

Evidence of precessional and eccentricity orbital cycles in a Tithonian source rock: The mid-outer carbonate ramp of the Vaca Muerta Formation, northern Neuquén Basin, Argentina

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ABSTRACT

Basin to mid-ramp cyclic facies of the Tithonian Vaca Muerta Formation are exposed in the Loncoche Creek section of the Neuquén Basin, Mendoza province, Argentina. This unit is characterized by a decimeter-scale rhythmic alternation of marls, shales and limestones and extends from the lower Tithonian to the upper Berriasian. Cyclostratigraphic studies based on a detailed facies analysis allowed the identification of cyclic patterns with frequencies within the Milankovitch band. According to biostratigraphic data, the dominant cycle in the studied section has a period of 20 k.y., which correlates with the Earth's axis precession element. Spectral analysis based on a series of compacted and decompacted cycle thickness identified a subordinate frequency of about 90 to 120 k.y., which we interpret as the modulation of the precessional cycle caused by the Earth's orbital eccentricity. The strength of the precession signal, together with the absence of a well-defined cyclicity attributable to the obliquity orbital cycle (i.e., ~40 k.y.), is in agreement with previous data from the Northern Hemisphere.

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INTRODUCTION

Analysis of cycle stacking patterns in marine carbonate sequences is a powerful technique for reconstructing relative sea level and cyclic climate changes in very different time scales, particularly those controlled by variations in the Earth's orbit at frequencies of 10^4 to 10^5 yr (Milankovitch cycles) (Berger et al., 1989; Strasser, 1994; Husinec and Read, 2007). In this article, cycles from the depositional sequence to decimeter-scale rhythmic alternation of limestone and marl in the Tithonian outer-middle ramp succession of the Vaca Muerta Formation are studied, using a cyclostratigraphic approach. Interestingly, this stratigraphic interval is considered to be the most effective source rock in the Neuquén Basin (Mitchum and Uliana, 1985).

Cyclostratigraphic works on Tithonian successions are still scarce and mostly based on shallow-water carbonate environments (Strasser, 1994; Husinec and Read, 2007). Additional Jurassic–Cretaceous examples are described by Weedon et al. (1999, 2004), Bádenas et al. (2003), Anderson (2004), and Strasser et al. (2004).

Cyclostratigraphic studies have been frequently used in the Northern Hemisphere but rarely applied to the Southern Hemisphere geologic record. Only a few works have dealt with this subject in Argentina (Sagasti, 2005; Scasso et al., 2005). Although the Vaca Muerta Formation indicates a great potential for cyclostratigraphic analysis, no detailed work has yet been conducted, despite the excellent existence of repetitive succession of limestone-marlstone couplets throughout the entire basin.

The aim of this article includes the description and interpretation of the cyclicity of the Tithonian interval of the Vaca Muerta Formation. The cyclostratigraphic study is supported by a facies analysis and biostratigraphic data. The Late Jurassic–Early Cretaceous interval is a key time of global source rock development. The recognition of orbital cycles in the Vaca Muerta Formation should contribute to a better evaluation of the depositional controls influencing the most prolific source rock in the Neuquén Basin and a better characterization of the Late Jurassic–Early Cretaceous global climate.

GEOLOGIC FRAMEWORK

The Neuquén Basin was a back-arc basin located on the western margin of the South American platform and limited by the magmatic arc to the west and by a tectonic foreland to the southeast (Howell et al., 2005) between a 36 and 40°S latitude (Figure 1A).

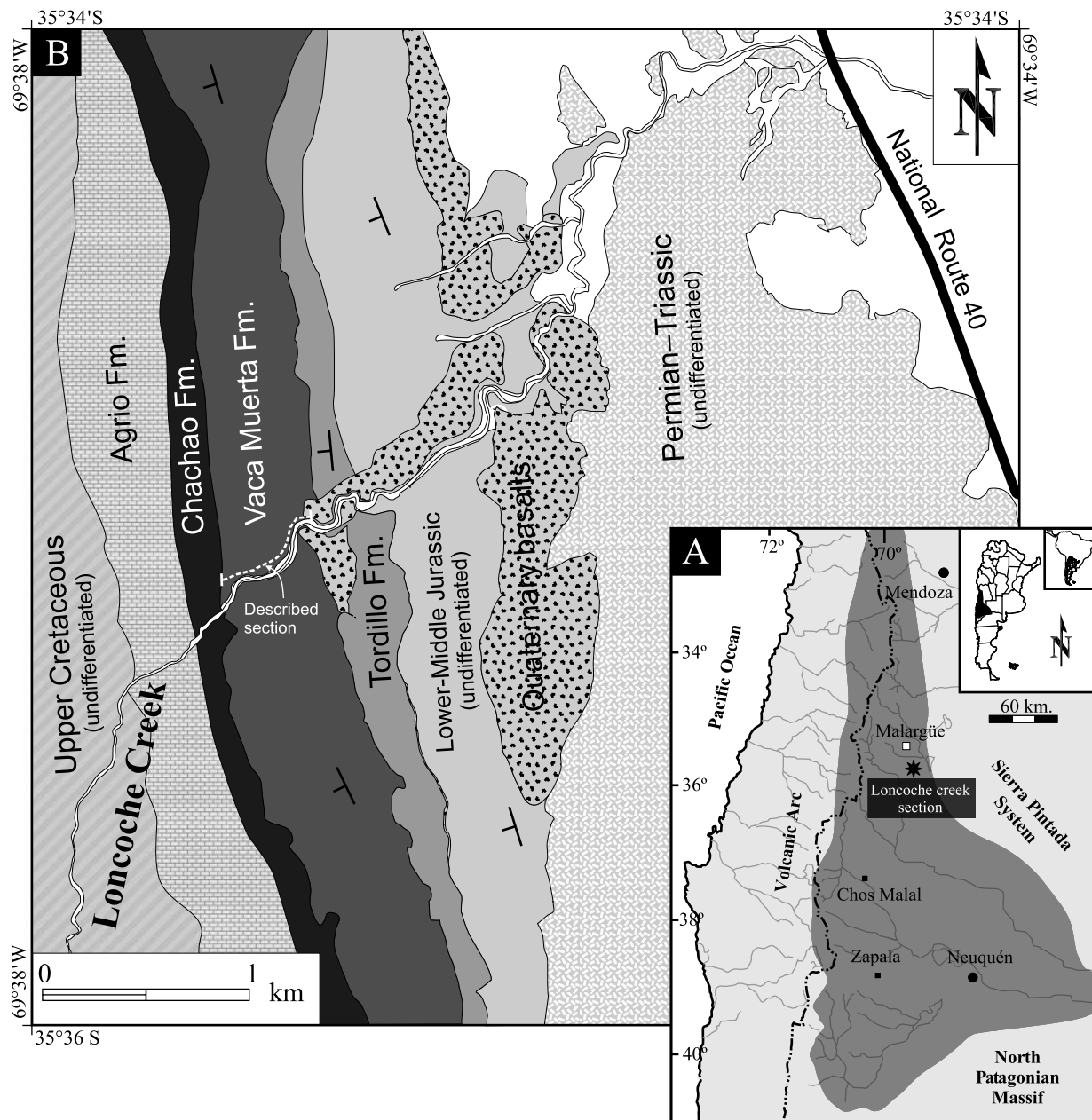


Figure 1. (A) Location map of the Neuquén Basin and the Loncoche section. (B) Geologic map of the study area (modified from Kietzmann et al., 2008).

