# INTEGRATION OF 3D SEISMIC, HIGH-RESOLUTION WELL-LOG SEQUENCE STRATIGRAPHY AND GEOSTEERING FOR IMPROVED LANDING ZONE PREDICTION IN VACA MUERTA, LOMA CAMPANA BLOCK

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## RESUMEN

Loma Campana es uno de los principales yacimientos no convencionales de la Argentina, cuya producción proviene del sistema depositacional Vaca Muerta-Quintuco que está compuesto por clinoformas progradantes. El campo se desarrolla actualmente mediante pozos horizontales que navegan los bottomsets de las clinoformas, aunque también se han perforado pozos exploratorios en áreas prospectivas de los foresets (o progradaciones). Mientras que los bottomsets reflejan poca variabilidad en cuanto a espesor y propiedades de reservorio, los foresets por lo contrario muestran cambios de espesor y propiedades estáticas ligadas a un fuerte control estratigráfico. Para la zona de estudio, las facies de foreset son altamente continuas a lo largo del rumbo deposicional N42E, mientras que las propiedades y espesores cambian drásticamente a 90 grados, en el sentido de avance de la depositación.
El objetivo del presente trabajo fue integrar el dato sísmico con datos de pozos verticales y horizontales del bloque para así crear un esqueleto estratigráfico robusto por debajo de la resolución sísmica y a escala de nivel de geonavegación (5-30m), apuntado a mejorar la predicción espacial de propiedades estáticas, para optimizar el planeamiento y prognosis de propuestas de pozos horizontales, los cuales navegan intervalos estratigráficos muy acotados (6-10 m). Para ello, desarrollamos un esquema estratigráfico secuencial basado en: 1) análisis sísmico utilizando la trayectoria de la línea de costa / quiebre de plataforma, 2) horizontes sísmicos interpretados en cubos migrados en profundidad (PSDM), 3) una rigurosa correlación de patrones de apilamiento de registros de pozos en ~450 pozos verticales (43 topes por pozo), y 4) los puntos en profundidad generados en base a modelos de geonavegación en ~235 pozos horizontales ejecutados. Para construir la grilla del modelo estático, utilizamos una técnica híbrida entre Volume-Based Modeling (VBM) y Pillar gridding que combina horizontes sísmicos y topes de pozos.
En base a correlaciones en detalle de patrones de apilamiento de registros de pozos que se adelgazan por debajo de la resolución sísmica, hemos demostrado que las terminaciones de reflectores sísmicos, no se traducen necesariamente en terminaciones estratales. El marco

estratigráfico resultante, a escala de landing zone (capas de 5 a 30 m de espesor / secuencias de quinto orden) es único en la cuenca debido a su alta resolución vertical y espacial (680+ pozos, 40+ capas, 18000+ topes de pozos). Como control de calidad, las trayectorias de pozos horizontales ejecutadas posteriormente se compararon con el esqueleto del modelo, mostrando una consistencia notable con errores por debajo de 2 m.

## INTRODUCTION

Vaca Muerta is a world-class self-sourced unconventional Play and Loma Campana was the first block in Argentina to move to unconventional-shale development drilling in 2012. The project began with vertical-well development drilling, followed by horizontal-well drilling in 2015. Licitra *et al.* (2015, 2016), Vittore *et al.* (2014, 2016, 2017); Marlats *et al.* (2016); Crousse *et al.* (2018); Cuervo *et al.* (2016); Reijenstein *et al.* (2017, 2018); Rimedio *et al.* (2015), Anis *et al.* (2022, this congress), helped progress our current understanding of the block, with a special focus on stratigraphic, structural, sedimentological, petrophysical, and well production performance analyses.

The Vaca Muerta-Quintuco depositional system consists of a set of prograding clinoforms (shelf-attached), with well-developed bottomsets, foresets and topsets (Fig. 1A). Bottomsets constitute the organic-rich mudstones currently being developed with horizontal wells, whereas the overlying undeveloped prospective clinoform forests contain interfingered organic-rich mudstones and organic-lean limestones, which are currently under appraisal/exploration in some areas of the basin. While bottomsets are highly continuous spatially and lack drastic changes in reservoir properties and thickness, the foresets in contrast, display a clear stratigraphic control on their spatial distribution. Traditional seismic stratigraphy (Vail *et al.*, 1977, Mitchum *et al.* 1977) and seismic geomorphology analyses (Posamentier, 2000, 2001, Posamentier and Kolla, 2003, Posamentier *et al*, 2007; Miall, 2002; Pangaro *et al.*, 2002; Reijenstein *et al.*, 2011) allowed defining key regional markers and facies trends for the Vaca Muerta (Mitchum and Uliana, 1985; Pose *et al.*, 2014; Dominguez *et al.*, 2017, 2020; Reijenstein *et al.*, 2014, 2020). Striking N42E, foreset facies are highly continuous along this direction (Fig. 1B) in the study area, but drastically change along depositional dip, both in terms of reservoir properties and thickness.

## OBJECTIVES / WORKFLOW

The main objective of this study was to build a high-resolution static model capable of capturing stratigraphic heterogeneity at the landing-zone scale, focused on 3 concrete goals:

