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Understanding of Deepwater Sedimentary Model based on Geophysical Data Interpretation to identify the possible scope of Hydrogen Exploration in the Northern Part of the Andaman area, India

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Highlights

1. Identify the feasible environment for exploration of Geologic Hydrogen.
2. Analysis was conducted based on limited geoscientific data.
3. Identify the seismic responses based on attribute analysis for the presence of Geologic Hydrogen.
4. Development of a conceptual sedimentary model to capture the feasible environment for exploration of Geologic Hydrogen.
5. Revealing the enormous potential for exploration of Geologic Hydrogen in the Andaman region.

Abstract

The study has been conducted in the Andaman basin to explore hydrogen or white hydrogen as a part of key energy transition process for current days energy scenarios. The primary focus of the current study is to identify the feasible sweet spot where geologic hydrogen has been accumulated with sustainable support of the carbon-neutral energy resources. The main challenge of this study is to develop the deepwater sedimentary model to capture the occurrence and accumulation process of the geologic hydrogen based on the limited available geoscientific data, which was not established earlier. The study evaluates the Andaman basin, located along the active Sunda subduction zone, a tectonically active seafloor spreading centre, as a potential

frontier for exploration of white hydrogen. Subsurface geological architecture and environment provide feasible support for fluid generation and migration of the hydrogen. A couple of sparse 2D seismic data post-stack seismic data were utilised in this study. The whole study towards the development of a sedimentary model was based on suitably incorporated attribute-driven interpretation, analysis of seismic sequence stratigraphy connected with chronostratigraphy, and analog well-constrained lithologic modelling. A few key seismic attribute analyses delineates mass transport complexes, basement-rooted faults, channel levee systems, and lobe deposits, which represents the feasible support for identifying the potential pathways for hydrogen migration and structural stratigraphic trap mechanisms. It has also been identified that the environment of the Andaman subduction complex and the adjacent deepwater area is conducive to the natural generation and accumulation of hydrogen through the serpentinization process.

Introduction

Hydrogen is emerging as a crucial component in the global energy transition, offering the promise of mitigating carbon emissions in the energy, industry, and transport sectors. Hydrogen attracts global attention as a crucial component in the energy transition outlook towards a developed, sustainable future of energy systems. The International Energy Agency's Net-zero by 2050 plan outlines a global hydrogen demand of approximately 500 Mt per year in the middle of the century, which is significantly higher than the current production (IEA 2019, 2021, DOE 2021). The demand for low carbon hydrogen to achieve climate objectives is of utmost importance, but the current production process is constrained by high costs, infrastructure, and energy requirements.

Though hydrogen is the most abundant element in the universe with a high energy density per weight, it rarely exists freely on Earth. Its presence depends mainly on industrial or geological production methods. Currently, most hydrogen is derived from fossil fuels, mainly as grey hydrogen (without capturing carbon) and blue hydrogen (with carbon capture and storage), while green hydrogen is produced through electrolysis powered by renewable energy sources (Zgonnik, 2020; Kelemen and Hirth, 2012).

Many recent studies have shown the potential to produce "Natural Hydrogen" or "White Hydrogen" in the tectonically active regions, especially in areas where ophiolitic and ultramafic rocks (Swain et al., 2025) undergo rock water chemical reactions, such as the serpentinization of ultramafic rocks like olivine and pyroxene. Hydrogen produced through serpentinization, a

chemical reaction between water and ferrous iron [Fe (II)], in which ferrous iron is oxidized to ferric iron [Fe (III)], which usually precipitates as magnetite. The hydrogen part of the water molecule is reduced, resulting in the production of the molecular hydrogen (H₂).

Even though interest in geologic hydrogen is increasing, we do not fully understand the processes involved in its formation, movement, and accumulation. Therefore, in sediment-covered, subduction-related deep-marine basins, the majority of reported occurrences are located in continental ophiolites and mid-ocean ridge systems. Sedimentary modelling offers extreme insights into the generation of potential hydrogen, its migration pathways, entrapment mechanism and also the accumulation zones, paving the way for White Hydrogen exploration in this geotectonically active zone. In this context, geophysical data interpretation plays a crucial role to enhanced subsurface overview and understanding of such a complex deep marine setup (Zhang & Li., 2024; Li & Zhang., 2025). Furthermore, hydrogen potential in offshore deep-water environments has rarely been assessed using high-resolution seismic and well-log data, which are frequently utilised in hydrocarbon exploration. Our capacity to precisely evaluate the potential of natural hydrogen resources in intricate marine basins is hampered by this gap in combined tectono-sedimentary and geophysical studies.

The Andaman Basin (Fig.1) is a Category-II sedimentary basin of India. It is a part of Sunda Arc system and has a extension of approximately 1250 Kms starting from Myanmar to Sumatra (Srivastava et al., 2021). The basin is created due to the oblique convergence collision between subducting Eastern Indian Plate and overriding Burmese plate (West Burma). Subduction related active tectonic setup, sediment supply from rivers such as Ganges- Brahmaputra system and a frequent change of sea-levels are the major elements responsible for dynamic variability in Andaman region (Subrahmanyam et al., 2008; Curray et al., 2003). The subduction related activity in the region contributes to a rapid basin subsidence, development of accretionary complex and corresponding sedimentation in the deepwater part (Curray, 2005). Similar type of convergent tectonic worldwide such as Mid Atlantic Ridge (Konn et al., 2015), Oman ophiolite complex (Neal & Stanger, 1983; Ellison et al., 2021), Marina forearc (Ohara et al., 2012), parts of Philippines and Turkey (Beaumont et al, 2013) have demonstrated the natural generation of hydrogen through serpentinization, making Andaman a captivating analogue for investigation of geological hydrogen systems.

The main objective of this paper is to develop a high-resolution deepwater sedimentary model of the Andaman Basin using a geophysical data set, particularly 2D and 3D seismic data, by

integrating it with available well logs to delineate spatial and temporal variability of depositional and stratigraphic environments in the deepwater system. Such an approach is not only for insights into hydrocarbon exploration but also for the prospectivity analysis of Hydrogen exploration in deepwater frontiers of the Indian Ocean.

The Andaman basin (Fig.2) has a complex architecture follows by asymmetry in stratigraphy, prominent high and low features, basement level normal faults and thrust faulting feature at the accretionary prism (Bandopadhyay & Carter, 2017). These influences the sediment depositional environment in the basin. Sediments in this region is a complex mixture of hemipelagic mud, mass transport deposits, turbidites – which are deposited through some gravity driven processes such as debris flow, slumps and turbidity currents (Kolla, 2007; Shankar & Manjunatha, 1997; Mayall et al., 2006). These depositional systems contribute to build the deepwater sedimentary features like submarine fans, sheeted lobes, channel-levee complexes etc (Posamentier & Kolla, 2003; Clark & Pickering, 1996; Shanmugam, 2016). There are numerous subduction-related and margin basins around the world exhibit this type of tectonic and sedimentary organization, which is not exclusive to the Andaman region. As global demand for clean hydrogen rises, geoscience-based prospectivity tools that incorporate tectonics, sedimentology and fluid-flow pathways are vital for broadening the search for natural hydrogen beyond onshore ophiolites and ridge settings into offshore frontier basins.

Geologic background and Study area

The Andaman Basin which is a part of the broader Indonesian Island Arc system, shaped by the oblique convergence of the Indian Plate beneath the Burma (or West Burma) Plate. The Andaman region forms the northernmost part of the vast Sumatra–Andaman subduction system, where the Indo-Australian Plate descends beneath the Eurasian Plate in a distinctly oblique manner (Curry, 2005). This subduction becomes highly oblique north of 8°N, with convergence occurring at angles of ~11° relative to the trench and at rates of 14–34 mm/yr, creating a tectonic environment where both compression and strike-slip motion operate simultaneously (Moeremans & Singh, 2015). This active tectonic interaction results in the formation of a complex basin architecture defined by six major geotectonic elements, as shown in (Fig.3).

125 Andaman Trench is the westernmost architectural feature of the basin. It continues in the
126 northward direction after the Java Trench. This region is filled with sediments majorly sourced
127 from the Ganges-Brahmaputra system. The Inner Slope (Subduction Complex) this zone is
128 situated to the east of the trench, and it is marked by intense deformation caused by imbricated
129 and folded sediments driven thrusting activity. It represents the active subduction complex of
130 Andaman region (Srivastava et al., 2021; Curray, 2005).

131 Further east, the Outer High is the main Andaman group of Islands are part of this zone. It
132 consists of flysch, olistoliths, and sedimentary rocks which ranges from Late Cretaceous to
133 Oligocene age. Neogene sediments are present in the structural depressions along its flanks.
134 The zone reflects thrusting activity and is segmented by strike-slip faults (Srivastava et al.,
135 2021; Curray, 2005).

136 The Fore Arc, including Ritchie's Archipelago, lies between the Outer High and the Volcanic
137 Arc. It is a flexural subsidence-generated depression, and its sediments show folded structures
138 that trend with the islands, resulting from compressional tectonics. Lateral wrench faulting has
139 also disrupted this alignment (Srivastava et al., 2021; Curray, 2005).

140 The Volcanic Arc is the easternmost structural zone features the active Barren and dormant
141 Narcondam volcanoes. The arc is marked by the West Boundary Fault and flanked by a
142 structural depression known as the Ponged Low (Srivastava et al., 2021; Curray, 2005). East
143 of the arc lies the Back Arc Basin. This deep marine basin is believed to have formed due to
144 back-arc spreading since the Miocene. It contains relatively thin sediments beneath ~4 km of
145 water and connects to the Mergui Terrace. This region exhibits high heat flow and tectonic
146 extension (Srivastava et al., 2021; Curray, 2005).

147 Structural studies also reveal that the Burma–Andaman slab is steeply dipping beneath the
148 island arc (Prinzhofer et al., 2019), with a geometry that transitions from near-vertical beneath
149 the volcanic arc to shallower angles toward the trench and fore-arc (The Geometry of the
150 Burma–Andaman Subducting Lithosphere). This slab configuration influences seismicity
151 patterns, the distribution of volcanism, and the nature of deformation observed on the surface.

152 This study mainly focuses on the deep marine environment of Andaman basin in the North-
153 West region of the western flank of the main island (Fig.4). The study area is marked by red
154 square on the map and then zoomed in to show the 2D seismic lines which are plotted using
155 the information of shape files in the region. The extension of the lines are approximately 70 to
156 100 Km each. All these maps are generated using Earth relief PyGMT in Python programming.

Only a few no. of seismic lines are available in the study area for interpretation. The approximate water column depth at the region is around 3000 m. In this deep marine setup there is no well yet, so for the support of interpretation, two nearby wells Well-A and Well-B (pointed in Fig.3), are used, which are already reported in a published paper (Srivastava et al., 2021).

Ophiolite exposures in the Andaman Islands reveal another dimension to the tectonic framework of the region. The ophiolite sequence (Fig.5), which includes mantle peridotite, gabbro, basalt and associated sedimentary formation represent fragments of oceanic lithosphere that were emplaced during subduction related activities. Some studies conclude that the Andaman Ophiolite is a suprasubduction-zone (SSZ) type (Wang et al., 2025), formed in a fore-arc setting above an active subduction zone, and later tectonically uplifted and dismembered. These ophiolites represent evidence of multiple magmatic and tectonic episodes rather than a single continuous sequence. It suggests prolonged and complex interactions between the subducting and overriding plates. Serpentinization of mantle peridotites (Malvoisin et al., 2012) within the Andaman Ophiolite is a well-known geological reaction that produces molecular hydrogen when olivine and pyroxene interact with water (Moeremans & Singh, 2015).

The overall studies suggest that the Andaman Basin represents a rare and dynamic setting where oblique subduction, strike-slip motion, back-arc spreading, arc volcanism, and ophiolite emplacement all occur within a relatively narrow corridor. These processes have produced a landscape characterised by intense faulting, fractured ultramafic exposures, elevated heat flow, and active hydrothermal circulation conditions that are highly favourable for natural hydrogen generation. These conditions are analogues to other globally reported hydrogen explored regions, like Marina Forearc (Western Pacific Ocean), Philippines, Brazil (Donzé et al., 2020) and Papua New Guinea (Gena et al., 2006) Oman ophiolite belt (Rollinson, 2017) at Hellenic Subduction zone , Greece (Bonnemains et al., 2016) and also in Mid-Atlantic Ridge. Comparing with these globally reported regions, there is also a probability of the generation of natural hydrogen in Andaman, which is why the Andaman subduction complex and associated deepwater region is our main area of interest.

Methodology

An integrated seismic, stratigraphic and sedimentary modelling workflow (Fig.6) is adopted in this study based on the approaches of geophysical data interpretation. In the primary step, as a part of structural interpretation key seismic horizons are interpreted based on laterally continuous reflectors and faults are identified from reflector discontinuities, dip variation and strike pattern (Cunningham et al., 2020). Attribute-assisted interpretation is employed to enhance the structural delineation. Similarly, Energy and spectral Decomposition attributes are applied to highlight the deepwater structural and depositional features (Akinwale et al., 2022; Shouair et al., 2025).

Spectral decomposition was used on the post-stack seismic volume to examine how subsurface structures vary with frequency. This method converts each seismic trace into multiple band-limited traces, each representing different frequency components. It helps identify geological features that become more distinct at certain frequencies because of tuning effects and thickness changes. The process relies on a continuous wavelet transform with complex Gabor (or Gabor–Morlet) wavelets. Each seismic trace is convolved with the real and imaginary parts of the wavelet to produce complex, band-limited traces. From these, instantaneous attributes like amplitude (envelope) and phase are calculated for each frequency band.

For n frequencies between F_{low} and F_{high} In octave increment mode, the central frequencies were calculated as:

$$F_i = F_{low} \left(\frac{F_{high}}{F_{low}} \right)^{\frac{i}{n-1}}, i = 0, 1, 2, \dots, n-1$$

where $F_0 = F_{low}$ and $F_{n-1} = F_{high}$.

The output of the process consists of multiple frequency-dependent seismic volumes, each highlighting subsurface features at different resolution scales (Subrahmanyam & Rao, 2008).

The term “Average Energy” refers to the sum of the envelopes between paranormal experiences (Ismail et al., 2020a). Each time sample’s average energy attribute is calculated via the following relationship

$$E = \frac{1}{N} \sum_{n=1}^N (Xn^2)$$

where E(avg) is defined as Average energy, N is the number of samples, and Xn is amplitude (Khan et al., 2023).

Similarity attribute reflects how much similar one seismic trace is comparing to its neighbouring traces, it compares waveform shapes between adjacent traces within a small window. The mathematical equation of similarity can be expressed as –

$$S = \sum_{k=1}^N U_i(k)U_{i+1}(k) / \sqrt{\sum_{k=1}^N U_i^2(k) \sum_{k=1}^N U_{i+1}^2(k)}$$

Where N: Number of samples in the analysis time window along the trace, in the analysis time window along the trace, k: Sample index, running from 1 to N within the window, $u_i(k)$: Seismic amplitude at sample k on trace i (reference trace), $u_{i+1}(k)$: Seismic amplitude at sample k on the neighbouring trace i+1.

Subsequently, multiple hierarchical orders of stratigraphic sequences are identified and validated through comparison with some published regional studies (Charoensrisomboon, 2019; Chakraborty et al., 2023; Raveendra singhe et al., 2024, Morley & Searle, 2017). Intra-sequence deepwater depositional architectures were interpreted from seismic facies characteristics and geomorphological expressions (La Marca & Bedle, 2022).

Due to the absence of wells in the deepwater domain (~3 km bathymetry), an analog well-driven approach was adopted. The synthetic log data is reconstructed from published work (Srivastava et al., 2021), followed by reinterpretation of lithology. The lithology interpretation and well correlation is done in Python based programming. Ultimately the correlation result is verified with Singh & Singh, 2021. The reconstructed log responses provide the stratigraphic framework which is extrapolated basinward into the deepwater region using reflector continuities and depositional patterns. Though there is uncertainty in this stratigraphical modelling but it gives a overall framework of depositional patterns starting from the shallow marine shelf to the deepwater environment.

The Time Structure Maps are generated for each interpreted horizons using Convergent interpolation technique to estimate the structural surface at the virgin zone in between two lines (Caumon et al., 2009; Léger & Clochard, 2020). The contours are produced at equal time (TWT) elevation and visualized in 3D space with TWT(ms) as the vertical axis. It enables the assessment of temporal structural variability across the study area.

