# Seismic Carbonate Reservoir Prediction and Drilling Results, Offshore Nicaragua, Caribbean Sea*

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## Abstract

Offshore Nicaragua in the Mosquito Basin offers a frontier exploration area. Noble Energy, Inc. and partners conducted exploration studies from 2D seismic to 3D seismic to drilling from 2009-2013. A potential carbonate target was first identified on 2D seismic data. Once identified, extensive effort went into characterizing the carbonate as a drilling target and understanding both the petroleum system and reservoir potential utilizing 3D seismic. Seismic facies, gravity modeling, and acoustic properties were tied together with depositional models for two working hypotheses of reservoir conditions, depending on the age of sediments encountered. The two depositional models considered were a framework carbonate buildup and a carbonate shoal, with the shoal model favored based on the anticipated age of the buildup. Paraiso Sur #1 was drilled to test the carbonate buildup in late 2013. This was the first well in the offshore Caribbean of Nicaragua drilled in 30 years. Drilling results were very close to the prognosis for the reservoir in terms of depth (within 1%), thickness (>500m), porosity (average 19%), age (Eocene), and depositional environment (a carbonate shoal was encountered). Despite the excellent match of reservoir and depth structure to the prognosis, only residual oil was encountered. The primary failure mechanism appears to have been either migration or seal.

## Paraiso Prospect

The Paraiso prospect is located offshore eastern Nicaragua, within the Caribbean Sea. Present-day Nicaragua is an agglomeration of the Chortis and Siuna blocks and a triangular-shaped region of attenuated continental crust, known as the Nicaragua Rise. It is bounded by the Hess Escarpment to the south, Cayman Trough to the north and the Middle America Trench/Cocos Plate to the west.

There are a total of 23 wells documented for offshore eastern Nicaragua and two onshore along the coast (Figure 1). The two onshore wells were drilled in the 1940s, and the offshore wells were drilled from 1957 to 1978. All the historic wells were drilled to the north and west of the Paraiso prospect and in shallow water (≤169ft). Historic wells were drilled based on structures identified utilizing 2D seismic data, and all the structures appear to be within an attached carbonate shelf environment. Many historic wells had hydrocarbon shows, and some had limited production while running flow tests. Reported oil gravity ranged from 21-28° API. However, no commercial hydrocarbon accumulations were encountered. Paraiso South #1 (PS-1) was the first well drilled offshore eastern Nicaragua since 1978, the first deepwater well (water depth 370m, 1214ft), and the first well in the area drilled utilizing 3D seismic data.

Four volumes of seismic data were used to define the Paraiso prospect (Figure 2). Three volumes of 2D seismic data were acquired as part of the Nicaragua Bid Package, and one volume of 3D seismic data was acquired under contract by Noble. The Paraiso prospect was initially identified using historic 2D seismic data purchased from the Nicaraguan Government (1977, source unknown) and 2D seismic spec data, PSTM, selected PSDM, and Grav-Mag (circa 1999, Fugro and SeaGap). Noble contracted CGG Veritas in 2010 to acquire the Tyra 3D seismic data which was used to define the Paraiso prospect and progress it to drill-ready status. The Tyra 3D seismic survey covered almost 5000 sq. km.

The Paraiso reservoir was predicted to be an isolated carbonate buildup consisting of approximately 539m of Paleocene-Eocene carbonates deposited on a paleo-high of eroded Cretaceous volcanics (Figures 3 and 4).

The Paraiso carbonate buildup is approximately 8 km wide and 35 km long and trends NNE with the windward side to the east and the leeward side to the west (see Figures 6 and 7). Paraiso is generally triangular in cross section being widest at its base and narrowing upward. The buildup is subdivided into a deeper Stage 1 and a shallower Stage 2, separated by an unconformity. These stages were named in the order they formed geologically and predicted to be Paleocene-Eocene age. Four structural culminations were identified in the buildup. The system plunges to the NNE, with the northern culmination being nearly 400m deeper than the southern culmination. A NW-SE-trending normal fault separates the northern culmination from the one to the south. The fault dips SW and is syn-depositional with offset decreasing upward, with nearly no offset at the top of the buildup; carbonate strata are juxtaposed against carbonate along the fault. At the PS-1 programed well location, the buildup was sealed by interpreted overlying shale and marl that seismically thickens to the west into a paleo-basin that separates the Paraiso buildup from the shelf.

The age uncertainty at the Paraiso prospect was due to the limited data available from historic drilling activities in the area. Prior to PS-1, the most recent well drilled in the area was in 1978. Historic wells were drilled to test shallower structures identified with 2D seismic data, and results and reports are sparse at best.

During the Paleocene-Eocene thermal maximum there was little coral reef growth globally. Due to age uncertainty of the Paraiso buildup, Noble carried two carbonate depositional concepts, Concept 1 and Concept 2, both consisting of a profile containing an outer ramp, mid-ramp, and inner ramp (Figure 5). Concept 1 was a ramp profile with large shoals, little restriction, and higher energy dispersed through the platform. Concept 2 was a reef-rimmed buildup with a steep profile, restricted lagoon sheltered by rim facies. Based on the age uncertainty, the Paraiso buildup may contain some characteristics of each concept.

An unsupervised neural network algorithm within OpendTect software was used to generate seismic facies from seismic attributes. Many iterations were run; however, the results with 6 seismic facies appeared to generate the most plausible geologic depositional patterns. The seismic facies were imported into the Petrel model with examples of the results in cross section (Figure 6) and plan view (Figure 7). Facies and concept models were used for porosity and permeability distribution.

Porosity was estimated using multiple techniques to cross verify predictions (Figures 8 and 9). Seismic velocities were used along with empirical relations from Mavko et al. (2009) to estimate density, which was then used to estimate average porosity. This was correlated with depositional model concepts in Petrel.

Lastly, gravity modeling (performed by Bird Geophysical) based on seismic interpretation was performed (Figure 9). The best match to the gravity data suggested a density of 2.3g/cc in buildup. These independent processes all predicted a mean porosity of 22%. The lower density of the gravity modeling compared to the volcanic body below also helped support the presence of a carbonate body rather than igneous rocks.

The seal was predicted to be a mix of shale and marl of early mid-Eocene age (Punta Gorda Formation) with a thickness that could range from a few 10s of meters to a couple hundred meters. Faulting across the top of the feature is consistent with differential compaction, and stress analysis suggested that the faults should be closed present-day.

The Paraiso Sur-1 well drilled from September 4 to November 29, 2013, offshore Nicaragua (Figures 10, 11, and 12). Traces of residual hydrocarbons were encountered. However, the hydrocarbon system failed for this Paleocene-Eocene reservoir, and PS1 was declared a dry hole. The following is a summary of the conclusions based on drilling results and post-well analyses. Hydrocarbon system elements are discussed below along with possible failure mechanisms. In short, there may have been as much as a 25m paleo-column of hydrocarbons, with several possible failure mechanisms that include weak charge, late charge/timing, poor conduit for migration, breached seal, or some combination.