The foreland consists of the Sierra Pintada belt to the northeast and the North Patagonian massif to the south. The base-ment consists of lower Paleozoic to Upper Triassic metamorphic, plutonic, and volcanic rocks. The Neuquén Basin has been interpreted as a retro-arc basin (Mitchum and Uliana, 1985; Legarreta and Uliana, 1991, among others). It is characterized by

a very continuous Mesozoic and Cenozoic sedi-mentary record, comprising continental and ma-rine clastic, carbonate, and evaporitic deposits as much as 2600 m (8530 ft) thick. Marine incursions occurred at different time intervals through the connection with the Pacific Ocean (Legarreta and Uliana, 1991).

Legarreta and Gulisano (1989) described four tectonic episodes of basin development: (1) rifting

Age	Stratigraphy		Sedimentary Environment	
Barremian	Mendoza Mesosequence	Mendoza Gr.	Mixed Carbonate/Siliciclastic Ramp	
Hauterivian				Agrio Fm.
Valanginian			Loncoche creek Chachao Fm.	Inner Carbonate Ramp
Berriasian			Vaca Muerta Fm.	Outer to Middle Carbonate Ramp
Tithonian				
Kimmeridgian			Tordillo Fm.	Fluvial/Alluvial

Figure 2. Stratigraphic chart for the Mendoza mesosequence of the Neuquén Basin, Mendoza province (data from Legarreta and Uliana, 1991).

(Late Triassic–Early Jurassic); (2) thermal subsidence (Early Jurassic–Late Cretaceous); (3) subsidence caused by loading (Late Cretaceous–Paleogene); and (4) Andean tectonism (Paleogene–early Quaternary).

The sequence-stratigraphic framework is based on seismic and outcrop data (Mitchum and Uliana, 1985; Legarreta and Gulisano, 1989; Legarreta and Uliana, 1991). Legarreta and Gulisano (1989) group all the Tithonian–Valanginian deposits of the Neuquén Basin into a broad shallowing-upward cycle (the lower Mendoza mesosequence, Figure 2), which was subdivided into nine depositional sequences. Legarreta and Uliana (1991) suggest a correlation between the depositional sequences with the global chart of third-order eustatic sea level variations (Haq et al., 1987). The Jurassic biostratigraphy is well defined based on ammonites and, to a lesser extent, on bivalves, brachiopods, and microfossils, such as foraminifers, radiolarians, and calcareous nanofossils (Riccardi et al., 2000; Riccardi, 2008).

The lower Tithonian to lower Valanginian Vaca Muerta Formation is widely distributed throughout the Neuquén Basin. It consists of dark bituminous shales, marls, and limestones deposited in response to a rapid and widespread marine transgression originating from the Pacific Ocean, as a consequence of a tectonic phase of compressional relaxation (Legarreta and Uliana, 1991).

Previous works on this unit are abundant and cover sedimentologic, petrologic, and paleontologic aspects, as well as its economic importance for hydrocarbon exploration (Leanza, 1980; Uliana and Legarreta, 1993; Urien and Zambrano, 1994; Riccardi et al., 2000; Spalletti et al., 2000; Scasso et al., 2005; Kietzmann et al., 2008).

STUDY AREA

The studied area is located in the northern part of the Neuquén Basin, in the Mendoza province (Figure 1A). The measured section is located 20 km (12 mi) south of the city of Malargüe, along the Loncoche Creek (Figure 1B). It exposes a 286-m (938-ft)-thick stratigraphic interval consisting of a homogeneous succession dominated by black shales, marls, and limestones, with a markedly cyclic aspect defined by the alternation of these lithologies at a decimeter scale. The age of the Vaca Muerta Formation in this section is early Tithonian to late Berriasian (Kietzmann et al., 2008). This study concentrates on the Tithonian part of the succession (Figure 3) because of its importance as a source rock interval, the excellent out-crop conditions, and the minor tectonic disruptions.

METHODOLOGY

A detailed sedimentologic section was measured and described bed by bed. Carbonate and siliciclastic lithofacies were analyzed considering bed geometry, lithology, sedimentary structures, and fossil content.

Cyclostratigraphic analysis is based on the differentiation of decimeter-scale couplets of carbonate lithofacies/siliciclastic lithofacies (herein termed “elementary cycles”). Lower frequencies are searched using spectral analysis with the software POWGRAF2 (Pardo-Igúzquiza and Rodríguez-Tovar, 2004) by means of different methods: the fast Fourier transform (FFT), the smoothed periodogram method, and the Blackman-Tukey method. Advantages and limitations of the different mathematical procedures can be consulted in Pestiaux and Berger (1984) and Weedon (2003).

