
Early Paleogene climate at mid latitude in South America: Mineralogical and paleobotanical proxies from continental sequences in Golfo San Jorge basin (Patagonia, Argentina)

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| ABSTRACT |

The Paleocene-Eocene boundary was a period of transient and intense global warming that had a deep effect on middle and high latitude plant groups. Nevertheless, only scarce early Paleogene paleoclimatic records are known from the South American continental sequences deposited at these latitudes. In this contribution clay mineralogy and paleobotanical analyses (fossil woods and phytoliths) were used as paleoclimate proxies from the lower and middle parts of the Río Chico Group (Golfo San Jorge basin, Patagonia, Argentina). These new data may enable to understand the changing climatic conditions during part of the Paleocene-Eocene transition. In this setting, three clay mineral assemblages were identified: *S1* assemblage (smectite) dominates the Peñas Coloradas Formation; *S2* assemblage (smectite>kaolinite) occurs in the stratigraphic transition to the Las Flores Formation; and *S3* assemblage (kaolinite>smectite) dominates the Las Flores Formation. These trend of change in the detrital clay mineral composition is interpreted as resulting mainly from the changing paleoclimatic conditions that shifted from seasonal warm temperate to tropical affecting the same source area lithology. Moreover, the paleobotanical data suggest that the Early Paleogene vegetation in the Golfo San Jorge basin underwent significant composition and diversity changes, ranging from mixed temperate - subtropical forest to mixed subtropical - tropical, humid forest. The integrated analysis of the clay mineral composition and the palaeobotanical assemblages suggests that, in central Argentinean Patagonia, the Paleocene-Eocene climate changed from temperate warm, humid and highly seasonal precipitation conditions to subtropical-tropical, more continuous year-round rainfall conditions.

KEYWORDS | Paleocene-Eocene. Clay Minerals. Fossil Woods. Phytoliths. Paleoclimatic proxies.

INTRODUCTION

Paleoclimatic proxies applied to the study of Early Paleogene (~45-65 Ma) have suggested that this was a global warming period with global mean annual temperatures of 17-21°C (Wilf, 2000) with exceptional warmth from Mid-Paleocene (59 Ma) to Early Eocene (52 Ma) that peaked with the 52 to 50 Ma oxygen isotopic shift (Zachos et al., 2001). This global warming interval during the Paleocene-Eocene transition (formally the “Late Paleocene Thermal Maximum”, LPTM and the “Early Eocene Climatic Optimum”, EECO; Zachos et al., 2001) was accompanied by a transient shift in increased precipitation at higher latitudes (Robert and Kennett, 1994), which enhanced continental weathering (Higgins and Schrag, 2006) and favoured kaolinite formation (Gibson et al., 2000). These climatic changes had a major effect on land plants and mammals, which experienced important changes during this time (Harrington and Kemp, 2001). Despite the significance of this Late Paleocene-Early Eocene time span, there are scarce studies on South American continental records of this age (especially in central Argentinean Patagonia) that allow us to precise the paleoclimatic conditions (Romero, 1986).

The Upper Paleocene-Middle Eocene continental deposits of the Río Chico Group (*sensu* Bellosi and Madden, 2005) crop out in the area of the Golfo San Jorge basin, (Ameghino, 1906; Windhausen, 1924; Feruglio, 1929, 1938, 1949; Simpson, 1933, 1935a, 1935b; Andreis et al., 1975; Andreis, 1977) and constitute a suitable depositional record to provide paleoclimatic data for this period, by means of paleobotanical and mineralogical proxies. The paleobotanical records, preserved as fossil woods and phytolith assemblages in the Río Chico Group (Zucol et al., 2005; Brea and Zucol, 2006), provide evidence to reconstruct paleofloristic communities and paleoclimatic conditions. In particular, the anatomical characteristics of dicotyledonous woods can be used not only to establish the specialization lines of the secondary xylem and hence the wood species (Frost, 1930a, 1930b, 1931; Carlquist, 1975), but also to reconstruct by inference the climate and climatic changes in the geologic past (Wheeler and Baas, 1991, 1993; Wiemann et al., 1998; Poole, 2000). Moreover, the phytolith studies on continental units can be a valuable tool to clarify the paleoenvironmental conditions, due to the fact that phytoliths play an important role in understanding the ecosystem diversity, climate and paleoecology (Kondo et al., 1988). At the same time, the clay mineral in sedimentary sequences can provide important information on pre- and post-burial conditions. Pre-burial controls include source area lithology, paleoclimate (chemical and physical weathering), depositional environment and topography, among others (Chamley, 1989; Inglès and Ramos-Guerrero, 1995).

Although this information can be disturbed or concealed by burial diagenetic effects that change the original clay mineral composition (Egger et al., 2002), the study of the changes of detrital clay minerals in sequences that did not undergo intense diagenesis, becomes a significant tool for untangling the environmental conditions of deposition.

In this paper, changing clay mineral composition and paleobotanical assemblages are documented, considering the plant megafossil record (silicified woods) and the phytolith remains from the Peñas Coloradas and the Las Flores formations, which are the lower and middle units of the Río Chico Group respectively, in the eastern area of the Golfo San Jorge basin. This paper deals with interpreting the variations in clay mineral assemblages and their relation to coeval changing environmental conditions, and with characterizing and reconstructing vegetation communities to interpret paleoclimatic conditions during the early Paleogene in the Patagonia. This record may cover a time span that is probably simultaneous with part of the global warming interval during the “Late Paleocene Thermal Maximum” (LPTM) and the “Early Eocene Climatic Optimum” (EECO) proposed by Zachos et al., (2001).

GEOLOGICAL SETTING AND STRATIGRAPHY

The mostly of extensional Golfo San Jorge basin (Fig. 1) evolved during Jurassic and Cretaceous times as one of the intraplate basins that developed over a continental Paleozoic crust (Fig. 2 in Scafati et al., this issue). The

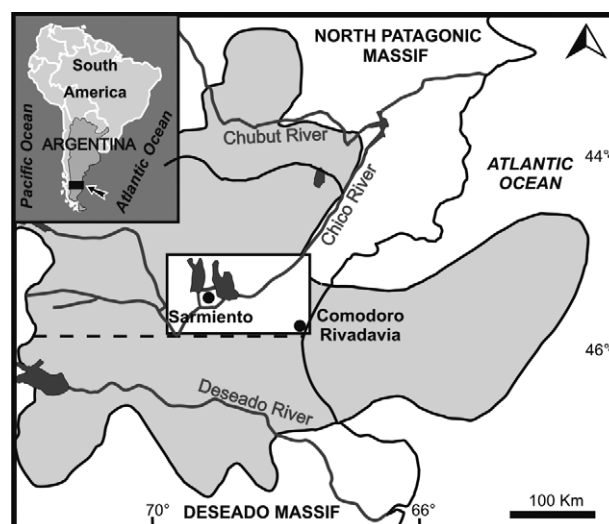


FIGURE 1 | Location map of the onshore and offshore zones of the Golfo San Jorge basin (south-eastern Argentina) in relation to the Andes and the surrounding basement Massifs (Hervé et al., 2008). The rectangle outlines the area shown in Fig. 2.

geotectonic processes related to the Gondwanan break-up and the opening of the Atlantic Ocean in the Upper Jurassic (Hechem and Strelkov, 2002) influenced on this development. From Maastrichtian (late Cretaceous) until Danian (early Paleocene) a widespread shallow marine epeiric transgression was caused by the general subsidence of the Patagonia continental margin. This transgression resulted in the nearly continuous sedimentation of the so-called Salamanca Formation (Fm) (Uliana and Legarreta, 1999). Upper layers of the Salamanca Fm (Banco Verde-Banco Negro) are bounded by an unconformity and overlain by the Late Paleocene to middle Eocene Río Chico Group. Late Paleocene to middle Eocene sedimentation in the Golfo San Jorge Basin was essentially continental and resulted in the deposition of the units that make up the Río Chico Group, i.e. the Peñas Coloradas, Las Flores and

Koluél Kaike Fms (Fig. 2). The gravel-sand deposits of the Peñas Coloradas Fm unconformably overly the Salamanca Fm and are in turn covered by the muddy-sandy beds of the Las Flores Fm. These units were deposited in lacustrine to fluvial environments (Legarreta and Uliana, 1994). The Río Chico Group sequence ends with the volcanoclastic deposits of the Koluél Kaike Fm that are overlain by the Middle Eocene-Early Miocene volcanic tuffs and fine ashes of the Sarmiento Fm and the Paleogene-Neogene deposits of the Patagonia and Santa Cruz formations, which in turn are overlain by Quaternary sediments (Fig. 2).

Peñas Coloradas Fm has an average thickness of 80 m (Fig. 3) and is composed of fine conglomerates, very fine to very coarse sandstone, and grey to reddish massive volcanoclastic and epiclastic mudstone levels. This unit was

