes and reservoir characterization.

CHAPTER IV

CASE STUDY

4.1 Study Area

The study area is within the Mozambique Basin (**Figure 10**). The Mozambique Basin is located along the eastern margin of central and southern Mozambique, it occupies the coastal plain of Mozambique, extending onto the continental shelf and slope.

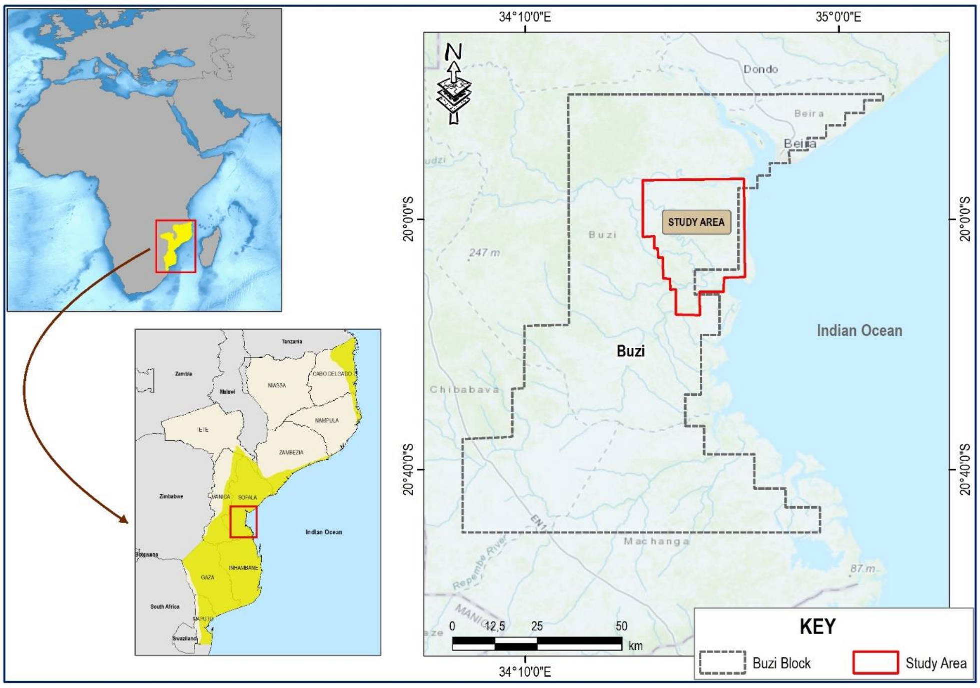


Figure 10. Location of study area Northern part of Buzi Block, Mozambique Basin.

Regional Geology

The portion of Mozambique Basin covers an area of approximately 500,000 km2, of which 275,000 km2 are onshore and 225,000 km2 offshore out to the 2000 m isobath (ENH & ECL, 2000).

The Mozambique basin is characterized by Nort-South (N/S) and North West-South East (NW/SE) structural trends (**Figure 11**). Where the main structural elements are: Lebombo Monocline, Nuanetsi-Sabi, Palmeiras graben, Changani graben system, Lower Zambeze graben, Mazenga Graben System, Chissenga graben, Limpopo graben, Chidenguele graben, Xai-Xai Graben, Urema Graben, Zambeze delta depression, Beira high, Angoche volcanic zone (ENH & ECL, 2000).

The sedimentary Mozambique Basin was formed as a result of the break-up of Gondwana and formation of the Indian Ocean at the end of the Mesozoic. Pre-Cambrian crystalline and metamorphic rocks form a common basement for the basin. The sedimentary cover is subdivided into two units: the Gondwana and post-Gondwana units separated by a major discordance (Salman & Abdula, 1996).

The sedimentary fill is composed of Upper Jurassic sediments which overlay the volcanics rocks, Cretaceous and Cenozoic rocks which discordantly overly the Karoo basalts. The Upper Jurassic occurs as continental Red-Beds, mostly distributed within buried grabens. Cretaceous rocks occur as terrigenous sediments of continental and marine genesis. Cenozoic deposits are of predominantly marine and deltaic origin (Salman & Abdula, 1996).

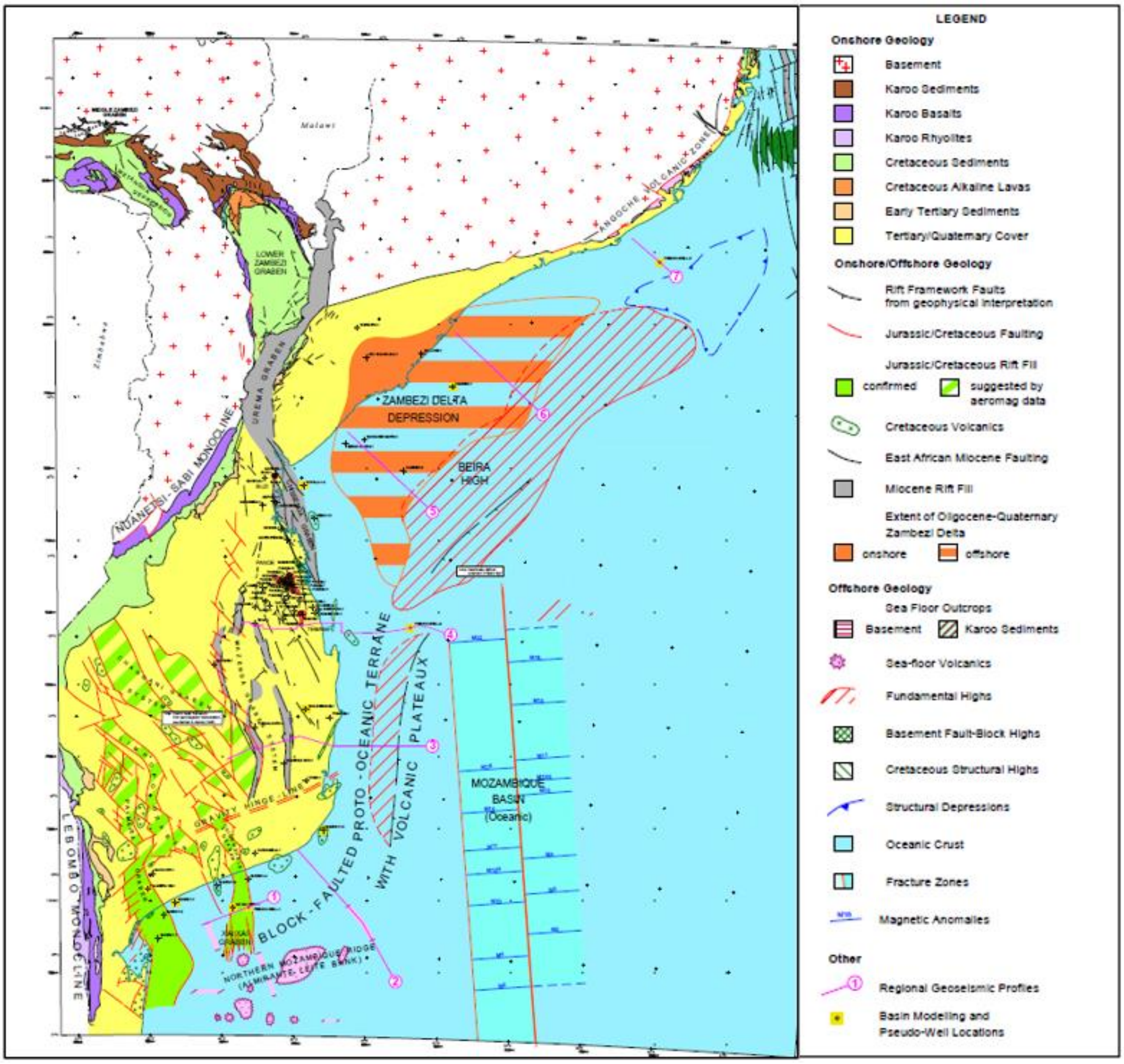


Figure 11. Mozambique Basin structural framework (ENH & ECL, 2000).

Stratigraphy of Mozambique Basin

According to (ENH & ECL, 2000), two Megasequence are recognized in Mozambique Basin. Intra-volcanic and Drift Megasequence. The Drift Megasequence encompasses four (4) sedimentary sequences with several geological (**Figure 12**), described below:

I. Sequence 1 (Late Jurassic – Late Cretaceous)

This Sequence 1, encompasses the Lupata, Sena, Red Beds and Maputo formations and represents the initial flooding of the shelf in the Late Jurassic and subsequent deposition of the first true drift deposits.

a. *Lupata Formation*

This formation is equivalent to the Red Beds Formation in the northwest part of the basin as continental sandstones.

b. *Sena Formation*

The Sena Formation occupies the central and northern parts of the Mozambique Basin. This is a continental rock sequence of variegated fluvial and alluvial formations: arkose sandstones, conglomerates and argillites enriched with coaly detritus. The Sena Formation deposits are widely developed in the Lower Zambezi graben and have been penetrated by boreholes in the central part of the basin. The thickness of this formation in the Nhamura-1 well is 2700 m. The Sena Formation continental sediments also include deposits of Upper Cretaceous (Cenomanian- Turonian) age.

c. *Red Beds Formation*

The Red Beds Formation is found in the southern part of the Basin at the base of the post-Karoo sedimentary section with a thick (over 900 m) as a layer of red of continental sediments. The formation is distributed in the Palmeira and Chidenguele grabens and is evidently developed in the axial zone in the Changani graben system to the west. Towards the east the facies change from continental sandstones of the Lupata Formation to deposits of the ancient delta, a sandy clay layer of which has been penetrated by the Nhamura-1 borehole.

d. *Maputo Formation*

The Maputo formation is marine equivalent of Sena Formation. The time at which the "Red Beds", Lupata and Sena formations and their equivalents were formed is typified by intense volcanic activity.

II. Sequence 2 (Domo Formation)

This sequence represents the major Mid Cretaceous drowning of the shelf and widespread deposition of basinal facies throughout the Mozambique Basin. Three (3) formations have been identified according to their stratigraphic position and lithology: Lower Domo Shale, the Domo Sandstones (Upper Cenomanian-Turonian); Upper Domo Shales (Turonian-Lower Senonian). The formations lie on the eroded surface of the underlying deposits.

a. *Lower Domo Shales Formation*

The Lower Domo Shale is distributed in the southern and central areas of the Mozambique Basin, both onshore and offshore, where it occurs as dark marine argillites with occasional bands of arkose sandstones. The thickness varies from 700 to 1500 m. The argillites contain Aptian-Albian and Cenomanian fauna.

b. *Domo Sandstones Formation*

The Domo Sandstones Formation is the basal unit and occurs primarily as quartzose sandstone, interbedded with dark argillite. The sandstones are distributed in the central part of the Mozambique Basin, where their total thickness exceeds 200-250 m. Towards the south and east the sandstones decrease in importance and the section becomes primarily argillaceous.

c. *Upper Domo Shale Formation*

The Upper Domo Shales Formation is a sequence of dense clays, 600-650 m thick. The maximum thickness of these has been reported in the Sengo Marin-1 well as 1225 m. These deposits are also known in the central part of the basin where they grade into continental sandstones and become part of the Sena Formation sequence towards the northwest.

III. Sequence 3 (Grudja Formation)

This sequence represents the continued infilling of the basin by clastics in the Late Cretaceous and then, when siliciclastic input diminished, a switch to an increasingly carbonate rich environment in the Early Tertiary and encompasses Lower and Upper Grudja formations.

a. *Lower Grudja*

The Lower Grudja Formation is spread widely in the central part of the basin, where it has been encountered in most of the wells. In the north of the basin the sediments of the Lower Grudja Formation are developed along the western flank of the Zambezi Delta Depression. The formation occurs as a layer of clay with bands of glauconitic-quartzose sandstone. Commercial gas pools have been found in different layers. The thickness of the sandstone layers varies from a few meters to as much as 50 m.

The overall thickness of the sequence in the central part of the basin reaches 1100-1200 m and decreases at the periphery. Because of subsequent erosion, deposits of the Lower Grudja Formation are absent from the buried elevated areas and horsts in the southern parts of the basin. The sandstone beds are buried shoals and bars which had formed in a shallow water shelf environment. Towards the east the sandy bodies gradually disappear from the section and synchronous deposits occur as a thick uniform layer of Upper Cretaceous shale, deposited on a continental palaeoslope.

In the western direction the Lower Grudja grades into continental sands and conglomerates.

The following formations in the sequence have been identified in areas where shallow-water facies have developed, distributed mainly within the boundaries of the present-day coastal plain.

b. *Upper Grudja (Paleocene - Lower Eocene)*

The Upper Grudja Formation is a sequence of glauconitic sand, clay and marl with bands of limestone. The total thickness of the formation is 300-400 m.

A shallow-water shelf is represented by interbedded sandstone, arenaceous limestone and marl of the lower part of the Upper Grudja Formation. Several small paleontographical highs can be outlined within the shelf area. The edge of the shelf is limited by carbonate buildups with a thickness of 100-150 m.

IV. Sequence 3 (Cheringoma – Middle to Upper Eocene)

This sequence represents a period of major flooding of the shelf and widespread deposition of carbonates in the Mozambique Basin and occurs as nummulitic limestones with bands of clay and calcareous sandstone. The thickness of the formation is 250 m.

The sediments of the Upper Grudja and the Cheringoma formations are replaced by terrigenous and calcareous rocks which progradationally built up the palaeoshelf outer edge.

V. Sequence 4 (Deltaic – Oligoceno to Present)

This sequence represents fluvio-deltaic depositional processes which dominate the Limpopo/Zambezi deltas and mixed carbonate/clastic environments which dominated the intervening shelf.

The depression was filled with terrigenous sediments and rate of deposition was higher than the rate of subsidence and as a result the delta plain prograded towards the east.

The most widely distributed deposits are Miocene in age and are subdivided into the following formations (from the bottom of the section upwards): Inharrime, Temane and Jofane.

a. Inharrime Formation

This Formation unconformably overlies the Cheringoma deposits and occurs as a layer of red dolomite, red clay and sandstone with individual bands of anhydrite. The thickness of the formation is 100 -350 m. These sediments were deposited in a restricted lagoonal environment.

b. Temane Formation

This Formation is distributed at the central part and comprises a thick evaporite rock (gypsum).

c. Jofane Formation

Jofane Formation occurs primarily as marine carbonate: limestone, calcarenite and arenaceous limestone, which are distributed practically everywhere within the coastal plain and the observed thickness is up to 200 m.

Several play-types have been identified in Mozambique Basin (ENH & ECL, 2000). The plays include structural and stratigraphic traps represented by faulted blocks in Southern Offshore (Play Zone 1), stratigraphic traps and combination of stratigraphic and structural traps in Domo Sandstone and Lower Grudja, respectively representing Central Onshore/Offshore (Play Zone 2) where the discoveries known in Mozambique Basin are within this Play and are associated with Lower Grudja Formation. Zambezi/Beira High (Play Zone 3) comprises stratigraphic traps in basin floor as fans/channels, rollover or low relief structures and stratigraphic by onlap to Beira High. Northern Offshore (Play Zone 4) identified as roll-over/slum combination and stratigraphic in wedge-outs along basin margin. Lower Zambezi Graben (Play Zone 5), comprises fault-blocks associated with Rift phase and interference faulted block. Inner Graben (Play Zone 6), early formed rift related structural traps represented by rift faulted blocks.

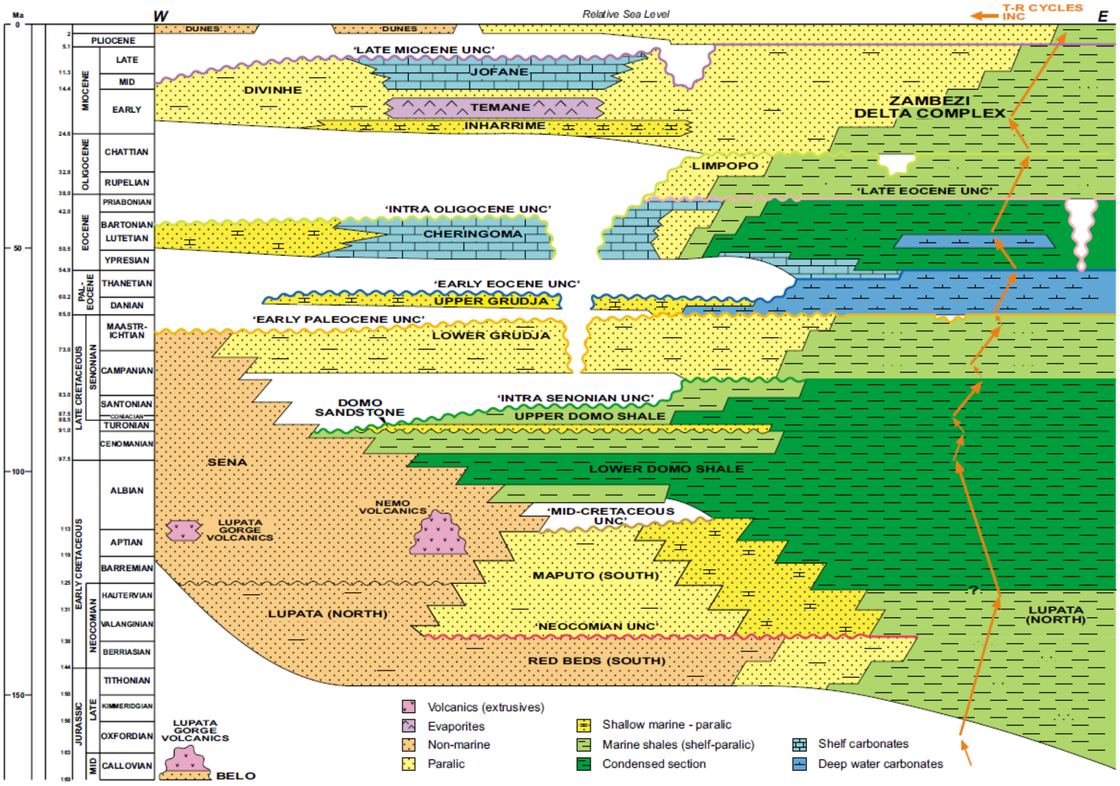


Figure 12. Mozambique Basin generalized stratigraphy (Late Jurassic to Present) (ENH & ECL, 2000).

4.2 Data Quality and Verification

The study area is in onshore Mozambique Basin, south of Mozambique and the original area it covers an area of approximately 10 000 Sqk and the remaining area after first relinquishment covers approximately 7500 Sqk in the vicinity of currently producing fields (Pande – Temane) and development field (Inhassoro). The study will mainly focus on the northern part of the block where there is seismic survey was acquired and processed in 2011/2012 by Buzi Hydrocarbon during the first exploration Sub-period activities and seismic survey acquired by Scimitar in 1996 (**Figure 13**), additionally will be used well log data from four (4) wells drilled in the block (**Table 2**). The data used in this study were generously provided by the Instituto Nacional de Petróleo (INP).

The good and excellent bi-dimensional (2D) seismic data include Post-Stack Time Migration (PSTM). The total survey length in the study area is about 369,4 km. The BHPL 2011/2012 is spaced 25 meters, sampled at 2 milliseconds and recorded down to 6000 milliseconds. The SCH96 is spaced 25 meters, sampled at 2 milliseconds and recorded down to 4000 milliseconds (**Figure 14**).

The well log curves from four (4) wells include: caliper, gamma ray, spontaneous potential, neutron porosity, density, resistivity, sonic and check-shot data from two (2) wells were also available. Petrel E&P Platform 2016 was used for this study.

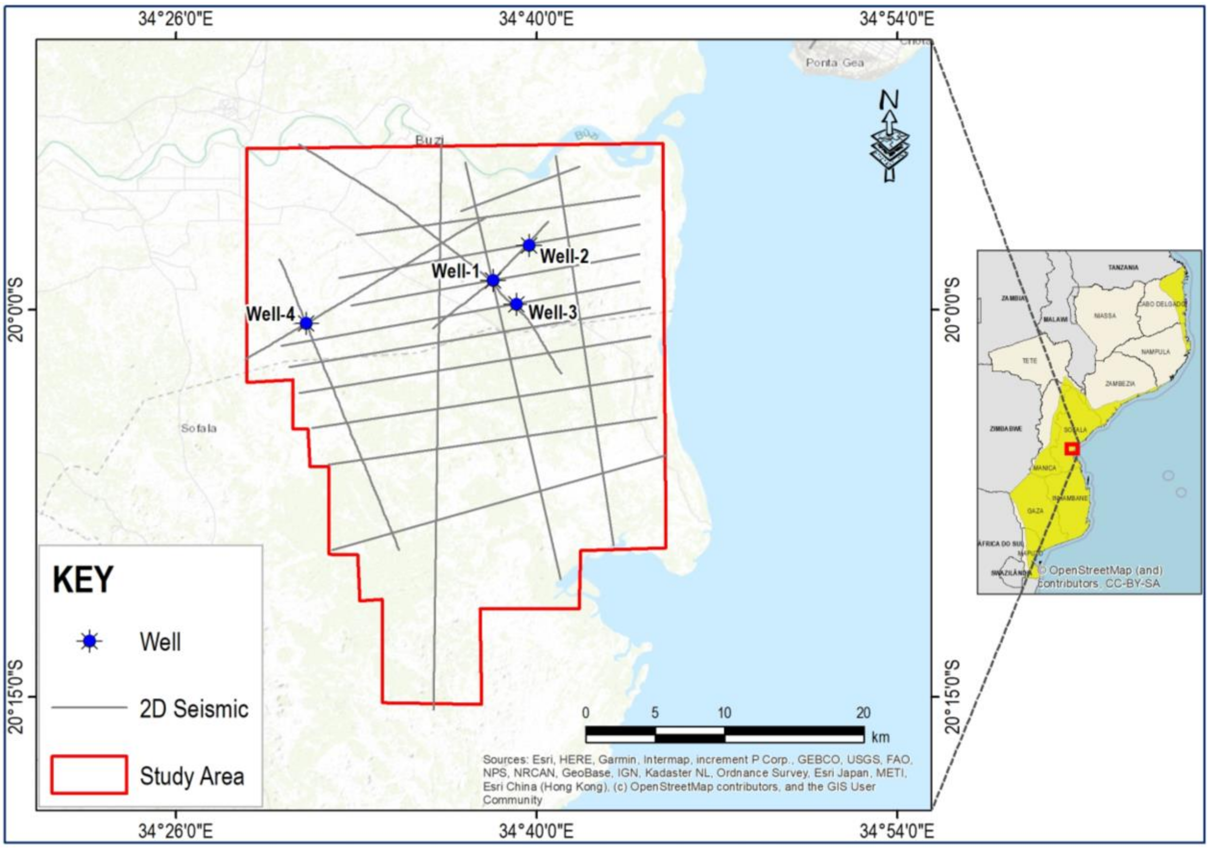


Figure 13. Map showing the location of 2D seismic survey that defines the study area, outlined by the red polygon Quality Control of Data Loaded (Display)

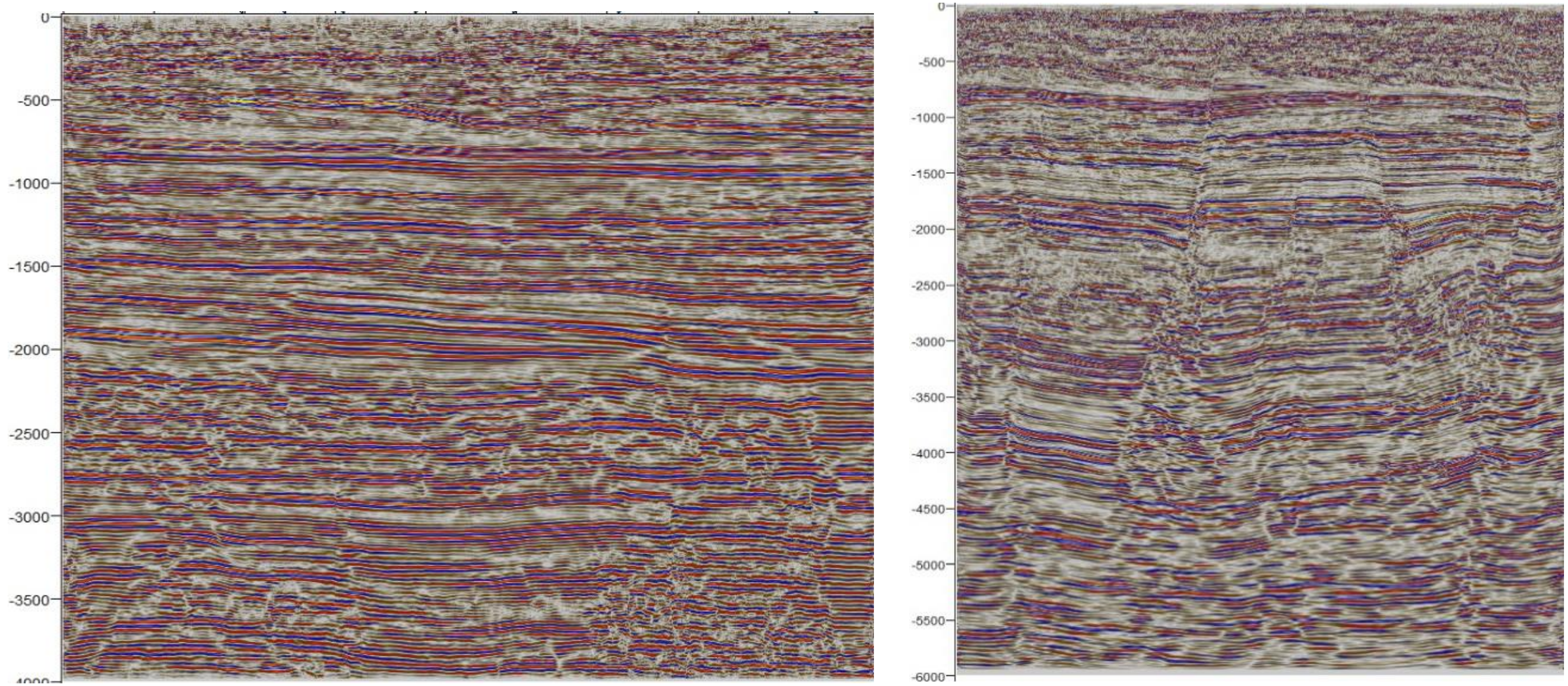


Figure 14. Post Stack Time Migrated (PSTM): Survey SHC1996 good seismic quality (left) although the section displays some noises evidence at the shallow and deep section and survey BHPL 2011/2012 consider excellent 2D seismic quality (right) displaying in generally relatively less noises.