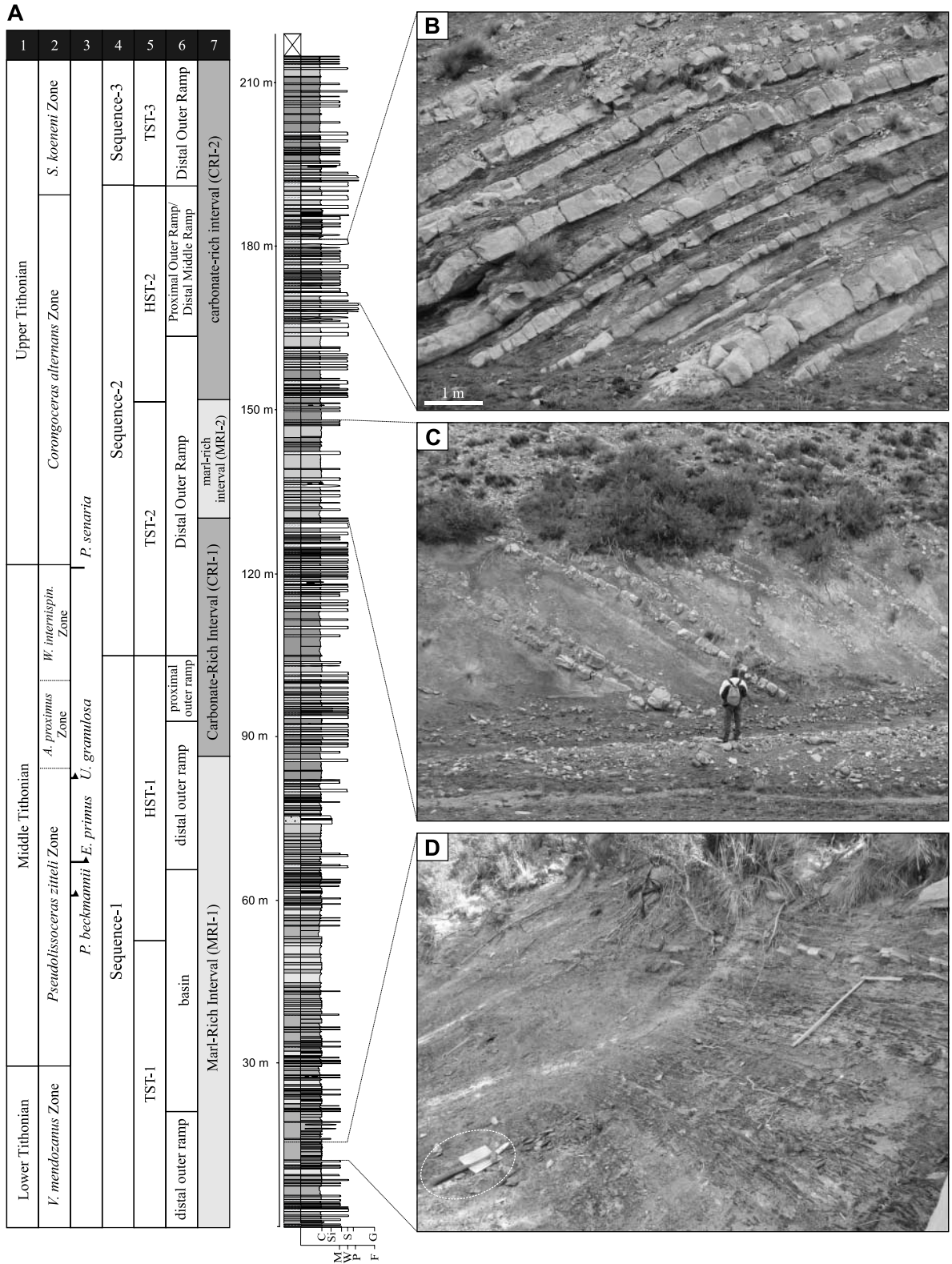


Figure 3. (A) Stratigraphic section of the Tithonian interval of the Vaca Muerta Formation in the Loncoche area, showing chronostratigraphic subdivision (1), ammonite biozones (2), nannofossil events (3), depositional sequences (4), systems tracts (5), depositional setting interpretation (6), and marl-rich and carbonate-rich intervals (7). (B) Carbonate-rich interval CRI-2 in the upper Tithonian section. (C) Marl-rich interval MRI-2 in the upper Tithonian section. (D) Black-shale-dominated interval without rhythmicity at the base of the Vaca Muerta Formation (lower Tithonian).

Spectral analyses are based on the following basic premises: (1) The section consists of a succession of elementary cycles showing similar thicknesses—always within the range of several decimeters—that are considered to be similar in average duration. (2) Vertical changes in facies and bed thickness throughout the section could be related to periodic climate factors or to other nonperiodic factors as basin evolution. (3) Noncyclic intervals are not incorporated to the spectral analysis. These non-cyclic intervals need to be considered for interpreting the long-term variations as well as for estimations of the total number of cycles in the stratigraphic section. An estimate of the number of hidden cycles was given by simply dividing their thicknesses by the average cycle thickness of the interval. With this approach, we got 251 cycles. (4) Sedimentation was essentially continuous through-out the studied time interval. This assumption is reasonable because field observations do not reveal any evidence of subaerial exposure, relevant erosional features, or condensed sedimentation.

To avoid possible effects of differential diagenetic compaction of different lithologies in the spectral calculations, all the statistical procedures were performed with both measured and decompacted thickness data. We have used the Baldwin (1971) factors for the backstripping approach.

BIOCHRONOSTRATIGRAPHY

The Tithonian interval of the Vaca Muerta Formation in the Loncoche Creek has been characterized by means of detailed ammonite and nannoplankton biostratigraphy (Figure 3), with the aim of getting a chronostratigraphic framework as robust as possible for the cyclostratigraphic analysis. According to Gradstein et al. (2004), the duration of the Tithonian stage is 5.3 m.y. The six Andean ammonite biozones of the Tithonian interval of the Neuquén Basin (Riccardi, 2008) and three calcareous nannofossil bioevents are recognized in the studied section (Figure 3). They include the first occurrences (FOs) of *Polycostella beckmanii*, *Eiffelithus primus*, *Umbria granulosa*, and the presence of *Polycostella senaria*.

SEDIMENTARY FACIES

In the Loncoche section, the Tithonian interval of the Vaca Muerta Formation consists of several facies (Table 1) that can be grouped into four main facies associations. These characterize different paleoenvironmental conditions and settings within a mid-outer carbonate ramp (e.g., Mitchum and Uliana, 1985).

Facies Association I

This facies association consists of laminated black shales rich in organic matter (as much as 6.6%). It forms laterally persistent beds, decimeter to meter thick, with local occurrence of ellipsoidal carbonate concretions, commonly concentrated along stratigraphic horizons. The shale contains scarce fossils including ammonite fragments, oysters, infaunal bivalves, and fish scales.

Black shale intervals commonly alternate with decimeter-scale beds consisting of microbial mats (Figure 4A) with a conspicuous lamination defined by wavy to crinkly carbonaceous laminae and massive to laminated black to dark-gray lime mudstones-wackestones (Table 1). These carbonate intervals contain oysters, infaunal bivalves (*Lucina neuquensis*), ammonites, echinoderm fragments, benthic foraminifers (*Epistomina* sp.), and radiolarians (Figure 5A). Subordinately, this assemblage can include centimeter-scale beds of siltstones and fine-grained carbonate sandstones with small-scale ripple lamination (Table 1).

Sedimentation occurred in a landlocked restricted marine environment with anoxic bottom waters, below storm-wave base (basin to outer ramp setting), as indicated by the absence of wave-induced structures, and the benthic microbial activity coexisting with the passive accumulation of organic materials and pelagic microfossils. The high organic matter content suggests elevated organic productivity or good preservation, as well as the absence of bottom-dwelling organisms (Savrdá and Bottjer, 1986).

