SHELF EDGE TRAJECTORY AND STRATIGRAPHIC ANALYSIS OF THE COLORADO BASIN CRETACEOUS SEQUENCE, OFFSHORE ARGENTINA

Gabriel Giacomone[1], Leandro Venara[1], Yonathan Quintero[1]

1: Pluspetrol S.A. ggiacomone@pluspetrol.net, lvenara@pluspetrol.net, yquintero@pluspetrol.net

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RESUMEN

Las trayectorias de los quiebres de plataforma describen la migración de los sistemas sedimentarios por medio de su evolución temporal. El uso exclusivo de la estratigrafía secuencial puede llevar a interpretaciones sesgadas y modelo-dependientes. Se propone un uso combinado, donde el análisis de las trayectorias de los quiebres de plataforma sustenta los modelos clásicos de estratigrafía secuencial.
El objetivo del estudio presenta tres aristas: 1-Descripción cuantitativa de la evolución de las clinoformas de la cuenca; 2-Proveer un modelo estratigráfico-secuencial 3D; 3-Interpretar los controles alogénicos y autogénicos de la cuenca.
8000 kilómetros de sísmica 2D se utilizaron para el estudio de clinoformas de plataforma cretácicas de la cuenca del Colorado. Éstas se mapearon regionalmente y fueron agrupadas en 15 clinotemas basadas en las trayectorias de sus rollovers. Cuatro secuencias transgresivo-regresivas de 2° orden se identificaron según el reconocimiento de trayectorias retrogradacionales de los quiebres de plataforma (relaciones progradación/agradación (P/A) negativas de -5 a -880). Cada transgresión es sucedida por una regresión con diferentes tipos de trayectorias hacia la cuenca.
La primera secuencia progrrada sobre la máxima inundación aptiana. La progradación principal es hacia el este, primero centrada en el sur (P/A >80 y ángulos de trayectoria de rollover (Tro) <1°), para luego moverse gradualmente hacia el norte, estabilizándose en el centro del área (P/A >70 y Tro <1°). Las progradaciones de las siguientes secuencias permanecen en las adyacencias del sector. Para el caso de las secuencias 2 a 4, la plataforma evolucionó hasta alcanzar el borde del talud continental, generando morfologías de colapso.
Factores tectónicos, eustáticos y el aporte sedimentario son los principales mecanismos alogénicos, para las secuencias de 2° 3° y 4° orden. La primera transgresión está relacionada a subsidencia, debido a enfriamiento de la corteza oceánica y las siguientes se deben a subsidencia regional, aumento del nivel global del mar o una combinación de ambos. La progradación de la plataforma probablemente esté asociada a un sistema fluvial regional, de origen andino, vinculado a un levantamiento tectónico del Albiano. Controles autogénicos se identifican en la secuencia 1, donde los sistemas fluviales se trasladan hacia el norte conforme su evolución.
El análisis cuantitativo y estudio de las trayectorias de clinoformas a escala de plataforma, es de utilidad para el entendimiento de la distribución de sedimentos en una cuenca y, a su vez, permite realizar interpretaciones paleo-ambientales consistentes a la hora de la identificación de potenciales reservorios y sellos regionales.

INTRODUCTION

Sequence stratigraphy has proven to be an important and useful tool to understand the evolution of sedimentary systems in time and space. This methodology is no longer used uniquely by the academia, but it is also used by non-stratigraphic disciplines in the industry and governments (Catuneanu *et al.* 2009). Its applications cover a wide range, from understanding local to global variations in paleogeography, the controls behind those changes (Catuneanu *et al.* 2009; Posamentier *et al.* 1988), improving success of natural resources exploitation (Embry 2009; Posamentier & Weimer 1993) and climate crisis mitigation techniques (e.g. CO_2 sequestration; Miller *et al.* 2017).

Different and widely accepted methods within sequence stratigraphy exist and are valid, with some being more useful than others depending on the geologic setting (Bhattacharya & Abreu 2016; Catuneanu *et al.* 2009), however consensus and standardization has been a hurdle (Catuneanu *et al.* 2009). Historically, sequence stratigraphy has had two approaches on its workflows; a model independent approach in which the focus was put on mapping key stratigraphic surfaces and sequences (Mitchum Jr *et al.* 1977; Vail *et al.* 1977), and a model-dependent approach, where the efforts were set in establishing conceptual sequence models (Catuneanu 2002; Galloway 1989; Posamentier *et al.* 1988; Posamentier & Vail 1988). During the last decades, there have been attempts to return to observation based and data driven interpretations, made possible by trajectory analysis (Helland-Hansen & Hampson 2009) and the accommodation succession method (Neal & Abreu 2009; Neal *et al.* 2016).

This new methodology consists in studying migration direction of geomorphological features (e.g. shelf breaks), and understanding how paleoenvironmental conditions and lithostratigraphic units vary through time. This school focuses on the evolution of the strata using a quantitative and practical methodology in which the emphasis is put on the location and evolution of the rollovers through time. (e.g. Helland-Hansen & Martinsen 1996; Helland-Hansen & Hampson 2009; Neal & Abreu 2009; Neal *et al.* 2016). This methodology can be an effective approach since it links directly to the accommodation supply ratio, which states that changes in sediment supply interacting with variations in accommodation space control strata stacking patterns.

However, along-strike variability of depositional environments is yet a hurdle to surpass when it comes to 3D sequence stratigraphy analyses (Burgess 2016). These variability has been recognized for some time now and it is acknowledged in the sequence stratigraphy paradigm (Burgess 2016). Nevertheless, many authors claim that 3D heterogeneity produced by autogenic processes is less important than allogenic processes that control large scale architecture of the basins (Catuneanu 2006). Still, it has been proven that autogenic responses can have an important imprint on the stratigraphic record (Burgess 2016; Paola 2016). On the last years some authors have made an attempt to conciliate sequence stratigraphy interpretations in space, and integrate along-strike variability objectively and quantitatively into a robust framework (Burgess 2016; Madof *et al*. 2016; Paumard *et al*. 2019).