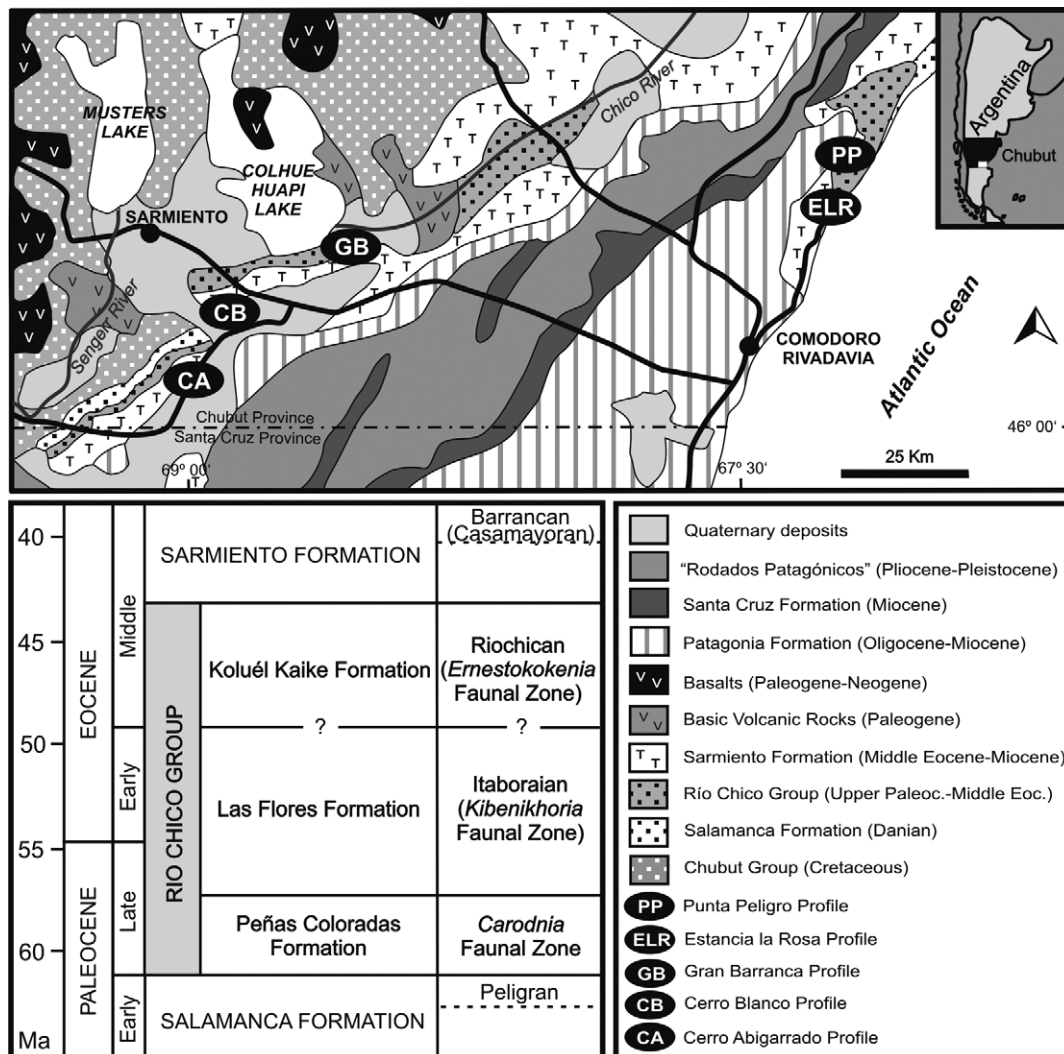


FIGURE 2 | Geological sketch of the study area showing the logged sections, and a lithostratigraphic-chronostratigraphic sketch including time scale in Ma and epoch boundaries, following Berggren et al., 1995; and time scale for lower Cenozoic mammalian faunas of South America (SALMAS), modified by Kay et al., 1999.

deposited on fluvial plains with high to moderate sinuosity channels. The main sandstone lithologies in the fluvial channel bodies are feldspathic litharenites and lithic feldsarenites (plagioclases>K-feldspars and volcanic lithics>total lithics), with a magmatic arc provenance (Raigemborn, 2006; 2007). Nevertheless, sandstones of the Peñas Coloradas Fm in Cerro Abigarrado profile are more quartzose in composition (sublithic arenites). The petrographic data suggest that the unit was not affected by deep-burial diagenesis (Raigemborn, 2006; 2007). The mudstones levels associated with floodplain deposits show in some cases root traces, mottling, nodules and slickensides, indicating some degree of pedogenesis. This unit yielded permineralized fossil wood remains (Brea and Zucol, 2006).

The Las Flores Fm is 30 to 40 m thick and mainly consists of grayish mudstones and minor epiclastic and volcanoclastic sandstones deposited in floodplain-shallow lacustrine environments (Fig. 3). The composition of these sandstones is more feldspathic (lithic feldsarenites: plagioclases>K-feldspars and volcanic lithics>total lithics) than that of the Peñas Coloradas Fm, indicating a magmatic arc provenance. The sandstone petrography suggests shallow burial diagenetic transformations (Raigemborn, 2007). The mudstone facies, which show some pedogenetic features (root traces and Fe-nodules, mainly goethite), yielded abundant siliceous microfossils (phytoliths and other siliceous remains; Zucol et al., 2005) and fossil leaves with affinity to Lauraceae (Iglesias, pers. comm.).

Although the South American early Paleogene geochronology is poorly established and isotopic ages have not been produced extensively from these units, a recently dated tuff horizon near the top of the Peñas Coloradas Fm (Iglesias et al., 2007) indicates an age of 57.8 Ma, which allows correlating this unit with Late Paleocene times. This unit also yielded fossil mammal remains belonging to the *Carodnia* faunal zone (Simpson, 1935a; Bond et al., 1995), correlated with an unnamed mammal age between the Peligran (Flynn and Swisher, 1995; Gelfo, 2007) and the Itaboraian SALMA (South American Land Mammal Ages; Bond et al., 1995; Flynn and Swisher, 1995), and attributed to the Late Paleocene (Fig. 2). Moreover, one of the richest Paleogene mammal faunas documented so far in Patagonia (Goin, pers. comm.) comes from the basal levels of the overlying Las Flores formation. This fauna corresponds to the *Kibenikhorja* faunal zone (Simpson, 1935a) and is correlated to the Itaboraian SALMA (Bond et al., 1995; Flynn and Swisher, 1995; Pascual et al., 1996) that is attributed to the Late Paleocene-Early Eocene (Fig. 2).

This study was performed in outcrops of the Peñas Coloradas and the Las Flores formations (Southeastern

Chubut province). The study area comprises a coastal sector located 40 km north from the city of Comodoro Rivadavia, integrated by Punta Peligro-Estancia La Rosa locality (PP-ELR: 45° 32' 25" S and 67° 14' 39" W – 45° 34' 45" S and 67° 17' 32" W, respectively); and a western area located to the south of the Sarmiento city. The latter includes a first section located at the southeastern end of the Gran Barranca (GB: 45° 43' 26" S and 68° 37' 14" W); a second section near Cerro Blanco (CB: 45° 47' 33" S and 68° 56' 06" W); and finally, the southernmost section located close to the Bosque Petrificado Ormaechea, in the Cerro Abigarrado (CA: 45° 50' 38" S and 69° 03' 34" W; Fig. 2).

MATERIALS AND METHODS

A total of 41 samples (36 mudstones and 5 sandstones) from four localities were collected for X-ray diffraction (XRD) analysis (Fig. 3). Soft grinding with a rubber mortar was applied to disaggregate the more indurated samples, followed by repeated washes in distilled water until deflocculation occurred. The <4 µm fraction was separated by gravity settling in suspension, and oriented mounts were prepared on glass slides. Clay mineralogy was determined from diffraction patterns obtained by using samples that were air dried, ethylene glycol solvated and heated to 550°C for 2 hours (Brindley and Brown, 1980). Diffractograms were run on a Philips PW 1011/00 diffractometer, using Cu/Ni radiation and generation settings of 36 KV and 18 mA. Routine air-dried mounts were run between 2 and 32 °2θ at scan speed of 2 °2θ/min (Fig. 4). Ethylene glycol solvated and heated samples were run from 2 to 26 °2θ and 3 to 15 °2θ, respectively, at a scan speed of 2 °2θ/min (Fig. 4). Semiquantitative estimates of the clay mineral relative concentrations were based on the peak area method (Biscaye, 1965) on glycolated samples (17 Å for smectite, 10 Å for illite and 7 Å for chlorite and kaolinite; Fig. 4). The relative percentages of each clay mineral were determined with the application of empiric factors (Moore and Reynolds, 1989). Semiquantification was considered sufficient to define clay mineral composition because presence/absence or dominate/subordination relationships clearly allowed to establish significant groups.

Eight sedimentary samples for phytolith analysis were obtained from the Las Flores Fm in the Gran Barranca profile (Fig. 3). Twenty grams of sediment were analyzed for each sample and processed by following the protocol described in Zucol and Osterrieth (2002). Accordingly, various chemical agents were used in order to remove soluble salts, organic matter and carbonates, after which sodium hexametaphosphate was used to disaggregate the clastic material. Granulometric fractionations were

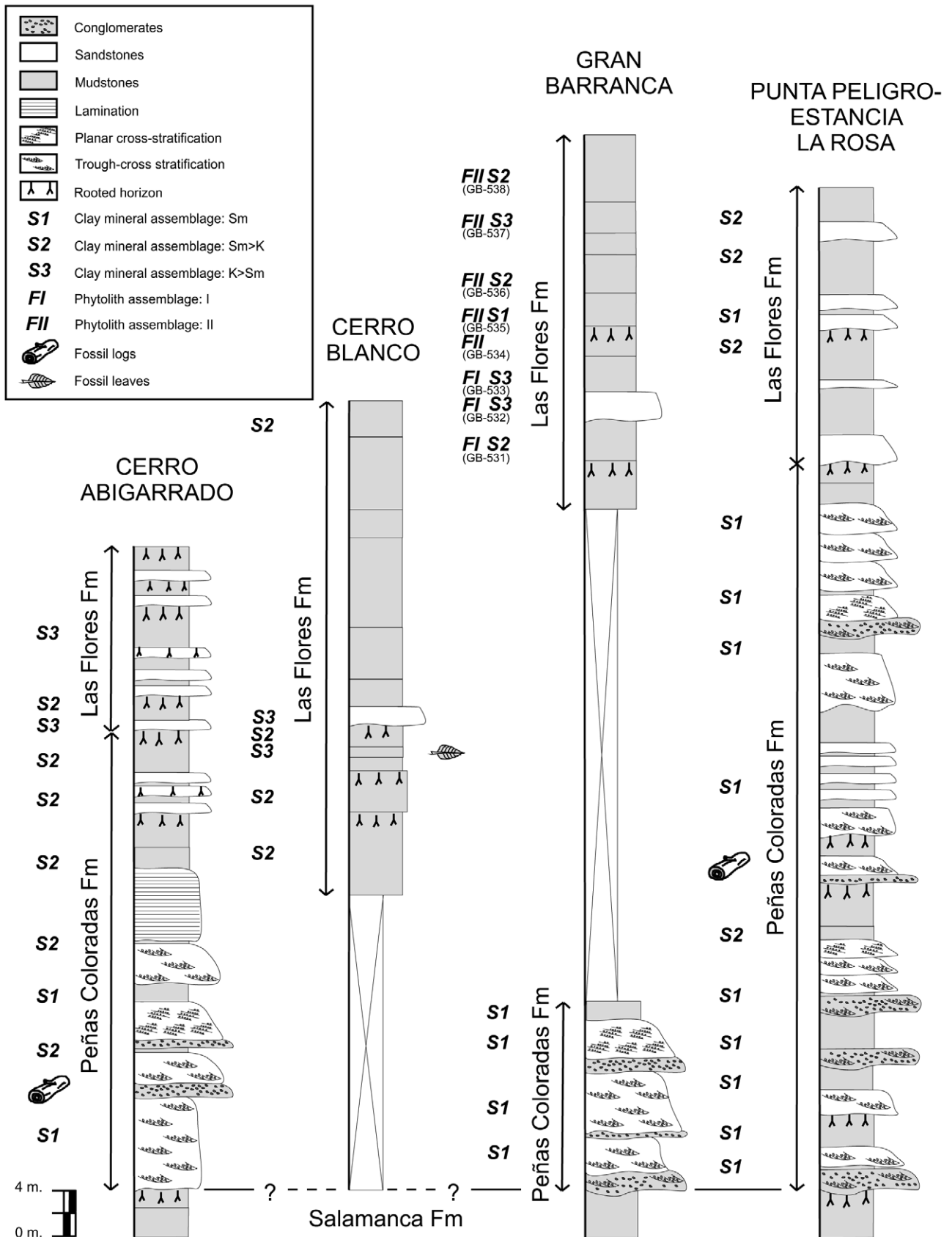


FIGURE 3 | Schematic sections of the Peñas Coloradas and Las Flores formations in the study area, showing the distribution of the clay mineral and phytolith assemblages, and the fossil wood bearing levels.

