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ORIGINAL ARTICLE

# New contributions to the palaeoenvironmental framework of the Los Molles Formation (Early-to-Middle Jurassic), Neuquén Basin, based on palynological data

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## Abstract

Being the main oil-bearing basin of Argentina, the Neuquén Basin contains a well-documented stratigraphic record of continental and marine sedimentation during the Jurassic and Cretaceous in the western margin of Gondwana. Marine sedimentation started in the Early Jurassic with the deposition of the offshore to prodelta shales of the Los Molles Formation, the basal unit of the Cuyo Group. A palynological study of outcrop samples of the Los Molles Formation at two localities, Puente Picún Leufú, southern Neuquén Basin, and Cordillera del Viento, central basin area, is presented. The palynological evidence allows inferring two different palaeoceanographic contexts during the deposition of the Los Molles Fm. At Puente Picún Leufú and the lower part of the Cordillera del Viento localities, the record of acritarchs and prasinophytes suggests a stratified water column, suboxic-to-anoxic bottom conditions, and a reduced salinity within the photic zone, associated with a marginal marine environment under restricted oceanic circulation. These conditions would have last at least until the Early Bajocian. Conversely, at the middle and mainly the upper part of Cordillera del Viento locality, the predominance of dinocysts in the assemblages indicates a hydrographically unstable shelf (non-stratified water mass column) with well-oxygenated bottom waters developed under open-marine settings with non-restricted oceanic circulation. The abundance and diversity of dinocyst assemblages are comparable with those observed in the Late Callovian Lotena Formation. These evidences suggest an open oceanic circulation due to the establishment of different seaways in the Neuquén Basin, during the final accumulation of the Los Molles Formation (Early Callovian).

**Keywords** Los Molles Formation · Early-Middle Jurassic · Palaeoceanographic changes · Neuquén Basin · Organic-walled marine microplankton

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## Introduction

The Neuquén Basin is located in western central Argentina, between 34° and 41°S. It is currently one of the most proliferous oil-bearing basins of South America. During recent years, the increasing demand for fossil fuels added to the worldwide scarcity of conventional reserves of oil and gas has promoted the exploration of unconventional resources. In Argentina, unconventional resource exploration started in 2007 targeting the Upper Jurassic–Lower Cretaceous Vaca Muerta Formation, a well-known source-rock exhibiting excellent unconventional properties. More recently, the exploratory interest has been expanded to the Lower–Middle Jurassic Los Molles Formation (Weaver 1931), another source-rock unit of the Neuquén Basin that exhibits stimulating unconventional properties (e.g., Chebli et al. 2011; Giunta et al. 2018; Gutiérrez Pleimling et al. 2018).

The Los Molles Formation is stratigraphically located at the base of the Cuyo Group (also referred to as "Cuyano", Groeber 1946). It is a thick (up to 1000 m) succession of organic-rich fine-grained sediments and represents the first major marine transgression in the Neuquén Basin during the Early Jurassic. In the northern Neuquén Basin marine flooding coming from the Pacific Ocean started in the Hettangian, progressively advancing to the south until the entire basin was flooded in the Pleinsbachian (Riccardi et al. 1988). The Cuyo Group represents a prograding, shallowing-upward sedimentary cycle that infilled a tectonically induced irregular relief inherited from the initial basin configuration (synrift phase).

Although the Los Molles Formation has been studied in several contributions from a palynological point of view by Volkheimer (1973, 1974), Martínez and Quattrocchio 2005, García et al. 2006), Martínez et al. (2005, 2008), and Quattrocchio et al. (2007), these studies provided partial information only from the southern part of the basin. In this contribution, palynological results from southern and northern areas were integrated for the first time, allowing us to analyze the accumulation of the Cuyo Group in terms of oceanic circulation.

This paper aims to improve the current understanding of the palaeoenvironmental conditions of the Neuquén Basin during the deposition of the Los Molles Formation, (Early-to-Middle Jurassic), mainly based on the record of organic-walled marine microplankton assemblages having different palaeoecological requirements. Complementary information was provided by the analysis of the sedimentary organic matter (palynofacies analysis) carried out on these levels. Outcrop samples were collected in two sections located at a distance of about 200 km (Fig. 1). The Puente Picún Leufú Sect. (39°11′13.88"S—70° 4′0.48"W) is placed at the intersection of the Ruta Nacional 40 and the Picún Leufú river (approximately 40 km southward from Zapala city). This section is located in the Picún Leufú Sub-basin (Hogg 1993). The Cordillera del Viento Sect. (37°14′17.92"S—70°30′18.68"W) is located 23 km northwest from Andacollo city in the central area of the Neuquén Basin.

## Geological setting and stratigraphy

### The Neuquén Basin

The Neuquén Basin is a triangular-shaped basin that covers more than 160,000 km$^2$. Basin boundaries are defined by the Sierra Pintada belt to the northeast and the North Patagonian Massif towards the southeast, whereas the occidental margin is defined by the Andean magmatic arc. The Neuquén Basin has been interpreted as a back-arc basin associated with the thermal–tectonic collapse of the continental crust behind a stationary magmatic arc during the Late Triassic (Mpodozis and Ramos 1989; Vergani et al. 1995). During the Jurassic and Early Cretaceous, the Neuquén Basin was an important depocenter. It presents a sedimentary record of more than 7000 m of marine and continental deposits laying on top of a highly heterogeneous Paleozoic basement (Mosquera et al. 2011). The infill of the Neuquén Basin was mainly controlled by tectonic activity and repeated sea-level oscillations that conditioned the basin connection with the palaeo-Pacific Ocean (Legarreta and Uliana 1991; Mutti et al. 1994). As a result, periods of high eustatic sea level resulted in marine flooding from the Pacific Ocean, providing anoxic to suboxic bottom conditions, which favored source-rock development (Legarreta 2002). On the other hand, lowstand periods caused forced regressions and the consequent development of evaporites and non-marine clastics sourced from the eastern and southern margin of the basin (Gulisano et al. 1984; Legarreta and Uliana 1991; Mutti et al. 1994). These transgressive–regressive cycles are repeatedly recorded in the stratigraphic record of the Neuquén Basin. According to Zavala et al. (2006), periods of marine disconnection are usually associated with regional unconformities defined by sharp lithologic contacts between continental and marine deposits. Locally, angular unconformities can be recognized at the boundary between major sequences, thus suggesting some tectonic overprint (Zavala et al. 2020).

Groeber (1946) recognized three main transgressive–regressive sedimentary cycles: Jurásico, Ándico, and Riográndico. The "Jurásico" Cycle (Groeber 1946) comprises three main depositional sequences bounded by regional unconformities, known as Cuyano, Loteniano, and Chacayano. These major depositional sequences were later redefined as Precuyo, Cuyo, and Lotena groups (Stipanicic 1969; Gulisano et al. 1984), each of them characterized by the alternation of marine and continental deposits.

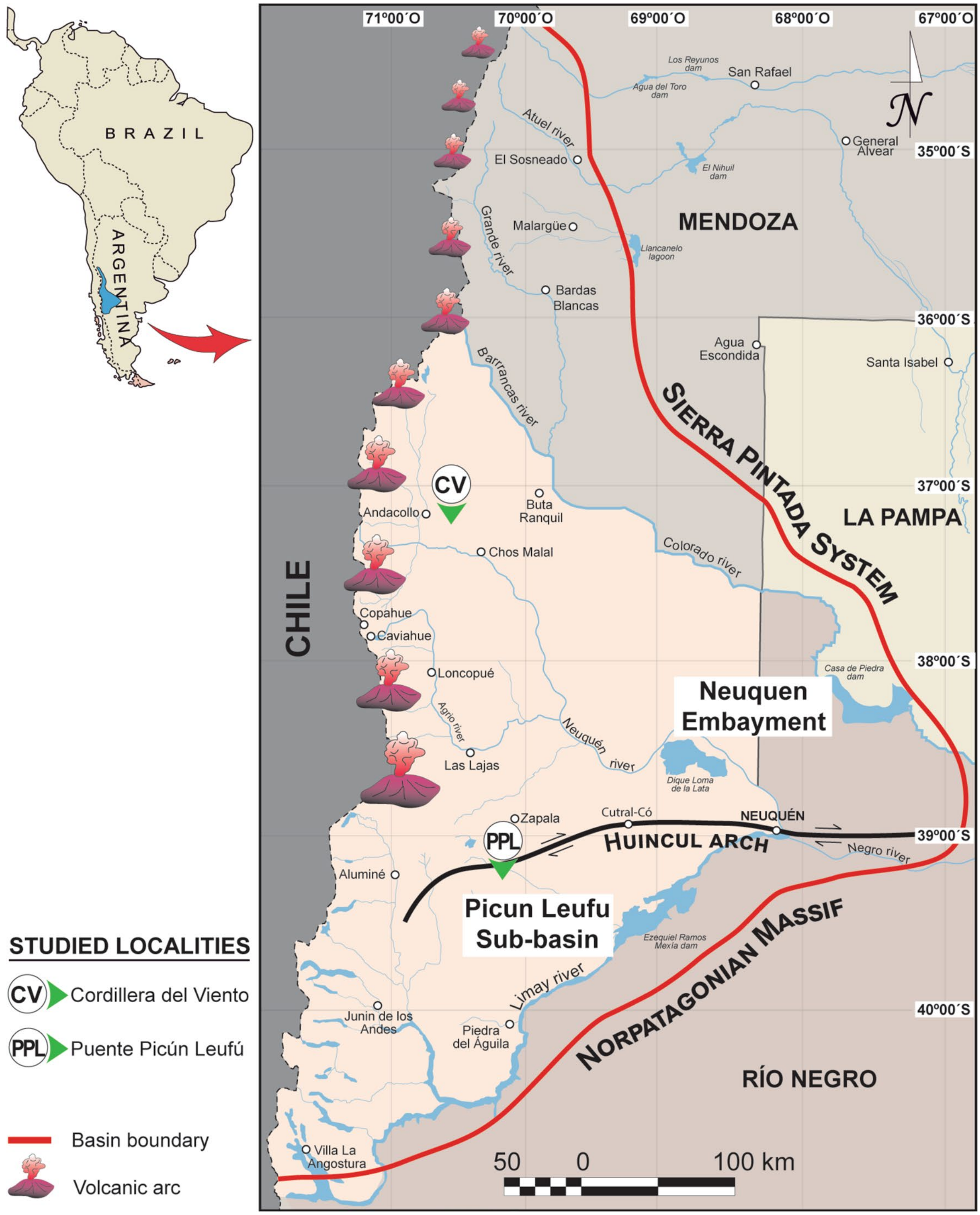
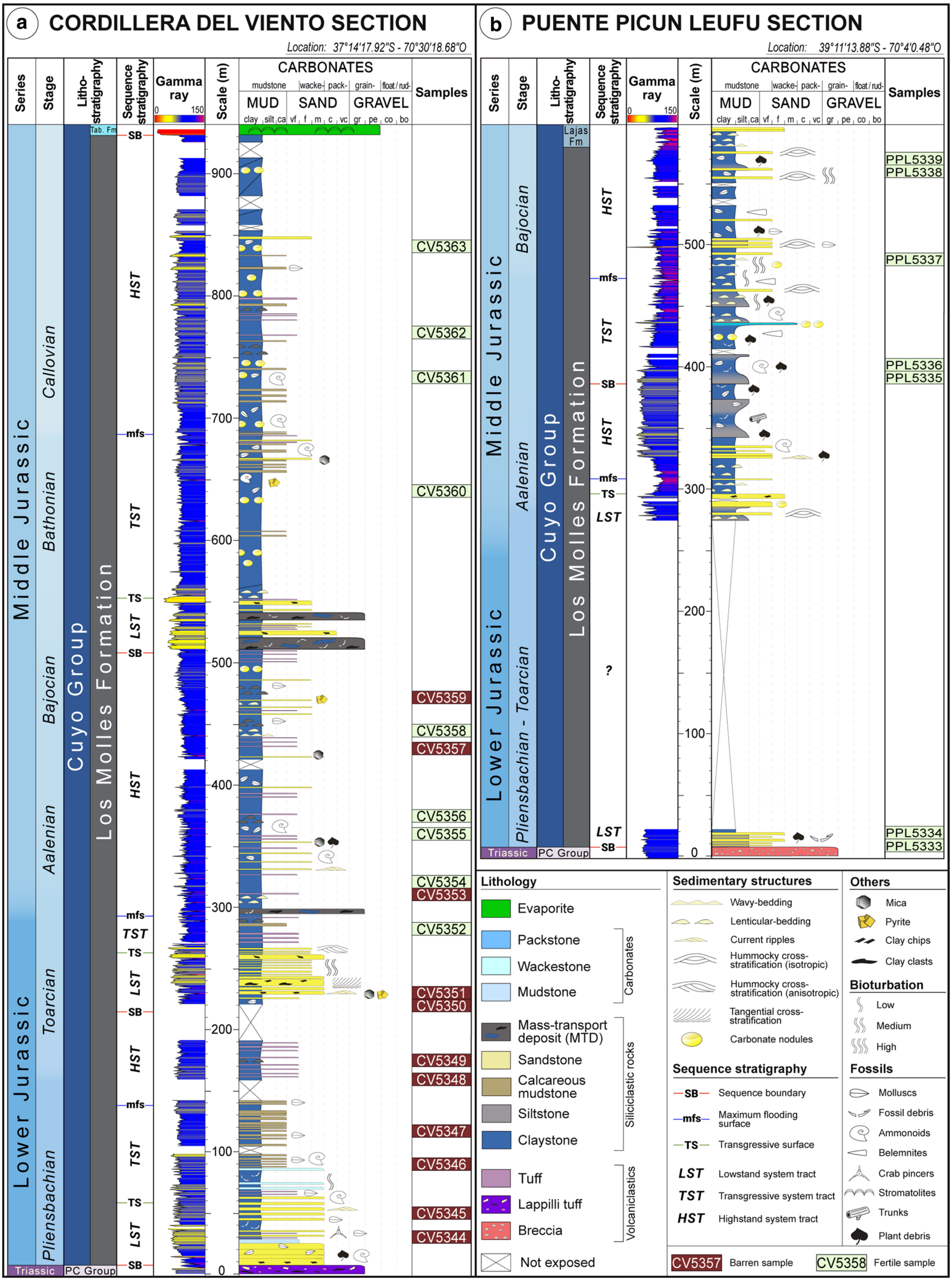


