SEISMIC EXPRESSIONS OF THE QUINTUCO – VACA MUERTA SYSTEM BASED ON OUTCROP FACIES AND GEOMETRY

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Keywords: **Quintuco, Vaca Muerta, Synthetic seismic modeling, Picún Leufú, Sequence stratigraphy**

RESUMEN

Imágenes sísmicas del sistema Quintuco-Vaca Muerta a partir de facies y geometrías de afloramiento
Se presentan los resultados de una técnica que combina geología de campo con la interpretación de imágenes de satélite. Este enfoque permite la documentación de la arquitectura secuencial de un sistema progradante y además permite la asignación de heterogeneidades en escalas sísmicas dentro del marco de la estratigrafía secuencial. Para poder comparar esta arquitectura con datos de subsuelo, se construyeron modelos sísmicos sintéticos derivados de la distribución de facies observadas. Los modelos sísmicos sintéticos comparados con líneas sismicas adquiridas a través de la zona de estudio proporcionan la conexión necesaria con los estudios de subsuelo y puede ayudar a comprender mejor los elementos arquitectónicos presentes y la esperable composición sedimentaria, que es importante en la evaluación de proyectos no-convencionales.

INTRODUCTION

The Quintuco-Picún Leufú-Vaca Muerta System in the Neuquén Basin recently received much attention due to its potential as a major unconventional play (Spalletti *et al.*, 2000; Howell *et al.*, 2005, Armella *et al.*, 2007; Kietzmann *et al.*, 2008; Kietzmann *et al.*, 2011; Leanza *et al.*, 2011). Sedimentological studies of the Quintuco - Vaca Muerta Formations are generally restricted to 1D reference sections and do not cover the architecture and heterogeneities within the depositional system.

In order to identify best exploration and production techniques, the stratigraphic architecture as well as the bed-scale heterogeneities have to be understood. They are best studied in field-scale outcrop analogs. The Picún Leufú Anticline (PLA) and the Sierra de la Vaca Muerta (SdlVM) represent key study areas with excellent exposures displaying the architecture of this mixed carbonate-siliciclastic system (Figure 1). Using the detailed facies descriptions from the outcrop and a geometrical framework derived from high-resolution satellite imagery, a new large-scale correlation provides insights into the sequence architecture and places the observed small-scale heterogeneities within this framework. This information is most useful if directly linked to the subsurface exploration fields.

Synthetic seismic models of large-scale outcrop analogs are commonly used to bridge the gap between low-resolution seismic architectures and the higher resolution outcrop scale geometries observed in the field (Tomasso *et al.*, 2010). This process is even more crucial in mixed carbonate siliciclastic successions, where the wide variability of petrophysical properties introduces additional uncertainty into seismic interpretations. Field campaigns reveal striking facies similarities between outcrop and subsurface and therefore it is important to investigate how much of the outcrop geometry would be preserved and to what extent the outcrop facies model could be used for subsurface reservoir characterization. In order to develop reliable synthetic seismic models, a workflow from outcrop to seismic is implemented including the characterization of petrophysical properties of mixed carbonate siliciclastic facies, their distribution within a geometrical model and the adjustment of modeling parameters to ensure a close match to the real world seismic data.

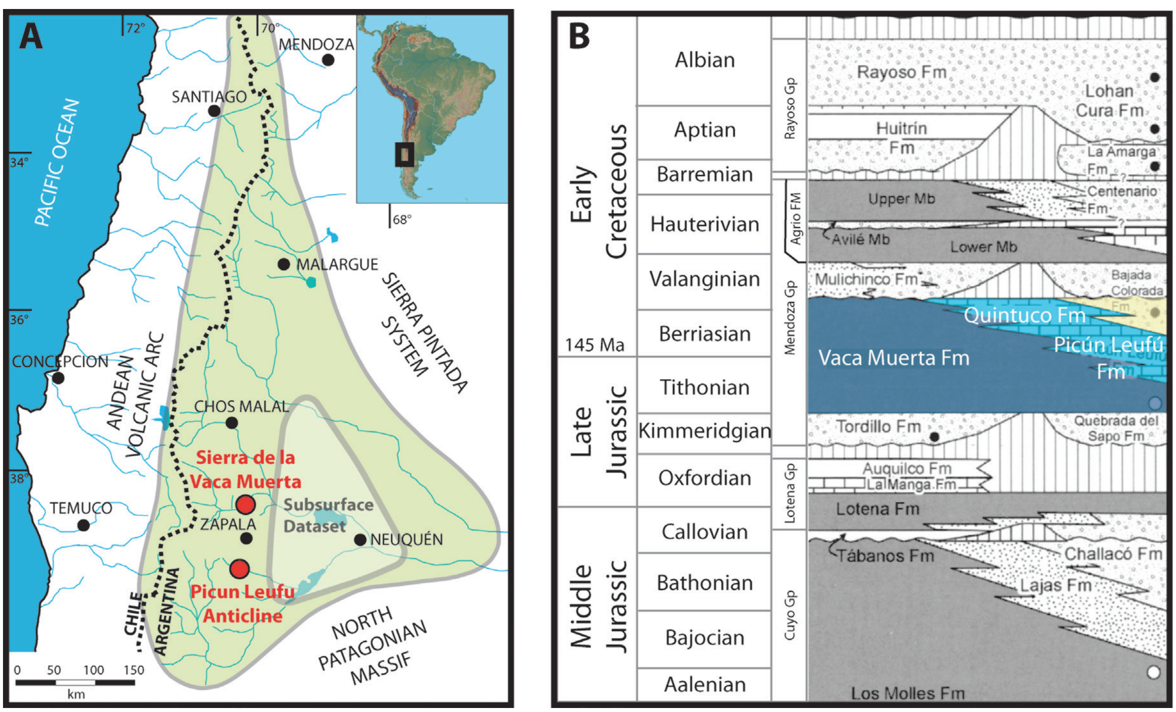

Figure 1. Location and Stratigraphy: A) Map of the Neuquén Basin. Locations of the main outcrop areas and the main producing fields are indicated (modified after Howell *et al.* (2005)). B) Stratigraphic subdivision of the Middle Jurassic to Early Cretaceous successions in the Neuquén Basin (modified from Howell *et al.* (2005)). Studied interval is highlighted in color.

The comparison between the resulting synthetic dataset with seismic lines from producing fields validates the usability of the outcrop study for subsurface characterization. Comparing outcrop facies and seismic facies helps to explain the lithological changes related to amplitude variations. In addition, the model represents a key-linking tool from the outcrop to close-by 2D lines. Relating the synthetic seismic lines to the regional line of Leanza *et al.* (2011) also provides valuable information about the stratigraphic position of the individual facies successions.