**Reservoir**

Approximately 553m of carbonate reservoir was encountered in PS1, in descending order include Stage 2 (265m), Stage 1 (271m), and Stage 1 to TD (17m). Stage 2 consists of upper to middle Eocene and upper Paleocene carbonates and is interpreted to be a stable carbonate platform, possibly deposited in more open-marine conditions (based on planktonic forams, because nannos are just about barren in the reservoir section). The lower Eocene is missing, representing about 8.2 million years of missing section. The middle Eocene has a seismically conformable contact with underlying upper Paleocene carbonates. Stage 1 to TD consists of upper Paleocene carbonates and is interpreted to be inner neritic deposits, with a fossil assemblage dominated by larger forams. At around 3000m there is a transition in dominance in the foram assemblage, indicating a significant reduction of wave energy. The Stage 1/Stage 2 seismic boundary is within the upper Paleocene section and is correlated with a low-porosity hard streak of carbonate. The overall lithological sequence encountered during drilling is an extensive limestone carbonate buildup overlain by marlstone and calcareous sands. The transition from a clean carbonate to marlstone is gradational, interpreted to be driven by increased detrital input. No siliciclastic sands were identified, and a generally low clay volume was encountered, but it increases in the uppermost portion of Stage 2. No significant ash beds or dolomite was encountered. Using modified Dunham classification, sediment textures consist of grainstone (algal/skeletal), packstone (skeletal and algal/foraminiferal), grainstone/bindstone, and floatstone. The combination of texture, allochem assemblages, and degree of preservation of the skeletal allochems suggest deposition in inner ramp, backshoal, shoal and foreshoal to mid-ramp settings. Concept 1, a shoal, was the accurate model.

Stage 1 is interpreted to consist of an upward-deepening (i.e., towards more distal settings) from an inner ramp back-shoal to a high-energy shoal setting characterized by a 'pulsed' sedimentation, with more restricted conditions possibly associated with the development of hardgrounds in the shallowest deposits. The lower part of Stage 2 is interpreted to be a relatively subtle shallowing-up (i.e., towards more proximal settings) from mid-ramp/fore-shoal to back-shoal. The upper part of Stage 2 is interpreted to be shallowing-up with a dominant inner ramp deposition with patches of clay and/or organic-prone material.

Measured rotary sidewall core porosity ranges from 5.78 to 28.42%. Log-derived porosity averages 23% in Stage 2 and 15% in Stage 1, with a total average of 19%. Porosity is bimodal, predominantly moldic and intraparticle microporosity. Porosity generally decreases with depth and is the result of normal compaction and burial diagenesis. Measured permeability ranges from 0.061 to 18.7 mD, generally decreasing with depth. Although a shoal was predicted, the porosity distribution did not match prediction. CT scans of rotary sidewall cores reveal abundant fractures, providing little porosity, while locally increasing permeability. The grainstone is pervasively cemented and could host good pore volumes; however, the pore connectivity is occluded by a non-ferroan calcite cementation phase. The packstone-grainstone possesses the best reservoir properties (combined porosity and permeability) where the pore connectivity is mainly a function of the microporous network hosted within the micritic matrix. Unfortunately, even the best reservoir textures have very low permeability.

**Source**

The trace of hydrocarbons in the reservoir were generated from a proximal, Eocene marine carbonate deposited in an anoxic environment. The seal interval penetrated at the well has little to no hydrocarbon source potential. However, away from the Paraiso structural culmination, the seal interval is predicted to have increasing hydrocarbon source potential along the flanks of the structure and into the basin to the northwest.

**Timing and Migration**

Migration is likely the dominate failure mechanism, either by poor migration fairway or timing of migration. Minor residual hydrocarbons and staining were encountered in the upper portion of the reservoir, indicating hydrocarbon migration occurred. Unfortunately, no moveable hydrocarbons were encountered (based on resistivity logs and the presence of dead oil in moldic pores). Little to no fluorescence was observed in rotary sidewall cores. Most hydrocarbons were observed in moldic porosity, intraparticle micropores, and as lining in vugs and stylolites. Any charge appears to have occurred primarily along stylolites and open fractures with little hydrocarbons trapped. In the upper, upper Eocene section there was a high abundance of visible liquid petroleum inclusions (“dead” oil in moldic pores) in rotary sidewall cores from 2620 to 2645m suggesting up to 25m of paleo-accumulation of liquid hydrocarbons. In the lower upper and middle Eocene section fluid inclusion abundance decreases with depth, becoming rare, suggesting late migration, after faulting and occlusion of the primary pore structure with sparry calcite cement. It is also possible that the hydrocarbon charge was weak.

Fluid-inclusion hydrocarbon type is wet gas to gas-condensate. Fluid inclusions have predominantly white fluorescence implying 30-40° API, with some blue fluorescence indicating high 30s° API. Salinities indicate fresh to brackish pore fluids. No $H_2S$ was encountered.

**Containment**

The reservoir is unconformably overlain by a seal of Oligocene (Chattian) muddy carbonate with some siliciclastic deposits in a middle bathyal setting. The Oligocene (Rupelian) section is missing, representing about 5.8 million years of missing section and corresponding to a major seismic event. Lithology indicates competent top seal with all samples of the seal classified as Sneider Seal Type A (may hold ≥ 300 - < 1500m oil column) (Sneider et al., 1997). Calculations of potential seal capacity indicate the average oil column that could be held is 1034 m (range 810-1216 m), and the average gas column that could be held is 493 m (range 386-579 m). Faulting may have breached the top seal. Lateral seal integrity is not known based on available information.

## Conclusion

Drilling results were very close to the prognosis for the reservoir in terms of depth (within 1%), thickness (>500m), porosity (average 19%), age (Eocene), and depositional environment (a carbonate shoal was encountered). Despite the excellent match of reservoir and depth structure to the well prognosis, only residual oil was encountered. The primary failure mechanism appears to have been either migration or seal.

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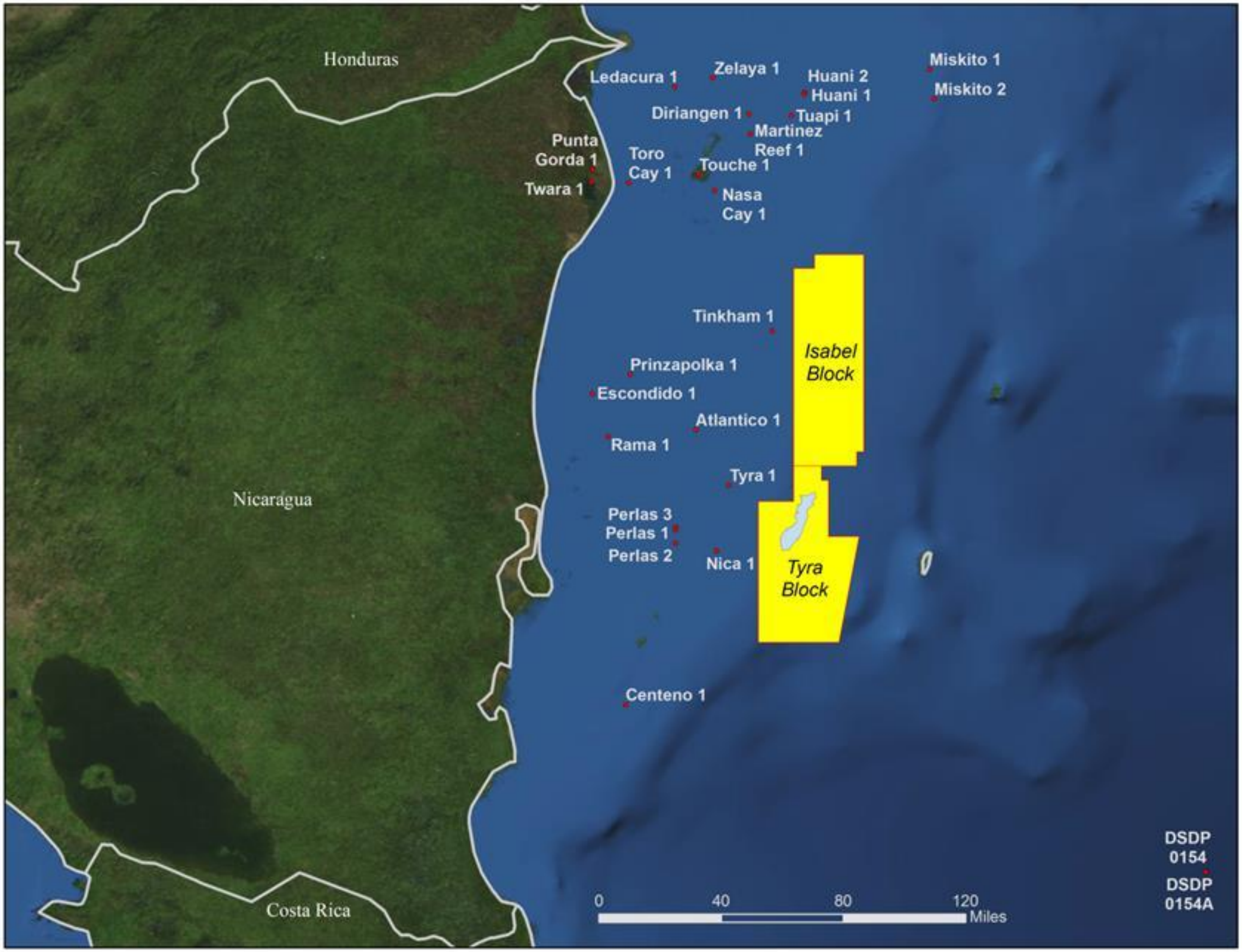