obtained by sieving (coarse fraction) and sedimentation (medium to fine fractions). Four fractions were obtained according to particle diameter: coarse ($>250\mu\text{m}$), medium ($8\text{--}53\mu\text{m}$ and $53\text{--}250\mu\text{m}$) and fine ($<8\mu\text{m}$). Separation of phytoliths within the medium granulometric fractions was performed by means of a flotation in a heavy liquid (sodium polytungstate) solution with a density of 2.3. Phytoliths were mounted for viewing on microscope slides in both liquid (oil immersion) and solid (Canada balsam) media. The phytoliths were studied with a Nikon Eclipse E200 light microscope (with a magnification of 4x, 10x, 40x and 100x used according to the studied material) and the photomicrographs were taken with a Nikon Coolpix 990 digital camera. Phytolith morphotypes were determined and classified according to previous classifications (Twiss et al., 1969; Bertoldi de Pomar, 1971; Piperno, 1988, 1989; Bozarth, 1992; Rapp and Mulholland, 1992; Twiss, 1992; Kondo et al., 1994; Piperno and Becker, 1996; Runge, 1999; Wallis, 2003; Zucol and Brea, 2005; Pearsall, 2006) and the morphotypes were approved by the taxonomic rules proposed recently (Madella et al. 2005). Phytolith-based zones were obtained with constrained single link cluster analysis. The square root (SQRT) method was used for data transformation. The rarefacted number of taxa was calculated by the sum of the probabilities of each taxon. Data processing and its representation as phytolith diagrams were carried out with the POLPAL, Numerical Analysis program (Walanus and Nalepka, 1999a, 1999b, 2002; Nalepka and Walanus, 2003). Sedimentary samples and microscope slides were deposited in the Paleobotanical Laboratory Collection of the Centro de Investigaciones Científicas de Diamante (CICYTTP- CONICET, Diamante), Argentina, under the acronyms CIDPalbomic.

Five fossil wood specimens from the Punta Peligro-Estancia La Rosa and Cerro Abigarrado localities that were permineralized by silicification were examined (Fig. 3). All these fossil woods are 10–150 cm long, whitish in color, moderately well preserved and in some cases they show signs of compression. Standard thin sections (cross-section, tangential longitudinal section and radial tangential section) were used to analyze the woods. The terminology for this study was taken from glossaries of wood anatomy (Tortorelli, 1963; Cozzo, 1964; Boureau, 1957; IAWA Committee, 1989), and Chattaway (1932) standard classifications. Comparisons were made to the Gregory (1994) and Roig Juñent (1996) bibliographic compilation and contribution on wood anatomy by Heimsch (1942), Wagemann (1948), Metcalfe and Chalk (1950), Tortorelli (1956), Tuset (1963), Tuset and Duran (1970), Barros and Callado (1997) and Richter and Dallwitz (2000) and searches of the computerized

(OPCN) wood database (InsideWood, 2004). Material fossils and microscope slides were kept in the Museo Egidio Feruglio (MEF), Trelew, Argentina, under the acronyms MPEF-Pb.

CLAY MINERALOGY

Clay minerals identified in the lower and middle part of the Río Chico Group include smectite (Sm), kaolinite (K), illite (I), chlorite (Ch) and mixed layer clays containing illite/smectite (I/S). The results obtained from the XRD analysis in the $<4\mu\text{m}$ fraction are listed in Table 1. Non-clay minerals identified in this fraction, in decreasing order, are quartz, amorphous silica (opal), feldspars and small amounts of zeolite (clinoptilolite).

The origin of clay minerals in modern environments has been widely studied (Robert and Kennett, 1994; Thiry, 2000). In general, illite and chlorite are indicators for mechanical erosion that affected the parent rocks either as a result of cool and dry climatic conditions or as a consequence of a pronounced relief. Illite, chlorite and mixed layer illite/smectite are the dominant clay minerals of immature soils that have undergone little chemical weathering. On the other hand, smectite and kaolinite are typical of enhanced chemical weathering and soil formation under warm and wet conditions. In particular, kaolinite typically develops in tropical areas with high precipitation and high rates of chemical erosion. Smectite is formed within weakly drained soils under warm seasonal climates with alternating wet and dry conditions, and has less water percolation than that needed for kaolinite formation.

Distribution of clay minerals and clay mineral assemblages

Throughout the studied sequence, the smectite is the most frequent clay mineral, and is present in almost all analysed samples. Kaolinite is abundant in some beds, especially in Gran Barranca, Cerro Blanco and Cerro Abigarrado localities. Chlorite, illite and mixed layer clays are very scarce and restricted mainly to the Cerro Abigarrado locality.

On the basis of the presence, type and relative amount of the above mentioned clay minerals in the studied samples, three clay mineral assemblages have been defined (Table 1). The *S1* assemblage is composed by Sm, the *S2* assemblage is composed by Sm>K and the *S3* assemblage is composed by K>Sm. Distribution and proportion of clay minerals in stratigraphic sense and X-ray diffraction patterns of the $<4\mu\text{m}$ fraction representative of each assemblages are shown in Fig. 4.

TABLE 1 | Clay mineral composition from the Peñas Coloradas and Las Flores formations in the Golfo San Jorge basin.

Mineralogical composition from lower and middle units of Río Chico Group.

Section	Sample	% Sm	% K	% I	% Ch	% I/S	Clay assemblage
		Relative percentage					
<i>Punta Peligro-Estancia La Rosa</i>							
Las Flores Formation	ELR-14	70	30	0	0	0	S 2
	ELR-13	90	10	0	0	0	S 2
	ELR-12	100	0	0	0	tr	S 1
	ELR-11	81	19	0	0	tr	S 2
Peñas Coloradas Formation	ELR-10*	100	0	0	0	tr	S 1
	ELR-9	100	0	0	0	0	S 1
	ELR-8	100	0	0	0	tr	S 1
	ELR7	95	0	5	0	0	S 1
	ELR-6	89	11	0	0	0	S 2
	PP-5	95	5	0	0	0	S 1
	PP-4	100	0	0	0	0	S 1
	PP-3	100	0	0	0	0	S 1
	PP-2	100	0	0	0	0	S 1
	PP-1	100	0	0	0	0	S 1
<i>Gran Barranca</i>							
Las Flores Formation	GB-11	58	37	0	5	0	S 2
	GB-10	15	80	0	5	tr	S 3
	GB-9	75	25	0	0	0	S 2
	GB-8	95	5	0	0	0	S 1
	GB-7	20	80	0	0	0	S 3
	GB-6*	12	75	13	0	tr	S 3
	GB-5	79	21	0	0	0	S 2
Peñas Coloradas Formation	GB-4	100	0	0	0	0	S 1
	GB-3	100	0	0	0	0	S 1
	GB-2	100	0	0	0	0	S 1
	GB-1	100	0	0	0	0	S 1
<i>Cerro Blanco</i>							
Las Flores Formation	CB-6	60	33	7	0	tr	S 2
	CB-5*	35	65	0	0	0	S 3
	CB-4	70	30	0	0	tr	S 2
	CB-3	5	95	0	0	0	S 3
	CB-2	66	34	0	0	0	S 2
	CB-1	59	41	0	0	tr	S 2
<i>Cerro Abigarrado</i>							
Las Flores Formation	CA-10	47	50	3	0	tr	S 3
	CA-9	70	30	0	0	tr	S 2
	CA-8*	38	62	0	0	tr	S 3
Peñas Coloradas Formation	CA-7	76	24	0	0	tr	S 2
	CA-6	93	7	0	0	0	S 2
	CA-5	69	20	0	11	tr	S 2
	CA-4	61	27	12	0	tr	S 2
	CA-3	95	5	0	0	0	S 1
	CA-2	50	34	16	0	tr	S 2
	CA-1*	95	5	0	0	tr	S 1

*: Sandstone sample

Smectite dominated Assemblage (S1)

This association is characterized by smectite-dominated (>95%) clays, although minor proportions of other clays, especially kaolinite (<5%) may occur. The S1 assemblage dominates the Peñas Coloradas Fm at the Punta Peligro-Estancia La Rosa profile. It also appears at the Gran Barranca and to a lesser extent at Cerro Abigarrado localities, mainly in the same unit. This association is poorly represented in the Las Flores Fm (Table 1, Figs. 3 and 4).

Smectite-Kaolinite bearing Assemblage (S2)

The presence of variable proportions of smectite (50-90%) associated with frequent kaolinite (7-37%) and small quantity of chlorite, illite and mixed layer clays (<16%) characterizes this association. The S2 assemblage dominates the Cerro Abigarrado section, principally in the Peñas Coloradas Fm, and the Cerro Blanco profile in the Las Flores Fm, and is less represented at the Punta Peligro-Estancia La Rosa and the Gran Barranca profiles, mainly in the Las Flores Fm (Table 1, Figs. 3 and 4).

Kaolinite dominated Assemblage (S3)

A semiquantitative analysis indicates that high kaolinite (80-50%) concentration compared to smectite (47-5%), and minor chlorite and illite proportions (<13%), is

typical of this assemblage. The S3 association has been identified at Gran Barranca, Cerro Blanco and Cerro Abigarrado areas, where it is dominant in the Las Flores Fm. This assemblage is absent in Punta Peligro-Estancia La Rosa locality (Table 1, Figs. 3 and 4).