The Colorado Fm. (Aptian to Campanian) deposited in the Colorado basin, offshore Argentina (Fig. 1 and 2), presents a unique opportunity to study shelf scale clinoforms (heights of 100s meters scale) that develop during the post rift to passive margin phase of the basin (Gerster *et al*. 2011). During the Middle to Late cretaceous a shelf margin was formed and prograded until reaching the continental margin, giving compound and hybrid clinoforms (shelf edge deltas reaching the continental margin). Lateral variations in rates of accommodation and sediment supply impacted greatly the stratigraphic architecture of the margin, as well as the distribution of different elements of the petroleum systems (mainly reservoirs and seals). This study uses 2D seismic and a trajectory analysis approach in order to: (1) provide a quantitative description of the evolution of the clinoforms depicted in the basin; (2) provide a 3D sequence stratigraphic interpretation; and (3) interpr*et al*logenic vs autogenic controls in the basin.

REGIONAL SETTING

The study area (Fig. 1) is located offshore Argentina and comprises the outermost shelf and the slope portion of Colorado Basin, located in the austral region of South Atlantic margin. The Colorado basin has more than 125.000 km2 and a NW-SE orientation, oblique to the NNE Atlantic margin trend (Autin *et al*. 2013; Loegering *et al*. 2013).

The Colorado basin highlights a complex Mesozoic rifting history that initiated in the Early Jurassic with a NW-SE oriented main depocenter, continued on the Mid Jurassic with W-E oriented grabens, and ended with a NW-SE oriented depocenters associated with the breakup of Gondwana (Fig. 2; Franke *et al*. 2006; Lovecchio *et al*. 2018). Afterwards, on Barremian to Aptian times, the generation of transitional and oceanic crust leads to a cease in fault activity and the subsidence mechanism is then associated with thermal cooling on a post-rift to passive margin stage (Gerster *et al*. 2011).

The basement is composed of igneous and metamorphic rocks of Precambrian age (Loegering *et al*. 2013). Late carboniferous – Early Permian glacial and lacustrine deposits with affinity to the Great Karoo Basin are found on top (López-Gamundí & Rossello 1998). The synrift deposits were only drilled on a flank block by the Cruz del Sur-1 well, which encountered sandstones with andesites and tuffs (Bushnell *et al*. 1997). On the main depocenters, the stratigraphy is speculative, but seismic facies indicate possible lacustrine shales (Loegering *et al*. 2013). During the thermal sag phase (Aptian - Maastrichtian), the Colorado Fm. was deposited (Fig. 2). It is mainly composed of continental siliciclastic deposits to the west, transitioning to marine platform deposits and a deepwater environment to the east (Gerster *et al*. 2011).

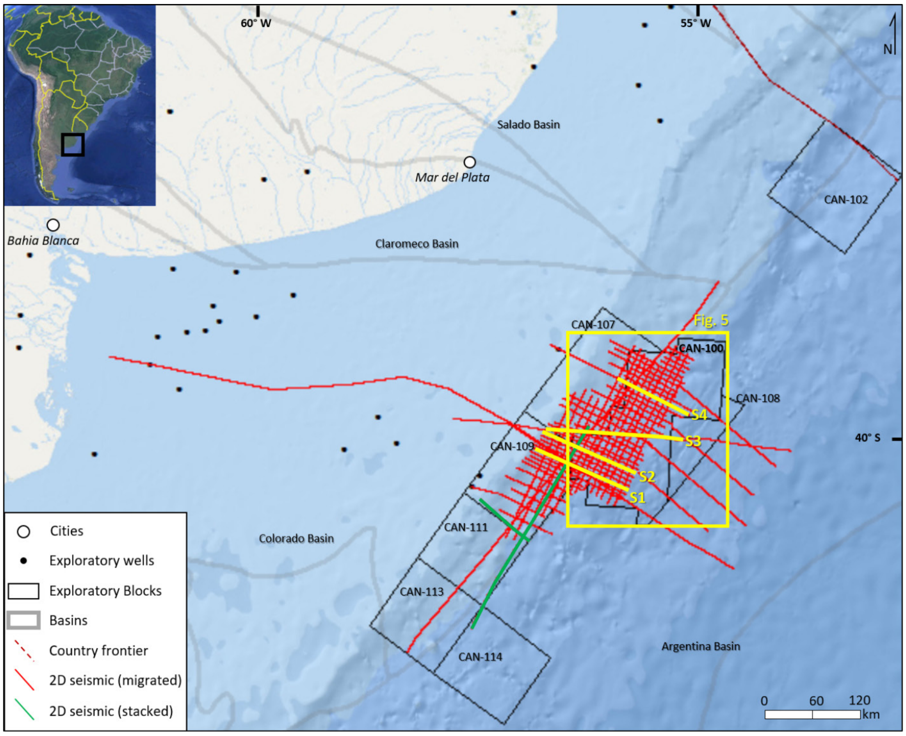

Figure 1. Location map and data used in this study. Coordinates are in geographic system. S1: Seismic section 1. S2: Seismic section 2. S3: Seismic section 3. S4: Seismic section 4.

The end of the Cretaceous is marked by a regional transgression, in which the marine shales of the Pedro Luro Fm are deposited (Fig. 2). Fine grained sediments and limestones of the Elvira Fm. (mid to upper Eocene) are deposited on top. Next, the Oligocene to Pliocene Barranca Final Fm. is deposited, which is composed of fine grained clastics, deposited in a shallow marine environment that deepens to the east (Gerster *et al.* 2011).