Structural modelling is performed by integrating horizon interpretations, attribute-derived structural elements, stratigraphic correlations, and time structure maps (Fathy et al., 2025; Thota et al., 2022; Wellmann & Caumon, 2018). A 3D grid was first established using a boundary polygon encompassing the entire study area. Reference surfaces (top, middle, and base) were generated to define the structural framework. Modelling proceeded in three stages: basement-level modelling, Oligocene sequence modelling, and Neogene sequence modelling. Pillar gridding was applied between top and base surfaces, with variable vertical discretization for each structural domains. Horizon surfaces were incorporated into the model assuming depositional relationships defined as basal, conformable middle, and erosional top surfaces, consistent with their stratigraphic orders.

Finally, a comprehensive three-dimensional deepwater sedimentary model (Cao et al., 2024; Jacquemyn et al., 2021, Stow & Mayall, 2000) was developed through integration of stratigraphic interpretation, structural architecture, and regional geotectonic evolution. To contextualize basin development, a conceptual geological cross-section was constructed by synthesizing seismic interpretation, 3D modelling results, and regional tectonic knowledge from (Kivior et al., 2012; Ray & Radhakrishna, 2020; Rao et al., 2011; Hu et al., 2021 and Singha et al., 2023), with particular emphasis on the accretionary prism, subduction complex, and adjacent deepwater domains.

Results and Discussion

Horizon and Fault Interpretation

The horizon and fault interpretation is the first and foremost part of the seismic interpretation. The horizon and fault interpretation are shown in Fig.7-a and Fig.7-b on the seismic section (Line-1 and Line- 2). The horizons are picked where there is a unconformity of discontinuity between two formation. The unconformity can be seen clearly in the processed seismic section above. There are some tectonic activity or erosion or any depositional gap associated with the unconformity which can reflect the chronological order of the sequence boundary. In the figures H4 is the basement because at this portion there is the lowest reflector seen in the seismic section. Then comes the other horizons H3, H2, H1 and H0 respectively in the upward direction. These horizons will be used for stratigraphic interpretation in upcoming section. The basement level faults are marked on the seismic section, these are F1, F2 and F3 all have a dip direction towards the subduction zone. These are mainly normal faults on the subducting

oceanic crust. These faults are built due to the compression and bending of the oceanic crust while subducting beneath the continental crust. But, thrust faults form at the subduction complex beyond our study area due to the subduction of the oceanic crust and development of the accretionary prism mainly on the overriding plate.

Attribute Analysis based Structure Identification

In the horizon and fault interpretation we have identified several deep marine features on the seismic section based on the application of attributes. We have mainly used three attributes – Similarity, Energy and Spectral Decomposition which are built based on the fundamental seismic attributes – Instantaneous Amplitude, Phase and Frequency. Similarity attribute reflects how much similar one seismic trace is comparing to its neighbouring traces. Low similarity generally suggest faults, fractures, channels or any other abrupt change of seismic amplitude. Energy attribute is termed as square of seismic amplitude, it indicates the strength of the reflector. High energy suggests the presence of a strong reflector. Spectral decomposition breaks the seismic signals into different frequencies to visualize the proper pattern of frequency distribution. It enhances the visibility which may be missed in conventional amplitude section. These attributes are used to identify different structures, sequence boundaries, or any discontinuities if present in the section. These three attributes are applied on the seismic sections and some deep water features like biogenic gas pocket, submarine channel, channel-levee complex etc are identified in Fig.8-a & b. Gas chimney is also identified by applying the Spectral Decomposition attribute (Fig.8-d). The high amplitude shale layers are also clearly visible after application of Energy attribute (Fig.8-c).

Stratigraphic Interpretation

The different order sequence boundaries are identified on the seismic section and then established with the help of core data analysis based well log correlation from two nearby wells. We have identified mainly three first order sequences: 1) late Cretaceous-Late Eocene First order Sequence, 2) Oligocene First order Sequence and then 3) Neogene First order Sequence. These are marked in the Fig.9-a. We can identify mainly three second order sequences (Fig.9-b) under the first-order Neogene sequence, those are: 1) Early Miocene-Middle Miocene 2nd order Sequence, 2) Middle Miocene-Middle Pliocene 2nd order Sequence and 3) Late Pliocene – Pleistocene 2nd order Sequence. The deepwater depositional environment in the Neogene first order sequence is clearly shown in the Fig.9-c. When there is rise in sea level, then younger sediments flow towards land and deposits on older strata. This is called marine Onlap. In this

particular phase of sea level changes the deposition of sediments is called Transgressive System Tract (TST). After the Maximum Flooded Surface (MFS) when the sediment supply from land side increases, then the water column decreases and sediments from land flows towards down slop. In In this particular phase of sea level change Regressive System Tract (RST) occurs.

Stratigraphic Modelling from Analog Wells

For stratigraphic modelling we have used two nearby wells (Well-A and Well-B) that are already pointed on the architectural map of Andaman. There is not drilled any well in the deepwater setup of Andaman yet, that is why we have used these analogical wells at nearby places for well correlation and stratigraphic sequence establishment. These analog well logs were constructed and reinterpreted using information from Srivastava et al.(2021). In the Well-A we can see mainly there are shale, sandstone and mudstone based lithology in Fig.10-a. These well is at accretionary prism complex, where the sediment is loosely bound, compactness is low and also water saturated due to the water influx through several faults and fractures at the subduction complex and accretionary prism part. So there is a little changes in the log values in comparison with the conventional shale, sand scenario. In the Well-B (Fig.10-b) there is also similar type of sand stone and shale based lithology, and a small limestone part is there in the upward section. The well correlation (Fig.10-c) is done based on the reported information of core data analysis and well completion reports. The information and timewise variation is also checked and verified from (Singh & Singh, 2021) before correlating the wells. After correlation three major first order sequences are identified through out the area, these are 1) late Cretaceous-Late Eocene First order Sequence, 2) Oligocene First order Sequence and then 3) Neogene First order Sequence. The stratigraphic interpretation in the previous section and the stratigraphic modelling is done base on this establishment of sequences. The second order sequences in the Neogene first order sequences are identified from the Well-A similarly by the published information of foraminifera analysis. The stratigraphic modelling in the deep water part is done based on the extensional interpretation from these two wells majorly.

Time and Structure Maps

On the basis of the horizon interpretation the time map is generated in Petrel software. Time map reflects the variation of the seismic horizon in TWT (Two Way Travel time) domain. The contours represent same time zones on the horizon surface. The Fig.11-a shows the basement level Time Map based on H4 horizon. The major fault polygons are also shown on the time surface. The Fig.11-b indicates the time map at the H3 horizon which is basically Late

Cretaceous -Late Eocene to Oligocene first order sequence boundary. The color in the plots represents the flattened view of the different TWT according to the color-bar. We have made the other time maps similarly based on the other horizons Such as H2, H1, H0 etc. Though there was only few lines of 2D seismic, we have interpolated the surface in between two consecutive lines by applying Inverse Distance and Convergent Interpolation techniques. The convergent interpolation technique, using an optimal window size, yielded the most reliable results; therefore, only these results are presented here. The basement level time structure map(Fig.12-a) is made by setting the time map along the vertical TWT axis of the data set. It reflects how the structure in the zone is varying in time domain. It gives a proper overview of the structural framework of the study area along the basement surface. Where there is a dense contour lines, it represents a steep variation of the slope, which indicates the presence of faulted surface. Similarly, the other time structure maps (Fig.12-b) are generated based on the corresponding horizons along the seismic profile. These represent the different order sequence boundary surface throughout our study area. These are very important to understand the depositional scenario and sediment flow direction in the complex geological setup of the deep marine region of Andaman. These will be used in the next section for structural modelling and layers building.

Structural Modelling

The structural modelling is done by integrating all the information from horizon interpretation, attribute analysis driven structural interpretation, stratigraphic correlation and time structure maps. First, comes this basement level modelling(Segment-0) as shown in Fig.13-a. Here the bottom surface is a artificial plane to give the model a proper view, the top surface is our basement level surface that was made in the time structure mapping section. The in-between layers are added by following the trend of the top surface of the model (Actually the basement) taking the general basement surface as the reference surface. The basement level model reflects key tectonic framework of the region on the oceanic crust. The dip of the subducting plate is also visible in this model. There are also some basement level faults dipping towards the trench, the deformation of the block due to major faulting caused by subduction related activity can also be understood from the model.

After the basement level modelling, the Oligocene sequence based model(Segment-1) is built. Here the basement surface is the general basement (1 st order sequence boundary) and the top surface is the Oligocene to Neogene 1 st order sequence boundary. The in-between layers are

made based on the picked sedimentary layers. From the figure(Fig.13-b) we can see that there is flow of sediments from the accretionary prism part to this deepwater lows, some of the deposition comes from Ganges-Brahmaputra system, so there is a complex mixture of both sediments.

Lastly the Neogene sequence based top most model(Segment-2) is built. Here the basement surface is the Oligocene to Neogene 1 st order sequence boundary and the top surface is the Middle Pliocene to Late Pliocene second order sequence boundary. The in-between layers are made based on the picked sedimentary layers and basin fill patterns as visualized from the seismic profile. From the figure(Fig.13-c) we can see that there is flow of sediments from the western side of Indian ocean to the structural lows. Marine onlap happens here. The sediment is the complex mixture from Ganges-Brahmaputra system through Bengal Fan and the Himalayan orogeny both. Some of the eroded sediments also comes from the accretionary complex of Andaman structural highs. The deep water features that are already identified are geologically created due to this different phase of depositional environment. These will be integrated to the model in the final sedimentary modelling section.

3D Sedimentary Model

By Integrating all the previous information – Horizon - Fault interpretation, structure identification, stratigraphic interpretation, stratigraphic modelling and finally the structural modelling; we have made the final sedimentary model, shown in Fig.14. The figure shows the 3d sedimentary model in the deep marine setup of the study area. The three structural models are combined from the base to the top in a sequential manner. Then all the in-between layers are added, which indicates the sediment flow pattern. The first order and second sequence boundaries are also present in the model. At the basement level there are some major normal faults dipping towards the subduction complex, making some structural lows. So we can say that beyond this section, the oceanic crust starts to bend and subduct under the continental crust. That is why the normal faults are created on the oceanic crust due to subduction related compression and bending. We have expanded the model towards the accretionary prism through the subduction complex to understand the overall tectonic and depositional set up of the region, and made a conceptual sedimentary cross section as shown in Fig.15. These two models in together, reflects the depositional and geotectonic control of the regions towards hydrogen exploration.

404 Just after the initialization of the subduction the sediments on the oceanic plate start to accrete
405 on the continental crust at the subduction zone and nearby places by making thrust faults; as
406 shown in Fig.15. So the accretionary prism forms there by making the structural highs. The
407 surface above which the accreted sediments are uplifted on the subducting plate is called the
408 Decollement surface. The surface which distinguish the accretionary complex sedimentation
409 from the forearc sedimentation on the overriding plate is called the Backstop surface. The sea
410 water interacts and collide with the structural high and erosion initiates. The eroded accreted
411 material starts to flow and deposit in the nearby lows at subduction zone, fore arc or the deep
412 water region. So in the model (Fig.14) the oligocene sequence is actually made of the
413 sediments, flowed from accretionary complex. But some of the sediments are also come from
414 bengal fan through Ganges-Brahmaputra system and mix here. Similarly the marine onlap,
415 transgressive and regressive system tracts are occurred in the Neogene period. The model
416 reveals key deepwater elements such as submarine channels, channel-levee complexes, lobes,
417 biogenic gas pockets, etc., reflecting sediment flow patterns and depositional environments in
418 the deep-marine setup, primarily controlled by gravity-driven processes such as slumps, debris
419 flows, submarine avalanches, and turbidity currents. So the deepwater depositional
420 environment is properly established and justified by this 3D sedimentary model.

421 Serpentinization is a process in which olivine, pyroxene and peridotite rich ultramafic rock
422 reacts geochemically with water and make serpentine and Hydrogen(H_2) and methane (CH_4)
423 as products. In the Andaman island geochemical survey is already done and it has reported the
424 presence of serpentine as a outcrop in the southern Andaman as well as in the northern
425 Andaman. So now according to our sedimentary model there is a high probability of formation
426 of serpentine and serpentinized hydrogen in the subduction complex and nearby shallow to
427 deep water region. Ophiolite is basically Mg and Fe rich fragments of oceanic crust, which is
428 generated when the oceanic crust goes through any tectonic activity that generally happens at
429 subduction zone, mid oceanic ridge or spreading centre. The presence of pyroxene and olivine
430 rich ophiolite sequence is high at the subduction and accretionary complex. There are so many
431 faults and fracture at the subduction complex (shown in Fig.15) and nearby shallow to deep
432 water region, so cold sea water can flow towards the ophiolite sequence through these faults
433 and fractures and reacts with olivine and pyroxene. As the product of this reaction, serpentine
434 and white hydrogen form. So obviously, there is a favourable environment at the Andaman
435 subduction complex for serpentinization and generation of hydrogen.

From the previous discussion it is clear that Andaman subduction complex is favourable for generation natural hydrogen(H_2). If hydrogen is generating in the region it must migrate, we can propose that the generated natural hydrogen gas can migrate through the basement level faults and fractures. It can also migrate towards the deep marine setup of the Andaman region because there are also many basement level faults and fractures which can act as a migration pathway for hydrogen. So now our main concern is the entrapment mechanism of the region, so that hydrogen can be trapped and can be accumulated. The high reflective shale layers in the Oligocene and Neogene sequences that are shown in the sedimentary model (Fig-14) can act as the caprock for the entrapment of hydrogen in subsurface. So, we can say that the prospectivity of generation and accumulation of hydrogen at the subduction complex and the deepwater region is high. But for more robust characterization of the hydrogen accumulation zone and identification of proper migration pathway as well as entrapment mechanism, more high resolution data set is needed. Geochemical sample analysis and caprock integrity test at the region is also necessary for identification of hydrogen accumulation zone. Overall, the results indicate that the geological, sedimentological and geochemical environment of the Andaman basin for natural hydrogen generation and accumulation is analogous to other globally reported hydrogen explored regions, like Marina Forearc (Western Pacific Ocean), Philippines and Papua New Guinea, Oman ophiolite belt at Hellenic Subduction zone (Greece) and also in Mid-Atlantic Ridge.

Conclusion

The study is mainly concentrated within the Andaman subduction complex because the area has a unique geological setting where several geological processes relevant to the generation of natural hydrogen coexist, including active subduction related deformation, ophiolite emplacement and deep-marine sedimentation.

In this work, a three dimensional structural and sedimentary framework of the Andaman deep-water region is developed by integrating all the available seismic profiles and analog well constraints with regional geotectonic information. At first, the sedimentary model is established at the area constrained by seismic data and subsequently it is extended to the outer structural highs through the subduction zone using published tectonostratigraphic interpretation.

The most significant outcome of this study is the identification of serpentization as the primary source of molecular hydrogen in the Andaman region. Interaction between the iron

rich ultramafic rocks and infiltrating cold sea water within the ophiolite sequence provides a perfect mechanism favourable for hydrogen generation with serpentine as a reaction bi-product. Structural features, particularly the fault and fracture networks are interpreted to act as the migration pathways, enabling generated hydrogen to move to shallower subsurface. Shale rich layers at the deepwater domain may act as the potential sealing horizons, but their effectiveness becomes uncertain with respect to the current data resolution. As the analysis is constrained by sparse 2D seismic coverage, lack of direct well control in the deep-marine setup and the absence of geomechanical estimations, the hydrogen generation, migration and trapping mechanism are built indirectly from geophysical and geological indicators rather than direct observation. Therefore, the proposal of fault-controlled migration and sealing capacity of the shale layers remains conceptual and it require further validation and established support.

In future study should be focused on acquiring of higher resolution seismic data set integrating with cap rock integrity testing, geochemical analysis of outcrops as well as the ophiolitic units, analysis of the degree of serpentinization and thermal modelling of the zone. Though the developed model in the study is not the exact one to establish the sweet spot of hydrogen in the region, it reflects the favourability of the environment for White hydrogen generation, making Andaman a highly promising natural laboratory for geological hydrogen production.

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Figure Captions:

Figures	Caption
Figure 1	The Andaman Basin (marked in red square) as a part of Sunda Arc system associated with the Indian subcontinent [Plotted in Earth relief – PyGMT].