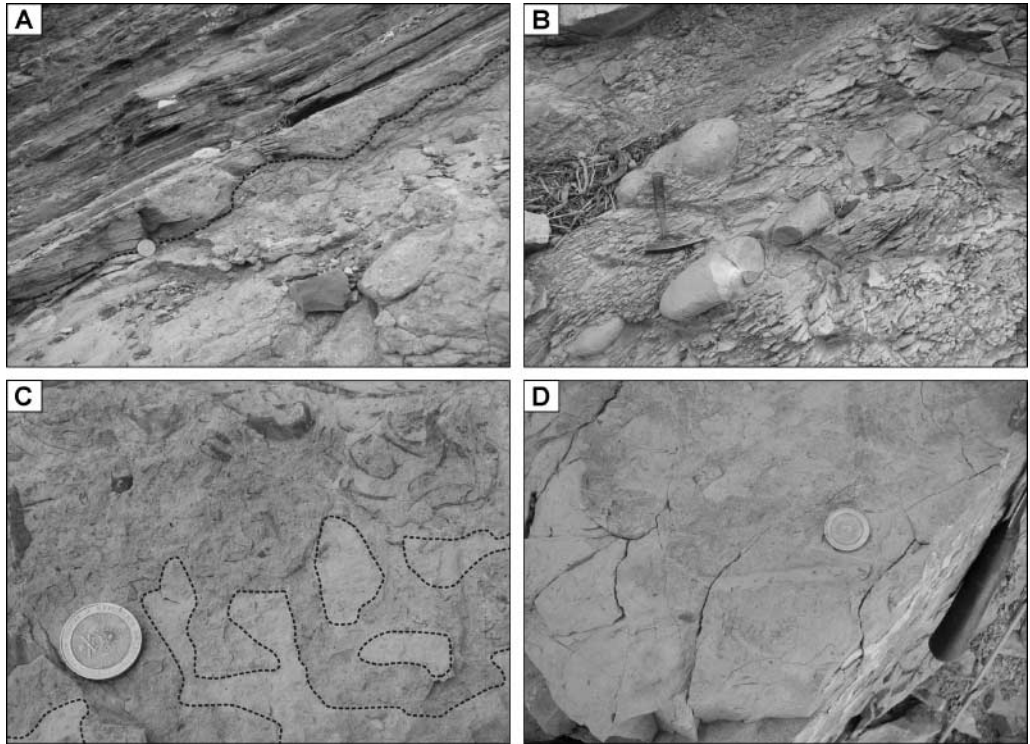
Sedimentation occurred mainly from suspension. However, the presence of fine-grained ripple laminated carbonate sandstones, as well as bioclastic

Table 1. Facies Chart and Interpretation of Depositional Environment

Lithologies	Geometry/Thickness	Primary Grain Types/Ichnofossils	Sedimentary Structures	Depositional Setting
Black shales	Tabular geometry; 0.01–1 m in thickness	Ammonite fragments, oysters, former aragonitic bivalves	Laminated or massive Planar laminated or massive	Basin to outer ramp setting. Anoxic to dysaerobic conditions
Brown shales	Tabular geometry; 2–80 cm in thickness	Ammonites, small bivalves, oyster fragments, radiolarian, forams. Chondrites isp.		Outer ramp setting. Dysaerobic to eventually aerobic conditions
Siltstones	Tabular geometry; 10–80 cm in thickness	Former aragonitic bivalves (Lucina), oysters, fish scales	Planar laminated; current ripple lamination	Outer ramp setting. Dysaerobic to aerobic conditions
Marls	Tabular geometry; 2–380 cm in thickness. Interbedded with nodular mud wackestones	Ammonite, serpulids, and bivalves. Thalassinoides isp.	Thinly laminated	Outer to middle ramp setting. Dysaerobic to aerobic conditions
Mudstones-wackestones	Tabular geometry; 2–20 cm in thickness Interbedded with shales and marls	Oysters, thin bivalves, ammonites, radiolarian, and foraminifera	Planar laminated or massive	Outer ramp setting. Anoxic to dysaerobic conditions
Bioclastic wackestones	Tabular geometry to nodular; 5–70 cm in thickness	Ammonites, bivalves, oysters, radiolarian, forams, gastropods, and echinoderms. Thalassinoides, Planolites, and Palaeophycus	Planar laminated or massive	Outer to middle ramp setting. Aerobic conditions
Bioclastic packstones	Tabular geometry to nodular; 10–30 cm in thickness	Ammonites, bivalves, oysters, gastropods, echinoderms, and serpulids. Phosphatized intraclasts and peloids. Thalassinoides	Massive to planar laminated	Outer to middle ramp setting. Aerobic conditions

Figure 4. Sedimentary facies in the Loncoche

Creek section. (A) Black shales interbedded with laminated lime mudstones and microbial mats at the contact between the Vaca Muerta and Tordillo formations (dashed line). (B) Concretionary lime mudstones/wackestones interbedded with marls. (C) Bioclastic wackestones/packstones tempestite with an erosional contact and passive filling of *Thalassinoides* galleries (dashed line). (D) Bioclastic wackestones with *Thalassinoides* (top bed view). Coin scale of 2.5 cm (0.98 in.).



remains such as in faunal bivalves and echinoderm fragments (bioclastic mudstone-wackestone), suggests shallow-water sediment input (Pittet and Strasser, 1998) probably associated with storm-generated turbidite flows.

Facies Association II

This facies is defined by brown laminated shales, centimeter- to decimeter-scale thick, rhythmically alternating with (argillaceous) lime mudstones-wackestones. Shale beds contain transported infaunal bivalves and oyster fragments (*Aetostreon* sp.). Limestone beds are centimeter- to decimeter-scale thick, dark-gray, massive or laminated, bioclastic-peloidal mudstones-wackestones. Bioclasts include oyster (*Aetostreon* sp.), infaunal bivalves, echinoderms fragments, scarce brachiopods (*Lingularia* sp.), and ammonites. Microfossils are benthonic foraminifera (*Epistomina* sp.) and radiolarians (Figure 5B). Locally, some bioturbation represented by *Chondrites* can be present.

Horizontal lamination of the brown shales suggests that the deposition occurred in a low-energy

environment, probably mostly from suspension. In contrast with the previous facies association, the sea bottom should have been dominantly dysaerobic, but eventually aerobic, as indicated by the sporadic presence of in-situ fauna remains. *Chondrites* traces are also considered typical of dysaerobic settings (Savrda and Bottjer, 1986).

Facies association II is interpreted as deposited in a dysaerobic outer ramp setting, dominated by fallout of fine muddy sediments. Bioclastic carbonate facies are probably produced by a combination of normal fallout of muddy sediments and suspended sediment transported during minor storms.