DATA & METHODOLOGY

During 2018 and 2019, the Argentinean government launched the Argentina Offshore Round 1, and gave access to public non-confidential sub-surface information (seismic and wells) through the Energy and Mining Ministry (MINEM) databank. Seismic coverage and wells locations are depicted in Fig. 1.

The seismic dataset used in the current work, consists of ninety-seven 2D seismic lines processed in the time domain, which totalize approximately 7696 kilometers (7393 km of migrated data and 303 km of stacked data, Fig. 1). The 2D seismic grid presents areas with denser density, with spacings between lines of approximately 5 kilometers and regions with sparser coverage with distances between lines of about 30 kilometers.

The time interval corresponding to the Mesozoic and Cenozoic sedimentary fill of the basin, presents average frequencies, in the case of the time migrated data, of 30 Hz, which gives a seismic vertical resolution of approximately 25 m.

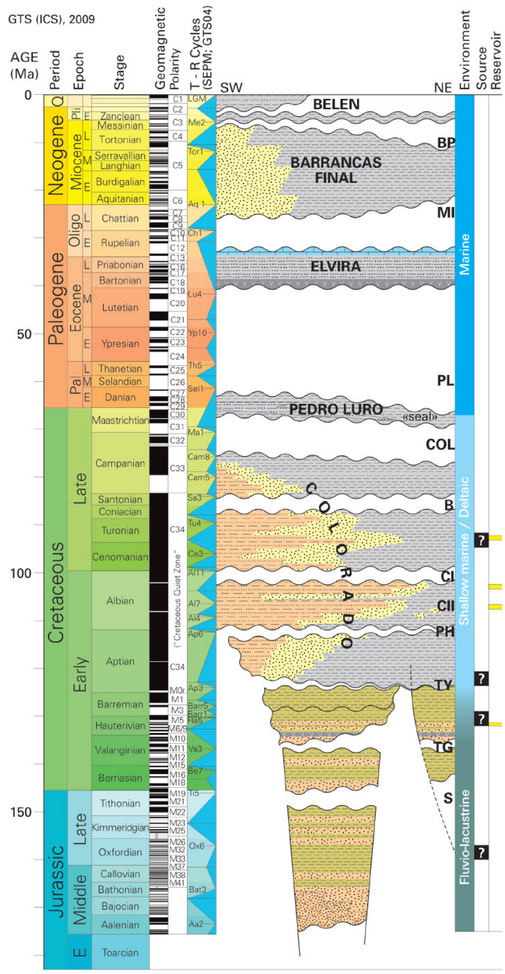

Figure 2. Chronostratigraphic chart and generalized tectonic evolution of the basin (Taken from Gerster *et al.* 2011).

Data was converted to the depth domain by means of a velocity model. The model was populated with pseudo-velocity grids estimated from the time structural maps of the main markers mapped along the existing seismic and their corresponding tops interpreted in the available wells.

Four dip oriented 2D seismic sections distributed in the area were chosen based on their quality, and all terminations in them were interpreted, with focus on the identification of clinoforms, and large-scale morphologies and structures (seismic sections 1 to 4 in Fig. 1). Rollovers were defined for each clinoform at the point where the gradient of the shelf rapidly increases basinward (Steel *et al*. 2002). The clinoforms were grouped in clinothems in each section independently, based on their rollover trajectories. One section presented the best quality (seismic section 1, Fig.1 and 3); rollovers and clinothems were identified for the entire Cretaceous sequence, and the horizons (clinoforms) corresponding to the top of each clinothem in this section were correlated laterally to the entire area.

Measurements were taken for each clinothem, including lateral and vertical displacement of the shelf edge between each clinoform, giving a quantitative value of progradation and aggradation respectively. With these values, the trajectory angle of the rollover (Tro) and progradation/aggradation ratio (P/A, Helland-Hansen & Hampson 2009; J. Neal & Abreu 2009; Paumard *et al*. 2019) were calculated. P/A ratios can be a proxy of the relation between sediment supply and accommodation space, with a high P/A associated with a relatively high sediment supply and/or low accommodation space. However, quantitative values should only be considered for comparison within a same sequence that can be correlated, otherwise the analyses should be constrained with age data. All values were measured in depth using a velocity model for the entire area and in case of the clinothems that were affected by structure, identification of rollovers and measurements were taken compensating for that structure by flattening to the closest regional surface available. Measurements were not corrected for compaction.

RESULTS

20 surfaces were interpreted in the area. These correspond to the Top Pre-rift, Top Synrift, Near Top Aptian, 16 horizons of Late Cretaceous age and the top of the Cretaceous. The 16 interpreted horizons correspond to clinoforms at the top of clinothems, that were grouped together based on the rollover trajectory they presented (Fig. 3 and 4). Four types were recognized: Falling trajectories, which correspond to progradational and degradational patterns in which the T_{ro} <0° and P/A <0; flat trajectories, which present a purely progradational pattern with 0°< T_{ro} < 1° and P/A >58; rising trajectories, with a T_{ro}> 1° and 0<P/A<58; and backstepping trajectories, with T_{ro} <0° and P/A <0 (Fig. 5).

Since seismic section 1 (Fig. 3 and 4) presented the best seismic quality and identifiable sequences, the surfaces delimiting the geometries in this section were followed laterally into the rest of the seismic in the studied area. It is important to mention that when grouping clinoforms into clinothems based on their trajectory type in individual dip sections, not always these correlate with each other regionally. The top of the clinothems interpreted in seismic section 1 (Fig. 4), when followed laterally towards the northern area not always correspond to the top of clinothems interpreted in that specific seismic line. For instance, Cl_3 and Cl_4 are amalgamated into one in seismic section 2, and they present a rising trajectory but do not correspond to the top of the recognized clinothem in the section; moreover, two flat trajectories and a backstepping type clinothem are found between horizons $Cl_{3/4}$ and Cl_5 in seismic section 2, that have no expression in seismic section 1. A more detailed analysis should focus on these clinothems within the main sequences, that have no regional correlation.