FACIES AND GEOMETRIES OF THE OUTCROP AREAS

The Mixed System at the Picún Leufú Anticline

The prograding to aggrading Picun Leufu – Vaca Muerta System represents a time-equivalent succession for the subsurface reservoirs of the Quintuco - Vaca Muerta Formations in the eastern part of the basin. In the outcrop these two formations form a mixed system that consists of a lower prograding unit mainly composed of siliciclastics with a coarsening upwards trend (Figure 2). Following an erosional unconformity, the aggrading middle unit can be subdivided into a lower mixed carbonate-siliciclastic interval capped by a clean carbonate interval, which is separated by a hardground from the aggrading upper unit in which siltstones and sandstones alternate with minor carbonates.

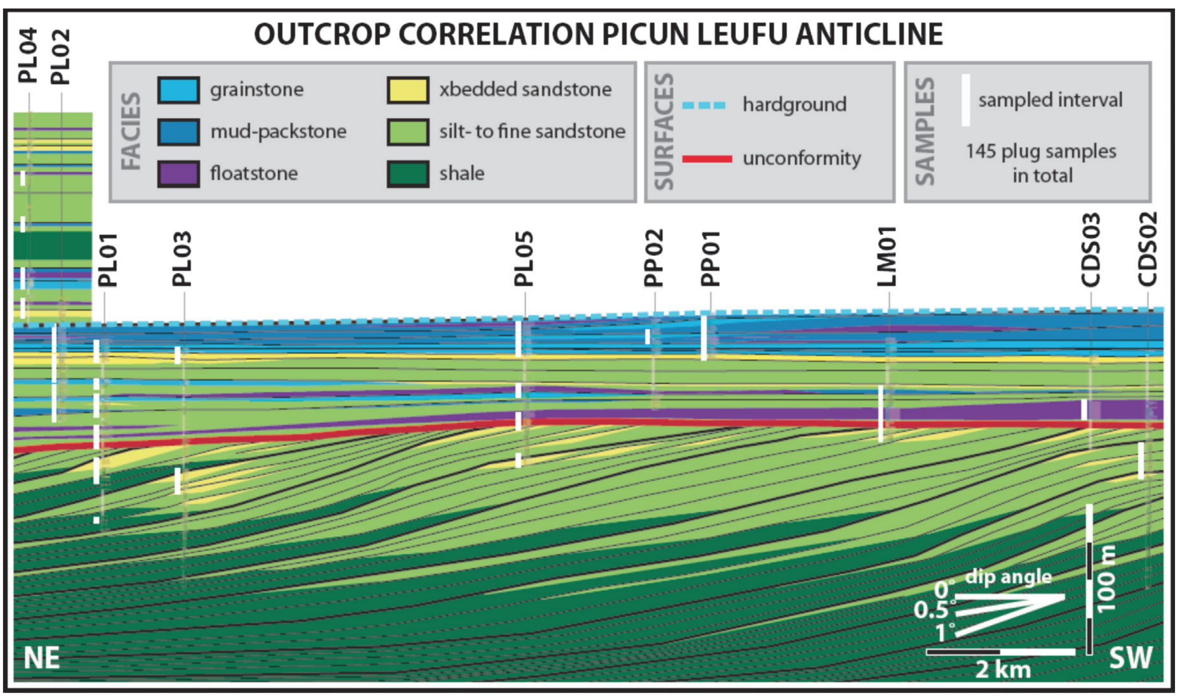

Figure 2. Correlation at the Picun Leufu Anticline, based on logged sections and analysis of geometries from high-resolution satellite imagery. Approximately 15 km long along maximum dip.

The System in the Sierra de la Vaca Muerta

Large-Scale Architecture: Lithologically the studied interval represents a truly mixed succession. Both pure carbonate and pure siliciclastic portions are very scarce. Overall the package follows a prograding/shallowing upward trend with lower basinal deposits overlain by shelfal sediments that finally shifts rapidly into deltaic deposits (Figure 3). This long-term trend is repeatedly interrupted by marine transgressions on the shelf. The succession is subdivided into eight depositional sequences (Figure 3). The sequences are commonly asymmetric with thick regressive portions on the shelf, while this pattern is slightly alleviated in the basinal portions with the thickening of the transgressive portions. Depositional geometries are mostly gentle with dip angles around 0.5-1°, with the exception of sequence V, where a pure carbonate system produces a strong break along the shelf and a depositional dip of around 3° along its lower portion.

The largest shift of the depositional environment occurs within sequence VIII with the onset of unidirectional prograding deltaic facies (Figure 4B) on top of the otherwise tidally dominated shelfal succession. This strong change could have been associated with a change in subsidence rate and tectonic movement in the hinterland, increasing the siliciclastic input to the study area.