1) reduce depth uncertainty in horizontal-well trajectory planning & execution,

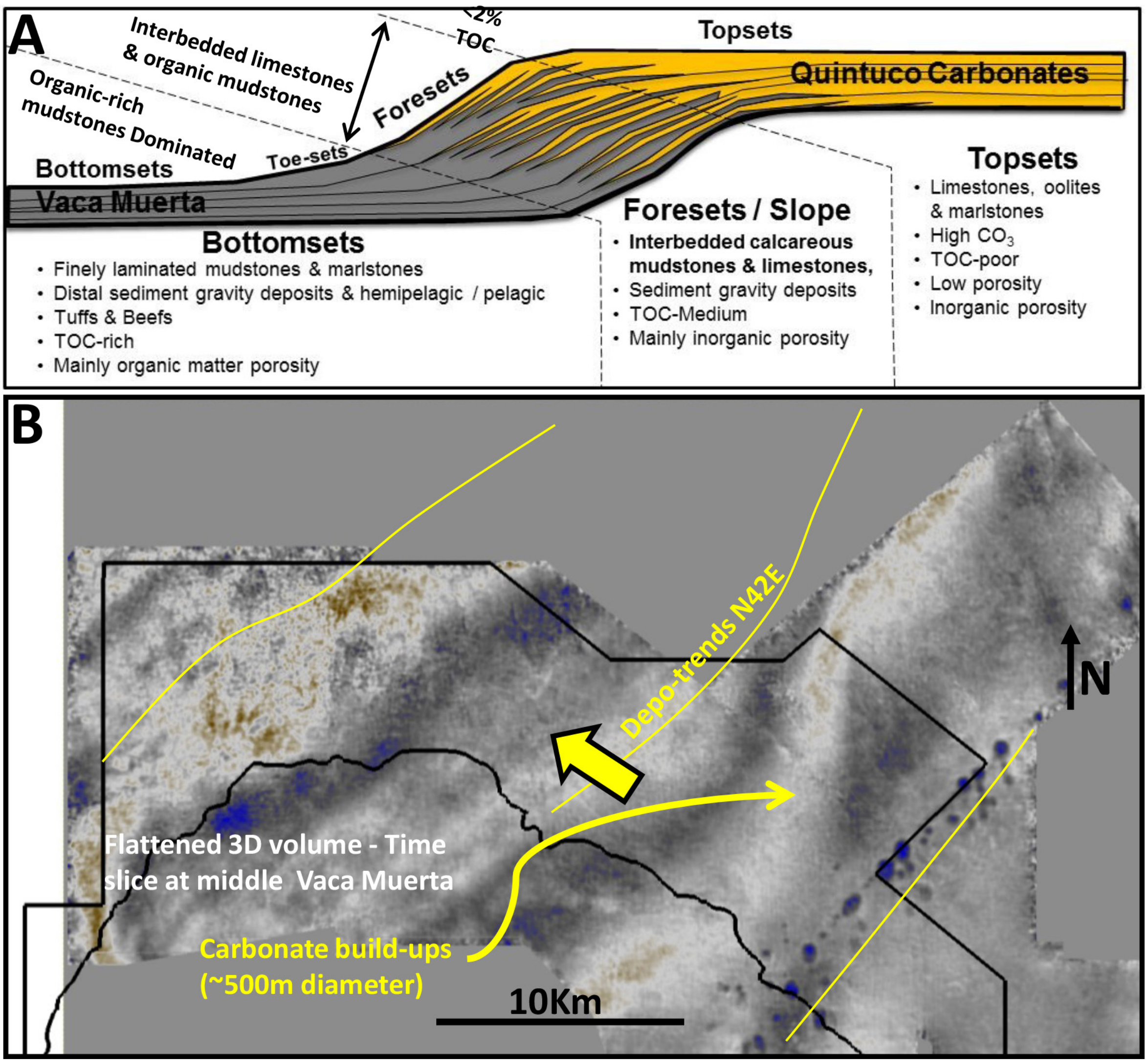


**Figure 1.** A) Schematic diagram showing the architecture of the Vaca Muerta-Quintuco prograding clinoforms. Orange color represents carbonate facies of the Quintuco Formation whereas grey color represents organic-rich facies of the Vaca Muerta Formation. Topsets are dominated by limestones and calcareous muds, bottomsets are dominated by organic-rich silicious and calcareous mudstones, and foresets contain interbedded calcareous mudstones, organic-rich mudstones, and organic-lean limestones (taken from Reijenstein *et al*, 2017). B) Horizon slice over a flattened 3D seismic volume showing distinctive geobodies interpreted to be carbonate buildups (modified from Reijenstein *et al*, 2017). These geobodies, which are excellent paleoenvironmental indicators, allowed us to define depositional / facies trends with an approximate N42E strike direction.

2) better constrain reservoir properties during static model population, and

3) better predict reservoir presence, quality, and spatial distribution away from well control.

For that, we developed a sequence stratigraphic scheme based on 3D seismic interpretation, and rigorous well-log stacking patterns correlation across ~450 vertical wells. Additionally, we included geosteering depth-control pointsets from ~235 horizontal wells, which were key to build consistent surfaces and improve spatial distribution of bottomset landing zones (Fig. 2).

Dataset wise, we utilized a 3D PSDM seismic volume where we interpreted regional markers and performed a shoreline trajectory interpretation approach to define seismic stacking patterns and identify seismic lapouts. Additionally, we used more than 450 vertical wells to define a high-resolution well-log stacking pattern correlation framework with nearly 40 well tops per well, which translates to over 18000 well tops in total. Correlation of Resistivity-log stacking patterns was the key tool to deliver a reliable framework when correlating in the foreset sections, not GR log which is highly discouraged. Geosteering pointsets (x, y, z) along drilled horizontal wells, and interpreted based on offset vertical wells were also integrated to build the final frame. To construct the model grid itself, we utilized a hybrid VBM (Vargas *et al.* 2017) - Pillar gridding technique combining seismic horizons, well tops and geosteering pointsets.

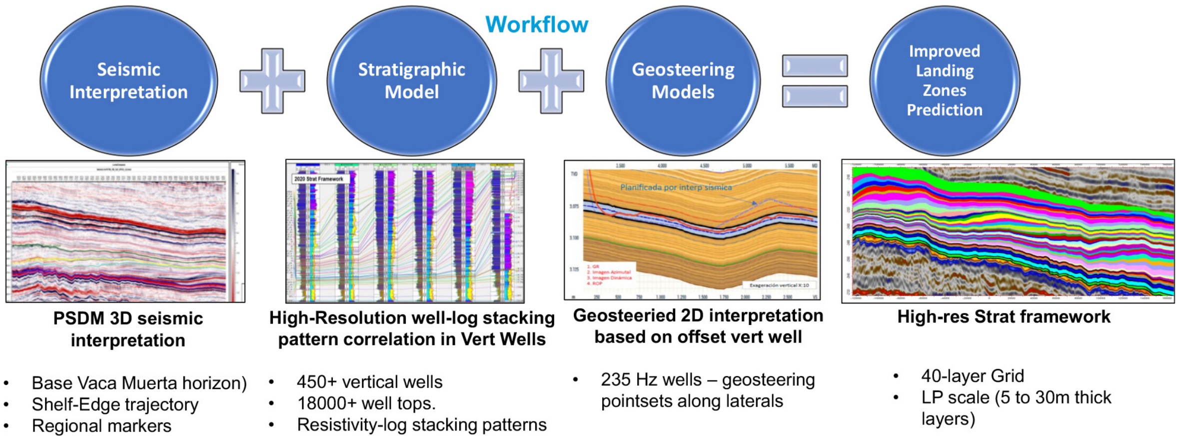


Figure 2. Visual workflow and data utilized to build the high-resolution stratigraphic frame of Loma Campana.