Quantitative information for each clinothem was taken on four different seismic sections laterally distributed across the area (Fig. 5). The 15 clinothems exhibit important lateral variation in terms of their trajectories and only 5 of these exhibit the same trajectory type regionally (clinothems 5, 6, 8, 10, and 13).

The 3 backstepping clinothems Cl_6, Cl_{10} and Cl_{13} were used to divide the entire interval into 4 sequences (Fig. 4, 5 and 6).

The Cl_0 clinoform (Fig.4 and 6A) is the first clinoform with a clear rollover that can be traceable laterally in the area. It is worth mentioning that older clinoforms and ramp style geometries with no clear rollover were identified towards the west, but these were not possible to follow laterally, and most likely they represent an incipient shelf-break being formed.

The first sequence is composed of 5 clinothems that prograde fairly eastwards (Fig. 6A). Cl_0 is the surface from which the first measurements are made, therefore it does not have information regarding progradation or aggradation. Cl_1 progrades greatly to the east with a maximum displacement of 33000 m and P/A ratio of 81 and a fairly low Tro of $<1°$, however to the south on the position of section 1 it presents and aggrading trajectory with a low P/A ratio of 11. Towards the north no quantitative data was taken since Cl_0 did not present a rollover at this position (Fig. 6A). Cl_2 presents a flat trajectory on the southern sector, prograding a maximum of 11000 m and a P/A ratio of 110, however, it purely aggrades to the north and it eventually amalgamates to the previous clinothem where it has no clear expression on its own. Cl_3 presents the maximum progradation of the entire sequence with a displacement of 33300 m and a P/A ratio of 71 in the center of the area, however, progradation is not as important to the north (P/A ratio of 39), and it purely aggrades to the south with a P/A ratio below 1. Cl_4 continues the tendency of Cl_3, with a flat trajectory in the center of the area of study with P/A ratio above 70. Towards the south, Cl_4 presents a localized falling trajectory with a -1.8° descending angle. There is a new change in the location of progradation in Cl_5, with P/A ratio increasing towards the northern area until reaching almost 50. This is the first clinothem with a consistent regional rising trajectory. To the south, trajectory angles are greater reaching 9°, whereas to the north, where progradation is greater, angles are just above 1°.

Cl_6 is the first regional backstepping clinothem, with negative P/A values between -5 and -600 and variable Tro between -11° to the south and -0.1° to the north (Fig. 6B) and it marks