Figure 1. Historic wells in eastern Nicaragua and offshore eastern Nicaragua. Tyra and Isabel blocks are license areas formerly operated by Noble. The grey oval is the outline of the Paraiso carbonate buildup.

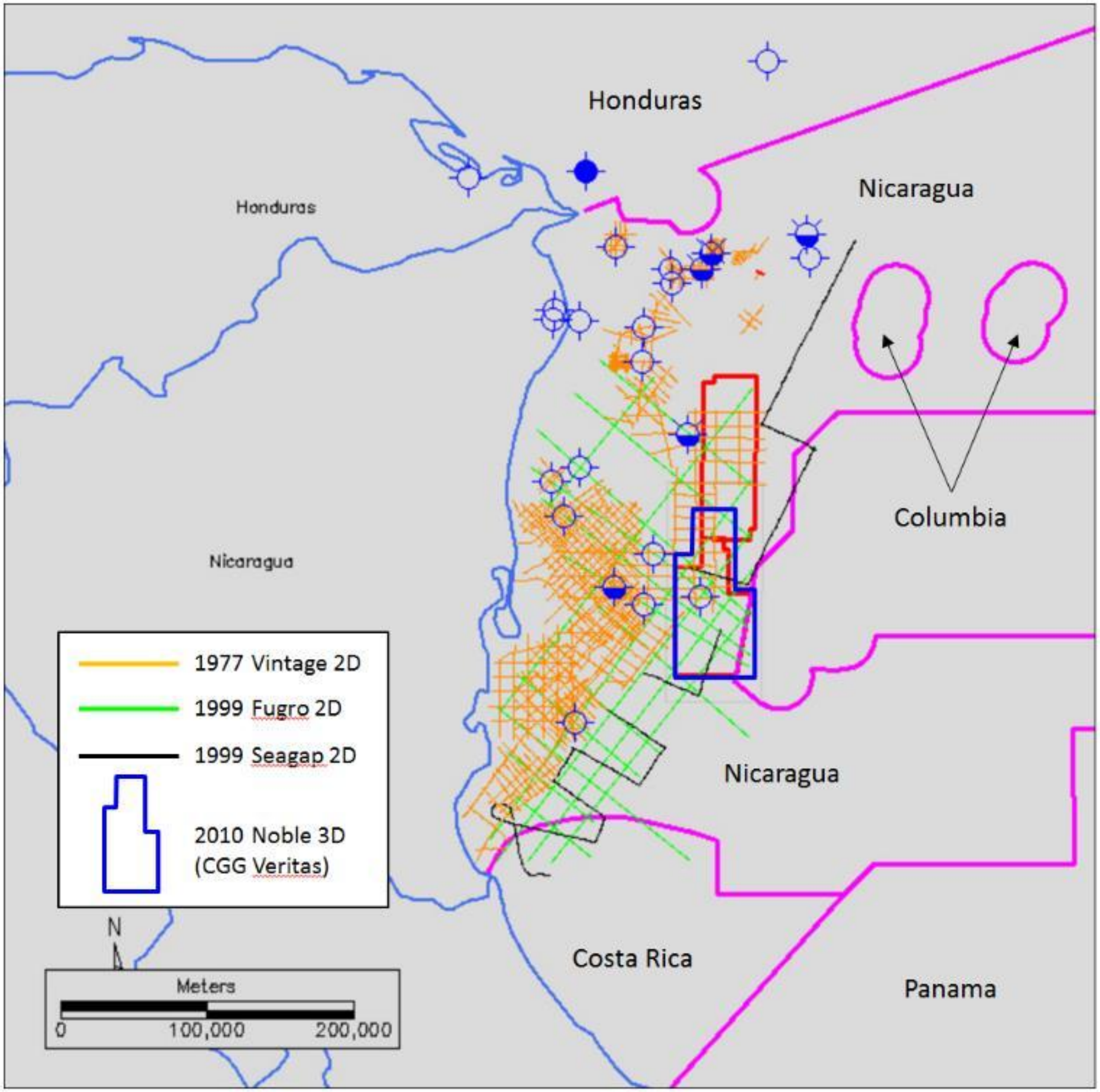


Figure 2. Regional seismic data coverage. Pink outlines are maritime country borders. The Tyra and Isabel license areas are defined by the red outlines, and the 3D data is outlined in darker blue.