- Figure 2 The topographic map of Andaman Group of Islands [Plotted in Earth relief – PyGMT]
- Figure 3 Geo-tectonic Setup of Andaman containing Andaman Trench, Sedimentary Accretionary Prism as a part of subduction complex, Outer structural high, Fore arc sub-basin, Volcanic arc and Back arc sub-basin. Spreading centre, ridges and volcanoes are represented by proper labelling. The Seismic survey area is marked in red rectangle in the deepwater part, two marked wells Well-A and Well-B are used for study. [Modified after (Curry, 2005)]
- Figure 4 The study area in deepwater region with a bathymetry around 3 Km. 2D seismic survey is done in the area with seismic line length ranging from 50 to 80 Km and sampling interval 2 ms.
- Figure 5 Ophiolite sequence containing Permian-Cretaceous Sediments(carbonates), melange, Metamorphic sole, Mantle Peridotite, layered and Massive gabbro, Dikes, Pillow basalts and Crustal Sediments (modified after Ekka, 2020).
- Figure 6 Workflow for seismic interpretation, Structural and stratigraphic modelling, development of Sedimentary model and Geological cross section.
- Figure 7 (a) Horizon and Fault Interpretation on Seismic Line-1(SEG Normal polarity); (b) Horizon and Fault Interpretation on Seismic Line-2(SEG Normal polarity); Five horizons – H0, H1, H2, H3, H4 and three Major basement level faults - F1, F2 and F3 are marked on the seismic sections.
- Figure 8 (a) Similarity attribute applied on Seismic Line-1 showing structural features like Channel and biogenic gas pocket; (b) Similarity attribute applied on Seismic Line-2 reflecting Channel-Levee complex; (c) Energy attribute applied on Seismic Line-1 showing high amplitude continuous shale layers; (d) Spectral Decomposition attribute applied on Seismic Line-3 reflecting the presence of Gas Chimney.
- Figure 9 (a) Stratigraphic interpretation representing three first order sequences - Late Cretaceous to Late Eocene (80 to 35 Ma), Oligocene (24 to 35 Ma) and Neogene (20 to 2.5 Ma) first order sequence; (b) Three second order sequences under the first-order Neogene sequence - Early

Miocene-Middle Miocene 2nd order Sequence, Middle Miocene-Middle Pliocene 2nd order Sequence and Late Pliocene – Pleistocene 2nd order Sequence; (c) Deepwater depositional environment representing Transgressive and Regressive System Tracts (TST and RST respectively) deposited under the first-order Neogene sequence.

Figure 10

Lithology interpretation based on analog well log data with the help of Gamma Ray (GR), Density (RHOB), Resistivity (RES) and Neutron Porosity (NPHI) logs - representing clay, limestone, shale and sandstone based lithology for (a) Well-A and (b) Well-B respectively; (c) Well correlation between Analog Well-A and Well-B representing three major first order sequences. [Modified after (D. K. Srivastava et al., 2021) and verified from (S. D. Singh & Shefali Singh, 2021)]

Figure 11

(a) Time map along the H4 horizon, representing the basement level subsurface (First order sequence boundary) variation in time domain. There are two major basement level faults dipping towards the subduction complex are represented by the brown color fault polygons; (b) Time map along the H3 horizon, representing the variation of Oligocene-Neogene first order sequence boundary in time domain. The left side(West) represents structural low where sediment was deposited in later ages and the right side(East) represents structural high towards the main Island; In both figures, the contours are generated by connecting the equal time elevated points along the horizon. Dense contour lines at a particular region represents steeply dipping layer, gapped lines stands for comparatively smooth subsurface.

Figure 12

(a) Time structure map(TSM4) of the layer along H4 horizon representing the proper structural variabilities in basement level supporting the structural interpretation of corresponding time map containing dip direction, structural high - lows and major faults; (b) Time structure maps TSM0, TSM1, TSM2 and TSM3 of the layers along H0, H1, H2 and H3 horizons respectively representing the sediments depositional pattern, dips of the layers and corresponding structural variation; In both figures Z axis represents Elevation time (TWT) in ms.

Figure 13

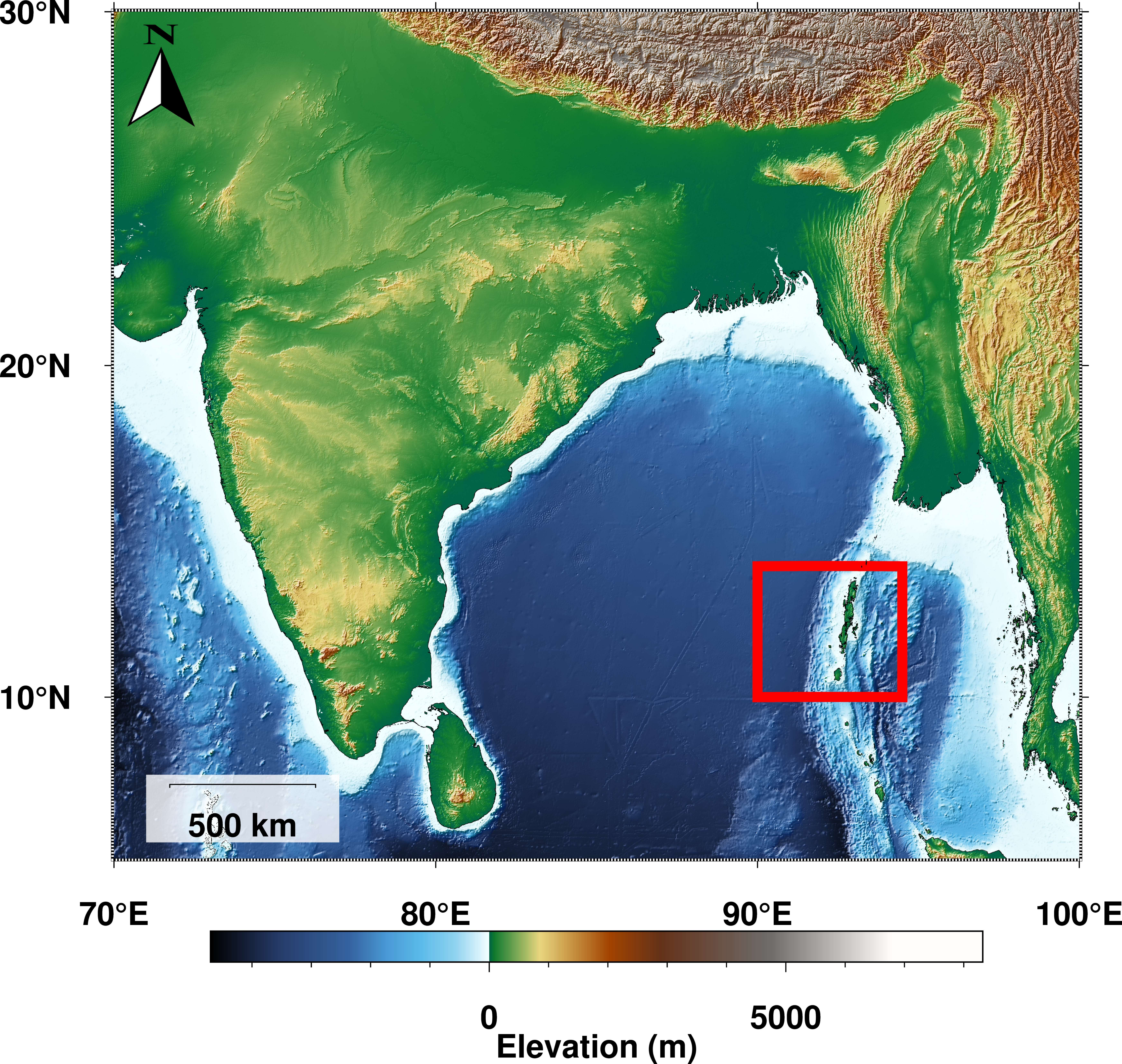
(a) Basement level structural model (Segment-0) representing the depositional pattern in Late Cretaceous - Late Eocene first order sequence and the top surface represents corresponding structural variation along the first order sequence boundary; (b) Oligocene sequence based structural model (Segment-1) representing the sediment depositional framework in the Oligocene first order sequence; (c) Neogene sequence based structural model (Segment-2) indicating the sediment depositional framework in the Neogene first order sequence; In all three figures Z axis represents Elevation time (TWT) in ms.

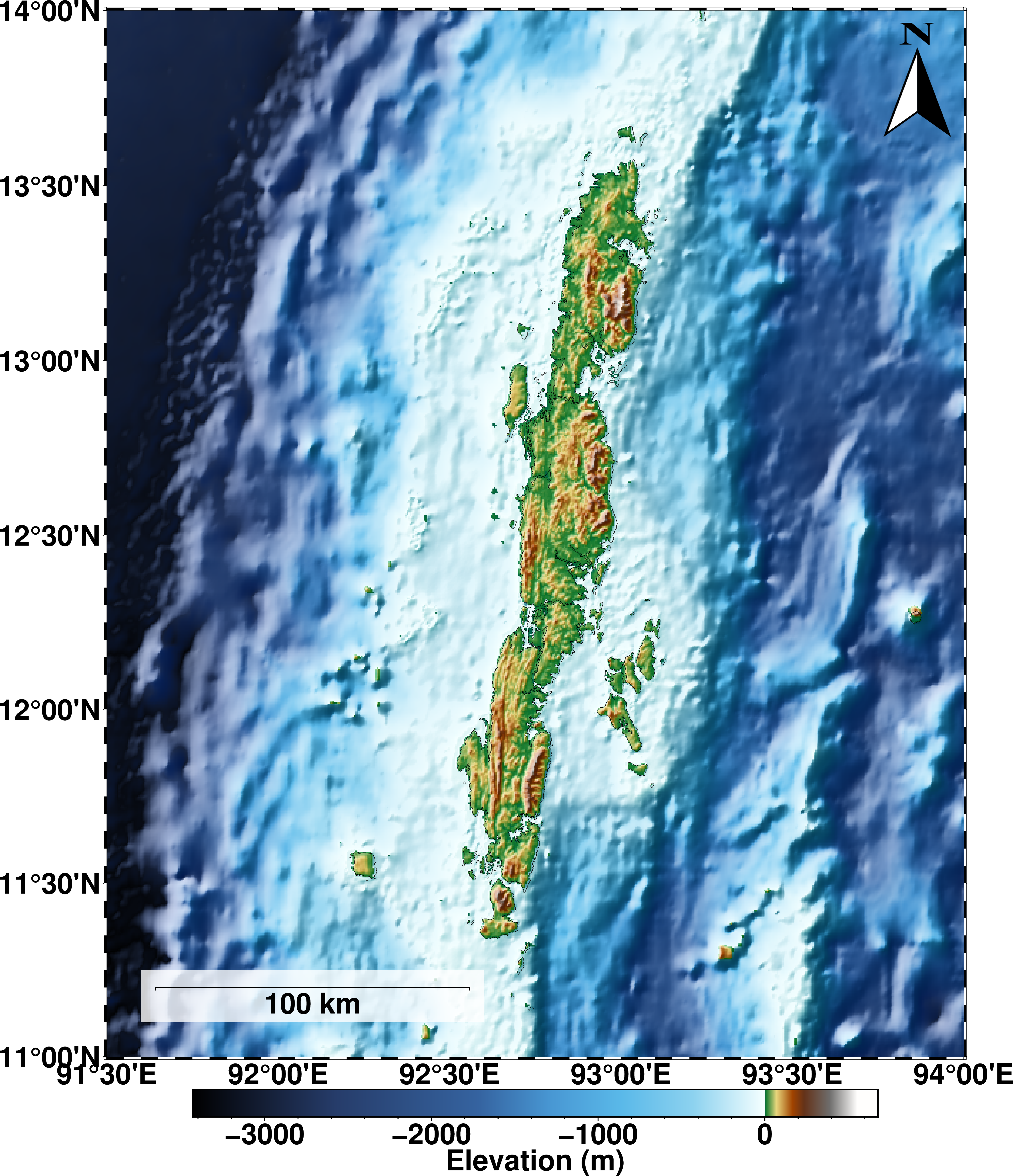
Figure 14

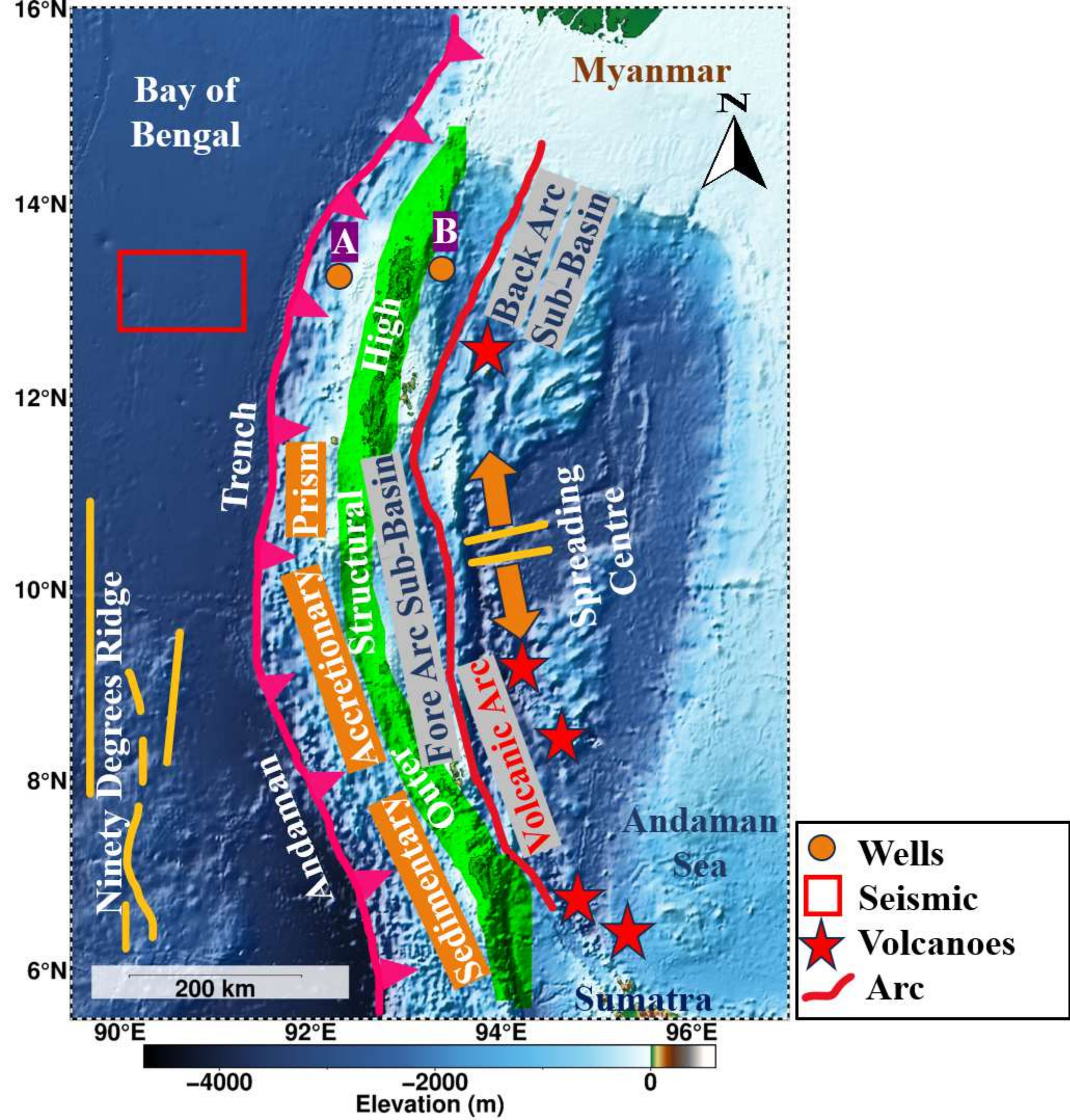
The 3D sedimentary model of the deep marine setup of Andaman basin at the western flank of main islands, representing overall sediment flow patterns, depositional architectures, stratigraphic sequences, and corresponding system tracts for the particular phase of sea level changes. Structural highs-lows and basement level major faults indicates sediment flow direction and tectonic bending of lithospheric block towards the Andaman Trench. Model shows some deep water features like submarine channels, channel-levee complexes, biogenic gas pockets and marine shale deposition – majorly controlled by gravity driven flows(due to density contrast) like turbidity current, debris flow, slump, and submarine avalanche.

