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PROVENANCE AND DEPOSITIONAL PROCESSES OF EXTRABASINAL (SILICICLASTIC) AND INTRABASINAL (CARBONATE) PARTICLES OF THE TITHONIAN–BERRIASIAN VACA MUERTA–QUINTUCO SYSTEM (NEUQUÉN BASIN, ARGENTINA)

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ABSTRACT

During the Early Jurassic–Early Cretaceous, between 32° and 40° S latitude, a steeply dipping active subduction zone along the western margin of Gondwana led to the development of a magmatic arc and a large back-arc depression known as the Neuquén Basin. A thick record of Tithonian–Berriasian organic rich sediments resulted from back-arc subsidence, expansion of the marine realm and flooding of the basin, which was presumably connected to the proto-Pacific Ocean through gaps in the magmatic arc. Widespread and persistent starved conditions in the basinal areas of the Neuquén Sea allowed the accumulation of a thick record of hybrid siliciclastic-carbonate sediments (“Vaca Muerta facies”), while along the eastern and southeastern cratonic basin margins, inner ramp deposits (“Quintuco facies”) were dominated by biogenic and clastic carbonates with subordinated muds, sands and salt deposits. The “Vaca Muerta Facies” is essentially composed of two (aggradational and progradational) accommodation sets. The aggradational set consists of hundred meters thick and widely distributed organic-rich silty and clayey mudstones with varying proportion of hemipelagic/pelagic siliceous and carbonate contribution, accumulated in the more distal sectors of the marine ramp under anoxic to suboxic conditions. The progradational sets, developed between the inner ramp and the deeper sectors of the basin, extend hundreds of kilometres both along and across the depositional dip, showing sigmoidal or clinoform geometries with well-defined topset, foreset, and bottomset configurations. In comparison with the aggradational sets, these intraplatform clinoforms are enriched in intrabasinal carbonate components and exhibit a reduction in organic matter content denoting a comparative increase in oxygenation of the marine bottom waters. If the productivity of pelagic biogenic carbonates was approximately constant at the basin level, the increase in the proportion of these components in the intraplatform clinoform deposits is attributed to the resuspension and dispersal of biogenic and clastic carbonate particles and grains from the internal ramp deposits (“Quintuco facies”) by cross-shelf oriented barotropic currents. These currents seem to be related either to storms and/or to deflection by the Coriolis Effect (Ekman component) of highly efficient geostrophic contour currents at depths above the pycnocline. In the

"Vaca Muerta facies" the supply of terrigenous siliciclastic particles has been voluminous and persistent, and the main source for these components was most probably the magmatic arc located to the western flank of the Neuquén Basin. Due to the marked stagnation and density stratification of the Neuquén Sea waters, much of the terrigenous fine-grained material was dispersed in the basinal and offshore settings of the basin by suspension plumes mobilised by baroclinic currents that travelled for long distances above the pycnocline.

INTRODUCTION

An epicontinental sea (epeiric sea) is a shallow-water inland sea or within a continental shelf almost surrounded by mainland, floored by continental crust, and usually connected to an ocean by rivers, straits or arms of sea. It is extensive (hundreds to thousands of kilometres), shallow, and with a very gentle slope (less than 1º) (Schieber, 2016). For the distal fine-grained deposits of epicontinental seas, two sedimentary models have been proposed: clear water and muddy water. The clear water model is dominated by (essentially biogenic) carbonate deposits, while the muddy water model is characterised by terrigenous clastic sediments (Feng, 1994, in Wang *et al.*, 2023). However, taken as a whole, the sedimentary record of the deeper settings (below wave-base) within epicontinental seas is far from being purely clear water or muddy water. The most common situation is the development of mixed or hybrid fine-grained sedimentary successions. These deposits can reach hundreds of meters thick and are composed of highly variable proportions of carbonate and siliciclastic components (Wei *et al.*, 2021; Schwarz *et al.*, 2022), depending on environmental factors such as the properties of marine waters, the sediment supply, and the climatic conditions (Tucker, 2003; Coffey and Fred, 2004; Seyedmehdi *et al.* 2016).

During the Tithonian–Berriasian, an epicontinental sea was laid down in the back-arc of the Neuquén Basin (central-western Argentina; Fig. 1A) in which marine ramp deposits accumulated. The more distal sectors of the ramp received the accumulation of pelagic and hemipelagic organic-rich sediments, essentially accumulated under anoxic conditions. The resulting black shale facies comprise the most important unconventional hydrocarbon reservoir in Argentina and the first economical unconventional self-sourced play outside North America (Minisini *et al.*, 2020). In this paper, we analyse the characteristics and distribution of sediment types in the Tithonian–Berriasian marine ramp of the Neuquén Basin, the primary accumulation processes, the potential areas of terrigenous input, and the main drivers that could have produced the redistribution of fine-grained particles (=components of sedimentary rocks less than 62 μm; Teruggi, 1982) at a basin scale.

GEOLOGICAL SETTING

The Neuquén Basin is located in west central Argentina and eastern Chile between 36° and 40°S (Fig. 1A). The basin fill covers an area greater than 120,000 km^2 (Yrigoyen, 1991) and is composed of continental and marine siliciclastic deposits, carbonates and evaporites that range in age from Late Triassic to early Cenozoic (Gulisano and Gutiérrez Pleimling, 1995; Vergani *et al.*, 1995). During the Middle Jurassic and the Early Cretaceous, the basin behaved as a back-arc setting. It was limited to the east and south by the cratonic areas of the Sierra Pintada System and the North Patagonian Massif, while to the west it was linked to the magmatic arc generated by the subduction of the proto-Pacific oceanic plate along the active western margin of southern Gondwana (Digregorio *et al.*, 1984; Legarreta and Uliana, 1991) (Fig. 1A). Thermal subsidence and regional extension favoured the development of an epeiric sea connected with the proto-Pacific Ocean through gaps in the arc (Spalletti *et al.*, 2000; Macdonald *et al.*, 2003; Spalletti, 2013), and thick successions, characterised by transgressive-regressive cycles of different scales, were deposited as a result of changes in eustatic sea-level oscillations and subsidence rates (Vergani *et* *al.*, 1995; Howell *et al.*, 2005; Schwarz *et al.*, 2006, 2016).

The Neuquén Basin has a broadly triangular shape (Fig. 1A) and two main regions are commonly recognized: the Andean Region to the west, and the Neuquén Embayment to the east and southeast (Fig. 1A). In the Andean region a series of N–S-oriented fold and thrust belts (Aconcagua, Marlargüe and Agrio fold and thrust belts) provide excellent outcrops of the Mesozoic successions (Howell *et al.*, 2005). In contrast, in the Neuquén Embayment most of the Mesozoic sedimentary record is in the subsurface and the beds are relatively undeformed (Howell *et al.*, 2005; Acevedo *et al.*, 2023).

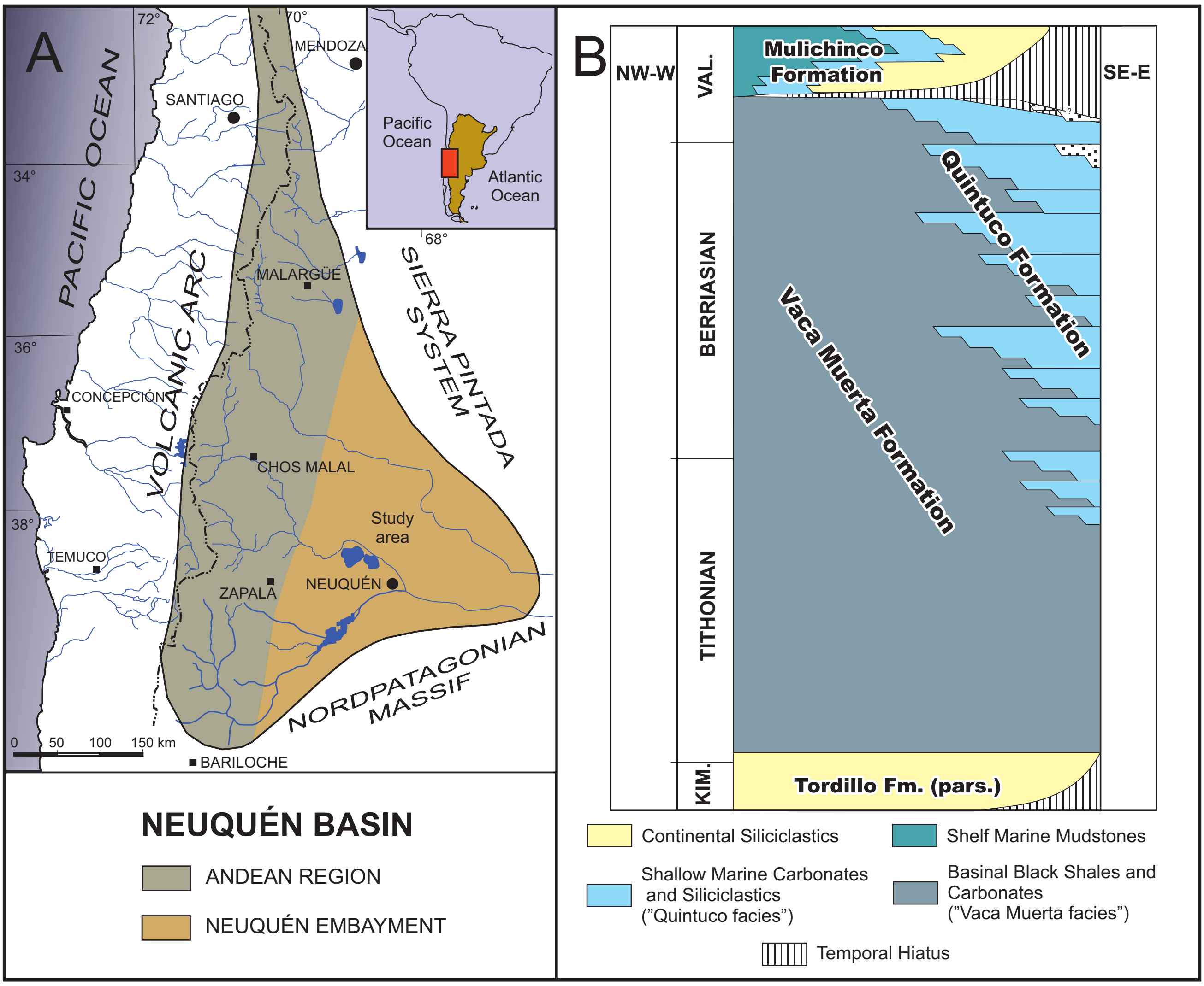

Figure 1. General context for the Neuquén Basin. **a)** Location map of the Neuquén Basin. **b)** Tithonian – Berriasian stratigraphy (Vaca Muerta – Quintuco System).

In the Neuquén Embayment the Upper Jurassic–Lower Cretaceous (Tithonian–Berriasian) sedimentary record is known as the Vaca Muerta–Quintuco mixed siliciclastic–carbonate system (Massaferro *et al.*, 2014). These deposits represent a shoreface to basin setting developed in a ramp-type interior sea. The Vaca Muerta Formation is an alternating shale-marl succession rich in organic matter, accumulated in the mid-distal ramp and basinal sectors of the depositional system. The Quintuco Formation is essentially composed of shallow marine moderate to high-energy deposits, dominated by bioclastic carbonates (Fig. 1B).

DATASETS AND METHODOLOGY

This study is based on detailed bed-scale sedimentological logging of the Tithonian–Berriasian outcrops located in the central-western sector of the Neuquén Basin (Fig. 2). Detailed lithological descriptions of siliciclastic and carbonate deposits were made on a centimetre scale, and include texture, composition, sedimentary structures, degree of reactivity with acid, geometry of lithosomes, and vertical relationships between successive bedforms. The study was complemented by the results of earlier surveys on sedimentary facies and stratigraphic sequences (Gasparini *et al.*, 1997; Spalletti *et al.*, 1999, 2000, 2008, 2014, 2015, 2019; Zeller *et al.*, 2015b) and the reader is directed to those for additional details concerning methods and results. These data were compared to previous sedimentological surveys on the Upper Jurassic–Lower Cretaceous marine deposits of the Neuquén Basin (Leanza, 1973, 2003; Carozzi *et al.*, 1993; Scasso *et al.*, 2005; Armella *et al.*, 2007; Kietzmann *et al.*, 2008, 2014, 2015; Massaferro *et al.*, 2014; Zeller *et al.*, 2014, 2015a: Krim *et al.*, 2017, 2019; Iñigo *et al.*, 2018; Paz *et al.*, 2019, 2022a, 2022b, 2023; Otharán *et al.*, 2020; Rodríguez Blanco *et al.*, 2020; Capelli *et al.*, 2021).