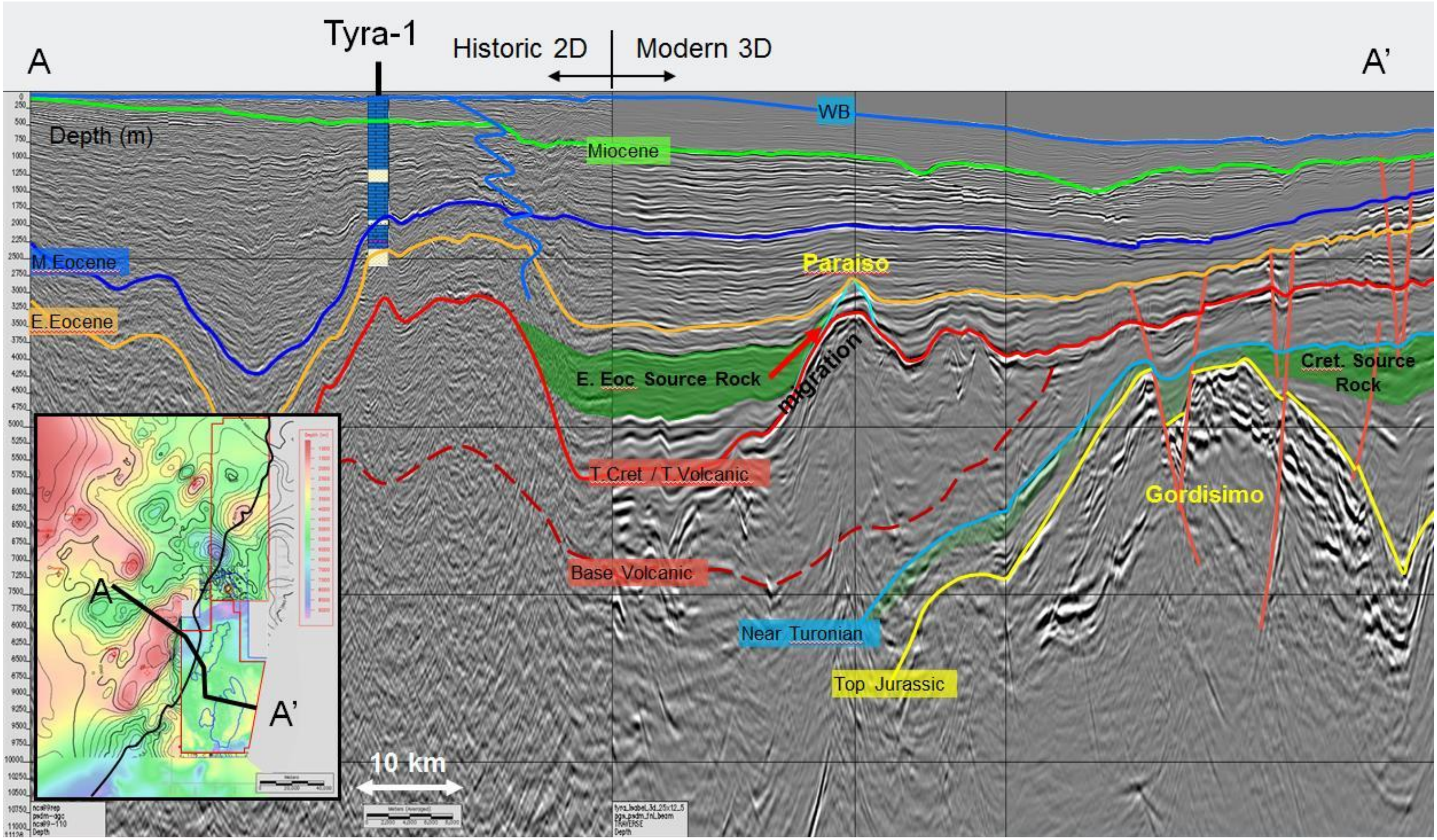


Figure 3. Seismic section illustrating the relationship between the predicted Paleocene to lower Eocene Paraiso reservoir, lower Eocene source rock, lower to middle Eocene seal and migration pathway. Gordisimo is a large untested anticline lead. The Paraiso feature began as a paleo-high consisting of eroded Cretaceous volcanics. Stage 1 Paleocene carbonates were deposited directly over the volcanics, followed by a potential unconformity and deposition of Stage 2 lower Eocene carbonates. The top of Stage 2 appears to be the end of the Paraiso carbonate buildup, and it may have been exposed and eroded based on observed karst features and gullies. The Paraiso buildup was then buried by carbonate marls and possibly shale, as the surrounding basin fill onlaps the Paraiso structure, forming the seal.

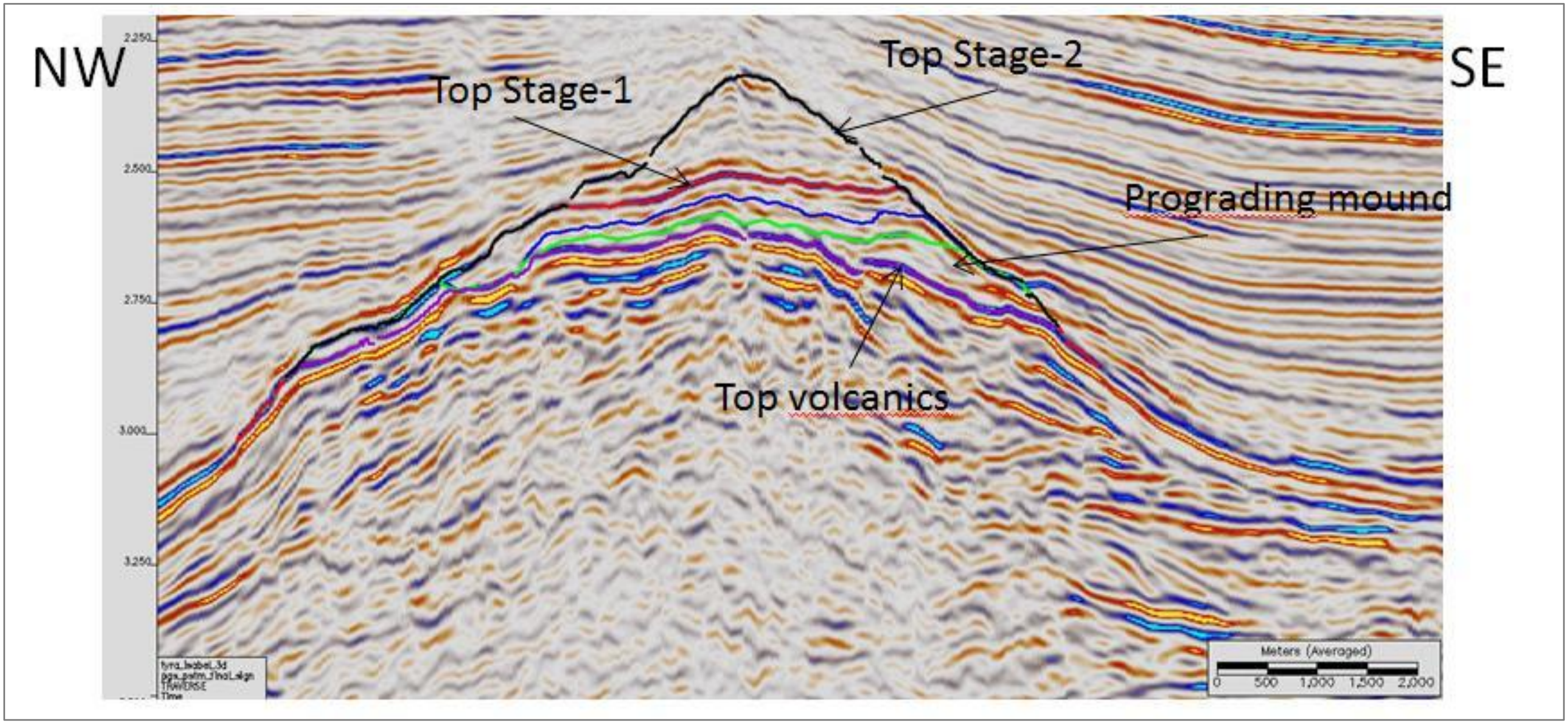


Figure 4. Prograding mound and erosion at Paraiso.