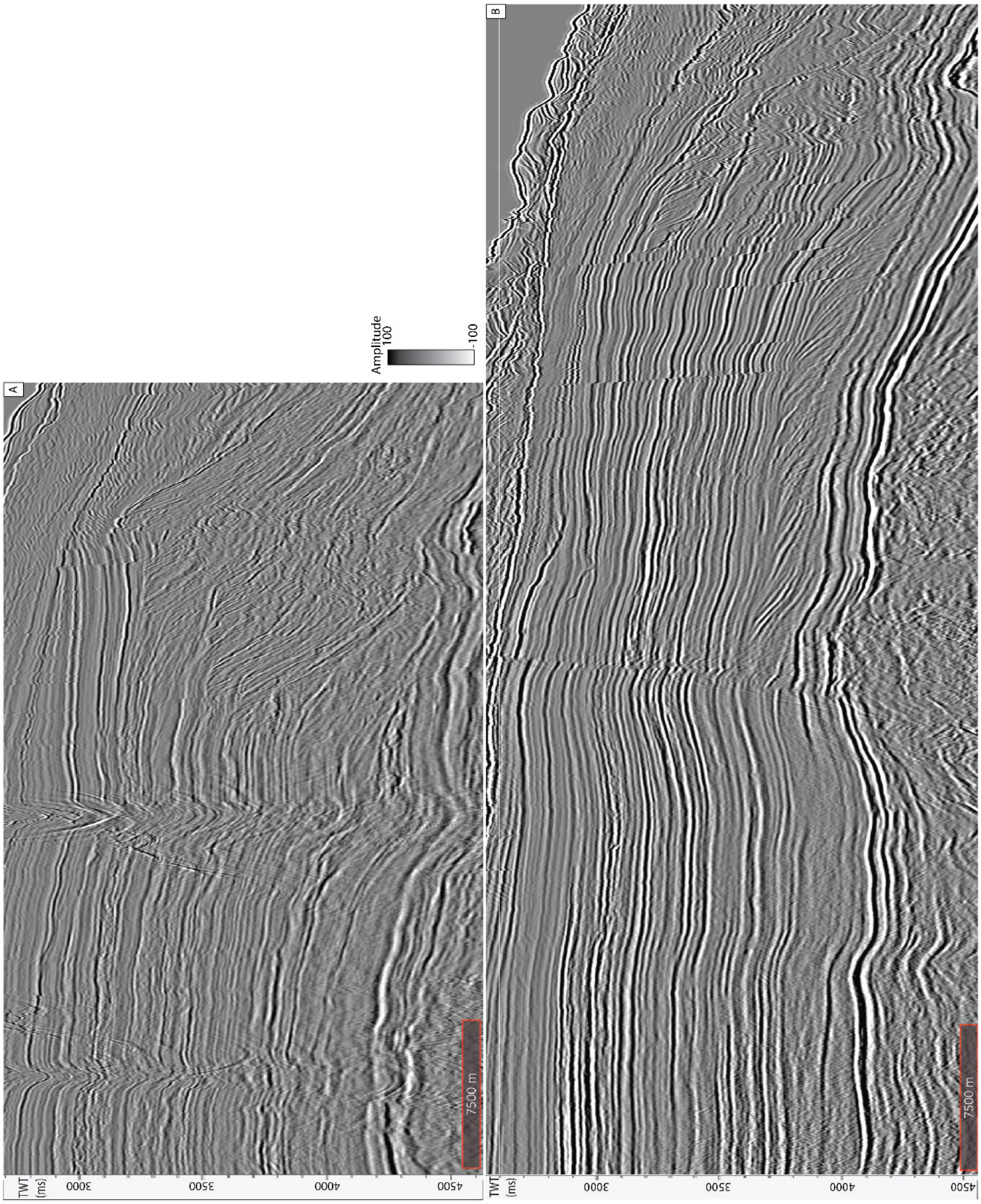

Figure 3. TWT seismic sections in the study area. A- Seismic section 1, located in the southern area of the block. B- Seismic section 4, located in the northern area of the block.

the beginning of the second sequence, which is composed of Cl_6, Cl_7, Cl_8 and Cl_9 clinothems (Fig. 6B).

Cl_7 retakes the progradation surpassing the last point of maximum progradation in the basin, advancing 15000 m, mostly with a flat trajectory with P/A values that vary between 100 and 400, with local exceptions of aggradation and falling trajectories to the south. There are specific areas in the central to northern part of the studied area in which shelf-

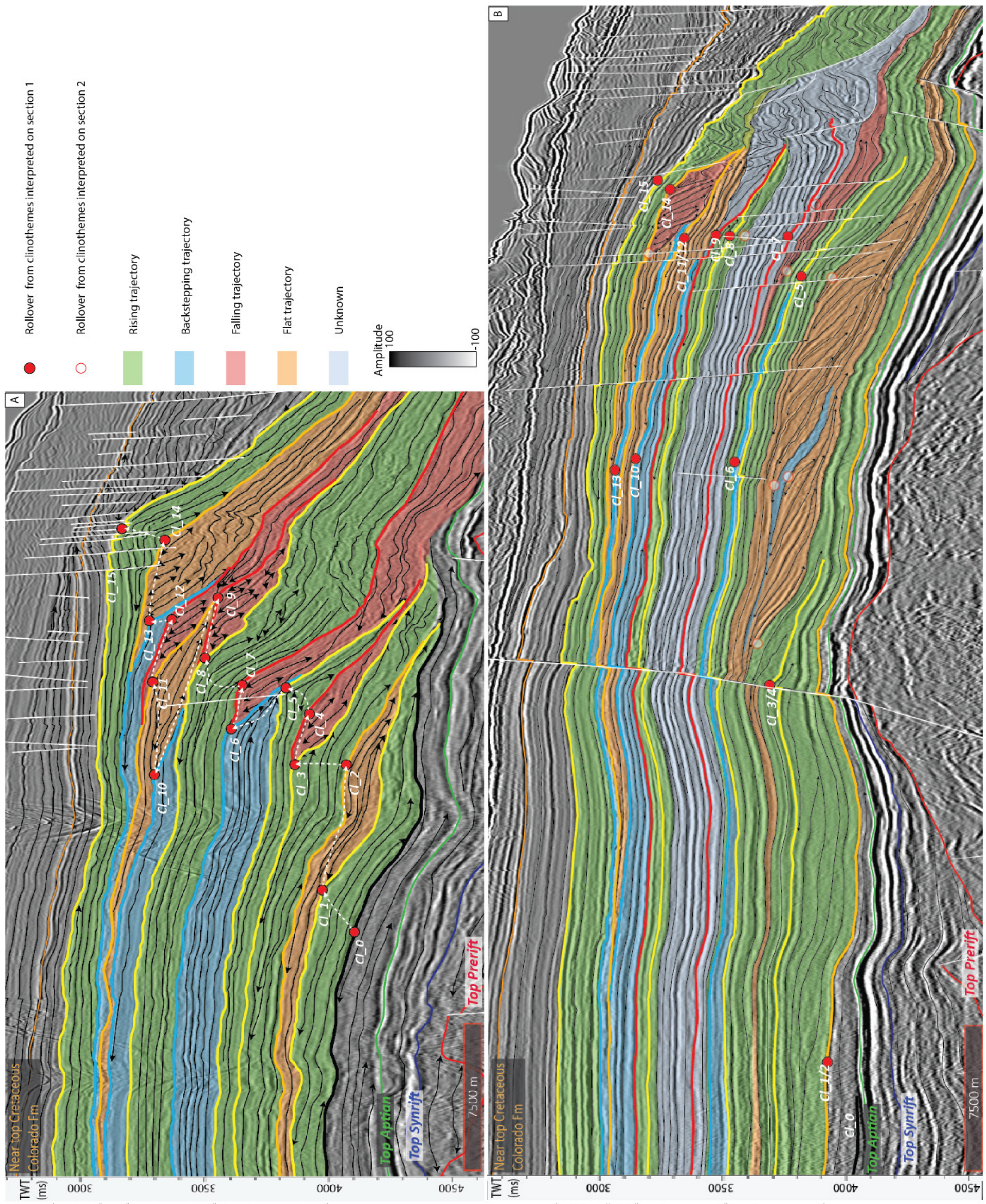

Figure 4. Interpreted TWT seismic sections in the study area, colored by type of trajectory. A- Seismic section 1, located in the southern area of the block. B- Seismic section 4, located in the northern area of the block. The horizons at the top of the interpreted clinothems from section A are also shown in section B. Notice the great lateral variability in the system, e.g. Cl_1 and Cl_2 are superimposed on section 4, as well as Cl_3 and Cl_4.

breaks are not identifiable due to collapse or erosion in the continental shelf-break and, on these cases, interpolation was used (Fig. 6B). Cl_8 is the second clinothem that presents a consistent rising trajectory measured in the entire area of study with uniform P/A values below 20 and T_{ro} reaching 20°. The clinoforms prograded larger distances towards the south with a maximum displacement of 5000 m. Cl_9 presents mostly a flat trajectory with P/A ratios of 66 to the north and localized falling trajectory in the southernmost area with a maximum progradation of 3300 m.