**Fig. 1** Location map of the Neuquén Basin in west-central Argentina. Detail of the studied sections (Puente Picún Leufú and Cordillera del Viento)

Several authors have postulated that the initial infill of the Neuquén Basin (Precuyo Group) was developed under a palaeogeographic configuration characterized by isolated rift depocenters (e.g., Vergani et al. 1995; Howell et al. 2005). This tectonic control partially remained during the accumulation of the lower Cuyo Group (Gulisano et al. 1984). The Lotena Formation (Late Callovian) represents the second episode of marine sedimentation in the Neuquén Basin developed after an important desiccation event (Zavala 2005). In contrast with the underlying Cuyo Group, the Lotena Formation was developed under open (non-restricted) marine conditions (Martínez and Olivera 2016).


a
CORDILLERA DEL VIENTO SECTION
Location: 37°14'17.92"S - 70°30'18.68"O
Series
Stage
Litho-stratigraphy
Sequence stratigraphy
Gamma ray
0 150
Scale (m)
CARBONATES
mudstone wacke- pack- grain- float / rud-
MUD SAND GRAVEL
clay silt ca vf f m c vc gr pe co bo
Samples
Middle Jurassic
Lower Jurassic
Triassic
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Cuyo Group
PC Group
Los Molles Formation
Tab. Fm
SB
HST
mfs
TST
TS
LST
SB
HST
mfs
TST
TS
LST
SB
HST
mfs
TST
TS
LST
SB
900
800
700
600
500
400
300
200
100
0
CV5363
CV5362
CV5361
CV5360
CV5359
CV5358
CV5357
CV5356
CV5355
CV5354
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CV5351
CV5350
CV5349
CV5348
CV5347
CV5346
CV5345
CV5344
b
PUENTE PICUN LEUFU SECTION
Location: 39°11'13.88"S - 70°4'0.48"O
Series
Stage
Litho-stratigraphy
Sequence stratigraphy
Gamma ray
0 150
Scale (m)
CARBONATES
mudstone wacke- pack- grain- float / rud-
MUD SAND GRAVEL
clay silt ca vf f m c vc gr pe co bo
Samples
Middle Jurassic
Lower Jurassic
Triassic
Bajocian
Aalenian
Pliensbachian - Toarcian
Cuyo Group
PC Group
Los Molles Formation
Lajas Fm
HST
mfs
TST
SB
HST
mfs
TS
LST
?
LST
SB
500
400
300
200
100
0
PPL5339
PPL5338
PPL5337
PPL5336
PPL5335
PPL5334
PPL5333
Lithology
Evaporite
Packstone
Wackestone
Mudstone
Carbonates
Mass-transport deposit (MTD)
Sandstone
Calcareous mudstone
Siltstone
Claystone
Siliciclastic rocks
Tuff
Lappilli tuff
Breccia
Volcaniclastics
Not exposed
Sedimentary structures
Wavy-bedding
Lenticular-bedding
Current ripples
Hummocky cross-stratification (isotropic)
Hummocky cross-stratification (anisotropic)
Tangential cross-stratification
Carbonate nodules
Sequence stratigraphy
SB Sequence boundary
mfs Maximum flooding surface
TS Transgressive surface
LST Lowstand system tract
TST Transgressive system tract
HST Highstand system tract
Others
Mica
Pyrite
Clay chips
Clay clasts
Bioturbation
Low
Medium
High
Fossils
Molluscs
Fossil debris
Ammonoids
Belemnites
Crab pincers
Stromatolites
Trunks
Plant debris
CV5357 Barren sample
CV5358 Fertile sample

◂**Fig. 2** Generalized stratigraphic columns studied in this contribution. The analyzed palynological samples are indicated (barren and fertile); **a** Cordillera del Viento Section; **b** Puente Picún Leufú Section

The Cuyo Group represents the first transgressive–regressive episode, which was developed between Hettangian–Middle Callovian (Zavala 1996a). Although the transgression is dated to the Hettangian–Sinemurian in the northern part of the basin (Río Atuel locality) based on ammonites (Riccardi et al. 1988), it did not reach the central and southern Neuquén Basin until the Pliensbachian (e.g., Rosenfeld and Volkheimer 1980; Gulisano 1981). The base of the Cuyo Group is located at the Intraliasic unconformity (Gulisano et al. 1984). Along this unconformity, shelfal and shallow-marine clastics and carbonate deposits of the Los Molles Formation overlay basement rocks or syn-rift volcanic/volcaniclastic deposits of the Precuyo Cycle. The Cuyo Group starts with offshore to prodeltaic marine shales and turbidites of the Los Molles Formation (Weaver 1931), a thick, organic-rich unit (1–5% TOC, Chebli et al. 2011) originally interpreted as deposited in a deep-marine environment characterized by euxinic bottom waters. More recently, Zavala et al. (2014, 2020), based on facies analysis, reinterpreted these deposits as a complete suite of offshore to prodelta deposits, which are in part the result of muddy hyperpycnal flows. The Los Molles Formation is transitionally overlain by a thick succession of shelfal to shallow-marine sandstones and conglomerates of the Lajas Formation (Weaver 1931).

## Los Molles Formation at the studied localities

In the Puente Picún Leufú Section, the Los Molles Formation was deposited in an offshore to prodelta marine environment partially disconnected from the open sea. Mudstones commonly compose dm-thick graded beds with abundant plant remains disposed over sharp or erosional boundaries (Fig. 2b). These characteristics suggest the common occurrence of muddy hyperpycnal flows probably punctuated by normal fallout processes from hypopycnal buoyant plumes (Zavala and Arcuri 2016). Hyperpycnal flows develop at river mouth when the fluvial discharge has higher bulk density respect to that of the water in the sea, due to the high suspended load in the incoming flow. These flows are fully turbulent flows with interstitial freshwater and dispersed plant remains, and can be sustained for long time by relatively dense and long-lived river discharges. A number of recent studies have documented the erosional power of diluted muddy turbulent flows traveling along the sea bottom. These evidences have been recognized in ancient deposits (see summary on Lazar et al. 2015), actual systems (Macquaker et al. 2010), and flume experiments (Schieber et al. 2007). During their travel basinward, muddy hyperpycnal flows can erode the uppermost part (poorly consolidated or “soupy”) of intrabasinal silt–clay deposits, and incorporate marine microfossils to the original hyperpycnal flow (Schieber et al. 2007; Otharán et al. 2018a, b). Consequently, hyperpycnal flows are considered an efficient mechanism for the erosion and basinward transport of sediments and microfossils initially stored in littoral/shallow-marine environments (Zavala and Pan 2018). Therefore, the final products of these flows commonly show a mixture of intrabasinal (autochthonous) and extrabasinal (allochthonous) components, reflecting a complex sedimentological and taphonomic history (Lash 2016; Martínez et al. 2016; Zavala and Arcuri 2016).

At Cordillera del Viento Section, the Los Molles Formation is composed of a very thick succession of massive to laminated black shales interbedded with fine-grained sandstone beds accumulated in a basinal setting located far away (> 100 km) from the ancient coastline. Muddy hyperpycnites and fallout deposits are dominant, but sandy hyerpycnites (extrabasinal turbidites), intrabasinal turbidites, and mass transport complexes (MTCs) are also common (Fig. 2a). MTCs are triggered by an instantaneous or a progressive collapse (regressive scar) of the depositional slope (Moore 1969), thus suggesting the presence of an important relief in surrounding areas. As previously mentioned, the aperture of the Neuquén Basin during the Late Triassic resulted in the development of an irregular basin topography characterized by different hemigraben depocenters (Gulisano et al. 1984). The anomalous thickness of the Los Molles Formation at the Cordillera del Viento locality (> 900 m, Fig. 2a) together with the presence of MTCs suggest that at least during the Early Jurassic this area was still controlled by an irregular relief inherited from the initial rifting phase. In addition, the lower part of the Los Molles Formation is characterized by the common presence of cm-thick ash layers (commonly referred to as bentonites) interbedded with offshore mudstones and minor sandstone deposits (Fig. 2a). The characteristics of these volcaniclastic deposits suggest an eolian supply of ash clouds during powerful volcanic eruptions, and a deposition by suspension settling through the water column during periods of reduced terrigenous input. These deposits related to synsedimentary volcanism are significantly reduced towards the upper part of the Los Molles Formation (Fig. 2a).