ACCUMULATION SYSTEMS OF THE NEUQUÉN EPICONTINENTAL SEA DURING THE LATE JURASSIC - EARLY CRETACEOUS: STACKING PATTERNS AND CLINOFORM CONFIGURATION

During Tithonian–Berriasian times, the basinal areas of the epicontinental Neuquén Sea were dominated by widespread starved conditions, from anoxic to suboxic in the marine substrate, which favoured the sedimentation of mixed, siliciclastic–carbonate fine-grained pelagic and hemipelagic components (Spalletti *et al.*, 2019). These deposits are characterised as “Vaca Muerta facies” (Figs. 2 and 3). They have a wide regional distribution in the Neuquén Basin and are the product of restricted vertical circulation of the marine waters, generalized eustatic rise (Legarreta and Uliana, 1991, 1996), and warm water temperature resulting in a high nutrient productivity (Spalletti, 2013). The development of a marked pycnocline (controlled by both halocline and thermocline) and oxycline during the accumulation of the “Vaca Muerta facies” resulted in stagnation of the deeper marine waters and hypoxia, with minimum levels of oxygenation on the substratum (Spalletti *et al.*, 1999), while surficial and shallow waters remained with a high degree of oxygenation that allowed the proliferation of abundant planktonic and nektonic biota (Gasparini *et al.*, 1997, 2002). These environmental conditions have been associated with global warming processes due to the increase in the level of atmospheric CO2 and widespread transgressions on a planetary scale (Spalletti *et al.*, 2014).

It is worth noting that, while in the deeper areas of the basin anoxia-suboxia persisted during the entire studied interval with the accumulation of pelagic and hemipelagic fine-grained sediments, an extensive inner marine ramp environment occupied a continuous belt along the eastern and southeastern margins of the basin (Fig. 3). In contrast to the basinal areas, the substrate of the inner ramp was characterised by high levels of oxygenation. The resulting deposits were dominated by skeletal, ooidal, and peloidal carbonate sands together with tidal- and storm-related sands, algal carbonates, and gypsum/anhydrite deposits. These complex associations of shallow, marginal or nearshore marine settings together with sabkha, coastal plain and estuarine environments are known as the Quintuco, Loma Montosa and Picún Leufú formations (Leanza, 1973; Carozzi *et al.*, 1993; Massaferro *et al.*, 2014), and can be simplified as the “Quintuco facies” for the objective of this contribution (Figs. 2 and 3). Moreover, it is important to note that the studied stratigraphic interval does not include the late Berriasian–early Valanginian that clearly marks a change in depositional systems with the development of siliciclastic-dominated deltaic systems attributed to the Quintuco Formation (Olivo *et al.*, 2016). It is therefore possible to deduce that the pycnocline of the marine realm was placed around the depth limit between the nearshore and offshore areas of the basin.

Likewise, the overall stacking of the Tithonian–Berriasian sedimentary record shows a clear trend towards the dominance of the “Vaca Muerta facies” in the basal intervals of the succession (anoxic-suboxic starved basin state due to the Tithonian transgression), as well as a progressive increase in the participation of the “Quintuco facies” as a result of the gradual decrease in accommodation towards the younger sections of the sedimentary succession (Figs. 1 and 2).

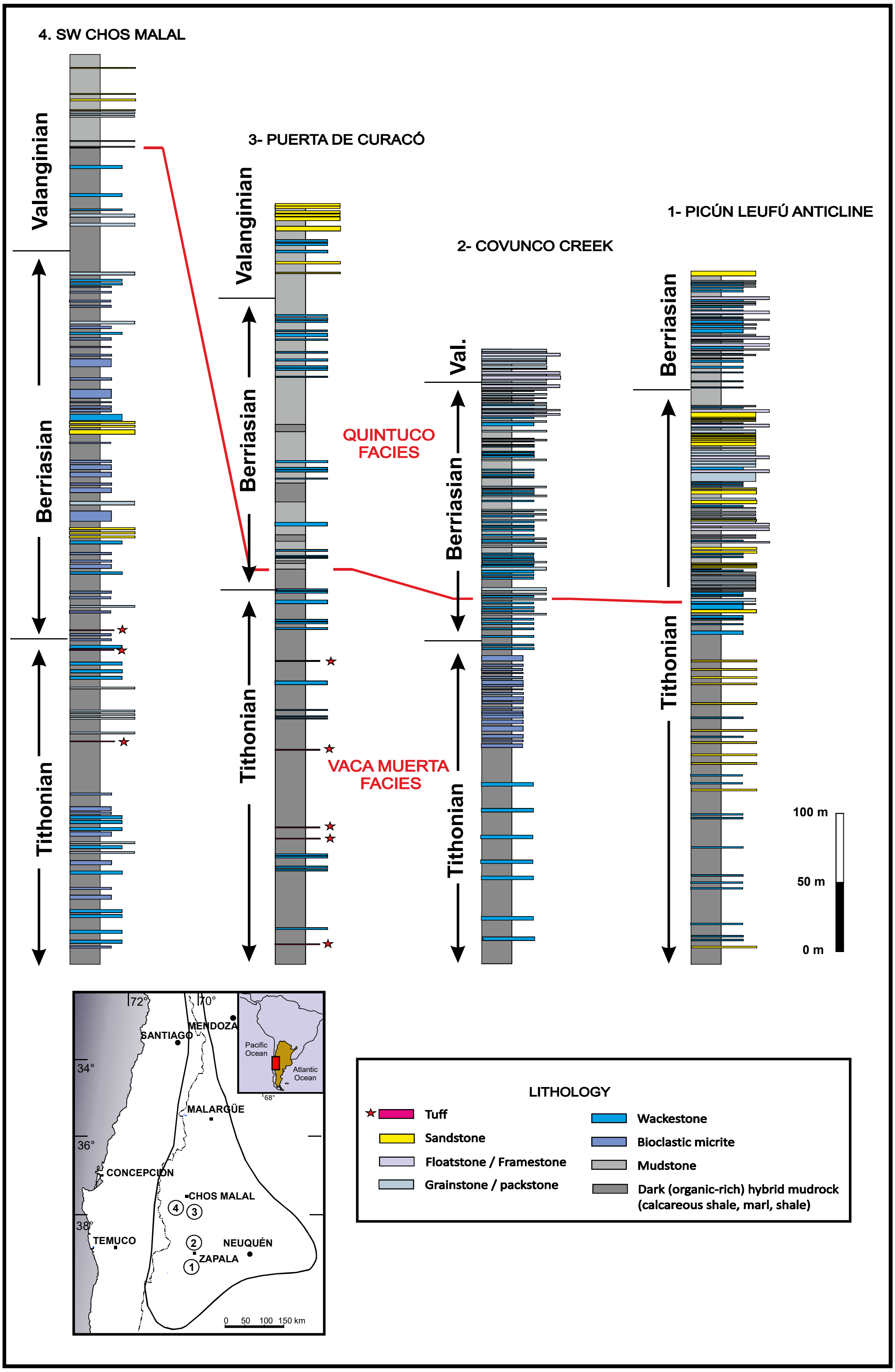

Figure 2. Graphic sedimentary logs of the "Vaca Muerta facies" and "Quintuco facies" exposed at four sections oriented N-S along the Andean Region of the Neuquén Basin.

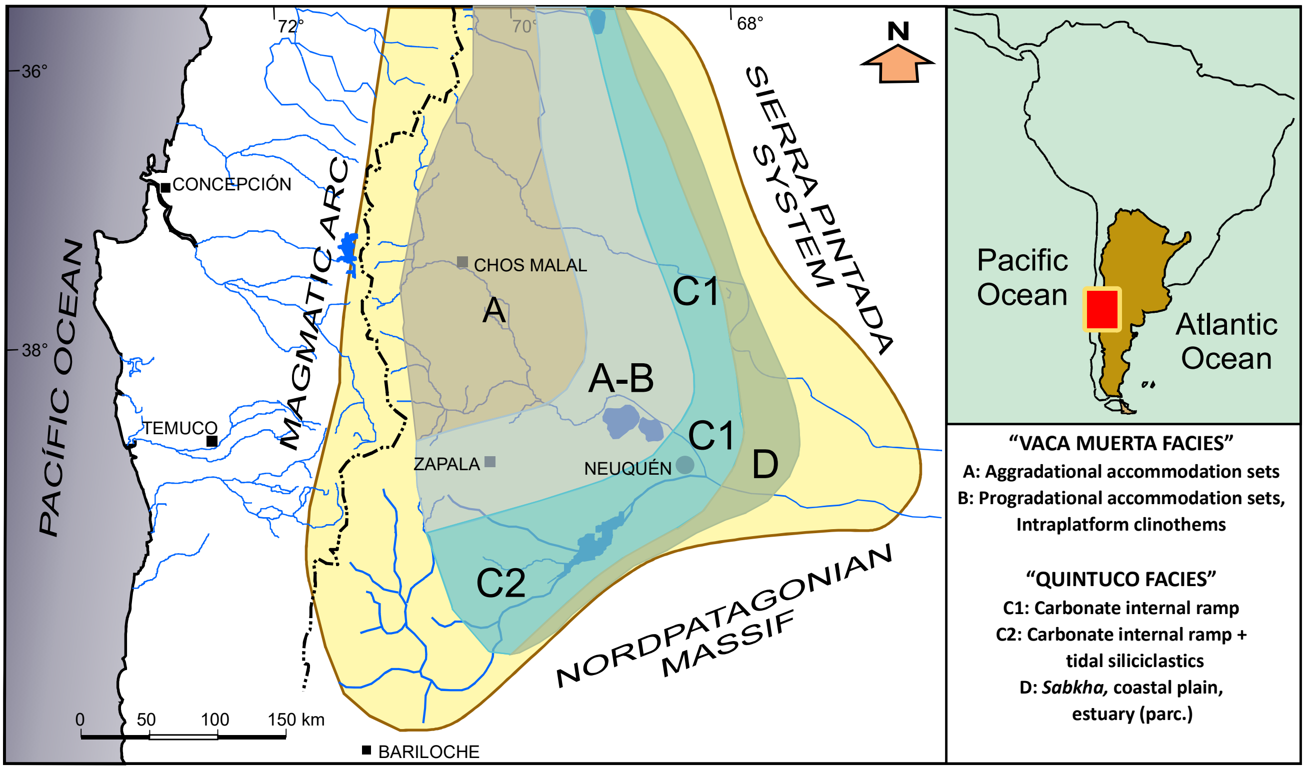

Figure 3. Regional distribution of the "Vaca Muerta facies" and "Quintuco facies".

In the "Vaca Muerta facies", Spalletti *et al.* (2019) have differentiated two accumulation models, which they called aggradational and progradational accommodation sets (Figs. 3 and 4). The aggradational accommodation set consists of clastic black shale successions composed of pelagic and hemipelagic deposits that reached a wide regional distribution occupying a large part of the marine basin during the Tithonian–Berriasian time. These aggradational sets are characterised by a typical tabular stacking, with thicknesses of hundreds of metres, and they represent accumulation processes occurring in the most distal sectors of the Neuquén Sea.