Facies Association III

This association is dominated by massive marls and bioclastic wackestones. The marls are laminated and olive gray, dark gray, or brown in color. They commonly yield horizontally arranged ammonites and bivalves. The latter include *Aetostreon* sp., *Eriphyla* sp., and *Lucina neuquensis*, which appear commonly disarticulated but rarely broken or abraded. *Serpulids* are also present (*Rotularia* sp.). The

marls contain horizons of carbonate concretions (Figure 4B) and are moderately bioturbated, with rare *Thalassinoides*.

The bioclastic wackestones are black to dark gray and form massive or laminated beds. Bioturbation is common, with *Thalassinoides* (Figure 4C), *Rhynchonellid*, and *Palaeophycus*. Bivalves such as *Ano-paea* sp., *Eriphyla* sp., *Lucina neuquensis*, *Cucullacea* sp., and *Aetostreon* sp. are the dominant macrofossils. With the exception of the oysters, they are commonly articulated. Breakage and abrasion are minor. Ammonites, small gastropods, serpulids (*Rotularia* sp.), echinoderm fragments, foraminifers (*Epistomina* sp.), and radiolarians are also present (Figure 5C, D). Nonskeletal components include fecal pellets and phosphatic particles.

Thin-bedded normal-graded bioclastic packstones-grainstones, typically with sharp bases, are intercalated within the other facies. They contain disarticulated and broken bivalves, ammonites and serpulid fragments, small gastropods, and foraminifers (*Epistomina* sp.).

Facies association III was probably deposited in a proximal outer ramp setting under moderately aerobic to dysaerobic conditions, below storm-wave base, as suggested by the bioclastic content, the generally good preservation state, occurrence of a benthonic community, and the moderately common bioturbation.

Marls and bioclastic wackestones represent fallout sedimentation during fair-weather conditions. Graded bioclastic packstones-grainstones with disarticulated and broken bioclasts, and sharp erosive bases, are interpreted as low-density tempestite flows originated by major storms.

Facies Association IV

This facies is defined by a higher abundance of carbonate. Decimeter-scale rhythmic changes in vertical facies successions are still recognizable. The dominant facies are dark-gray to gray-brown bioclastic wackestone-packstones, marly wackestones, and marls. Benthonic communities include epi- and infaunal bivalves, gastropods, echinoderms, and serpulids (*Rotularia* sp.). Among the bivalves, oysters are dominant (*Aetostreon* sp.), but others

such as *Grammatodon* sp., *Pholadomya* sp., *Eriphyla* sp., and some pectinids are also common. Bivalves are generally articulated, with minor breakage and abrasion.

In some levels, oysters are aggregated to form biostromes that are up to several decimeters thick and have a conspicuous lateral continuity. Bioclastic levels show densely packed fabric and poor to moderate sorting. Oysters have convex-up, convex-down, nested, and/or random orientation. Nonskeletal components include phosphatized intraclasts and gastropods steinkerns (internal cast of gastropod cameras) (Figure 5F).

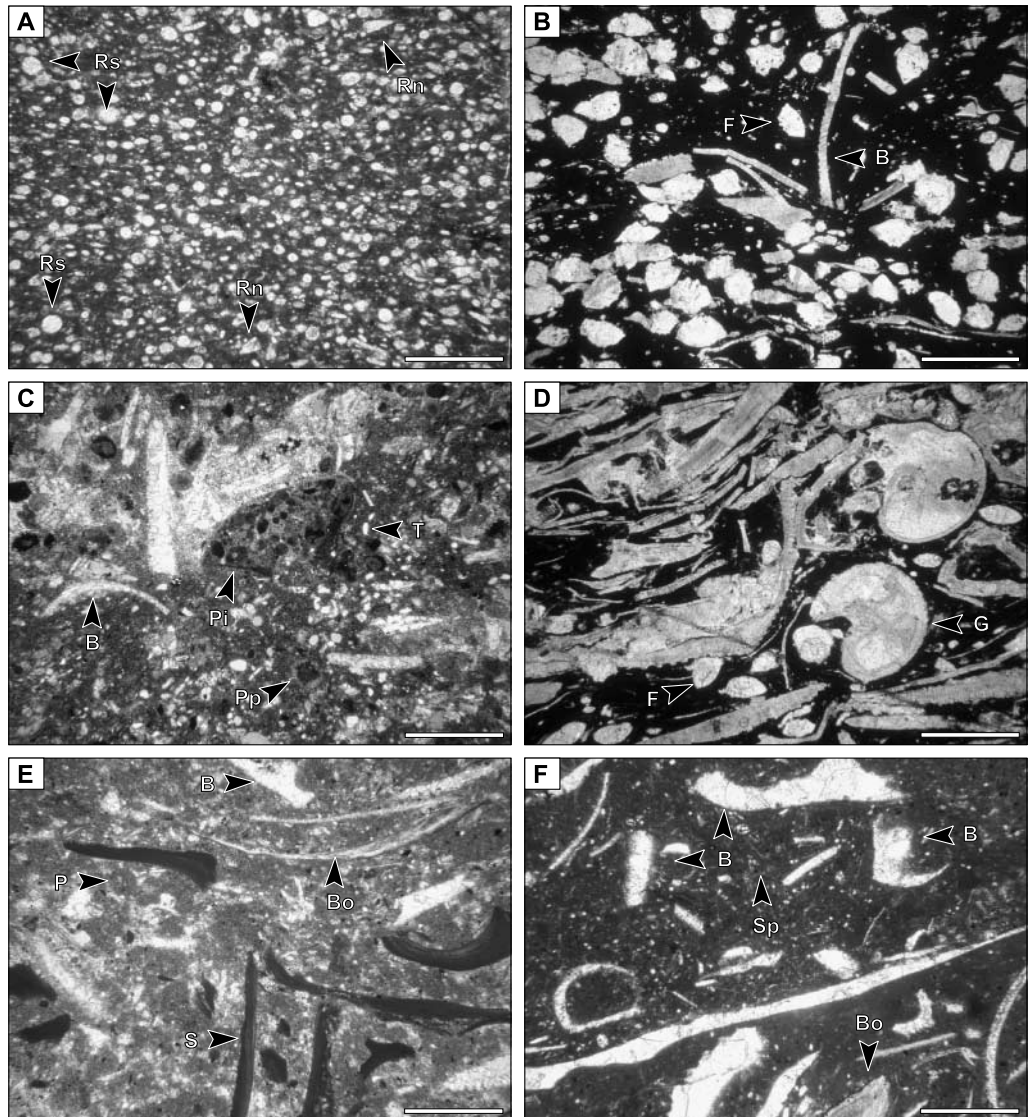
This facies association is characteristic of well-oxygenated muddy bottoms commonly located in the middle ramp between the storm-wave base and the fair-weather wave base (Burchette and Wright, 1992). The development of oyster biostromes, with convex-up, convex-down, nested, and/or random shell orientation, is probably related to bottom remobilization occurring during major storms (Kietzmann and Palma, 2009; Kuhnt et al., 2009). Phosphatized intraclasts and steinkerns are typically associated with fluctuating sedimentation rates and reworking and redepositional processes within the winnowing zone (Flügel, 2004). The coexistence of endobenthic (*Grammatodon* sp., *Pholadomya* sp., *Eriphyla* sp., and *Thalassinoides* sp.) and epibenthic organisms (gastropods, echinoids, oysters, and pectinids) is also an evidence of alternating hydrodynamic and energy conditions (Kietzmann and Palma, 2009) that support this interpretation.