# Materials and methods

## Sampling, laboratory treatments, and microscopy techniques

A total of 27 outcrop samples of siltstones and mudstones of the Los Molles Formation were studied (Fig. 2). The physical and chemical extraction of palynological organic matter was carried out using standard palynological techniques including processing with hydrochloric and hydrofluoric acids (Volkheimer and Melendi 1976). The slides were analyzed using transmitted white light (TWL) microscopes (Olympus BX40 and Nikon eclipse50i). Palynomorphs were evaluated under reflected fluorescence light microscope (RFL; Olympus BH2) with the aim of assessing their preservation state. Additionally, blue light fluorescence microscopy was used for palynological analysis as shown by Tyson (1995). The palynological slides are housed in the Instituto Geológico del Sur-Universidad Nacional del Sur, Bahía Blanca, Buenos Aires province, Argentina. They are identified by catalog numbers preceded by the abbreviation UNSP (Universidad Nacional del Sur, Palynology), followed by the abbreviation of the studied localities: PPL (Puente Picún Leufú) and CV (Cordillera del Viento). Specimen locations are referred to England Finder coordinates. A total of at least 250 palynomorphs per sample were counted taking into account their preservation state and deterioration type following Delcourt and Delcourt (1980) and Martínez et al. (2016). Then, they were clustered into eight groups based on their biological affinities: bryophyte/pteridophyte spores, pollen grains (Cheirolepidiaceae, Araucariaceae, Cycadales/Bennettitales/Ginkgoales, Pteridospermales, and Podocarpaceae), organic-walled marine microplankton = OWMM (acritarchs, prasinophytes, and dinocysts), and palynoforaminifera (foraminiferal test linings). A full list of the palynomorphs recognized in the samples studied herein is given in Online Resource 1.

The evaluation of the total palynological matter (PM) was made based on counts of at least 500 particles per sample considering two major categories (Table 1): (1) structured organic matter (i.e., Palynomorphs, Translucent, and Opaque Phytoclasts); and (2) structureless organic matter (i.e., Amorphous Organic Matter, AOM). The palynomorph group frequencies (%) were worked out considering the total number of counted particles (500), and the percentages of its constituents (i.e., pollen, spores, and microplankton) were calculated on the palynological count (250 palynomorphs as minimum). Then, the different constituents of the PM were interpreted in terms of palynofacies parameters (Table 2). The OWMM assemblages registered in the Los Molles Formation were compared to the marine palynoflora recognized in other Jurassic units of the Neuquén Basin, with which at least one taxon is shared. The assemblages considered in the matrixes, include the Los Molles (previous contributions),

**Table 1** Classification of palynological organic matter

| Major categories | Categories | | | Source |
|---|---|---|---|---|
| Structured | Palynomorphs | Sporomorphs | Spores | Reproductive structures of vascular land plants |
| | | | Pollen grains | |
| | | Organic-walled microplankton | Acritarchs | Organic-walled marine microplankton |
| | | | Prasinophytes | |
| | | | Dinocysts | |
| | | | Fresh-water algae | Chlorophyte algae |
| | | Zoomorphs | Palynoforaminifera | Benthic foraminifera |
| | Phytoclasts | Translucent | Tracheids with pits | Macrophyte plant debris |
| | | | Tracheids without pits | |
| | | | Other woody remains | |
| | | | Membranes | |
| | | | Cuticles | |
| | | | Tissues | |
| | | | Brown-black fragments | |
| | | | Yellow–brown fragments | |
| | | | Degraded fragments | |
| | | Opaque | Blade-shape | |
| | | | Equidimensional | |
| Structureless | Amorphous organic matter (AOM) | Fibrous | | Mainly derived from degradation of macrophyte tissues |
| | | Spongy | | Mainly derived from degradation of continental algae |
| | | Granular | | Degradation of phytoplankton or bacteria |
| | | Pelicular sensu Combaz (1980) | | |

**Table 2** Summary of palynofacies parameters used for palaeoenvironmental interpretation, based on: 1. Tyson (1995), 2. Batten (1996), 3. Mendonça Filho et al. (2012), 4. Van der Zwan (1990), 5. Gorin and Steffen (1991), 6. Frank and Tyson (1995), 7. Götz et al., 2003, 8. Martínez et al. (2008), 9. Olivera et al. (2010), 10. Martínez and Quattrocchio (2004), 11. Prauss (1989), 12. Prauss (1996), 13. Prauss (2001), 14. Prauss and Riegel (1989), 15. Brocke and Riegel (1996), 16. Parry et al. (1981), 17. Bucefalo Palliani et al. (2002), 18. van de Schootbrugge et al. (2005), 19. Smelror and Leereveld (1989), 20. Frieling and Sluijs (2018), 21. Pross and Brinkhuis (2005), 22. Whitaker (1984), and 23. Carvalho et al. (2005)

| Palynofacies parameters | Palaeoenvironmental interpretation | | References |
|---|---|---|---|
| | Proximal | Distal | |
| High % phytoclasts of total PM | Increases | Decreases | 1, 2 |
| | Close proximity to, or redeposition from, fluvio-deltaic source(s) of terrestrial organic matter. (*) Especially applies in fluid flows; in the hyperpycnal flows the interpretation is opposite | | |
| Phytoclast particle size | Increases | Decreases | 1, 2 |
| | Especially applies in fluid flows; in the hyperpycnal flows, the sorting of particles is less evident | | |
| Opaque:translucent phytoclasts (op:tp) ratio | Decreases | Increases | 1, 3, 8, 9, 23 |
| | Long distance or duration of transport of phytoclasts i.e. distal depositional environments removed from sources of fresh phytoclasts | | |
| Equidimensional:blade-shaped (eo:bo) opaque phytoclasts ratio | Increases | Decreases | 1, 4, 5, 6, 7, 8, 10, 16, 22 |
| | Especially applies where equant = largest particles; if this is not true interpretation is opposite | | |
| High % AOM of total PM | Decreases | Increases | 1, 2 |
| | Reducing (i.e. at least temporarily dysoxic to anoxic) and distal environments | | |
| AOM fluorescence | Relatively high intensity indicates strongly reducing environments with good preservation of lipoid-rich materials (especially in algal/bacterial AOM derived) | | 1, 2, 3 |
| High % sporomorphs (of total palynomorphs) | Increases | Decreases | 1, 2 |
| | Proximity to, or redeposition from, fluvio-deltaic source(s). (*) | | |
| High % dinocysts (of total OWMM) | Deposition beneath, or redeposition from, unstable, seasonal, shelf watermasses. Normal marine salinities | | 1, 18 |
| Diversity dinocysts | Decreases | Increases | 1, 9, 21 |
| | Higher diversities in outer neritic environments | | |
| High % proximate apical gonyauacoid dinocyst (PAGC) | Increases | Decreases | 19, 20 |
| | Very shallow marine to brackish environments (coastal to inner shelf) | | |
| High % prasinophytes (of total OWMM) | Increases | Decreases | 17, 18 |
| | Stably stratified watermasses. Bloom associated with the black shale deposition in epicontinental seas | | |
| prasinophytes → acritarchs → dinoflagellates | Salinity gradient from restricted marginal marine (near shore) of reduced salinity to open-marine of normal salinity | | 1, 8, 10, 11, 12, 13, 14, 15 |
| High % foraminiferal test linings | Decreases | Increases | 10 |
| | Higher frequencies in outer neritic environments | | |

Lajas, Bosque Petrificado, Lotena, Vaca Muerta, and Picún Leufú formations. This data set was taken from Martínez and Olivera (2016). The relative frequencies (%) diagrams were calculated using TGview 2.0.41 (Grimm 2004). Palynomorph data were interpreted using the multivariate statistical program PAST (PAlaeontological STatistics) by Hammer et al. (2001). Cluster analysis was selected as the most appropriate technique for this data set. It was performed on the basis of the presence/absence matrix data of the registered taxa with the Jaccard Index and the unweighted pair group method (UPGM). The cluster analysis graphics indicate the cophenetic correlation coefficient as a measure of the relation degree between the original distances and the final transformed distances, following Anderberg (1973) and Kovach (1989). The magnitude of this value should be close to 1 for a high-quality solution.

## Biostratigraphy of the Los Molles Formation

The Cuyo Group is composed of marine and minor continental deposits yielding abundant fossil biotas. These deposits crop out practically all around the basin, covering widespread areas of the Neuquén and Mendoza provinces.

In the Picún Leufú Sub-basin in the southern Neuquén Basin, Zavala (1993; 1996a, b) recognized four third-order depositional sequences in the Picún Leufú Sub-basin, termed as JC (Jurásico Cuyano) 4–7. Particularly, the JC4 sequence has been subdivided into minor fourth-order sequences (JC4.1–5). The Los Molles Formation is mainly represented by the sequences JC4.1 and JC4.2. Ammonoid faunas suggest a Late Aalenian-to-early Early Bajocian age for the sequence JC4.1, and an Early Bajocian age for the JC4.2. In the Puente Picún Leufú Section, Los Molles Formation encompasses the Aalenian-Bajocian boundary. Ballent (2004 and references therein) mentioned the presence of ammonoids belonging to the *Malarguensis* Standard Zone (see Riccardi et al. 1990, 2000; Hillebrandt et al. 1992), which is considered Late Aalenian to Early Bajocian in age. However, the lower boundary can be extended up to Pliensbachian–Toarcian based on field relationships (Fig. 2).

In the Cordillera del Viento locality, the Los Molles Formation is characterized by a thick succession of black shales outcropping in widespread areas around the southeastern margin of the Cordillera del Viento mountain belt. The age of these deposits is well known based on its palaeontological content and stratigraphic relationships. The ammonoid faunas suggest a Toarcian–Early Callovian age for these deposits (in Leanza et al. 2005). In the lowermost part of the unit, ammonoids belonging to the early Late Toarcian *Collina chilensis* Assemblage Zone (see Riccardi 2008) were recognized (Gulisano and Gutiérrez Pleimling 1994; Riccardi 2008). On top of this basal interval, ammonoids of the *Phlyseogrammoceras* (?) *tenuicostatum* Assemblage Zone (see Riccardi 2008) were identified. This zone pointed out a Late Toarcian age (Gulisano and Gutiérrez Pleimling 1994; Riccardi 2008). In the upper part of the section ammonoids belonging to the *Proximum* and *Bodenbenderi,* Standard Zones indicate a latest Early Callovian age (Gulisano and Gutiérrez Pleimling 1994; Riccardi 2008; Kamo and Riccardi 2009).

The diachronism of the upper boundary of the Los Molles Formation between the southern margin of the basin (Picún Leufú Sub-basin) and central basin positions (Cordillera del Viento locality) is associated with the northward progradation of deltaic and littoral clastic sediments of the Lajas Formation during the regression. At the southern margin of the basin, the Los Molles Formation terminates in the Early Bajocian, and is rapidly overlain by the Lajas Formation. The Lajas Formation is restricted to proximal depositional settings, being completely absent in at basinal settings. At central basin areas (Cordillera del Viento locality), the Cuyo Group is mainly composed of black shales of the Los Molles Formation, which extends up to the latest Early Callovian.