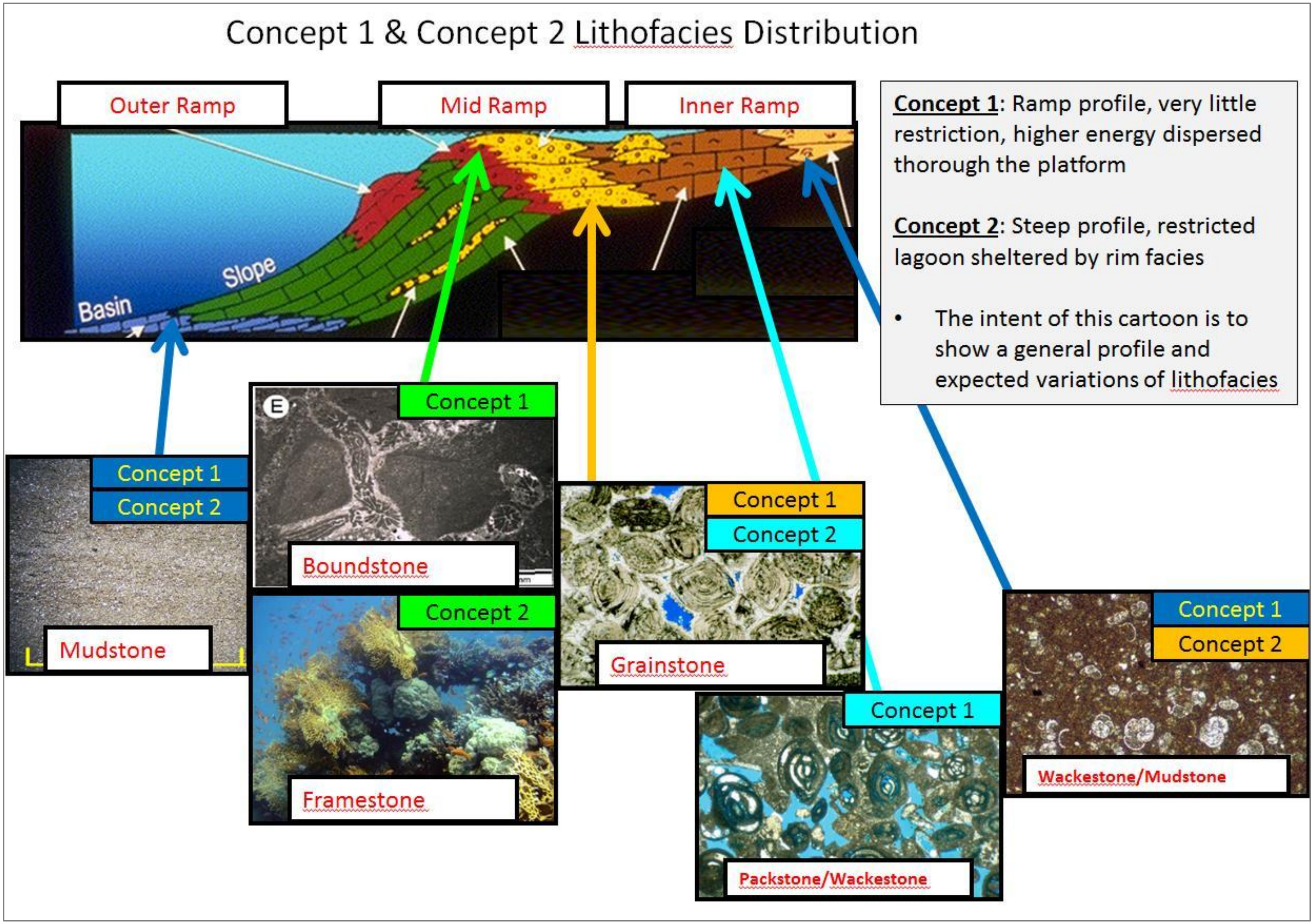


Figure 5. Depositional concepts and expected lithofacies for the Paraiso carbonate buildup.

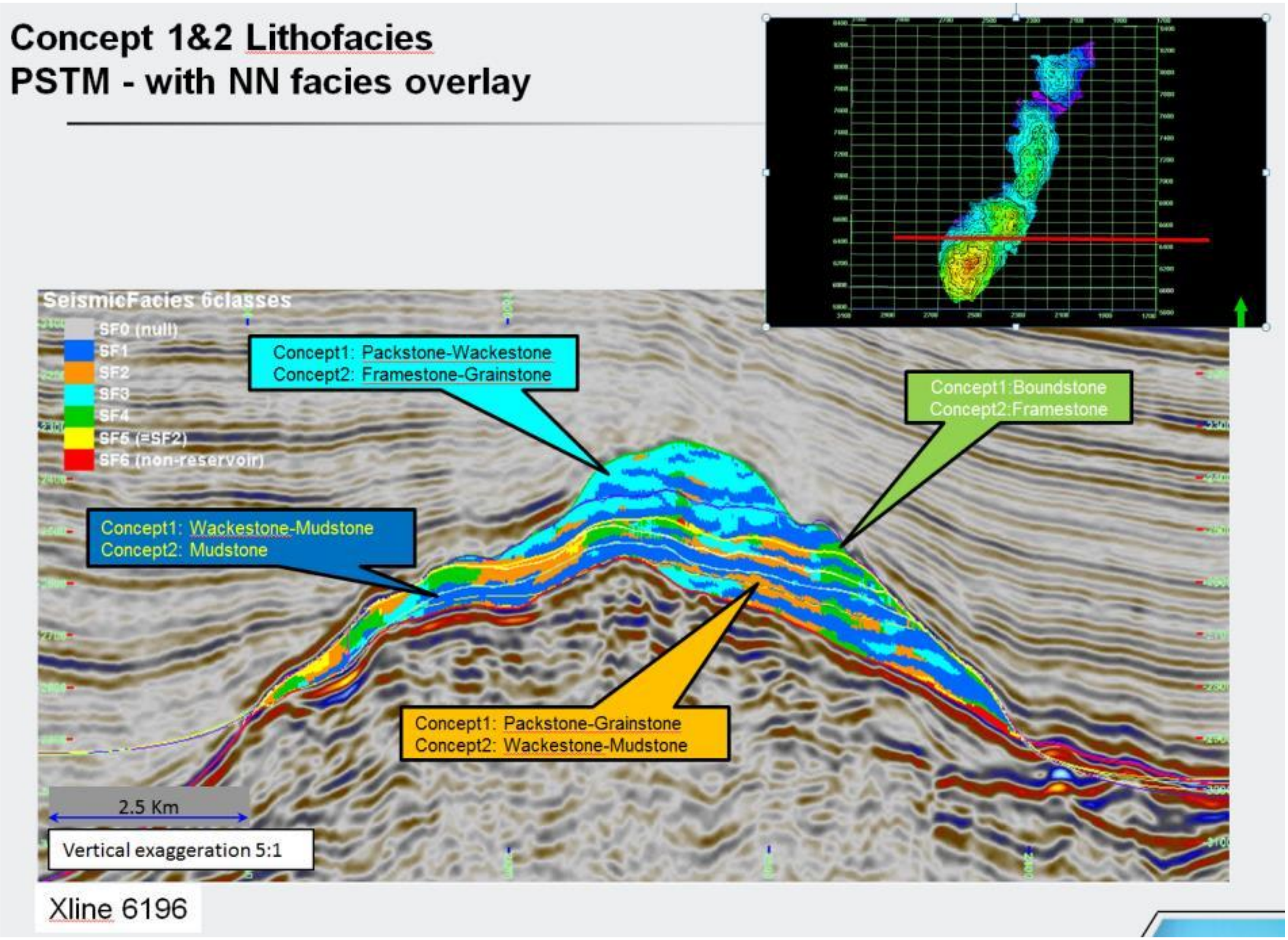


Figure 6. Cross section of seismic facies within the Petrel geologic model for Paraiso. Interpreted coarser grained facies stack on the inferred windward side.