The progradational accommodation sets of the "Vaca Muerta facies" were accumulated in the middle sectors of the marine ramp (Spalletti *et al.*, 2019). Their sedimentary sequences show a typical sigmoidal or clinoform geometry (Mitchum and Uliana, 1985; Rodrigues *et al.*, 2009; Spalletti, 2013) with topset, foreset and bottomset configurations (Massaferro *et al.*, 2014; Reijenstein *et al.*, 2014; Zeller *et al.*, 2015a, b; Spalletti *et al.*, 2019) prograding towards the deeper sectors of the marine environment (Fig. 4). According to their location in the offshore settings of the basin, they are defined as intraplatform clinoforms (Hogdson *et al.*, 2017). Due to their very low slope (0.5 to 1-1.3°; Zeller *et al.*, 2014; Reijenstein *et al.*, 2014), they can be appreciated only when the vertical scale of the stratigraphic and/or seismic sections is greatly exaggerated (Fig. 4).

These progradational accommodation sets are large-scale features, as they reach an extent of hundreds of kilometres and their deposits are on the order of hundreds of metres thick (Fig. 4). These wedges accumulated on top of transgressive deposits of the aggradational accommodation set; they correlate with inner ramp carbonate sediments towards the basin margin, and with aggradational accommodation set deposits accumulated under subpycnoclinal waters towards the deeper sectors of the epicontinental marine ramp (Spalletti *et al.*, 2006, 2019; Zeller *et al.*, 2015a, b; Krim *et al.*, 2017).

SEDIMENTARY DEPOSITS OF THE MIXED VACA MUERTA - QUINTUCO SYSTEM

The most characteristic sediments of the "Quintuco facies" occur along the marginal areas of the basin, particularly located towards the eastern and southern sectors of the Neuquén Embayment (Fig. 3), and from a stratigraphic point of view they are preferentially located above the "Vaca Muerta

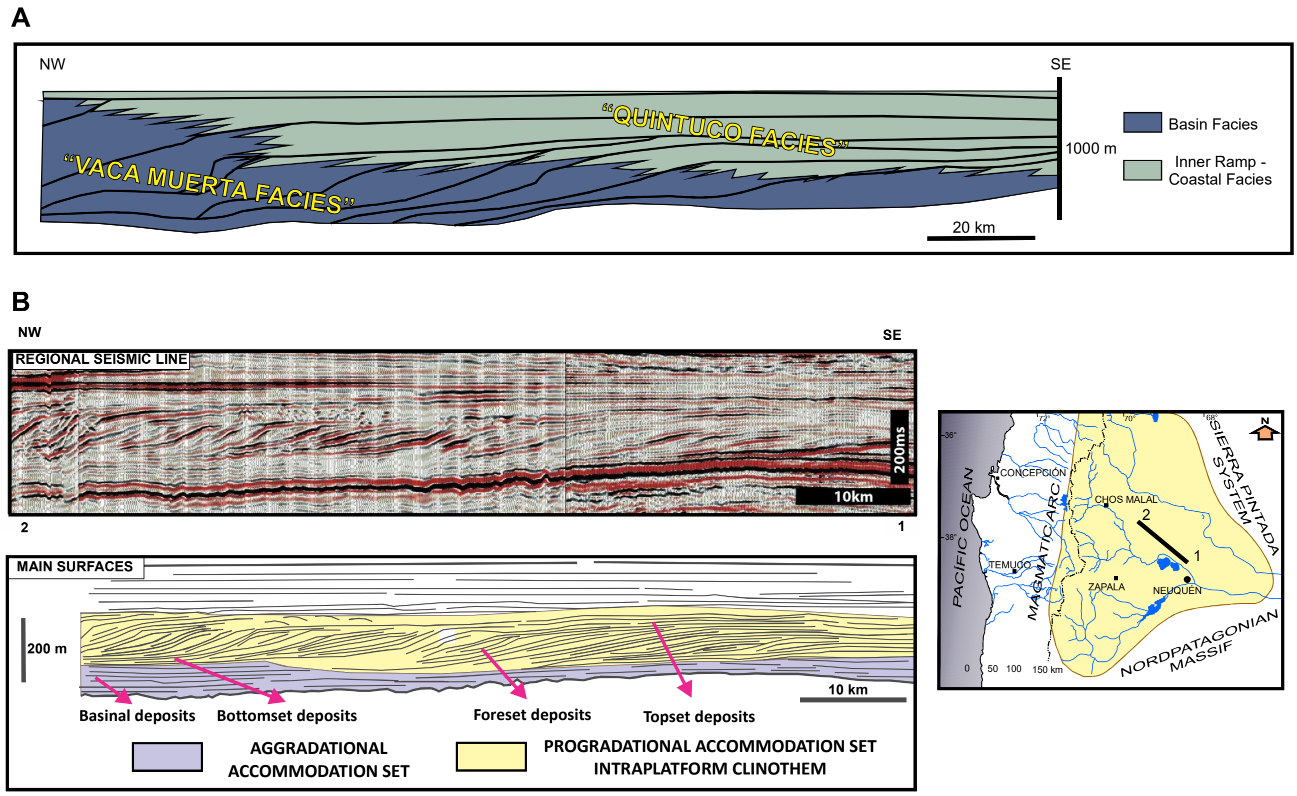

Figure 4. a) Regional geoseismic section of the Vaca Muerta–Quintuco System, after Rodrigues *et al.* (2009), modified from Mitchum and Uliana (1985). Check the large differences between vertical and horizontal scales. **b)** Regional seismic line and seismic interpretation from 1 to 2, based and modified from Massaferro *et al.* (2014) and Zeller *et al.* (2015b).

facies" (Figs. 1B and 4). The carbonates essentially consist of biogenic skeletal grains produced and accumulated in the shallow inner areas of the marine ramp. Volumetrically speaking, shell fragments are mainly derived from crinoids, echinoderms, shallow and deep infaunal bivalves, epifaunal bivalves (ostreids), and free-living bivalves (pectinids), gastropods, serpulids, and corals. They are associated with non-skeletal grains, such as peloids, ooids and carbonate mud. The most conspicuous varieties of resulting carbonate rocks are oolitic and bioclastic grainstones, packstones, mudstones, wackestones, paraautoctonous bioclastic rudstones, and float/framestones (Spalletti *et al.*, 2000; Armella *et al.*, 2007; Kietzmann *et al.*, 2008, 2014; Zeller *et al.*, 2015b; Paz *et al.*, 2019; Rodríguez Blanco *et al.*, 2020). Bodies of algal stromatolite bindstones, argillaceous dolostones, and massive and chickenwire anhydrite are also recorded in the region towards the eastern margin of the basin (Carozzi *et al.*, 1993; Iñigo *et al.*, 2018; Schwarz and Veiga, 2019). All these carbonate-dominated deposits are commonly associated with laterally continuous sigmoidal and mounded fine- to coarse-grained sandstone bodies. Oolitic/bioclastic grainstones and packstones, as well as siliciclastic sandstones, show a great variety of sedimentary structures, particularly planar and trough cross-stratification, planar parallel lamination, hummocky cross-stratification, and herrigbone cross-bedding (Spalletti *et al.*, 2000; Zeller *et al.*, 2015b, Schwarz and Veiga, 2019, Acuña Podestá, 2022; among others).

The Tithonian–Berriasian fine-grained sediments of the "Vaca Muerta facies" accumulated in a basinal marine environment are texturally homogeneous silty mudstones to clayey mudstones rich in organic matter and with minimal participation of sand grains, showing marked fissility, tabular geometry, and great areal continuity. Fine-grained ash layers occur interbedded within these deposits. The main accumulation process of the "Vaca Muerta facies" is settling from suspension, resulting in sediments of a mixed or hybrid nature, with varying proportions of siliceous and carbonate components, whereby carbonate-rich mudstones (> 66% carbonate), marls (33%–66%) and siliciclastic-rich mudstones (< 33% carbonate) are recognised (Fig. 5).

Siliceous components can be either hemipelagic, *i.e.* consisting of extrabasinal allotigenous particles (Spalletti *et al.*, 2014, 2015; Krim *et al.*, 2017), or pelagic, resulting from the accumulation of very fine biogenic debris (predominantly radiolarian skeletons). For the carbonates of the "Vaca Muerta facies", it is essential to consider two main types of provenances, both typically intra-basinal. Pelagic components were supplied by planktonic microfossils, mostly derived from sponges (spicules), foraminifera, ostracods, and nannofossils (halophytic algae, calcispheres and juvenile foraminifera). These pelagic-derived carbonate debris prevailed in the deeper sectors of the Tithonian–Berriasian ramp and were most likely deposited by settling from suspension. The second provenance is represented by carbonate debris derived from biogenic nektonic fossils, such as ammonites, and skeletal remains of marine reptiles (ichthyosaurs, plesiosaurs, crocodiles, turtles) and fish. In contrast, the carbonate population of the topset, foreset and bottomset deposits of the progradational accommodation sets includes both the planktonic and nektonic components mentioned above and finely disaggregated grains of intra-basinal carbonates that are the product of erosion, remobilization and resedimentation of previously formed deposits in the shallow inner ramp regions (Krim *et al.*, 2017).

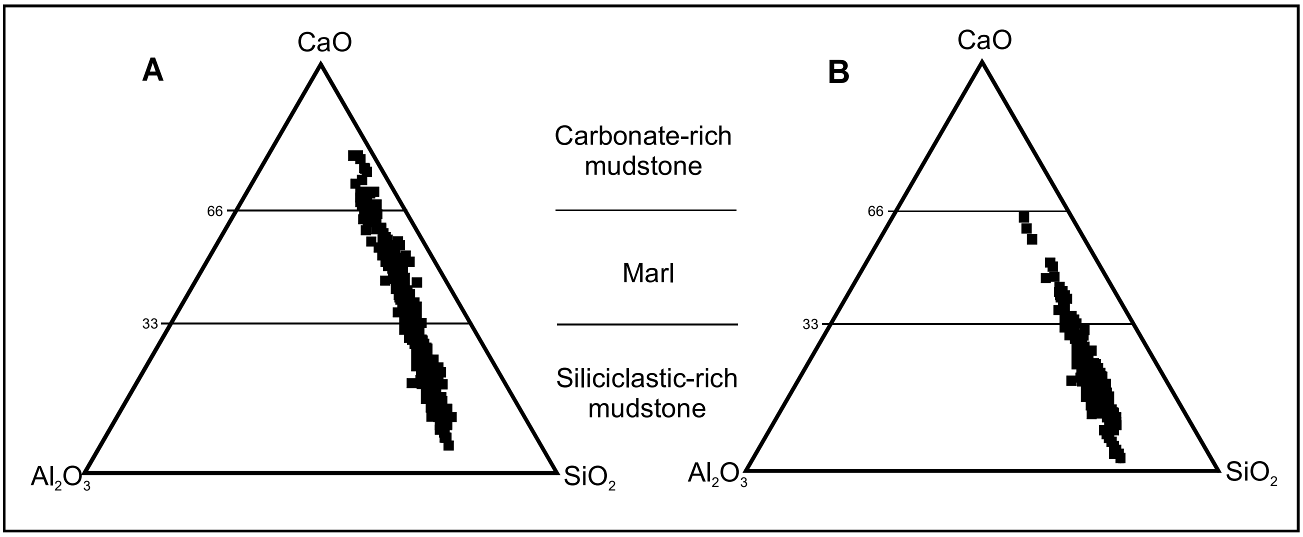

Figure 5. Ternary plots CaO–Al_2O_3–SiO_2 showing compositional differences between fine-grained samples of the "Vaca Muerta facies" (data from Spalletti *et al.*, 2019). **a)** Progradational and **b)** the aggradational accommodation set. Each point represents and individual sample.

The resulting sedimentary successions often have a rhythmic vertical stacking (Fig. 6). Elemental cycles, bundles and superbundles with frequencies in the Milankovitch band (Kietzmann *et al.*, 2015; Kohan Martínez *et al.*, 2018) were attributed to high and low frequency precession and eccentricity periodicities. In the fine-grained deposits of the aggradational accommodation sets, which represent the deepest sectors of the marine basin, the input of fine-grained terrigenous siliciclastic components was voluminous and may well have remained essentially constant. In contrast, the production of pelagic carbonate components showed significant variations related to global climatic changes, which regulated nutrient supply from the ocean (Kietzmann *et al.*, 2015). In short, there was a clear trend towards differential accumulation in these fine-grained mixed successions, essentially driven by changes in biogenic productivity.