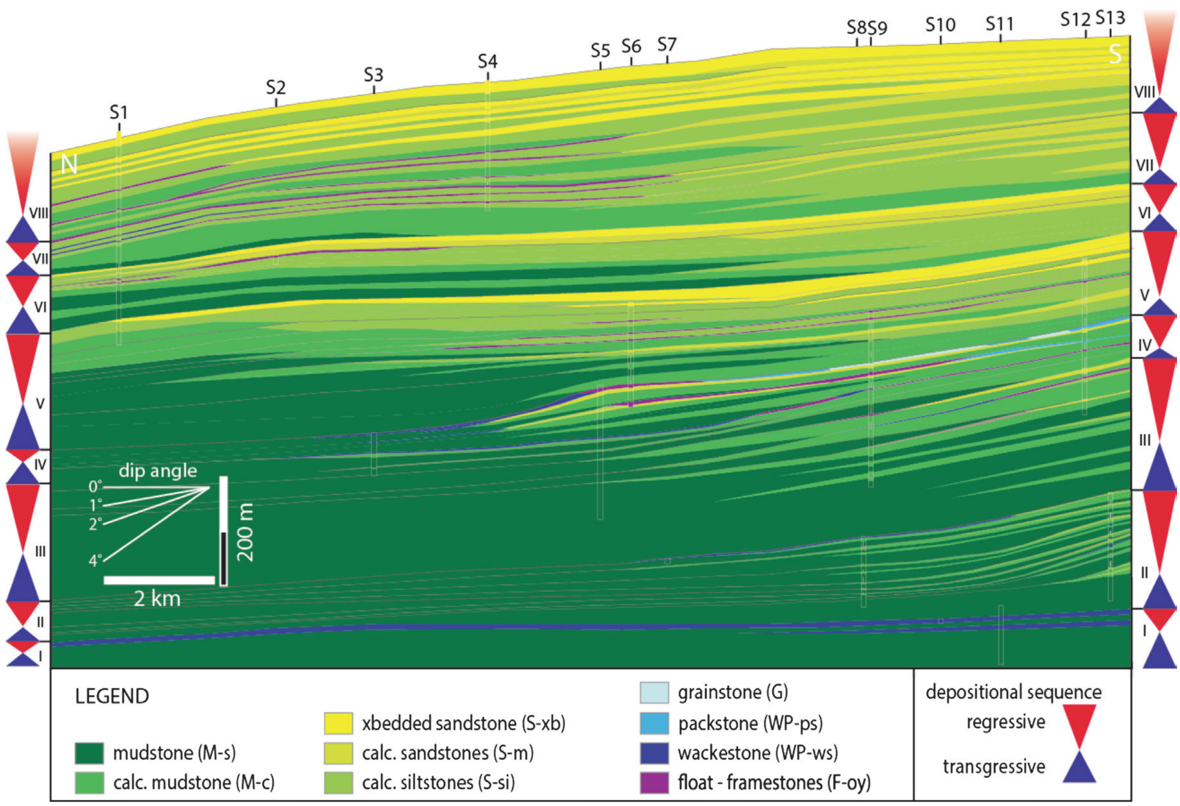

Figure 3. Lithofacies correlation at the Sierra de la Vaca Muerta: Based on the 13 logged sections, 6 logged beds, the observed geometries and lateral facies changes on satellite imagery. Sequence stratigraphic subdivision in regressive and transgressive hemicycles is indicated by red and blue triangles.

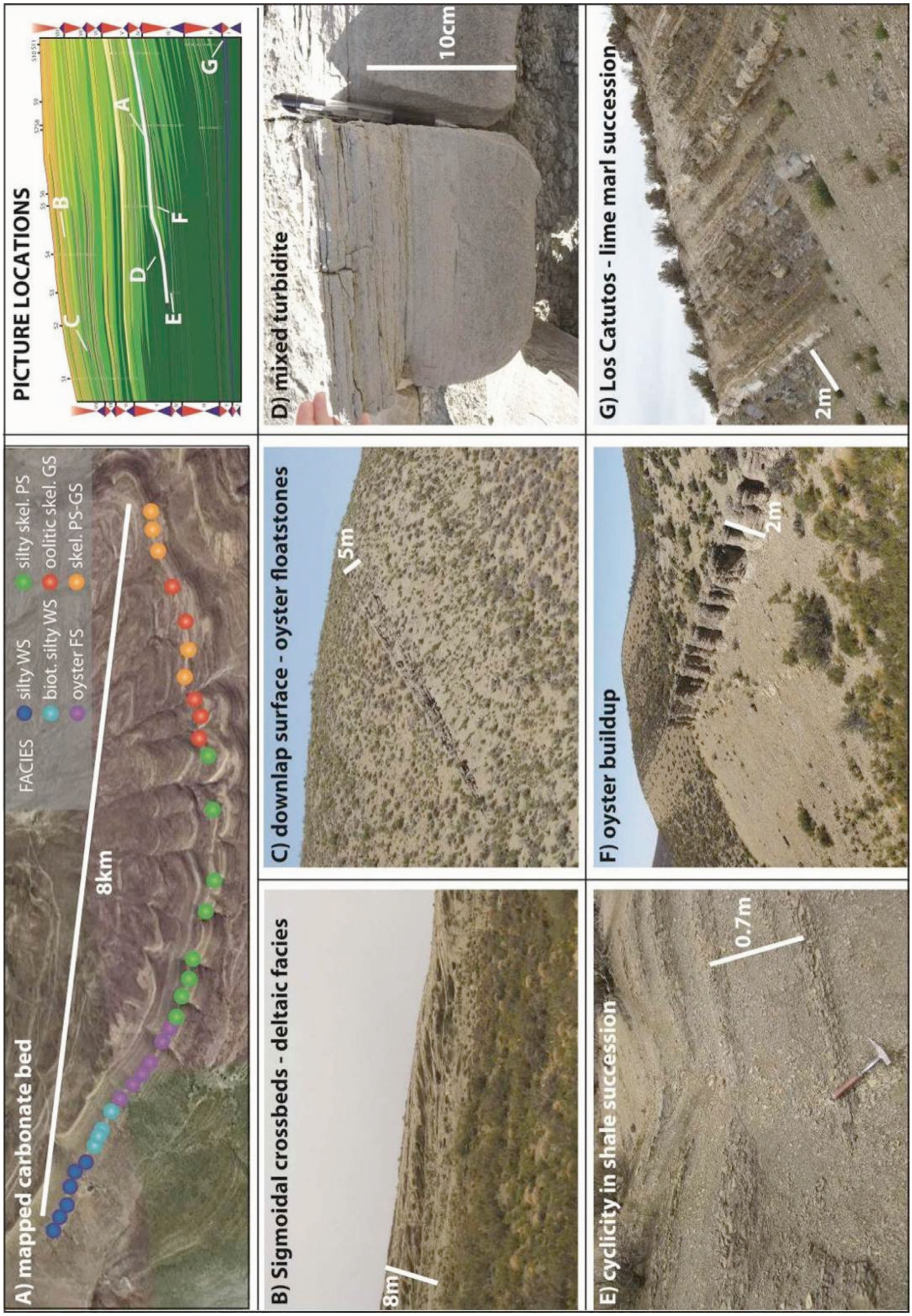

Figure 4. Heterogeneities in the SdlVM (Locations marked top right). A) mapped carbonate bed; B) sigmoidal uni-directional prograding beds in contrast to typical tidal structures; C) downlapping oyster floatstone; D) dm-scale mixed turbidite; E) typical m-scale shale cycles (differences in carbonate content); F) oyster buildups reaching several meters; G) Los Catutos Member, cyclic marls –limestone.

Small-Scale Heterogeneities: Within this large-scale facies architecture the outcrops at the SdlVM also allow more detailed insights into the smaller scale heterogeneities of the mixed system. These include cyclic variations, lateral facies transitions and event beds. The Los Catutos Member (Figure 4G) is a meter-scale alternation of skeletal wackestones with marls (Figure 4E). Shale successions follow the same pattern and display on a meter scale variations of more and less carbonate content. These cycles are laterally associated with more carbonate-rich systems on the shelf. Similar limestone – marl successions in the northern part of the Neuquén Basin have been associated with orbital cyclicity and interpreted as regressive carbonates covered by transgressive marl layers (Kietzmann *et al.*, 2011).