Source Rock Characteristics

Source beds of oil in the Vaca Muerta Formation occur in the Tithonian basal black shales that are considered to be the most effective source interval in the basin (Mitchum and Uliana, 1985).

Actually, more than 75% of the discovered hydrocarbons in Argentina were generated in Upper Jurassic and Lower Cretaceous source rocks, concomitant with rapid basinwide sea level rises (Uliana et al., 1999). Remaining reserves and production data associated with petroleum systems indicate that about 50% of hydrocarbons are from

Figure 5. (A) Radiolarian wackestones (*Rs* = *sputumellarian*; *Rn* = *nassellar-ian*). (B) Wackestones with *Epistomina* sp. (*F*) and former aragonitic bivalve fragments (*B*). (C) Phos-phatic wackestone with aragonitic bivalve fragments (*B*), phosphatized intra-clast (*Pi*), phosphatized peloids (*Pp*), and terrige-nous particles (*T*). (D) Bio-clastic wackestones/ packstones with formerly aragonitic bivalve fragments, gastropods (*G*), and *Epistomina* sp. (*F*). (E) Bio-clastic wackestone with former aragonitic bivalve fragments (*B*), oyster fragments (*Bo*), serpulid fragments (*S*), and terrige-nous particles. (F) Bioclastic wackestone with former aragonitic bivalve fragments (*B*), oyster fragments (*Bo*), and sponge spicules (*Sp*). Scale = 1 mm.



the Vaca Muerta Formation, which shows a prevalence of oil over gas (Legarreta et al., 2005).

These basal organic-rich deposits, that reach 50 m (164 ft) in thickness, occur in the *Virgatospinctes mendozanus* zone up to the base of the *Pseudolissoseras zitteli* zone (Figure 3). Geochemical work toward the characterization of types and maturity of the organic matter in these levels through the basin shows that kerogen quality is remarkably homogeneous (Cruz et al., 1999). Organic matter richness in the black shales is variable, with total organic carbon (TOC) ranging between 3 and 8wt. % on average, although notably higher TOC contents, as much as 10 to 12 wt. %, were also recognized (Villar et al., 1998). The visual

kerogen analysis shows a predominance of amorphous organic matter, marine microplankton, and low participation of continental elements. Hydro-gen indices range from 400 to 800 (mg HC/g TOC), which indicate hydrogen-rich organic matter (types I-II kerogen) that qualifies these laminated black shale sequences as excellent oil-prone source rocks. Spectral data reported by Villar et al. (1998) showed that ions monitored had mass-to-charge ratios (*m/z*) of 191 for triterpanes and 217 for steranes. The hopane distribution is characterized by a regular progression of C29 to C34, suggesting anoxic conditions during deposition. In the *m/z* 217 chromatogram, the C29 and C27 are the most predominant member series, pointing toward a

continental origin (Palaces et al., 1984). Also, the degree of thermal evolution of the organic matter was evaluated by vitrinite reflectance. Data from the central area of the Neuquen Basin (Cruz et al., 2002) show that Vaca Muerta Formation is mostly in the oil-generation window.

CYCLOSTRATIGRAPHIC ANALYSIS

Periodicity of Elementary Cycles and Spectral Analysis

To establish the periodicity of the elementary cycles, the number of elementary cycles was divided by the total duration of the succession (251 cycles for 5.3 m.y.). The calculated average duration of each elementary cycle is 21.1 k.y. This value is a good approximation to the average periodicity of the orbital precession, which according to astronomical models, is about 20 k.y. for the Late Jurassic (Berger et al., 1989). Data from other Jurassic examples are consistent with this average value (e.g., Hinnov and Park, 1999; Weedon et al., 1999; Husinec and Read, 2007).

Spectral analysis is applied to test the occurrence of Milankovitch cyclic elements of lower frequencies than the precessional elementary cycles using FFT periodogram, smoothed periodogram, and Blackman-Tukey estimators.

The FFT periodogram shows three peaks corresponding respectively to periods of 119, 280, and 597 k.y. within the 99% confidence limit. An additional peak at 86 k.y. more than 95% confidence limit is recognized. Peaks below 95% confidence levels (e.g., 44 k.y.) were not considered (Figure 6B).

In the smoothed periodogram, the peaks identified are similar to those found using the FFT periodogram, with three main peaks at 87, 119, and 275 k.y. more than 95% confidence limit. A peak at 44 k.y. is also recognized, but because it is well below the 90% confidence limit, it was not taken into account (Figure 6C).

Finally, the Blackman-Tukey power spectrum shows two prominent peaks at 91 and 118 k.y. more than 95% confidence limit. A peak at 46 k.y. is also

recognized, but it was not considered because its confidence level was less than 90% (Figure 6D).

Both diagrams from compacted and decompacted thickness show peaks at frequencies of about 0.155, 0.170, and 0.194, indicating relatively significant spectral peaks, with periods about 5.15, 5.85, and 6.38 times of duration for the elementary cycle. These peaks represent frequencies between 103 and 127 k.y. These results are consistent with the high-frequency components of the eccentricity cycle, which range between 90 and 120 k.y. (e.g., Weedon and Jenkyns, 1999; Weedon et al., 1999). In addition, we identify potential longer term oscillations, which are not coincident with the lowest components of the orbital-eccentricity cycle (413 k.y. and 1.3 m.y., Weedon and Jenkyns, 1999). Contrary to the length of the precession and obliquity cycles, which has become longer through the Phanerozoic, the periodicity of the eccentricity is thought to have remained stable (Berger et al., 1989; Laskar, 1999).

Diagenetic compaction could have notably altered the original cycle thickness. As compaction affects differentially clay-rich and carbonate-rich cycles, a bed-by-bed correction has been introduced in the procedure. The ratio between the initial depositional thickness and the measured present-day thickness is defined by the decompaction factor (Baldwin, 1971). The adopted values for decompaction factors for shallow to medium burial depth range from 1.2 for grain-supported carbonates, 2 to 2.5 for mud-dominated carbonates, and 3 for marls and shales. The results are summarized in the spectral diagrams of Figure 7.

Main Genetic Intervals and Long-Term Cycles

To avoid a specific genetic connotation, the Loncoche section is divided into four successive sedimentary intervals termed "marl-rich intervals" and "carbonate-rich intervals" according to the facies distribution (MRI-1, CRI-1, MRI-2, and CRI-2; see Figure 3).