PHYTOLITH RECORD

The phytolith assemblages were characterized by widespread dicotyledonous and palm phytoliths, associated with grass, sedge, Zingiberales and Podostemaceae phytoliths (Table 2, Figs. 5, 6, and 7). Siliceous freshwater sponge spicules (Figs. 5O-S), *Ephydatia* sp. type spicules and diatoms with radial and bilateral symmetry were also found (Figs. 5T-V). Stomatocysts of Crysosomataceae (Figs. 5W-Y) were also recorded in these assemblages.

Phytolith description

The Las Flores Fm samples yielded globular (spherical and ellipsoidal) phytoliths with spinulose ornamentation (Figs. 5J and K respectively), globular phytoliths 10-12 μm in diameter, with smooth surfaces (Fig. 5D), globular phytoliths with rugulose and irregular ornamentation (Fig. 5E), and ellipsoidal phytoliths with smooth surface and faceted spherical phytoliths (Fig. 6R). There were elongated faceted phytoliths (Fig. 6R); prismatic

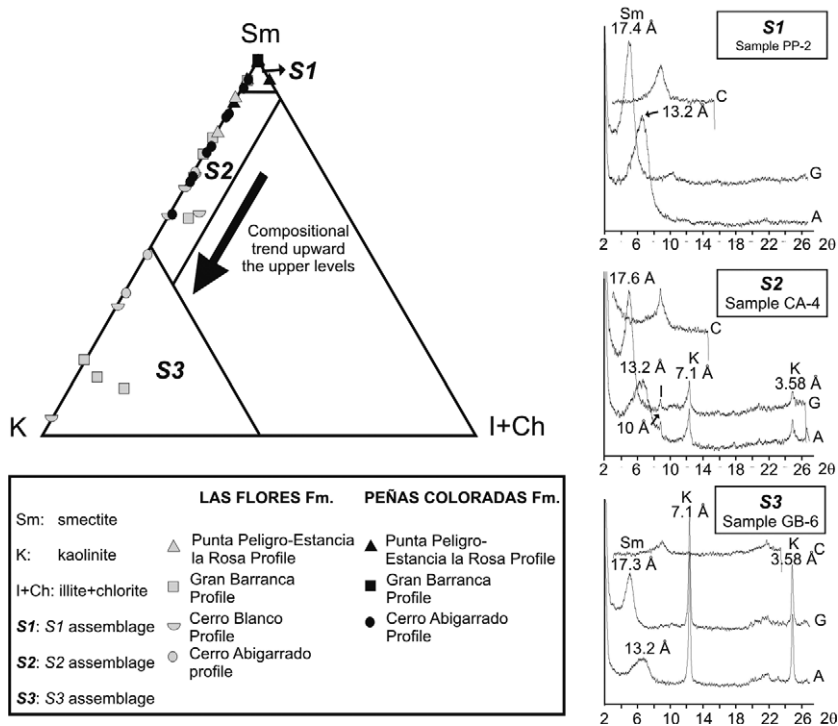


FIGURE 4 | Distribution of clay minerals and clay-mineral proportion in the Peñas Coloradas and Las Flores formations. Representative X-ray diffraction patterns (A: air dried; E: ethylene-glycol solvated and H: 550°C-heated) of the <4 μm fraction samples are shown.

TABLE 2 | Abundance in percentages of the Phytolith morphotypes obtained counting 450 phytolith/sedimentary sample.

Morphotype	Samples							
	GB-531	GB-532	GB-533	GB-534	GB-535	GB-536	GB-537	GB-538
Globular type 1	36.11	24.84	4.32	6.73	8.98	23.90	13.31	10.87
Globular type 12	2.35	4.84	4.03	5.61	2.40	7.97	2.96	4.53
Smooth spherical type 1	1.71	1.29	0.29	0.00	0.00	0.00	0.00	0.00
Smooth elipsoidal	0.43	1.29	4.32	0.45	1.20	0.00	2.37	1.27
Smooth spherical type 2	0.00	0.00	0.58	4.04	0.00	0.00	0.00	3.99
Faceted spherical	2.78	9.68	17.29	13.45	14.97	3.98	7.40	3.26
Faceted elongate	1.07	0.00	0.00	1.79	2.40	2.39	2.96	0.00
Puzzles	6.20	12.90	12.39	11.43	5.99	6.37	8.88	10.14
Hair bases	0.00	0.00	5.76	0.00	0.00	0.00	0.00	0.00
Helical thickenings	1.92	3.87	2.02	1.35	1.80	0.00	2.96	0.00
Echinate plates	1.71	0.00	1.15	0.45	0.00	3.19	2.07	0.00
Irregular type 1	3.21	1.61	0.00	0.00	0.00	0.00	0.00	0.00
Irregular type 2	0.85	0.65	0.00	0.00	0.00	0.00	0.00	0.00
Vascular element with simple perforate plates	1.07	0.32	6.05	1.79	0.60	0.80	1.48	1.45
Vascular element with scalariform perforate plates	0.00	3.23	1.44	3.81	8.98	5.98	2.96	7.25
Vascular element with intervessel pits alternate	0.00	1.61	2.59	2.02	4.79	3.19	3.55	9.06
Vascular element with intervessel pits scalariform	0.00	1.29	1.44	1.79	1.20	3.19	0.00	7.25
Rugulose spherical	13.25	3.87	11.53	8.97	5.39	5.58	7.10	10.87
Dumbbell	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.36
Truncated conical	0.64	0.97	0.00	0.00	0.00	0.00	0.00	0.00
Prismatic smooth type 1	2.78	0.00	5.76	0.00	0.00	0.00	0.00	0.00
Point-shaped	0.43	1.61	2.31	2.69	0.00	3.98	2.96	3.26
Fan-shaped	0.64	2.26	2.88	4.71	4.19	7.97	5.62	1.45
Cyperoid type	2.14	0.00	0.58	0.67	1.80	0.00	0.00	0.00
Podostemaceae type	2.14	0.00	1.15	0.00	0.00	0.00	0.00	0.00
Prismatic smooth type 2	11.11	11.29	5.48	11.21	16.77	11.16	17.75	14.49
Prismatic serrate	1.50	2.58	0.86	7.40	6.59	3.98	2.96	0.00
Prismatic denticulate	2.56	1.94	2.88	0.00	0.00	0.00	2.37	0.00
Polyhedrons	3.21	8.06	2.88	9.64	11.98	6.37	10.36	10.51

phytoliths with more or less parallel sides, and smooth, serrated or denticulated contours (Figs. 6J-L); and prismatic phytoliths with irregular transversal section length.

Furthermore, it is possible to identify epidermal phytoliths, such as puzzle-piece shaped phytoliths with undulating margins (Figs. 6P and Q), hair bases (Figs. 5L-N) and point-shaped phytoliths (Figs. 6A) as well as short cells such as dumbbell and truncated conical types (Fig. 5C). There were also phytoliths with irregular bodies with striate ornamentation and irregular bodies with widely spaced verrucate nodes (Figs. 5A and B respectively). Fan-shaped (Figs. 6M-O) and polyhedron shaped phytoliths were also present.

There were vascular elements, such as tracheids (Figs. 5F-H), vessel elements with simple perforation plates (Figs. 6F and H) or scalariform perforation plates (Figs. 6E, G, and I) and alternate (Figs. 6C and D) or scalariform (Fig. 6B) intervessel pits. Phytoliths derived from vascular tissue were separated into two groups according to their morphological features. The first group of vascular elements (VE type 1) showed morphotypes derived from vessel elements with thin diameter, long, thin-walled, without helical thickenings and oblique end walls. A few morphotypes derived from vessel elements with intervessel pit scalariform, transitional and opposite, and several phytoliths derived from vessel elements with scalariform perforation plates that can have 6-8 bars and 12-16 bars. The second group (VE type