## Palaeoecology of marine palynomorphs of the Los Molles Formation

### Prasinophycean algae

Prasinophytes are a green algae group composed of unicellular forms characterized by the development of two distinct phases in their life cycle, a motile flagellate phase and a non-motile phase. Parke and den Hartog-Adams (1965) termed the latter one phycoma. These algae have a life cycle entirely developed in the water column, a holoplanktonic life cycle, in contrast with the meroplanktonic life cycle of the cyst-forming dinoflagellates (Tyson 1995). The outer wall of the mature phycoma opens by a simple slit to release the inner wall plus its content. Then, the discarded empty phycoma sinks and accumulates at the seafloor. Prasinophytes are common in marine to brackish environments, and their blooms are associated with black shale deposition in epicontinental seas (Bucefalo Palliani et al. 2002). These environmental conditions are typical of the global anoxic events such as the Toarcian Oceanic Anoxic Event or TOAE (van de Schootbrugge et al. 2005). Moreover, its ability to obtain nitrogen in waters depleted of this vital element (oligotrophic conditions) has been suggested as one of the most important reasons of its proliferation when other species are very scarce (Prauss 2006 and references therein).

### Cyst-forming dinoflagellates

Cyst-forming dinoflagellates are unicellular protists which are distinguished by one of two features, a dinokaryon, a unique eukaryotic type of nucleus that lacks histones and in which the chromosomes remain condensed throughout the mitotic cycle, and a motile stage with two flagella. This group is composed of exclusively marine forms until the Lower Cretaceous. Since then, it also colonized brackish to fresh-water environments (Batten and Lister 1988). The meroplanktonic life cycle of dinoflagellates involves the alternation of a motile stage (cannot be fossilized) and a cyst stage (yielding fossil remains). Studies on actual dinoflagellates have shown that oxygen availability plays a crucial role in cyst germination, whereas anaerobic conditions completely inhibit the excystment of most taxa (van de Schootbrugge et al. 2005; Sluijs et al. 2005 and references therein). Therefore, dinocysts show a negative correlation with the prasinophycean algae, because dinocysts proliferate in hydrographically unstable, normal marine shelf environments, under well-oxygenated bottom water conditions (Bucefalo Palliani et al. 2002).

### Benthic foraminifera

Foraminiferal test linings or palynoforaminifera (Pantic and Bajraktarevic 1988) refer to the inner organic lining mainly of benthic foraminifera, both calcareous and agglutinated (de Vernal 2009), which remains in palynological residues after laboratory treatment of the samples. Although these linings lack relevance to taxonomic studies, they are very useful to palaeoenvironmental and palaeoecological interpretations. Benthic foraminifera is mainly marine and adapted to normal marine salinities. If benthic foraminifera is recognized in brackish lagoon and marsh environments, the assemblages are characterized by low diversities of opportunistic forms (Armstrong and Brasier 2005). Several environmental and sedimentological factors have been proposed to control the distribution of marine benthic foraminifera. One of the most important controls is the high amount of organic carbon (in Ghasemi-Nejad et al. 1999). The high abundance of foraminiferal test linings can reflect marine shelf or slope sediments with normal marine salinities (oxic to suboxic conditions), and/or a selective concentration by bottom currents (Tyson 1995).

## Results

### Puente Picún Leufú Section

#### Composition of the palynoflora

Seven palynologically productive samples taken from this section were studied. The most conspicuous feature of this palynoflora is the dominance of the continental material, with values higher than 90% (Figs. 3 and 4a–m), except for the UNSP-PPL5336 sample, where the marine components reach up to 83% of the total palynological assemblage. Among the continental material, Cheirolepidiaceae pollen

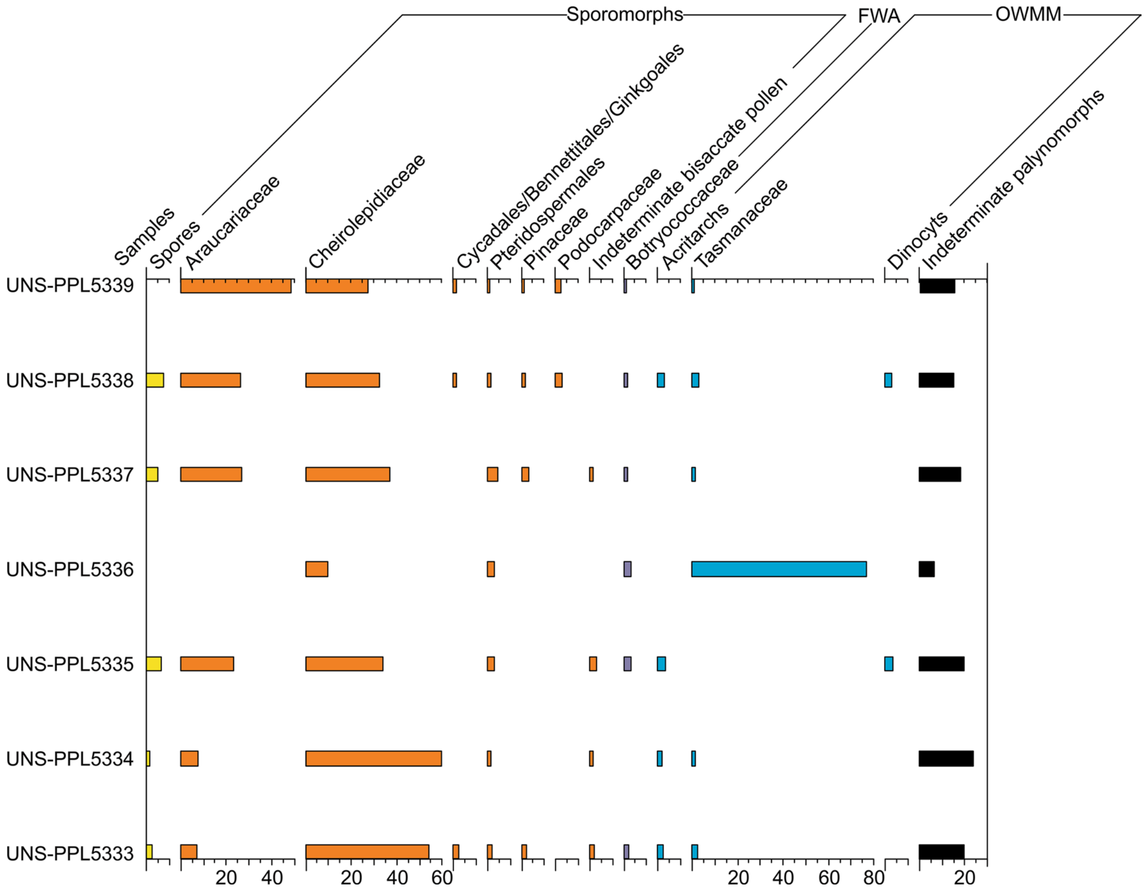
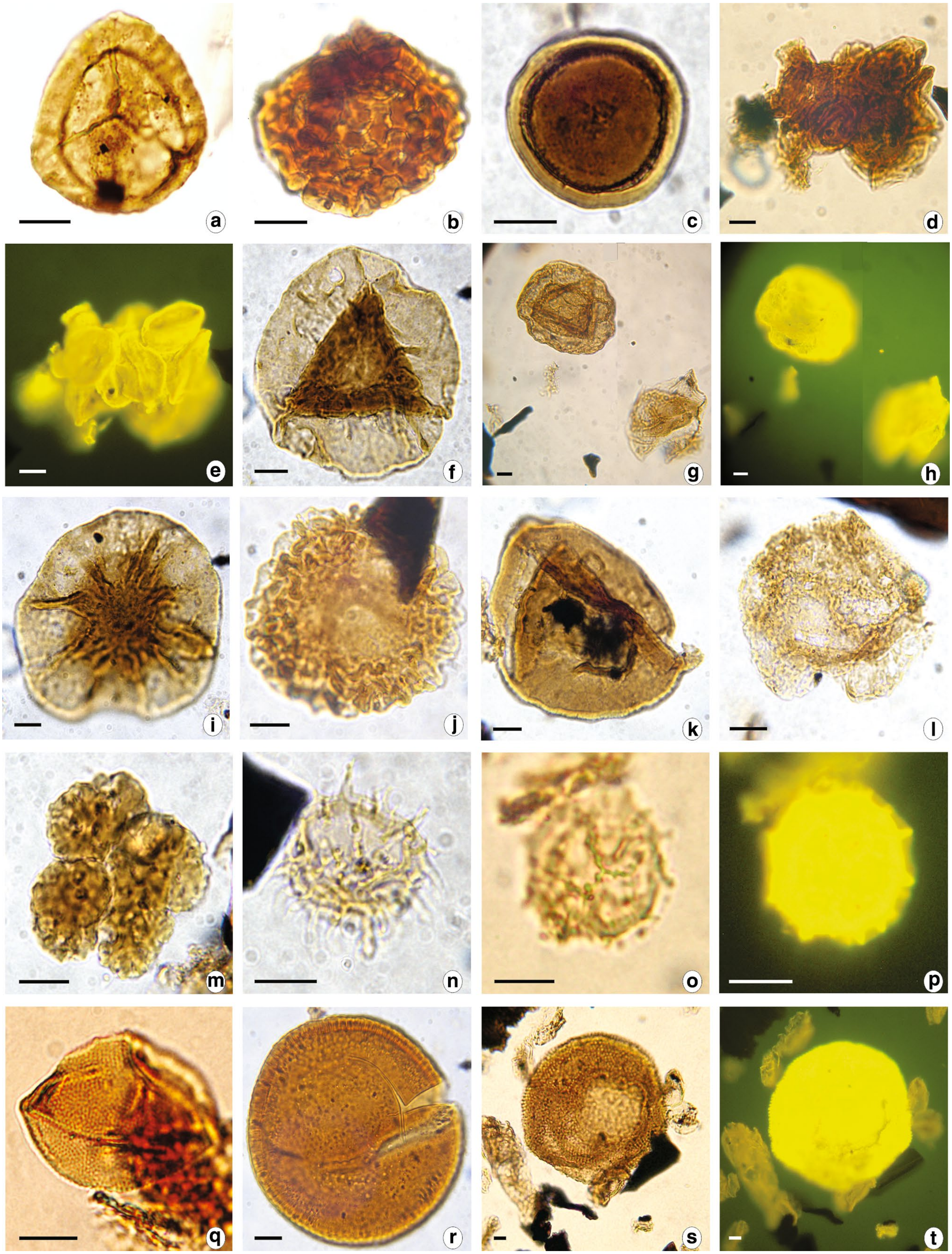