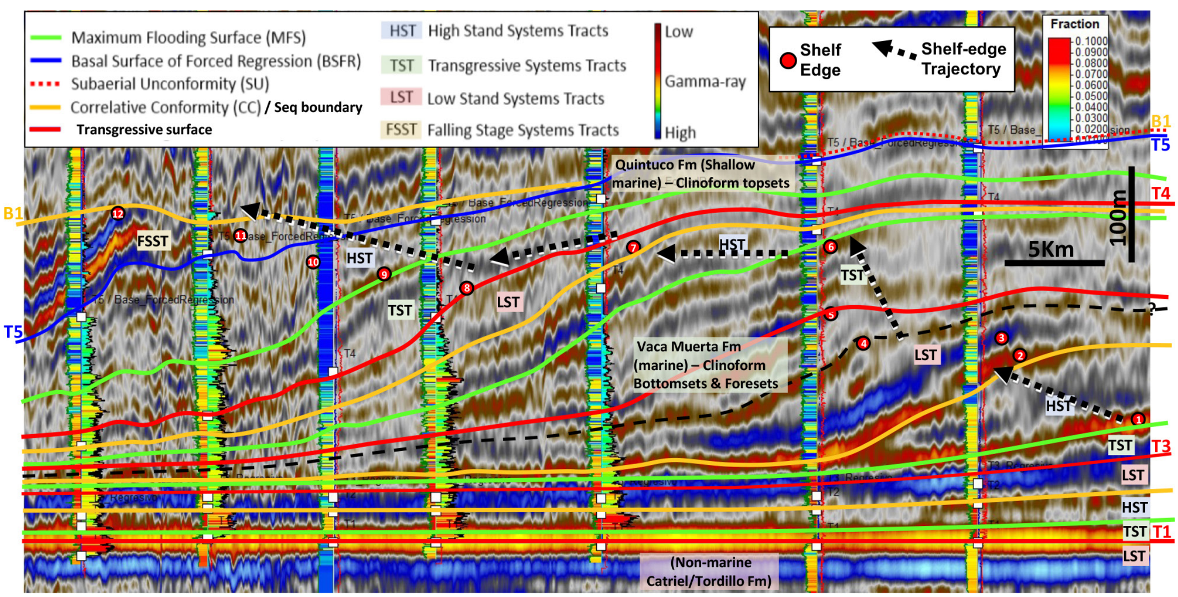


Figure 3. SE-NW seismic cross section across Loma Campana Block (depth migrated volume), flattened @ base of Vaca Muerta & vertically exaggerated. Interpreted surfaces T1, T3, T4, T5 and B1 correlated with regional nomenclature proposed by Desjardins *et al.* (2018). Stacking patterns show an initial progradation to aggradation architecture (normal regression) between surfaces T1 and the MFS below T4, followed by less aggradation and a higher progradational component that includes a subtle down-stepping forced-regressive stacking pattern between surfaces T5 and B1 (FSST), as evidenced by the shoreline / shelf-edge trajectory.

## BUILDING A STRATIGRAPHIC FRAMEWORK

### Seismic stratigraphy

In addition to defining lapout seismic terminations (Vail *et al.*, 1977; Mitchum *et al.*, 1977) as a first exercise, we primarily focused our interpretation on a shoreline / shelf-edge trajectory approach (Helland-Hansen, and Gjelberg, 1994; Helland-Hansen and Martinsen, 1996), to define stacking patterns, predict thickness changes between wells, and identify key bounding surfaces. Figure 3 summarizes our interpretation of how the position of the shelf edge migrated spatially from the oldest Tithonian sequences in the Southeast, to the younger Berriasian units in the Northwest. Bounding surfaces define Highstand, Lowstand, Transgressive, and Falling-stage Systems Tracts (HST, LST, TST, FSST). Wells on x-section show GR log (left track) and calculated TOC from Cuervo *et al.* (2016), on the right track.

Challenges

While tying seismic to wells, we Identified inconsistencies with the 3D PSDM seismic velocity model which resulted in mismatches between the seismic horizons (legacy depth-migrated volume), and well tops defined based of well-log stacking patterns. While these mismatches (up to 40-45m) can be acceptable in exploration, depth accuracy at development scale is critical given that we are landing horizontal wells in 6 to 10 m target windows. As a result, we decided to put a strong emphasis on the well-based stratigraphic interpretation.

### Well-based high-frequency sequence stratigraphy

Van Wagoner *et al.* (1990) took many of the original seismic stratigraphy models (Vail *et al.*, 1977; Mitchum *et al.*, 1977) and defined a sequence stratigraphic approach and key concepts for working at a higher resolution by utilizing well logs, cores, and outcrops in siliciclastic systems. The following 2 statements from Van Wagoner *et al.* (1990) show that having resistivity logs when correlating in marine successions is critical: “Correlation of similar resistivity-curve patterns from well to well in the marine mudstones… provides an accurate and detailed chronostratigraphic framework, derived independently from biostratigraphic or radiometric control, for recognition of stratal terminations” and “This boundary can be traced basinward into a diagnostic resistivity marker bed in the shale”.

Stacking patterns correlation criteria in Vaca Muerta

When applied to Vaca Muerta, correlation of resistivity-log stacking patterns proved to be a key tool to deliver a reliable framework when correlating in the foreset sections, even when thickness and facies change drastically in short distances. Correlation of GR log alone is highly discouraged when correlating in prograding sections due to: 1) rapidly changing U-Th concentrations that result in drastic changes in GR readings and make chronostratigraphic correlations difficult, and 2) it is common to have GR logs from multiple vendors, with non-normalized logs, which also makes it very difficult for stacking patterns recognition and correlation. However, from the ~450 vertical wells in Loma Campana only ~150 have resistivity log, therefore our approach was first to generate a reliable stratigraphic framework with those ~150 wells with good special coverage and later extrapolate to all the remaining wells with GR only.