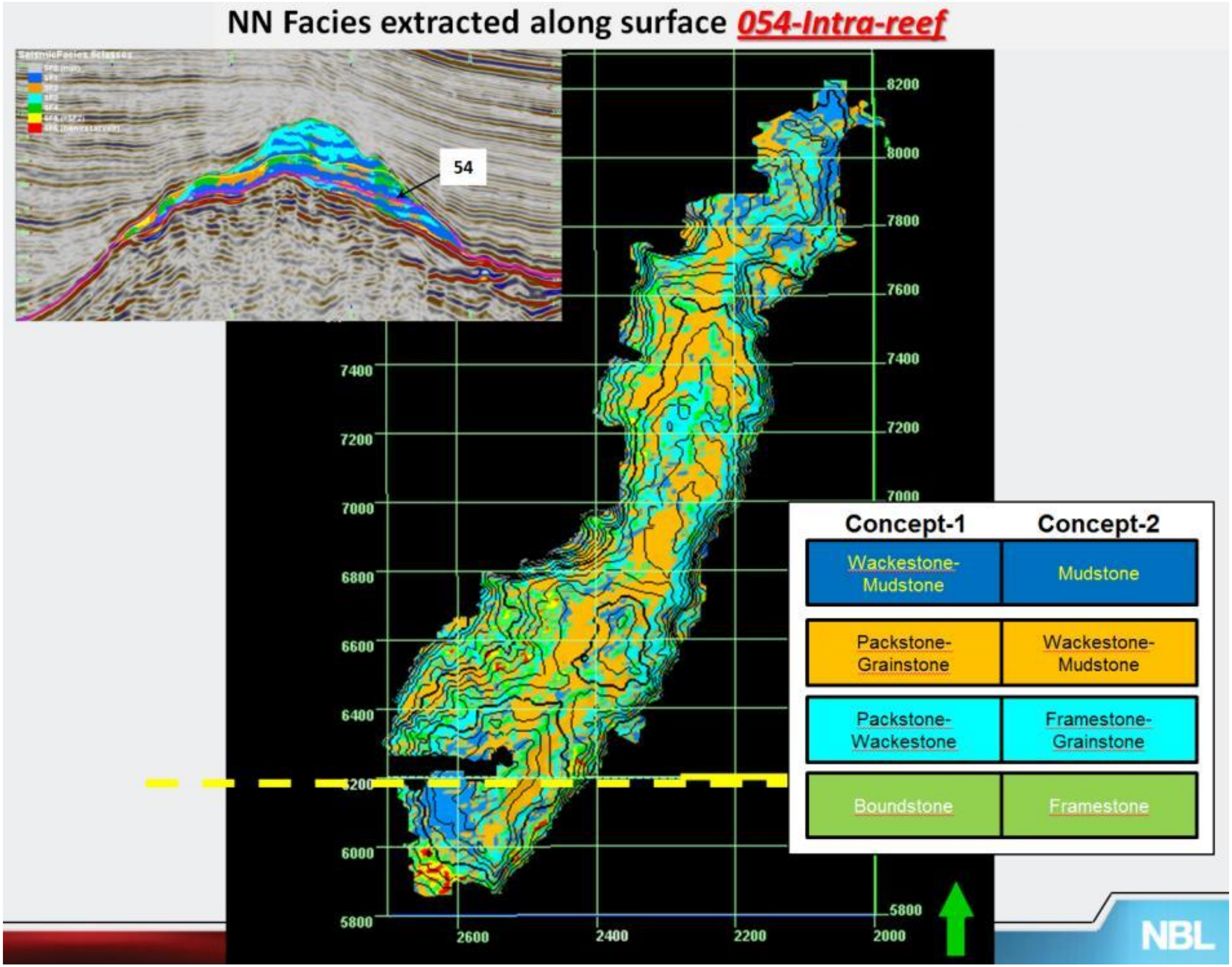


Figure 7. Plan view of seismic facies within the Petrel geologic model for Paraiso.

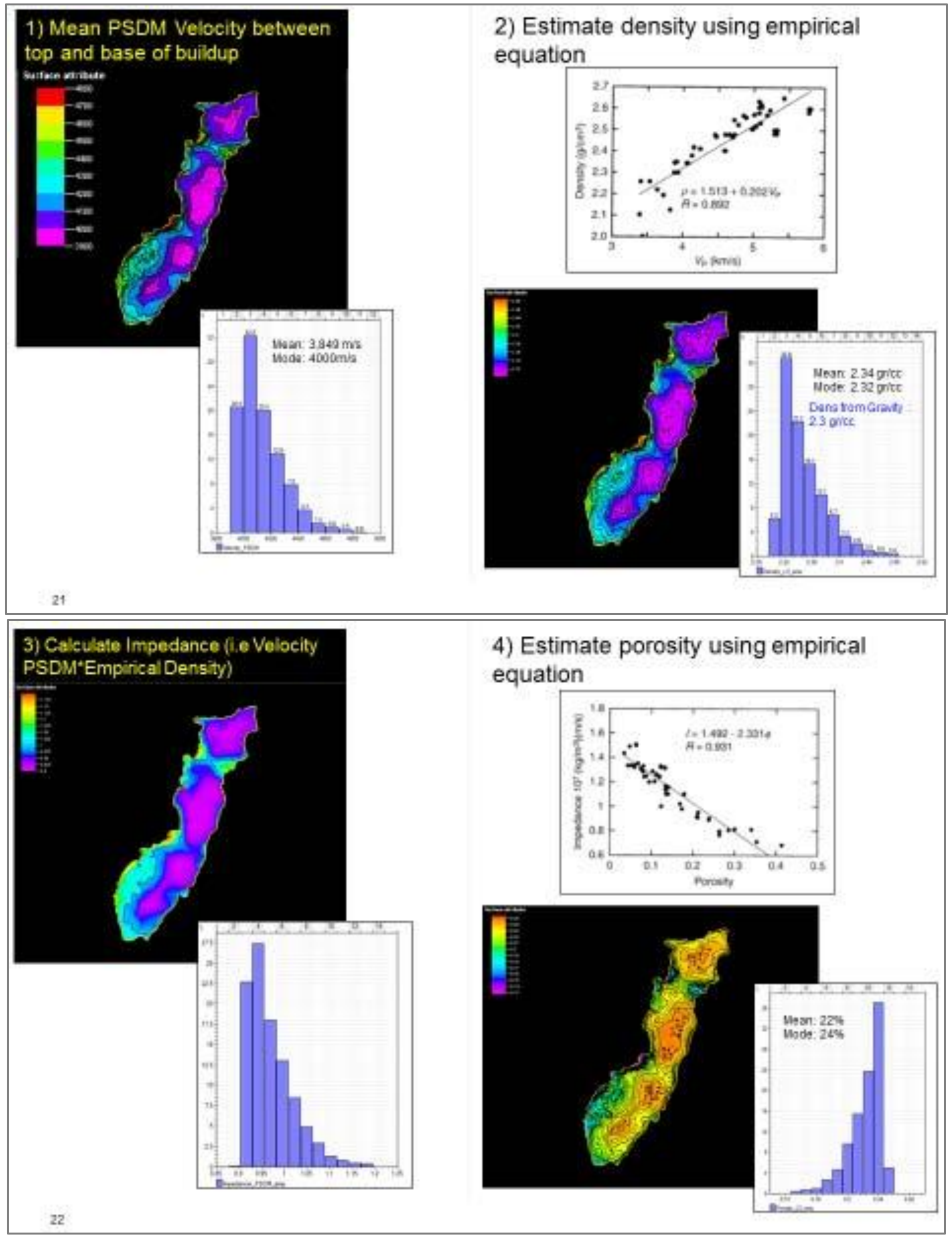


Figure 8. Seismic velocities to predict porosity using Mavko et al. (2009).