Table 2. Well database

Well Database									
Well Name	**Caliper**	**Gamma Ray**	**Spontaneous Potential**	**Bulk Density**	**Neutron Porosity**	**Deep Resistivity**	**Sonic**	**Checkshot**	**Well Status**
Well_1	✓	✓	✓		✓	✓	✓	✓	P&A
Well_2	✓	✓	✓	✓		✓			P&A
Well_3	✓	✓	✓	✓		✓			P&A
Well_4	✓	✓	✓	✓	✓	✓	✓	✓	P&A

VSP/Checkshot

The availability of Vertical Seismic Profile (VSP) and checkshot data for Wells-1 and Well-4 (see **Table 3**), represents a pivotal advancement in subsurface exploration within the context of the Mozambique basin's Buzi area. VSP, a high-resolution seismic technique, involves measuring the travel times of seismic waves directly at the well location. This method provides detailed insights into the subsurface velocity structure, aiding in the characterization of geological formations with greater precision. Checkshot data, on the other hand, entails recording the travel times of seismic waves at the surface, which is crucial for calibrating and aligning seismic data.

The significance of these data sources lies in their ability to enhance the accuracy of the time-depth relationship. By directly measuring seismic wave travel times at the well locations, VSP data allows for a more fine-grained calibration, contributing to a refined understanding of the subsurface. Checkshot data, complementing the VSP information, further refines the correlation between seismic travel times and true subsurface depths.

In the exploration workflow, the integration of VSP and checkshot data becomes paramount during seismic interpretation. These datasets serve as invaluable tools for adjusting seismic data and models to accurately represent the subsurface conditions. The high resolution provided by VSP data is particularly beneficial for capturing detailed geological features, ensuring that the interpretation aligns closely with the actual subsurface structure.

Having VSP and checkshot data for multiple wells introduces an additional layer of complexity and richness to the exploration strategy. Cross-validation and comparative analysis across different well locations allow geoscientists to assess the consistency or variability of geological features. This multi-well approach facilitates a more comprehensive understanding of the subsurface, enabling a more accurate representation of geological structures.

The collective application of VSP and checkshot data plays a crucial role in subsurface exploration methodologies, contributing to the construction of robust geological and geophysical models. These models, grounded in the high-resolution insights provided by VSP, enable geoscientists to make informed decisions regarding resource estimation, structural mapping, and reservoir characterization.

In summary, the availability of VSP and checkshot data for Well-1 and Well-4 enhance the exploration strategy in the Mozambique basin's Buzi block. These data sources are integral components in refining the time-depth relationship, ensuring accurate depth measurements, and contributing to a comprehensive subsurface understanding. This multi-well approach fortifies the foundation for precise geological and geophysical analyses, advancing the exploration efforts in the region.

Table 3. VSP/Checkshot data import to Petrel Software and visualization.

ID	MD	TWT	Average velocity	Interval velocity	Sonic time	Sonic Int. Vel	Drift	Well
1104	1870.08	1368	2704.8	3180				Well-4
1105	1871.67	1369	2705.14	3140				Well-4
1106	1873.24	1370	2705.46	3140				Well-4
1107	1874.81	1371	2705.78	3080				Well-4
1108	1876.35	1372	2706.05	3120				Well-4
1109	1877.91	1373	2706.35	2940				Well-4
1110	1879.38	1374	2706.52	2900				Well-4
1111	1880.83	1375	2706.66	3000				Well-4
1112	1882.33	1376	2706.88	3180				Well-4
1113	1883.92	1377	2707.22	3020				Well-4
1114	1885.43	1378	2707.45	3140				Well-4
1115	1887	1379	2707.76					Well-4
1121	307.8	282.8	2101.13	2307.69	141.4		0	Well-1
1122	307.95	282.93	2101.23	2307.69	141.46	2357.98	0	Well-1
1123	308.1	283.06	2101.32	2307.69	141.53	2351.21	0	Well-1
1124	308.25	283.19	2101.42	2461.54	141.59	2348.4	0	Well-1
1125	308.41	283.32	2101.58	2276.92	141.66	2347.91	0	Well-1
1126	308.56	283.45	2101.66	2338.46	141.72	2347.94	0	Well-1
1127	308.71	283.58	2101.77	2338.46	141.79	2287.89	0	Well-1
1128	308.86	283.71	2101.88	2338.46	141.86	2257.3	0	Well-1
1129	309.01	283.84	2101.99	2338.46	141.92	2257.3	0	Well-1
1130	309.17	283.97	2102.1	2338.46	141.99	2257.3	0.01	Well-1
1131	309.32	284.1	2102.2	2338.46	142.06	2290.52	0.01	Well-1
1132	309.47	284.23	2102.31	2338.46	142.12	2308.57	0.01	Well-1

Quality Control

In the realm of subsurface exploration, the integration of checkshot data from wells such as Well-1 and Well-4 is pivotal for establishing a robust seismic-to-well tie. The process begins with the careful loading of checkshot data, a critical step in ensuring the accuracy of subsequent analyses. The quality control procedures that follow play a crucial role in enhancing the reliability of the time-depth relationship and the subsequent creation of synthetic seismograms.

Checkshot data, representing in situ measured travel times through sedimentary layers, serves as a direct measurement of subsurface velocity (Schlumberger, 2014). Its incorporation into the seismic-to-well tie process is vital for calibrating Sonic logs and achieving a precise understanding of the subsurface. To achieve this, Schlumberger recommends a thorough quality control process that scrutinizes the time/depth relationship and involves the careful editing of logs (Schlumberger, 2014).

The significance of editing data points in the checkshot dataset lies in its impact on the calculated interval velocities. By selectively editing or deleting data points, the interval velocities are recalculated based on neighboring points. This note only addresses errors but also contributes to the generation of a more accurate time-depth relationship. The confidence in velocity extraction is thereby increased, laying a solid foundation for building velocity models.

Furthermore, the meticulously edited checkshot data substantially contributes to the generation of synthetic seismograms. These synthetics, built on a refined time-depth relationship, are crucial for Sonic log calibration and subsequent seismic interpretation. The process of editing checkshot data is not just a corrective measure but an enhancement strategy that elevates the overall quality and reliability of the seismic-to-well tie.

In conclusion, the careful processing of checkshot data from wells such as Well-1 and Well-4 is a crucial step in subsurface exploration. The methodical quality control, including time/depth relationship verification and log editing, ensures the accuracy of the time-depth relationship. The edited checkshot data, when integrated into the seismic-to-well tie process, not only enhances the calibration of Sonic logs but also contributes to the creation of reliable synthetic seismograms, thereby advancing the precision and reliability of subsurface interpretations.

The **Figure 15** and **Figure 16**, show the data (VSP/Checkshot) preparation process with aim to remove the outlier's data.

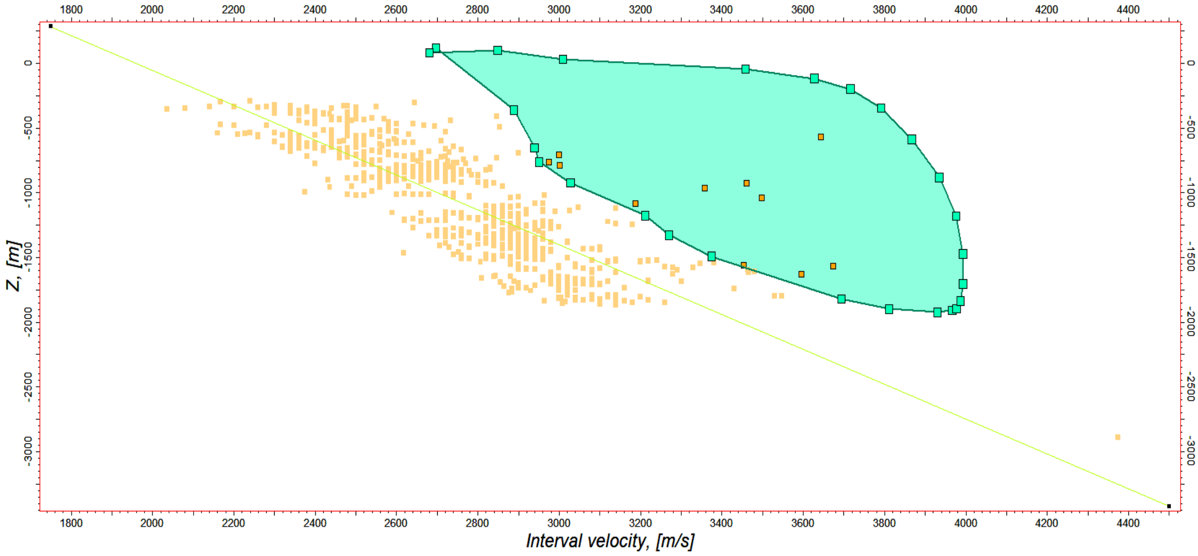


Figure 15. The cross-plot represent the relationship Depth(Z) Vs Interval Velocity and some outlier identified and removed.

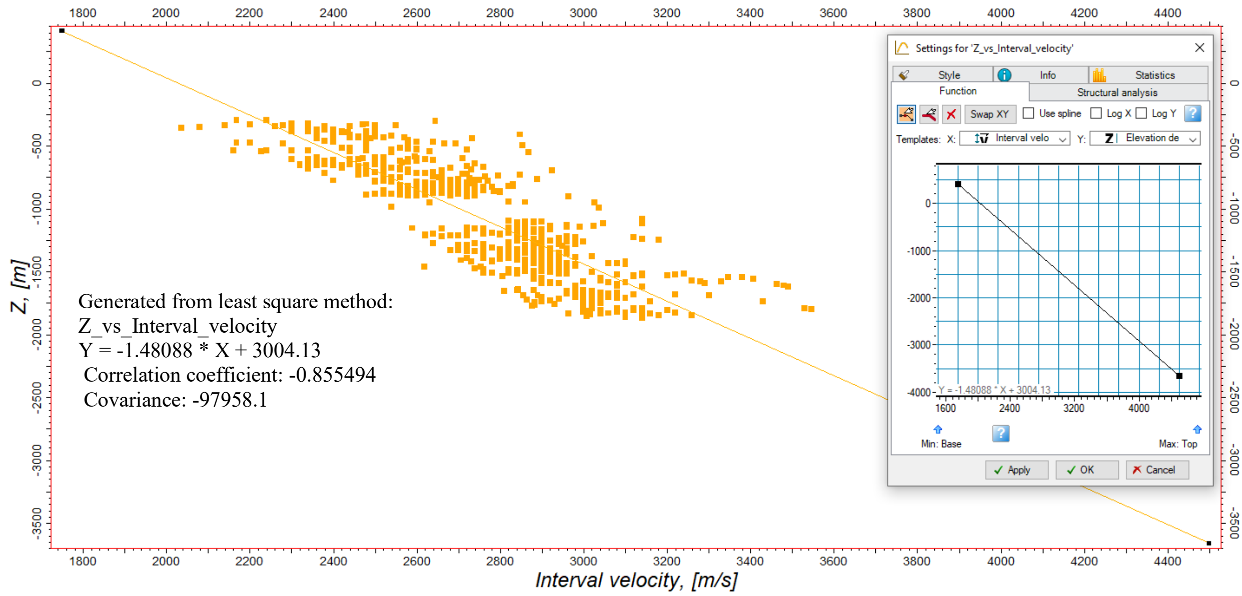


Figure 16. The cross-plot represent the relationship Depth(Z) Vs Interval Velocity with outlier removed and the equation represent the new relationship.

Formations Tops

The integration of available data from **Table 4** and the corresponding chart has been instrumental in establishing a robust time-depth relationship, a cornerstone for refining the well top information for Well-1. This intricate process involved meticulous computations, ensuring that the updated well top information aligns precisely with the established time-depth correlation.

The Eq. 5, played a pivotal role in this endeavor, providing a mathematical framework to define the well top information for Well-1. This equation, rooted in geophysics, represents a crucial tool for converting time measurements into accurate depth readings. The application of such mathematical models is essential in refining well top information, contributing to a more nuanced understanding of subsurface structures.

The updated information, as presented in the refined **Table 5**, signifies a commitment to precision in the characterization of Well-1's depth profile. This depth information is vital for various aspects of subsurface exploration, from resource estimation to structural analysis. The reliability of this information directly impacts the effectiveness of subsequent analyses and decision-making processes in the exploration domain.

In conclusion, the meticulous computation of the time-depth relationship and the subsequent update of well top information exemplify a rigorous and systematic approach to subsurface exploration. The marriage of empirical data and mathematical modeling ensures that the updated information reflects the true geological conditions of Well-1 (**Figure 17**).

Table 4. Well top information from Well-1

Formation	Depth(m)(KB)	Depth m (ASL)	Time (s)	Time (ms)
Datum	10.6	0		
Moz-14	600	-599.4	0.5	500
Moz-13	800	-789	0.6	600
Moz-12	1074	-1063.4	0.8	800
Moz-10	2900	-2889.4	2	2000
FTD	3337.5	-3326.9	2.2	2200

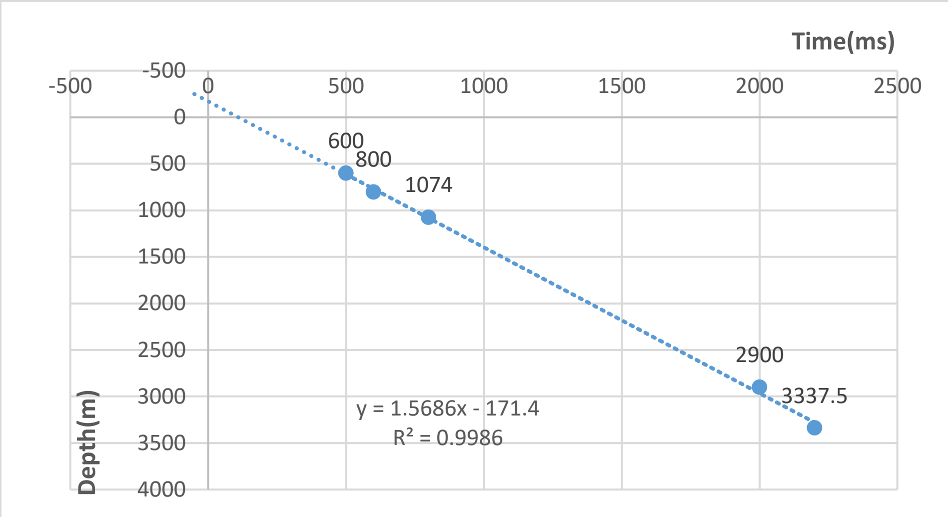


Figure 17. Relationship Depth vs time (Checkshot model for Well-1).

$$y = 1.5686x - 171.4 \qquad \textbf{(Equation. 5)}$$

Table 5. Twt determination from checkshot data

Top Formation	**Depth (MDm, KB)**	**TWT (ms)**
Miocene	249.936	268.6064
Cheringoma	598.932	491.0952
Upper Grudja	814.1208	628.2805
P-Marker	975.36	731.0723
Lower Grudja	1135.9896	833.4755
G6	1207.008	878.7505
G7	1245.108	903.0397
G8	1327.404	955.5043
G9	1450.848	1034.201
G10	1508.76	1071.121
G11	1549.908	1097.353
Upper Domo Shale	2015.0328	1393.875
Domo Sand	2667	1809.512
Lower Domo Shale	2898.0384	1956.801
Sena	3112.008	2093.209
TD	3328.416	2231.172

Mis-tie-Analysis

"Mis-ties" in seismic interpretation refer to discrepancies that occur when predicted and actual values differ, or when seismic reflections do not match or close correctly when intersecting seismic lines are interpreted.

Mis-tie analysis is a crucial process facilitating the extraction and application of mis-tie value corrections across diverse seismic surveys. The methodology involves utilizing all seismic lines within the survey folder sharing the same vintage to create a mis-tie set. This set is then instrumental in estimating and rectifying mis-tie values inherent in the seismic data (Schlumberger, 2014).

In the specific context of this study, seismic data is sourced from two distinct vintages: one acquired in 2012/13 by BHPL and another in 1996 by Scmittar. Notably, these vintages originate from disparate time periods and involve different seismic acquisition companies, resulting in varying geophysical acquisition parameters. Consequently, the presence of mis-tie values between these vintages is anticipated and considered normal within the seismic data integration process.

Acknowledging and addressing these mis-tie values is paramount for ensuring the accurate integration of seismic data acquired at different times and under diverse acquisition conditions. The mis-tie analysis enables the quantification of these discrepancies, allowing for precise corrections. This meticulous approach aligns with industry best practices, emphasizing the importance of mitigating potential inaccuracies stemming from differences in acquisition parameters and vintage disparities.

In essence, the mis-tie analysis serves as a crucial step in harmonizing seismic data from multiple vintages, contributing to a more coherent and reliable subsurface interpretation. By recognizing and correcting mis-tie values, the study aims to enhance the overall quality and consistency of the integrated seismic dataset, thereby improving the accuracy of subsequent geological and geophysical analyses.

In conducting the mis-tie analysis, the Buzi Hydrocarbon Pte. Ltd (BHPL) seismic line is designated as the reference, implying that no corrections will be applied to this set of seismic lines. The focus of the correction process is exclusively on the Scmittar vintage (see **Table 6**). Notably, the intersection value between BHPL lines is determined to be zero, indicating a lack of mis-tie between lines from this specific acquisition. This implies that the BHPL vintage is one step ahead of the Scmittar vintage in terms of processing quality, signifying a high degree of alignment between the lines from the BHPL seismic acquisition.

This strategic approach streamlines the correction process by concentrating efforts on rectifying mis-tie values within the Scmittar vintage, where differences in processing quality are identified. By utilizing the BHPL seismic line as a stable reference, the analysis ensures that the corrections applied are targeted and effective, contributing to a more accurate and coherent integration of seismic data from different vintages.

The decision to employ the BHPL seismic line as the reference underscores its reliability and consistency, positioning it as a benchmark for evaluating and refining the Scmittar vintage. This meticulous mis-tie analysis methodology aligns with industry standards, emphasizing a systematic approach to addressing discrepancies in seismic data acquired under distinct conditions and timeframes.

This approach not only enhances the accuracy of seismic data integration but also provides valuable insights into the relative processing quality between the two vintages, guiding subsequent interpretations and analyses (see **Figures 18, 19 & 20**) the entire process and the results.

Table 6. Show the result of the mis-tie analysis between BHPL (A0/B0)and Scmittar (SHC) vintages.

Line/Cube	CDP/Inline	Trace/Xline	Vertical mis-tie	Vertical residual	Vertical Correction	Vertical residual	Intersecting line/cube
11_A03_PSTM	2796	795	8.32	0.8318	0	8.32	SHC-96-01
11_A03_PSTM	2757	756	12.89	0.8761	0	12.89	SHC-96-02A
11_A08_PSTM	2182	181	-8.41	0.8265	0	-8.41	SHC-96-05
11_A04_PSTM	2939	938	9	0.8245	0	9	SHC-96-01
11_A04_PSTM	3274	1273	26.55	0.8924	0	26.55	SHC-96-02A
11_A04_PSTM	2179	178	6.82	0.8299	0	6.82	SHC-96-05
11_A07_PSTM	2186	185	-1.13	0.8296	0	-1.13	SHC-96-05
11_A05_PSTM	3332	1331	32.49	0.8364	0	32.49	SHC-96-02A
11_A05_PSTM	2177	176	6.75	0.8256	0	6.75	SHC-96-05
SHC-96-01	158	158	0.39	0.8385	-8.36	8.75	11_A02_PSTM
SHC-96-01	426	426	-8.32	0.8318	-8.36	0.03	11_A03_PSTM
SHC-96-01	453	453	-8.16	0.874	-8.36	0.2	11_B02_PSTM
SHC-96-01	751	751	-9	0.8245	-8.36	-0.64	11_A04_PSTM
SHC-96-01	843	843	20.83	0.8311	-8.36	-12.47	11_B01_PSTM

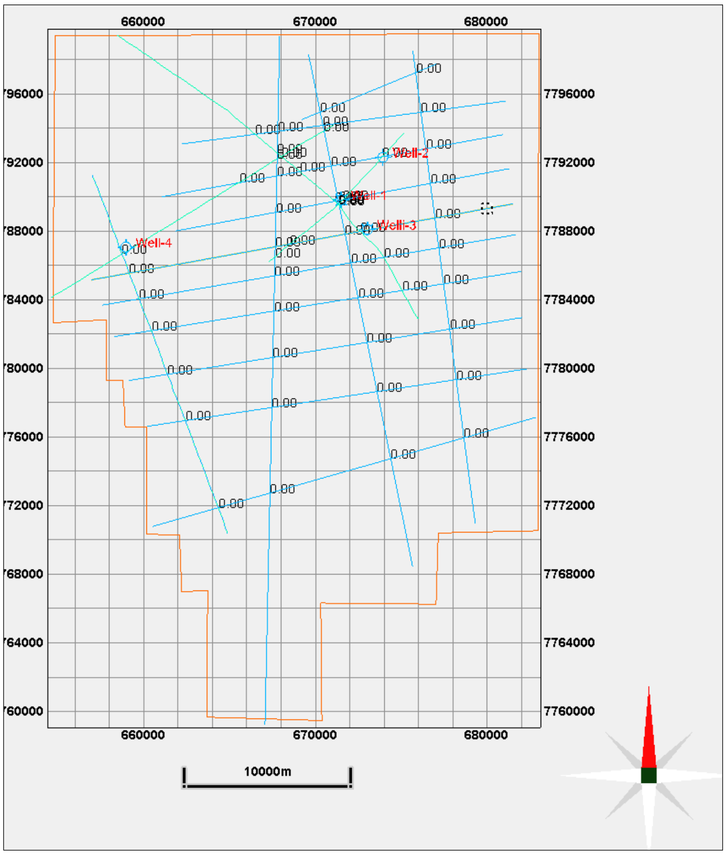


Figure 18. Show the result of the mis-tie analysis between BHPL(blue lines) and Scmittar vintage (green lines).