**Fig. 3** Quantitative distribution of major palynomorph groups in the Los Molles Formation, Puente Picún Leufú locality, expressed in percentages of total palynoflora based on a total count of 250 palynomorphs per sample. *FWA* fresh-water algae, *OWMM* organic-walled marine microplankton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◂**Fig. 4** Selected palynomorphs from the Puente Picún Leufú Section. **a** *Staplinisporites caminus* (Balme) Pocock, UNSP-PPL5335: L16; **b** *Klukisporites labiatus* (Volkheimer) Baldoni y Archangelsky, UNSP-PPL5338b: R24/1; **c** *Classopollis simplex* (Danzé-Corsin and Laveine) Reiser and Williams, UNSP-PPL5334b: G22/4; **d-e** polyad of *Classopollis classoides* Pflug, UNSP-PPL5339b: S19/4; **f–h** *Callialasporites turbatus* (Balme) Schulz, 5338b: Y22/1; **i** *Callialasporites dampieri* (Balme) Dev, UNSP-PPL5338b: K27/3; **j** *Callialasporites segmentatus* (Balme) Srivastava UNSP-PPL5338b: E2/7; **k** *Araucariacites fissus* Reiser and Williams, UNSP-PPL5334b: Z20; **l** *Podosporites variabilis* Dev, UNSP-PPL5338b: Y27/1; **m** *Botryococcus braunii* Kützing, UNSP-PPL5338b: A11; **n** *Micrhystridium recurvatum* Valensi, UNSP-PPL5338b: D7/3;o-p. *Cymatiosphaera eupeplos* (Valensi) Deflandre, UNSP-PPL5338b:T7/3; **q** *Pleurozonaria picunensis* Quattrocchio, UNSP-PPL5339: A33/0; **r– t.** *Tasmanites* sp. Martínez et al. **r** UNSP-PPL5336b: Q6/4, **s-t** UNSP-PPL5334b: N23. Scale bars = 10 μm; **e**, **h**, **p** and **t** were taken with reflected fluorescence light microscopy

grains (*Classopollis*) (Figs. 3 and 4c–e) are the most abundant group in all samples, except for UNSP-PPL5339. In this sample, the Araucariaceae pollen grains are the most abundant terrestrial palynomorphs (e.g., *Callialasporites turbatus* reaching 18.4%) (Figs. 3 and 4f–k). In the rest of the samples, this family is the second most abundant sporomorph group (i.e., spores and pollen grains). Marine palynomorphs are exclusively represented by organic-walled microplankton, dominated by acritarchs (*Micrhystridium* complex) (Fig. 4n) and prasinophyte algae (Fig. 4o–t). Dinocysts only appear as subordinated constituents (Fig. 3). All samples show a similar frequency of marine palynomorphs, between 1.4 and 10%, except UNSP-PPL5336. In this sample, marine palynomorphs, exclusively prasinophyte algae, represent 82.2% of the palynomorph assemblage (Fig. 4o–t).

## Palynofacies analysis

The PM recognized in Puente Picún Leufú Section exhibit a high content of continental components (i.e., phytoclasts, sporomorphs, and, in minor proportion, freshwater algae) (Fig. 5). The material shows a good state of preservation with a strong fluorescence. Even the terrestrial palynomorphs show moderate-to-strong orangish-yellow fluorescence colors (Fig. 4e, h). The two basal samples (i.e., UNSP-PPL5333 and UNSP-PPL5334) are characterized by the high percentages of palynomorphs, mainly sporomorphs, the highest opaque to translucent phytoclasts ratio (op:tp), 4.61 and 2.57, respectively, and the lowest equidimensional:blade-shaped opaque particles ratio (eo:bo), 0.54 and 0.44, respectively. The AOM is present in very low proportion; but the remaining samples show an increase of this structureless material. Two main AOM types were identified: allochthonous organic matter, derived primarily from continental sources (fibrous and spongy), and autochthonous organic matter, derived from phytoplankton and/or bacteria (granular and pelicular). The UNSP-PPL5336 sample reaches the maximum values of AOM (39.2%) and marine palynomorphs (Figs. 3 and 5). From this sample upward the section, a progressively decrease in the AOM frequencies can be observed (Fig. 5). The upper UNSP-PPL5339 level shows the highest percentages of phytoclasts recognized in the samples studied herein (Figs. 5 and 6c). The op:tp ratio is 1.3, with blade-shaped predominating (nearly 25%), reaching the eo:bo ratio 0.7.

## Cordillera del Viento Section

### Composition of the palynoflora

Twenty levels were sampled in this section, of which nine were palynologically productive (Fig. 7). The recovered palynological assemblages show a high degree of deterioration. Palynomorphs are very dark (TAI/Thermal alteration index: 4). Especially terrestrial palynomorphs often show “blistered” surfaces (Fig. 8a). Circular holes are produced when the blisters are burst and, with progressive deterioration, a network pattern can be recognized (Fig. 8b). The continental components are predominant (75–100% of all palynomorphs) in the lower and middle parts of the section between samples UNSP-CV5352 and UNSP-CV5360 (Figs. 2a and 7). In contrast, the three uppermost samples, UNSP-CV5361, UNSP-CV5362, and UNSP-CV5363, show an increase of the marine palynomorphs (40–63.6%), with a terrestrial: marine ratio (t:m) increasing upwards (i.e., 0.85, 0.88, and 1.5, respectively). The continental palynoflora is characterized by the greatest abundance of Cheirolepidiaceae pollen grains. This family dominates the palynomorph assemblages in all samples, except in UNSP-CV5356 and UNSP-CV5362 levels, where Araucariaceae pollen grains are most abundant (Fig. 7). Trilete spores (Fig. 8c) and Caytonieaceae pollen grains are also common in some samples (Fig. 7). The marine components are made of dinocysts (2.7–31.8%) (Fig. 8f, g, i) and foraminiferal test linings (5.4–19.5%) (Fig. 8h).

### Palynofacies analysis

All the studied material in this section is non-fluorescent. Although phytoclasts show variable frequencies throughout the section, as a general feature opaque phytoclasts always exceed translucent ones (opaque:translucent ratio between 2.3 to 12.85).

The two basal samples, UNSP-CV5352 and UNSP-CV5354, are characterized by a high content of phytoclasts, between 79 and 89%, with a op:tp ratio of 12.85 and 7.8, respectively (Fig. 9). The blade-shaped fragments are most abundant (43–45%), with an eo:bo ratio of 0.69 and 0.71 respectively. Between the UNSP-CV5355 (Fig. 6f) and

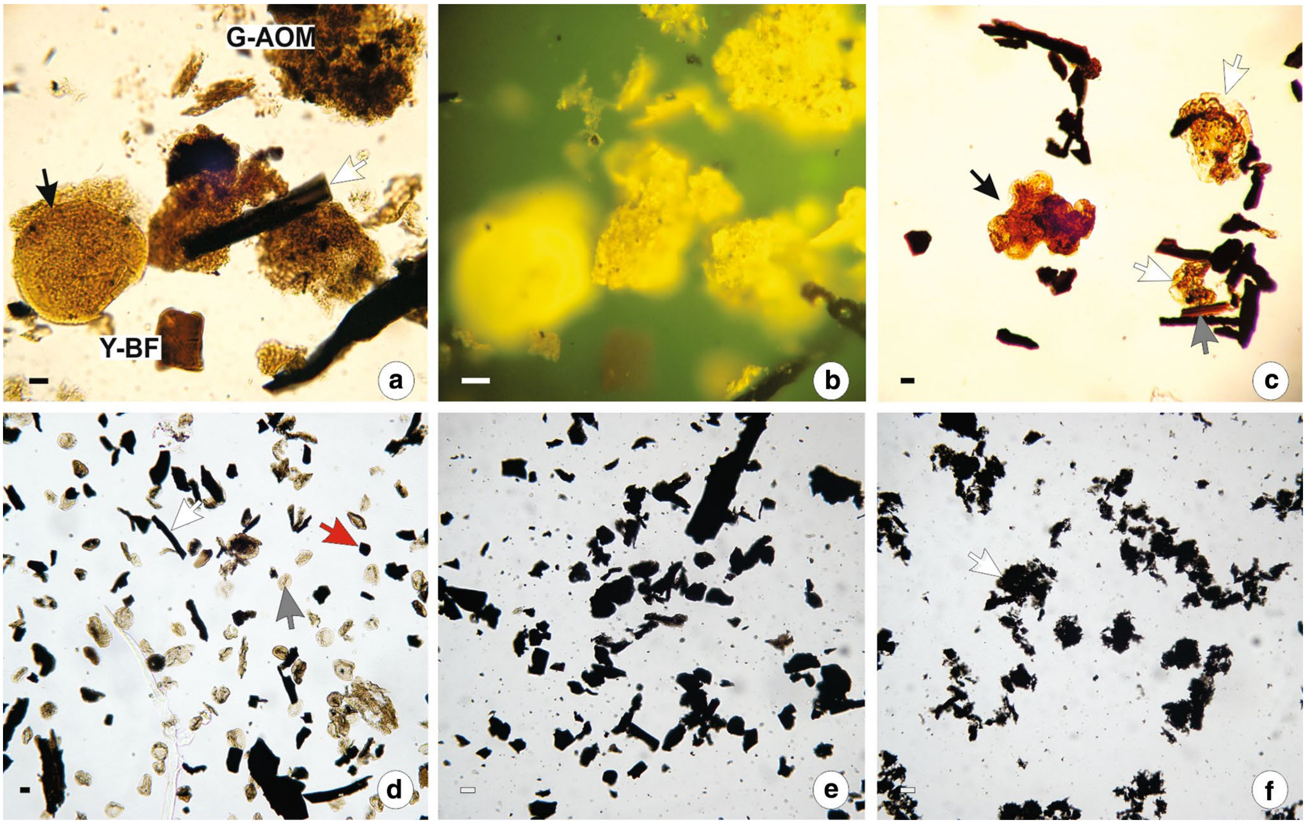

**Fig. 5** Palynofacies of Los Molles Formation from Puente Picún Leufú and Cordillera del Viento sections. **a–b.** UNSP-PPL5336b: L16; **a** The black arrow indicates a *Tasmanites* sp. Martínez et al. specimen and the white arrow points out a woody remain, G-AOM: granular AOM, Y-BF: yellow–brown fragment, **b** RFL photomicrography; **c** UNSP-PPL5339: A26/4; polyad of *Classopollis* sp. indicated by a black arrow, *Callialasporites turbatus* (Balme) Schulz specimens indicated by the white arrows and tracheid without pits indicated by a gray arrow; **d** UNSP-PPL5334b: R18; the white arrow indicates a blade-shape phytoclast, the red arrow indicates an equidimensional opaque phytoclast, and the gray arrow points out an indeterminate palynomorph; **e** UNSP-CV5362: K15/3; **f** UNSP-CV5355b: U33/4; granular AOM is indicated by a white arrow. Scale bars = 10 µm

UNSP-CV5360 samples, the palynofacies assemblages show a great participation of the AOM with percentages higher than 58%, except in the UNSP-CV5356 sample (Fig. 9). In this sample, the dominant group is the phytoclast (i.e., 52.9%) with an op:tp ratio 5.7 and eo:bo ratio of 0.83. The uppermost three levels show a wide predominance of opaque phytoclasts, varying from 56 to 82% (Figs. 6e and 9). The UNSP-CV5361 and UNSP-CV5362 samples are characterized by the presence of small equidimensional fragments, while the blade-shaped particles show a relatively large size (eo:bo ratio, 1.9 and 3.51 respectively).