The third sequence is composed of 3 clinothems, Cl_{10}, Cl_{11} and Cl_{12} (Fig 6C). Cl_{10} is the second regional backstepping clinothem, with P/A values below -50 in the southern sector and maximum values of -680 in the northern sector. Tro are low, generally below -2°. Cl_{11} is a local clinothem, present only in the southern sector, it has a flat trajectory with P/A ratios around 400 and progrades only 4000 m. Cl_{12} recaptures the main progradation in the center and northern sector with high P/A values that reach 1000, with a predominance of flat and falling trajectories along the entire area.

Finally, the fourth sequence is also composed of 3 clinothems Cl_{13}, Cl_{14} and Cl_{15} (Fig. 6D). Cl_{13} is the last regional backstepping clinothem of the interval, with P/A values that reach up to -880 in the northern sector. Tro are generally low, frequently below -2°, except in the south where they reach -16°. Cl_{14} progrades with flat to aggradational trajectories with some uncertainty in the center of the area, due to a collapse in the continental slope, where rollovers are not preserved. Lastly, Cl_{15} presents a regionally consistent rising trajectory with a P/A below 11.

The last interval between Cl_{15} and the top of the Cretaceous, has onlapping reflectors from the west onto the continental slope, that eventually surpass the interpreted rollover of Cl_{15}. No shelf scale clinoforms are evidenced (Fig. 4).

Section	Sequence	Clinothem	Trajectory type	Shelf margin progradation (m)	Shelf margin aggradation (m)	P/A ratio	Trajectory angle (Tro, degrees °)
1	1	1	RISE	2200	205	10.73	5.3
		2	FLAT	6350	50	127.00	0.5
		3	RISE	350	380	0.92	47.4
		4	FALL	2075	-65	-31.92	-1.8
		5	RISE	1200	195	6.15	9.2
	2	6	BACK	-2000	375	-5.33	-10.6
		7	FALL	2400	-70	-34.29	-1.7
		8	RISE	1000	370	2.70	20.3
		9	FALL	3300	-30	-110.00	-0.5
	3	10	BACK	-8300	260	-31.92	-1.8
		11	FLAT	4300	10	430.00	0.1
		12	FALL	3500	-30	-116.67	-0.5
	4	13	BACK	-350	100	-3.50	-15.9
		14	FLAT	3800	10	380.00	0.2
		15	RISE	500	160	3.13	17.7
2	1	1	FLAT	33000	408	80.98	0.7
		2	FLAT	11000	100	110.00	0.5
		3	RISE	4000	345	11.59	4.9
		4	FLAT	2500	10	250.00	0.2
		5	RISE	9000	203	44.44	1.3
	2	6	BACK	-2200	193	-11.43	-5.0
		7	RISE	300	30	10.00	5.7
		8	RISE	1400	410	3.41	16.3
		9	FLAT	1100	20	55.00	1.0
	3	10	BACK	-9000	188	-48.00	-1.2
		11	FLAT	3900	10	390.00	0.1
		12	FLAT	3600	5	720.00	0.1
	4	13	BACK	-400	10	-40.00	-1.4
		14	RISE	1100	95	11.58	4.9
		15	RISE	1300	115	11.30	5.1
3	1	1	FLAT	25000	345	72.46	0.8
		2	RISE	2200	80	27.50	2.1
		3	FLAT	33300	470	71.00	0.8
		4	FLAT	11600	90	128.89	0.4
		5	RISE	6500	260	25.00	2.3
	2	6	BACK	-11500	230	-50.00	-1.1
		7	FLAT	12000	30	400.00	0.1
		8	RISE	2000	480	4.17	13.5
		9	FLAT	1000	15	66.67	0.9
	3	10	BACK	-33000	100	-330.00	-0.2
		11	not present				
		12	FALL	38000	-150	-253.33	-0.2
	4	13	BACK	-25000	210	-119.05	-0.5
		14	unknown				
		15					
4	1	1	FLAT	24000	200	120.00	0.5
		2	not present				
		3	RISE	19500	498	39.16	1.5
		4	not present				
		5	RISE	18000	368	48.91	1.2
	2	6	BACK	-8000	14	-571.43	-0.1
		7	FLAT	11500	110	104.55	0.5
		8	RISE	2400	124	19.35	3.0
		9	FLAT	1000	15	66.67	0.9
	3	10	BACK	-34000	50	-680.00	-0.1
		11	not present				
		12	FLAT	39000	35	1114.29	0.1
	4	13	BACK	-22000	25	-880.00	-0.1
		14	FLAT	17000	115	147.83	0.4
		15	RISE	500	115	4.35	13.0

Figure 5. Quantitative information and trajectory type from each clinothem on the four different seismic sections distributed on the area of study.