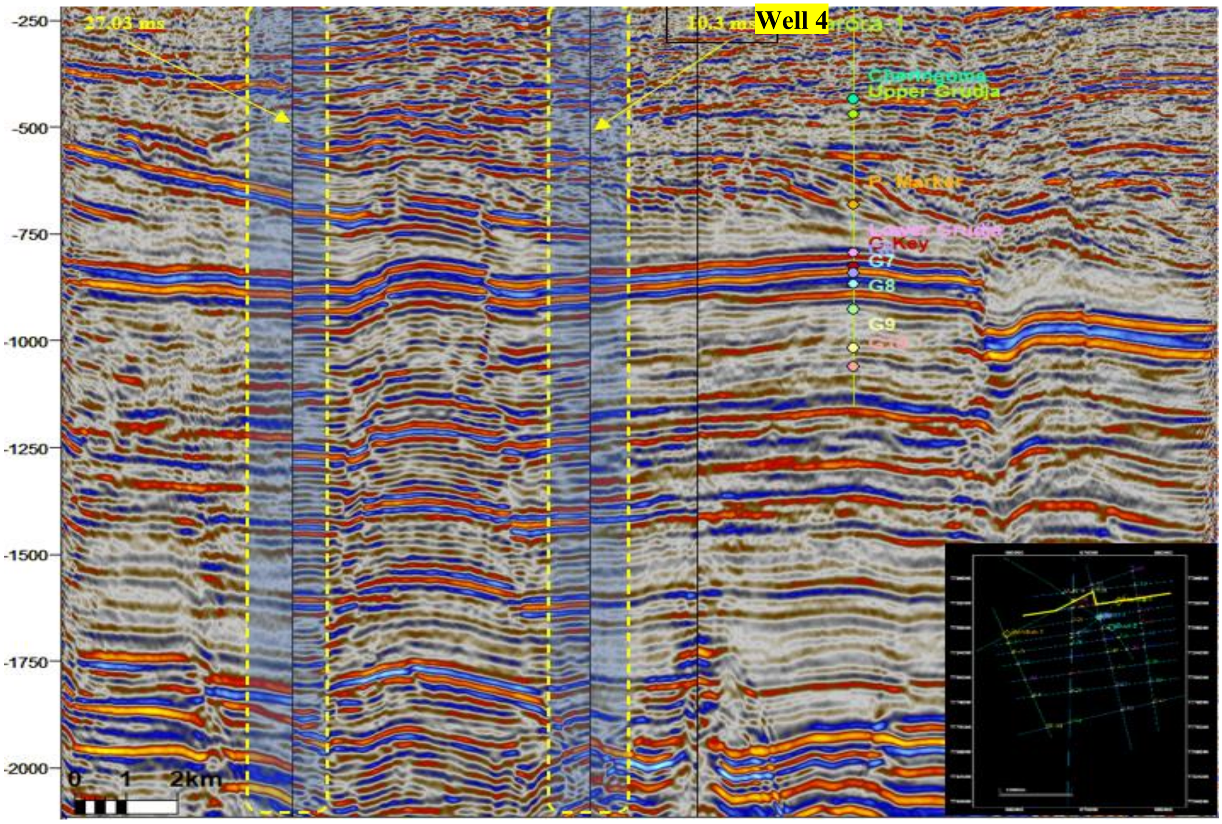


Figure 19. Display the difference between intersection lines - BHPL (blue color) and Scmittar (green color).

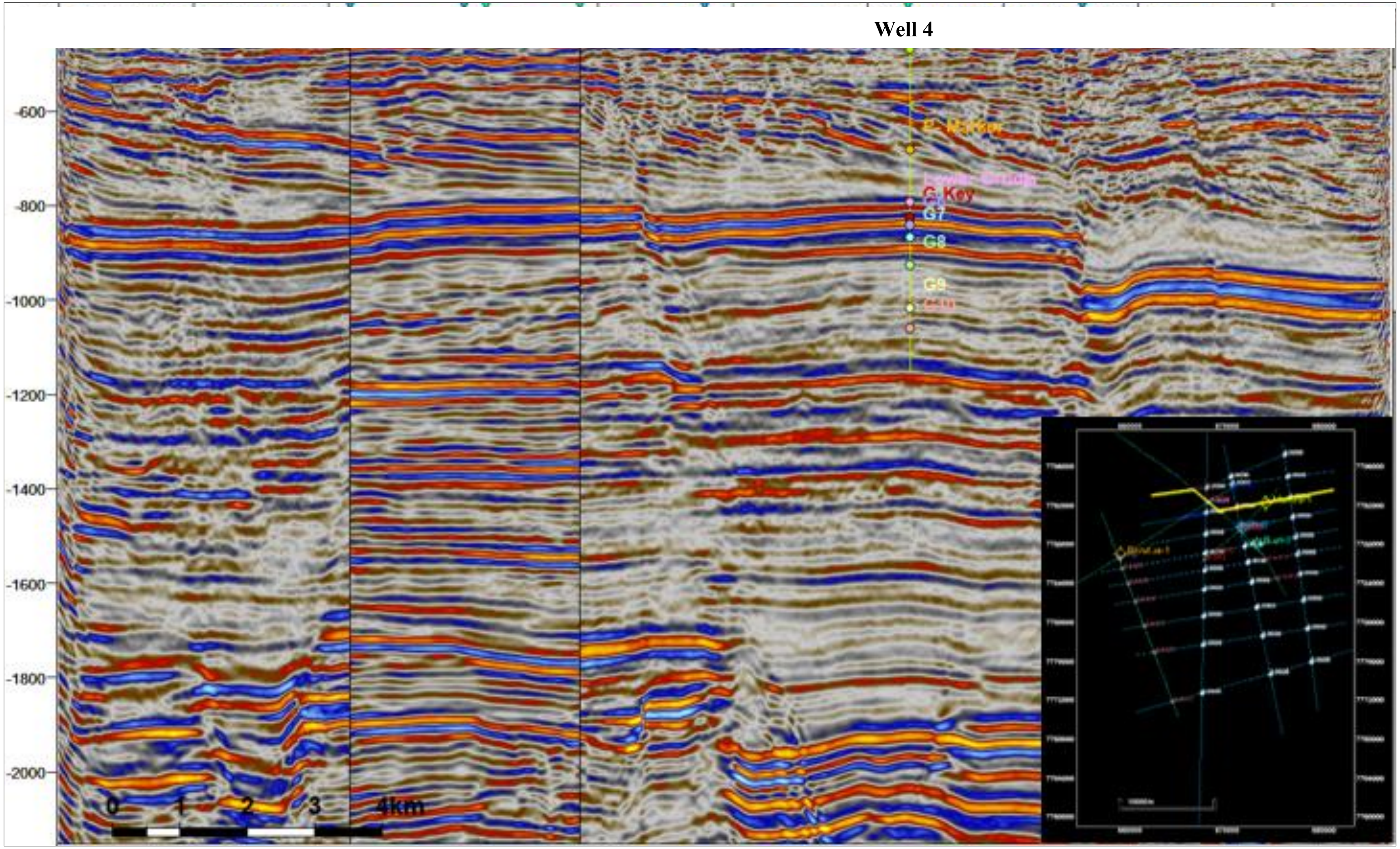


Figure 20. Display the resulted of mis-tie-analysis (vertical shifted) between two surveys BHPL and Scmittar.

Log Conditioning

The processing methodology involves mitigating the impact of anomalous spikes in sonic data to ensure the accuracy of acoustic impedance calculations. Acoustic impedance, a product of velocity and density, is a crucial parameter in subsurface exploration. Anomalous spikes in sonic data, if not addressed, can distort the results and compromise the reliability of the acoustic impedance values. To address this, the process focuses on systematically removing spikes deemed anomalous. These spikes can arise due to various factors and may adversely affect the integrated sonic log travel times The objective is to harmonize the sonic log data with the times derived from the checkshot/VSP survey, ensuring a consistent and accurate representation of subsurface properties.

The approach involves incrementally adjusting sonic slowness values over specific sections of the log. This meticulous adjustment aims to bring the integrated sonic log travel times in line with the times obtained from the checkshot/VSP survey. By doing so, the methodology seeks to eliminate discrepancies and align the sonic data with the ground-truth measurements provided by the survey.

Two key curves, Sonic and Density, play a pivotal role in this process. The Sonic curve provides insights into the velocity of subsurface formations, while the Density curve offers information about the density of the materials. Both these parameters are essential components in calculating Acoustic Impedance (AI), a fundamental property for understanding subsurface characteristics. The **Figure 21**, show Sonic and density log conditioning process cared out in this study using data information from Well 4.

By systematically addressing anomalous spikes and ensuring coherence between sonic data and ground-truth measurements, this methodology enhances the reliability of the subsequent acoustic impedance calculations. The resulting AI values, derived from the integrated Sonic and Density curve, provide a more accurate representation of the subsurface properties. This refined data contributes to a more comprehensive understanding of the geological and geophysical aspects of the surveyed area.

Well 4

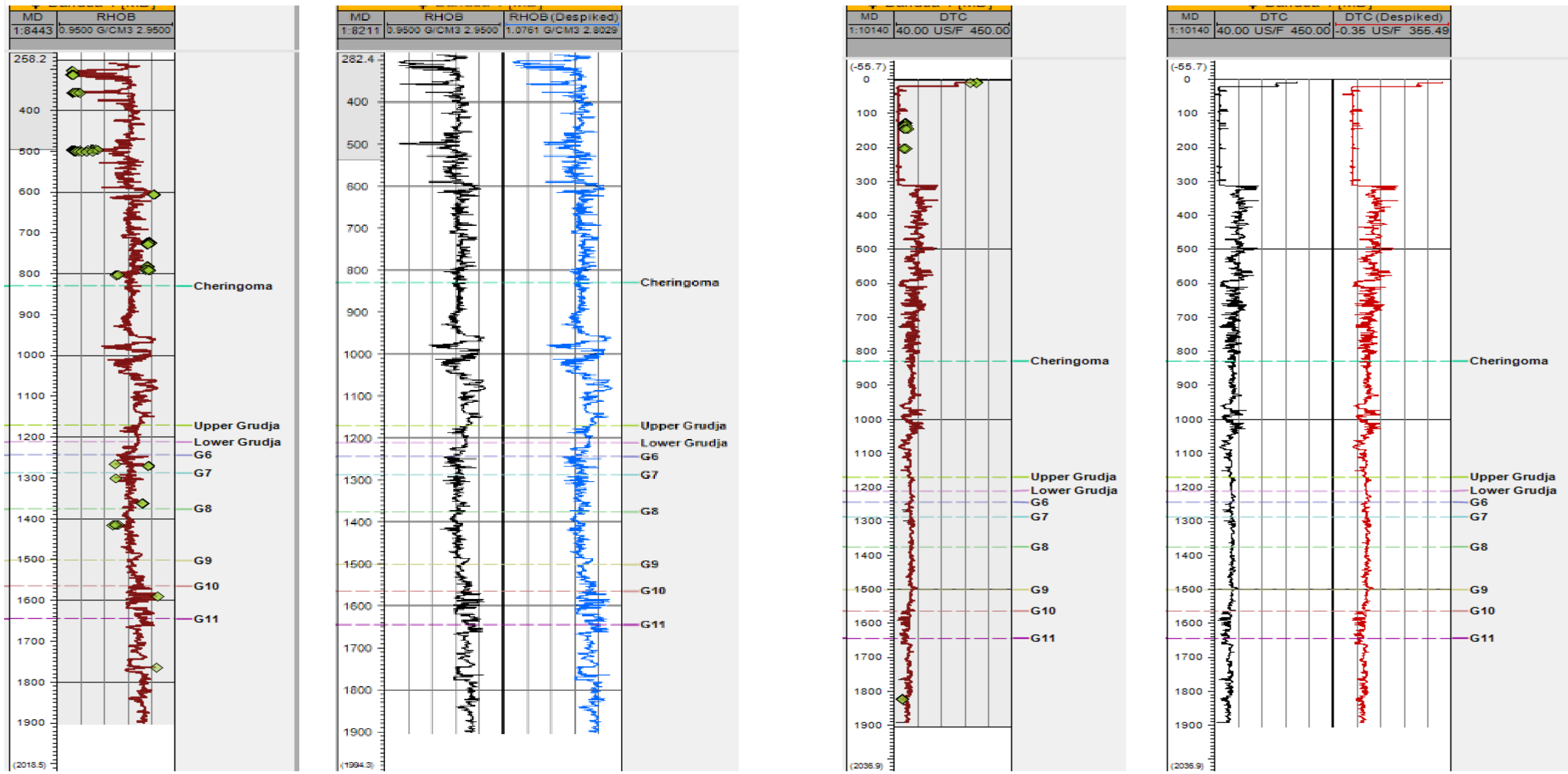


Figure 21. Sonic and density log conditioning Process for the sonic calibration and Seismic Well-Tie Process.

Sonic Log Calibration

Sonic logs, prized for their dense sampling, play a crucial role in velocity model construction. However, directly utilizing original sonic logs for seismic data conversion can result in erroneous velocities, particularly in the upper well section, and is complicated by differences in frequency range (dispersion). Potential extreme spikes in sonic logs can accumulate as incorrect integrated time values throughout the well length. Therefore, a prerequisite step involves calibrating sonic logs with checkshot data to rectify these discrepancies before proceeding with velocity modeling (Schlumberger, 2014).

The calibration process rectifies log velocities to align with time-depth data, usually obtained from checkshot surveys. This ensures accurate synchronization of the sonic log with the time-depth relationship. The resulting calibrated sonic log serves as a reliable foundation for generating an accurate time-depth relationship, facilitating precise subsurface interpretations in subsequent analyses. This method enhances the reliability of the velocity model, contributing to a more comprehensive understanding of the subsurface geological and geophysical characteristics. The **Figure 22**, show the sonic calibration process using checkshot and the new depth /time relationship using Petrel Platform.

Well 4

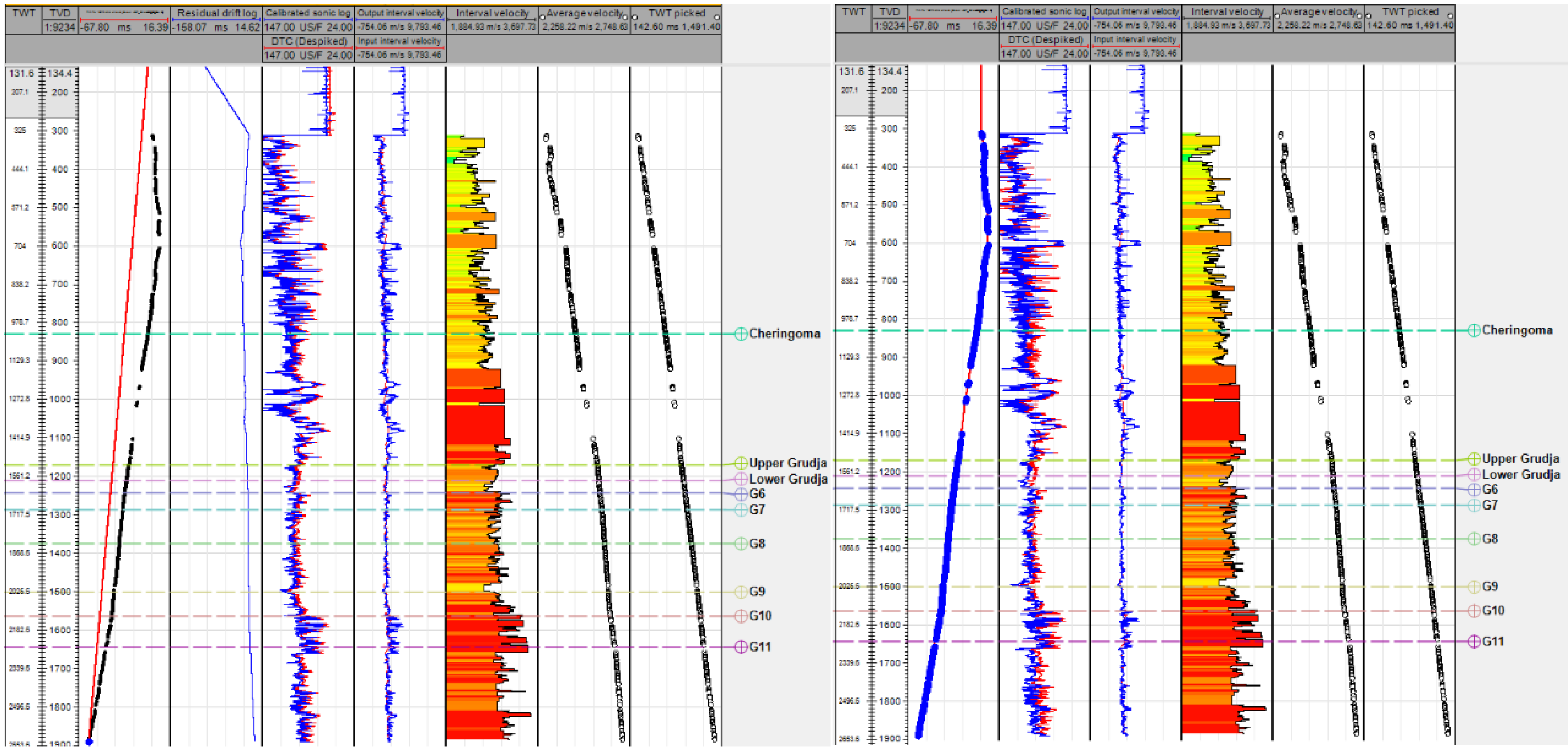


Figure 22. Sonic calibration process using checkshot and left side the new depth – time relationship.

4.3 Study Limitations

The generation of synthetic seismograms for the four wells in the study relies on velocity data obtained from sonic and/or checkshot measurements. However, a notable challenge arises for Well-1, where there is a lack of available data concerning the tops of formations. This limitation reduces confidence in the determined tops, as it relies on outdated information for Well-1 and has potential repercussions on the velocity model construction.

Velocity data, crucial for constructing accurate synthetic seismograms, aids in interpreting subsurface features. Sonic and checkshot measurements offer insights into subsurface velocity variations, impacting seismic data interpretation. The absence of current data on formation tops for Well-1 complicates the correlation of seismic events with geological features and hinders the calibration of the velocity model.

Formation tops serve as vital markers in seismic interpretation, facilitating the identification of subsurface structures. The absence of current formation top data for Well-1 introduces uncertainties about the accuracy of the velocity model, potentially leading to misalignments between synthetic seismograms and actual subsurface conditions.

To address this limitation, efforts should be directed towards obtaining updated information on Well-1's formation tops. Additional geological data, such as well logs or geological surveys, could provide essential details to enhance the reliability of the velocity model and, consequently, the synthetic seismograms.

The absence of data on the tops of formations in Well-1 poses a challenge in generating synthetic seismograms. Resolving this limitation by acquiring current information on formation tops is essential for improving the accuracy and confidence in the velocity model, ensuring a more reliable interpretation of seismic data in the study area.

4.4 Summary

The Mozambique Basin, situated along the eastern margin of central and southern Mozambique, covers approximately 500,000 km², with 275,000 km² onshore and 225,000 km² offshore. Characterized by N/S and NW/SE structural trends, key elements include the Lebombo Monocline, Nuanetsi-Sabi, Palmeiras Graben, Changani Graben System, Lower Zambeze graben, and more. The basin's sedimentary fill, resulting from Gondwana's breakup, comprises pre-Cambrian crystalline and metamorphic rocks serving as the basement, overlain by Gondwana and post-Gondwana units (ENH & ECL, 2000).

The Drift Megasequence, part of the sedimentary fill, consists of four sequences, with Sequence 1 (Late Jurassic – Late Cretaceous) including formations like Lupata, Sena, Red Beds, and Maputo. Sequence 2 (Domo Formation) represents Mid-Cretaceous drowning, featuring Domo Sandstones, Upper Domo Shales, and Domo Sandstone. Sequence 3 (Grudja Formation) encompasses Lower and Upper Grudja formations, transitioning from clastics in the Late Cretaceous to a carbonate-rich environment in the Early Tertiary. Sequence 4 (Deltaic – Oligocene to Present) signifies fluvio-deltaic depositional processes, with formations like Inharrime, Temane, and Jofane in the Miocene.

The study area within the Mozambique Basin focuses on onshore regions, covering approximately 10,000 Sqk. Seismic surveys by BHPL in 2011/2012 and Scimitar in 1996, along with well log data from four wells, form the dataset. Vertical Seismic Profile (VSP) and checkshot data for Wells-1 and Well-4 enhance subsurface exploration precision. The mis-tie analysis addresses variations in seismic data vintages. Well-1's time-depth relationship is computed, refining well top information. The integration of checkshot data, VSP, and well log information ensures accurate seismic-to-well ties, enhancing the reliability of subsurface interpretations. The mis-tie analysis, focused on the Scmittar Vintage, aims to harmonize seismic data from different vintages, ensuring coherent integration.

The processing methodology involves addressing anomalous spikes in sonic data to ensure accurate acoustic impedance calculations. Calibration of sonic logs with checkshot data rectifies discrepancies, providing a reliable foundation for velocity model construction. The synthetic seismogram generation process highlights the importance of well data, especially velocity information, in producing accurate seismic representations.

CHAPTER V

RESULTS AND DISCUSSION

5.1 Introduction

Chapter V, focuses on the results of seismic well-tie and seismic interpretation. It analyzes the integration of seismic data with well data to ensure consistency and accuracy in the subsurface model. The discussion evaluates the insights gained from seismic interpretation, including the identification of geological features and structures. It assesses how these interpretations contribute to understanding the depositional environment.