## Discussions

Sedimentological analyses of the studied localities in the Los Molles Formation show significant differences in terms of sediment transport and depositional processes, bottom water oxygen concentration and benthic activity, and relative energy of the associated depositional environments.

Palynofacies studies of sediments of hyperpycnal flows are rare (e.g., Biscara et al. 2011; Carrillo-Berumen et al. 2013; Martínez et al. 2016; Mignard et al. 2017; Slater et al. 2017; Quattrocchio et al. 2018). However, profound palynological contributions of classical or intrabasinal turbidites, provided detailed insights into the distribution of organic matter in such flows (McArthur et al. 2016a,b; 2017).

The PM recovered from the Puente Picún Leufú Section is dominated by terrestrial organic matter. This suggests an important input of extrabasinal components by fluvial discharges. During periods of low river discharges, hypo-or homopycnal plumes would have been the main source of terrestrial components in the marine realm. On the other hand, during extreme rainfall periods, sustained river discharge with high suspended sediment concentration (35–45 km/m$^3$, Mulder et al. 2003) would have resulted in the development of long-lasting hyperpycnal flows (Mulder et al. 2003; Zavala et al. 2006; Nakajima 2006; Soyinka and Slatt 2008).

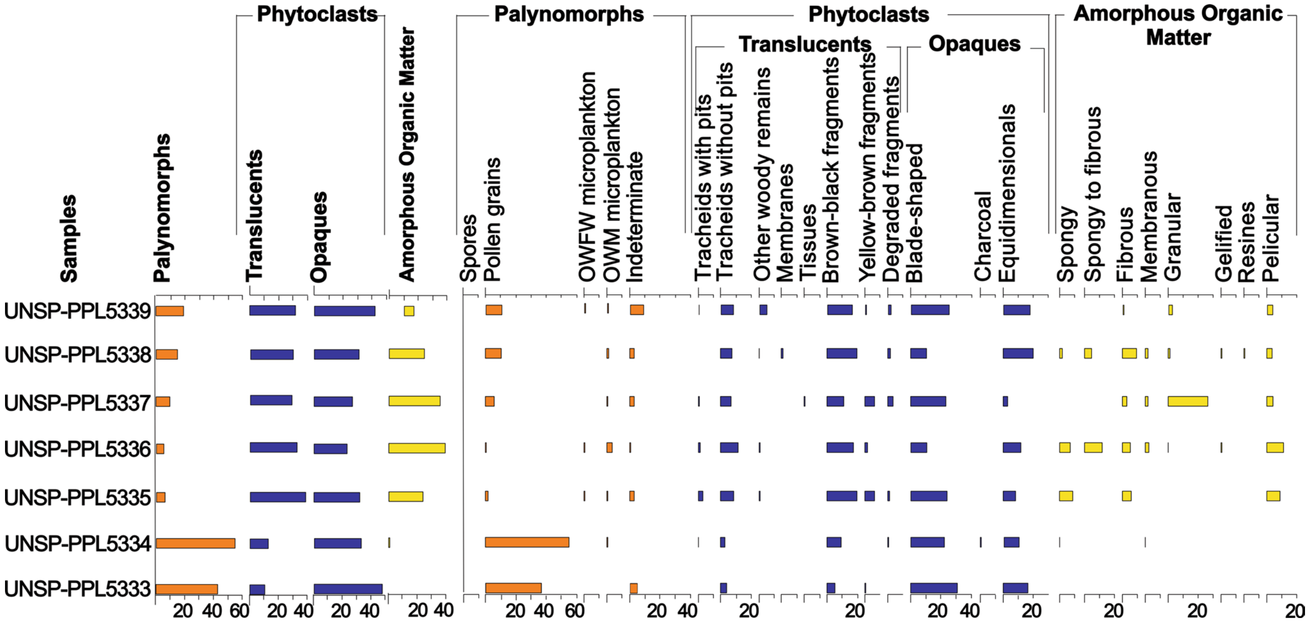

**Fig. 6** Composite chart of data at PPL section showing the frequency distribution of the different recognized categories of PM based on the total count of 500 particles per sample

The mixture of autochthonous and allochthonous constituents observed in the studied samples (Fig. 5) could be the result of an accumulation by muddy hyperpycnal flows. The accumulation of autochthonous marine components on the seabed may have been produced during the quiescence period between consecutive hyperpycnal events. The erosion and bulking of intrabasinal components by the overpassing of hyperpycnal flows could explain the mixture between autochthonous and allochthonous materials in these palynofacies (Otharán et al. 2018a, b; Quattrocchio et al. 2018). In all samples, the OWMM are dominated by prasinophyte algae and acritarchs and represent a minor component of the associations. The exception is the UNSP-PPL5336 level dominated by prasinophyte algae (Fig. 3), which suggests a reduced marine salinity. The environment in which this group competes most successfully is generally known from a stratified water column with reduced salinities in the photic zone (e.g., Loh et al. 1986; Prauss 1989, 2006; Prauss and Riegel 1989). This stratification due to different densities in the water column is generally associated with oxygen depletion of bottom water. Since muddy hyperpycnal flows remain attached to the sea bottom until their final accumulation, the stratified water column would not be disturbed. It is for this reason that the palaeoecological framework of the prasinophyte algae would not be affected. These suboxic–anoxic bottom water conditions play a crucial role in the excellent preservation state of the sedimentary organic matter, which shows a strong fluorescence. The TOC (total organic carbon) of the samples exhibit values ranging from 1 to 4.7%. It is important to highlight that high percentages of TOC are associated with the highest frequencies of prasinophyte algae (Tasmanaceae) in the UNSP-PPL5336 sample. Positive correlation between *Tasmanites* spp. and TOC values has previously been registered by Bucefalo Palliani et al. (2002) in Early Toarcian samples from North Yorkshire (northern England). These authors recognized that an increase in TOC values associated with the tasmanacean algae was coincident with the gradual stratification of the marine system, which led to the development of an oxygen-minimum zone within the water column. The rare dinocysts in the UNSP-PPL5335 and UNSP-PPL5338 samples are proximal apical gonyaulacoid cysts (PAGC) as *Escharisphaeridia* spp.. Smelror and Leereveld (1989) proposed that these cysts are characteristics of very shallow-marine (coastal-to-inner shelf) conditions. High abundances of PAGC have been registered in Middle-to-Late Jurassic very shallow-marine to brackish environments of southern France and the Early Cretaceous of Portugal, Spain, and Denmark (Smelror and Leereveld 1989 and references therein), just as in Palaeogene deposits in several localities around the world (Frieling and Sluijs 2018). Although the distribution of the total PM suggests a marginal marine setting, the relationship between some specific organic groups shows relatively variations within this environment. In the UNSP-PPL5333, UNSP-PPL5334, and UNSP-PPL5339 samples, the highest values of the op:tp ratio and the lowest values of the eo:bo ratio suggest a relatively more distal position (Table 2). Therefore, based on the palynological assemblages, a marginal marine environment with restricted oceanic circulation can be suggested for the Los Molles Formation in this sector of the basin (Puente

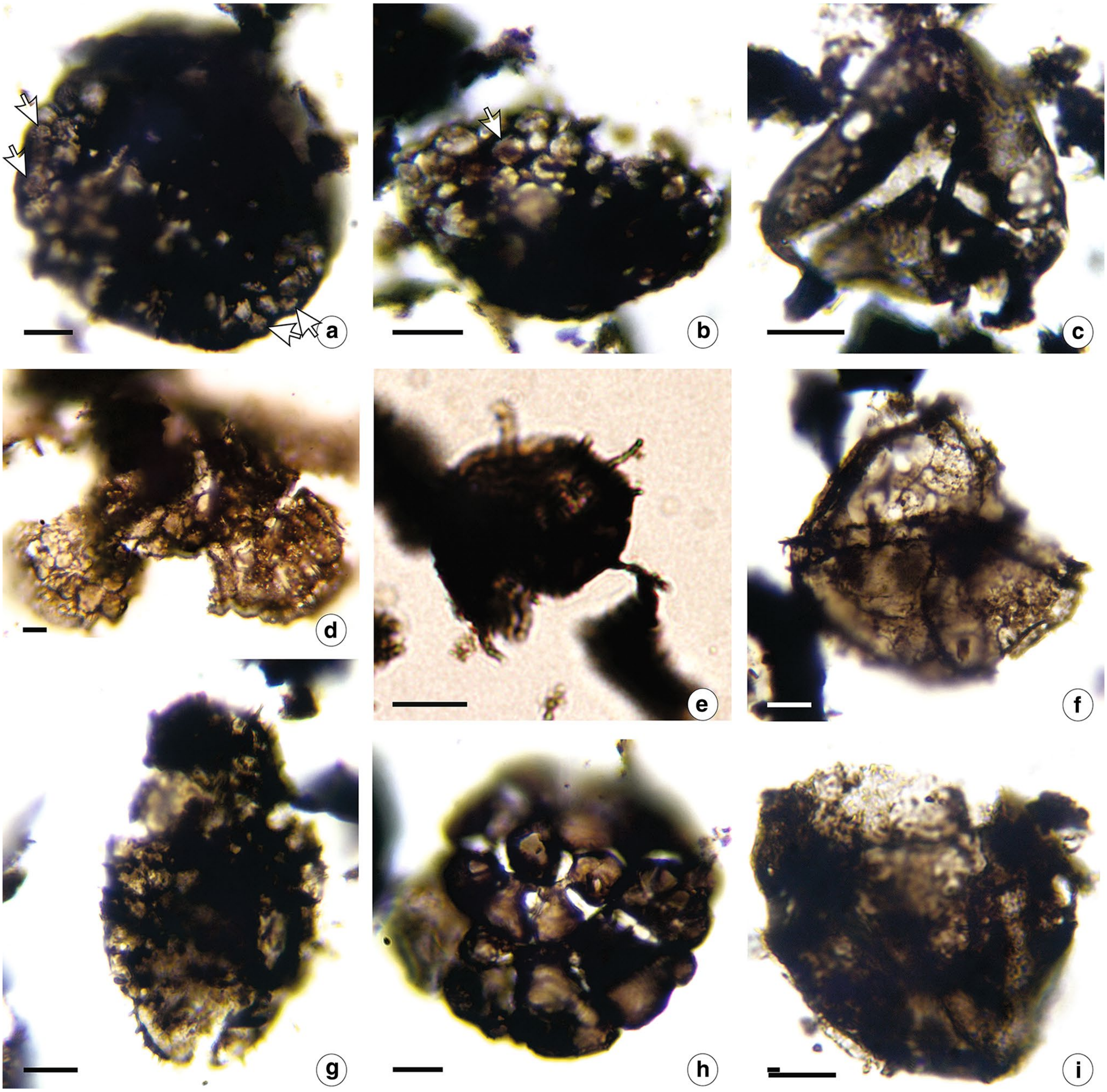

**Fig. 7** Selected palynomorphs from the Cordillera del Viento Section. **a** *Callialasporites* sp., UNSP-CV5356: Q17/3; the white arrows indicate the "blisters" in the exine; **b** Indeterminate palynomorph, UNSP-CV5356: N9; circular holes in the exine are indicated by a white arrow; **c**Deltoidospora minor (Couper) Pocock, UNSP-CV5355b: J30; **d** *Podocarpidites* spp., UNSP-CV5354: A26/4; **e** *Micrhystridium* spp., UNSP-CV5354: X10/1; **f** *Durotrigia* sp. Martínez and Quattrocchio, UNSP-CV5361: A42/4; **g** *Sentusidinium villersense* (Sarjeant) Sarjeant and Stover, UNSP-CV5361: K2; **h** Palynoforaminifera, UNSP-CV5361: Q27/5; **i** *Lithodinia* spp., UNSP-CV5361: E27. Scale bars = 10 µm

Picún Leufú locality). From a sedimentological point of view, the development of muddy hyperpycnal flows was proposed by these deposits, and the recognized palynological associations are in agreement with this interpretation. During their travel basinward, these flows can erode the littoral/marginal silt–clay deposits, and incorporate mud and marine microfossil to the hyperpycnal flow.