In prograding intervals of Vaca Muerta, individual stratigraphic packages show well-defined updip thinning into the topsets (partial bypass), thickening along the foreset (depocenter), and downdip thinning towards the bottomsets (condensed section), as highlighted with black arrows in the cross section on Fig. 4A and the associated map on Fig. 4B. Map shows a clear thicker N42E foreset facies trend with cool colors (up to 70 m thick) and thinner topset and bottomset

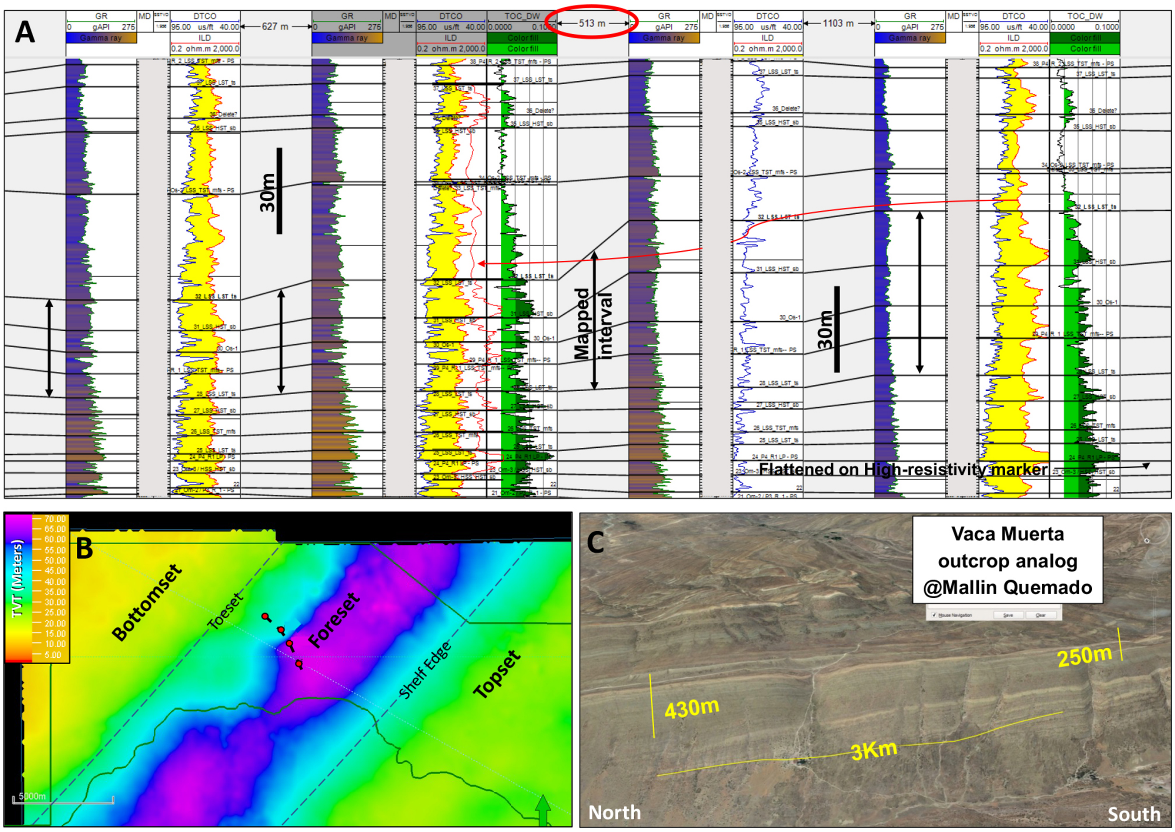


Figure 4. A) Southeast to Northwest (right to left) cross section displaying 4 wells with GR on the left track, Passey crossover with sonic (DTCO) and Resistivity (ILD) logs on the right track, and calculated TOC from deterministic petrophysical model (Cuervo *et al*., 2016) on the far-right track if available. Resistivity log from well on the far right was stretched, squeezed, and ghosted over the 3rd well from the right to visualize high correlation of individual bedsets (2nd well from right does not have resistivity log). B) Well-based Tre Stratigraphic Thickness (TVT) map of the interval marked with black arrows in Fig. 4A and location of the 4-well cross section within the NE-SW foreset trend. C) Google Earth satellite image of the Mallin Quemado outcrop where drastic thickness changes can be observed, like those identified in subsurface. Note there is a change of ~45º in the direction of progradation from subsurface to the outcrops, being Southeast to Northwest in the study area, and South to North in the Andean outcrops.

facies trends than thin down to 10 meters, highlighting the drastic thickness variations that exists in these sigmoidal units. Thickness can increase twice or decrease by half in just 0.5 km as shown in Fig. 4A. Outcrops show similar order-of-magnitude thickness variations that range from 250 m-thick to 430 m-thick in just 3 km (Fig. 4C). These changes were appropriately identified and modeled to plan for horizontal wells trajectories in Loma Campana, which currently average lateral lengths of 3 km, and has 4 wells longer than 4 km (includes a recent 4476 m-long basin-record well).

## Geosteering models from Horizontal wells

Once each horizontal well is executed, the geosteering team delivers to the asset development team, a set of files with x, y, z pointsets for different stratigraphic layers along the lateral well (Fig. 5). This interpretation is based on the correlation of the LWD GR log from the horizontal well to the GR log of a nearby vertical well (informally called type well). By doing so, we are intrinsically extrapolating the 1D GR log from the vertical well and generating a 2D GR model. A key assumption of performing this correlation is that it assumes layer-cake stratigraphy (constant thickness based on the well tops defined on type well). Therefore, utilizing geosteering pointsets is not recommended for prograding layers with variable thickness, but it provides extremely useful information for bottomset facies trends where thickness has minimal to no variation at a block scale.