In addition to these deposits, sporadic fine-grained, non-bioturbated, massive strata with mud intraclasts are due to local remobilization and resedimentation of sediments by mudflows caused by underflows or hyperpycnal or frictional currents (cf. Paz *et al.*, 2019; Otharán *et al.*, 2020). These intercalations occur preferentially in progradational accommodation sets where mudflows are favoured by the gentle gradient of the intraplatform clinoforms (Fig. 7).

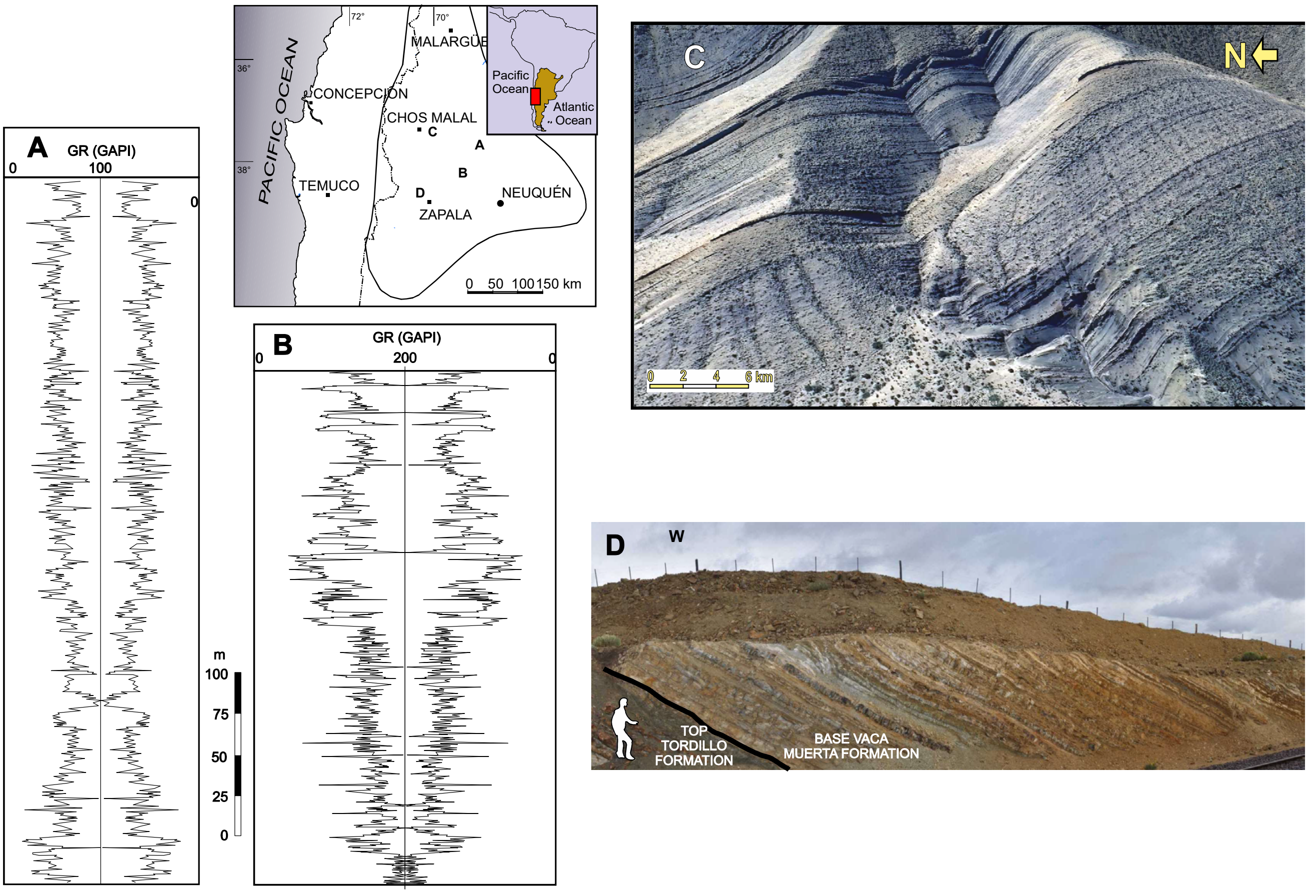

Figure 6. Rhythmic stacking of the Vaca Muerta fine-grained deposits. **a)** Gamma ray log at Aguada San Roque oil field. **b)** Gamma ray log at Aguada Pichana oil field. **c)** Satellite image of the Vaca Muerta outcrops at Puerta de Curacó locality. **d)** Cyclic stacking (bioclastic micrite/marl, marl/mudstone) within the Milankovitch spectrum band in the lowermost section of the Vaca Muerta Formation at Los Catutos (north of Zapala).

In the foresets and bottomsets of the progradational accommodation sets of the "Vaca Muerta facies", isolated intercalations of thin-bedded sandstones, coarse mudstones and bioclastic mudstones with low-energy tractional structures (parallel, low angle cross-lamination, ripple cross-lamination) and bioturbation, as well as completed bioturbated mudstones, are also identified. Paz *et al.* (2022a, b) have interpreted these deposits as contourites. However, these sporadic deposits mentioned for the substratum of a basin essentially dominated by anoxic conditions and very poor water circulation have a very marked difference in comparison with the thick and very continuous contouritic successions developed on the slopes of continental margins (cf. Shanmugam, 2017, 2021; Stow and Smillie, 2020, and references therein). These latter deposits are formed by the quasi-continuous circulation of depth contour bottom currents driven by Coriolis forces and temperature/salinity dependent density gradients. These processes are unlikely to occur persistently under restricted vertical circulation of the marine waters as occurred during the Tithonian–Berriasian in the Neuquén Basin (Fig. 7).

TRANSPORT-ACCUMULATION PROCESSES AND ORIGIN OF THE MAIN COMPONENTS OF THE "VACA MUERTA FACIES"

The fine-grained carbonate components

As the "Vaca Muerta facies" moves from the basinal deposits of the aggradational accommodation sets to the progradational accommodation sets of the intraplatform clinoforms (Fig. 4), progressive changes in the sedimentary deposits are recorded. The deeper, basinal and bottomset deposits of the clinoforms have comparatively higher organic-matter

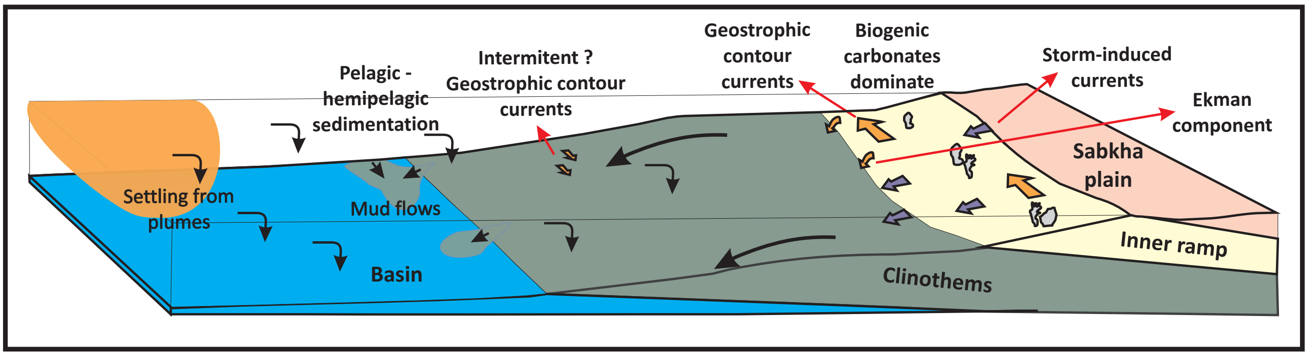

Figure 7. Schematic depositional model for the cratonic margin of the Neuquén Sea during the Tithonian–Berriasian interval.

content reflecting anoxic to suboxic conditions in the substratum. However, the bottomset deposits show a clear trend towards an increase in carbonate components when compared to the basinal deposits. On the other hand, the fine-grained sediments of the foresets and topsets exhibit a reduction in organic-matter content, which denotes a comparative increase in the oxygenation of the bottom waters (Spalletti *et al.*, 2019; Paz *et al.*, 2023), as well as a renewed increment in the proportion of carbonate components reflected by the greater participation of marl, micrite, carbonate mudstones, and bioclastic wackestones as dominant facies. These compositional changes in the sedimentary system are clearly reflected in the diagrams of Fig. 5.

Assuming that the productivity of pelagic biogenic carbonate components is approximately constant at the basin level, the increase in their proportion in the intraplatform clinoform deposits can be attributed to the supply of particles and grains from the shallower sectors of the marine environment, characterised by the high productivity of inner ramp carbonates, typical of the "Quintuco facies". The remobilization of these components could be attributed to the action of cross-shelf oriented barotropic currents, this is towards the deeper zones of the clinoforms (Figs. 7 and 8). It is assumed that these currents mobilized the carbonate particles essentially by suspension and might have been induced either by geostrophic contour currents or by seaward-oriented, storm-driven relaxation flows (Figs. 7 and 8).

Thermohaline or wind-induced geostrophic currents are considered excellent redistributors of sedimentary load, as they move over distances of hundreds of kilometres essentially parallel to isobathymetric lines (Heezen, 1968; Shanmugam, 2017 and references therein). In the case of the Tithonian–Berriasian record of the Neuquén Basin, as it is currently the case in the Black Sea (Kershaw, 2015), due to the anoxic conditions in the deeper and stagnant marine waters of the basinal regions, these currents could have been highly efficient at depths above the pycnocline, *i.e.* only in the nearshore or inner ramp marine environments where the accumulation of the "Quintuco facies" took place (Figs. 7 and 8). However, the wind-induced geostrophic currents can show important deflections due to the Coriolis Effect (Ekman component), generating an important cross-shelf oriented displacement from shallow to deep areas (Figs. 7 and 8). It is clear then that the Ekman component must be considered as an effective mechanism for offshore-directed transport of the preferentially resuspended carbonate particles from the inner ramp regions to the foreset areas of the intraplatform clinoforms.

On the other hand, it is highly probable that under storm conditions, characterised by intense wind activity, the erosion processes of the "Quintuco facies" were accentuated in the inner ramp due to the increase in wave height accompanied by the circulation of residual tidal currents (Figs. 7 and 8). These storms are also very effective transport/accumulation agents, as their action leads to an intensification of sediment resuspension and dispersal mechanisms, with the expansion and cross-shelf exchange of the plume of suspended particles and the consequent increase of their inputs in the direction of offshore environments (cf. Traykovski *et al.*, 2000; Lentz and Fewings, 2012; Ralston *et al.*, 2013; Wang *et al.*, 2014; Schieber, 2016; Pang *et al.*, 2020).