5.2 Results

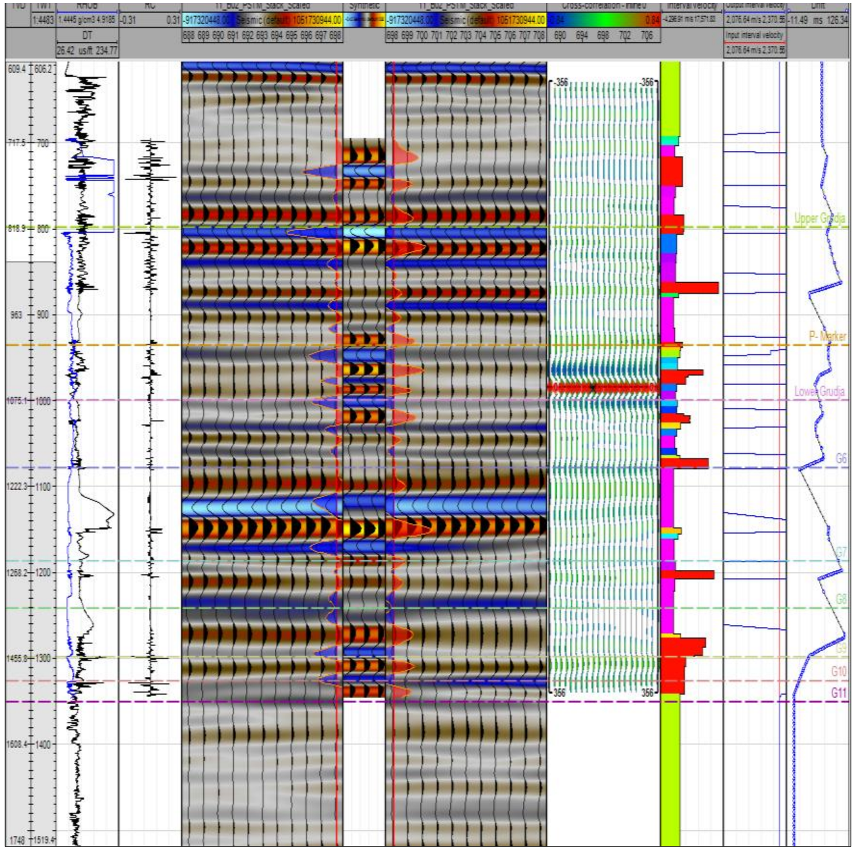
Seismic well to tie

The seismic well-tie process was conducted to establish a quantitative and qualitative relationship between well data and surface seismic data, enabling accurate time-depth conversions and improved interpretation of subsurface features. For this purpose, Well-1 and Well-4 were selected based on data availability and quality, particularly their Vertical Seismic Profile (VSP) data, which provided reliable time-depth relationships and wavelet information essential for synthetic seismic generation.

At Well-1, the synthetic seismic trace was generated using the reflectivity series derived from the well's acoustic impedance log (product of density and P-wave velocity), convolved with a wavelet extracted from nearby seismic data. This synthetic trace was then compared to the actual seismic trace at the well location. A cross-correlation coefficient of 84% was achieved (**Figure 23**), indicating an excellent match between the synthetic and recorded seismic data. This high correlati on suggests that the well log data is consistent with the seismic response and confirms the accuracy of the time-depth relationship derived from the VSP.

For Well-4, a commendable 68% cross-correlation was achieved (**Figure 24**), indicating a good but slightly lower-quality tie compared to Well-1. The lower correlation may be due to various factors, including: Slight inconsistencies or gaps in the well log data and Possible structural complexity or lateral lithological changes not captured in the 1D (one dimensional) synthetic model.

Well 1



Well 1

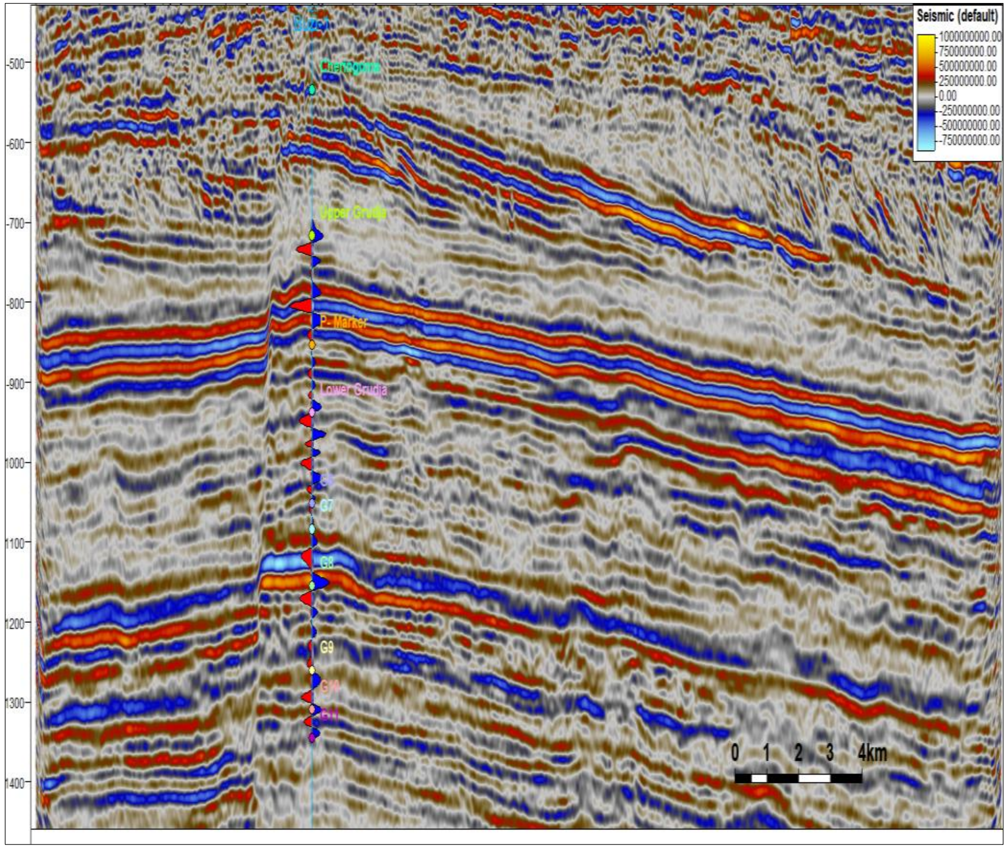


Figure 23. Seismic well to tie obtained from Well 1, showing very good match seismic and synthetic correlation resulting in 84 % cross-correlation.

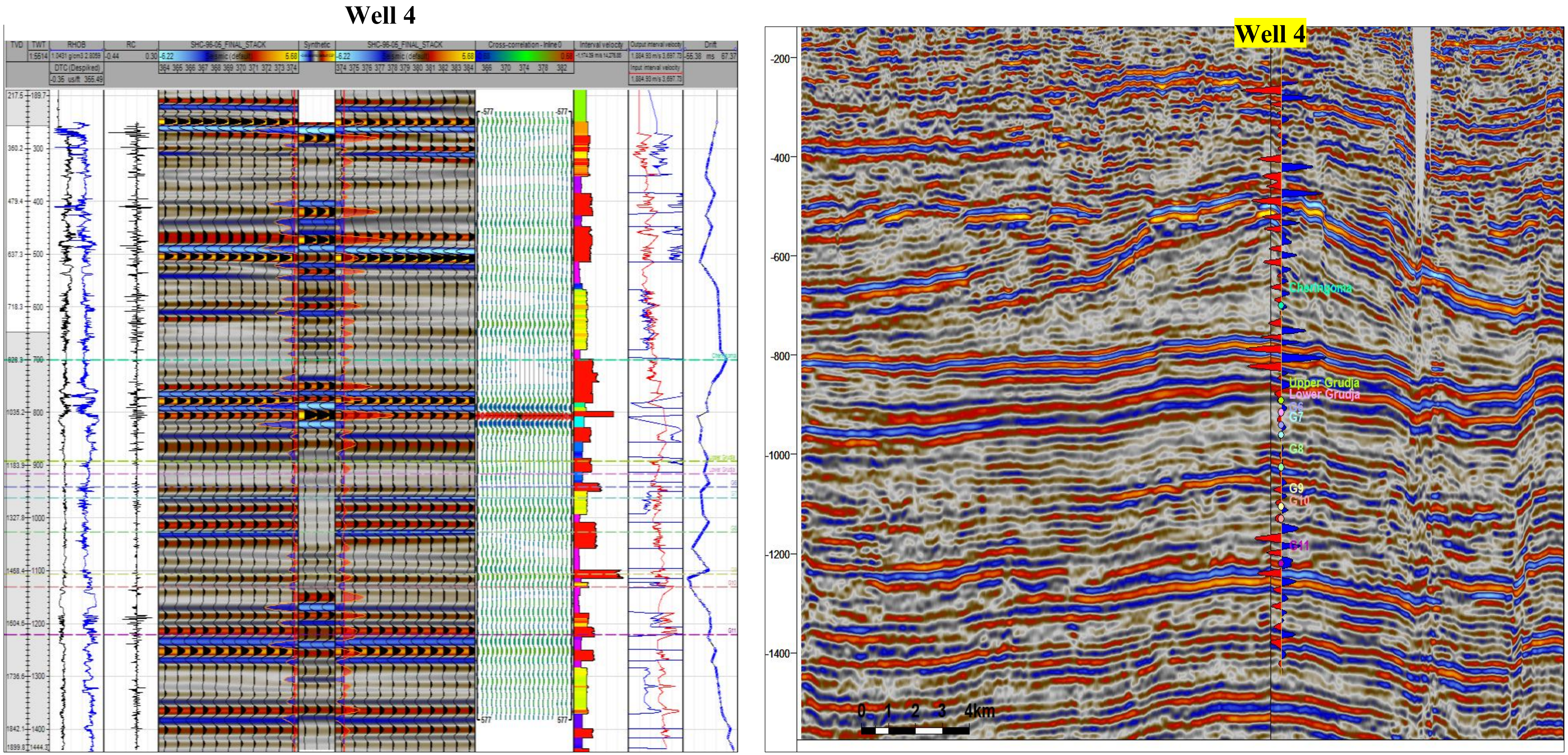


Figure 24. Seismic well-to-tie obtained from Well 4 showing good match between seismic and synthetic resulting in 68% trace cross-correlation.

Seismic interpretation

The detailed seismic interpretation of the Area of Interest (AOI) dataset has identified two distinct types of geological faults characterized by a predominant NW/SW trend. These faults traverse multiple sections ranging from the Domo Formation to the Sena Formation, intersecting various stratigraphic intervals (**Figure 25**).

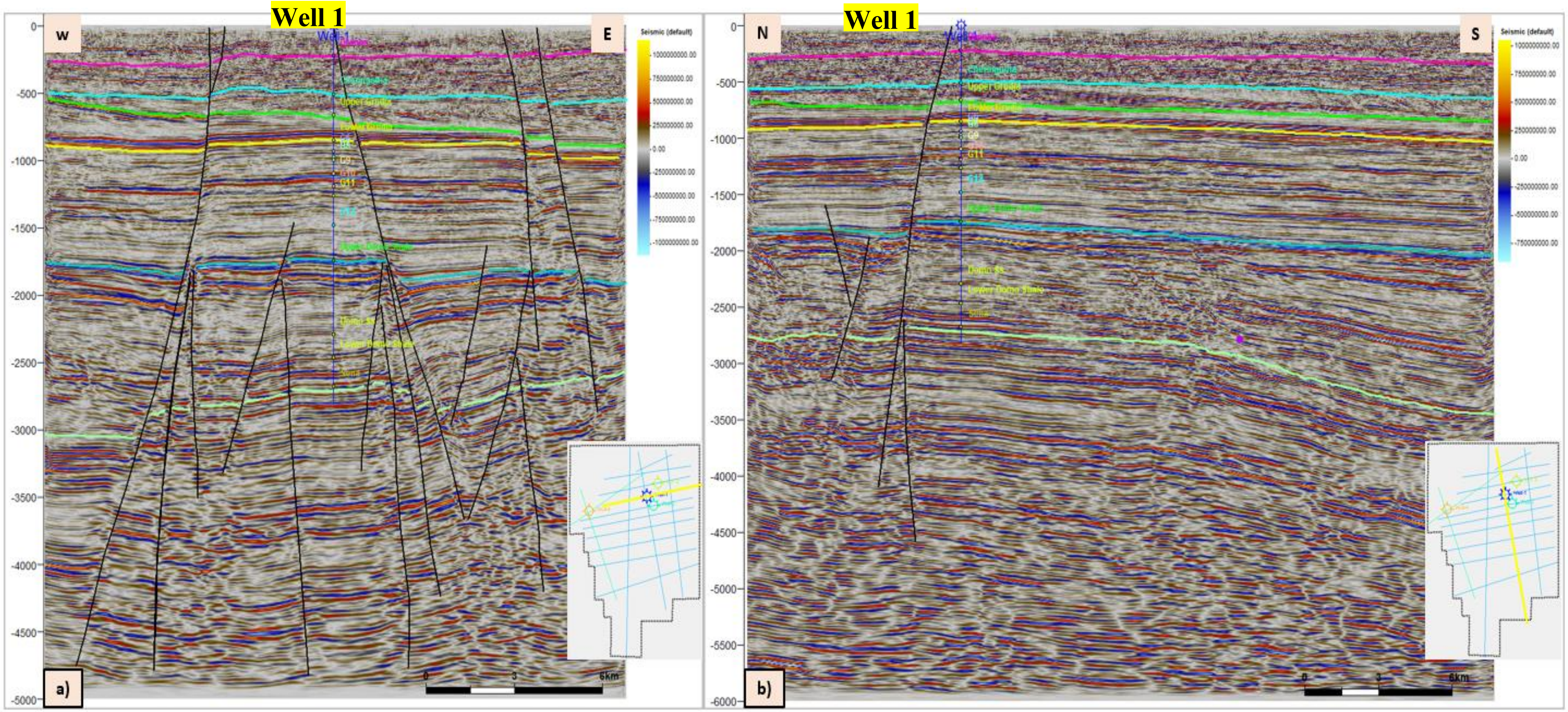


Figure 25. Horizons mapped in the area of interest (AOI): a) Seismic profile with E-W direction is observed six (6) horizons and the geological faults which intersect the referenced horizons and b) Seismic profile N-S direction where it is possible to observe a low density of geological faults in this direction.

Seism facies analysis

The seismic interpretation identified six (6) depositional sequences extending from the Quaternary to the Cretaceous records. These sequences, denoted as **Figure 26**, display distinct seismic-stratigraphic units. The seismic sections utilized in this study reached depths ranging from 4000 milliseconds to 6000 milliseconds, with variations observed among different lines.

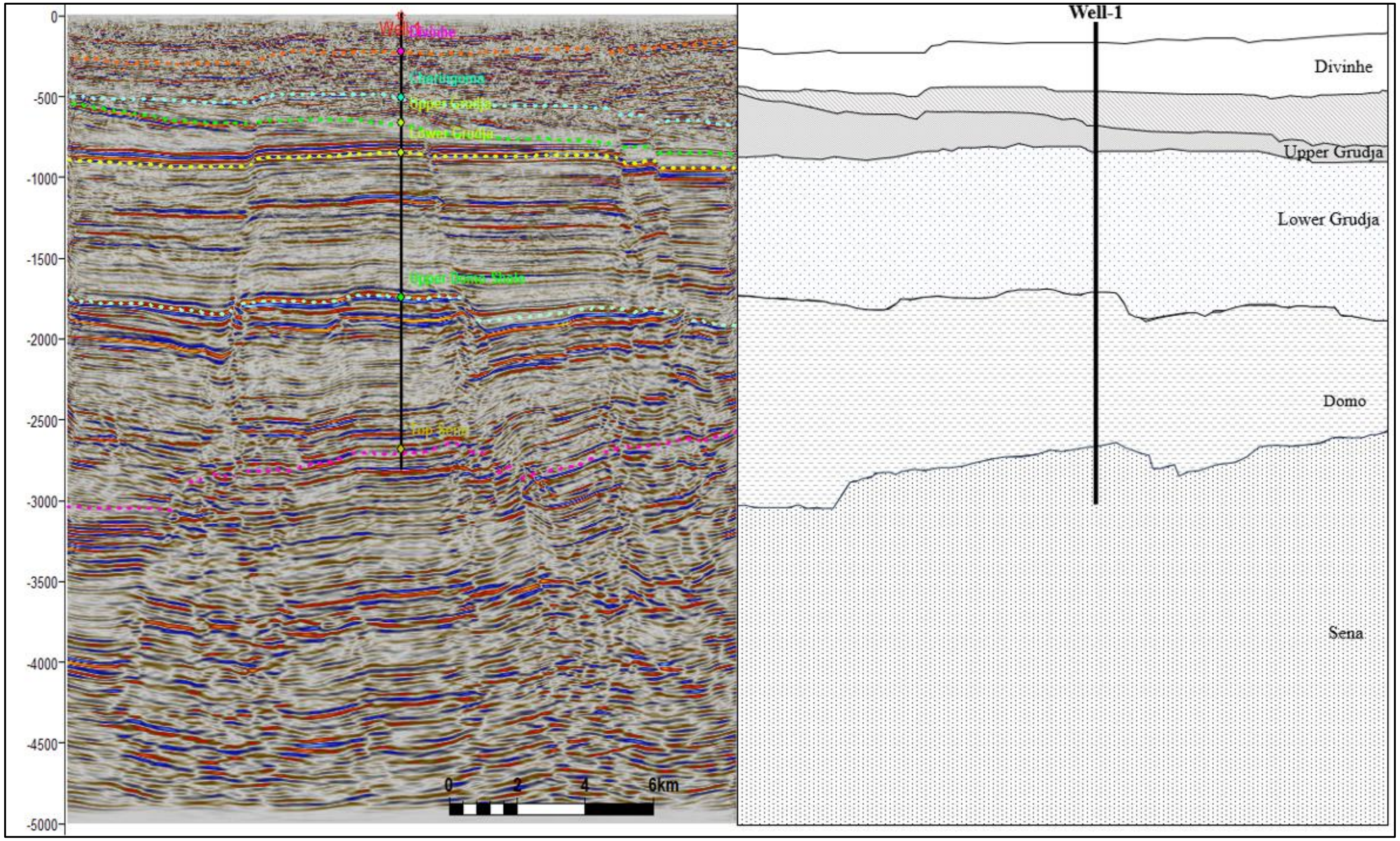


Figure 26. Seismic profile showing horizons interpreted and thick accumulation of Grudja, Domo and Sena formation, progradational body of Cheringoma formation.

Sena Formation

This formation occurs in the entire study area and represent the thicker formation. In the study area the formation was only intercepted by well-1.

The seismic facies of this formation are marked by number of chaotic reflection pattern, high frequency reflectors, strong amplitude reflectors. The Central part of study area is observed continues reflectors with strong amplitudes (**Figure 27**). The East side of the study area is observed chaotic internal reflectors.

Domo Formation

This formation occurs in the entire study area and represent one of the thick formations. The seismic facies of this formation are marked by number of parallel reflection pattern, alternance between strong and weak amplitude reflectors and are continuous reflectors. In this area is not clear to identify the reflectors with mark the boundary between lower Domo Shale/Domo Sandstone and between Domo Sandstone and Upper Domo Shale. The upper reflectors occur throughout the entire area. Locally this upper boundary reflector becomes markedly higher in amplitude (**Figure 28**).

Grudja Formation

The described formation is a prominent feature spanning the entire study area, distinguished by its significant thickness within the Mozambique Basin. Its seismic facies exhibit distinct characteristics, primarily marked by multiple continuous, parallel high-amplitude reflectors. These reflectors partially conform to the underlying topography and display an onlap geometry at their lateral boundaries, where they abut against the underlying deposits or formations (**Figure 29**).

The upper portion of the formation, represented by the Upper Grudja, demonstrates variability in thickness and orientation. It thickens in a westerly direction and thins towards the east, while also exhibiting a tilt towards the east.

Cheringoma Formation

Two different units are observed in the central-east part of the study area one represented with the mound shape and another marked by complex body formed by inclined reflectors geometry (**Figure 30**). This formation becomes thicker towards to the east and thinner towards to the west and the internal cliniforms are prograding towards the east.

<u>Divinhe Formation</u>

The top of Divinhe Formation is recognized on seismic profile from the strong reflector widespread in the entire of the study area. The seismic facies of this formation are marked by several continuous, parallel high amplitude reflectors which partly follow the underlying topography and show an onlap geometry at their lateral boundary and are against the underlying deposits or formations (**Figure 31**).

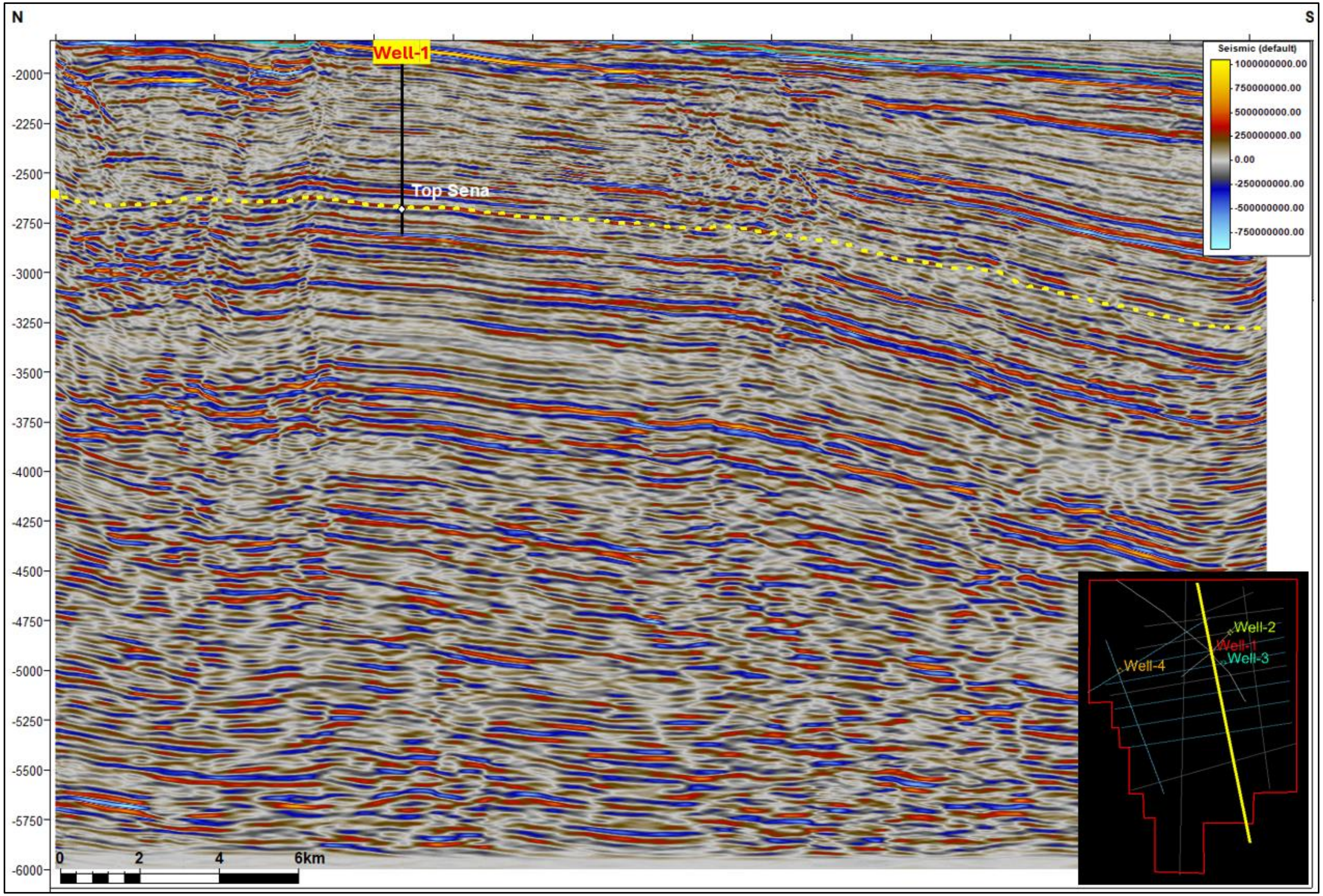


Figure 27. Seismic profile showing the interpreted line, thick accumulation of Sena Formation and the facies chaotically arranged.