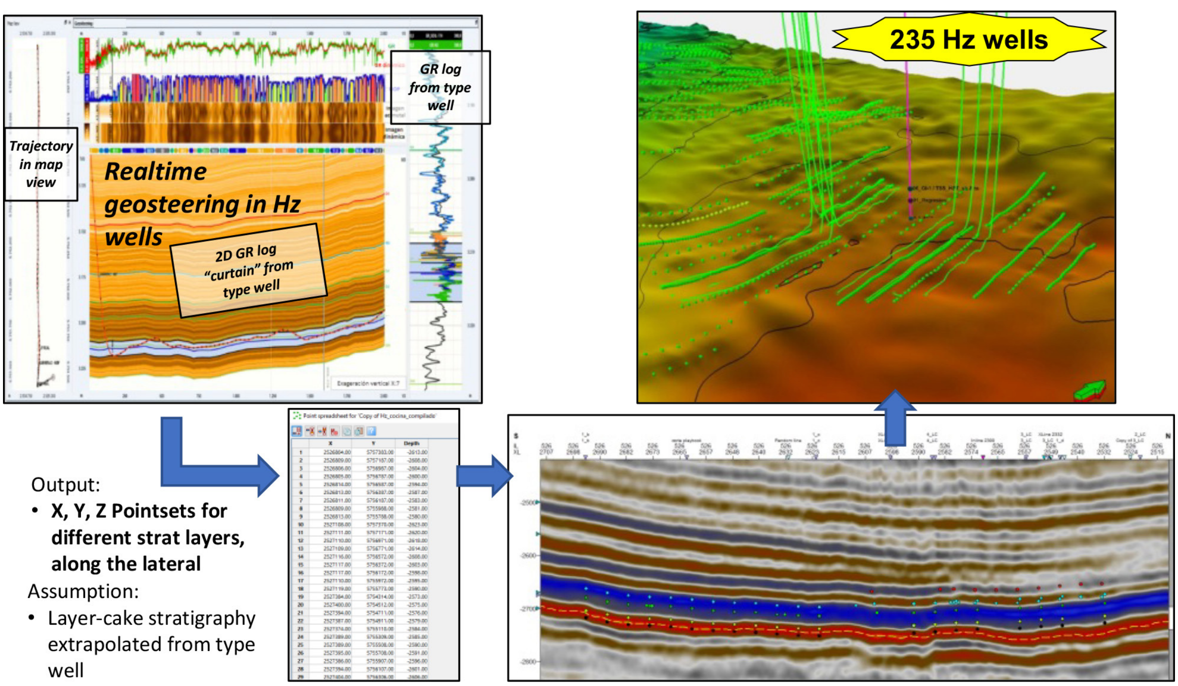


Figure 5. Workflow showing how the geosteering pointsets from 235 horizontal wells were used as input data to build the lower-most 5 surfaces of the static model.

This is why having a clear understanding of the depositional system, stratigraphy and paleo-geomorphology directly defines the criteria used to model surfaces in a static model. In this case, we decided to use geosteering pointsets from 235 horizontal wells only on the 5 lowermost surfaces from T1 to just above T3, where thickness variation is minimal. Surfaces sere "globally adjusted" to well tops and geosteering pointsets, and the base of Vaca Muerta seismic horizon was used as a "trend" surface to favor thickness consistency between layers.

## FRAMEWORK MODELING & INTEGRATION

Once all the interpretation products were concluded and quality controlled, we moved on to the integration phase in the modeling realm. In order to do so, we used a hybrid approach combining Volume-Based Modeling (VBM) and Pillar gridding technique while integrating seismic horizon interpretations, well tops and geosteering pointsets (Figs. 6, 7, 8). VBM is really good at modeling conformable successions and generating geologically-sound stratigraphic layering by modeling all the layers at the same time while compensating the volume of each layer but takes a lot of computing time to run and fails when working with thin layers. Pillar gridding instead, runs very fast, has better capabilities for handling thin layers (build from base/top horizons, proportional/equal volume correction, build along pillars/vertical thickness/stratigraphic thickness), but models layer by layer and generates more irregular layering models. Therefore, our approach was to use VBM for the thicker stratigraphic packages (3rd-order, seismic resolvable sigmoids, Fig. 7B) to constrain the regional markers and work the internal, thinner, and higher-resolution layering (4th to 5th-order, below seismic resolution units, Fig. 8D), within the pillar gridding space. Figures 6, 7, and 8 illustrate a step-by-step schematic workflow with the full modeling integration cycle that was subdivided into 3 broad steps:

**Step 1: Generating 5 basal bottomset input surfaces (layer-cake) from seismic, vertical, and horizontal well data (Fig. 6):**

- 3D seismic interpretation, base of Vaca Muerta horizon, well-adjusted to well tops from 450+ vertical wells.
- Pointsets (x, y, z) from geosteered wells added as "additional inputs" to adjust surfaces.
- Base of Vaca Muerta surface used as trend on overlaying surfaces to favor thickness consistency.
- Quality control of thickness maps for lowermost 4 layers (5 surface) from T1 to just above T3.