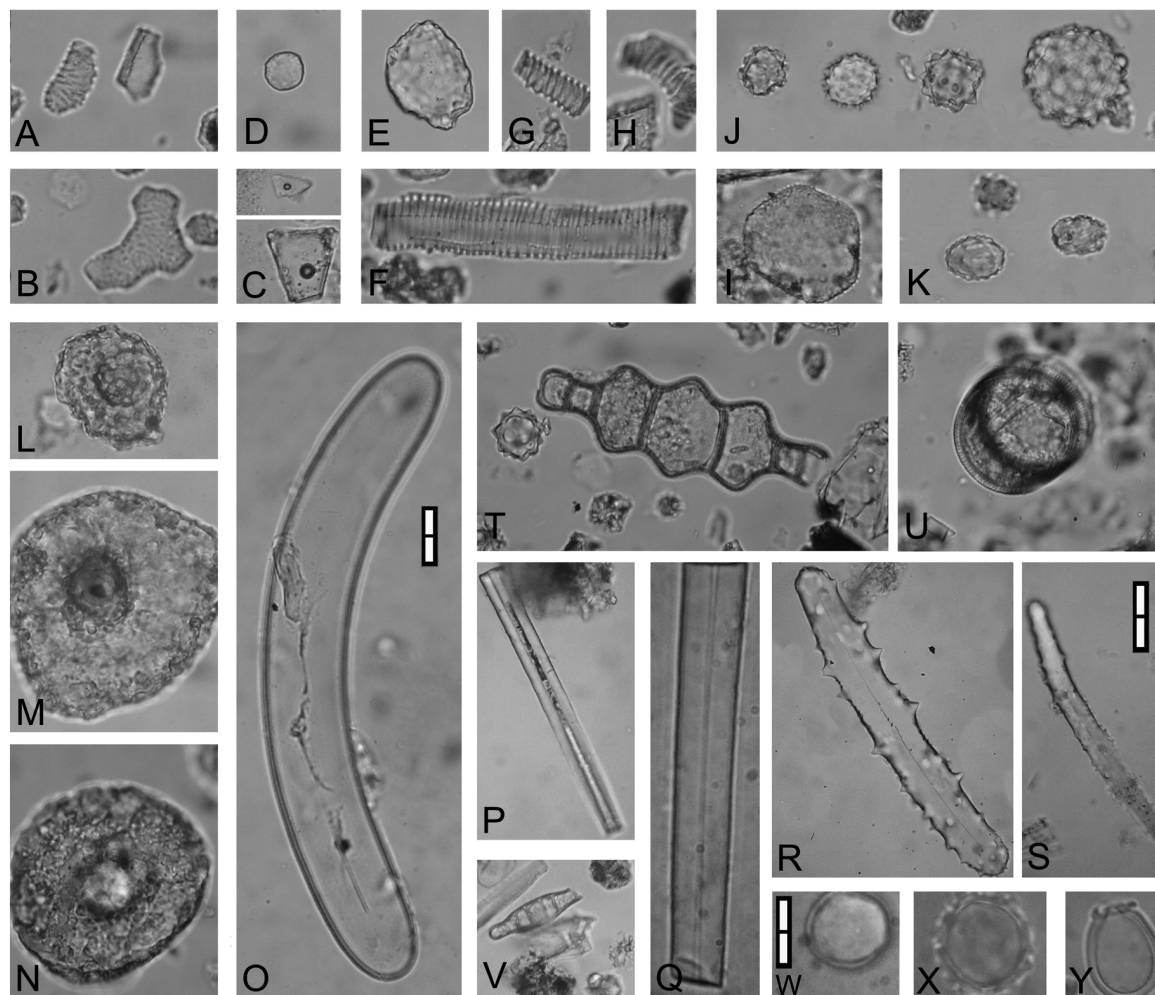


FIGURE 5 | Microphotographs of the phytolith morphotypes and other siliceous microfossils from Las Flores Formation. A) Irregular body with striate ornamentation. B) Irregular body with widely spaced verrucate nodes. C) Truncated conical. D) Smooth globular phytolith. E): Rugulose globular phytolith. F-H) Vessel elements with helical thickenings. I) Smooth phytoliths with hexagonal contour. J) Globular phytoliths with spinulose ornamentation. K) Ellipsoidal phytoliths with spinulose ornamentation. L-N) Hair bases. O-S) Sponge megascleres. T-V) Diatoms. W-Y) Chrysophyte stomatocysts. W) Stomatocysts with spherical contour, unornamented wall and pores without collar. X) Stomatocysts with oval contour with spinulose ornamentation. Y) Stomatocysts with spherical to oval contour, unornamented, pores with two collar. Scale bar = 10 μ m, in W (W-Y); 20 μ m, in O (A-O, Q, T and U); 100 μ m, in S (P, R and V).

2) was characterized by phytoliths derived from vessel elements with wide diameter, short and oblique end walls. There were also morphotypes with small, opposite to alternate intervessel pits, and phytoliths derived from vessel elements with simple perforation plates.

Spherical smooth, spherical rugulose, ellipsoidal smooth, faceted spherical, puzzle-pieced, hair base, elongated derived from epidermal cells, spiral-shaped surface derived from tracheids (Fig. 5F), echinate plates (Figs. 5S-V), faceted elongate and phytolith with irregular body with striate ornamentation, and irregular body with widely spaced verrucate nodes are present in some dicotyledonous angiosperms families (Fig. 7) (Piperno, 1988; Bozarth, 1992; Rapp and Mulholland, 1992; Kondo et al.,

1994; Piperno and Becker, 1996; Runge 1999; Wallis, 2003; Zucol and Brea, 2005; Pearsall, 2006).

Two morphotypes with palm affinities are present in these assemblages: spherical phytoliths with spinulose ornamentation (Globular type 1, Fig. 5J) and ellipsoidal phytoliths with abundant demarcated spinulose ornamentation (Globular type 2 Fig. 5K).

The grass phytoliths present in these assemblages include dumbbell and truncated conical types, formed in short epidermal cells. There are prismatic phytoliths with smooth, serrate and denticulate contour formed in long epidermal and short prismatic cells with smooth contour with grass affinities. While point-shaped and fan-shaped

phytoliths originate from hairs or prickles and bulliform cells, respectively (Twiss et al., 1969; Bertoldi de Pomar, 1971). They are scarcely represented.

The prismatic cyperoid types, characterized as a prismatic smooth body with a protuberance or arm forming a right angle with the main body (Bertoldi de Pomar, 1971; Piperno, 1988) were present in these assemblages and they were categorised as non-grass phytoliths.

The phytoliths with Podostemaceae affinities of these assemblages are characterized by their ovoid body with columellate ornamentation, with mesodermic origin (Bertoldi de Pomar, 1971; Tur, 1997, 2001).

The unclassified phytoliths include a range of forms with scarce diagnostic value, such as vascular elements

(derived from tracheid), short prismatic, irregular-shaped elements, spinulose bodies, “Y” shaped, triangular, and hexagonal phytoliths.

Phytolith assemblages from the Las Flores Formation

On the base of the presence and the percentage changes of 29 phytolith morphotypes used to develop constrained cluster analysis (Walanus and Nalepka, 2002) in the Las Flores Fm, the phytolith assemblages can be arranged in two groups (Fig. 7).

The phytolith assemblages of the samples that make up group I (GB-531 to GB-533) do not allow grouping them in a zone, due to their different composition. In a general sense, all samples are characterized by the pres-

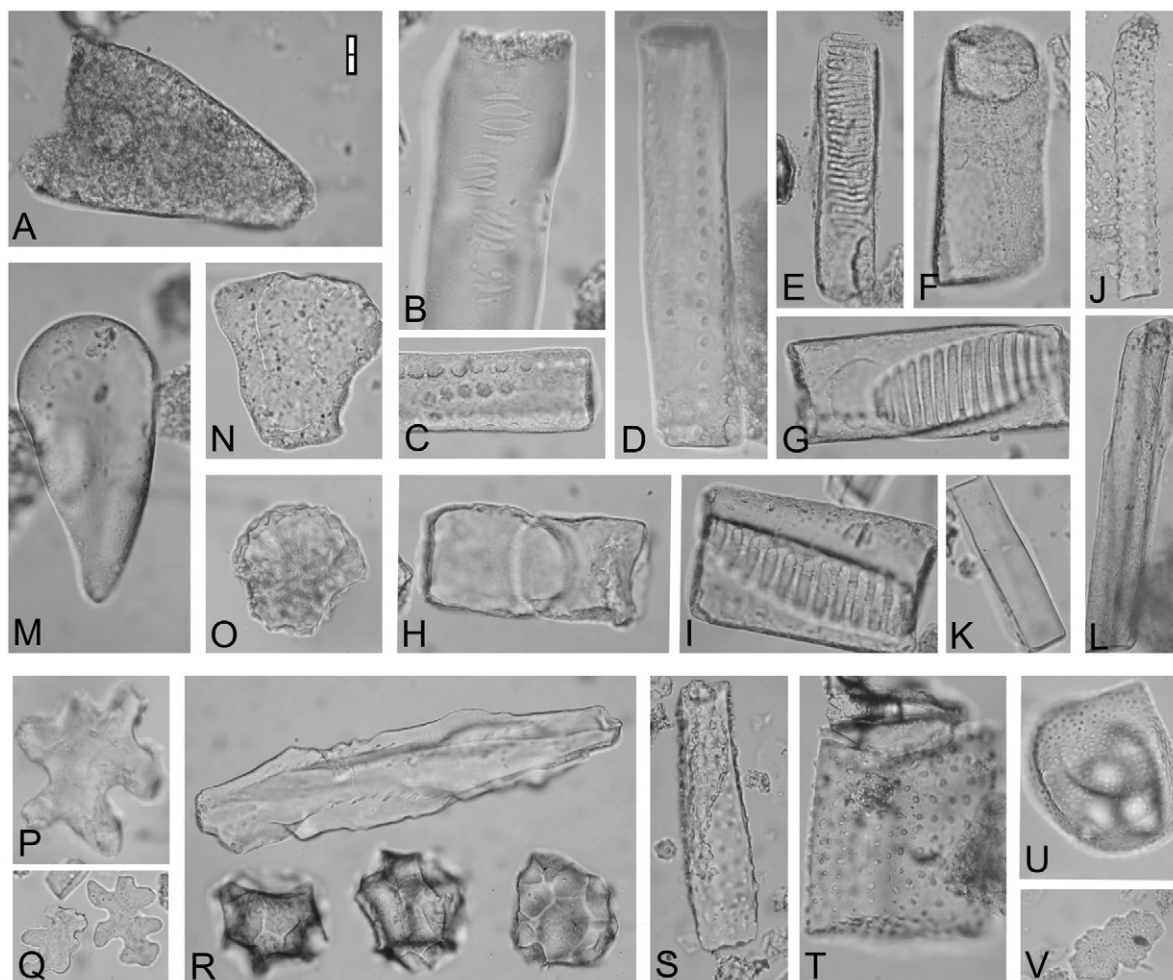


FIGURE 6 | Microphotographs of the phytolith morphotypes and other siliceous microfossils from Las Flores Formation (Cont.). A) Point-shaped phytolith. B-I) Vessel elements phytoliths. B: Vessel elements with interessel pits scalariform. C-D: Vessel elements with interessel pits alternate. E-G-I: Vessel elements with scalariform perforation plate. H-F) Vessel elements with simple perforation plate. J-L) Prismatic phytoliths. J: Prismatic dentate. K-L: Prismatic smooth. M-O) Fan-shaped phytoliths. P-Q) Jigsaw (puzzle forms) phytoliths. R) Faceted spherical and elongated phytoliths. S-V) Echiniate phytoliths. S: Echiniate elongated. T-V: Different echinate plate phytoliths. Scale bar = 20 μ m, in A (A-V).

ence of smooth spherical type 1 phytoliths, and other morphotypes that are present in the upper section of the globular phytolith with spinulose ornamentation, spherical faceted phytoliths, rugulose spherical phytolith, prismatic smooth phytoliths type 2 and polyhedrons. The lower samples (GB-531 and GB-532) share the presence of irregular (type 1 and 2) and truncated conical phytoliths; whereas other morphotypes such as prismatic smooth type 1, Podostemaceae types and echinate plates phytoliths, are observed in discontinuous form in the samples GB-531 and GB-533. The presence of phytoliths originating from vascular elements with simple perforation plates and hair bases were the most outstanding characteristic of the upper sector of group I (GB-533). Dumbbell phytoliths show a particular distribution in the profile since they are present in the basal sample of this group (GB-531) and only in the upper samples of group II (GB-538) were registered.