Lateral facies transitions occur in both clastic and carbonate dominated environments. As illustrated in Figure 4A, the high energy carbonate system, consisting of oolitic grainstone and skeletal packstone, shifts laterally into a mixed shelfal system and finally into slope facies (similar to Los Catutos) and basinal calcareous shale. Likewise, siliciclastic sandstones develop downdip from sand-siltstone mixtures to pure mudstone deposits over several kilometers. Oyster float- and framestones are the most common carbonate dominated facies in the system and can occur as extensive decimeter-meter thick beds (Figure 4C) or as up to 4m thick buildups. One particular buildup is mapped out and shows rapid thickening from 0.1m to more than 3m (Figure 4F).

In addition to the cyclic and lateral variations, some sedimentary structures provide evidence of sedimentation events during the time of deposition. Soft sediment deformation is a common feature within the regressive portions of siliciclastic-dominated sequences (Sequences VI-VIII) and can be explained by the rapid sedimentation of silt and sand on top of the shale. In contrast mixed carbonate clastic turbidites (Figure 4D) can be found just above carbonate dominated sequence tops (sequences I and IV) and might have been triggered by the steeper depositional profile built by the precursor carbonate systems.

SYNTHETIC MODELING WORKFLOW

Figure 5 illustrates the applied workflow, which was implemented in this study in order to develop tailored synthetic seismic models for comparison with real world seismic data.

Model Geometries

Since the key target of this study is the comparison with the subsurface seismic data, the succession was placed at an equivalent depth (2 km) and the trace spacing (30 m) was adjusted to the common seismic datasets. The kilometer long correlations (Figures 2 and 3) represent the synthesis of the field campaigns and are used as the main geometrical input for the synthetic model. In the Picún Leufú Anticline section the upper portion of the model (Figure 2) was

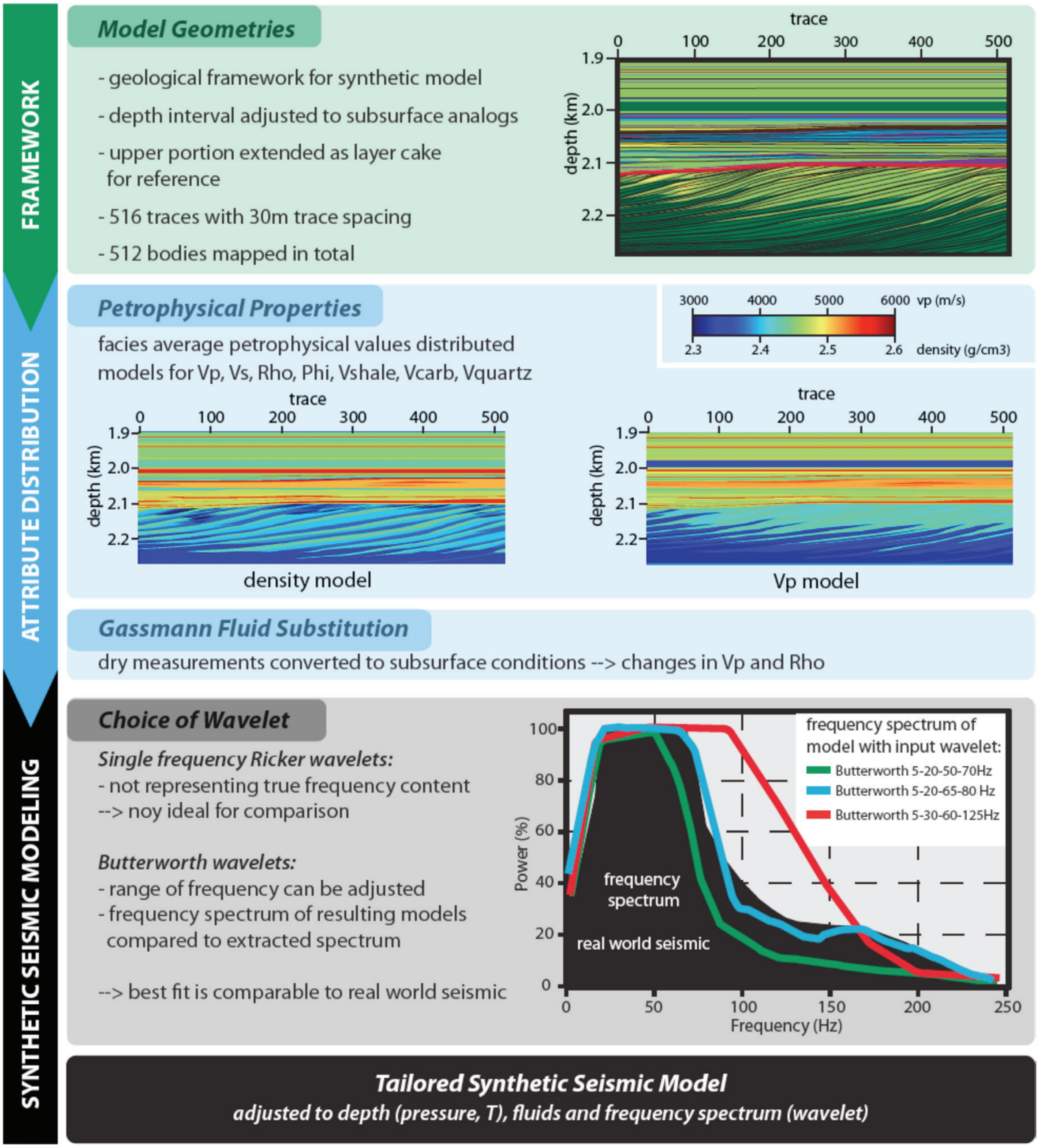

Figure 5. Outcrop to Synthetic Seismic Workflow, including geometry and acquisition setup, distribution of petrophysical properties and fluid substitution and the correct choice of modeling wavelet.

extended laterally in order to integrate the full section into the model. The seismic response along these beds is therefore rather uniform, but the general character can serve as a reference for subsurface comparison. The model was subdivided into 512 distinct facies bodies, which allowed the integration of petrophysical properties (Table 1) and observed trends (*e.g.* cleaning upward and coarsening upward trends) in a framework well below seismic resolution. In the Sierra de la Vaca Muerta area, the facies model (Figure 3) is used as the geometrical input and is placed at 2 km depth. To ensure sufficient lateral and horizontal resolution, 532 facies bodies were defined and 333 traces where used along the 10 km long section.