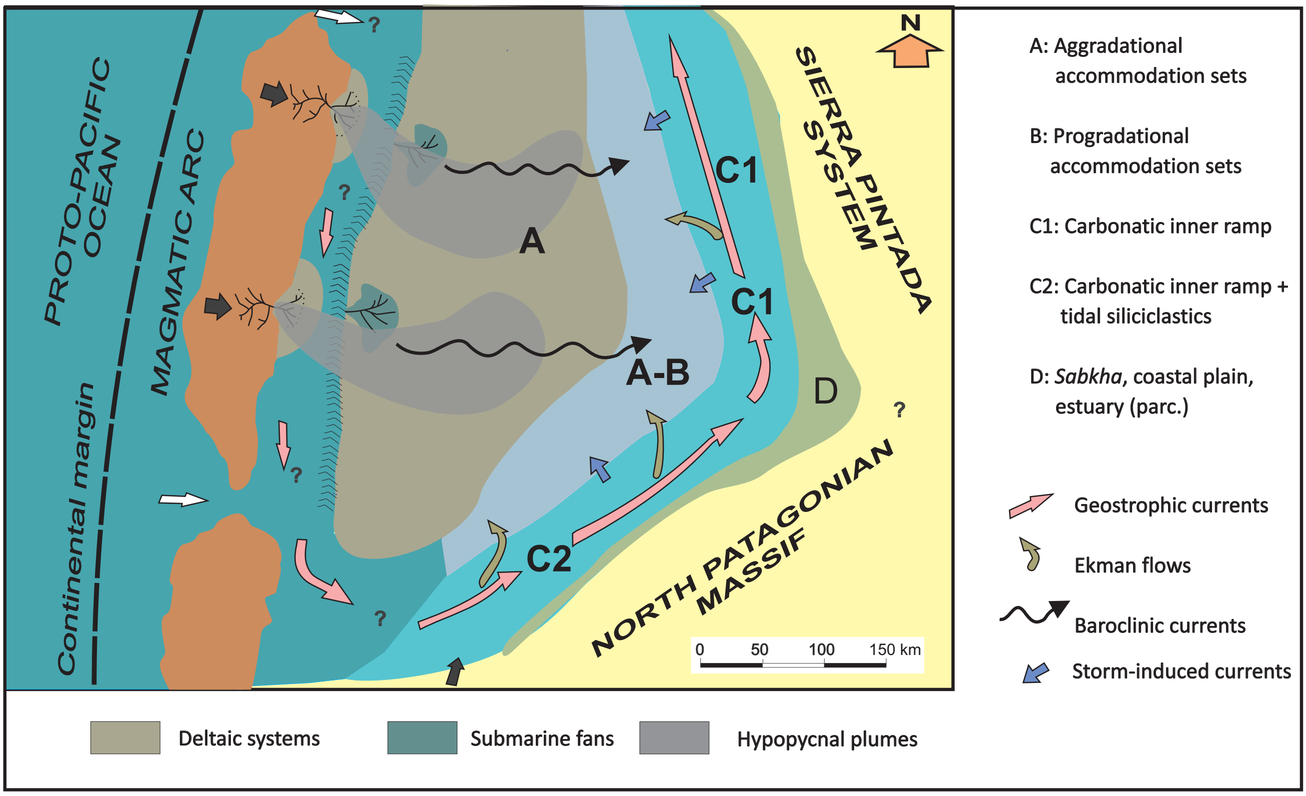

Figure 8. Conceptual model of the main marine current systems responsible for the redistribution and sedimentation of particles towards the outer ramp and basinal sectors of the Neuquén Sea during the Tithonian–Berriasian interval.

The fine-grained siliciclastic components

In the hybrid successions of the "Vaca Muerta facies", the contribution of siliciclastic particles has been voluminous and persistent, especially in the hundreds of meters thick aggradational accommodation sets (Fig. 4B). Two main questions arise in relation to the origin of the siliciclastic particles; one refers to the source areas and the other to the mechanisms that produced their continuous arrival at the seafloor over ca. 7 my.

Regarding the provenance of siliciclastics, it is important to note that during the Tithonian–early Berriasian along almost the entire eastern and southern margins of the Neuquén Embayment, no sedimentary systems efficient enough to provide considerable volumes of terrigenous components to the marine basin have been identified (Iñigo *et al.*, 2018). Neither extensive and integrated fluvial drainage networks nor well-developed deltaic systems are defined in these coastal regions (Fig. 8). The deficit in the contribution of extrabasinal materials can be explained by the existence of continental areas with low relief and predominantly dry climatic conditions. Under these circumstances, it could be assumed that terrigenous siliciclastic components could have been contributed by aeolian dust storms such as in present offshore Mauritania (Michel *et al.*, 2011; Klicpera *et al.*, 2015); however, the virtual absence of dune deposits in the marginal areas and the scarce participation of sands along the eastern marine margin of the Neuquén Embayment do not support this alternative.

Towards the southwestern margin of the basin, in the inner ramp facies, shallow marine carbonate deposits and siliciclastic sands/muds accumulated especially by tidal action (Spalletti *et al.*, 2000; Zeller *et al.*, 2015b). These sediments are associated with fluvial, deltaic and estuarine systems at different evolutionary stages of the sedimentary record (Leanza, 1993; Moyano Bohórquez, 2004; Paz *et al.*, 2019). The marginal or transitional record of this system is composed of thin and fine-grained interdistributary bay facies, mouth bars dominated by heterolithic deposits and poorly developed channels suggesting both low efficiency and tidal dominance. Although these systems may have provided a small part of the siliciclastic fine-grained components that contributed to the offshore/basinal deposits, they cannot be invoked to explain the enormous volume of siliciclastic particles that characterise the Tithonian-Berriasian record of the "Vaca Muerta facies" in the basinal distal most settings of the Neuquén Sea.

At the same time, along the western flank of the basin, a magmatic arc developed in a continuous meridian direction (Fig. 8), roughly parallel to the active continental margin of western Gondwana (Legarreta and Uliana, 1991; Howell *et al.*, 2005; Spalletti, 2013). This topographic barrier was probably dissected by relatively narrow corridors that connected the Neuquén Sea with the proto-Pacific Ocean (Spalletti *et al.*, 2000; Macdonald *et al.*, 2003; Spalletti, 2013) and contributed to the restricted connection of the Neuquén Basin with the consequent development of oxygen-deficient conditions in the deeper marine waters.

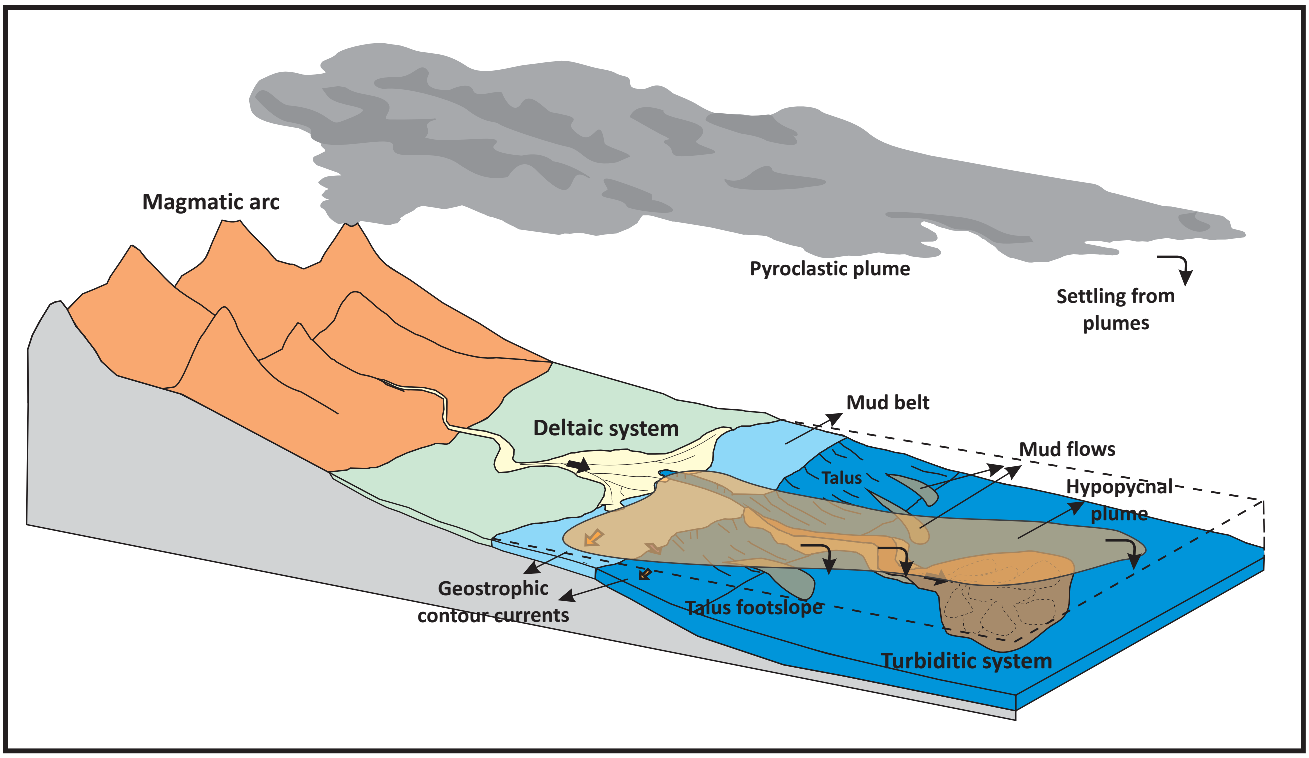

Figure 9. Schematic depositional model for the western (magmatic arc) margin of the Neuquén Sea during the Tithonian–Berriasian interval.

Marine deposits generated by gravitational sediment flows (high- and low-density turbidity currents, large-scale landslides) were identified in the western and deepest sector of the basin (Leanza *et al.*, 2003; Spalletti *et al.*, 2008; Spalletti, 2013). These features suggest the existence of a high-gradient zone on the active western flank of the basin and a seafloor profile with slope break and slope development, as well as the existence of efficient drainage networks in the magmatic arc region (Fig. 9). It is clear then that during the Tithonian–Berriasian there was a very high effectiveness of terrigenous contributions from the west (Fig. 9) where, in addition to the relief associated with the development of the magmatic arc, there were much wetter climatic conditions compared to the rest of the marginal areas of the Neuquén Basin.

However, the limited basinward extension of the gravity flow deposits suggests that the resulting hyperpycnal flows were not efficient enough to produce the wide distribution of fine-grained sediments throughout the basin interior. This was most likely related to the marked stagnation and density stratification of the Neuquén Sea waters and thus to the development of a persistent pycnocline. The activity of geostrophic bottom currents in subpycnoclinal waters, suggested by Paz *et al.* (2022a), could not have been effective as it would have produced a strong alteration of the system erasing the pycnocline and oxygenating the bottom waters. Therefore, it is inferred that much of the fine-grained particles were supplied to the marine basin by hypopycnal suspension plumes (Fig. 9) sourced either from one or multiple river mouths (cf. Vic *et al.*, 2014; Wu *et al.*, 2014; Luo *et al.*, 2017). This siliciclastic supply was probably combined with intermittent pyroclastic plumes and ash falls produced by active volcanism located along the Andean magmatic arc (Fig. 9). Worth to mention, marine hypopycnal plumes have been tracked in the marine environment at distances of hundreds of kilometres from the river mouth (Hopkins *et al.*, 2013; Shanmugam, 2019). Because of their low density they run at shallower depths and/or along the thermo-halocline without affecting the dominant physicochemical conditions in the substrate (Fig. 10). Under these circumstances, we suggest that the dispersal of the fine suspended particles of the plumes may have been driven by baroclinic currents controlled by vertical variations in seawater density, which are usually associated with internal tidal waves propagating along the boundary between waters of different density (the pycnocline, Fig. 10) (cf. Shanmugam, 2013; Wright, 2014). It is worth noting that mudflow deposits located preferentially on the foresets of the Vaca Muerta clinoforms (Fig. 7) would be the result of the baroclinic currents turnover around the contact between the marine ramp substrate and the pycnocline.

In conclusion, while thermohaline geostrophic currents and/or wind-induced marine currents redistributed the terrigenous fine-grained material in the inner ramp sectors of the basin, in the basinal and offshore settings of the Neuquén Sea, the dispersal of fine suspended sediments could have been produced from suspension plumes mobilised by marine currents that travelled for long distances above the pycnocline (Figs. 8 and 10).

DISCUSSION ON THE DEPOSITIONAL MODEL FOR THE "VACA MUERTA FACIES" IN THE NEUQUÉN SEA

The geographical, tectonic and climatic conditions under which sedimentation of black shales occurred in the Neuquén Basin during the Tithonian–Berriasian were extremely peculiar. The generation of these deposits is ultimately the result of a complex interaction of factors controlled by climate, oceanography, tectonic setting, and basin evolution, among which the circulation and oxygenation levels of marine waters, the existence of warm waters, the organic productivity (nutrient input), the accommodation (input/subsidence ratio), and the superimposition of short-term climatically induced variations on sea-level change stand out.