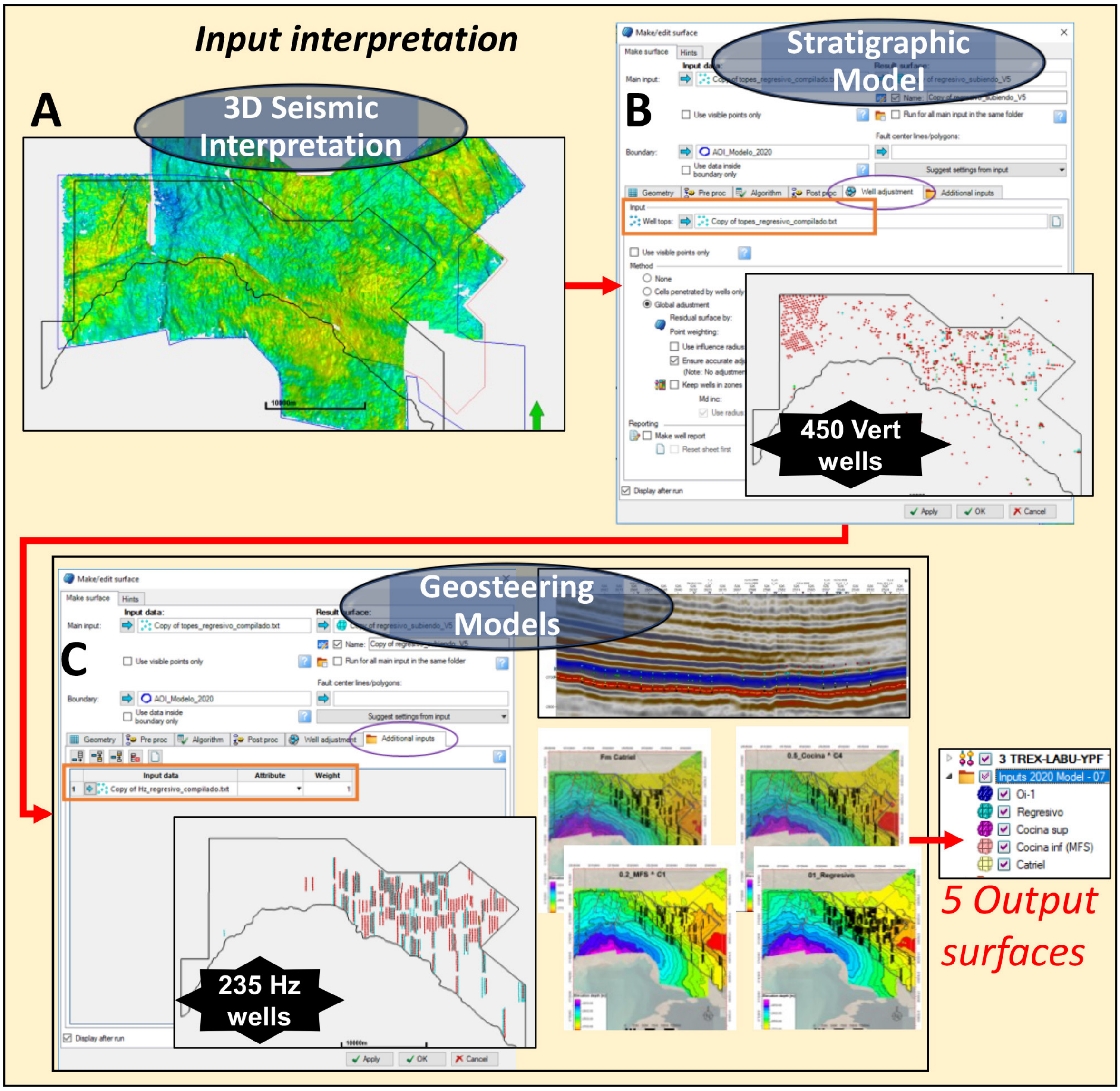


Figure 6. A) 3D seismic interpretation of base of Vaca Muerta, B) well-based stratigraphic model (450+ vertical wells), C) geosteering depth control (235 horizontal wells) and quality-control of 5 basal input surfaces (bottomsets).

**Step 2: Volume Based Modeling (VBM) of foreset 3rd order depositional sequences (Fig. 7):**

- Four validated bottomset layers used as fixed input for VBM modeling workflow.
- 10 additional overlaying conformable surfaces were modeled based solely on the well tops dataset and variable smoothing parameters, and later exported as triangle meshes to be used on pillar gridding.

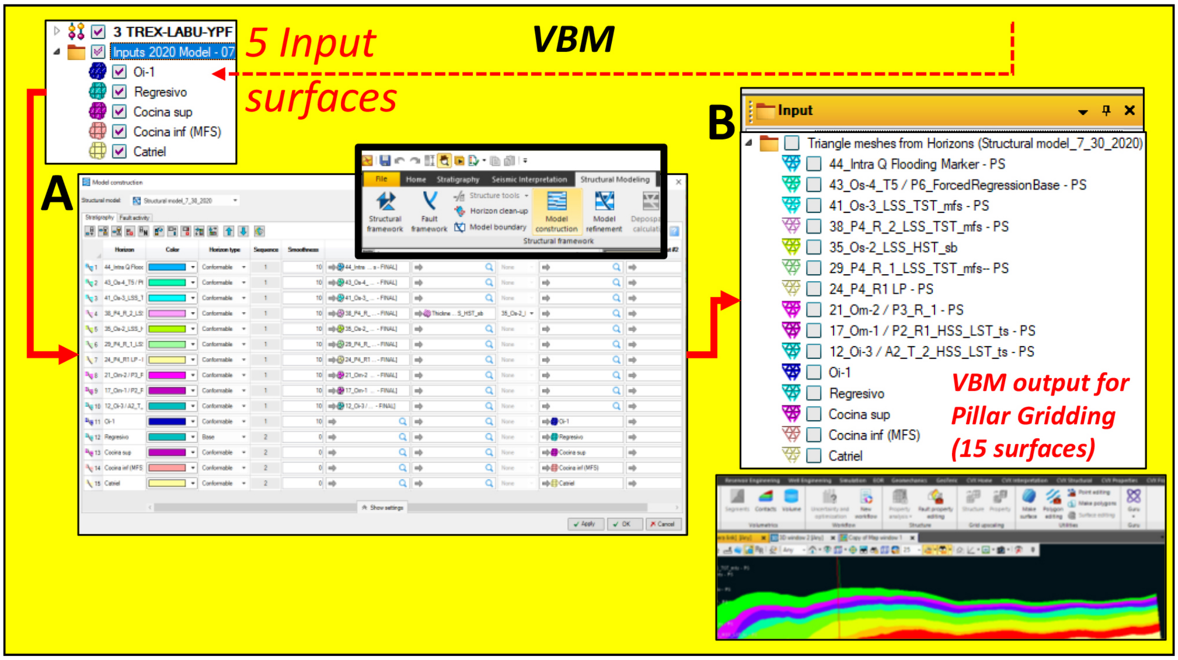


Figure 7. A) VBM modeling of 5 basal (bottomset) input surfaces together with 10 additional overlaying prograding surfaces (foresets) purely based on well tops from vertical wells, B) resultant 15 VBM surfaces were exported as triangle meshes and taken to the pillar gridding modeling domain,

**Step 3: Pillar Gridding modeling of foreset 4th & 5th order depositional sequences (Fig. 8):**

- Defined up to 5 internal layers within each of the course VBM units and modeled layer by layer based on the well-top dataset.
- Performed volume corrections either on the top, base or intermediate horizon to preserve thickness trends.
- Quality control of thickness maps for all 40 resultant layers in the grid.