The resulting synthetic seismic image will be on the resolution of the acquired seismic data. The main purpose of the synthetic modeling is to assess if the observed outcrop geometries and facies would produce similar seismic images. If indeed the similar seismic signature is achieved, a case could be made that the outcrop in the Picu Leufu and Sierra dell Vaca Muerta can be used to understand the sedimentary and stratigraphic evolution in areas of the Neuquen Basin where only subsurface data is available. The synthetic seismic data does, similarly to the real seismic data, not have the resolution for detailed reservoir modeling but since the synthetic model is derived from detailed description of outcrop geometries and facies, the outcrop information can serve as a conceptual guide to construct reservoir models from core and log data.

Petrophysical Properties

Picún Leufú Anticline (PLA): The average petrophysical properties (Table 1) were distributed into the geometrical framework. All observed facies types (except mudstones) were covered by the 145 collected samples. Measurements included acoustic velocities (5-60 MPa), porosity, bulk density and carbonate content (based on thermogravimetric analysis). The petrophysical characterization revealed clear trends and identified both porosity and carbonate content as the main controlling factor on sonic velocities. Increasing carbonate content leads to higher vp and higher vp/vs ratios, while increasing porosity decreases vp and vp/vs (Figure 6).

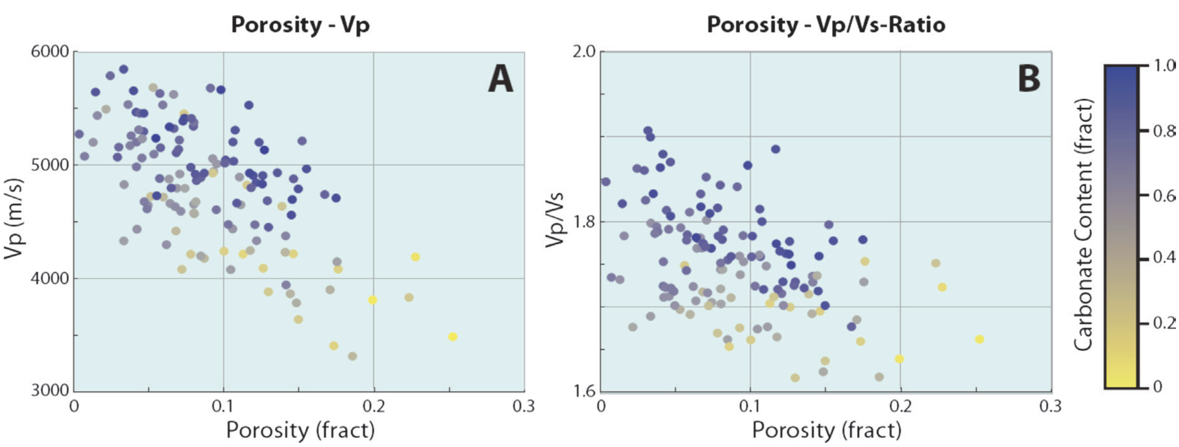

Figure 6. Petrophysical characteristics of the samples from the Picun Leufu Anticline: A) porosity vs v_p and B) porosity vs v_p/v_s, both color coded with measured carbonate content.

Subdivision into the different intervals and therein the various facies clarifies these trends even more (Table 1). Carbonate-rich facies from the clean carbonate interval and oyster floatstone represent the maximum P-velocities reaching up to more than 5000 m/s, while sandstones of the lower, mixed and upper interval are characterized by lower velocities. One key objective of this study was the investigation of the consequences of these strong petrophysical contrasts on the seismic images.

Sierra de la Vaca Muerta (SdlVM): Petrophysical properties of 70 samples, covering all facies types, are measured. They include dry v_p, dry v_s (both from 5 – 60 MPa), bulk and grain densities, porosity and carbonate content. The velocity values (for 50 MPa ~ 2 km burial depth) are corrected from dry to realistic wet state using the Gassmann fluid substitution equations. The average values determined for each facies (Table 2) are then distributed according to the facies model. The resulting acoustic impedance model (based on the velocity and density input) is then convolved with a 5-10-50-60 Butterworth wavelet and models for 0, 10, 20 and 30 degree incident angles are stacked to create a synthetic seismic section that can be compared with real subsurface datasets.

	Lower Unit		**Middle Unit – Mixed Interval**					
facies	***silt-sand***	***xbedded sand***	***sand***	***xbedded sand***	***oyster FS***	***WS-PS***	***quartz rich GS***	
v_p (m/s)	4140	3995	4481	4321	5418	4863	4716	
v_s (m/s)	2512	2387	2587	2565	3066	2757	2706	
ρ (g/cm³)	2.38	2.18	2.4	2.32	2.532	.51	2.45	
Φ (fract)	0.08	0.17	0.07	0.14	0.05	0.07	0.08	
	Middle Unit - Carbonate			**Up er Unit**				
facies	***oyster FS***	***WS-PS***	***GS***	***si t- fine sand***	***xbedded sand***	***oyster FS***	***WS-PS***	***GS***
v_p (m/s)	5384	5050	4980	4562	4341	5642	5103	4801
v_s (m/s)	2927	2890	2787	2635	2577	3 05	2969	2773
ρ (g/cm³)	2.507	2.46	2.44	2.39	2.31	2.51	2.49	2.52
Φ (fract)	0.07	0.08	0.1	0.09	0.13	0.06	0.04	0.06

Table 1. Average petrophysical properties of the Picún Leufú anticline section divided into intervals and facies types. These values are used for property distribution within the facies geometry model. Vp and Vs values for 50MPa effective pressure.

facies	***mudstone***	***calc. mudstone***	***calc.silt***	***calc.sand***	***pure sand***
v_p (m/s)	3547	4370	4676	4849	4215
v_s (m/s)	2109	2518	2687	2830	2623
ρ (g/cm³)	2.25	2.45	2.53	2.51	2.34
Φ (fract)	0.07	0.04	0.07	0.07	0.11
Carb (fract)	0.20	0.51	0.60	0.36	0.02
facies	***WS***	***PS***	***oyster FS***	***GS***	***deltaic sand***
v_p (m/s)	5652	5365	5650	5375	4174
v_s (m/s)	3090	2972	3077	2934	2466
ρ (g/cm³)	2.63	2.56	2.58	2.56	2.38
Φ (fract)	0.02	0.04	0.05	0.06	0.10
Carb (fract)	0.72	0.66	0.74	0.81	0.17

Table 2. Average petrophysical properties of the Sierra de la Vaca Muerta section for different facies associations after Gassmann Fluid Substitution. These values are used for property distribution within the geometry model and are the basis for the synthetic seismic modeling. Vp and Vs values are for 50 MPa effective pressure.