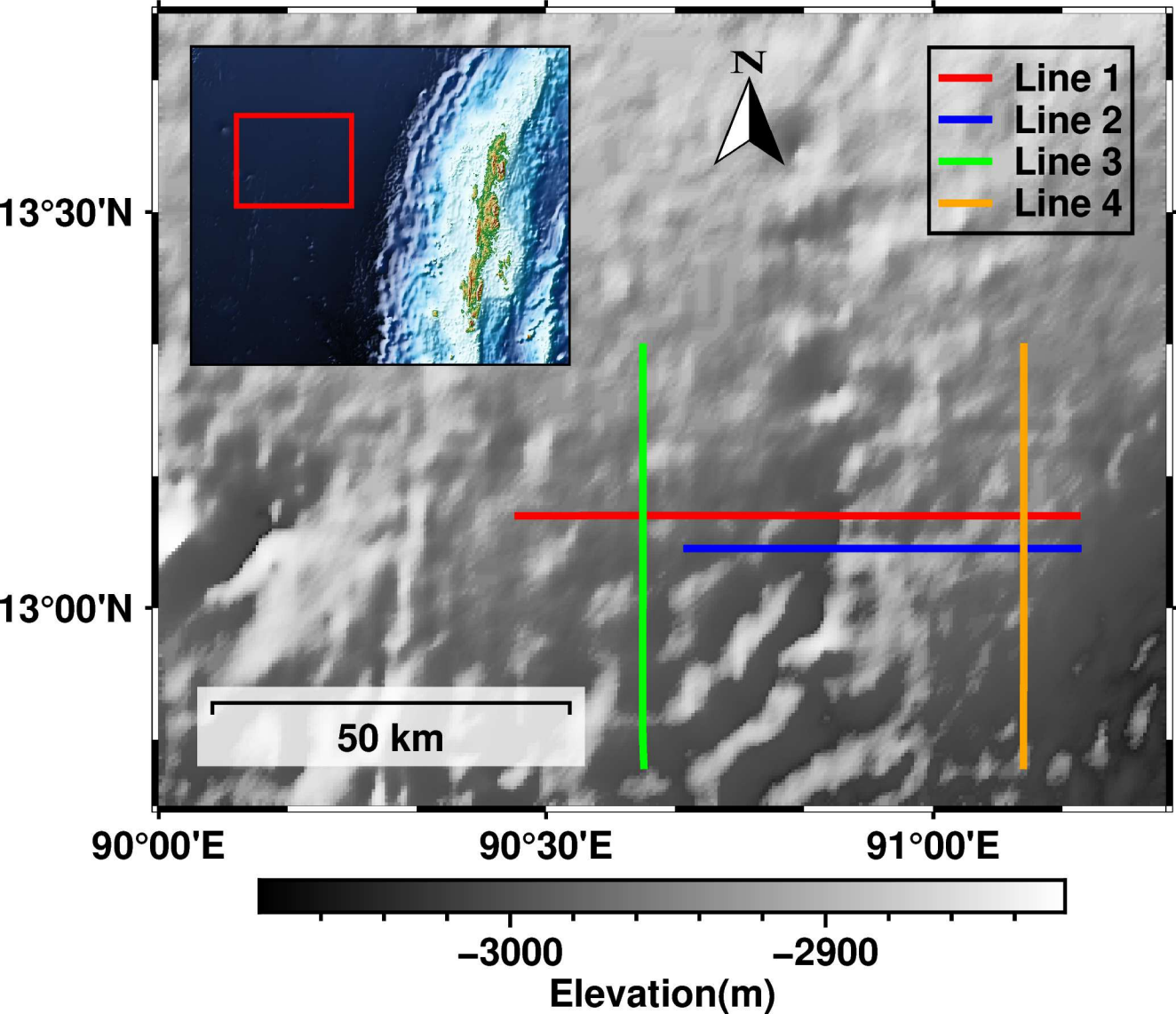
Figure 15

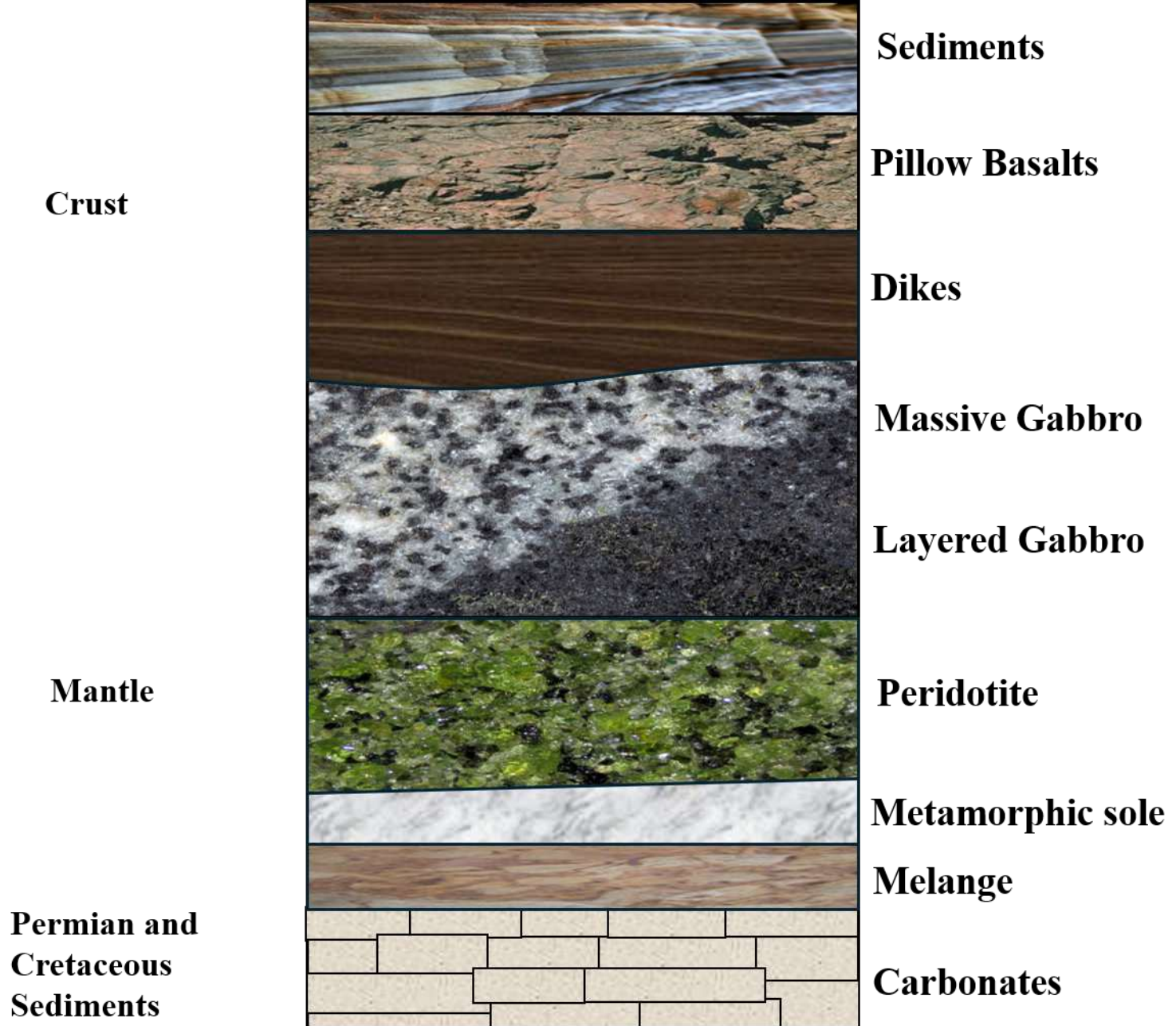
The conceptual 2D Geological cross section representing sediment depositional framework of the deepwater region of Andaman, Geotectonic control of subduction complex and structural variabilities of accretionary prism. Model represents a rare and dynamic setting where oblique subduction, strike-slip motion, thrust faulting mechanism, back-arc spreading, and ophiolite emplacement all occur within a relatively narrow corridor. This tectonic setting characterized by intense faulting, fractured ultramafic exposures, elevated heat flow, and active water influx to the ophiolite sequence - highly favourable for natural hydrogen generation by Serpentinization.