DISCUSSION

Sequence stratigraphy vs. trajectory analysis

The main advantage of trajectory analysis is that it is a model independent approach for the creation of a stratigraphic framework, without inferred assumptions of sea level fluctuations when predicting a succession (Paumard *et al.* 2019). Strata geometries are non-unique and can be the result of diverse mechanisms (Burgess & Prince 2015), that is why driving mechanisms should be avoided when using descriptive terminology. Paumard *et al.* (2019), show that less than 50% of the interpreted sequence stratigraphic surfaces and system tracts in their data presented the same interpretation 30 km apart. Only when an identifiable laterally continuous event is tracked, one could interpret these surfaces in terms of high order sequence surfaces. What is more, classic sequence stratigraphy can give the reader a biased interpretation. An interpreted falling stage system tract based on downstepping clinoforms that cannot be followed laterally, most likely does not respondse to a lowering in the accommodation space, and might be responding to something else (e.g. localized collapse in the slope on a still stand sea level).

On the other hand, the depositional sequence model (Catuneanu *et al.* 2009), has advantages like the ability to be applied when shelf margins are not preserved and establishing a relatively rapid sequence stratigraphic framework (Paumard *et al.* 2019), whereas measurements of shelf margin trajectories can be time consuming.

Stratigraphic evolution

Four sequences were identified based on the recognition of a backstepping trajectory of the shelf edge, where each of these can be interpreted as a transgressive event. Each transgressive event is followed by a regressive succession with different types of trajectories toward the basin. Although age information is scarce for most of the Cretaceous in the area of study, the transgressive-regressive (TR) sequences can be interpreted as 2nd order cycles, with variations corresponding to 3rd and 4th order cycles within each of these. A similar hierarchy of ciclicity was interpreted by other authors in the basin (Kress *et al.* 2021).

During the Barremian to Aptian times there was a deepening in the Colorado basin, associated with a broadening oceanic crust, marking a period of maximum flooding which can also be registered in other south atlantic basins of the Argentinean margin (Fig. 2 and 4; Arbe 2002; Kress *et al.* 2021). No shelf-break is interpreted in the area at the time and most likely it did not exist as such; the shelf-break was most likely formed at the onset of sedimentation in sequence 1. The first sequence progrades on top of the first marine transgression in the basin (Fig. 4). This sequence presents the most lateral variation in terms of P/A; the main progradation for

Cl_1 and Cl_2 is to the south, whereas Cl_3 and Cl_4 present higher P/A at the center of the area and Cl_5 shifts further to the north (Fig. 6A). This variation can be associated with a change in the location of fluvial feeder systems, with a consistent migration of these to the north. Once the feeder system is installed to the center and northern area it does not switch greatly, remaining in the same location following the forthcoming transgressive events, with a local exception in Cl_{11} to the south in sequence 3. Sequences 2 through 4 do not prograde further into the basin since they are constricted by the continental slope (Fig. 6A, Fig. 6B and Fig. 6D). Once they reached it, collapses were likely to occur (as seen in Cl_{15} in Fig. 4B). Most of the clinothems aggrade or prograde with a flat trajectory, however, falling trajectories are recognized in some clinothems (southern portion of Cl_5, Cl_8, Cl_{12} and Cl_{13} more regionally). These falling trajectories might not be associated with a lowering in the accommodation space, but perhaps with a collapse in

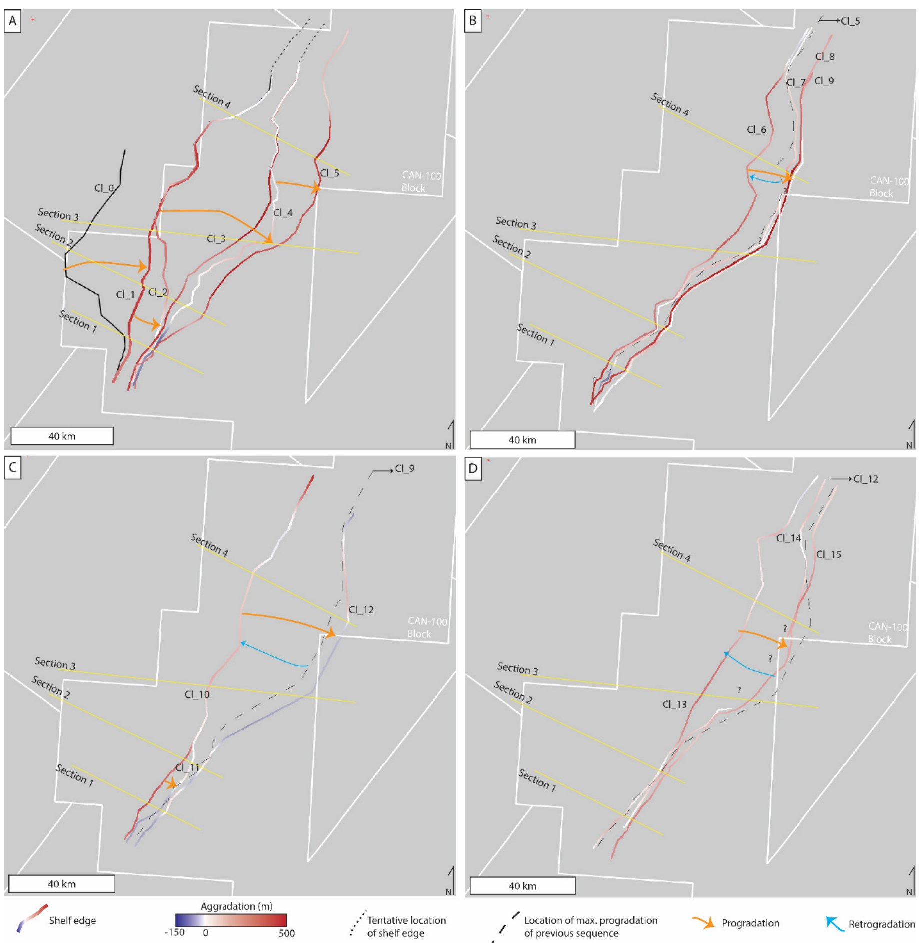

Figure 6. Map showing the evolution of the interpreted shelf margin rollovers for the Upper Cretaceous in the area of study. A- Sequence 1. B- Sequence 2. C- Sequence 3. D- Sequence 4. Sequences 2, 3 and 4, show the maximum progradation point of the previous sequence on dashed lines. Some reservations should be taken towards the center of the block (question marks on the map) where collapses in the continental slope occurred. Coordinates are in geographic system.

the upper slope. In addition, some small variations in the velocity model might have impacted on the differentiation between falling and flat trajectories. Specifically, towards the center, where the feeder systems were located and progradation was greater, great collapse morphologies are recognized, with sliding and slumping, most likely related to instability in the continental slope, where at the time of deposition, 3 types of clinoform coexisted at the same location (deltas building the shelf reaching the structural continental slope).