Gassmann Fluid Substitution

Density, Vp and Vs were measured on dry samples in the laboratory. Naturally this does not represent the subsurface conditions (here 80% oil, 20% water) and therefore it has to be adjusted to obtain a better match with the real world seismic. Gassmann (1951) proposed equations to estimate fluid filled values from dry measured values but there are some complications with carbonates due to their complex pore structure. Nonetheless, the Gassmann approximantion is used here.

Choice of Wavelet

In order to account for the full spectrum in this study, the frequency spectrum of the real world seismic was analyzed and several Butterworth wavelets were created to match the possible input wavelet. In the next step the models created with these wavelets were analyzed for their spectrum and the best fitting option (here: Butterworth 5-20-65-80 Hz, Figure 5) was taken as the synthetic seismic for subsequent comparison.

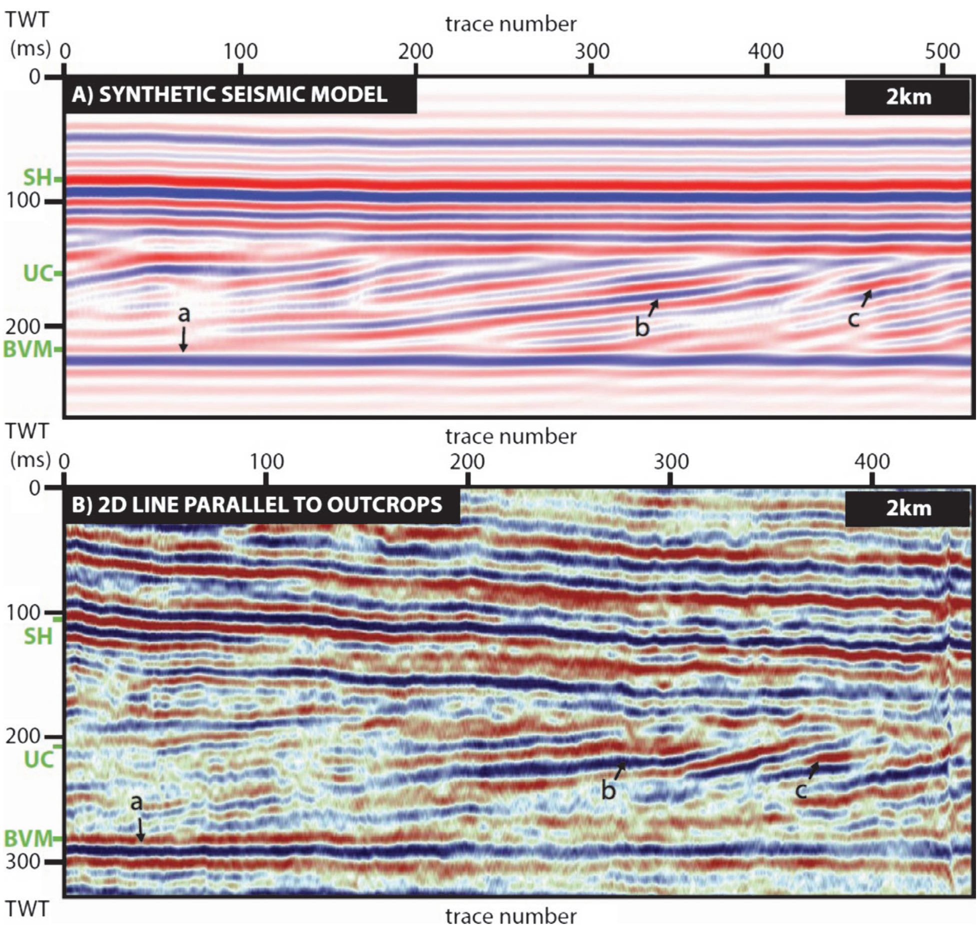

Figure 7. Synthetic seismic section of the Picún Leufú Anticline section. Comparison of the synthetic seismic model (A) with a close-by seismic line (B) flattened on the base of the Vaca Muerta (BVM).

Tailored Synthetic Seismic Models

The resulting synthetic seismic models (Figure 7 and 8) are tailored to the subsurface data of interest in terms of depth (2 km, 50 MPa), fluid content (80% oil, 20% water) and frequency content. The model algorithm convolves the selected wavelet with the acoustic impedance model along every trace based on Zoeppritz equations. The synthetic model represents a perfectly time-migrated, zero-offset seismic line without multiples and refractions and is therefore the optimum which can be achieved by seismic processing with the given acquisition parameters.

RESULTS: SYNTHETIC SEISMIC MODEL

PLA: The observed outcrop facies geometries have been translated into seismic expressions and the general character is well preserved (Figures 2 and 7). In the lower unit all main clinoforms are represented, their bottomsets commonly coincide at the top of the BVM. The strongest amplitudes are encountered along the foresets, which then gradually decline towards the unconformity, represented by a continuous reflection of variable amplitude strength. Commonly clinoform tops are represented by pseudo-onlaps in the synthetic section (*e.g.* around trace 200 and around trace 400). The petrophysical variations, which were introduced into the middle unit, proved to be below seismic resolution, since parallel continuous reflectors characterize the entire interval. On closer examination, the amplitudes vary laterally emphasizing changes in acoustic impedances along the beds. The upper unit, which was modeled as a layer cake and does not hold any geometric information, exposes nonetheless a very important reflection along a major contrast between the mixed carbonate clastic strata and an overlying 20m shale interval. This surface could well serve as a regional correlation horizon, especially considering the potential extent of the transgressive mudstone deposition.

SdlVM: In the synthetic seismic model of the Sierra de la Vaca Muerta the general character of the prograding – aggrading succession is well preserved (Figures 3 and 8). In the lower portion of the model the beds downlap onto the Los Catutos Member (Figure 3). The strongest geometrical anomaly is represented by the carbonate succession of sequence IV. The following beds onlap onto this key reflection and are overlain by a more aggradational succession, which exposes quite commonly lateral variations in amplitudes and are very well-defined as downlapping beds in the lower portion. Identification of depositional sequences is not as straight forward as from the facies correlation. Some of the thin sequences would most likely be missed in seismic interpretation of real subsurface seismic data with similar resolution.