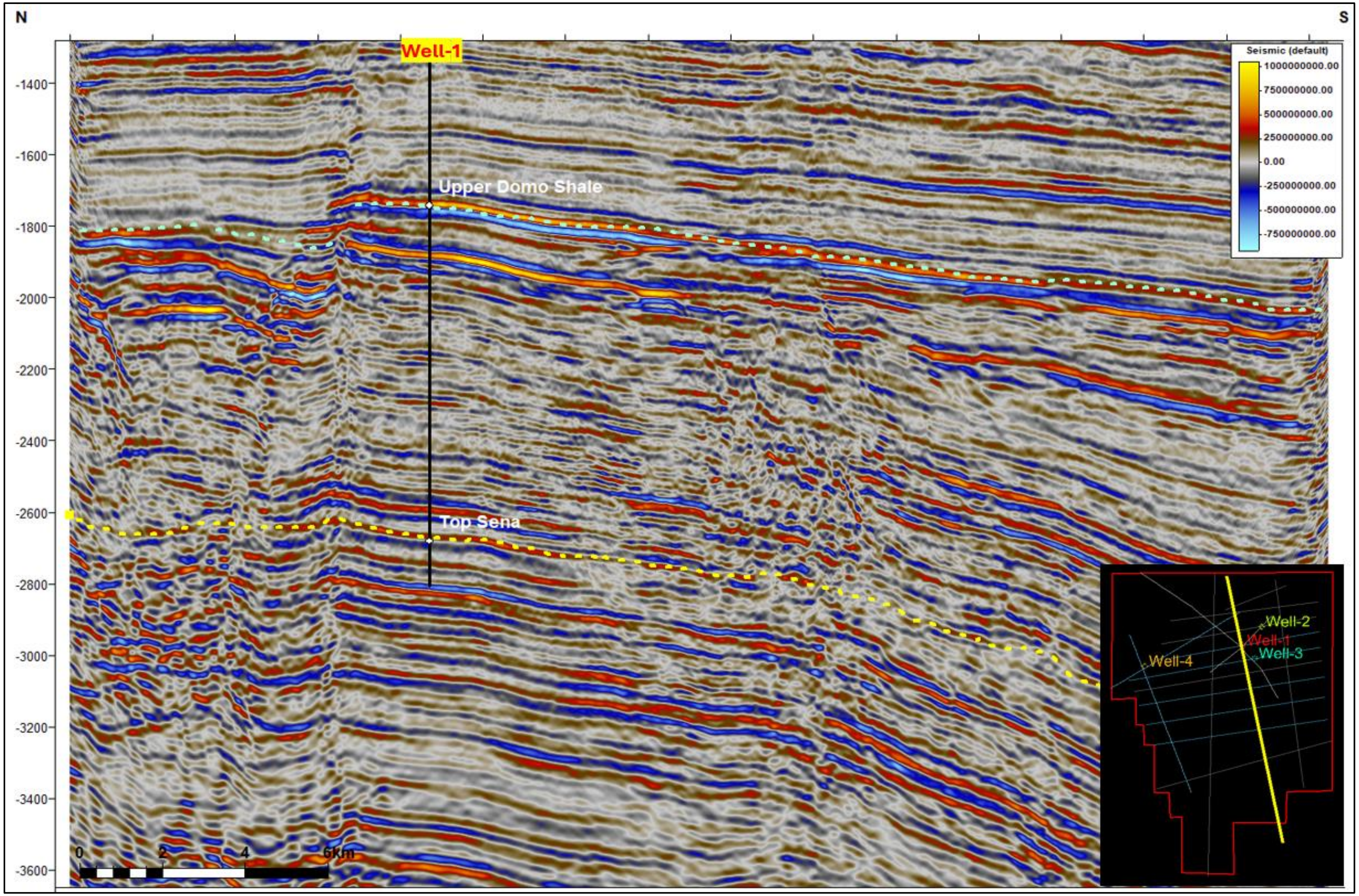


Figure 28. Seismic profile showing the interpreted line, thick accumulation of Domo and onlap termination with well-bedded pattern.

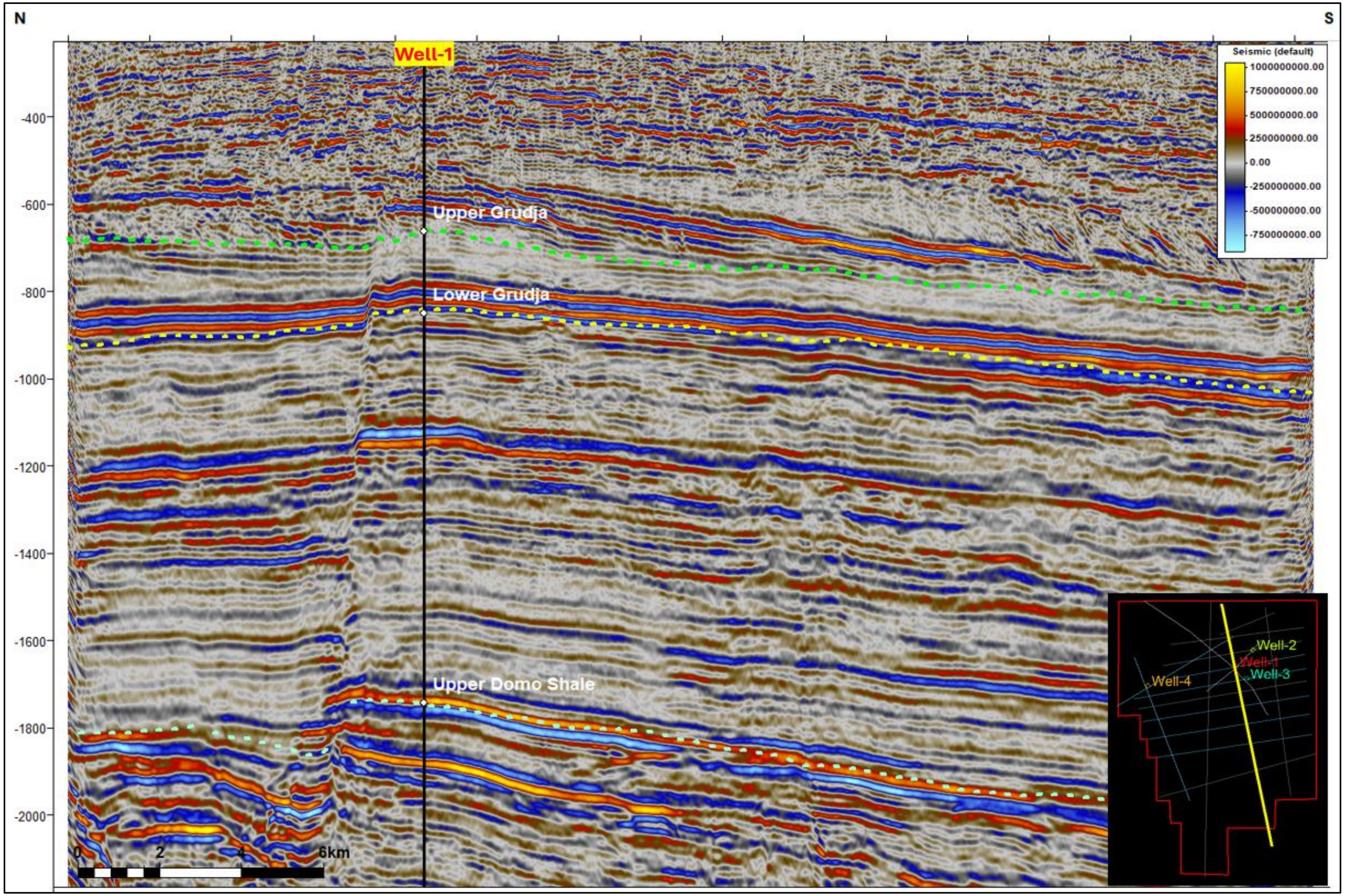


Figure 29. Seismic profile showing the interpreted line, thick accumulation of Grudja and onlap termination with well-bedded pattern.

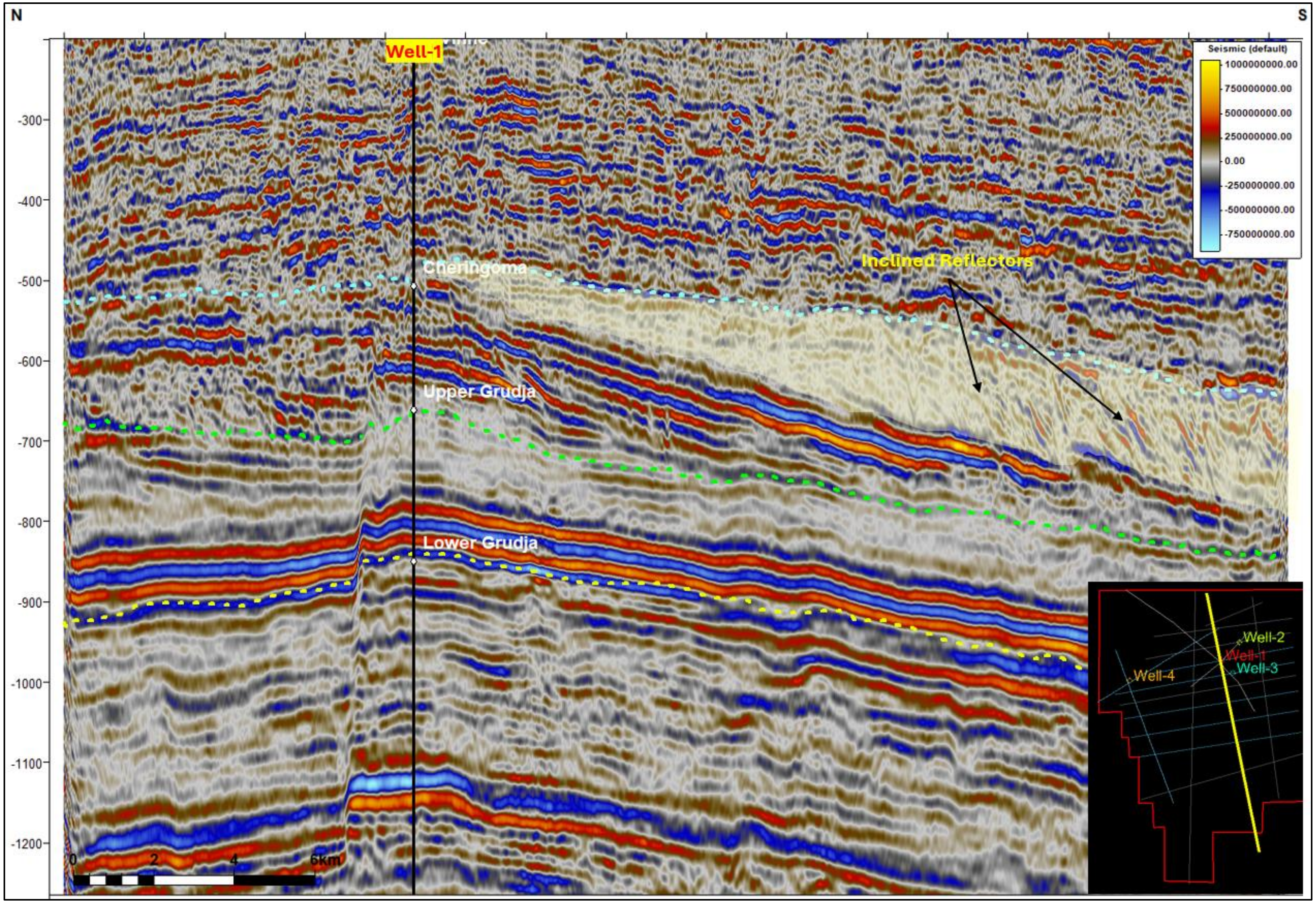


Figure 30. Seismic profile showing the interpreted line, mound shape and prograding cliniforms of Cheringoma.

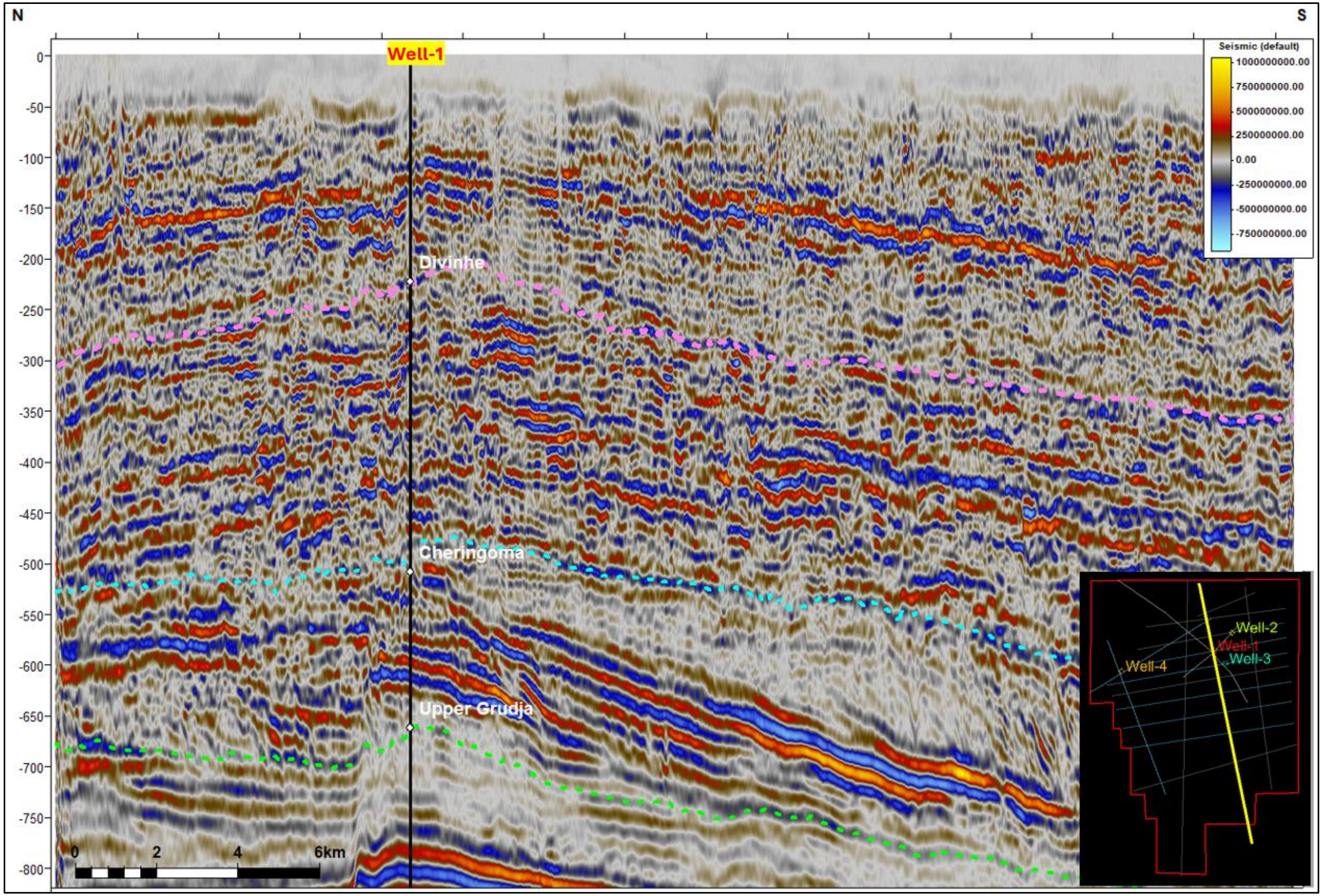


Figure 31. Seismic profile showing the interpreted line, and onlap termination with well-bedded pattern of Divinhe.

Structural Maps

Six structural maps, including Top Sena, Top Domo, Top Lower Grudja, Top Upper Grudja, Top Cheringoma, and Top Divinhe **(see APPENDIX A),** provide valuable insights into the geological structures and topographical trends within the study area. These maps aid in the interpretation of subsurface features and potential reservoir formations.

In the Top Sena formation, the structural mapping reveals a notable absence of distinct features across the area, except for a significant structural high located in the central region. This structural high suggests localized uplift or deformation within the formation and the contour interval (C.I) of 25 ms. Moving to the Top Domo Formation, the structure map illustrates a pronounced trend of deepening towards the southern and southeastern directions with contour interval (C.I) of 15 ms.

The Top Lower Grudja structure map displays a notable geological feature, characterized by a structural high primarily controlled by faults within a horst structure. In the Top Upper Grudja formation, the structure map showcases significant topographical variations, with elevated regions observed in the West and lower areas in the East.

Moving to the Top Cheringoma Formation, the structural map depicts prominent structural features with a northwest-southeast trend observed in the western part of the study area and the contour interval (C.I) of 15 ms. And finally, the structural map of the Top Divinhe Formation illustrates a significant high-relief structure located at the westernmost side of the study area. This high-relief structure displays a northwest-southeast trend similar to observations in the Top Cheringoma structure map.

Seismic Attributes

The seismic attribute analysis, tested various window extraction analysis and chose the best response for each top formation. Six horizons were considered in this analysis namely: Top of Sena, Top of Domo, Top of Grudja, Top of Cheringoma and Divinhe and the results are presented in **(APPENDIX B**). In the process of interpreting the RMS amplitude attribute, the extraction of the RMS amplitude attribute is carried out in the 5ms, 10 ms, 15 ms and 20 ms, analysis windows.

In the Top Sena Formation, the amplitude anomalies depicted in the map exhibit a widespread distribution across the study area. Two significant bodies of anomalies are discernible, primarily within the central region of the Domo area.

The first anomaly, centrally located within the Domo area, displays a distinct NW/SE trend. Notably strong, this anomaly coincides with the geological structure of the Domo.

Adjacent to this central anomaly lies a fault line oriented in a perpendicular N/S trend, effectively separating the central anomaly from the second body of anomalies observed in the eastern extremity of the study area.

The second anomaly, situated towards the easternmost part of the region, stretches approximately 10 kilometers in length. Exhibiting an elongated shape and following an N-S trend, this anomaly presents a distinct feature separate from the central anomaly.

In the Top of Lower Grudja Formation, the amplitude anomaly is characterized by varying degrees of intensity across the study area. This anomaly exhibits a gradient from weak amplitudes in the west to moderate in the central region, and finally to strong amplitudes in the east.

Lithology Prediction

In the analysis, four main lithology classes were considered: sandstone, siltstone, shale and limestone. These classes likely represent the dominant rock types present in the study area and are fundamental for characterizing subsurface formations.

In the lithology prediction for Wells 1 through 4, with Well-1 being the deepest drilled up to the Sena Formation and the other three wells drilled up to the Grudja Formation, five lithofacies were identified: Limestone, Sandstone, Shaly Sandstone, Sandy Shale, and Shale **(APPENDIX C).**

In the Sena Formation, Well-1 penetrated a small portion, encountering alternating layers of Sandy Shale and Shaly Sandstone.

Moving to the Domo Formation, Well-1 intercepted 1121 meters of sediments, identifying four lithofacies: Shale, Sandy Shale, Shaly Sandstone, and Sandstone. Notably, the lower part of this section exhibited interbedded Sandy Shale with very thin layers of Shaly Sandstone, with localized shale deposits concentrated in the central portion.

In the Lower Grudja Formation, the lithology observed in the log motif included a diverse range of sedimentary rock types, such as limestone, sandstone, sandy shale, and shaly sandstone.

Transitioning to the Upper Grudja Formation, interbedded Sandy Shale and Shaly Sandstone layers were predominant, with a notably thick layer of sandy shale.

In the Cheringoma Formation, the upper portion exhibited carbonate rocks like limestone or dolomite, while the middle section displayed interbedded shaly sandstone and sandstone layers, characterized by cyclic coarsening-upward sequences. The bottom part of the formation showed interbedded shaly sandstone, sandstone, and sandy shale.

Lastly, within the Divinhe Formation, a distinctive lithological pattern was observed, characterized by interbedded sandstone and shaly sandstone layers, displaying a cyclic coarsening-upward sequence. Additionally, locally observed sandy shale layers were present within the sequence.

5.5 Discussion

Seismic Well-Tie

The high cross-correlation value of 84% signifies a strong alignment between the synthetic seismic traces and the actual seismic data. This outcome is particularly valuable given the incorporation of time-depth relationships established from historical formations. The success of the well-tie is indicative of the effectiveness of the modeling approach in capturing the essential features present in the seismic data.

The well-tie results, with an 84% cross-correlation, not only validate the synthetic seismic data but also highlight the successful integration of historical formation data for time-depth relationships in Well-1.

In the case of Well 4, the synthetic seismic data was meticulously modeled using available Vertical Seismic Profile (VSP) data. The commendable cross-correlation value of 68%, attests to the effectiveness of this modeling approach, indicating a robust correlation between the synthetic and actual seismic data. This positive correlation implies that the synthetic seismic traces closely align with the seismic data obtained from Well 4.

Seismic Interpretation

The seism-structural mapping reveals two fault scenarios: one predominantly affecting deep horizons like the Sena and Domo formations, and the other impacting all horizons, including Sena, Domo, Grudja, Cheringoma, and Divinhe formations (**Figure 32**). The first scenario suggests significant influence on geological structures at considerable depths, while the second indicates widespread faulting across various geological strata.

The mapped faults exhibit a predominantly NW/SW trend and are identified as normal faults. The older fault system, intersecting the Sena and Domo horizons from the Jurassic age, underwent reactivation during the Tertiary period. These faults extend upward, intersecting the Grudja formation all the way to the surface. This reactivation is believed to be associated with the East African Rift system, which emerged during the Miocene age. It's likely that this rift represents the southern extension of the Eastern African Rift and is correlated with the structure known as the Chissenga Graben in Mozambique.

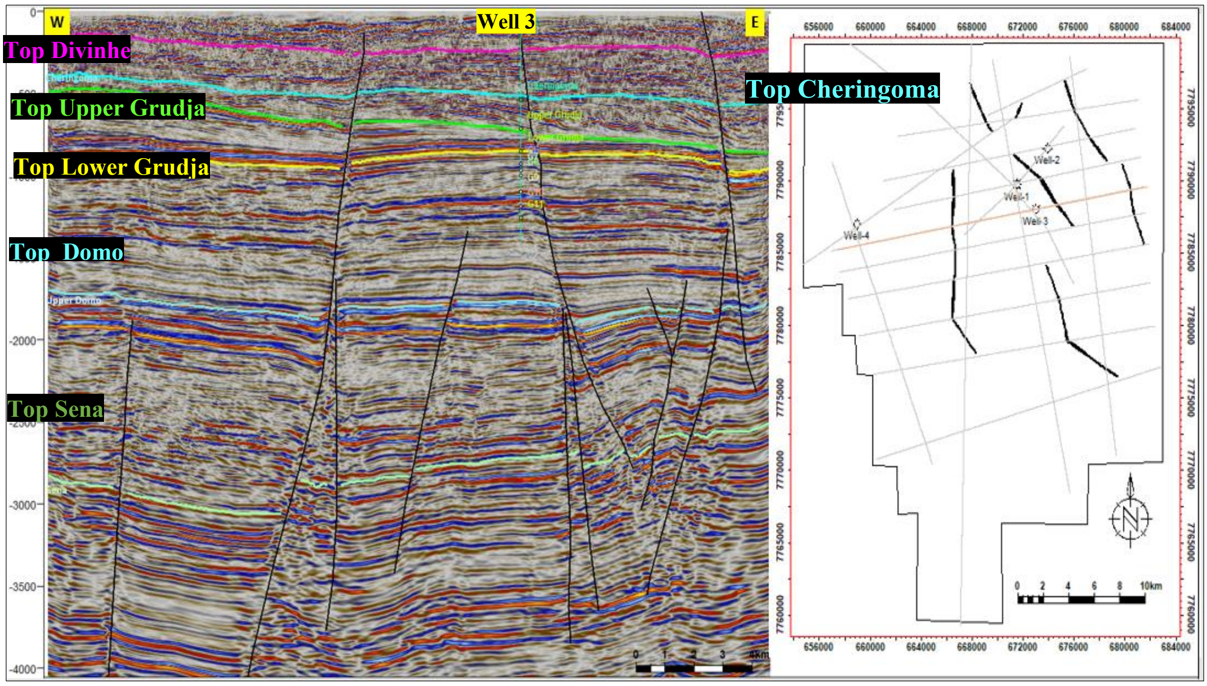


Figure 32. The seismic section shows the mapping of horizons and geological faults identification in the study area.