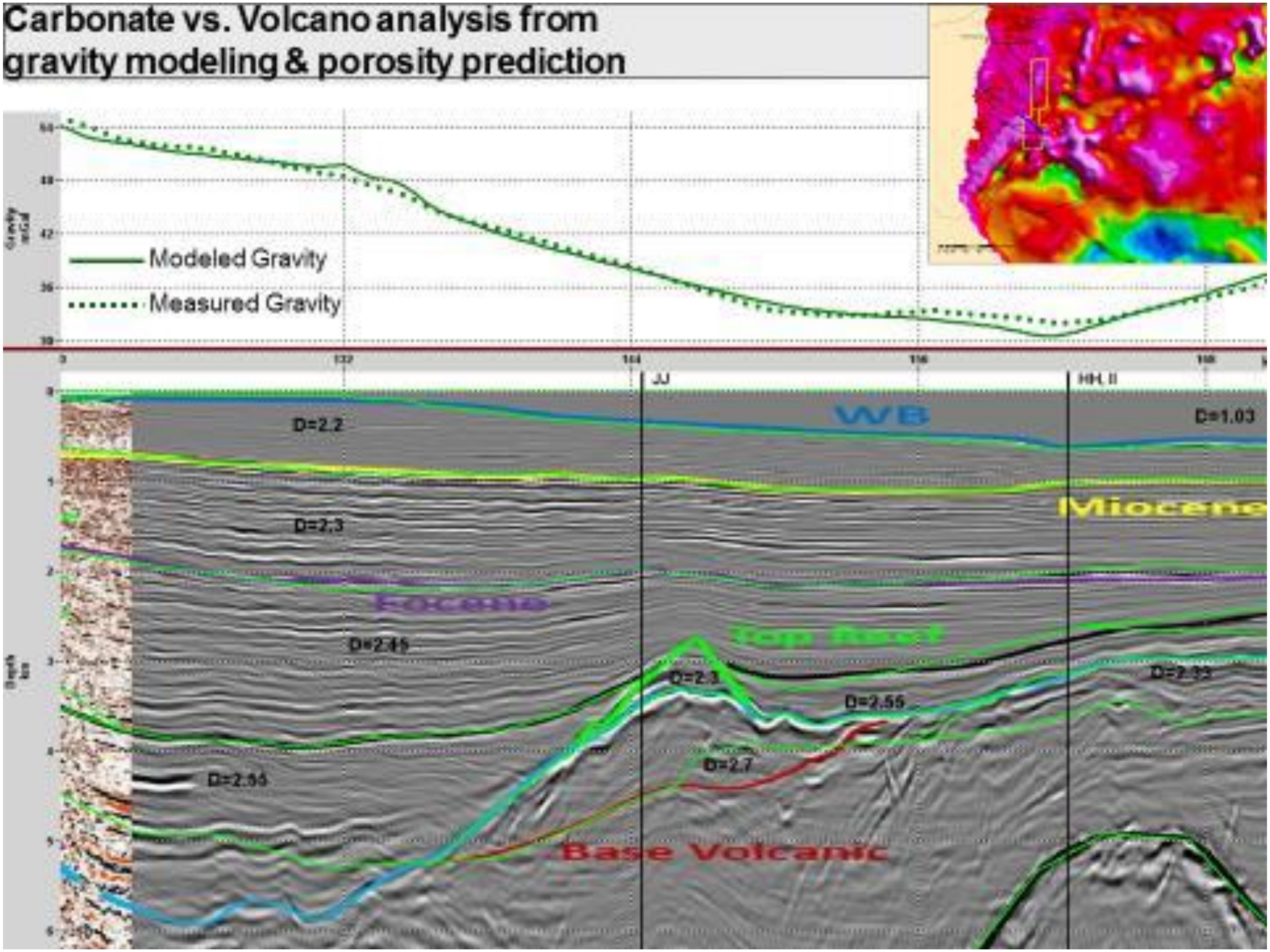


Figure 9. Gravity modeling based on the seismic data supported a density of 2.3 g/cc, lower than the surrounding interpreted marls and lower interpreted volcanics.

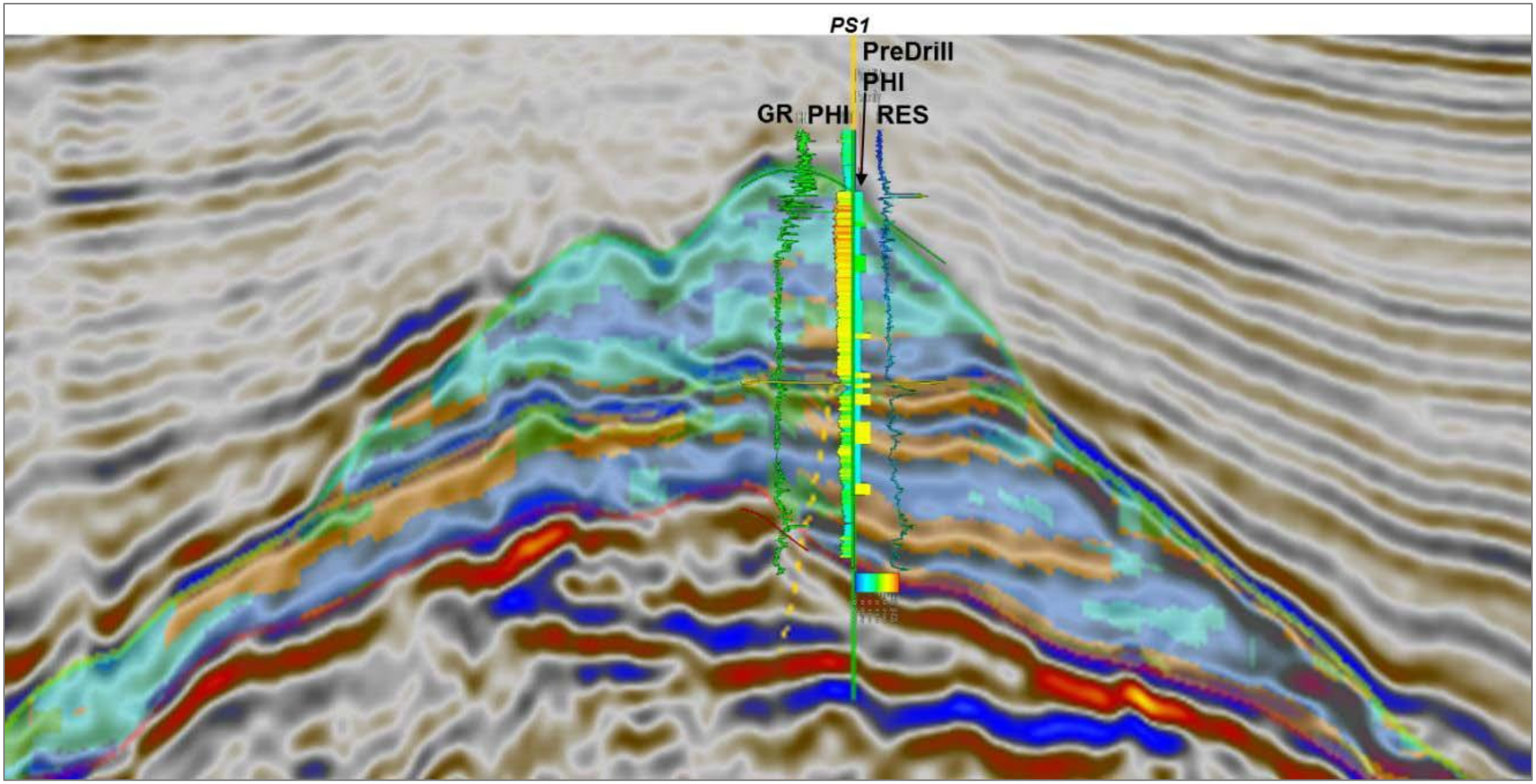


Figure 10. Paraiso Sur-1 well results: Gamma Ray (GR), Porosity (Phi) and Resistivity (RES) overlain on seismic facies. PreDrill Phi prediction from seismic facies also displayed; 553m of carbonate buildup was encountered with a net to gross reservoir of greater than 90%.