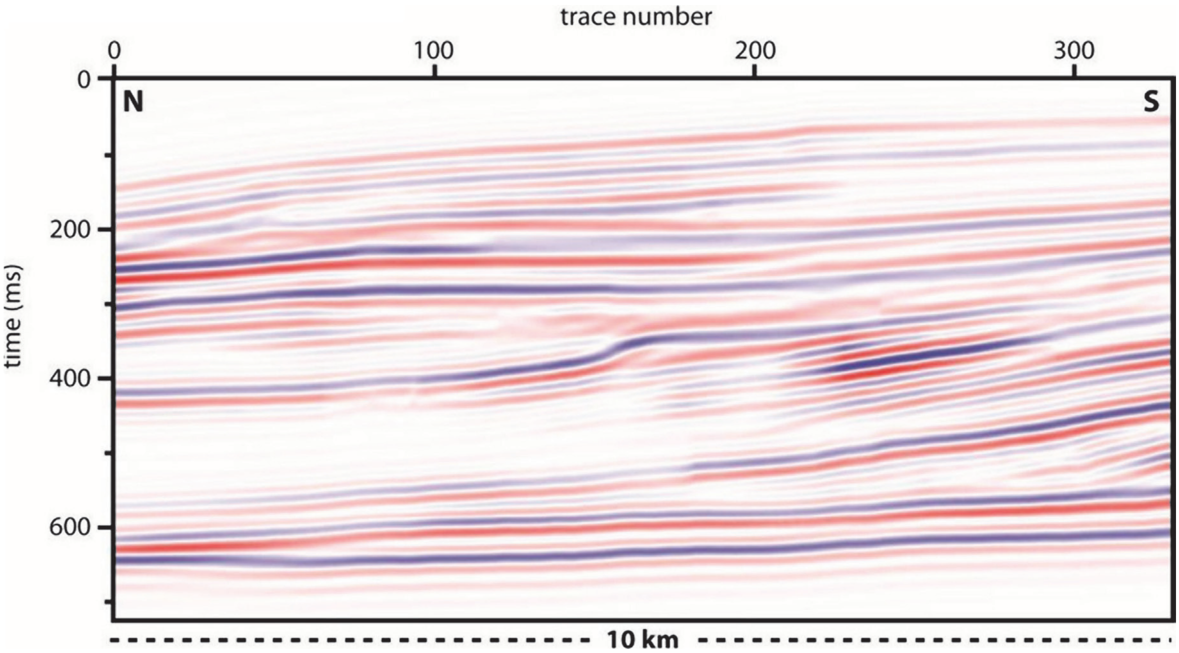

Figure 8. Synthetic seismic model of the Sierra de la Vaca Muerta section based on the acoustic impedance model from facies distribution, the petrophysical measurements at 50 MPa.

IMPLICATIONS

Comparison of Picún Leufú Anticline Seismic Model with Subsurface Data

The key objective of the synthetic modeling is to translate the outcrop geometries into subsurface seismic architecture and then compare to real world seismic data in order to understand to what extent subsurface and outcrop are alike, and how much information from the outcrop can be used for reservoir characterization.

In a 2D line imaging the same stratigraphic interval as exposed in the Picún Leufú outcrop approximately 8 km away (Figure 7B) one can easily identify the same architectural character (prograding-aggrading-aggrading). Additionally, clinoform reflections have comparable dip angles and follow similar trends, with coinciding bottomsets, strong foreset amplitudes and amplitude weakening to onlap geometries towards the top. Reflections above the unconformity, which can be recognized in both lines, are characterized by amplitude variations along parallel reflectors, which are probably increased due to noise and anomalies above the modeled interval. Strong reflections similar to the SH horizon (see Figure 7) can be found in approximately the same configuration in the synthetic seismic data, strengthening their potential usability as regional marker.

This general similarity has several important implications:

1. The synthetic seismic model successfully reproduced seismic expression of outcrop geometries, which are imaged in the close-by 2D line
2. Some interpreted key surfaces can be identified in the seismic and allow integration of outcrop information for regional correlation objectives.
3. If used with care, the observed outcrop geometries will serve as a guide when building subsurface reservoir models. In addition, they serve as a conceptual analog for targets and other sequences within the producing field.

Sequence Stratigraphy of the Sierra de la Vaca Muerta

In outcrop the succession can be subdivided into 8 depositional sequences. Based on biostratigraphic studies (Leanza *et al.*, 2011) the studied interval extends from the Early Tithonian to the Middle – Late Berriasian, a time span of approximately 10 Myr. In subsurface seismic data 7 sequences are identified that correspond to the 7 deepening and shallowing cycles represented in the eustatic sea-level curve proposed by Mitchum and Uliana (1985). The similar number of sequences indicates a similar stratigraphic framework for both outcrop and subsurface, presumably controlled by eustatic sea-level changes. This is important, since the value of the outcrop as an analog is greatly enhanced if similar depositional processes control both areas.

Heterogeneities

Small-scale variations of depositional facies within the Vaca Muerta Formation follow lateral and sequence stratigraphic trends. Even event beds like soft sediment deformation structures and turbidites occur in predictable intervals within the sequence stratigraphic framework. This has a considerable impact on identification of potential sweet spots for unconventional exploration. Intervals with higher carbonate content might represent best locations for hydraulic fracking, while intervals with high turbidite frequency would offer relatively elevated porosity and permeability streaks within an otherwise tight surrounding.

Regional Seismic Architecture (Outcrop – Subsurface)

With now two synthetic seismic models in place, both in proximal (PLA) and distal (SdlVM) positions, comparisons of the regional architecture of outcrop and subsurface hold very interesting insights. Figure 9 is a combination of a regional subsurface line from the producing fields towards the NW and the two synthetic seismic datasets from this study. When standardized to the same scales, they show very similar characteristics. Proximal portions (PLA and E subsurface) are relatively thin, have reflectors with gentle dips up to 1° and no breaks along their profile. In contrast, distal portions (SdlVM and W subsurface) are very thick. Both seismic and model show steeper dip angles in the lower portion and contain reflections with clear breaks. Despite the limits imposed by seismic resolution, these similar developments enhance the value of the outcrops as conceptual analogs and point to similar depositional processes and environments in the different areas over most of the studied interval.