Sena Formation

The described formation, found throughout the study area, is the thickest geological unit present. Well-1 is the only borehole to penetrate this formation. Seismic analysis reveals distinct facies characteristics, including chaotic reflection patterns with large amount of diffraction which is not easily traced, high-frequency reflectors, and strong amplitude reflectors. The chaotic nature of internal reflectors suggests massive sediments without bedding and internal order and the presence of diffractions could indicate the existence of unhomogenized and chaotically arranged sediments with different lithologies. This disorderly arrangement may indicate rapid deposition or geological disturbances in the eastern sector (**Figure 33 A**).

In the central part of the study area, continuous and parallel reflectors with robust amplitudes dominate. However, on the eastern side, internal reflectors appear chaotic, indicating the presence of massive sediments lacking bedding or internal order.

The structural map of the Top Sena formation depicts a general absence of clear structural features or noticeable patterns across the mapped area (**Figure 33 B**). However, within the central part of the study area, there is a notable exception with the presence of a prominent structural high.

The existence of a structural high in the central portion suggests localized uplift or deformation within the Top Sena formation. Structural highs typically represent areas where the geological strata have been uplifted or folded, resulting in elevated topography relative to the surrounding regions.

The attribute extraction shows sparse localized anomaly in the study area with NW/SE trends and the attribute extraction process has unveiled a significant finding: sparse localized anomalies within the study area exhibiting NW/SE trends. This observation suggests a structured pattern of anomalies that may hold geological significance.

The NW/SE trends observed in these anomalies could indicate potential geological features, such as faults, fractures, or sedimentary structures, that influence the distribution of properties in the study area (**Figure 33 C**).

Upon careful examination of the log motif, it is evident that the lower part exhibits a distinct pattern of alternating layers of Sandy Shale and Shaly Sandstone and the serrated log motif is observed at the gamma ray log.

The serrated log motif is observed at the gamma ray log is indicative of heterogeneous lithofacies succession implies deposition under the influence of rapidly alternating high and low energy such that when environmental energy is high, sand is deposited (if available), and when energy is low, mud or silt is deposited (**Figure 33 - D**).
This interbedded structure suggests cyclic sedimentation processes or variations suggest that this rapid energy variation can occur in nonmarine floodplain environments.

The East side of the study area is observed chaotic internal reflectors order suggests massive sediments without bedding and internal order and the presence of diffraction indicate the existence of unhomogenized and chaotically arranged sediments with different lithology.

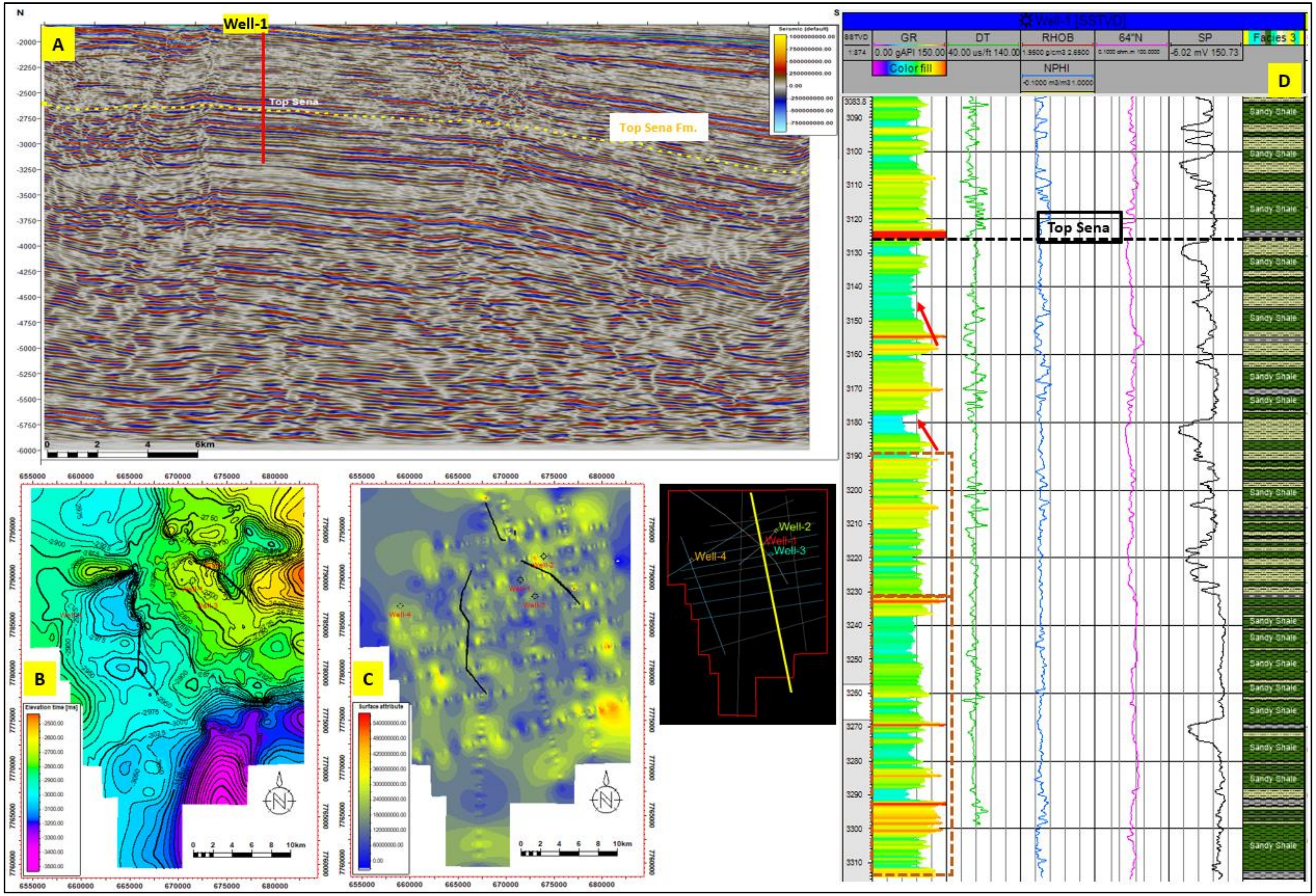


Figure 33. **A**-The seismic facies show number of chaotic reflection pattern and continues reflectors with strong amplitudes; **B**- Structural map of the Top Sena, C. I. =25 ms; **C**- Top of Sena RMS attribute extraction -/+ 20 ms; & **D**- Log motif representing upper part of Sena formation.

Domo Formation

This Formation, present throughout the study area, represents one of the thicker units. Seismic analysis reveals parallel reflection patterns with alternating strong and weak amplitude reflectors, suggesting well-bedded, fine-grained sediments additionally is recognized prograding clinoforms deeping NW/SE towards to the Indian ocean (**Figure 34 A**). Distinguishing boundaries between lithological units is challenging. Upper boundary reflectors, consistent across the area, occasionally exhibit higher amplitudes. The facies, coupled with lateral continuity and onlap contacts, suggest gradual basin filling through vertical accretion.

The structure map reveals a topographical trend of deepening towards the southern and southeastern directions, highlighting the influence of geological faults mapped (**Figure 34 B**). The spaced contour (C.I. 15 ms) emphasizes variations in subsurface structures with greater resolution and the deepening trend suggests the presence of fault-controlled structures influencing the subsurface topography.

The central part is characterized by high amplitude anomaly and this body is controlled by faults. There is a conformance between the structure observed and the anomaly observed in the central part (**Figure 34 C**). The central part of the area under consideration exhibits a notable high-amplitude anomaly. This observation suggests a correlation between the structural features and the RMS anomaly detected in the study area. Such structure and amplitude anomaly conformance implies the potential to have reservoir trap hydrocarbon.

On the other hand, the RMS map presents the presence of two distinct bodies within the area of interest. The first body, situated on the eastern side, exhibits a north-south trend, indicating a potential island barrier.

The second body, located in the central and western parts, displays a northwest-southeast trend. This directional trend suggests a different geological history or structural influence compared to the eastern body. The presence of such distinct trends within the region could signify complex tectonic interactions, geological formations, or depositional environments.

The identification of a high-amplitude anomaly in the central part of the study area, influenced by a fault, suggests a correlation between the observed structural features and the

RMS anomaly. This conformance between the structural characteristics and the anomaly amplitude raises the possibility of a reservoir trap for hydrocarbons.

The well for this formation intercepted 1121 m of sediments and four lithofacies was identified in this formation (Shale, Sandy Shale and Shaly Sandstone Sandstone).

In the lower part of the section, there is a notable presence of interbedded Sandy Shale and with very thin layer of Shaly Sandstone, with localized shale deposits particularly concentrated in the central portion of this section.

Interbedded formations typically indicate alternating layers of different sedimentary rock types, often deposited in an environment with variable depositional conditions. In this case, the interbedding of Sandy Shale and Shaly Sandstone suggests a sedimentary environment characterized by fluctuating energy levels, such as those found in coastal or deltaic settings. Sandy Shale indicates the presence of fine-grained sedimentary rocks with a notable sand content, while Shaly Sandstone refers to sandstone with a significant proportion of clay minerals, giving it a shaly texture.

The thin layers of Shaly Sandstone within the interbedded sequence suggest intermittent episodes of higher energy deposition, possibly associated with periods of increased sediment supply or transportation.

The presence of shale deposits within this interbedded sequence further indicates periods of reduced energy during sedimentation, allowing for the accumulation of fine-grained clay minerals. Shale is typically formed in low-energy environments, such as deep marine basins or distal portions of sedimentary systems, where fine particles settle out of suspension over time.

In the upper part of the observed section (**Figure 34 - D**), a similar interbedded scenario is noted, but with distinct differences from the lower part. Here, the episodes of sedimentation appear to have taken more time, resulting in thicker layers compared to the lower section. Additionally, at the bottom of this upper section, a prominent Sandstone layer is observed, which is presumed to be the well-known Domo Sandstone.

The seismic facies, together with lateral continuity, the onlap contact of the termination, seem to indicate well-bedded, fine-grained sediments that have gradually filled the basin by vertical accretion.

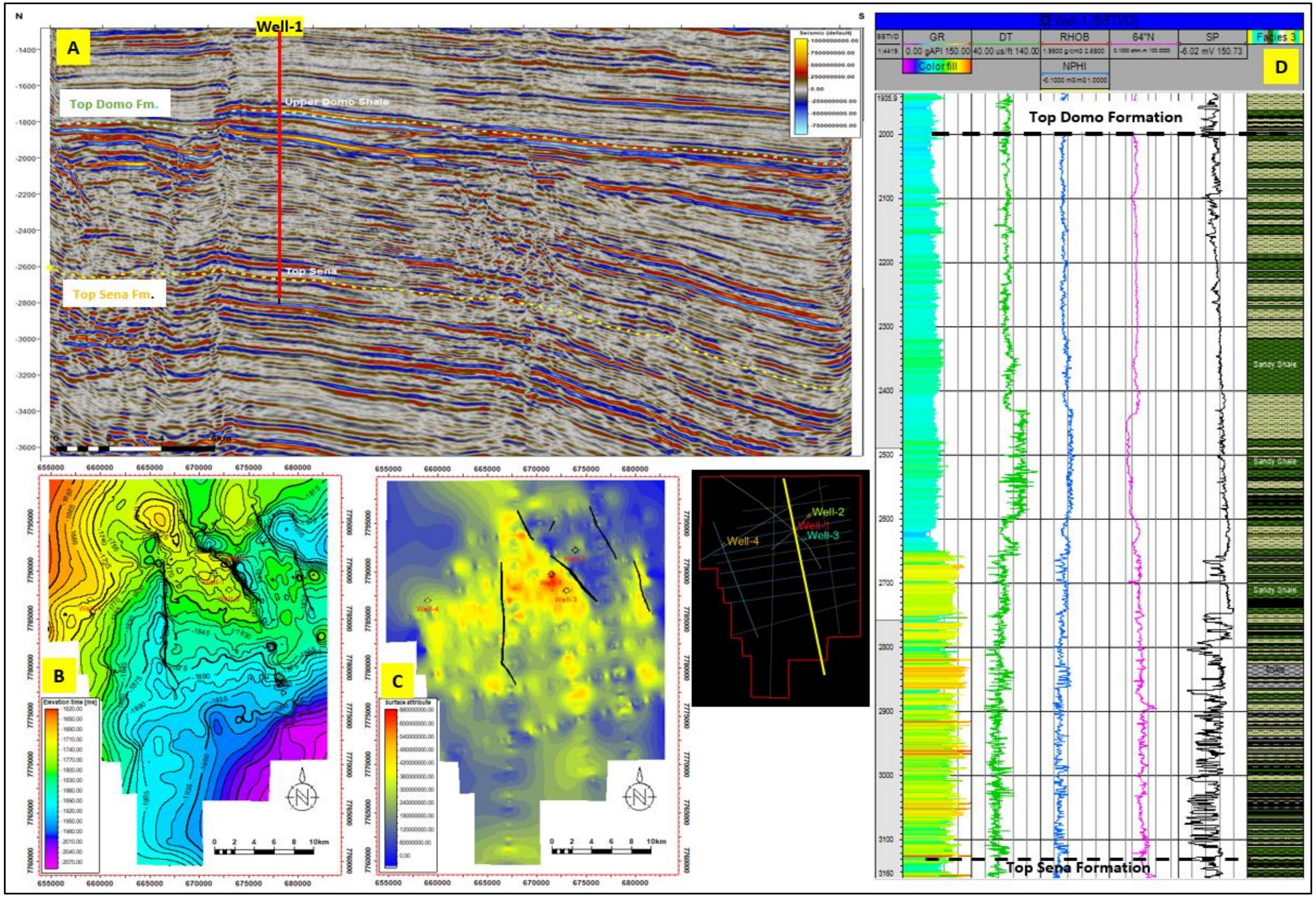


Figure 34. **A**-The seismic facies show continues reflectors with strong amplitudes; **B**- Structural map of the Top Domo structure strap, **C**. I. =15 ms; C- Top of Sena RMS attribute extraction -/+ 15 ms with high amplitude anomaly at Central part of the study area; & **D**- Log motif representing the interval between Top Sena and Top Domo formation.

Grudja Formation

The described formation is a significant feature across the Mozambique Basin, notable for its considerable thickness. These reflectors partially conform to underlying topography and exhibit an onlap geometry at their lateral boundaries, indicating their interaction with underlying deposits or formations (**Figure 35**).

Lower Grudja,

The Lower Grudja formation, representing the lower portion of the Grudja formation, exhibits a nearly homogeneous thickness across the study area. However, despite this uniformity in thickness, its seismic facies display distinct characteristics characterized by multiple continuous, parallel high-amplitude reflectors (**Figure 35 - A**).

The presence of continuous, parallel high-amplitude reflectors within the seismic facies of the Lower Grudja formation suggests a consistent lithological composition or depositional environment.

The parallel nature of the reflectors indicates relatively undisturbed sedimentation, with successive layers deposited in a consistent manner over time. This suggests a stable depositional environment without significant tectonic activity or erosional processes disrupting sedimentation.

The high amplitude of the reflectors suggests strong contrasts in acoustic impedance between adjacent sedimentary layers within the Lower Grudja formation. This could be due to variations in lithology, porosity, or fluid content, all of which influence the seismic response of the formation.

The structure map reveals the presence of a significant geological feature, a structural high, that is primarily controlled by faults within a horst structure (**Figure 35 - B**). The structural high suggests uplifted areas within the formation, potentially influencing sedimentary deposition and reservoir formation. The contour interval (C.I) of 10 ms provides detailed information on the topographical variations within the formation.

In the entire study area, there is a noticeable presence of amplitude anomalies in the seismic response, although the most significant anomalies are concentrated in the eastern part of the study area. Notably, these anomalies are observed within the structural high identified in the structural map (**Figure 35 - C**).

The presence of amplitude anomalies in the seismic response indicates variations in the reflection amplitudes of subsurface geological features. These variations can be attributed to changes in lithology, fluid content, porosity, or other geological properties within the rock layers.

The concentration of these anomalies within the structural high suggests a correlation between the structural features and the observed seismic anomalies. This correlation may indicate that the structural high has influenced the distribution and behavior of subsurface fluids or sedimentary deposition, leading to distinct seismic responses.

The western part of the anomaly displays weaker amplitudes compared to the central and eastern regions. This suggests that the geological features or processes contributing to the amplitude anomaly may be less pronounced or influential in the western area. Moving towards the central region, the amplitude anomaly becomes more pronounced, reaching a moderate level of intensity. This indicates that there may be significant geological structures or phenomena present in this area that contribute to the observed anomalies.

In the eastern part of the study area, the amplitude anomaly is characterized by strong intensities. This suggests the presence of prominent geological features or processes that strongly influence the amplitude of seismic waves in this region. Such features could include fault lines, geological formations, or hydrocarbon reservoirs, among others.

The lithology observed in the log motif comprises a diverse range of sedimentary rock types, including limestone, sandstone, sandy shale, and shaly sandstone. These lithologies form a distinct sequence characterized by coarsening upward, indicating a gradual increase in grain size from finer to coarser sediments within each cycle (**Figure 35 - D**).

The coarsening-upward sequence suggests a depositional environment where energy levels fluctuate over time, leading to the deposition of finer-grained sediments at the base of each cycle, followed by progressively coarser sediments towards the top. These type of well log motifs are more indicative of depositional environment than others. In siliciclastic deposits, this well-log signature indicates gradual encroachment of progressively higher-energy depositional environment. These characteristics suggest depositional environments such as prograding distributary-month-bar and shoreface deposits.

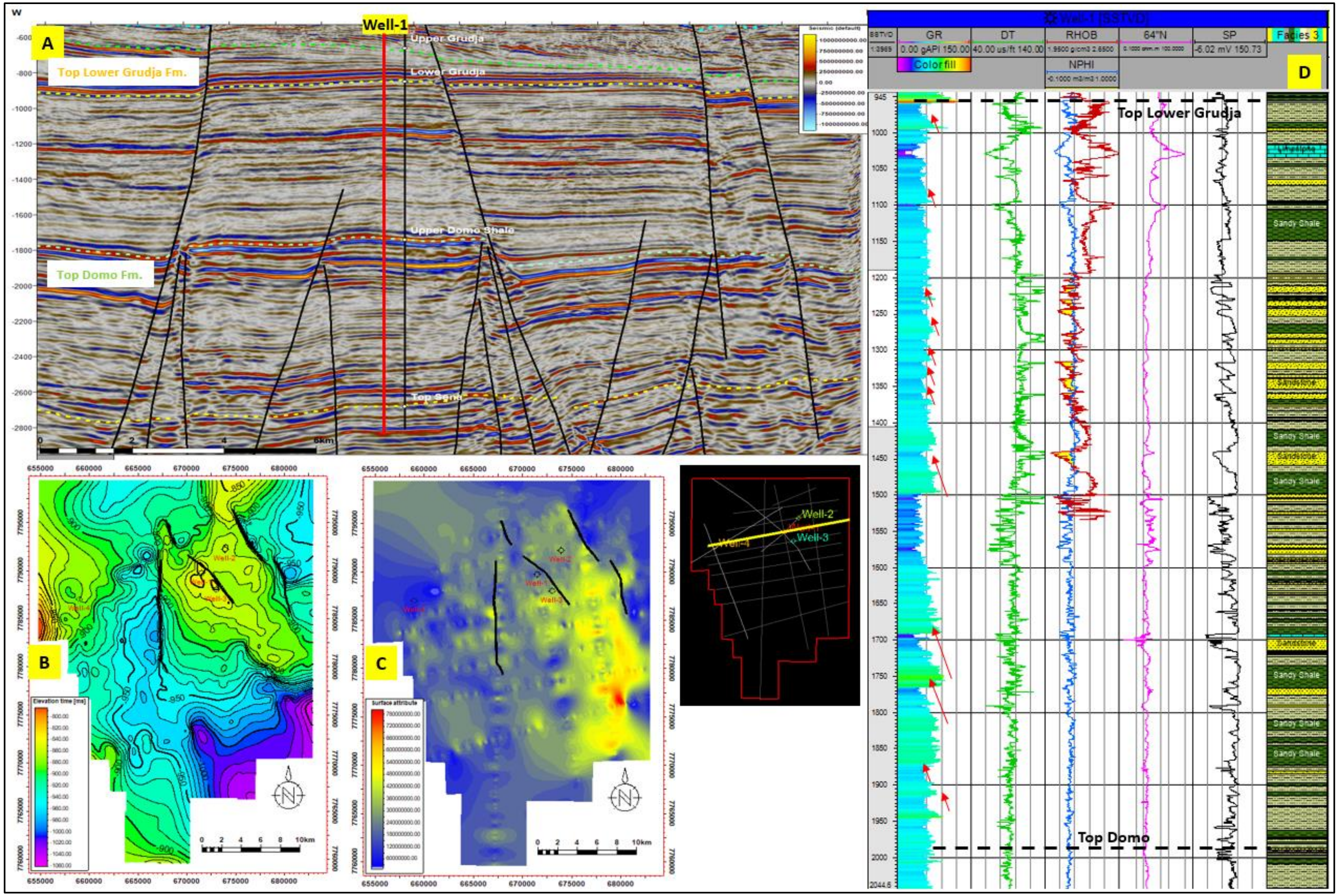


Figure 35. **A**-The seismic facies show continues reflectors with parallel and strong amplitudes; **B**- Structural map of the Top Lower Grudja structure, C. I. =10 ms; **C**- Top of Grudja RMS attribute extraction -/+ 10 ms with amplitude anomaly observed in the study area; & **D**- Log motif representing the interval between Top Domo and Top Lower Grudja formation.

The ***Upper Grudja***, representing the upper portion of the formation, shows very strong seismic amplitude at the bottom and wedging to the East. It thickens towards the west and thins towards the east, with a tilt also observed towards the east (**Figure 36 A**). The wedging pattern towards the East, indicating a gradual thinning of sedimentary layers or a narrowing of the formation in that direction.

The structure map delineates distinct features: elevated regions in the West and lower areas in the East. These characteristics suggest the presence of a structural high supported by faults, specifically a horst structure (**Figure 36 - B**). The topographical variations observed in the West suggest complex structural features influencing the subsurface geology. The contour interval (C.I) of 15 ms enhances the visualization of these topographical differences, allowing for more accurate interpretation.

No signs of erosion are evident, and the relief displays a gradual, smoothing deepening pattern. This indicates that the observed variations in elevation are likely the result of tectonic forces rather than surface processes such as weathering and erosion.

The RMS map for the extraction window of +/- 10 ms provides a detailed view of the amplitude variations within the seismic data, making it the optimal window for amplitude analysis (**Figure 36** - **C**). Despite this detailed examination, no significant amplitude anomalies were observed in the area corresponding to the observed structural features.

The Upper Grudja unit is characterized by interbedded Sandy Shale and Shaly Sandstone layers, along with a notably thick layer of sandy shale (**Figure 36** - **D**). These specific lithological compositions contribute to the formation of strong amplitude reflectors on the seismic profile associated with this unit.

The interbedded Sandy Shale and Shaly Sandstone layers likely exhibit contrasting acoustic properties, leading to distinct seismic responses. Sandy Shale typically contains higher proportions of sand, which tends to have higher acoustic impedance compared to the finer-grained shale matrix. This contrast in acoustic impedance between the sandy and shaly layers results in strong amplitude reflectors on the seismic profile.