MRI-1 is found at the lowermost part of the Vaca Muerta Formation and has a thickness of 47 m (154 ft). It is characterized by basin and distal-outer ramp facies, which show a clastic/limestone ratio of 4:1. Biostratigraphically, the interval MRI-1 covers the

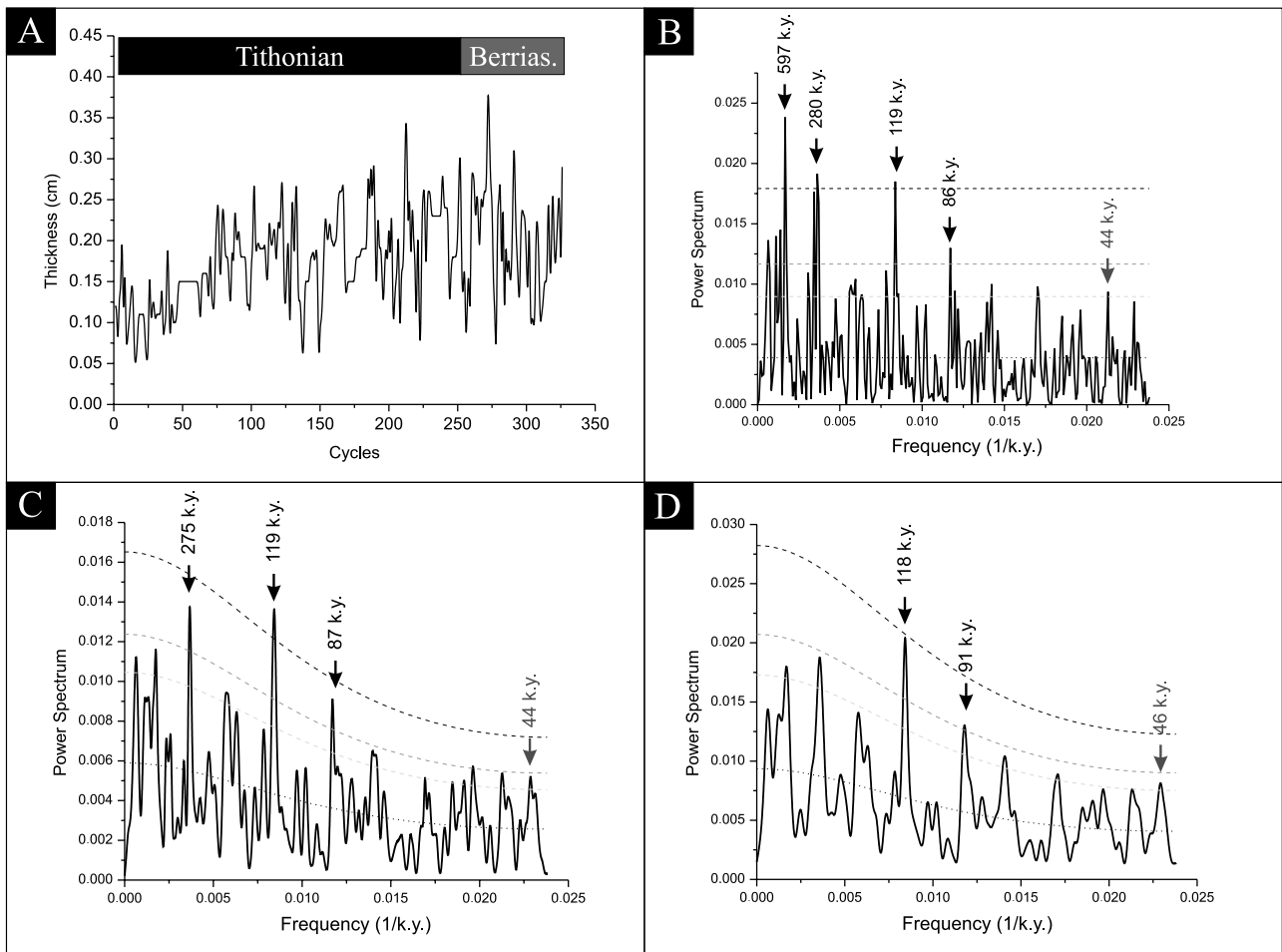


Figure 6. Cyclostratigraphic result of the Tithonian interval of the Vaca Muerta Formation. (A) Time series constructed with the precession elementary cycles. (B) Periodogram (fast Fourier transform) power spectrum without decompaction. (C) Smoothed peri-odogram power spectrum without decompaction. (D) Blackman-Tukey power spectrum without decompaction.

Virgatophinctes mendozanus zone (lower Tithonian) and part of the Pseudolissoceras zitteli (lower part of the middle Tithonian) (Figure 3).

MRI-1 is composed of a relatively monotonous succession consisting of facies association I and, to a lesser extent, facies association II. This interval contains 56 elementary cycles. The cycles range in thickness from 0.15 to 0.90m (0.49 to 2.95 ft) with a mean of 0.4 m (1.3 ft). The basal facies of the interval do not show a well-defined cyclicity.

CRI-1 is 57 m (187 ft) thick and characterized by distal outer ramp facies. The dominant facies associations are II and III. The clastic/limestone ratio approaches 1:1. The interval comprises the Pseudolissoceras zitteli zone (lowermost middle Tithonian) to the Windhausenicerias internispinosum zone (uppermost middle Tithonian).

This interval consists of 90 cycles. Elementary cycle thickness ranges from 0.12 to 1.25 m (0.39 to 4.1 ft), with a mean of 0.4 m (1.3 ft).

The MRI-2 is only 24 m (79 ft) thick. It consists of an alternation of brown shale and marls with fine-grained wackestones with a low faunal content. These facies characterized an outer ramp setting and mostly correspond to facies association

II. The clastic/limestone ratio is 3:1.

This interval extends from the Windhausenicerias internispinosum zone (uppermost middle Tithonian) to the Corongoceras alternas zone (lowermost upper Tithonian). It comprises 37 cycles (bed couples). Cycle thickness ranges from 0.15 to 0.30 m (0.49 to 0.98 ft), with an average of 0.20 m (0.66 ft). CRI-2 is 45 m (148 ft) thick. It is composed of laminated brown marls and laminated to massive