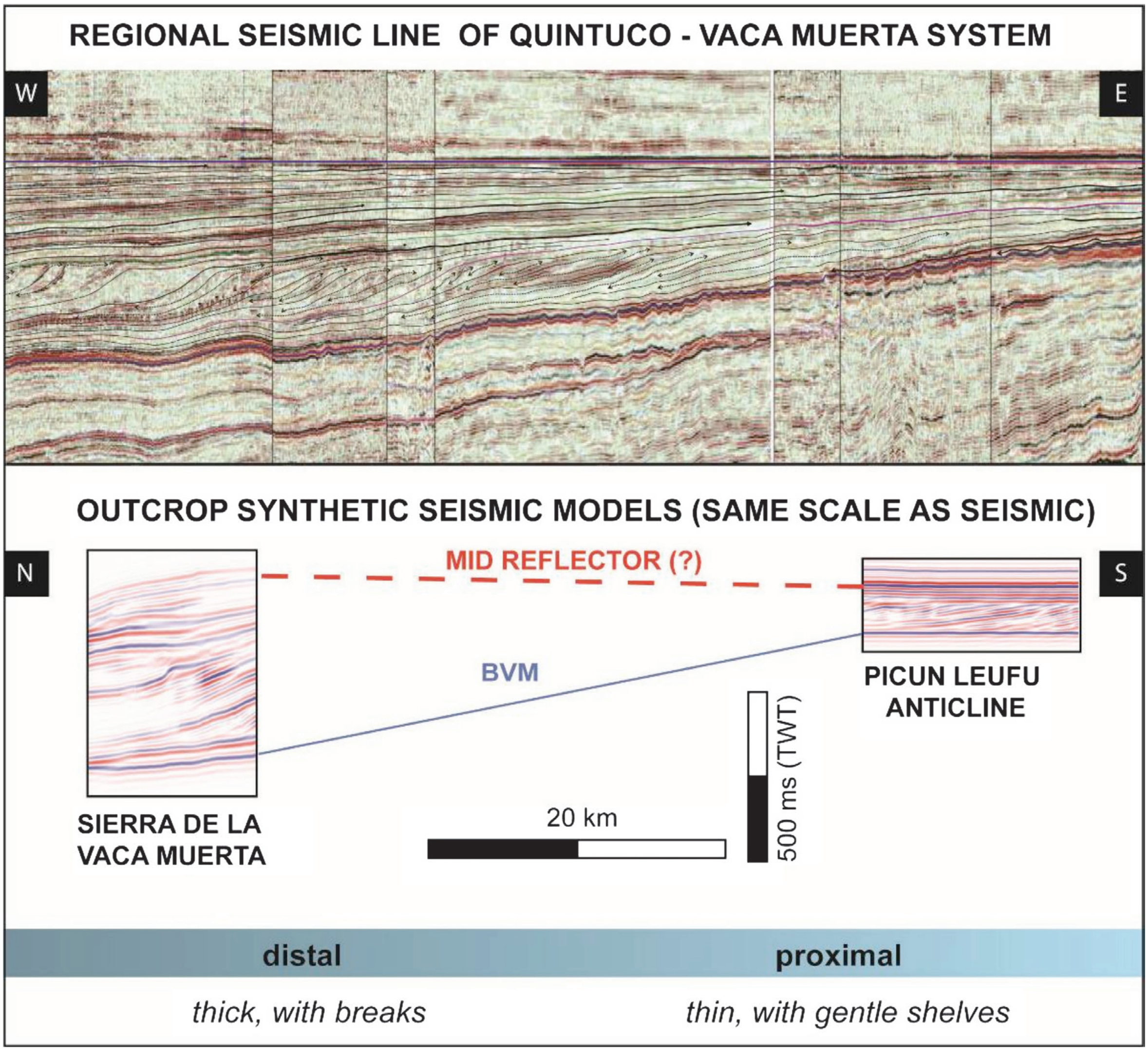

Figure 9. Comparison subsurface with synthetic seismic data from outcrop areas. Top: Regional seismic line (modified from Leanza *et al.*, 2011); Base: synthetic seismic sections from this study, using the same scale as the subsurface dataset.

Regional Facies Correlation

While biostratigraphy and tracking on satellite imagery offer the opportunity to link nearby outcrop sections in the north, direct correlation between the two major outcrop study areas (PLA and SdlVM) can only be established using seismic correlation throughout the central part of the basin. In this manner, the regional correlation surfaces provide the framework for outcrop-to-outcrop correlation. Based on the integration of the biostratigraphic framework and the link via seismic lines, a new detailed outcrop-to-outcrop correlation was developed (Figure 10). The correlation runs from the south of the PLA to the north of the SdlVM and the investigated interval can be subdivided into 8 depositional sequences. Sequence 1 contains the initial flooding and the first prograding system as observed at the PLA. Sequences 2-6 are all strongly prograding and indicate an increase in carbonate content towards the regressive portions, while pure carbonate deposition is established on top of sequences 2 and 4. In both cases a carbonate ramp links downdip to silty wackestones and marlstone alternations. Sequences 7 and 8 represent the sudden shift to very near shore deposits in the Sierra de la Vaca Muerta and can be linked to the onset of continental deposition and erosion in the southern areas.

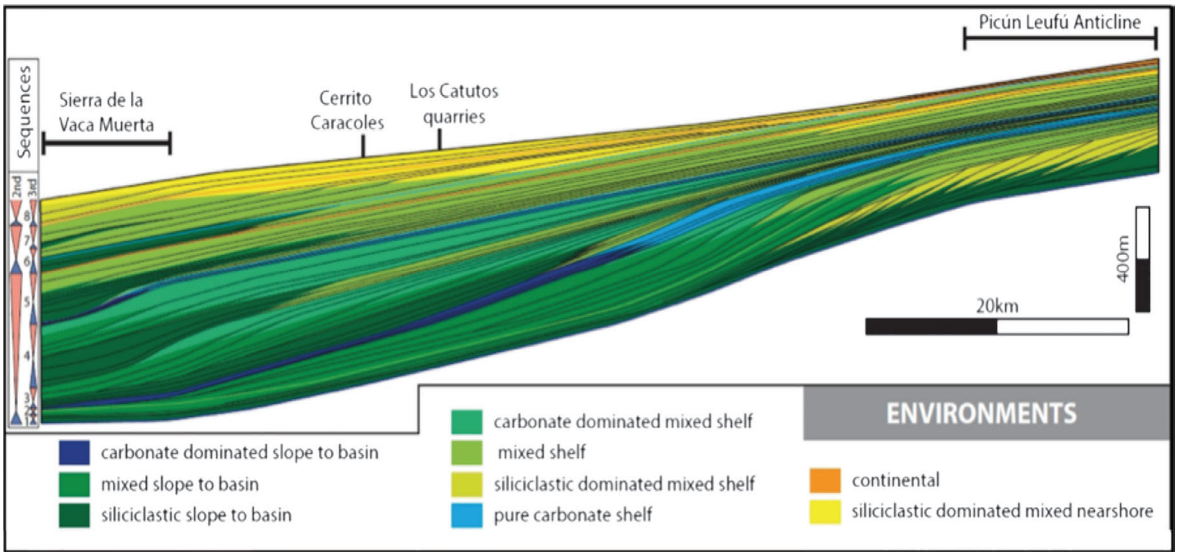

Figure 10. Schematic distribution of the facies and sequences based on outcrop correlation between the Picún Leufú Anticline and the Sierra de la Vaca Muerta with 2nd and 3rd order sequence stratigraphic framework.

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