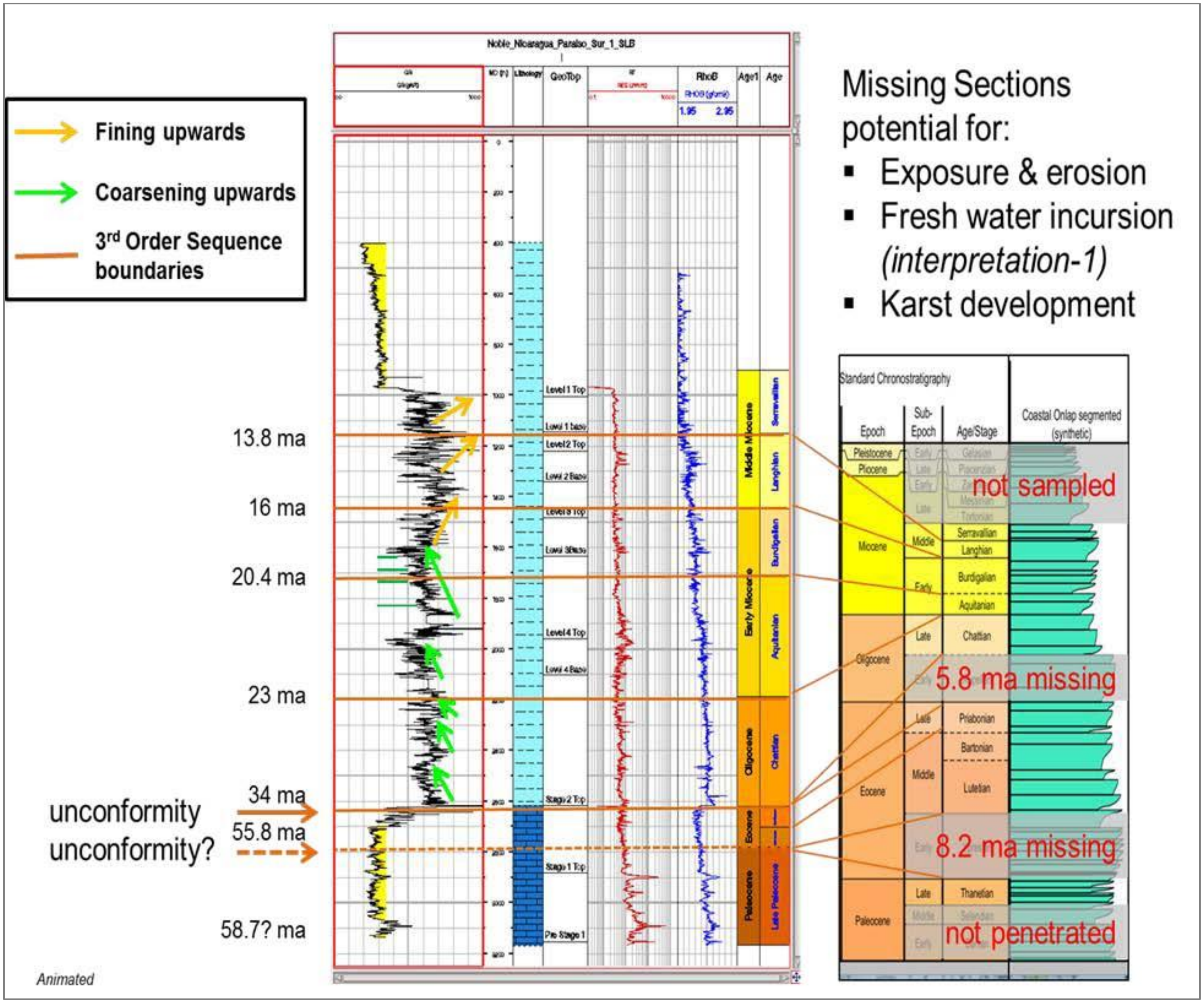


Figure 11. Chronostratigraphic chart using biostratigraphic results for PS1.

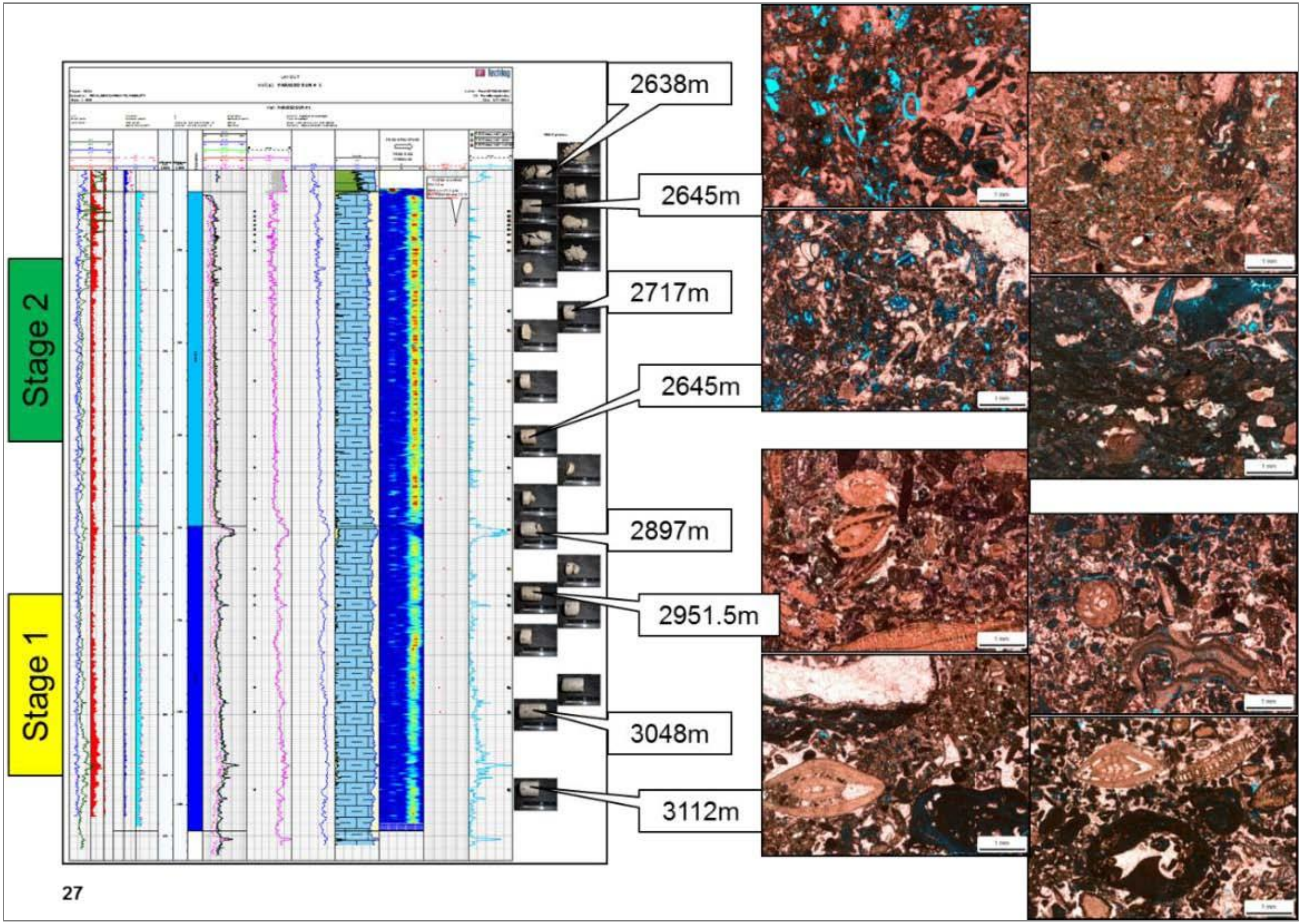


Figure 12. A sample of photomicrographs of thin sections from rotary sidewall cores.