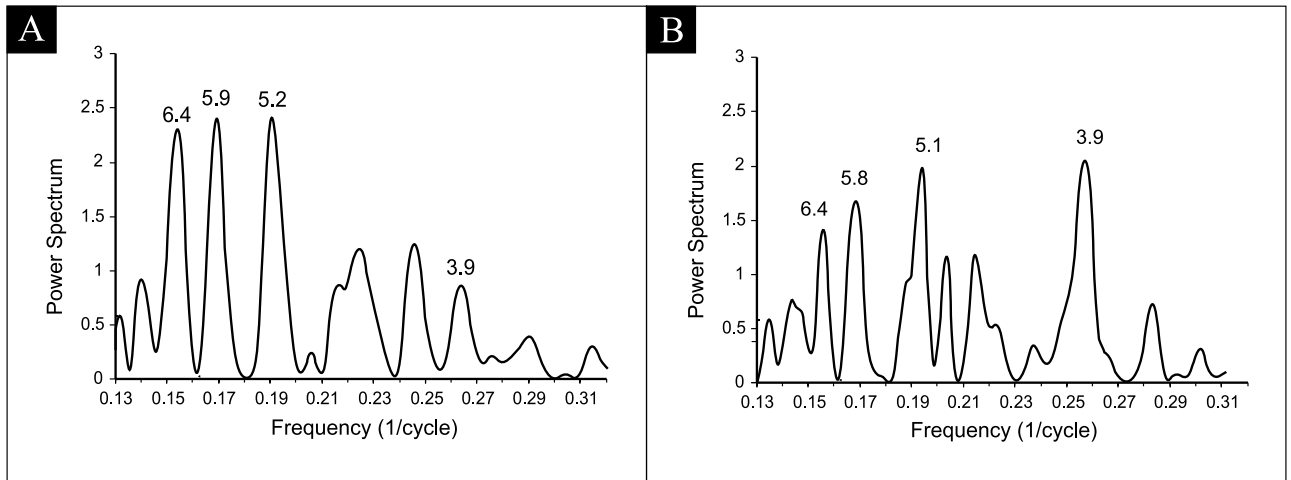


Figure 7. (A) Lomb-Scargle power spectrum without decompaction. (B) Lomb-Scargle power spectrum with decompaction.

bioclastic wackestones of facies association II and IV. The clastic/limestone ratio is 1:1. The time interval spans from the *Corongoceras alternas* zone (lowermost upper Tithonian) to the *Substeueroceras koeneni* zone (uppermost upper Tithonian). The elementary cycles are very well expressed and comprise 74 bed couples. The thickness of elementary cycles ranges from 0.12 to 0.97 m (0.39 to 3.18 ft), with a mean of 0.4 m (1.3 ft).

Interpretation

Marl-limestone cycles have been cited as key examples of climate-forced sedimentation resulting from numerous paleoenvironmental factors, including fluctuations in the supply of calcareous biogenic sediments produced by plankton (productivity cycles, Einsele and Ricken, 1991) and fluctuations in the input of fine terrigenous sediments (dilution cycles, Arthur et al., 1984; Einsele and Ricken, 1991). Additional potential mechanisms include diagenetic redistribution of calcium carbonate (dissolution cycles, Einsele and Ricken, 1991; Westphal et al., 2010), fluctuations in carbonate mud export from shallow areas (carbonate dilution cycles, Pittet and Strasser, 1998), and fluctuations in superficial fertility (fertility cycles, Premoli Silva et al., 1989).

The four identified intervals in the studied section of the Vaca Muerta Formation can be inter-

preted in terms of long-term changes of relative sea level and carbonate productivity. Using sequence-stratigraphy data from Mitchum and Uliana (1985), Kietzmann et al. (2008), and Kietzmann and Palma (2009), the two marl-rich intervals can be attributed to transgressive episodes, as a consequence of a rapid rise of relative sea level. This process would explain low productivity in the surface waters and shallow areas and low-oxygenated sea bottom. By contrast, carbonate-rich intervals coincide with a decrease in accommodation, which induces an increase in carbonate basinward export from shallower areas and an increase in oxygenation of sea bottom.

The vertical patterns in cycle thickness outline the long-term changes in sedimentary accumulation rates, which are essentially coeval with the long-term variations in the carbonate productivity of shallow ramp areas. Cycles could be produced by changes in carbonate production in shallow areas, and these changes would be driven by orbitally induced climate changes (change in solar radiation).

Other Upper Jurassic–Lower Cretaceous examples (Weedon et al., 1999, 2004; Strasser, 1994; Bádenas et al., 2003; Anderson, 2004; Strasser et al., 2004; Husinec and Read, 2007) show a similar pattern, although the obliquity signal is thought to dominate at high latitudes and the precessional signal at middle and low latitudes (Weedon et al., 1999, 2004).

Our analysis suggests that the elementary cycles of the Vaca Muerta Formation have an average duration of roughly 20 k.y. (precession) and are modulated by 100 k.y. (short-term eccentricity). Low-frequency orbital eccentricity and obliquity have not been identified in this study and seem to have minor importance. Therefore, our example is consistent with published data for similar latitudes in the Northern Hemisphere.

Cycles are probably driven by “carbonate dilution” processes, such as those described by Pittet and Strasser (1998), or by “carbonate exportation” processes proposed by Bádenas et al. (2003). These types of cycles are produced by changes in shallow-water carbonate production, which in turn involve changes in carbonate basinward exportation. Orbital variations induce climate changes by means of the control of solar radiation. This interpretation is supported by the dominance of storm-related processes, as well as the relative proportion of C₂₉ over C₂₇ steranes, which suggests some continental input for the organic matter.

CONCLUSIONS

The study interval of the Loncoche section comprises the early Tithonian *Virgatospinctes mendocanus* zone to the late Tithonian *Substeueroceras koeneni* zone. Three calcareous nannofossil bioevents have been found. They include the first occurrences (FOs) of *Polycostella beckmanii*, *Eiffellithus primus*, *Umbria granulosa*, and the presence of *Polycostella senaria*. Four main facies associations reflect different paleoenvironmental conditions. Facies association I consists of black shales deposited under anoxic conditions below a storm-wave base. Facies association II consists of alternating brown laminated shales and lime mudstones-wackestones deposited in a dysaerobic to aerobic low-energy environment. Facies association III, dominated by marls and bioclastic wackestones, is characterized by higher contents in carbonates than the previous associations and was deposited in anaerobic outer ramp environment. Facies association IV is dominated by peloidal wackestones-packstones, oyster biostromes and marls.

This facies was deposited in well-oxygenated muddy bottoms located within the storm-wave base.

Three prominent frequencies were identified at 20 (precession), 90, and 120 k.y., respectively (eccentricity). Our analysis strongly suggests that the elementary cycles of the Vaca Muerta Formation were of roughly average duration and were probably formed by precessional-driven climate changes modulated by high-frequency eccentricity. We suggest that the precession orbital element was the main driver of periodic climate changes during the Late Jurassic in mid latitudes of the Southern Hemisphere. Climatic or paleoceanographic changes controlled by low-frequency orbital eccentricity seem to have lesser importance, and those controlled by the obliquity have not been identified in this study.

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