The Upper Grudja, demonstrates variability in thickness and orientation. It thickens in a westerly direction and thins towards the east, while also exhibiting a tilt towards the east. This asymmetric distribution and tilting suggest dynamic geological processes influencing the deposition and deformation of the formation over time

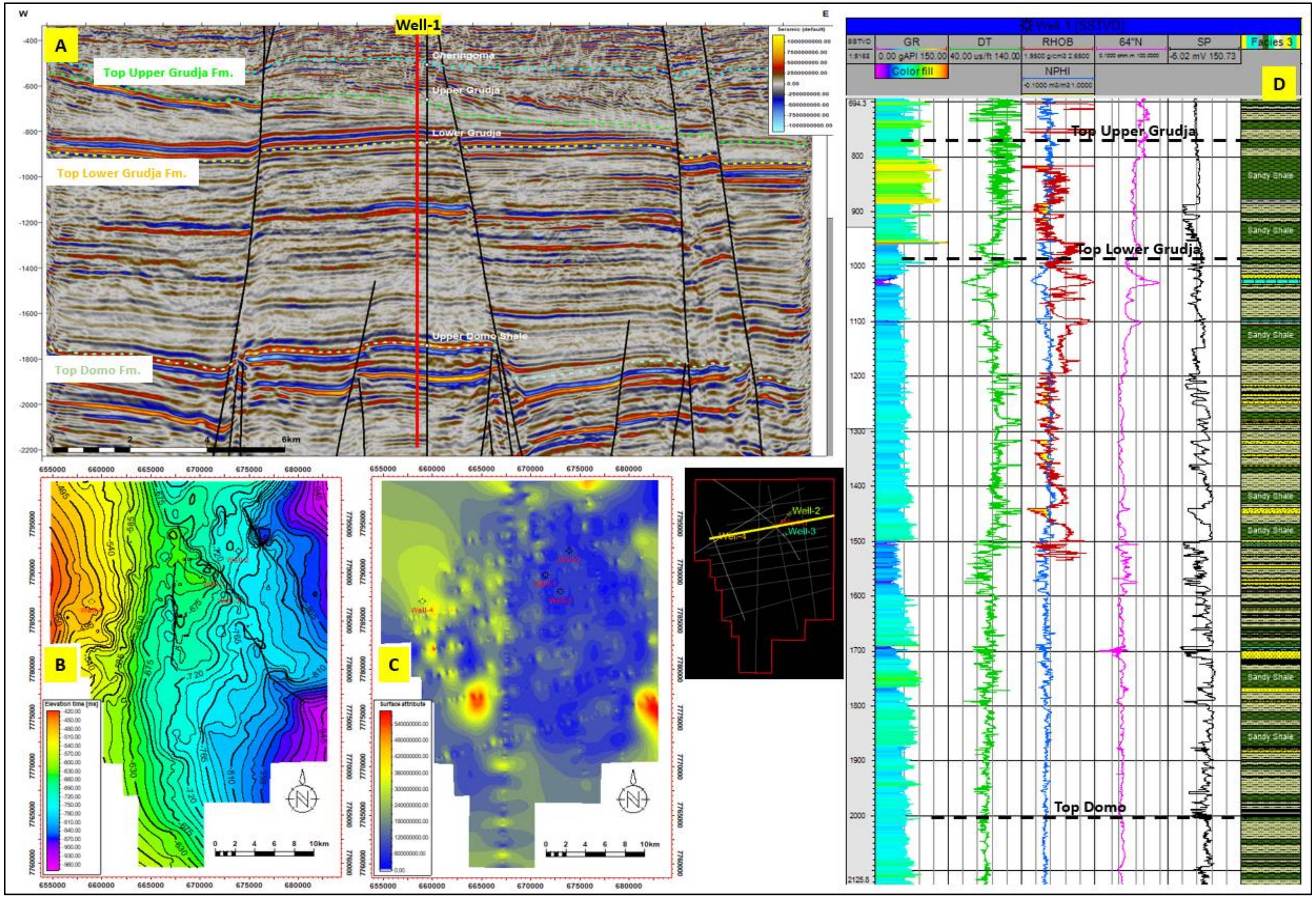


Figure 36. **A**-The seismic facies show continues reflectors with parallel and strong amplitudes; **B**- Structural map of the Top Upper Grudja structure, C. I. =15 ms; **C**- Top of Grudja RMS attribute extraction -/+ 10 ms with no amplitude anomaly observed in the study area; & **D**- Log motif representing the interval between Top Domo and Top Upper Grudja formation.

Cheringoma Formation

In the central-eastern portion of the study area, two distinct geological units are discernible. One unit is characterized by a mound-shaped morphology, while the other exhibits a complex body composed of inclined oblique reflectors (**Figure 37 - A**). Additionally, is observed the landward pinchout of the wedge, representing a very thin transgressive system tract represented by a retrogradational pattern, generally recognized in the inner shelf but unclear on the outer shelf suggesting a zone of sedimentary bypass between the provenance area and this wedge.

The formation displays pronounced thickness variations from east to west, with a trend of thickening towards the east and thinning towards the west. Additionally, internal cliniforms within the formation exhibit a prograding pattern towards the east. The progradational staking pattern observed in the seismic profile is a function of the ratio of rate of accommodation to rate of deposition.

The structural map reveals high structural features with a NW/SE trend in the western part and fault-controlled highs in the central region (**Figure 37 - B**). The prominent structural features with NW/SE trend Fault-controlled highs are also observed in the central region, indicating the influence of tectonic activity on the formation of geological structures. The contour interval (C.I) of 15 ms provides detailed information on the spatial distribution of these structural features.

The attribute anomaly, extracted within a +/- 10 ms window, revealed bodies exhibiting a NW/SE trend distributed throughout the study area. In the easternmost part, structural control appears evident, with faults aligned along the amplitude anomaly, serving as a boundary (**Figure 37 - C**). This alignment suggests a structural influence on the distribution of the anomaly, indicating potential fault-controlled compartments or zones of differential subsurface properties.

The Cheringoma Formation exhibits distinct lithological variations throughout its upper, middle, and bottom parts (**Figure 37 - D**). In the upper portion, carbonate rocks such as limestone or dolomite are observed, indicating deposition in a marine environment. The middle section displays interbedded shaly sandstone and sandstone layers, characterized by cyclic coarsening-upward sequences, suggesting deposition in nearshore environments. Locally, sandy shale layers are present, indicating fluctuations in energy levels during deposition.

The bottom part of the formation exhibits interbedded shaly sandstone, sandstone, and sandy shale, suggestive of shoreface facies. This configuration may indicate deposition in nearshore environments with periodic fluctuations in energy levels. Alternatively, it could signify sediment accumulation in a low-energy delta setting, characterized by alternating layers of sediment deposited by river channels and distributary channels.

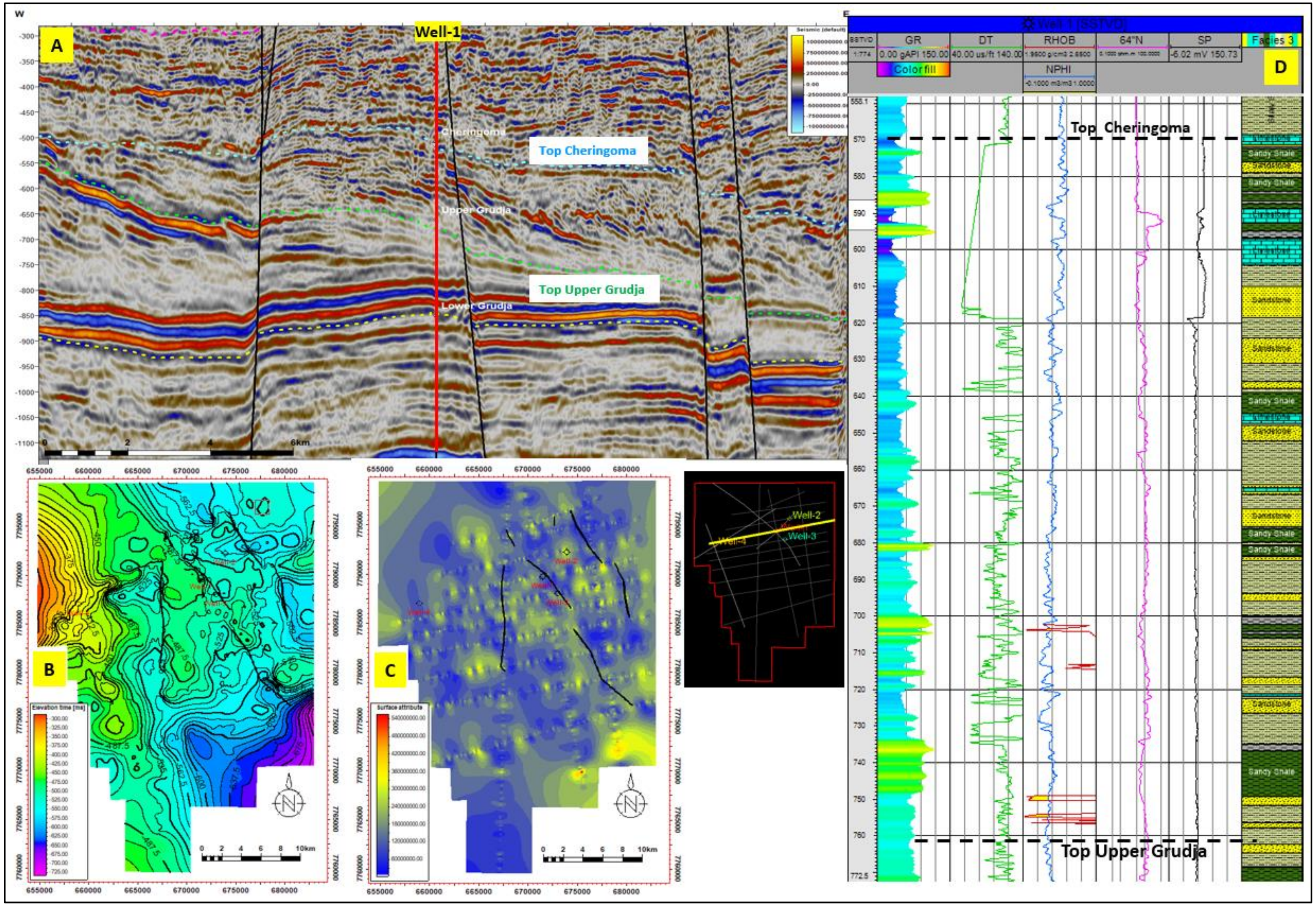


Figure 37. **A**-The seismic facies show prograding and strong amplitudes reflectors; **B**- Structural map of the Top Cheringoma with distinct highs, C. I. =15 ms; **C**- Top of Cheringoma RMS attribute extraction -/+ 10 ms with amplitude anomaly NW/SE trend; & **D**- Log motif representing the interval between Top Upper Grudja and Top Cheringoma formation.

Divinhe Formation

The top of the Divinhe Formation is identifiable on seismic profiles by a prominent, strong reflector that extends throughout the study area. Seismic facies within this formation are characterized by numerous continuous, parallel high-amplitude reflectors (**Figure 38** - **A**). These reflectors partially conform to the underlying topography and exhibit an onlap geometry at their lateral boundaries, where they abut against the underlying deposits or formations.

This distinctive seismic signature provides a reliable marker for identifying the top of the Divinhe formation across the study area. The consistent presence of these reflectors suggests uniform depositional processes or lithological characteristics within the formation.

The structural map delineates a prominent high-relief structure at the westernmost side of the study area, characterized by a NW/SE trend, consistent with observations in the Top Cheringoma structure map (**Figure 38** - **B**). This trend suggests a regional tectonic influence shaping the geological architecture. Additionally, sparse structural highs are observed in the central area, also controlled by faults. These structural features indicate localized areas of uplift or subsidence, likely influenced by faulting mechanisms or additionally carbonate build up.

The attribute extraction analysis, performed within a +/- 5 ms window, identified significant amplitude anomalies predominantly concentrated in the northeastern side of the study area (**Figure 38** - **C**). These anomalies display a clear NW/SE trend, mirroring the direction of prograding seismic facies observed in the seismic data.

The alignment of these anomalies with the direction of prograding seismic facies suggests a potential correlation between the two phenomena. Prograding seismic facies typically indicate sediment deposition in a direction perpendicular to the shoreline, commonly associated with deltaic or shallow marine environments.

The section described within the Divinhe Formation exhibits a distinctive lithological pattern characterized by interbedded sandstone and shaly sandstone layers, displaying a cyclic coarsening-upward sequence. Additionally, locally observed sandy shale layers are present within the sequence (**Figure 38** - **D**).

This lithological arrangement suggests cyclical variations in depositional conditions, with alternating periods of sediment accumulation and erosion. The cyclic coarsening-upward sequence indicates gradual changes in energy levels or sediment supply over time, resulting in the deposition of finer-grained shaly sandstone layers at the base of each cycle, followed by progressively coarser-grained sandstone layers towards the top.

The presence of sandy shale layers within the sequence indicates further variations in depositional environments or sediment sources. Sandy shale typically represents transitional lithologies between sandstone and shale, suggesting fluctuations in sediment composition or depositional processes.

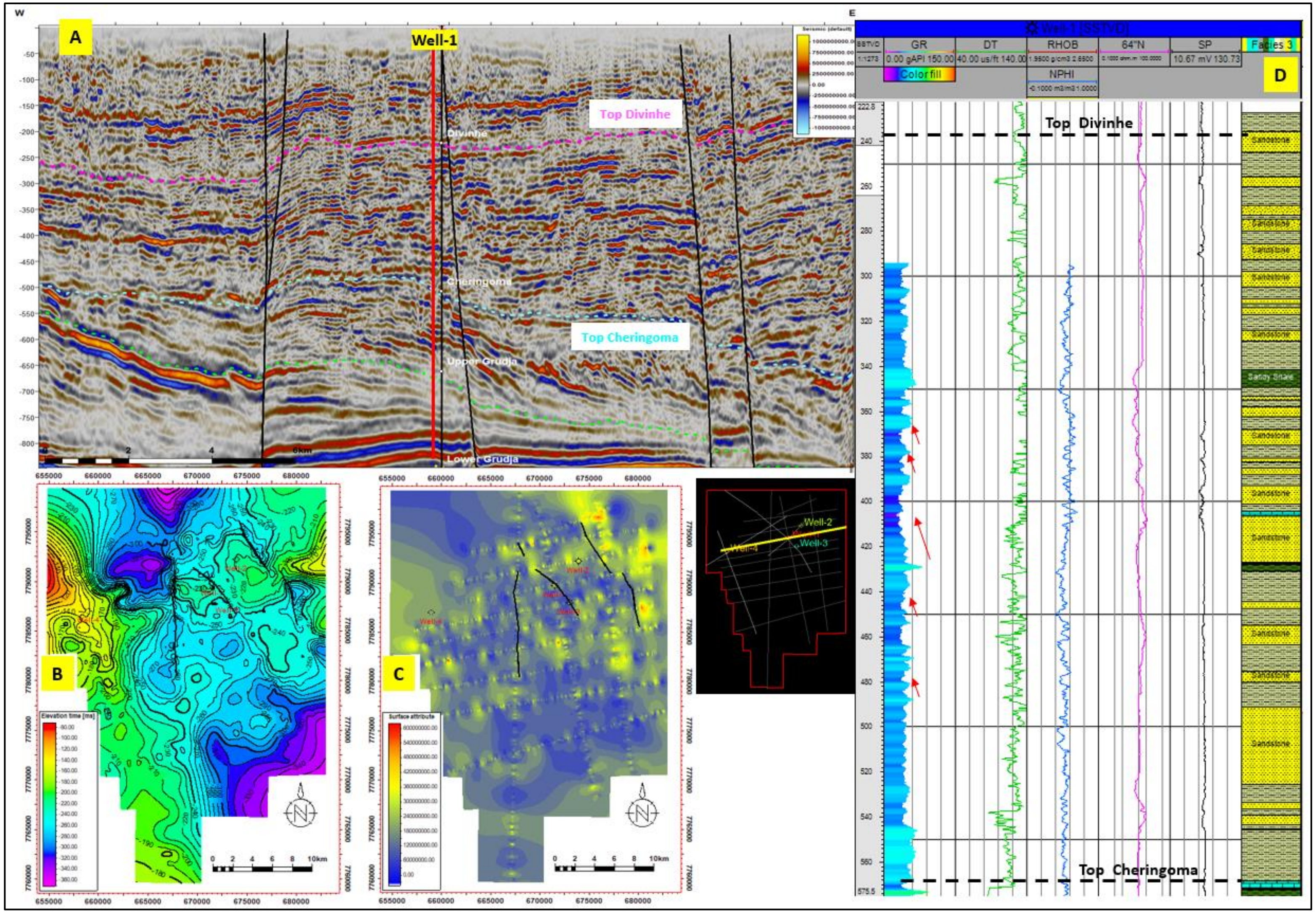


Figure 38. **A**-The seismic facies show parallel and strong to moderate amplitudes reflectors; **B**- Structural map of the Top Divinhe with distinct highs, C. I. =10 ms; **C**- Top of Divinhe RMS attribute extraction -/+ 5 ms with amplitude anomaly NW/SE trend; & **D**- Log motif representing the interval between Top Cheringoma to Top Divinhe formation

5.6 Self-Assessment (Study Limitation)

While the study provides valuable insights into the geological characteristics of the study area, several limitations should be acknowledged to ensure the interpretation and recommendations are appropriately contextualized:

Data Limitations

The study's conclusions heavily rely on seismic data interpretation and well logs. However, the availability and quality of these data may vary across different parts of the study area. Limited data coverage or poor data quality in certain areas could introduce uncertainties or biases into the interpretations.

Resolution Constraints

2D Seismic data, despite its usefulness, may have limitations in resolving fine-scale geological features or subtle structural complexities. The resolution of seismic images is influenced by factors such as acquisition parameters, processing techniques, and subsurface properties. As a result, some geological features or faults may not be adequately resolved or may be misinterpreted.

Assumptions and Interpretation Uncertainties

Geological interpretations are subject to various assumptions and uncertainties inherent in the interpretation process. Interpretation of seismic facies, fault geometries, and lithological boundaries involves subjective judgment and may vary among interpreters. Without independent validation or calibration with additional data sources, the interpretations could be prone to biases or inaccuracies.

Generalization Challenges

Extrapolating findings from a limited number of well logs or seismic profiles to broader geological interpretations of the entire study area can pose challenges. Geological heterogeneity, localized depositional environments, or structural complexities may not be fully captured by the available data, leading to generalizations that oversimplify the geological reality.

5.7 Summary

The Discussion chapter presents a thorough analysis and interpretation of the study's findings, focusing on their geological implications and broader significance. It begins by contextualizing the mapped fault scenarios and structural features within the regional tectonic framework, emphasizing their role in understanding the area's geological evolution.

The chapter then delves into the stratigraphic interpretations derived from seismic data analysis and well log correlations. It discusses the observed sedimentary facies characteristics, depositional environments, and stratigraphic sequences, offering insights into past geological processes and paleoenvironments.

A critical analysis of the structural features identified in the study area follows, exploring their potential implications for subsurface fluid dynamics, hydrocarbon reservoirs, and structural geology. The discussion highlights the relationship between faulting patterns, structural highs, and seismic anomalies, providing valuable insights into the controls on subsurface properties.

Acknowledging the inherent limitations and uncertainties in the study's interpretations, such as data constraints and resolution limitations, the chapter underscores the importance of cautious interpretation. It calls for a nuanced understanding of these limitations when drawing conclusions from the study's findings.

Lastly, the chapter outlines potential avenues for future research to address existing gaps in understanding and refine geological interpretations. Suggestions include integrating additional data sources, conducting field validation studies, and applying advanced analytical techniques to enhance the understanding of the study area's geological framework.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The Chapter VI, presents conclusions drawn from these findings and outlines strategic recommendations aimed at advancing geological understanding, refine reservoir characterization, and guide future exploration. Integrating multidisciplinary approaches (analyzing seismic facies patterns for depositional sequences, using RMS seismic attribute analysis for support depositional environment and correlating dominant log motifs with depositional environments).

6.2 Conclusions

Sena Formation: Seismic analysis identified a range of depositional environments, evidenced by varied facies patterns suggestive of mixed sedimentary settings, including marine, fluvial, and deltaic systems. This lithological heterogeneity indicates a high potential for reservoir compartmentalisation, which is critical for geological modelling and exploration risk assessment.

Domo Formation: Characterised by well-bedded, fine-grained sediments and prograding clinoforms, typical of shallow marine environments influenced by deltaic processes. RMS attributes highlighted sedimentation trends controlled by faulting. Log motifs indicated dynamic depositional conditions, with variations in energy and sediment supply, aiding in the identification of potential reservoir zones and interbedded seals.

Lower Grudja Formation: Displayed uniform thickness with distinct seismic facies, suggesting stable marine or lacustrine sedimentation. Structural interpretation linked seismic anomalies to fault-related highs, implying tectonic control during deposition. Log motifs showed cyclic sedimentation, likely driven by base-level changes, which is relevant for sequence stratigraphic frameworks.

Upper Grudja Formation: Exhibited westward-thickening seismic amplitudes, reflecting stable sedimentation in a marine or nearshore environment. The absence of significant structural anomalies supports a laterally continuous depositional setting. The data suggest the presence of laterally extensive reservoir zones with good connectivity, potentially favourable for hydrocarbon accumulation.

Cheringoma Formation: Displayed varied lithological characteristics across different sections. Seismic interpretation identified facies patterns indicative of marine and nearshore environments with cyclic deposition, suggesting fluctuating shallow marine to deltaic settings. Such variability may impact reservoir continuity and should be accounted for in petrophysical and simulation models.
Divinhe Formation: Although not considered prospective for conventional hydrocarbons due to its shallow nature, proved useful for interpreting depositional settings.

6.3 Recommendations

- Acquire higher-resolution 3D seismic data to better define facies and fault structures.for Enhance understanding of tectonic activity and faulting through new seismic data and detailed mapping to refine interpretations of structural features and their geological implications.
- Perform other study Integrate sedimentological and petrographic analyses to validate facies and reservoir quality, and develop detailed sequence stratigraphy and basin models to understand tectonic influences and reservoir distribution.