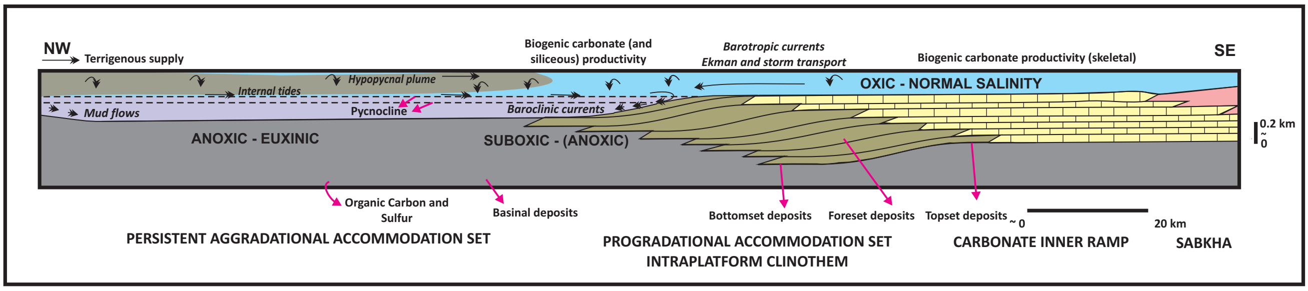

Figure 10. Inner ramp-basinal depositional model reconstructed for the Tithonian–Berriasian interval on the Vaca Muerta–Quintuco System.

The main attributes of the basin during the Tithonian–Berriasian are (1) its generation in an epicontinental sea surrounded to the east and southeast by cratonic areas and to the west by a magmatic arc generated by subduction of the proto-Pacific plate beneath the continental crust of western Gondwana; (2) the persistence of marked hypoxic conditions over very extensive basinal regions determined by a strong regional, persistent and stable pycnocline reducing vertical mixing of the water column; (3) comparatively shallow depth (100–400 m (Mitchum and Uliana, 1985; Rodríguez Blanco *et al.*, 2022) of the Neuquén Sea, which resulted in a limited volume of the sub-pycnocline water mass and facilitated benthic oxygen depletion; (4) connection of the Neuquén Sea with the eastern proto-Pacific Ocean, characterised by extreme shallowing of the oxygen-minimum zone, through shallow marine corridors that crossed the region of the active magmatic arc; (5) a long period of high glacio-eustatic highstand; (6) warm, arid to semi-arid climate along the eastern flanks of the basin and somewhat wetter towards the western basin margin represented by the orographic system of the magmatic arc. Although these six attributes were key elements in shaping the overall stratigraphic sequence, the cyclical vertical stacking of the Vaca Muerta fine-grained deposits also suggests productivity variations due to climatic oscillations of different periodicity (Kietzmann *et al.*, 2015), caused by orbital changes that affected the level of solar radiation over the Earth's surface.

The depositional features and the circumstances under which the accumulation of the Tithonian–Berriasian deposits in the Neuquén Basin occurred can only be partially compared to those of modern marine environments exhibiting widespread seafloor anoxia. The epicontinental character of the basin bears some similarities with the Hudson Bay, the Gulf of Carpentaria, the Baltic Sea, and the Black Sea. As in the Neuquén Basin during the Tithonian–Berriasian, the seawater depth in the first three examples is shallow (40 to 120 m; Algeo *et al.*, 2008); however, they differ in that they are located in humid regions and therefore receive important volumes of fluvial waters. On the other hand, the Black Sea shows similar environmental conditions to the Neuquén Basin, since it is located in a steppe continental region (average annual rainfall of 346 mm). However, the depth of the Black Sea is much greater and widespread, as it reaches more than 2,200 m in the central and deepest sector of the basin (cf. Poulos, 2023), while in the Tithonian–Berriasian Neuquén Sea the slopes were steeper only along the western flank of the basin and spent over short distances from uplands (arc) to the axis of the depocenter (Spalletti, 2013).

The sedimentary cycles comprising the "Vaca Muerta facies" in the aggradational sequence sets, essentially composed of fine-grained rocks rich in organic matter but with variable proportions of carbonates and siliciclastic particles, have a great lateral continuity that can be followed for hundreds of kilometres. The regional persistence of these deposits implies the uniformity of environmental conditions and the synchronism of changes in the properties of the water mass over large distances. These features can only develop under a stable and persistent pycnocline. Vertical mixing must have been significantly reduced and the pycnocline must have been relatively strong to maintain oxygen-deficient conditions in subpycnocline waters over wide areas for long intervals.

While anoxic conditions persisted permanently in the aggradational sequence sets, oxygenation levels varied from anoxic to suboxic in the marine substrate of the progradational sequence sets, precisely because the pycnocline was located at depths where the clinoforms accumulated (Fig. 10). Due to the large regional extent of the clinoforms and their very low gradient, a small variation in the position of the pycnocline led to relatively large changes in oxygenation on the seafloor. If it is assumed that the location of the pycnocline varied according to global climatic changes, it must be concluded that in periods with lower relative insolation (comparatively colder) physicochemical conditions at the sedimentary interface in the topsets and in the shallower part of the foresets changed from anoxic to suboxic, whereas in climatic periods with higher insolation (warmer) the tendency was towards a generalization of anoxia in wide areas of the deepest Neuquén Sea.

CONCLUSIONS

During the Tithonian–Berriasian a thick and widespread succession of organic-rich sediments ("Vaca Muerta facies") accumulated in the basinal and outer ramp setting of the back-arc Neuquén Basin, which was connected to the proto-Pacific Ocean through gaps in the magmatic arc. The sedimentary record is essentially composed of mixed or hybrid (siliciclastic-carbonate) fine-grained deposits accumulated under anoxic to suboxic conditions as a result of widespread and persistent starved conditions in the basinal areas of the Neuquén Sea. Aggradational and progradational accommodation sets are recognized in the "Vaca Muerta facies". The aggradational set accumulated in the more distal (basinal) areas of the marine setting and is composed of a thick and widely distributed succession of organic-rich silty and clayey mudstones with varying proportions of hemipelagic (siliciclastic) and pelagic (essentially carbonates) components. The progradational sets, characterised by clinoform geometries with topset, foreset and bottomset configurations, extend hundreds of kilometres both along and across the depositional dip, and are located between the inner ramp and the deeper sectors of the basin. Carbonate contents increase as one moves from the more distal deposits of the aggradational accommodation sets to the shallower deposits of the progradational accommodation sets. The increase in the proportion of these components in the clinoform deposits is attributed to resuspension and dispersal of particles and grains from the carbonate-rich inner ramp deposits ("Quintuco facies") by currents oriented cross-shelf, and related either to storms and/or to deflection by the Coriolis Effect (Ekman component) of highly efficient geostrophic contour currents flowing at depths above the pycnocline. In the "Vaca Muerta facies" the supply of terrigenous siliciclastic particles has been voluminous and persistent over 7 my, and the main source for these components was most likely the magmatic arc located to the western flank of the Neuquén Basin. Due to the marked stagnation and density stratification of the Neuquén Sea waters, much of the terrigenous fine-grained particles were probably dispersed in the basinal and offshore settings of the basin by suspension plumes mobilised by baroclinic currents that travelled for long distances above the pycnocline.

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REFERENCES

Acevedo, E., Fernández Paz, L, Encinas, A., Horton, B., Hernando, A., Valencia, V. and Folguera, A. (2023). Late Jurassic back arc extension in the Neuquén Basin (37°S): Insights from structural, sedimentological and provenance analyses. *Basin Research 35*, 3: 1012–1036. https://doi.org/10.1111/bre.12744.

Acuña Podestá, M. (2022). *Caracterización e interpretación sedimentológica de facies conglomerádicas de la Formación Quintuco/Loma Montosa (Yacimiento El Medanito), Cuenca Neuquina.* Trabajo Final de Licenciatura. Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata: 55 pp.

Algeo, T.J. Heckel, P.H., Maynard, J.B., Blakey, R.C. and Rowe, H. (2008). Modern and ancient epeiric seas and the super-estuarine circulation model of marine anoxia. In Pratt, B.R. and Holmden, C. (Eds.) Dynamics of Epeiric Seas: Sedimentological, paleontological and geochemical perspectives. *Geological Association of Canada, Special Paper 48*: 7–38.

Armella, C., Cabaleri, N. and Leanza, H. (2007). Tidally dominated, rimmed-shelf facies of the Picún Leufú Formation (Jurassic/Cretaceous boundary) in southwest Gondwana, Neuquén Basin, Argentina. *Cretaceous Research 28*, 6: 961–979. https://doi.org/10.1016/j.cretres.2007.01.001.

Capelli, I.A., Scasso, R.A., Spangenberg, J.E., Kietzmann, D.A., Cravero, F., Duperron, M. and Adatte, T (2021). Mineralogy and geochemistry of deeply-buried marine sediments of the Vaca Muerta-Quintuco system in the Neuquén Basin (Chacay Melehue section), Argentina: Paleoclimatic and paleoenvironmental implications for the global Tithonian-Valanginian reconstructions. *Journal of South American Earth Sciences 107*, 103103. 10.1016/j.jsames.2020.103103

Carozzi, A., Orchuela, I. and Rodríguez Schelotto, M. (1993). Depositional models of the Lower Cretaceous Quintuco-Loma Montosa Formation, Neuquen Basin, Argentina. *Journal of Petroleum Geology 16*, 4: 421–450. https://doi.org/10.1111/j.1747-5457.1993.tb00351.x

Coffey, B.P. and Fred, R.J. (2004). Mixed carbonate-siliciclastic sequence stratigraphy of a Paleogene transition zone continental shelf, southeastern USA. *Sedimentary Geology 166*: 21–57. https://doi.org/10.1016/j.sedgeo.2003.11.018.

Digregorio, R.E., Gulisano, C. A., Gutiérrez Pleimling, A.R. and Minitti, S.A. (1984). Esquema de la evolución geodinámica de la Cuenca Neuquina y sus implicancias paleogeográficas. *9º Congreso Geológico Argentino Actas 2*: 147–162. San Carlos de Bariloche.

Gasparini, Z., Spalletti, L., Fernández, M. and De La Fuente, M. (1997). Tithonian marine reptiles from the Neuquén Basin: diversity and palaeoenvironments. *Revue de Paleobiologie Geneve, 18*, 1: 335–345, Ginebra.

Gasparini, Z., Spalletti, L., Matheos, S. and Fernández, M. (2002). Reptiles marinos y paleoambiente del Jurásico Superior - Cretácico Inferior en la Yesera del Tromen (Neuquén, Argentina): un caso de estudio. *Actas del 15º Congreso Geológico Argentino, 1*: 473–478.

Gulisano, C.A. and Gutiérrez Pleimling, A.R. (1995). *The Jurassic of the Neuquén Basin, a) Neuquén Province*. Asociación Geológica Argentina, Series E 2, 111 pp., Buenos Aires.

Heezen, B.C. (1968). The Atlantic Continental Margin. *UMR Journal* -- V. H. McNutt Colloquium Series: Vol. 1, Article 3, 25 pp. https://scholarsmine.mst.edu/umr-journal/vol1/iss1/3.

Hogdson, D.M., Browning, J.V., Miller, K.G., Hesselbo, S.P., Poyatos-Moré, M., Mountain, G.S. and Proust, J.N. (2017). Sedimentology, stratigraphic context, and implications of Miocene intrashelf bottomset deposits, offshore New Jersey. *Geosphere 14*: 95–114. https://doi.org/10.1130/GES01530.1

Hopkins, J., Lucas, M., Dufau, C., Sutton, M., Stum, J., Lauret, O. and Channelliere, C. (2013). Detection and variability of the Congo River plume from satellite derived sea surface temperature, salinity, ocean colour and sea level. *Remote Sensing of Environment 139*: 365–385. https://doi.org/10.1016/j.rse.2013.08.015

Howell, J.A., Schwarz, E., Spalletti, L.A. and Veiga, G.D. (2005). The Neuquén Basin: an overview. In Veiga, G.D., Spalletti, L.A., Howell, J.A. and Schwarz, E. (Eds.). The Neuquén Basin, Argentina: a Case Study in Sequence Stratigraphy and Basin Dynamics. *Geological Society of London, Special Publications 252*: 1–14. https://doi.org/10.1144/GSL.SP.2005.252.01.01

Iñigo, J.F.P., Vargas, R., Novara, M.E., Pereira, M. and Schwarz, E. (2018). La Formación Loma Montosa en el borde noroeriental de la Cuenca Neuquina: análisis secuencial, caracterización paleoambiental y prospectividad remanente. *Actas del X Congreso de Exploración y Desarrollo de Hidrocarburos Instituto Argentino del Petróleo y el Gas*: 623–645.