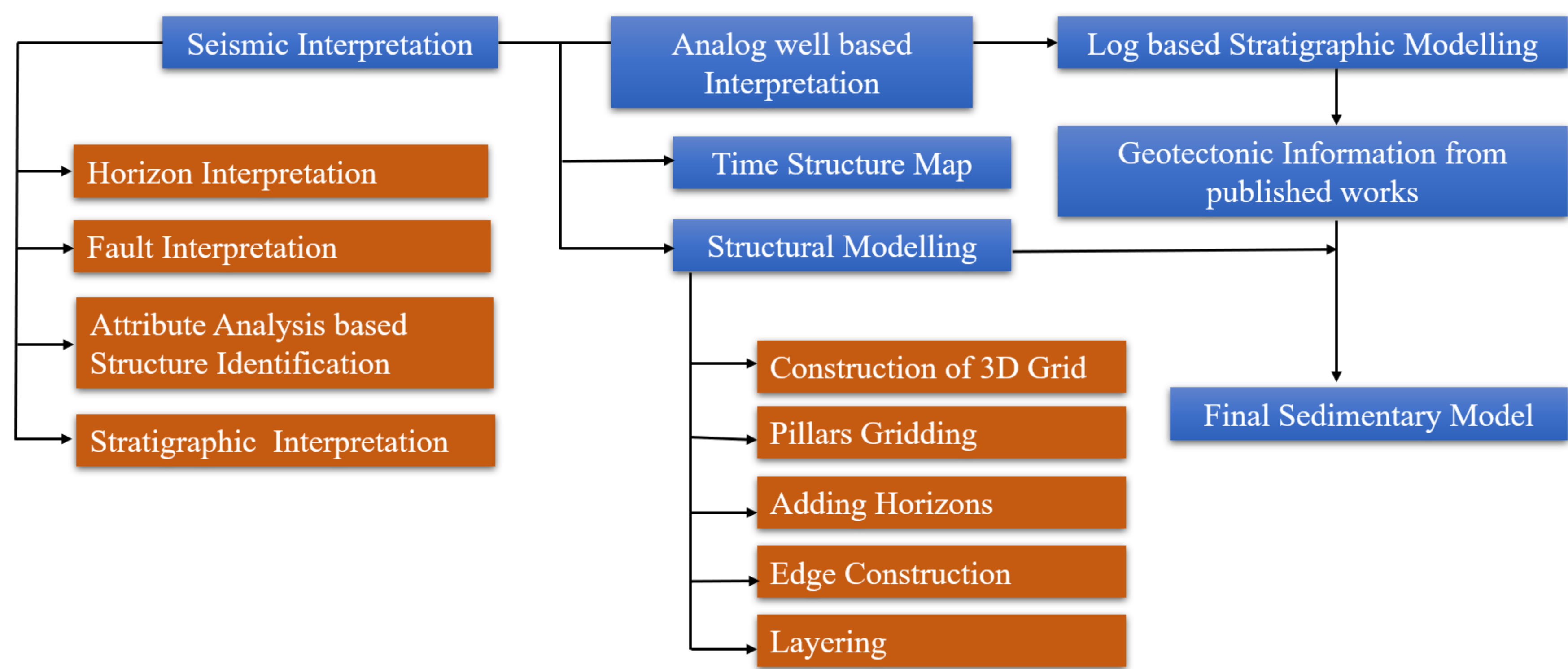


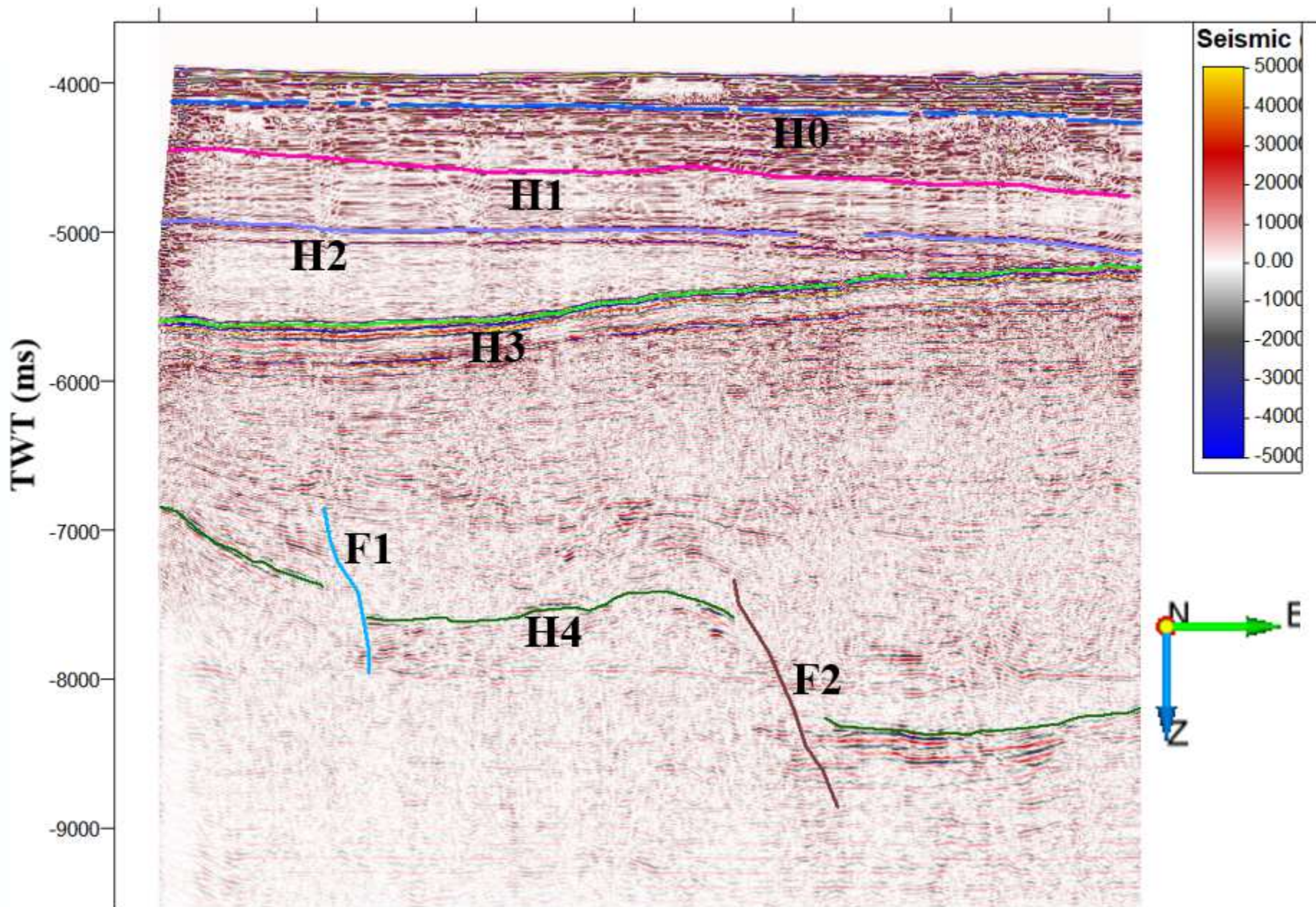


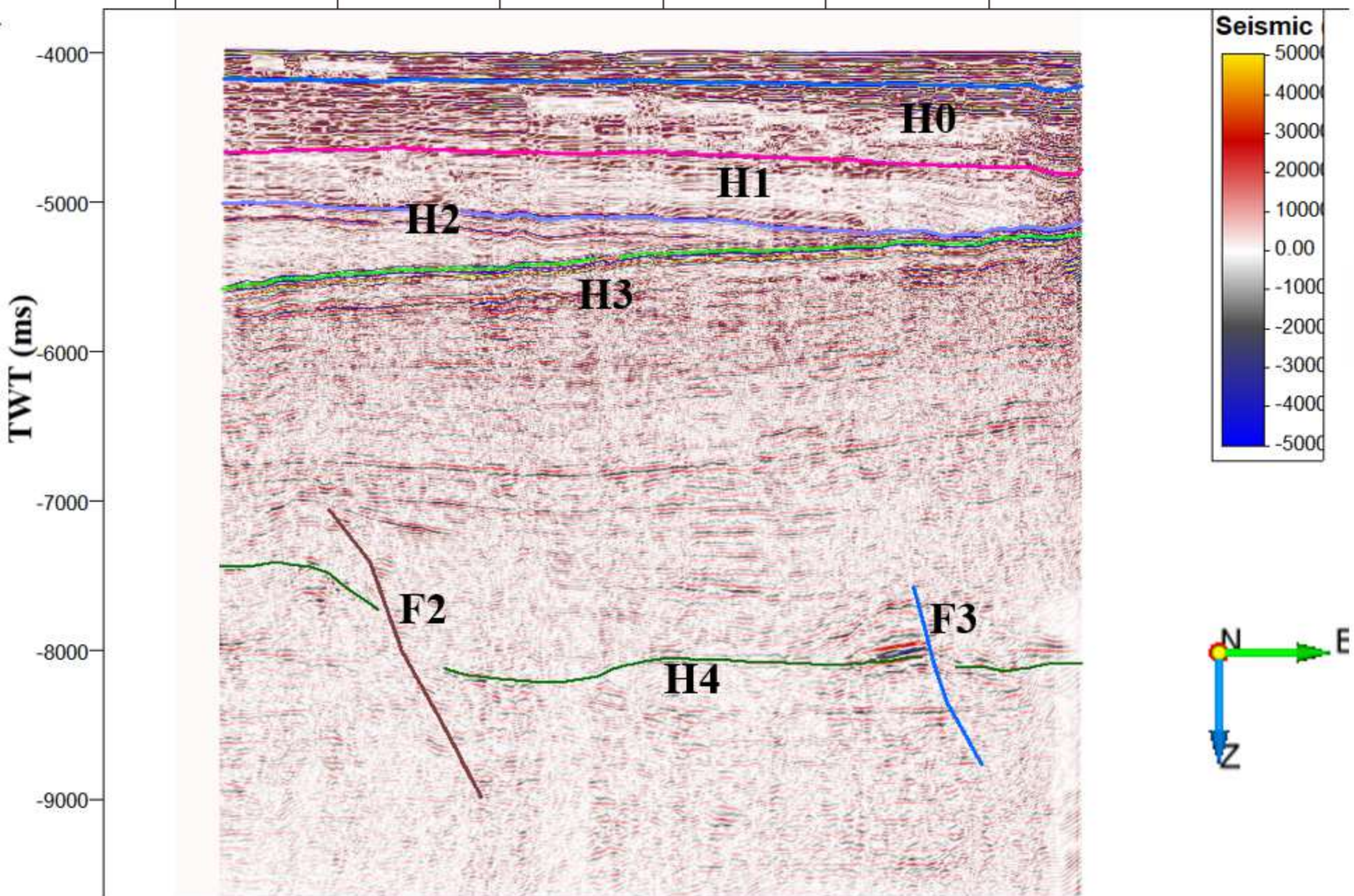




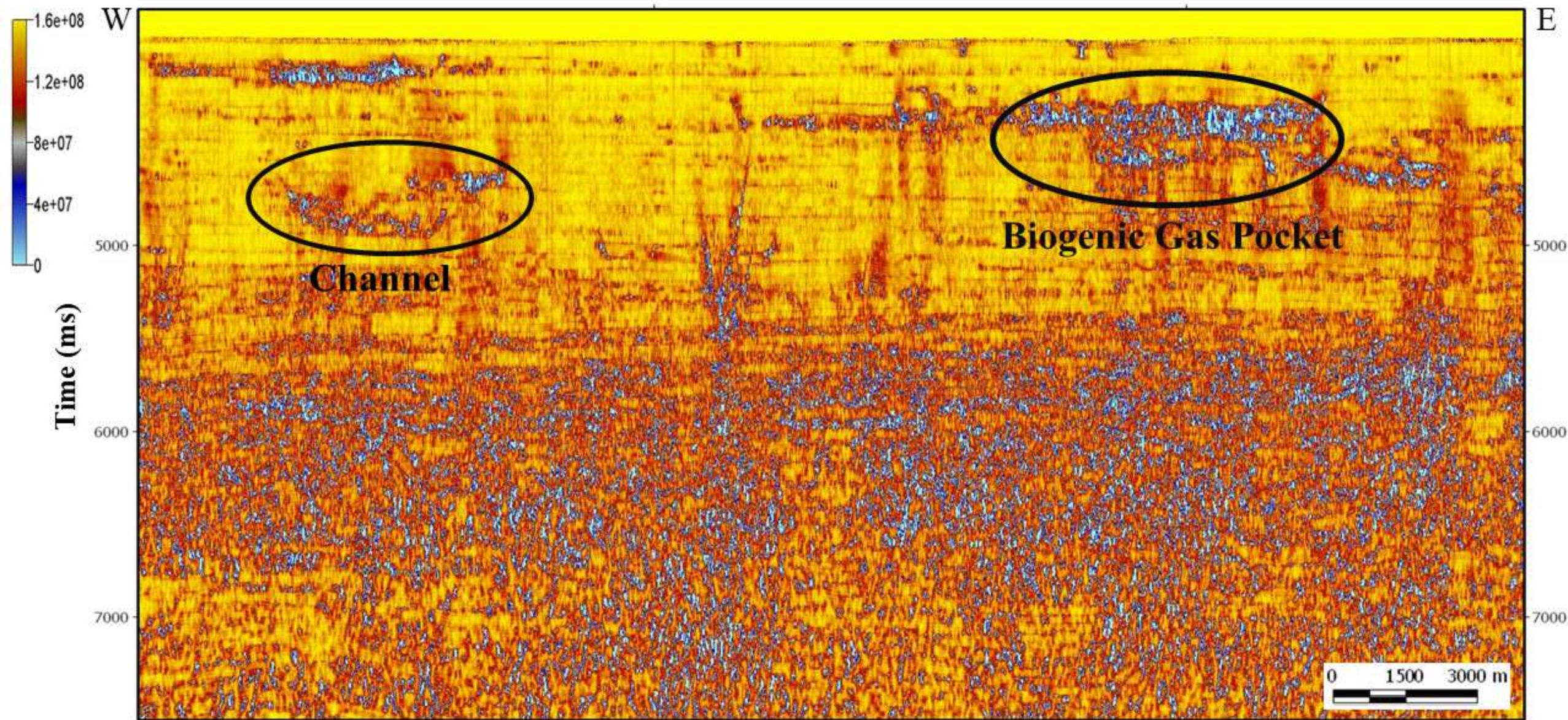




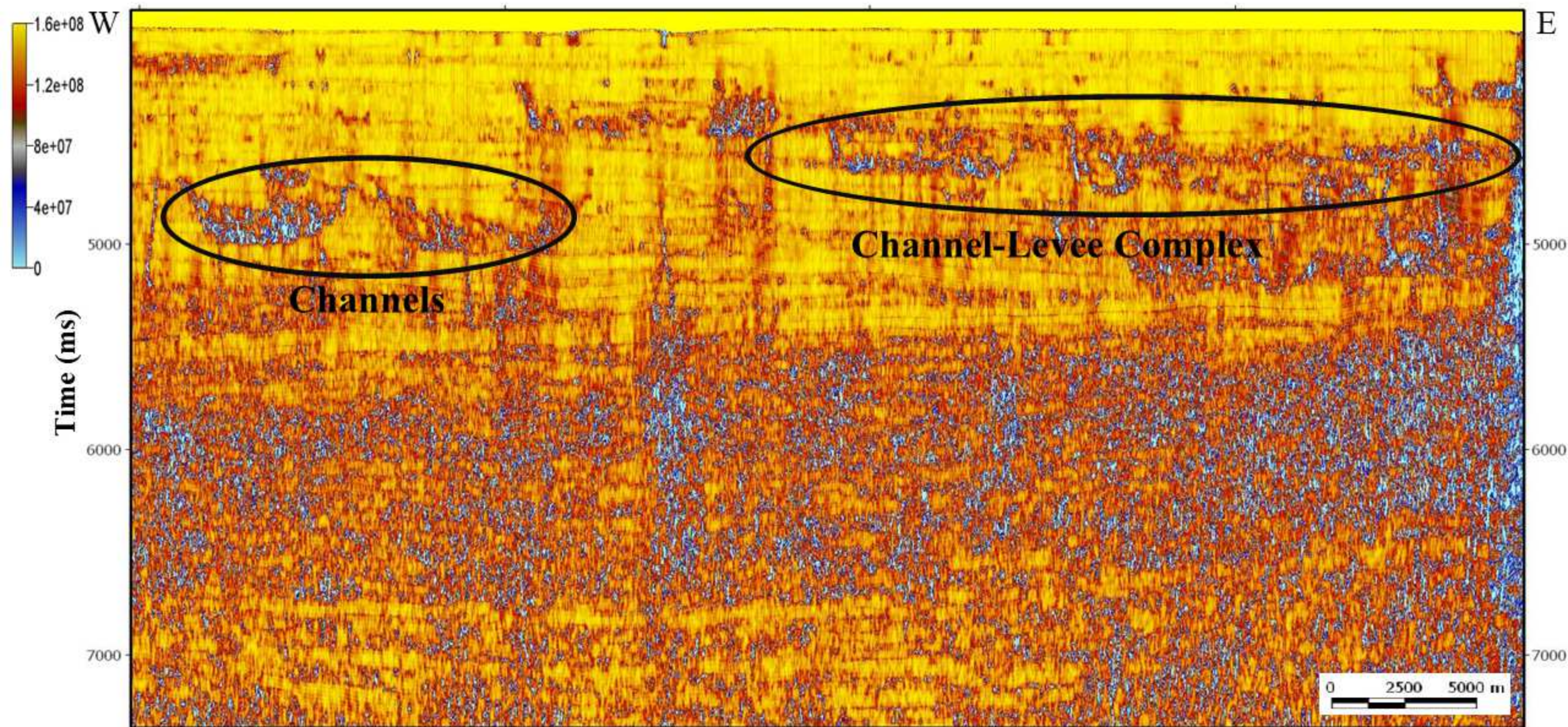




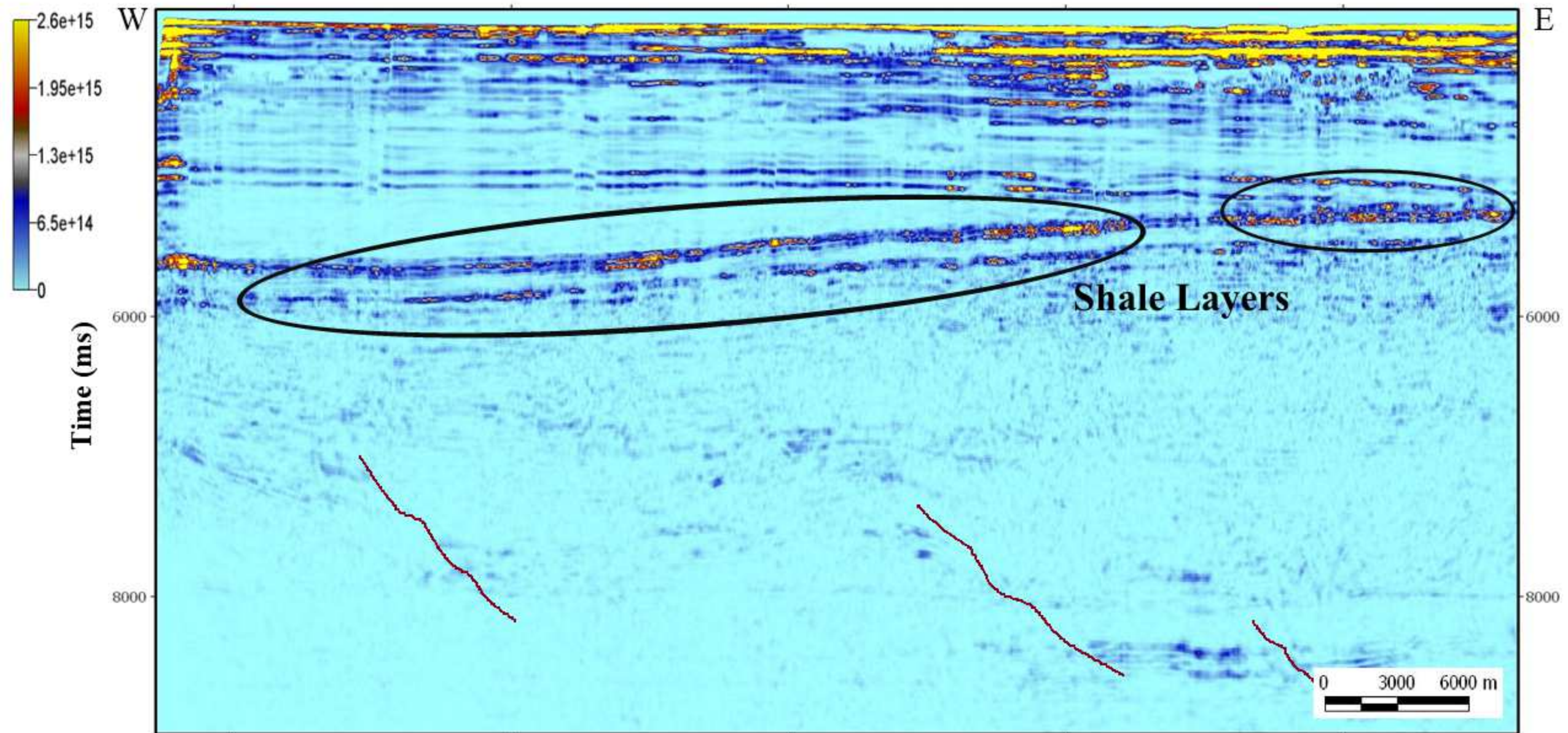
Line 1 (Similarity)