The distribution of the different constituents of the PM recognized in the Cordillera del Viento Section allows inferring different palaeoenvironmental conditions in the Los Molles Formation. The high abundance of terrestrial material (i.e., sporomorphs and phytoclasts) in the basal two samples, UNSP-CV5352 and UNSP-CV5354, suggests a high terrestrial input to the marine realm (Table 2). The co-occurrence

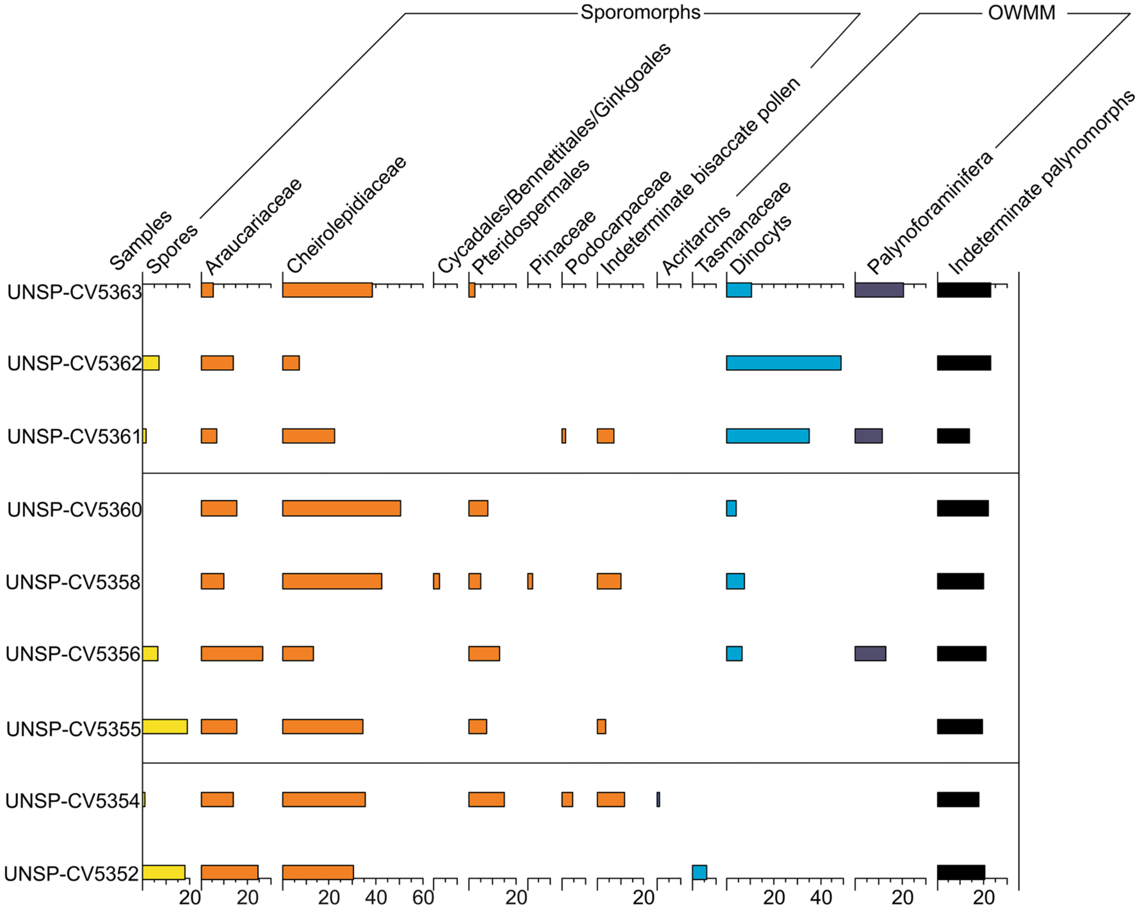

**Fig. 8** Quantitative distribution of major palynomorph groups in the Los Molles Formation, Cordillera del Viento locality, expressed in percentages of total palynoflora based on a total count of 250 palynomorphs per sample

of the high values of terrestrial constituents, distal palynofacies indicators such as blade-shaped opaque particles and typical marginal marine organic microplankton (i.e., acritarchs and prasinophyte algae) suggest the development of sediment-laden turbulent flows (Table 2). During their basinward travel, these flows incorporate microfossils and phytoclasts previously stored in littoral marine environments, so the resulting association shows a mixture of terrestrial, marginal marine, and more distal palynological organic matter.

The middle part of the succession, from the UNSP-CV5356 to UNSP-CV5360 samples, is characterized by the first appearance of dinocysts and foraminiferal test lining (Fig. 2a). Although these marine components are present in low proportions, they indicate an increase in the instability of the water column suggesting a change in the palaeoenvironmental conditions towards shelfal depositional settings. The high proportion of AOM registered from UNSP-CV5355 to UNSP-CV5360 samples could reflect distal depositional marine environments. The AOM associated with dinocysts suggests at least temporarily dysoxic conditions (Tyson 1995; Batten 1996). However, the features of the AOM (i.e., indeterminate and non-fluorescent) in these palynofacies show a high degree of deterioration, suggesting that the conditions were not always optimal for its preservation. Therefore, the distinctive feature of these palynofacies could reflect a taphonomic control (taphocenosis) rather than the origin of sedimentary-amorphous organic matter (biocenosis).

The recurrent presence of dinocysts observed in the middle part of the section becomes even more noticeable in the upper levels (UNSP-CV5361 to UNSP-CV5363). This trend was coeval with a reduced volcanic activity (Figs. 2a and 10b) and could indicate a poorly developed volcanic arc at the western margin of the basin, and a more open-marine connection with the Pacific realm via different corridors (Fig. 10). Furthermore, Martínez and Olivera (2016) suggested the possibility that the Mozambique Corridor would have opened during the Early Callovian, connecting the Neuquén Basin to the Australian Bonaparte Basin. The increase of marine palynomorphs (i.e., dinocysts and foraminiferal test lining) and the high op:tp ratio values in the upper three samples suggest relatively more distal conditions in an unstable, normal marine shelf environment

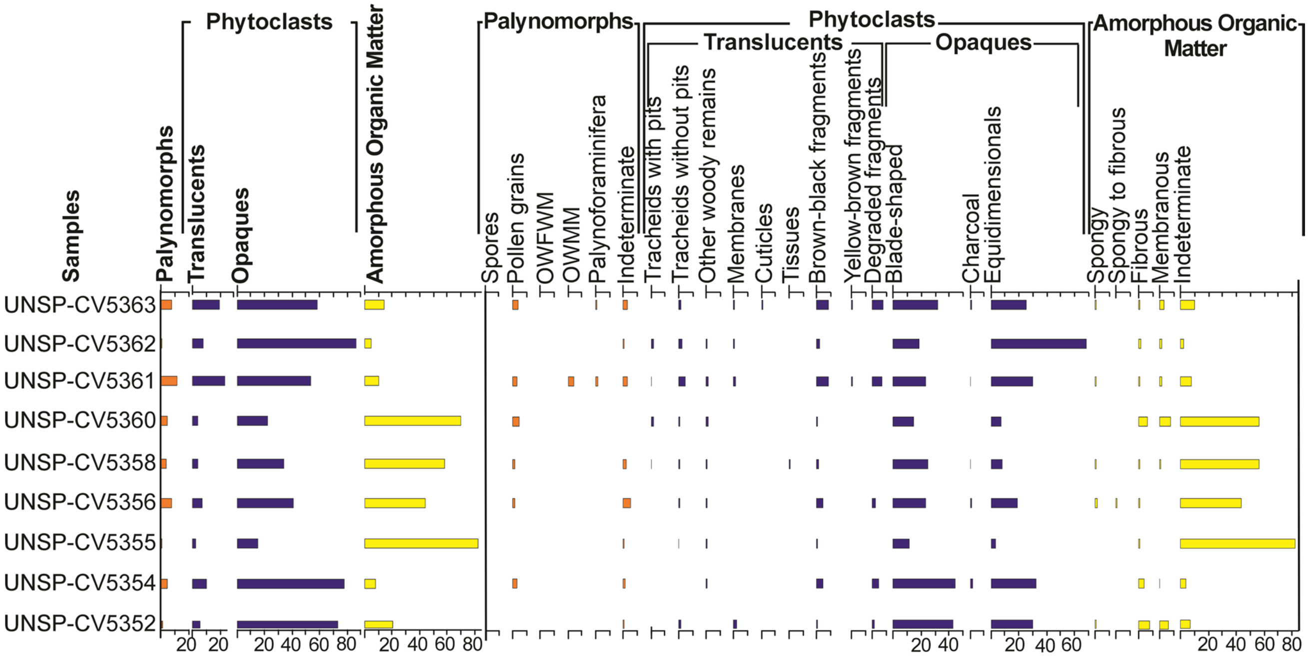

**Fig. 9** Composite chart of data at the CV Section showing the frequency distribution of the different recognized categories of PM based on the total count of 500 particles per sample