Group II (GB-534 to GB-538) is formed by more homogeneous phytolith assemblages in its composition and describe a phytolith zone split into three levels: the basal (GB-534 and GB-535), medium (GB-536 and GB-537) and upper (GB-538) levels. This zone is characterized by the abundance of phytoliths derived from vascular elements, including scalariform perforation plates, vascular elements with alternate or scalariform intervessel pits,

faceted elongate, fan-shaped, smooth and serrated prismatic and polyhedrons phytoliths. Spinulose globular and ellipsoidal phytoliths, echinate plates, prickles and prismatic cyperoids type phytoliths were also present.

The assemblages from the Las Flores Fm show a high percentage of phytoliths derived from arboreal elements along the profile; although in group I, the basal sector is characterized by abundant palm phytoliths and the upper sector, by a high percentage of vascular elements with simple perforation plate phytoliths. The basal sector from group II is characterized by an abundance of arboreal elements, but in this case, they are evidenced by the presence of vascular elements with scalariform perforation plates and with alternated and scalariform intervessel pit phytoliths. In the middle sector, these phytoliths are present in low percentages; nevertheless, the herbaceous component is increased, with abundant palm phytoliths in some levels. The upper sector shows a predominance of arboreal elements with similar compositional characteristics to those of the basal sector. In this sector, the presence of dumbbell can be observed at first.

MEGAFOSSIL WOOD RECORD

The Peñas Coloradas Fm includes an assemblage of fossil woods collected from the Punta Peligro-

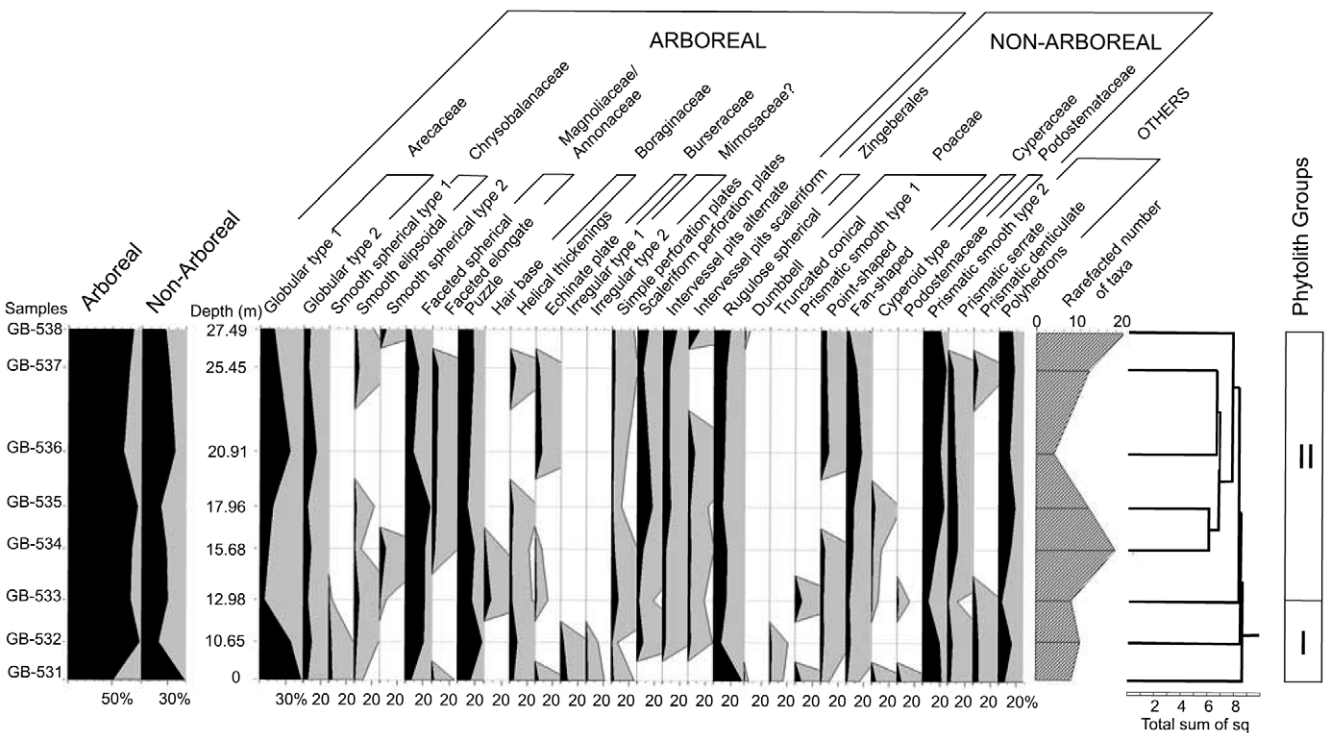


FIGURE 7 | Percentage data for major phytolith taxa from the Las Flores Formation, showing the rarefacted number of taxa of each sample and the cluster analysis dendrogram obtained with constrained single link with square root (SQRT) method transformation.

Estancia La Rosa and the Cerro Abigarrado localities. These woods were identified as *Podocarpoxyylon mazonii* from the Podocarpaceae, *Weinmannioxylon multiperforatum* from the Cunoniaceae, and the Styracaceae and the Araliaceae were indeterminate (Fig. 8). The latter wood types represent the first record of the Styracaceae and the Araliaceae in the Paleocene of Patagonia.

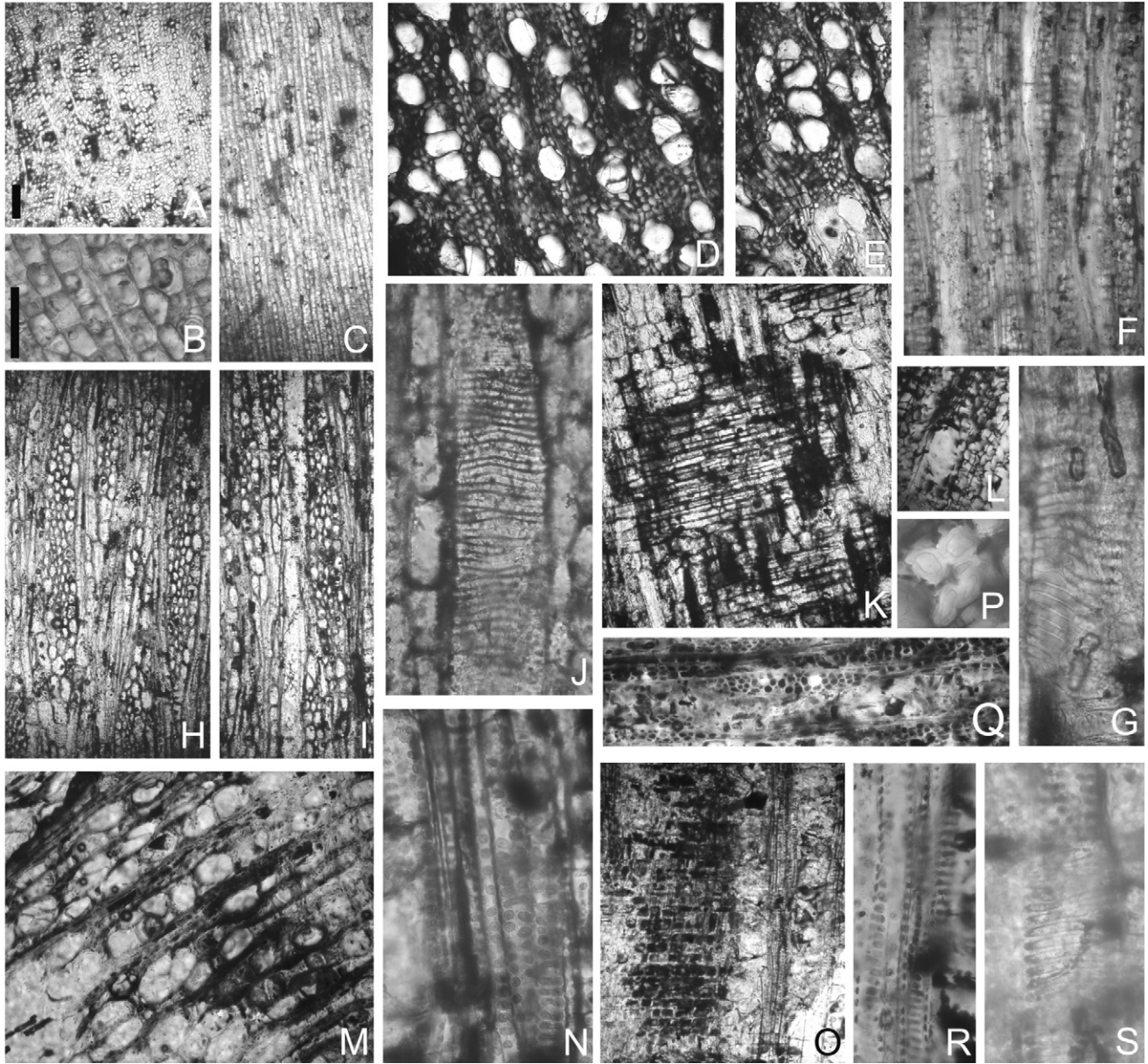


FIGURE 8 | *Podocarpoxyylon mazonii* (Petriella, 1972) Müller-Stoll and Schultze-Motel, 1990. A) General view of a transverse section. B) Transverse section showing the rectangular tracheids and the transverse wall of the ray cells. C) Tangential longitudinal section showing rays uniseriate, homocellular and homogeneous composed of parenchymous cells. Genus uncertain of Styracaceae. D-E) General aspect of the transverse section. F) Tangential longitudinal section showing biseriate, triseriate and multiseriate rays and vessel elements. G) Radial longitudinal section showing scalariform perforation plate. *Weinmannioxylon multiperforatum* Petriella, 1972. H-I) Tangential longitudinal section showing multiseriate rays. J) Radial longitudinal section showing scalariform perforation plate. K) Radial longitudinal section showing rays heterogeneous and heterocellular integrated by procumbent and square-upright cells. L) Transverse section showing elliptic and solitary vessel. Genus uncertain of Araliaceae. M) General view of a transverse section showing solitary vessels and short radial multiple series. N and R) Radial longitudinal section showing intervessels pitting alternate and scalariform. O) General view of radial longitudinal section showing heterocellular rays and vessels elements with intervessels pitting. P) Transverse section showing rectangular or circular fibers with thick walled and rectangular lumen, some fibers with septate. Q) Tangential longitudinal section showing ray with intercellular canals (gum?) in number of 1-2 per ray. S) Radial longitudinal section showing scalariform perforation plate. Scale bar = 10 µm in A (C, D, E, F, H, I, K, L, M, O, Q); 5 µm in B (G, J, N, P, R, S).