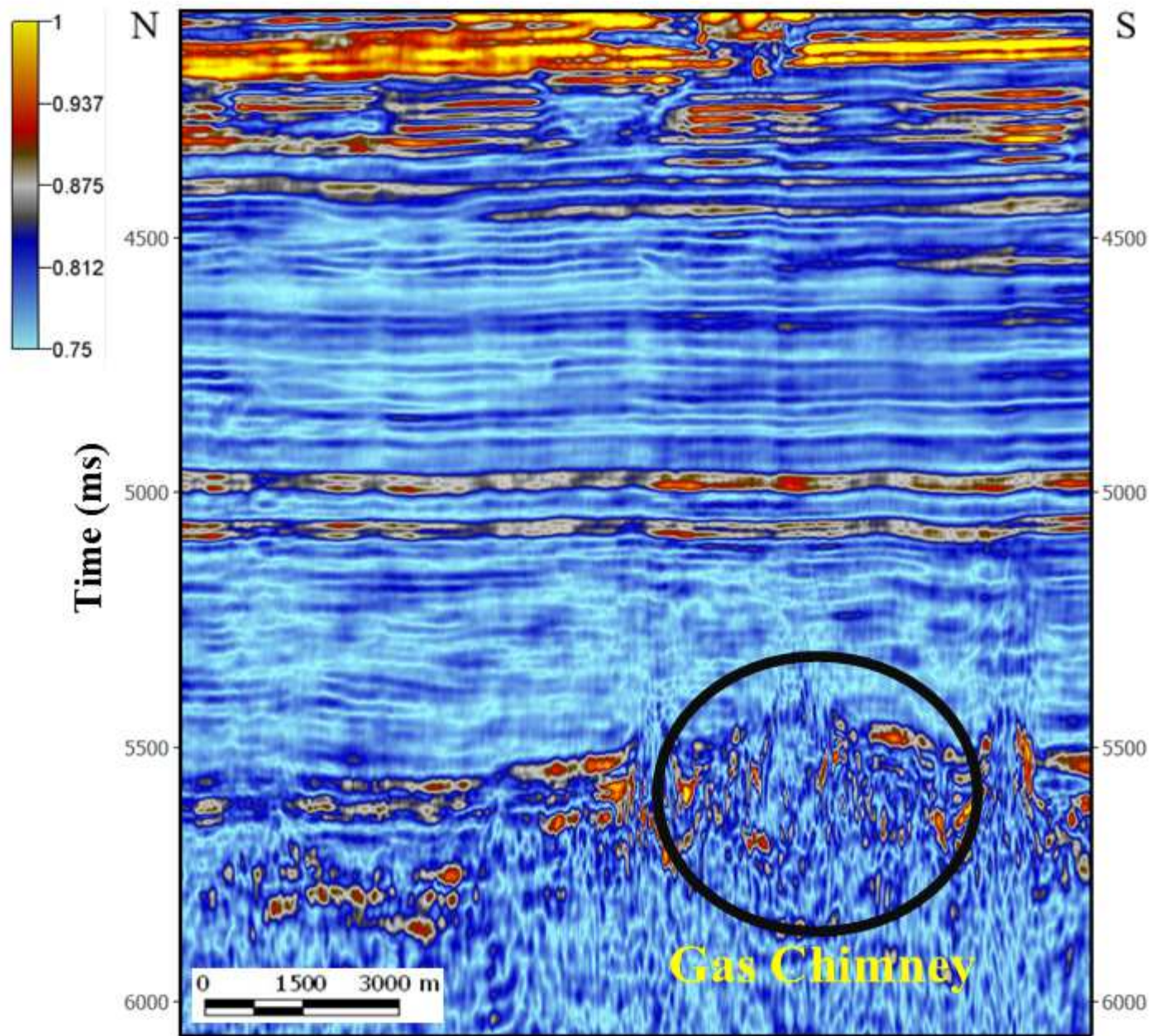
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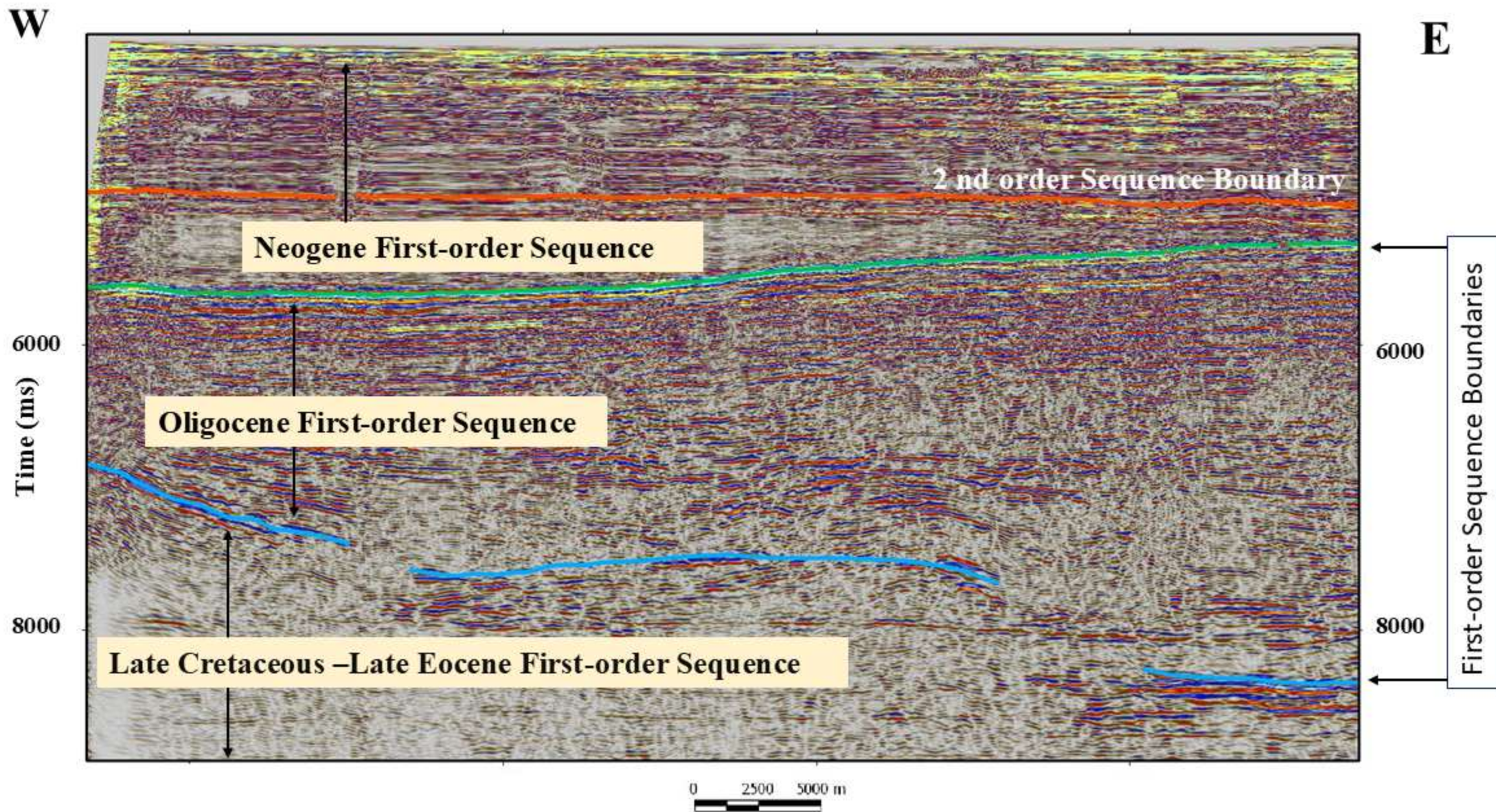


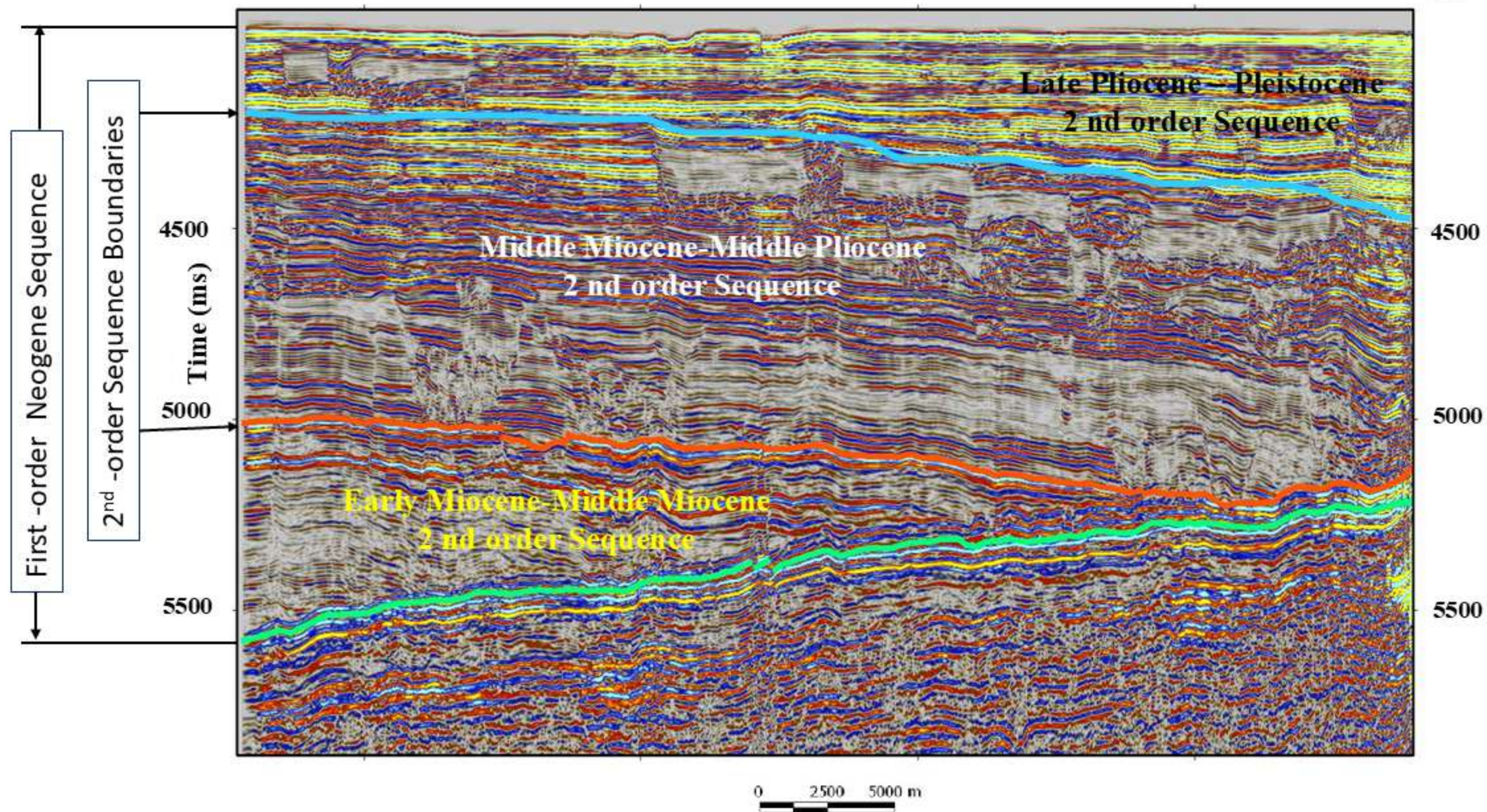
Energy

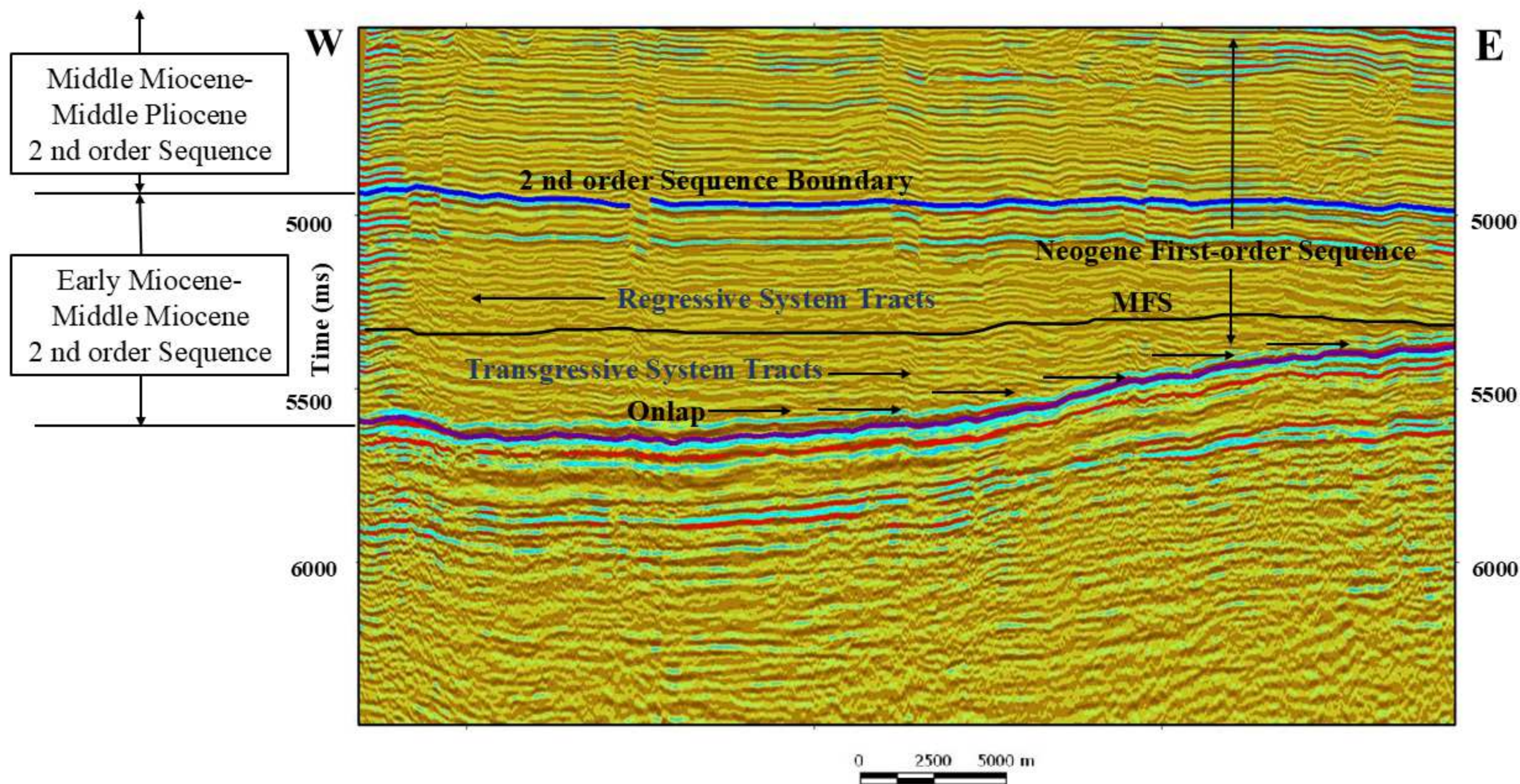


Line3 (Spectral Decomposition)