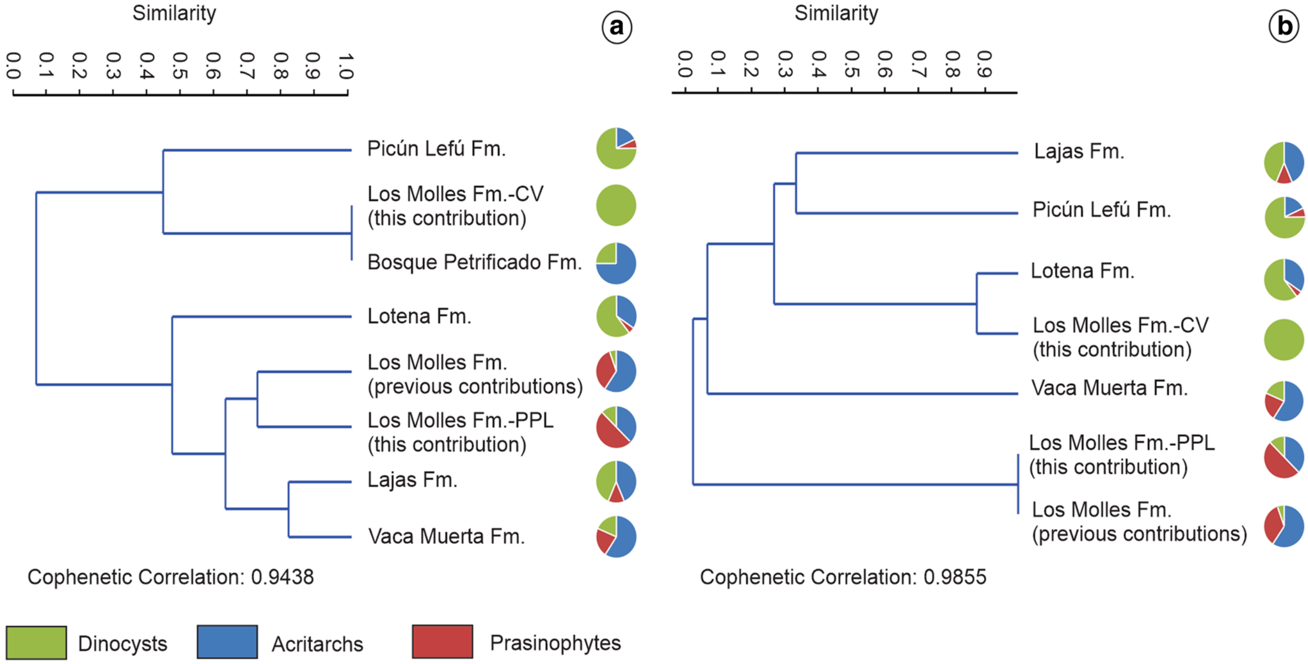

**Fig. 10** Dendrogram generated by Jaccard Index unweighted pair group method cluster analysis showing the comparison of the Los Molles Formation marine palynomorphs (this contribution) with other previously studied Jurassic marine palynofloras of the Neuquén Basin. The diversity of the marine components in each unit are shown in the pie charts; **a** Puente Picún Leufú locality; **b** Cordillera del Viento locality

(Table 2). Among these three samples, the eo:bo ratio higher than 1 observed in the UNSP-CV5361 to UNSP-CV5362 associations suggests relatively more distal condition compared with the UNSP-CV5363 sample. Furthermore, the UNSP-CV5361 sample shows the lowest value of the t:m ratio and the relatively highest diversity of dinocysts suggesting the more distal position (maximum flooding surface) among the three upper samples (Table 2). Pross and

Brinkhuis (2005) mentioned that high cyst-diversity coincides with intervals of high sea levels and large shelf seas. It is worthy to mention that some taxa identified in this sample (i.e., *Gonyaulacysta jurassica* and *Durotrigia* sp.) have been previously related to open-marine conditions with non-restricted circulation in the Neuquén Basin (Martínez and Quattrocchio 2004). Besides, other authors mentioned that *Gonyaulacysta jurassica* is considered a cosmopolitan taxa indicative of deeper marine setting (Smelror and Leereveld 1989; Riding et al. 2011). The abundance and diversity of dinocysts (Fig. 8f, g, i–m) registered in the UNSP-CV5361 and UNSP-CV5362 samples suggest an open oceanic circulation with well-oxygenated bottom water conditions in an outer neritic environment (Pross and Brinkhuis 2005). The UNSP-CV5363 sample shows a sharp decline in both, abundance and diversity of dinocysts, and the highest t:m ratio between the three upper samples, suggesting the beginning of a regressive phase (Table 2). The abundance of benthic palynoforaminifera, previously observed in the Neuquén Basin only in the Lotena Formation (Martínez and Quattrocchio 2004), confirms the interpretation of a palaeoenvironment characterized by normal marine salinities. The

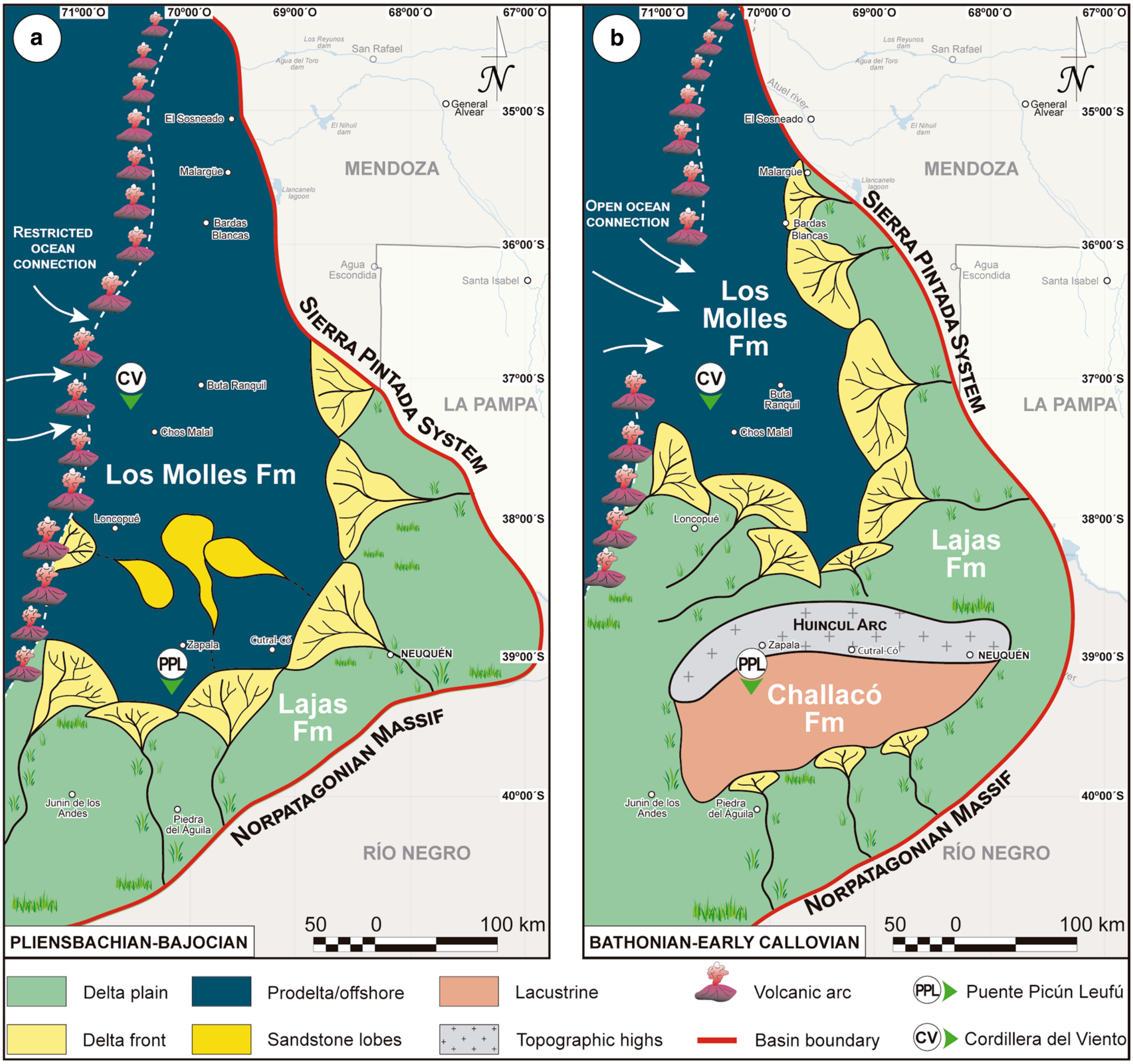

**Fig. 11** Paleogeographic reconstruction of the Neuquén Basin during Early–Middle Jurassic based on the main palynological results emerged from this study and regional data from previous works (e.g., Uliana and Legarreta 1993; Legarreta and Uliana 1996; Zavala 1996a, b; Zavala et al. 2020) **a** Pliensbachian–Bajocian; **b** Bathonian–Early Callovian

high maturity and poor preservation of the organic matter in this section could be related to the emplacement of several Cenozoic intrusions in the Cordillera del Viento area (Turienzo et al. 2018).

### Comparison with other Jurassic marine units of the Neuquén Basin

The palynological content of the Los Molles Formation recognized in the studied sections was compared with all the Jurassic marine units of the Neuquén Basin (based on the distribution of the OWMM taxa, Fig. 11). The studied unit (this paper) in the Puente Picún Leufú Section is clustering with the Los Molles Formation (previous contributions) in the first place (Fig. 11a). This group is associated in the second place with the Lajas and Vaca Muerta formations. The reason behind this is the predominance of acritarchs and prasinophytes in these units. These marine constituents suggest two different palaeoenvironmental conditions, a marginal marine environment and/or a stratified water column developed under restricted oceanic circulation. A deposition under this palaeoenvironmental framework is suggested at least until the Early Bajocian (Fig. 10a; see Sect. 3. Biostratigraphy of the Los Molles Formation). Conversely, the upper levels of the Los Molles Formation in the Cordillera del Viento Section show the highest similarity with the Lotena Formation (Fig. 11b), which has been previously interpreted as a marine unit characterized by an open oceanic (non-restricted) circulation (Riding et al. 2011). In this locality, the studied unit presents high percentages and diversity of dinocysts, similar to the Lotena Formation and, furthermore, they share several taxa. It is important to highlight the presence of *Sentusidinium villersense* in the sample UNSP-CV5361, previously registered in the Lotena and the Picún Leufú formations (Martínez and Quattrocchio 2004; Quattrocchio and Sarjeant 1992). This taxon is not older than Early Callovian (Wood et al. 2016). Therefore, the occurrence of *Sentusidinium villersense* reinforces the proposal of a Callovian age for the upper levels of the Los Molles Formation in the Cordillera del Viento locality. Moreover, it confirms the time-transgressive characteristics of the Cuyo Group, registering the youngest ages towards the north of the basin. These findings allow proposing an open oceanic circulation since the beginning of the Callovian in the Cordillera del Viento locality (Fig. 10b).

## Conclusions

The samples studied herein show a high environmental variability from restricted marine conditions to outer neritic settings during the deposition of the Los Molles Formation. The record of several microplanktonic groups with different palaeoecological requirements allowed reconstructing the oceanic circulation patterns during the Early–Middle Jurassic in both localities (Puente Picún Leufú and Cordillera del Viento). The studied levels of the Los Molles Formation from the PPL and the lower part of CV sections show a high predominance of acritarchs and prasinophytes. These algal groups proliferated with a stratified water column, suboxic–anoxic bottom, and reduced salinities within the photic zone. This suggests a marginal marine environment under restricted oceanic circulation that has remained at least until the Early Bajocian. Among the dinocysts recognized in Puente Picún Leufú Section, the sole presence of proximal apical gonyaulacoid cysts reinforces the development of shallow-marine to brackish environments. The registered microplankton assemblages at the upper part of CV Section are characterized by the dominance of dinocysts in the UNSP-CV5361 and UNSP-CV5362 levels, indicating an unstable shelf with well-oxygenated bottom waters. The highest diversity registered in the UNSP-CV5361 sample would correspond with the time of maximum marine flooding of the basin. From this sample upwards, a regressive trend is recognized. These conditions suggest an open-marine setting with non-restricted oceanic circulation, similar to the palaeoenvironment previously proposed for the Lotena Formation. Also, the appearance of palynoforaminifera in the upper samples of the CV Section is only previously reported in the Neuquén Basin from the Lotena Formation. The presence of *Sentusidinium villersense* in UNSP-CV 5361 sample suggests that a free oceanic circulation would have been installed in ages as early as the Early Callovian in the Neuquén Basin.

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