Fossil wood taxonomy from the Peñas Coloradas Formation

Class: Coniferopsida GIFFORD and FOSTER, 1989

Order: Coniferales GIFFORD and FOSTER, 1989

Family: Podocarpaceae PAGE, 1990

ORGAN GENUS *Podocarpoxylo* GOTHAN, 1908

Type species: *Podocarpoxylo juniperoides* GOTHAN, 1908

Podocarpoxylo mazonii (PETRIELLA, 1972) MÜLLER-STOLL and SCHULTZE-MOTEL, 1990

Material: MPEF-Pb 2184.

Locality: Cerro Abigarrado, Chubut, Argentina.

Stratigraphic unit: Peñas Coloradas Formation.

Age: Upper Paleocene-Eocene.

Description: Pycnoxylic secondary wood with growth rings slightly demarcated. Tracheids rectangular or square in transverse section; circulate lumen (Fig. 8A-B). Tracheids arranged in radial arrays separated by rays. The rays are separated by 4-5 tracheid lines. Tracheids are ornamented almost exclusively by uniseriate bordered pitting with very rare biseriate tracheids. Pits are circular and separated with circular apertures. Tracheids with probable thickenings of the walls are called crassulea or bars of Sanio. No tangential pitting. Cross-field pit type consists of one oval podocarpus pit with large apertures and thin weakly-defined borders in each field. Rays are uniseriate, homocellular and homogeneous and composed of parenchymous cells (Fig. 8C). Ray height ranges from 5-17 cells high (average: 9 cells high).

Comparison: This wood fossil is assigned to Podocarpaceae Family on the basis of its uniseriate radial tracheid pitting and podocarpoid cross-field pits. This material is almost identical to *Podocarpoxylo mazonii* (Petriella, 1972) from the Lower Paleocene of Cerro Bororó Fm (central Chubut, Argentina).

Class: Magnoliopsida CRONQUIST et al., 1966

Subclass: Rosidae TAKHTAJAN, 1967

Order: Cunoniales HUTCHINSON, 1924

Family: Cunoniaceae R. BROWN, 1814

ORGAN GENUS *Weinmannioxylon* PETRIELLA, 1972

Type species: *Weinmannioxylon multiperforatum* PETRIELLA, 1972

Weinmannioxylon multiperforatum (PETRIELLA, 1972)

Material: MPEF-Pb 2182.

Locality: Cerro Abigarrado, Chubut, Argentina.

Stratigraphic unit: Peñas Coloradas Formation.

Age: Upper Paleocene-Eocene.

Description: The xylem is diffuse porous. The vessels have elliptic outline, are small to medium and predominantly solitary (Fig. 8L). Vessels are numerous (20 vessels/mm²). Mean vessel radial diameter is 201 μ m (range: 173-254 μ m) and mean vessel tangential diameter is 90 μ m (range: 69-115 μ m). Intervessel pitting is opposite to scalariform, sometimes transitional between both types. The vessels have a rectilinear trajectory constituted by vessel elements, 456 μ m high (range: 196-600 μ m high). Scalariform perforation plate (Fig. 8J) with oblique end walls. The rays have a rectilinear trajectory. The rays are multiseriate ranging from three to five cells wide (Figs. 8H-I), heterogeneous and heterocellular integrated by procumbent and square-upright cells (Fig. 8K). The rays are numerous, with an average of 4 per millimeter (range: 4-6 per millimeter). The mean height of the rays is 1078 μ m (range: 577-1905 μ m) and the mean width is 107 μ m (range: 69-127 μ m). Fibers are not well preserved. The apotracheal axial parenchyma is diffuse and sparse.

Comparison: This fossil wood from Upper Paleocene-Eocene sediments of Cerro Abigarrado in the Chubut is identified as having the combination of anatomical characters most similar to modern Cunoniaceae. The material is characterised by diffuse porous wood, solitary vessels, scalariform perforation plates, scalariform intervessel pitting, transitional and opposite and apotracheal axial parenchymas diffuse. Anatomically, the specimen was assigned to *Weinmannioxylon multiperforatum*. The presence of *Weinmannioxylon* in the Early Paleogene suggests that these taxa might have been a component of the forest that covered the Golfo San Jorge basin during this time.

Subclass: Dilleniidae TAKHTAJAN, 1967

Order: Styracales BURNETT, 1835

Family: Styacaceae DUMORTIER, 1829

ORGAN GENUS uncertain

Material: MPEF-Pb 2181 and MPEF-Pb 2180.

Locality: Punta Peligro-Estancia La Rosa and Cerro Abigarrado, Chubut, Argentina.

Stratigraphic unit: Peñas Coloradas Formation.

Age: Upper Paleocene-Eocene.

Description: The xylem is diffuse porous. The vessels have circular outline without contents. The vessels are solitary, short radial multiple series from 2 to 4 elements and the same in clusters (Figs. 8D-E). Mean vessel radial diameter is 91 μ m (range: 69 μ m-115 μ m) and mean vessel tangential diameter is 77 μ m (range: 69 μ m-92 μ m). The vessels are small without tyloses. Vessels are nume-

rous (27 vessels/mm² with a range: 23-32 vessels/mm²) with scalariform, and sometimes opposite intervessels pitting. The vessels have a rectilinear trajectory constituted by short vessel elements, 370 µm (272-450 µm). The perforation plate is scalariform with 12-13 bars (Fig. 8G) and with transversal or oblique end walls. The rays have a rectilinear to slightly winding trajectory, numerous with an average of 6 per lineal mm (range: 4-8 per lineal mm). The rays are triseriate, biseriate and multiseriate (Fig. 8F). The mean height of rays is 811 µm high (range: 394-1270 µm) and the mean width of rays is 70 µm (range: 46-103 µm). The rays are heterogeneous and heterocellular integrated by procumbent and square-upright cells. Fibers are well preserved, hexagonal outline with thick walls, (17-23 µm) and small and circular lumen. Apotracheal axial parenchyma is scarce.

Comparison: Considering the similarities with extant styracacean wood (Tortorelli and Castiglioni, 1948; Tortorelli, 1956), this fossil wood is regarded as a probable Styracaceae. The Styracaceae wood are characterised by diffuse and semi-ring porous wood, vessels are solitary, in radial multiples and clusters, scalariform perforation plates, opposite or alternate intervessel pitting, Axial parenchymas is diffuse-in-aggregates, in narrow bands or lines up to three cells wide, and in marginal or in seemingly marginal bands (Dickison and Phend, 1985). The specimen has a special similarity with *Stirax* Tournef. Ex L.

Subclass: Cornidae FROHNE and JENSEN, 1994

Order: Araliales BURNETT, 1835

Family: Araliaceae JUSSIEU, 1789

GENUS uncertain

Material: MPEF-Pb 2183.

Locality: Cerro Abigarrado, Chubut, Argentina.

Stratigraphic unit: Peñas Coloradas Formation.

Age: Upper Paleocene-Eocene.

Description: Growth ring boundaries are indistinct or absent. The wood has diffuse porous. The vessels are solitary, short radial multiple series from 2 to 4 elements, and sometimes they can be bundled in small groups (Fig. 8M). The mean vessel radial diameter is 129 µm (range: 102-136 µm) and the mean vessel tangential diameter is 97 µm (range: 81-102 µm). The vessels are small and do not present tyloses; they are very common and very few have dark and brown contents. There are, on average, 26 vessels per mm² (range: 24-27 vessels/mm²). Intervessels pitting is alternate (pits rounded or angular with lineal apertures) and scalariform. The perforation plate is simple and scalariform with few bars. Vessels have transversal or slightly oblique end walls. The rays have slightly winding trajectory, and are moderately numerous with 8 per lineal

mm (range: 7-9 radios/mm). The rays are tetraseriates and triseriates, some biseriate. The mean height of rays is 736 µm (range: 443-1193 µm) and the mean width of the rays is 65 µm (range: 54-82 µm). Multiseriate rays have procumbent and upright cells (Fig. 8O). There are 1-2 intercellular canals (gums?) per ray (Fig. 8Q). Fibers have rectangular or circular outline with thick walls and rectangular lumen. Fibers are well preserved; some fibers are septate (Fig. 8P). Apotracheal axial parenchyma is diffuse and extremely rare and paratracheal axial parenchyma is scarce.

Comparison: This taxon is probably a member of the Araliaceae with affinity to the extant genus *Schefflera* J.R. Forst. and G. Forst. The Araliaceae wood is characterized by diffuse porous wood, vessels are solitary and in radial multiples, scalariform and simple perforation plates, alternate, opposite or/and opposite intervessel pitting, Rays commonly 4 to 10 seriate and some with 1-2 intercellular canals. Apotracheal axial parenchyma is absent or extremely rare and paratracheal axial parenchyma is scanty (InsideWood, 2004).

Paleoecological assemblage from the Peñas Coloradas Formation

The paleoecological remains found in the Peñas Coloradas Fm show the presence of several wood types with parautochthonous origin. All samples were identified as gymnosperm and angiosperm woods and assigned to the Podocarpaceae, Cunoniaceae, Styracaceae and Araliaceae families.

Both the extant species of the Podocarpaceae and the Cunoniaceae are distributed in the Southern Hemisphere, mainly in temperate to subtropical areas. Styracaceae and Araliaceae possess a greater distribution and embrace from the tropical up to the temperate regions of both hemispheres.

DISCUSSION

Changes in clay mineralogy and paleoclimatic meaning

As alleged above, although the clay minerals in sedimentary sequences are controlled by pre-burial conditions, some post-depositional clay formation may be expected. In this sense, kaolinite can develop by flushing sandstone with meteoric water (acidic conditions) or as a consequence of feldspar dissolution in an open system (Galán, 2006). At the same time, illite-smectite mixed layers appear at the expense of smectite with increasing burial depth (Chamley, 1989). However, the abundance of

smectite throughout the studied sections in the Río Chico Group, together with the near absence of mixed layer clays and other compositional aspects, indicate that these deposits were not affected by deep-burial diagenesis. This suggests that diagenetic effects on the composition of clay mineral assemblages can be ruled out, and that the assemblages reflect the pre-burial condition. Nonetheless, due to the feldspathic composition of some of these sandstones, the hypothesis of post-burial kaolinite formation from in situ weathering of feldspar under acidic pore water conditions cannot be disregarded.