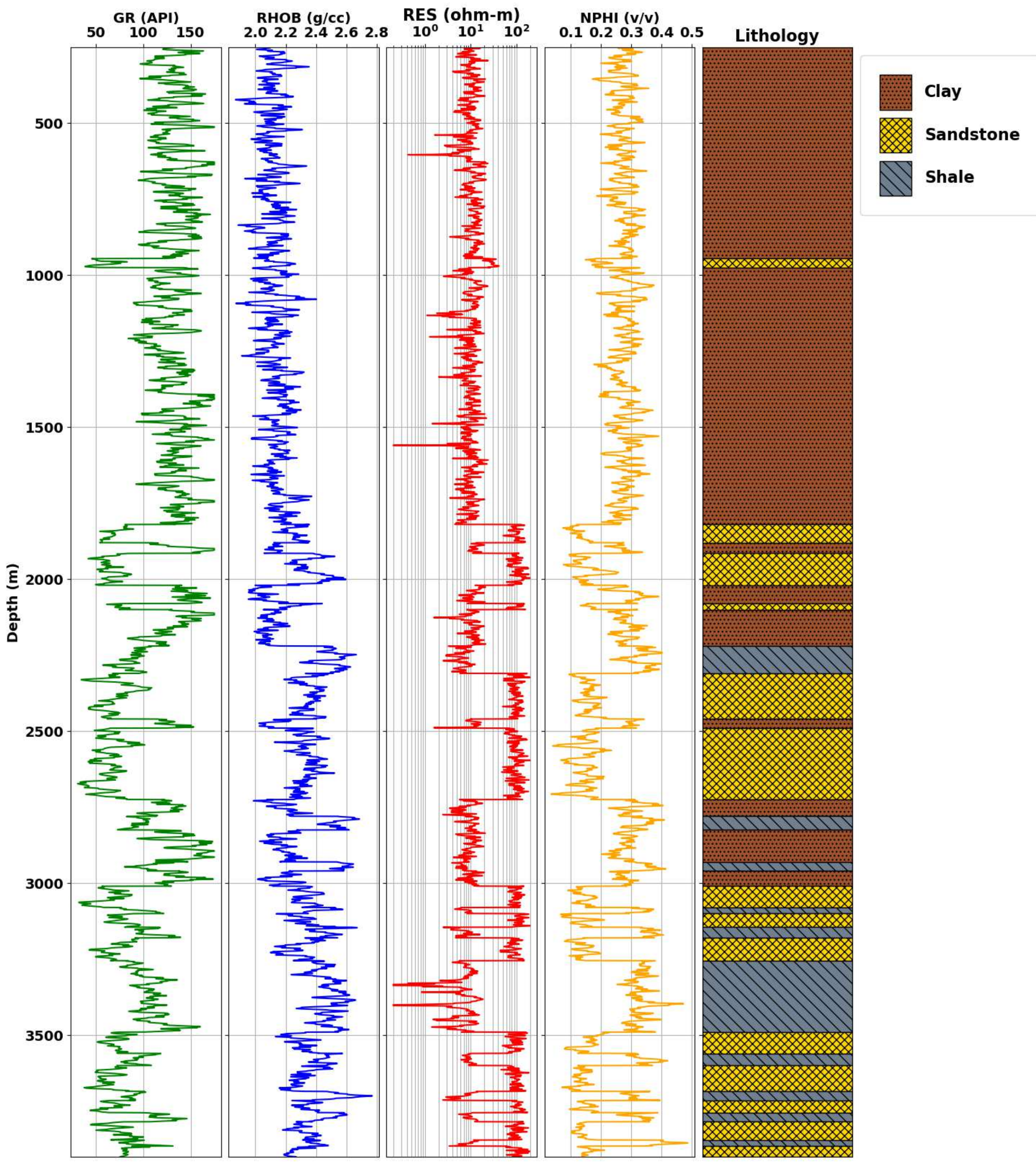




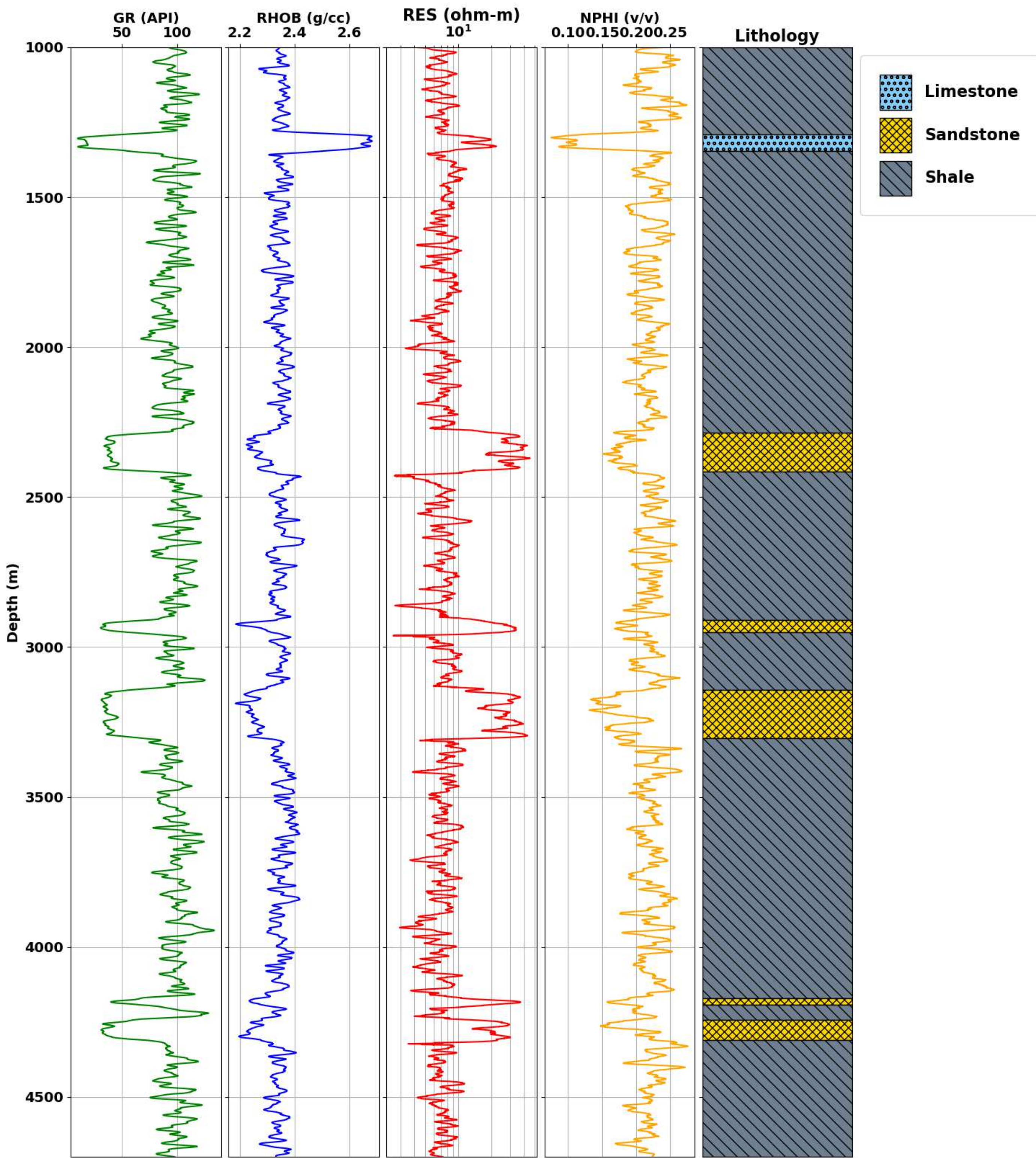
W**E**



Well Logs with Lithology Track (Well-A)



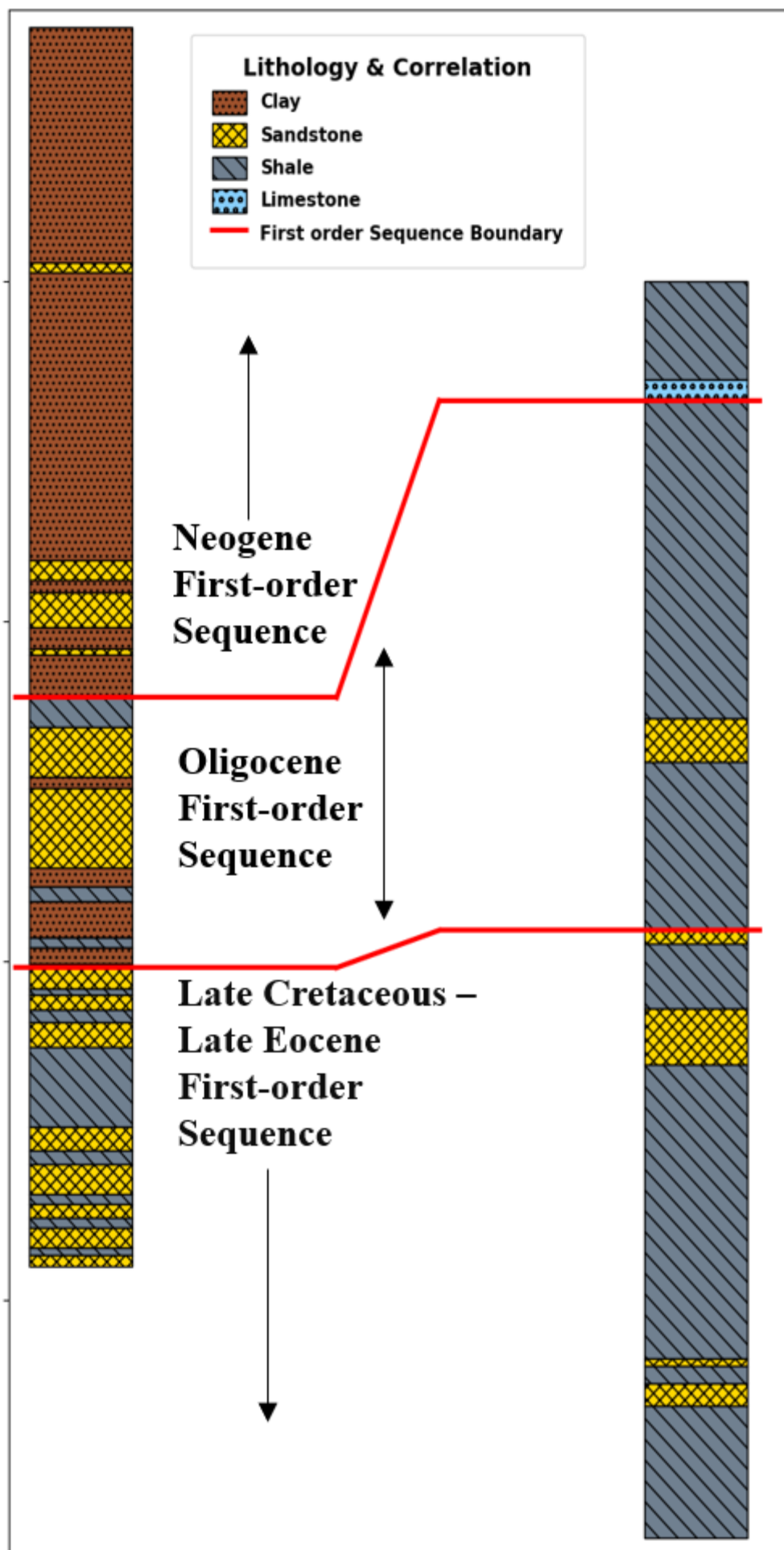
Well Logs with Lithology Track (Well-B)

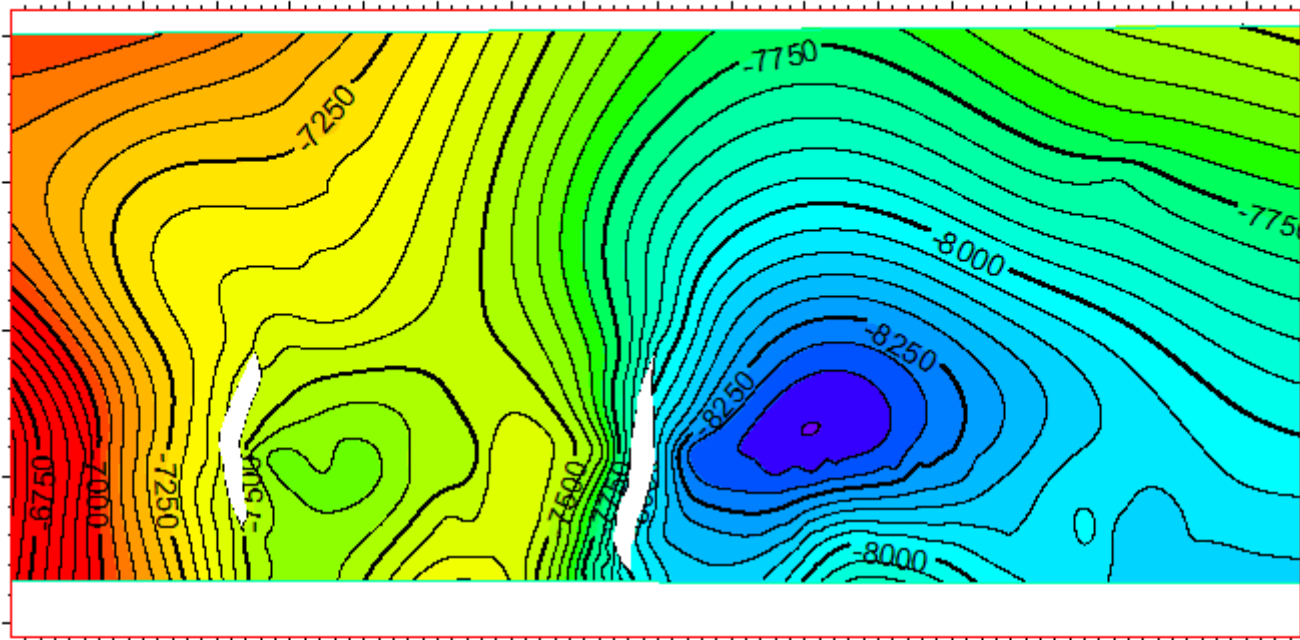


Well Correlation

Well A

Well B





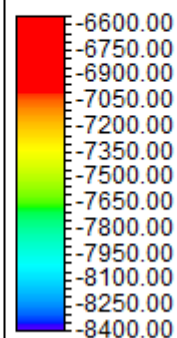
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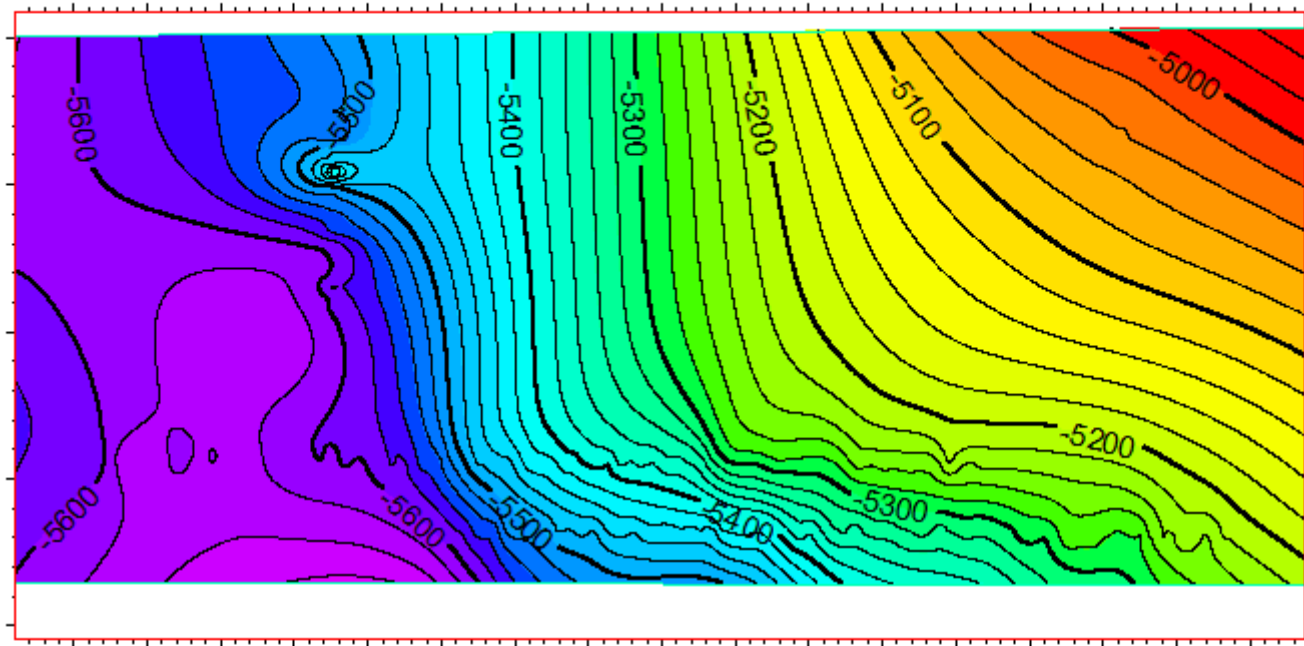
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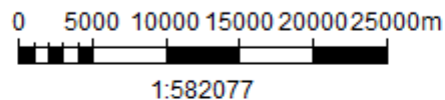
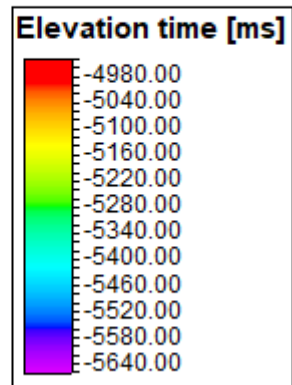
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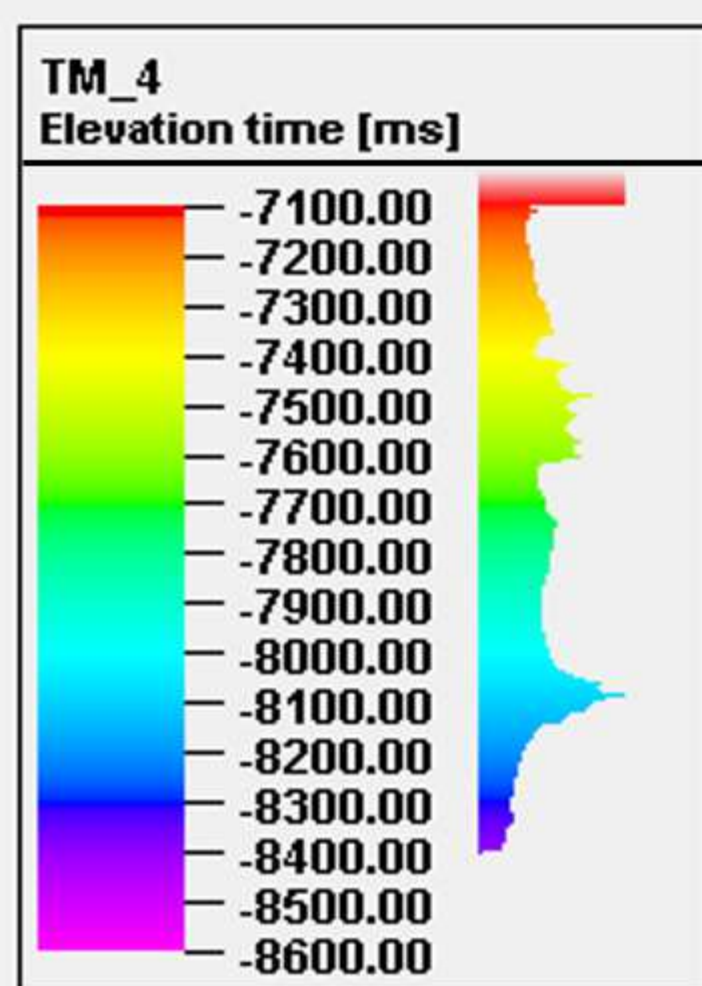
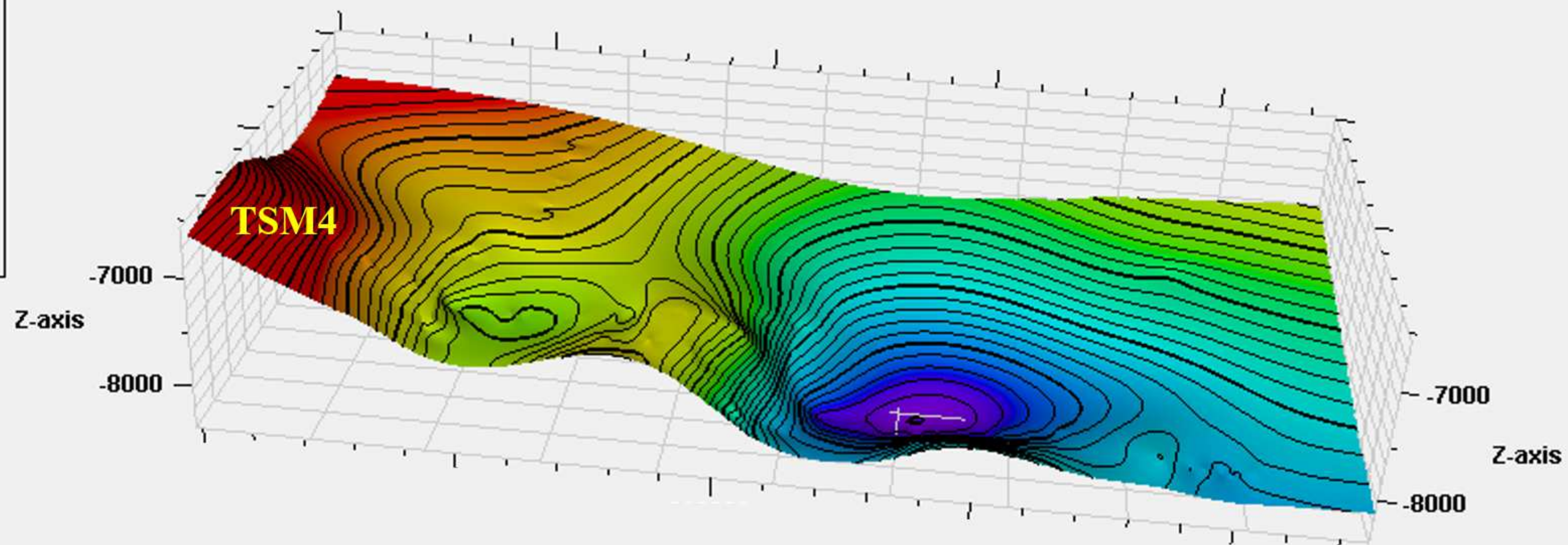
Elevation time [ms]