## RESULTS

Clinoform sigmoidal architectures seen on seismic data were very well captured by the layering framework and modeling workflow presented in this study (Fig. 9). Clinoform bottomsets thin out distally (condensed section) below seismic resolution, but rarely reach zero thickness. Resultant landing-zone scale stratigraphic framework (5-30 m thick layers / 5th-order sequences) shown in figure 9A, is unique in the basin due to its high resolution and spatial control. It has provided tremendous value and application in day-to-day operations, trajectory planning, real-time execution, and identification of prospective benches in the foresets. Horizontal-well trajectories executed after model construction were compared against the model frame as a quality-control blind test, showing remarkable consistency with errors below 2 m (Fig. 9B).

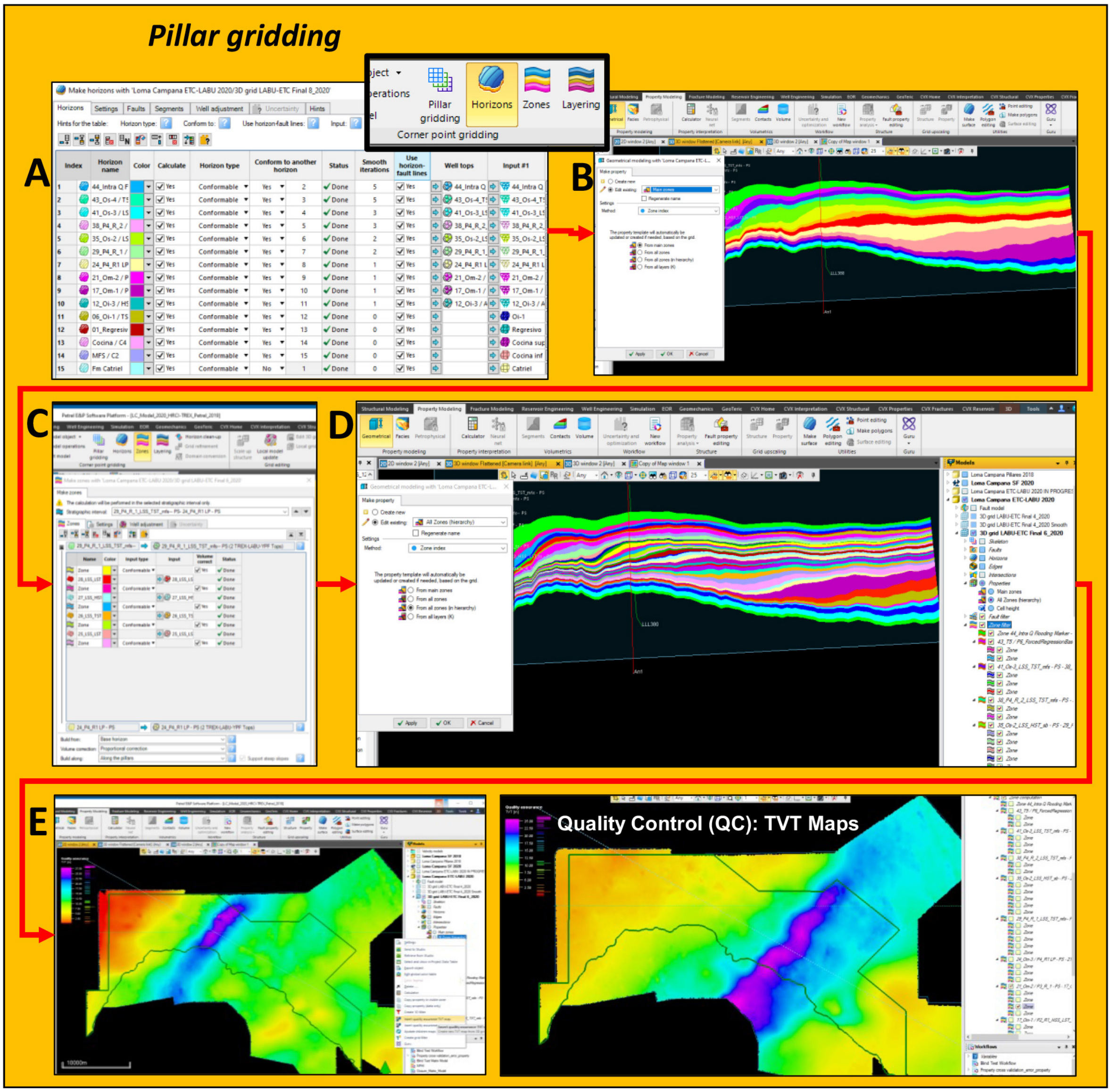


Figure 8. A) & B) regenerated 15 coarse surfaces in pillar gridding utilizing the triangle meshes that were exported from VBM, C) & D) modeled the thinner intervals layer by layer based on well-top dataset, E) Quality-controlled layer consistency utilizing automated TVT maps.

As a summary, we built a high-resolution stratigraphic framework composed of 41 surfaces (40 layers) on a 500 m thick section, which include:

- Integration of 3D seismic, 450+ vert wells (18000+ well tops) & 235 Hz wells.
- 18 key regional sequence stratigraphic markers per well (3rd order cycles).
- 23 additional higher resolution surfaces per well (4th & 5th order cycles).