Kershaw, S. (2015). Modern Black Sea oceanography applied to the end-Permian extinction event. *Journal of Palaeogeography 4*, 1: 52–62. https://doi.org/10.3724/SP.J.1261.2015.00067

Kietzmann, D.A., Palma, R.M. and Bressan, G.S. (2008). Facies y microfacies de la rampa tithoniana berriasiana de la Cuenca Neuquina (Formación Vaca Muerta) en la sección del Arroyo Loncoche - Malargüe, provincia de Mendoza. *Revista de la Asociación Geológica Argentina 63*, 4: 696–713. https://revista.geologica.org.ar/raga/article/view/1324

Kietzmann, D.A., Palma, R.M., Riccardi, A.C., Martín-Chivelet, J. and López-Gómez, J. (2014). Sedimentology and sequence stratigraphy of a Tithonian - Valanginian carbonate ramp (Vaca Muerta Formation): A misunderstood exceptional source rock in the Southern Mendoza area of the Neuquén Basin, Argentina. *Sedimentary Geology 302*: 64–86. https://doi.org/10.1016/j.sedgeo.2014.01.002

Kietzmann, D.A., Palma, R.M. and Iglesia Llanos, M.P. (2015). Cyclostratigraphy of an orbitally-driven Tithonian–Valanginian carbonate ramp succession, Southern Mendoza, Argentina: implications for the Jurassic–Cretaceous boundary in the Neuquén Basin. *Sedimentary Geology 315*: 29–46. https://doi.org/10.1016/j.sedgeo.2014.10.002

Klicpera, A., Michel, J. and Westphal, H. 2015. Facies patterns of a tropical heterozoan carbonate platform under eutrophic conditions: the Banc d'Arguin, Mauritania. *Facies 61* (421) https://doi.org/10.1007/s10347-014-0421-5

Kohan Martínez, M., Kietzmann, D.A, Iglesia Llanos, M.P., Leanza, H.A. and Luppo, T. (2018). Magnetostratigraphy and cyclostratigraphy of the Tithonian interval from the Vaca Muerta Formation, southern Neuquén Basin, Argentina. *Journal of South American Earth Sciences 85*: 209–228. https://doi.org/10.1016/j.jsames.2018.05.010

Krim, N., Bonnel, C., Tribovillard, N., Imbert, P., Aubourg, C., Riboulleau, A., Bout-Roumazeilles, V., Hoareau, G. and Fasentieux, B. (2017). Paleoenvironmental evolution of the southern Neuquén basin (Argentina) during the Tithonian-Berriasian (Vaca Muerta and Picún Leufú Formations): a multi-proxy approach. *Bulletin Societé Géologique France 188*, 34, 33 pp. https://doi.org/10.1051/bsgf/2017196

Krim, N., Tribovillard, N., Riboulleau, A. Bout-Roumazeilles, V., Bonnel, C., Imbert, P., Aubourg, C. Hoareau, G. and Fasentieux, B. (2019). Reconstruction of palaeoenvironmental conditions of the Vaca Muerta Formation in the southern part of the Neuquén Basin (Tithonian-Valanginian): Evidences of initial short-lived development of anoxia. *Marine and Petroleum Geology 103*, 176-201.

Leanza, H.A. (1973). Estudio sobre los cambios faciales de los estratos limítrofes jurásico-cretácicos entre Loncopué y Picún Leufú, Provincia del Neuquén, República Argentina. *Revista de la Asociación Geológica Argentina 28*: 97–132. https://revista.geologica.org.ar/raga/issue/view/197/120

Leanza, H.A. (1993). Estratigrafía del Mesozoico posterior a los Movimientos Intermálmicos en la comarca del Cerro Chachil, provincia del Neuquén. *Revista de la Asociación Geológica Argentina 48*: 71-84. https://revista.geologica.org.ar/raga/issue/view/46/31

Leanza, H.A., Hugo, C.A. and Repol, D. (2003). Miembro Huncal (Berriasiano inferior): un episodio turbidítico en la Formación Vaca Muerta, Cuenca Neuquina, Argentina. *Revista de la Asociación Geológica Argentina 58, 2*: 248–254. https://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S000448222003000200010&lng=es&tlng=es.

Leanza, H.A., Repol, D., Hugo, C.A. and Sruoga, P. (2006). Hoja Geológica 3769-31, Chorriaca, provincia del Neuquén. *Instituto de Geología y Recursos Naturales, Servicio Geológico Minero Argentina, Boletín 314*, 93 pp., Buenos Aires. https://repositorio.segemar.gob.ar/handle/308849217/213

Legarreta, L. and Uliana, M.A. (1991). Jurassic- Cretaceous marine oscillations and geometry of back-arc basin fill central Argentine Andes. In: Macdonald, D.I.M. (Ed.) Sea Level Changes at Active Plate Margins. *Process and Product. Special Publication International Association of Sedimentologists 12*: 429–450. https://doi.org/10.1002/9781444303896.ch23

Legarreta, L. and Uliana, M.A. (1996). La sucesión jurásica en el centro-oeste de Argentina. Arreglo estratigráfico, secuencias y evolución paleogeográfica. *Boletín de Informaciones Petroleras 12*(45): 66–78.

Lentz, S.J. and Fewings, M.R. (2012). The wind- and wave-driven inner-shelf circulation. A*nnual Review of Marine Science 4*: 317–343. https://doi.org/10.1146/annurev-marine-120709-142745

Luo, Z., Zhu, J., Wu, H. and Li, X. (2017). Dynamics of the sediment plume over the Yangtze Bank in the Yellow and East China Seas. *Journal of Geophysical Research*, Oceans, 122: 10,073–10,090. https://doi.org/10.1002/2017JC013215

Macdonald, D., Gómez-Pérez, I., Franzese, J., Spalletti, L., Lawver, L., Gahagan, L., Dalziel, I., Thomas, C., Trewin, N., Hole, M. and Paton, D. (2003). Mesozoic break-up of SW Gondwana: Implications for regional hydrocarbon potential of the southern South Atlantic. *Marine and Petroleum Geology 20*: 287–308. https://doi.org/10.1016/S0264-8172(03)00045-X

Massaferro, J.L., Zeller, M., Giunta, D.L., Sagasti, G. and Eberli, G. (2014). Evolución del sistema mixto Tithoniano-Valanginiano (Formaciones Vaca Muerta, Quintuco y equivalentes) a partir de estudios de afloramientos y subsuelo, Centro-Sur de la Cuenca Neuquina. Simposio de Recursos No Convencionales. *Actas del 9° Congreso de Exploración y Desarrollo de Hidrocarburos*: 251–274, Mendoza, Argentina.

Michel, J., Mateu-Vicens, G. and Westphal, H. (2011). Modern heterozoan carbonate facies from a eutrophic tropical shelf (Mauritania). *Journal of Sedimentary Research 81*: 641–655. https://doi.org/10.2110/jsr.2011.53

Minisini, D., Desjardins, P., Otharán, G., Paz, M., Kietzmann, D., Eberli, G., Zavala, C., Simo, T., Macquaker, J.H. and Heine, C. (2020). Sedimentology, depositional model and implications for reservoir quality. In: Minisini, D., Fantín, M., Lanusse Noguera, I., Leanza, H.A. (Eds.) *Integrated Geology of Unconventionals: The Case of the Vaca Muerta Play, Argentina*. Memoir 121 American Association of Petroleum Geologists, 201-236. Tulsa.

Mitchum, R.M. and Uliana, M.A. (1985). Seismic stratigraphy of carbonate depositional sequences, Upper Jurassic - Lower Cretaceous, Neuquén Basin, Argentina. In: Bero, B.R. and Woolverton, D.G. (Eds.) Seismic Stratigraphy: an Integrated Approach to Hydrocarbon Exploration. *American Association of Petroleum Geologists, Memoir 39*: 255–274. https://doi.org/10.1306/M39449C15

Moyano Bohórquez, F. (2004). *Los sistemas sedimentarios de la Formación Bajada Colorada (Cretácico temprano) en el sur de la Cuenca Neuquina, Argentina.* [Unpublished PhD Thesis]. Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata (Inédita). https://doi.org/10.35537/10915/4549

Olivo, M.S., Schwarz, E. and Veiga, G.D. (2016). Depositional model and sequential evolution of the upper Quintuco Formation in its type area: Implications for paleogeographic reconstruction for the southern Neuquén Basin during the Valanginian. *Andean Geology 43*: 215–239. http://dx.doi.org/10.5027/andgeoV43n2-a04

Otharán, G.A., Zavala, C., Arcuri, M., Di Meglio, M., Zorzano, A., Marchal, D. and Köhler, G. (2020). Facies analysis of fine-grained deposits related to muddy underflows. Vaca Muerta Formation (Tithonian-Valanginian), central Neuquen Basin, Argentina. *Andean Geology 47*: 384–417. http://dx.doi.org/10.5027/andgeov47n2-3061

Pang, C., Yuan, D., Jiang, M., Chu, F. and Li, Y. (2020). Observed cross-shelf suspended sediment flux in the southern Yellow Sea in winter. *Marine Geology 419*, 106067. https://doi.org/10.1016/j.margeo.2019.106067

Paz, M., Ponce, J.J., Buatois, L.A., Mángano, M.G., Carmona, N.B., Pereira, E. and Desjardins, P.R. (2019). Bottomset and foreset sedimentary processes in the mixed carbonate-siliciclastic Upper Jurassic-Lower Cretaceous Vaca Muerta Formation, Picún Leufú Area, Argentina. *Sedimentary Geology 389*: 161–185. https://doi.org/10.1016/j.sedgeo.2019.06.007

Paz, M., Buatois, L.A., Mángano, M.G., Desjardins, P.R., Notta, R., González Tomassini, F., Carmona, N.B. and Minisini, D. (2022a). Organic-rich, fine-grained contourites in an epicontinental basin: The Upper Jurassic-Lower Cretaceous Vaca Muerta Formation, Argentina. *Marine and Petroleum Geology 142*, 105757. https://doi.org/10.1016/j.marpetgeo.2022.105757

Paz, M., Mángano, M.G., Buatois, L.A., Desjardins, P.R., Notta, R., González Tomassini, F. and Carmona, N.B. (2022b). Ichnology of muddy shallow water contourites from the Upper Jurassic – Lower Cretaceous Vaca Muerta Formation, Argentina: Implications for trace fossil models. *Palaios 37*: 201–218. https://doi.org/10.2110/palo.2020.028

Paz, M., Buatois, L.A., Mángano, M.G., Desjardins, P.R., Rodríguez, M.N., Ponce, J.J., Minisini, D., González Tomassini, F., Pereira, E., Carmona, N.B., Fantín, M. and Vallejo, M.D. (2023). Basin circulation affecting sediment partitioning in a fine-grained carbonate–siliciclastic, subaqueous clinoform: the Upper Jurassic–Lower Cretaceous Vaca Muerta Formation, Neuquén Basin, Argentina. *Journal of the Geological Society of London 180*, 26 pp. https://doi.org/10.1144/jgs2022-055

Poulos, S.E. (2023). Water Masses of the Mediterranean Sea and Black Sea: An overview. *Water 15*, 3194. https://doi.org/10.3390/w15183194

Ralston, D.K., Warner, J.C., Geyer, W.R. and Wall, G.R. (2013). Sediment transport due to extreme events: the Hudson River estuary after tropical storms Irene and Lee. *Geophysical Research Letters 40*: 5451–5455. https://doi.org/10.1002/2013GL057906

Reijenstein H. M, Posamentier H. W., Fantin M., González Tomassini F. and Lipinski C. (2014). Vaca Muerta seismic stratigraphy and geomorphology: regional architectural trends for unconventional exploration. *Actas del 9º Congreso de Exploración y Desarrollo de Hidrocarburos, Instituto Argentino del Petróleo y el Gas*, 8 pp., Mendoza, Argentina.