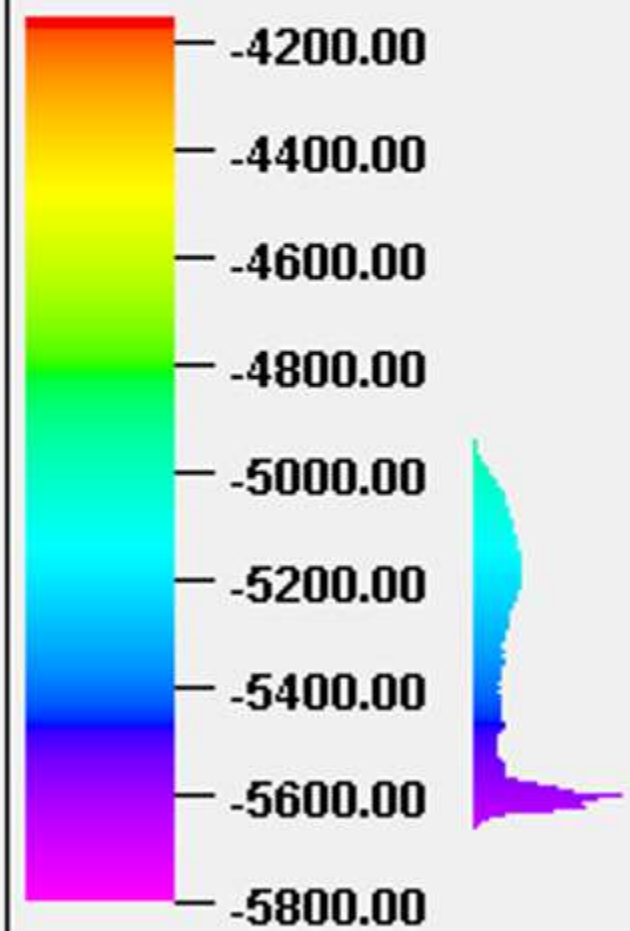
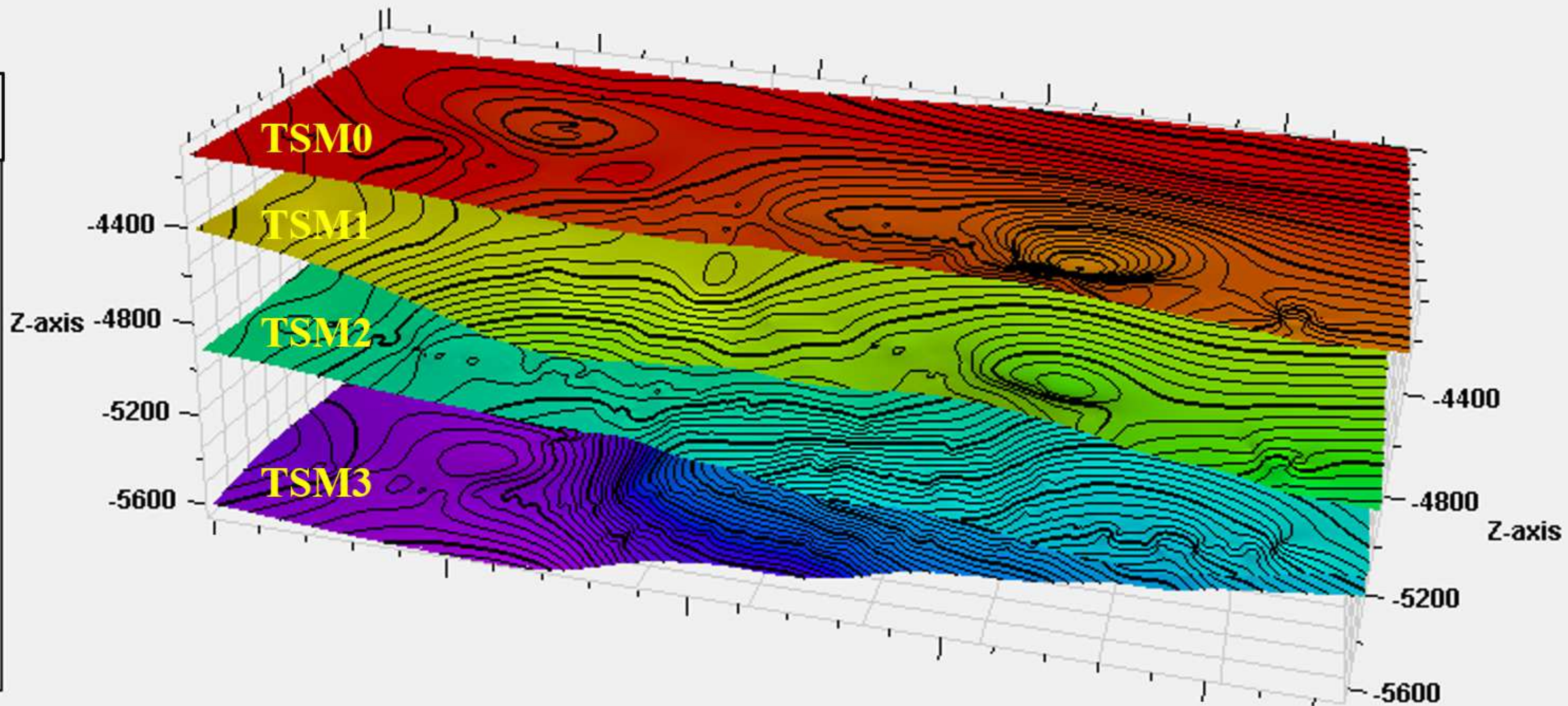


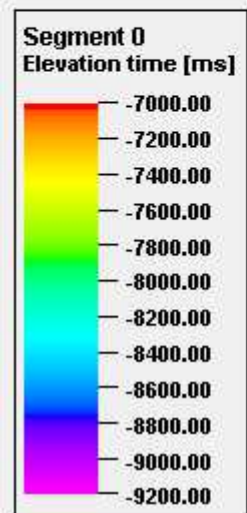
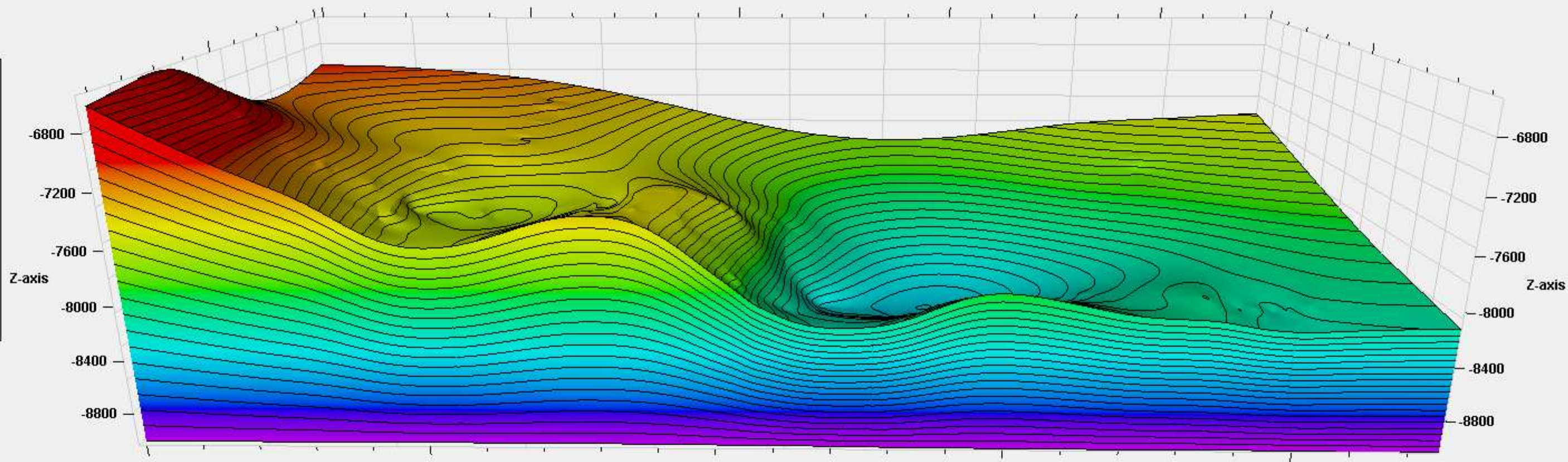
Map	
Country	Scale 1:582077
Block	Contour inc 20
License	User name Admin
Model name	Date 11/01/2025
Horizon name	Signature

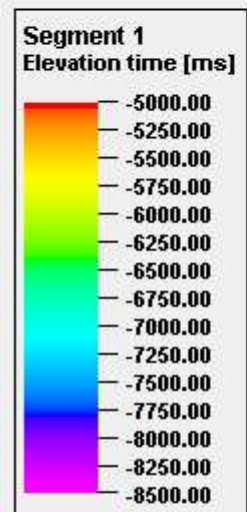
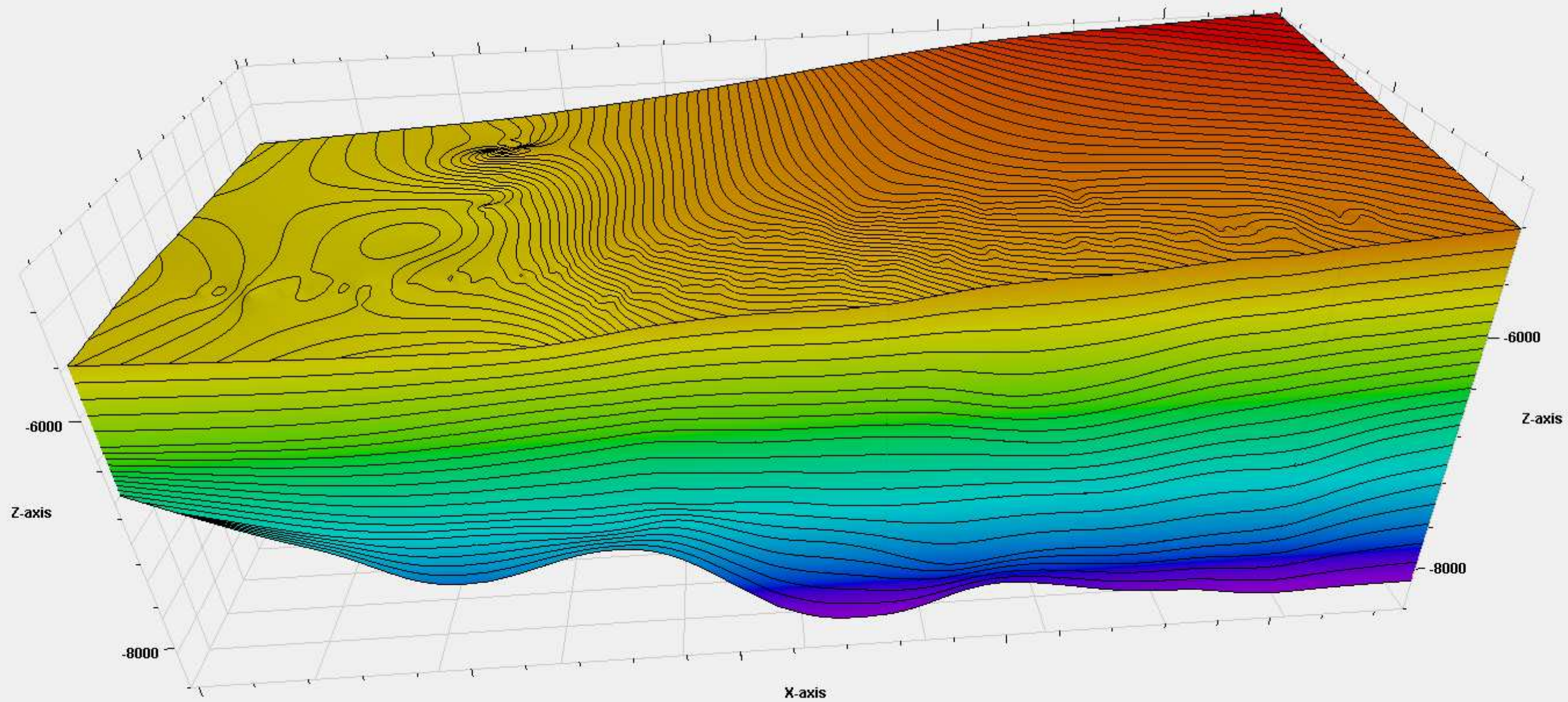


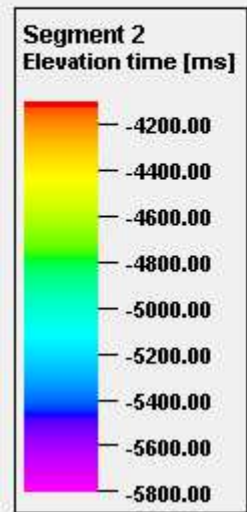
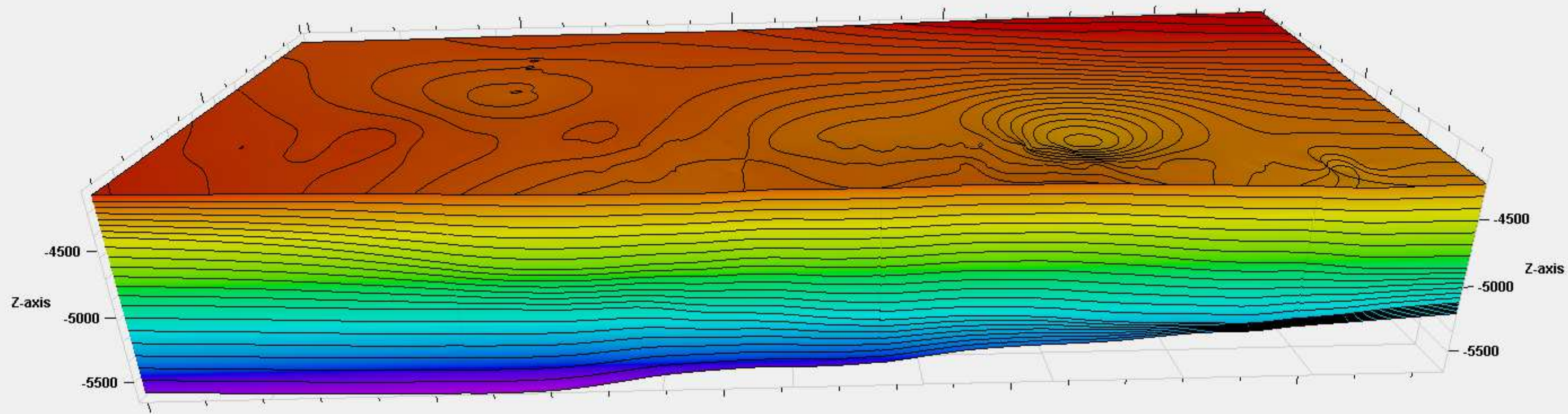


Time Structure Map
Elevation time [ms]









W

E