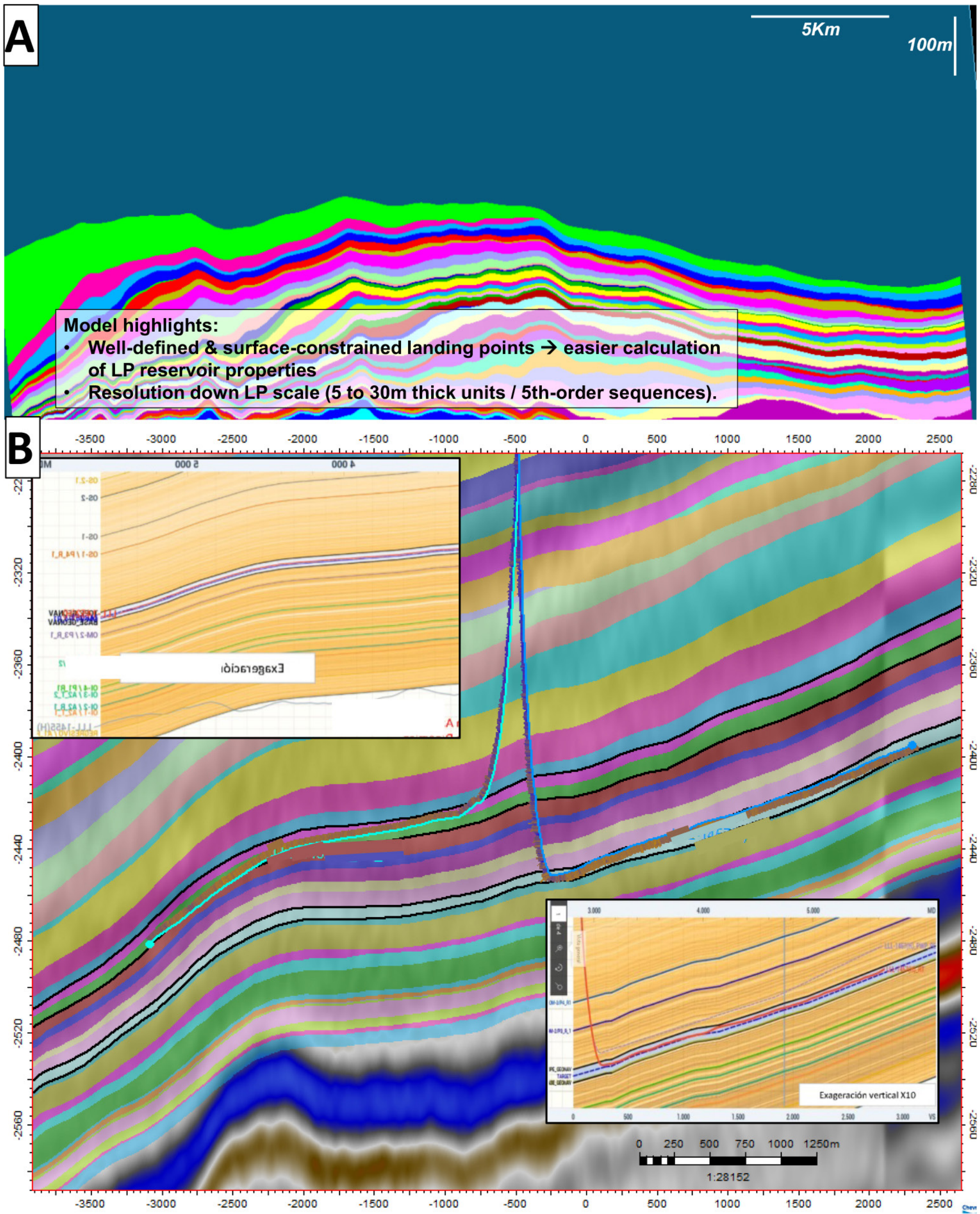


Figure 9. A) SE-NW cross-section through Loma Campana, visualizing the high-resolution stratigraphic framework composed of 41 surfaces (40 layers). B) Zoomed-in, pad-scale N-S view along horizontal well, of the framework and associated geosteering interpretations, showing a quality-control blind test of 2 wells executed in the progrades soon after the model was constructed. The landing and lateral execution of these wells was 100% on target along the 2500m-long laterals. Target windows of the 2 drilled prograde benches (6m to 8m thick) are highlighted with black contours and are within the T3-T4 interval shown in Fig. 3.

## CONCLUSIONS

We have summarized our concluding remarks in terms of 1) impact and applications, 2) lessons learned, 3) best practices utilized, and 4) challenges encountered along the journey to build a static model frame capable of improving our chances of success to better predict shale reservoir presence:

**Impact & Applications:**

- Model's landing-point-scale resolution (5 to 30 m thick units / 5th-order sequences) has Improved landing-point prediction and prognosis.
- Application in day-to-day operations, trajectory planning, real-time execution (~50 hz wells/year), and identification of prospective benches in the foresets.
- Successful execution of horizontal wells in the foresets with 100% landing-point target windows of 6-7 m.
- Proper delineation and depth uncertainty reduction in at least 4 foreset prospective Landing Points / benches.

**Lessons learned:**

- Based on detailed well-log staking pattern correlations that thin out below seismic resolution, we have proven that seismic reflector terminations, i.e., lapouts, do not necessarily translate to stratal terminations, as evidenced by bedsets continuity at well scale, both up and downdip along the clinoforms.
- In prograding intervals (foresets), thickness can increase twice or decrease by half in just 0.5 km. These changes need to be accounted for, especially when planning horizontal-well trajectories as those currently being executed with average lateral lengths of 3 km, reaching in some cases over 4.4 km.
- Rapid changes in thickness occur basin-side of each shelf edge.
- Geosteering pointsets from horizontal wells are critical to improve landing point depth accuracy in bottomsets, but should not be used in foreset sections, since they derive from a layer-cake stratigraphic model.

**Best Practices:**

- Resisitivity-log stacking patterns correlation was the primary input for generating a high-resolution sequence stratigraphic framework (680+ wells, 40+ layers, 18000+ well tops).
- It is highly recommended NOT to use GR logs for correlating in clinoform foreset bedsets. It is OK in bottomsets.
- Hybrid VBM and Pillar gridding workflow is easy to update and manipulate

Challenges & Next steps:

- Identifying mismatches between 3D PSDM seismic horizons (legacy depth-migrated volume), and well tops defined based of well-log stacking patterns, was time consuming. However, 3D PSDM seismic played a key complementary role in understanding stacking patterns, visualizing shelf-edge trajectory trends, and predicting stratal thickness changes between wells being correlated.

- Preliminary ongoing work to update the seismic velocity model based on this robust well-based stratigraphic framework, has shown vast improvement on seismic depth accuracy, correcting those 40-45 m depth mismatches mentioned before. This velocity model update incorporates new prograding seismic horizons (in time) that were not accounted for in legacy velocity models, approximately 32 well ties, and geosteering pointsets from horizontal wells to better constrain calibration of Time/Depth velocity interpolation.

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