Rodrigues, N., Cobbold, P.R., Løseth, H. and Ruffet, G. (2009). Widespread bedding-parallel veins of fibrous calcite ("beef") in a mature source rock (Vaca Muerta Formation, Neuquén Basin, Argentina): evidence for overpressure and horizontal compression. *Journal of the Geological Society of London 166/4*: 695–709. https://doi.org/10.1144/0016-76492008-111

Rodríguez Blanco, L., Eberli, G.P., Weger, R.J., Swart, P.K., Tenaglia, M., Rueda Sanchez, L.E. and McNeill, D.F. (2020). Periplatform ooze in a mixed siliciclastic-carbonate system - Vaca Muerta Formation, Argentina. *Sedimentary Geology 396*, 1–17. https://doi.org/10.1016/j.sedgeo.2019.105521

Rodríguez Blanco, L., Swart, P.K., Eberli, G.P. and Weger, R.J. (2022). Negative δ13Ccarb values at the Jurassic-Cretaceous boundary – Vaca Muerta Formation, Neuquén Basin, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology 603*, 111208. https://doi.org/10.1016/j.palaeo.2022.111208

Schieber, J. (2016). Mud re-distribution in epicontinental basins - exploring likely processes. *Marine and Petroleum Geology 71*: 119–133. https://doi.org/10.1016/j.marpetgeo.2015.12.014

Scasso, R.A., Alonso, M.S., Lánes, S., Villar, H.J. and Laffitte, G. (2005). Geochemistry and petrology of a Middle Tithonian limestone-marl rhythmite in the Neuquén Basin, Argentina: depositional and burial history. In: Veiga, G.D., Spalletti, L.A., Howell, J.A. and Schwarz, E. (Eds.) The Neuquén Basin, Argentina: A Case Study in Sequence Stratigraphy and Basin Dynamics. *Geological Society of London, Special Publications 252*: 207–229. https://doi.org/10.1144/gsl.sp.2005.252.01.10

Schwarz, E. and Veiga, G.D. (2019). *Estudio sedimentológico e interpretación paleoambiental de la Formación Loma Montosa en el Tren Productivo Río Colorado (Cuenca Neuquina nororiental)*. Informe inédito. 64 pp.

Schwarz, E., Spalletti, L.A. and Howell, J.A. (2006). Sedimentary response to a tectonically induced sea-level fall in a shallow back-arc basin: the Mulichinco Formation (Lower Cretaceous), Neuquén Basin, Argentina. *Sedimentology 53*: 55–81. https://doi.org/10.1111/j.1365-3091.2005.00753.x

Schwarz, E., Veiga, G.D., Álvarez-Trentini, G. and Spalletti, L.A. (2016). Climatically versus eustatically controlled, sediment-supply-driven cycles: carbonate-siliciclastic, high frequency sequences in the Valanginian of the Neuquén Basin (Argentina). *Journal of Sedimentary Research 86*: 312–335. https://doi.org/10.2110/jsr.2016.21

Schwarz, E., Remírez, M., Lazo, D.G., Veiga, G.D., Echevarría, C., Toscano, A.G. and Garberoglio, R.M. (2022). A review on depositional systems, bioevents and paleogeography of the Valanginian-Hauterivian Neuquén Sea: Refining sedimentary and biological signals linked to the dynamics of epeiric seas. *Earth-Science Reviews 234*, 104224. https://doi.org/10.1016/j.earscirev.2022.104224

Seyedmehdi, Z., George A.D. and Tucker, M.E. (2016). Sequence development of a latest Devonian-Tournaisian distally-steepened mixed carbonate-siliciclastic ramp, Canning Basin, Australia. *Sedimentary Geology 333*: 164–183. https://doi.org/10.1016/j.sedgeo.2015.12.012

Shanmugam, G. (2013). Modern internal waves and internal tides along oceanic pycnoclines: Challenges and implications for ancient deep-marine baroclinic sands. *American Association of Petroleum Geologists Bulletin 97*, 5: 799–843. https://doi.org/10.1306/10171212101

Shanmugam, G. (2017). Contourites: physical oceanography, process sedimentology, and petroleum geology. *Petroleum*

Exploration and Development 44(2): 183–216. https://doi.org/10.1016/S1876-3804(17)30023-X

Shanmugam, G. (2019). Global significance of wind forcing on deflecting sediment plumes at river mouths: Implications for hyperpycnal flows, sediment transport, and provenance. *Journal of the Indian Association of Sedimentologists 36*, 2: 1–37. https://journal.indiansedimentologists.com/ojs/index.php/1/article/view/74

Shanmugam, G. (2021). The turbidite-contourite-tidalite-baroclinite hybridite problem: orthodoxy vs. empirical evidence behind the "Bouma Sequence". *Journal of Palaeogeography 10*, 9: 1–32. https://doi.org/10.1186/s42501-021-00085-1

Spalletti, L.A. (2013). Influencia del arco magmático protoandino en la acomodación sedimentaria, la fisiografía y las características de los depósitos del Jurásico superior y Cretácico inferior en la Cuenca Neuquina. *Anales Academia Nacional de Ciencias Exactas, Físicas y Naturales 65*: 37–47.

Spalletti, L., Gasparini, Z., Veiga, G., Schwarz, E., Fernández, M. and Matheos, S. (1999). Facies anóxicas, procesos deposicionales y herpetofauna de la rampa marina titoniano-berriasiana en la Cuenca Neuquina (Yesera del Tromen, Neuquén, Argentina). *Revista Geológica de Chile 26*, 1: 109–123. http://dx.doi.org/10.4067/S0716-02081999000100006

Spalletti, L., Franzese, J., Matheos, S. and Schwarz, E. (2000). Sequence stratigraphy of a tidally-dominated carbonate-siliciclastic ramp; the Tithonian of the southern Neuquén Basin, Argentina. *Journal of the Geological Society of London 157*, 2: 433–446. https://doi.org/10.1144/jgs.157.2.433

Spalletti, L.A., Schwarz, E. and Franzese, J.R. (2006). Clinoformas deposicionales en la rampa marina tithoniana del sector austral de la Cuenca Neuquina. *Actas del 4° Congreso Latinoamericano de Sedimentología y 11° Reunión Argentina de Sedimentología*, pp. 216.

Spalletti, L., Veiga, G., Schwarz, E. and Franzese, J. (2008). Depósitos de flujos gravitacionales subácueos de sedimentos en el flanco activo de la Cuenca Neuquina durante el Cretácico Temprano. *Revista de la Asociación Geológica Argentina 63*, 3: 442–453. https://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S0004-48222008000300012&lng=es&nrm=iso

Spalletti, L.A.; Schwarz, E. and Veiga, G.D. (2014). Geoquímica inorgánica como indicador de procedencia y ambiente sedimentario en sucesiones de lutitas negras: los depósitos transgresivos tithonianos (Formación Vaca Muerta) de la Cuenca Neuquina, Argentina. *Andean Geology 41*, 2: 410–435. http://dx.doi.org/10.5027/andgeoV41n2-a07

Spalletti, L., Pirrie, D., Veiga, G., Schwarz, E., Rollinson, G., Shail, R., Haberlah, D. and Butcher, A. (2015). Análisis mineralógico integrado (QEMSCAN y DRX) de lutitas negras: los depósitos tithonianos basales de la Formación Vaca Muerta (Cuenca Neuquina, Argentina). *Latin American Journal of Sedimentology and Basin Analysis 22*, 1: 13–28. https://lajsba.sedimentologia.org.ar/lajsba/article/view/190

Spalletti, L.A., Remírez, M. and Sagasti, G. (2019). Geochemistry of aggradational – progradational sequence sets of the Upper Jurassic – Lower Cretaceous Vaca Muerta shales (Añelo area, Neuquén Basin, Argentina): relation to changes in accommodation and marine anoxia. *Journal of South American Earth Sciences 93*: 495–509. https://doi.org/10.1016/j.jsames.2019.02.011

Stow, D. and Smillie, Z. (2020). Distinguishing between deep-water sediment facies: *Turbidites, contourites and hemipelagites. Geosciences 10*, 68, 43 pp. https://doi.org/10.3390/geosciences10020068

Teruggi, M.E. 1982. *Diccionario Sedimentológico*. Volumen 1. *Rocas Clásticas y Piroclásticas*. Librart, Buenos Aires: 104 pp.

Traykovski, P., Geyer, W.P., Irish, J.D. and Lynch, J.F. (2000). The role of wave-induced density-driven fluid mud flows for cross-shelf transport on the Eel River continental shelf. *Continental Shelf Research 20*, 16: 2113–2140. https://doi.org/10.1016/S0278-4343(00)00071-6

Tucker, M.E. (2003). Mixed clastic–carbonate cycles and sequences; Quaternary of Egypt and Carboniferous of England. *Geologia Croatica 56*: 19–37. https://doi.org/10.4154/GC.2003.02

Vergani, G.D., Tankard, A.J., Belotti, H.J. and Welsink, H.J. (1995). Tectonic evolution and paleogeography of the Neuquen basin, Argentina. In Tankard, A.J., Suarez Soruco, R. and Welsink, H.J. (Eds.), Petroleum Basins of South America. *American Association of Petroleum Geologists Memoir 62*: 383–402 Tulsa. https://doi.org/10.1306/M62593C19

Vic, C., Berger, H., Treguier, A. M., & Couvelard, X. (2014). Dynamics of an equatorial river plume: Theory and numerical experiments applied to the Congo plume case. *Journal of physical oceanography, 44*(3), 980-994. https://doi.org/10.1175/JPO-D-13-0132.1

Wang, H., Wang, A., Bi, N., Zeng, X. and Xiao, H. (2014). Seasonal distribution of suspended sediment in the Bohai Sea, China. *Continental Shelf Research 90*: 17–32. https://doi.org/10.1016/j.csr.2014.03.006

Wang, H., Shi, Z., Sun, S., Zhao, Q., Zhou, T., Cheng, F. and Bai, W. (2023). Microfacies types and distribution of epicontinental shale: A case stud of the Wufeng-Longmaxi Shale in southern Sichuan Basin, China. *Petroleum Exploration and Development 50*: 57–71. https://doi.org/10.1016/S1876-3804(22)60369-0

Wei, X.J., Li, Z.X., Ma, Y.S., Li, Y.F., Hu, J.J., Liu, K. and Fang, X.X. (2021). Sedimentology and sequence stratigraphy of the mixed clastic-carbonate deposits in the Late Paleozoic icehouse period: A case study from the northern Qaidam Basin. *China Geology 4*: 673–685. https://doi.org/10.31035/cg2021068

Wright, L.D. (2014). Internal waves. Beaches and Coastal Geology. *Encyclopedia of Earth Sciences Series*: 402–493.

Wu, H., Shen, J., Zhu, J., Zhang, J. and Li, L. (2014). Characteristics of the Changjiang plume and its extension along the Jiangsu Coast. *Continental Shelf Research 76*: 108–123. https://doi.org/10.1016/j.csr.2014.01.007

Yrigoyen, M.R. (1991). Hydrocarbon resources of Argentina. *13th World Petroleum Congress. Petrotecnia, Special Issue*: 38–54. Buenos Aires.

Zeller, M., Eberli, G.P., Weger, R.J., Giunta, D.L. and Massaferro, J.L. (2014). Seismic expressions of the Quintuco – Vaca Muerta system based on outcrop facies and geometry. *Actas del 9º Congreso de Exploración y Desarrollo de Hidrocarburos Instituto Argentino del Petróleo y el Gas*: 209–224, Mendoza, Argentina.

Zeller, M., Reid, S.B., Eberli, G.P., Weger, R.J. and Massaferro, J.L. (2015a). Sequence architecture and heterogeneities of a field-Scale Vaca Muerta analog (Neuquén Basin, Argentina)-From outcrops to synthetic seismic. *Marine and Petroleum Geology 66*, 829–847. https://doi.org/10.1016/j.marpetgeo.2015.07.021

Zeller, M., Verwer, K., Eberli, G., Massaferro, J.L., Schwarz, E. and Spalletti, L. (2015b). Depositional controls on mixed carbonate-siliciclastic cycles and sequences on gently inclined shelf profiles – the Picún Leufú – Vaca Muerta System in Neuquén Basin, Argentina. *Sedimentology 62*, 7: 2009–2037. https://doi.org/10.1111/sed.12215