Low frequency controls

Tectonics and eustasy

In the area of study, although P/A relations vary laterally and through time, they are mostly positive, with sediment supply keeping up with the accommodation space. The relative sea level was rising most of the time, with periods of stillstand and high P/A, and periods with punctuated drowning events, represented by the regional transgressive tracts. The change from sequence 1 to sequence 2 can be related to a deepening of the basin, associated with a cooling of the oceanic crust and flexural bulging of the margin, and the development of a structurally controlled continental shelf-break (Kress *et al.* 2021). The following transgressive events represented by Cl_{10} and Cl_{13} might have been caused by regional subsidence of the passive margin, however, global sea level rises should not be disregarded.

The final transgressive event on top of Cl_{15} has been constrained as Campanian-Danian, by Ar/Ar dating of the Puelches volcanics (Lovecchio 2018) and it is interpreted to be time equivalent to the transgressive interval registered in the Neuquén Basin (Aguirre-Urreta *et al.* 2011).

Sediment input

During the Upper Cretaceous, the Colorado basin most likely represented the terminal sink of a source to sink system, with the source associated to the Andean region. The P/A is the highest in sequence 1, immediately after the maximum flooding of Aptian age. This great input of sediment should be explained by a major event in the hinterland. Coincidently, during the Albian there is a change in the subduction style in South America that causes the Neuquén basin to transition from a back-arc basin to a foreland basin, associated with the first phase of the Andean uplift (¨Peruvian Phase¨ by Cobbold & Rossello 2003). The sediments might have been transferred from the uplifted Andes region to the Colorado basin through a paleo Colorado river fluvial network (Kress *et al.* 2021). Even though supply areas are not well constrained and provenance analysis is needed to corroborate the upper mentioned hypothesis, some authors have emphasized the influence the Andean orogeny has had on younger sequences such as the Upper Miocene to Pliocene, where the basin was located in a backbulge position and subsidence occurred simultaneously with the Andean uplift (Folguera *et al.* 2015; Folguera & Zárate 2018).

High frequency controls

Tectonics and eustasy

Although the Cretaceous is known as a period of greenhouse climate (Haq 2014; Huber *et al.* 2002), some studies have suggested that ephemeral ice sheets might have developed at the poles, and shorter term glacio eustatic sea level variations might have existed (Miller *et al.* 2003; O'Brien *et al.* 2017; Sames *et al.* 2016). In addition, local subsidence may have played a role in creating accommodation space in preferred areas associated with structural features inherited from the rifting. This, along with high order eustatic variations might have been mechanisms influencing 3rd to 4th order cycles.

Sediment input

The different geometries and stratal arrangements that are internal to the identified TR sequences have a great lateral variation and this might be associated with autogenic responses of the system. The along-strike variability can be associated with the location of fluvial feeder systems, as evidenced in sequence 1, with progradation switching to the north as the system evolves. Other autogenic responses of the system should be hypothesized; e.g. the marine processes acting at the shoreline, like longshore drift currents that can have a great impact on the resulting morphology of the shelves (Steel *et al.* 2008). However, in order to better understand the higher order cycles and autogenic responses of the sequences more detailed information is needed (e.g. 3D seismic data and well logs).

CONCLUSIONS

An alternative to conventional sequence stratigraphic approach was used to describe and understand the evolution of the Upper Cretaceous shelf margin in the Colorado basin, with focus on trajectory analysis and along-strike variability.

Shelf scale clinoforms were identified in the basin and were grouped into 16 clinothems, based on the rollover trajectories they presented in a dip section. Once the rollovers of the 16 clinothems were laterally mapped, four 2nd order TR sequences were recognized. Sequence 1 presents great lateral variation; the main progradation for Cl_1 and Cl_2 is to the south, whereas

Cl_3 and Cl_4 presents higher P/A at the center of the area and then Cl_5 shifts further to the north. The main areas of progradation of the following sequences 2 through 4, do not vary laterally as the first. Towards the center of the area of study, where progradation was greater, collapse morphologies associated with sliding and slumping are recognized, most likely related to instability in the continental slope.

Allogenic controls in the basin are represented by tectonics, eustasy and sediment input. Four transgressive events were recognized, the first related to the cooling of oceanic crust, and the others by regional subsidence of the margin, global sea level rising or a combination of both. Eustatic variations might have also been important controls within each of the 2nd order cycles. The onset of sedimentation above a maximum flooding event is associated with a major fluvial system that progrades to the east, related to an Albian age Andean uplift. Autogenic responses have a great impact within each of the identified 2nd order sequences. It is better represented in sequence 1, where the location of the fluvial systems shifts to the north as the sequence evolves.

The identification of the areas of high P/A is key to understand sediment distribution in the basin and consequently the location of prospective reservoirs. It is far more likely to find high net to gross turbidite systems in the bottomsets of high P/A clinoforms rather than in low ones. In addition, using trajectory analysis, regional transgressive events were differentiated from local flooding events, which can be useful when identifying potential seals.

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