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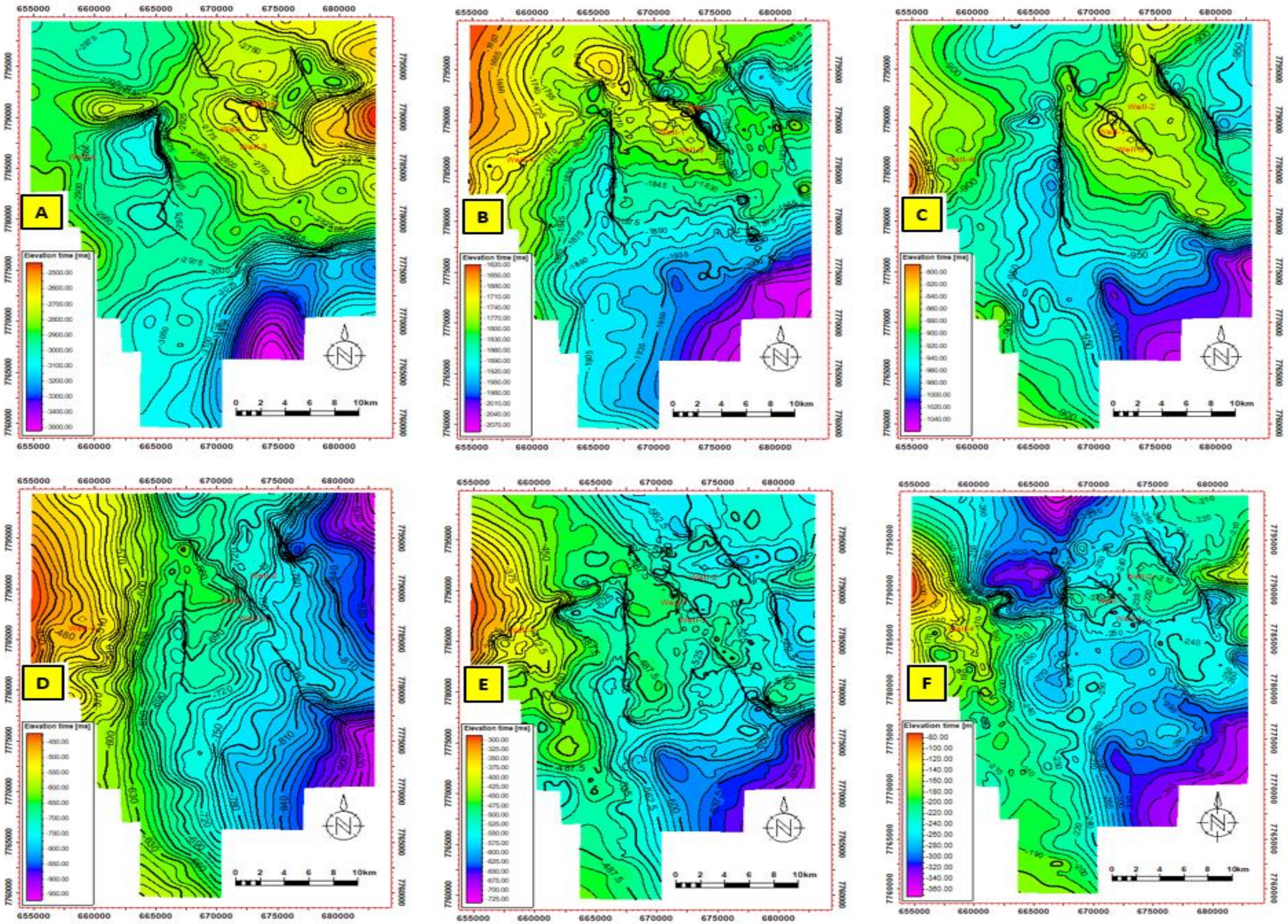
APPENDIX A

TWT STRUCTURAL MAPS

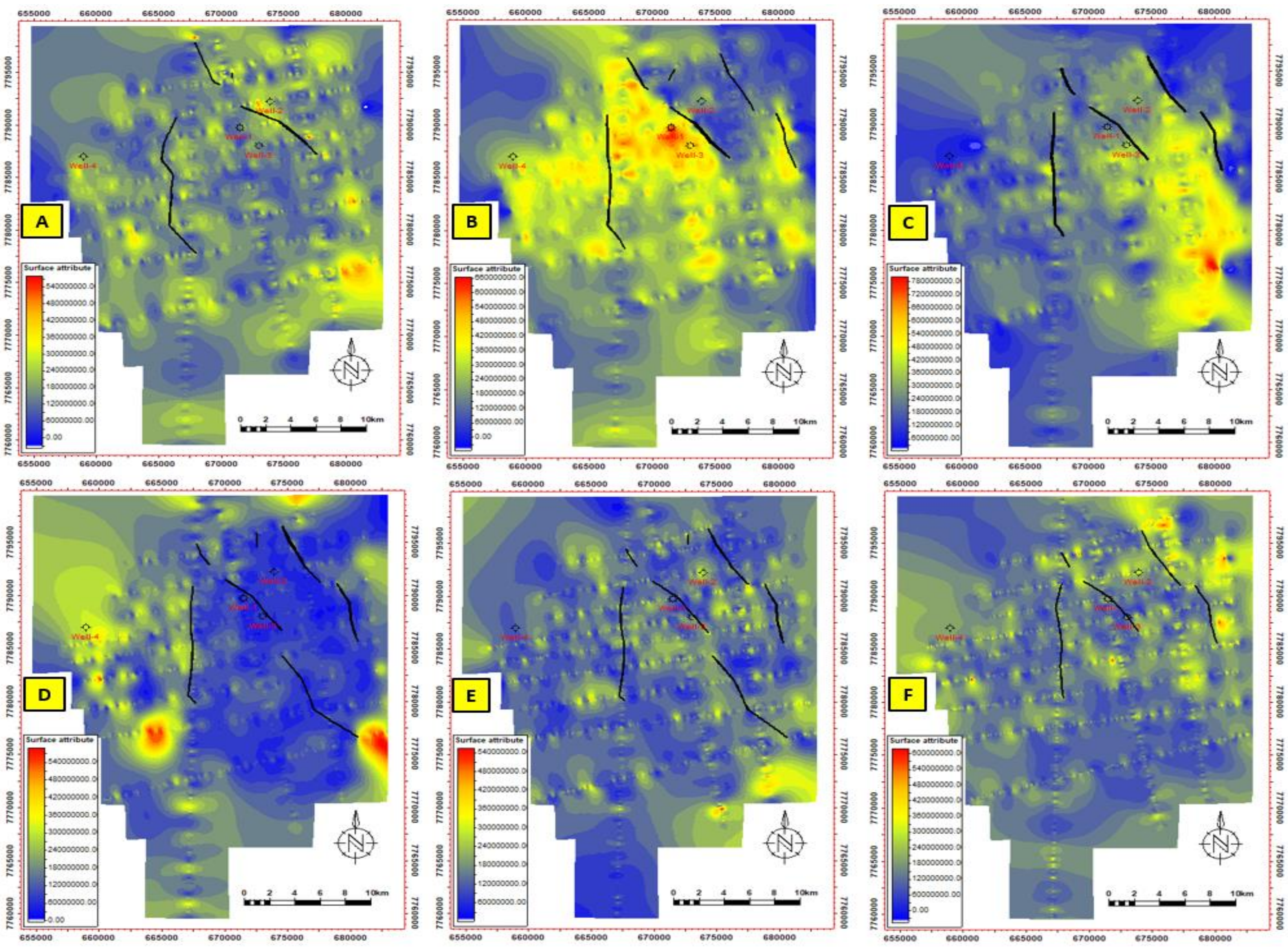
A) Structural map of the base of depositional sequence I (Base of Domo Formation). C.I=25 ms; **B)** Structural map of the base of depositional sequence II (Base of Lower Grudja Formation), C.I =15 ms: **C)** Structural map of the base of depositional sequence II (Base of Upper Grudja Formation). C. I=10 ms. **D)** Structural map of the base of depositional sequence II (Base of Cheringoma Formation). C. I=15 ms: **E)** Structural map of the base of depositional sequence II (Base of Divinhe Formation). C. I=15 ms.



APPENDIX B

RMS ATTRIBUTE MAPS

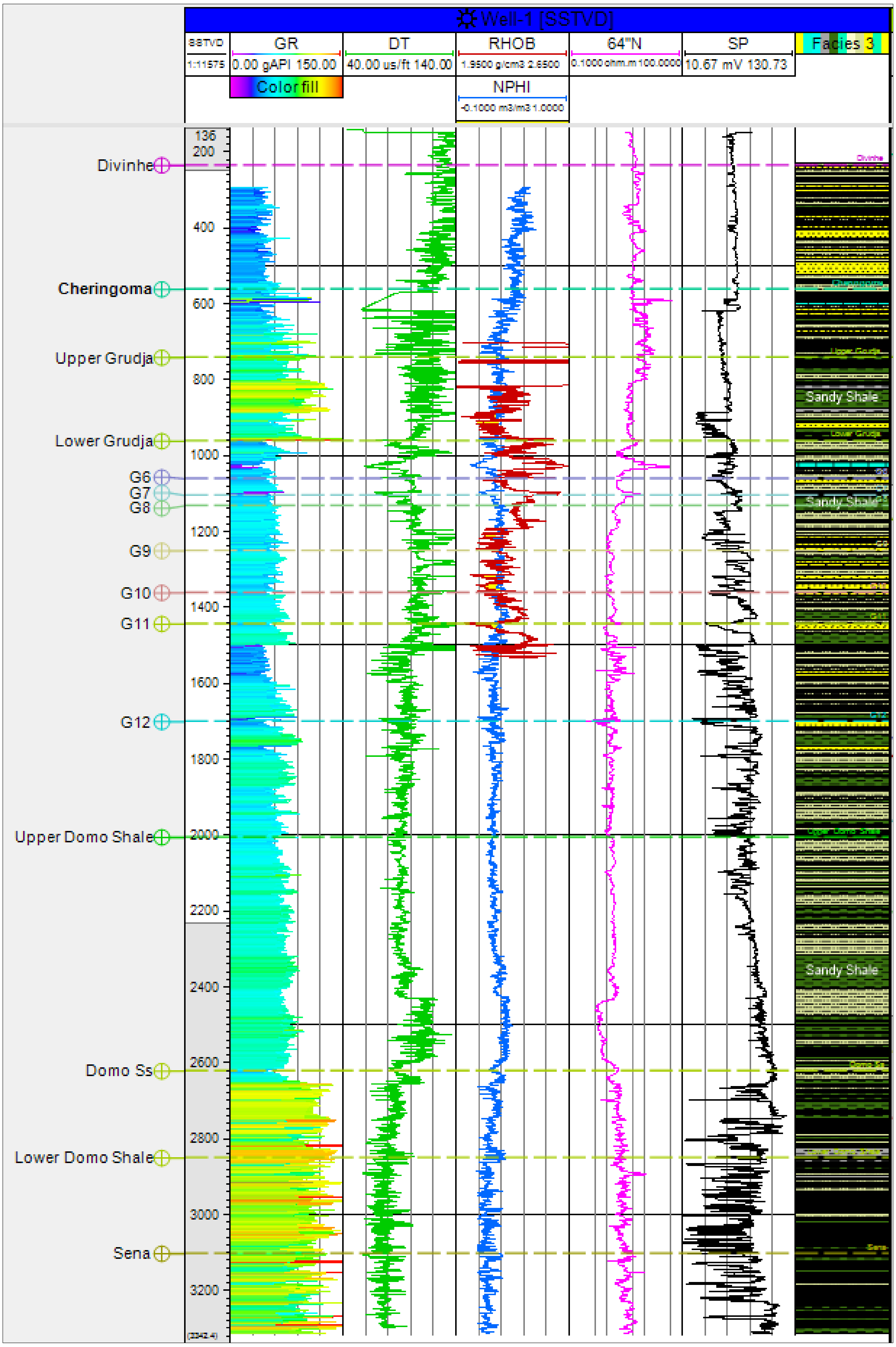
Show the RMS attribute extraction for different horizons: **A**) Top of Sena RMS attribute extraction -/+ 20 ms; **B**) Top of Domo RMS attribute extraction -/+ 15 ms: **C**) Top of Lower Grudja RMS attribute extraction -/+ 10 ms; **D**) Top of Upper Grudja RMS attribute extraction -/+ 10 ms: E) Top of Cheringoma RMS attribute extraction -/+ 10 ms & F) Top of Divinhe RMS attribute extraction -/+ 5 ms.

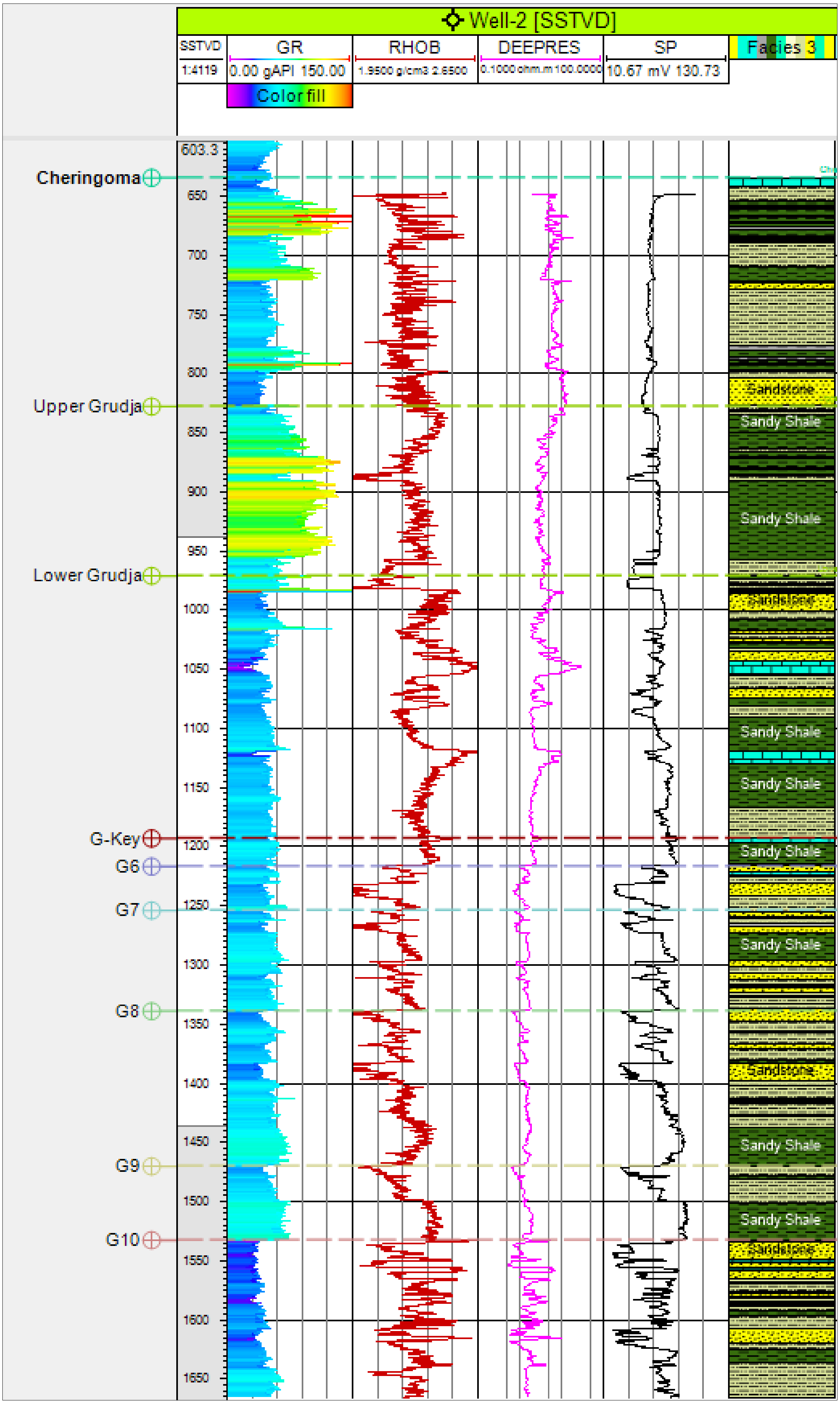


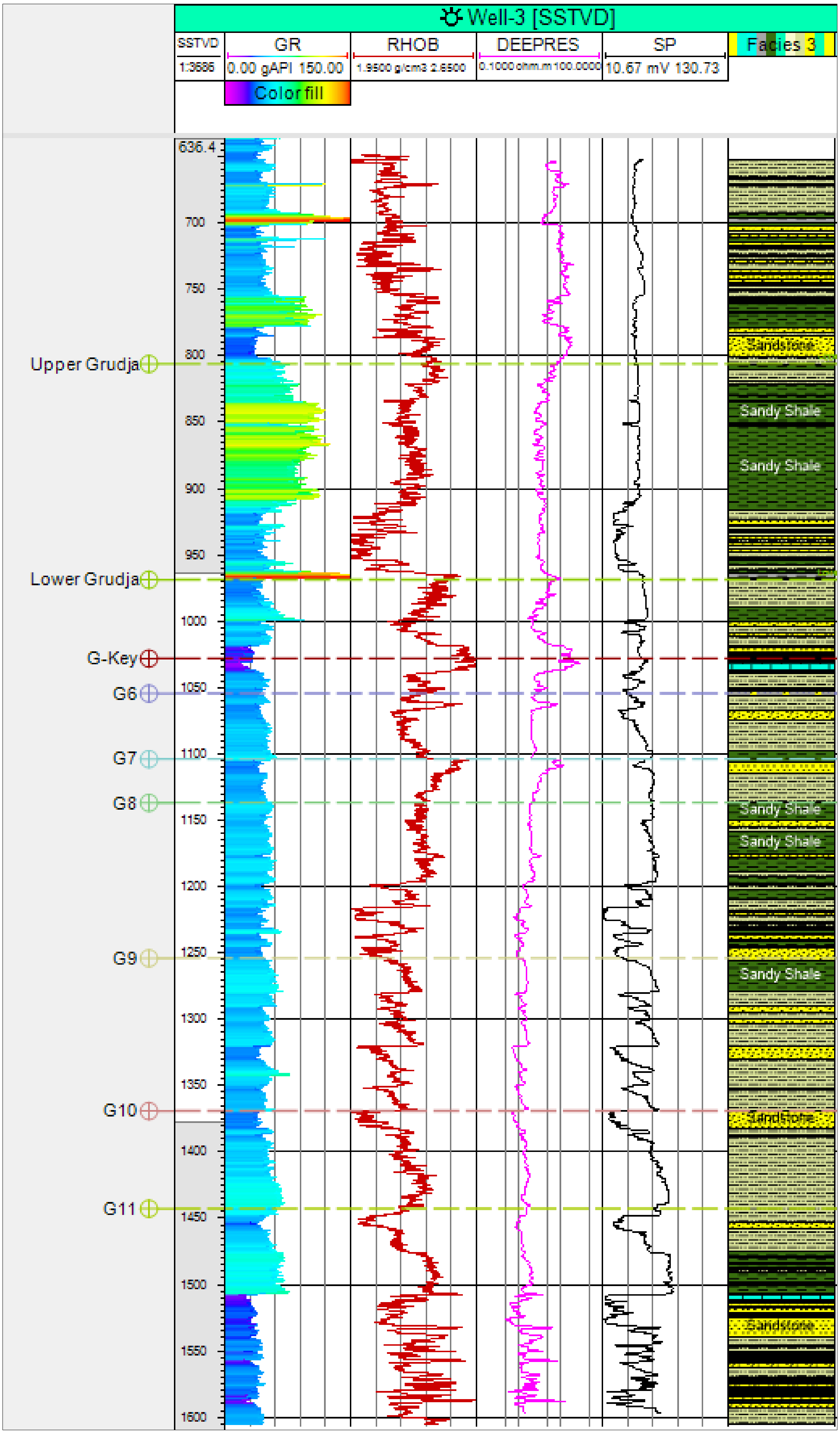
APPENDIX C

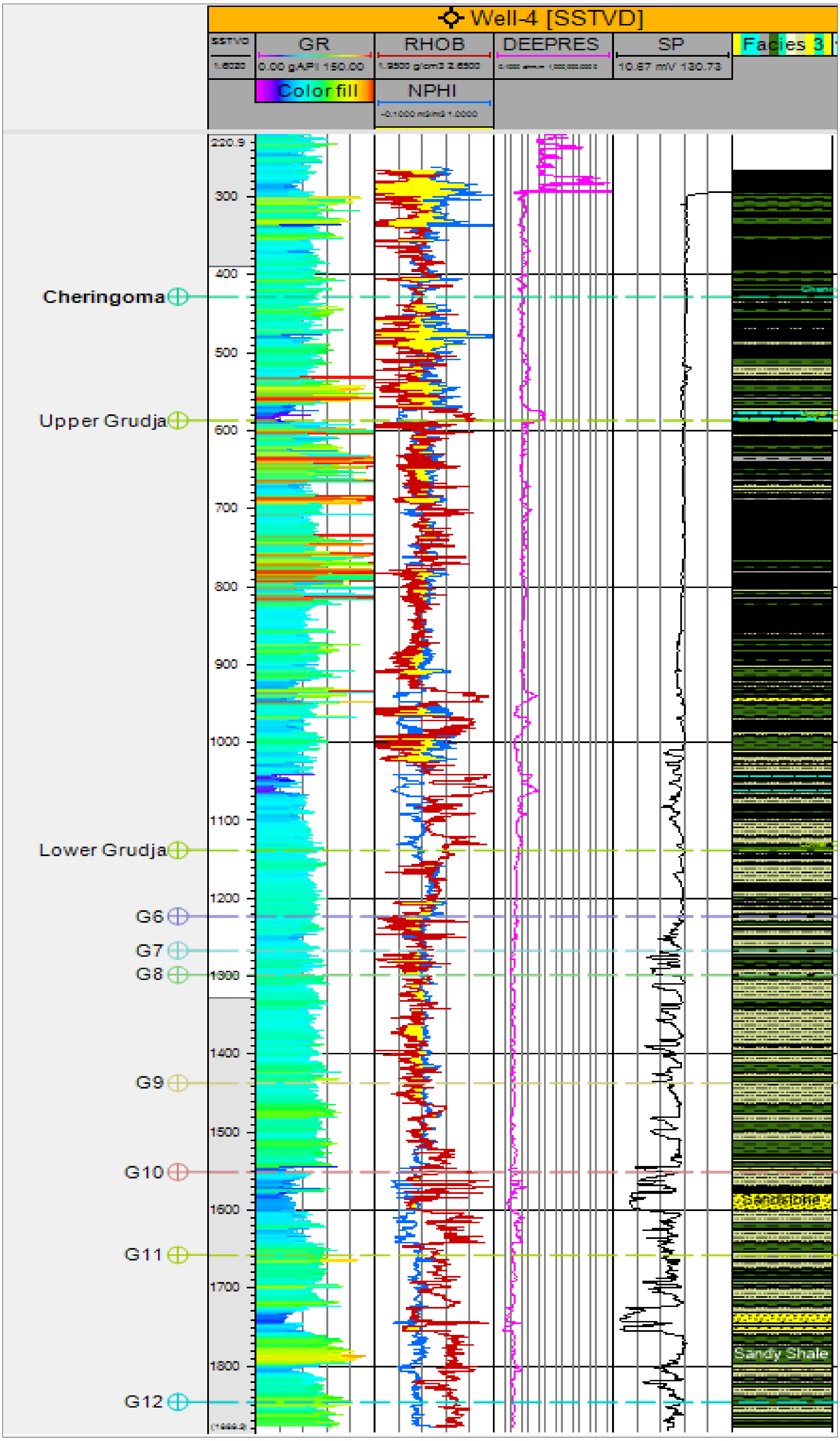
LITHOFACIES

The figures depict lithofacies definitions for four wells: Well-1, Well-2, Well-3, and Well-4, along with the corresponding logs utilized for facies classification. These lithofacies definitions are crucial for understanding the sedimentary characteristics and depositional environments encountered in each well.




Well-2 [SSTVD]
SSTVD
1:4119
GR
0.00 gAPI 150.00
Color fill
RHOB
1.9500 g/cm3 2.6500
DEEPRES
0.1000 ohm.m 100.0000
SP
10.67 mV 130.73
Facies 3
603.3
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
Cheringoma
Upper Grudja
Lower Grudja
G-Key
G6
G7
G8
G9
G10
Sandstone
Sandy Shale


Well-3 [SSTVD]
SSTVD
1:3686
GR
0.00 gAPI 150.00
Color fill
RHOB
1.9500 g/cm3 2.6500
DEEPRES
0.1000 ohm.m 100.0000
SP
10.67 mV 130.73
Facies 3
636.4
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
Upper Grudja
Lower Grudja
G-Key
G6
G7
G8
G9
G10
G11
Sandstone
Sandy Shale
Sandy Shale
Sandy Shale
Sandy Shale
Sandy Shale
Sandstone
Sandstone



Well-4 [SSTVD]
SSTVD
GR
0.00 gAPI 150.00
Color fill
RHOB
NPHI
DEEPRES
SP
10.67 mV 130.73
Facies 3
Cheringoma
Upper Grudja
Lower Grudja
G6
G7
G8
G9
G10
G11
G12
220.9
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
Sandstone
Sandy Shale