The field observations and sandstone modal composition data reveal the existence of a source area constituted by Early Paleocene to Middle Eocene (Rapela and Kay, 1988) volcanic rocks that crop out to the northwest of the study area (Raigemborn, 2006, 2007). At the same time, the mineralogical association in the $<4 \mu\text{m}$ fraction with opal and clinoptilolite, can be attributed to the alteration of volcanic ash under warm and humid climatic condition (De Ros et al., 1997; Dingle and Lavelle, 2000). Therefore, we assume that the influence of volcanism in the composition of clay mineral assemblages is clearly reflected through these units. As a result, the recorded clay mineral assemblages might be considered to reflect the environmental conditions at the time of deposition. In this context, the change from a smectite-dominated assemblage (*S1*) to a smectite and kaolinite bearing assemblage (*S2*) and to a kaolinite-dominated assemblage (*S3*) can be related mainly to different weathering histories of similar volcanic material in the source area. In this way, the change to a warmer and wetter climate could trigger chemical weathering (Suresh et al., 2004), which suggests that a higher rainfall may have played an important role in the stratigraphic distribution of smectite and kaolinite in the Río Chico Group. The intense rainfall resulted in enhanced chemical weathering and an increase in erosion would have caused exhumation and denudation of parent rocks, which in tropical areas would result in higher values on kaolinite (Egger et al., 2002). At the same time, the presence of both kaolinite and goethite in the Las Flores Fm indicates substantial chemical weathering, which is developed under high temperature and rainfall conditions (Inglès and Ramos-Guerrero, 1995). However, the Peñas Coloradas Fm at the Cerro Abigarrado profil is an exception because it probably had a local source of crystalline rocks that yielded more illite and kaolinite (*S2* assemblage). In addition, since the kaolinite particles are usually coarser than other clay minerals and tend to be deposited in more proximal environments, this increase in kaolinite might also be related to selective settling from proximal to distal zones on the fluvial plains (Chamley, 1989).

Nevertheless, this kaolinite increase event has also been observed in many sections of the Paleocene-Eocene

period and is considered probably the result of a global climatic change (e.g., Robert and Kennett, 1994; Malumíán et al., 1998; Gibson et al., 2000; Harrington and Kemp, 2001; Schmitz et al., 2001; Egger et al., 2002, 2005). The Paleogene paleoclimatic situation has been documented from the Antarctic Peninsula and from the southern high latitude open oceans. Oxygen isotope and floral data from shallow marine and terrestrial areas of the northern Antarctic Peninsula suggest temperature changes from relatively warm values during the late Maastrichtian time, through a short, cold period during the late Early Paleocene, before rising sharply in the Middle to Late Paleocene, when the Late Paleocene-Early Eocene Cenozoic Optimum took place. Temperatures thereafter became progressively cooler during a wet, strongly seasonal period in the Middle Eocene that lasted until 42 Ma (Dingle and Lavelle, 2000). In this setting we suggest that the *S1* assemblage in the Peñas Coloradas Fm successions records a warm climate with seasonal rainfall through part of the Late Paleocene. The gradual upward increase in the amount of kaolinite from around 7% to 37% (*S2* assemblage) and up to 95% (*S3* assemblage) through the Las Flores Fm could reflect the general Late Paleocene temperature raise trend (Zachos et al., 1993) and/or the beginning of increased precipitation and percolation. This kaolinite percentage increase and the occurrence of goethite might reflect both higher temperatures and precipitation increase across the Paleocene-Eocene boundary. The general kaolinite increase trend recorded in the Las Flores Fm (Fig. 3) is paralleled by decrease in smectite proportion, leading to the assumption that the precipitation changed from seasonal to more year-round with an increased rate of water percolation, although warm temperatures prevailed (Gibson et al., 2000). In this sense, kaolinite can be derived from intensive weathering of feldspar and mica from igneous rocks of the source area, under a tropical climate.

These Cenozoic climatic changes have been attributed to a number of causes. In particular, the Late Paleocene-Early Eocene thermal maximum is believed to have been caused by a sudden input of methane into the atmosphere from dissociation of methane hydrates in continental margin sediments (e.g., Zachos et al., 1993) and also attributed to changes in atmospheric pCO_2 concentration. The fragmentation of Gondwana through the Cretaceous and Paleogene had a major effect on the Earth's oceanic and atmospheric circulation system (Poole et al., 2005). The opening of high southern latitudes seaways is one of the factors that influenced the Cenozoic climate (Lawver and Gahagan, 2003). At the beginning of the Cenozoic, when the Peñas Coloradas and Las Flores formations were deposited, a nearly tropical seaway spanned the globe. Until about 56 Ma, generally equatorial, primarily halothermal circulation kept the oceans uniformly warm

with deep sea temperatures peaking during the Early Eocene Climatic Optimum at $\sim 12^{\circ}\text{C}$ (Zachos et al., 2001). After the closure of the eastern Tethyan Sea in Early Eocene closure, the westward ocean circulation moved out of the tropics, where sea surface temperatures have always been relatively high and constant, into the temperate zone so that gradual cooling began (Lawver and Gahagan, 2003).

Paleobotanic changes and paleoclimatic meaning

All analyzed samples from the Gran Barranca profile present an abundance of dicotyledonous and palm phytoliths, while herbaceous monocotyledonous morphotypes are less frequent (Figs. 5, 6, and 7).

The anatomical characters of the scalariform perforation plates (VE type 1) are unquestionably primitive features in the evolution of the secondary xylem (Frost, 1930a, 1930b, 1931; Carlquist, 1975). The paleoecological assemblages represented in the Las Flores Fm demonstrate that the paleoflora present in this interval included dicotyledonous woods with a number of ancestral characters.

The long-held view that scalariform perforations are more primitive than simple perforation plates is supported by recent angiosperm phylogenies, although homoplasy suggests their adaptive function in some environments (Baas, 1976; Baas and Wheeler, 1996; Jansen et al., 2004). Studies carried out on the ecological strategies of the anatomical characters of the wood in different types of vegetation and geographical areas include those by Van der Graaff and Baas (1974), Baas (1976), Wheeler and Baas (1991), and Jansen et al. (2004). The distribution of exclusively scalariform perforation plate confirms that the incidence of this feature gradually increases from deserts to tropical, subtropical, cool temperate, and boreal-artic climates. This feature is almost completely absent in deserts but very common in boreal-artic areas. Relatively high percentages of exclusively scalariform perforation plates are characteristic of woody plants in tropical montane regions, which indicate that the distribution of this feature increases with increasing altitude (Jansen et al., 2004).

The phytolith composition of group I can be linked to a forest with some humid subtropical to tropical characteristics. In the lower levels the *Arecaceae*, *Mimosoideae*? *Chrysobalanaceae* are characteristic of lowland forests, while the grass components can be interpreted as understory elements. In the upper levels, the arboreal elements with VE type 2 characters increase. Palms and herbaceous elements decrease, whereas the arboreal components are more abundant (Fig. 7). Diverse arboreal groups characterize group II by their presence or abundance: *Magnoli-*

aceae, *Annonaceae*, *Burseraceae*, *Boraginaceae*? and *Areaceae*, while the herbaceous component appears to be represented mainly by the *Zingiberales* and the *Poaceae* (Fig. 7). The composition of group II shows the presence of a humid subtropical to tropical forest with more diverse elements compared to what was observed in group I.

The study of fossil woods from the Peñas Coloradas Fm supports the position about primitive genera records within the dicotyledonous families registered for the Upper Paleocene-Eocene in central Patagonia. The fossil record is constituted by two floristic assemblages. The first one corresponds to austral elements, where the *Podocarpaceae* and *Cunoniaceae* are important components. Today, these families are distributed predominantly in temperate and subtropical areas of the South Hemisphere. On the other hand, temperate and tropical elements are also recorded, making up a second floristic assemblage that includes *Styracaceae* and *Araliaceae*, described in this paper, and *Boraginaceae* (described in Brea and Zucol, 2006), which possess a large distribution from the tropical to temperate zones in both hemispheres. In this sense, the paleoecological records indicate the existence of temperate to subtropical forests at the time of deposition of the Peñas Coloradas Fm in the Golfo San Jorge basin. This hypoautochthonous taphocenosis would record the development of mixed forests under temperate-warm and humid climatic conditions. These paleocommunities might be compared with the currently existing rainforests in Australia, Southeastern Asia and Southeastern Brazil.

The fossil leaves collected from the lower levels of the Las Flores Fm at the Cerro Blanco locality (Fig. 3) were identified as *Lauraceae* (Iglesias, pers. comm.), which is a family associated with subtropical to tropical regions.

CONCLUSIONS

Combining different proxies (i.e. clay mineral composition, phytolith assemblages and fossil woods) for the paleoclimatic analysis of continental sequences constitutes a valuable approach. The new combined use of phytoliths and wood assemblages enabled us to reconstruct paleovegetation assemblages by means of comparative analyses with modern analogs. The resulting data were then checked against the recorded clay mineral assemblages to infer the early Paleogene paleoclimate conditions in Patagonia.

The clay mineral assemblages in lower and middle sections of the Río Chico Group indicate that clay assemblages primarily resulted from source area lithology and

paleoclimatic conditions, which controlled the chemical and physical weathering. Nevertheless, it is possible to recognize a subsidiary role of depositional environment and post-depositional events. The clay mineral assemblages suggest that the climatic conditions during the early Paleogene in the Golfo San Jorge basin evolved to increasing year-round rainfall from the lower to the upper stratigraphic levels. High precipitation rates enhanced the chemical weathering mainly over volcanic material that gave rise to larger (with respect to smectite) kaolinite generation through the Las Flores Fm. Considering that this increase in kaolinite abundance is regarded as statistically significant, we suggest that Paleocene-Eocene boundary climatic changes affected the mid latitude Southern Hemisphere.

The paleoecological assemblages of the Peñas Coloradas Fm support the position of primitive genera records within the dicotyledonous families such as Styracaceae, Araliaceae and Cunoniaceae, which correspond to woody families that grow in temperate to subtropical climates. On the other hand, phytolith assemblages of the Las Flores Fm demonstrate the existence of mixed subtropical to tropical and humid forests. These forests were composed by Chrysobalanaceae, Mimosaceae? Magnoliaceae, Annonaceae, Burseraceae, Boraginaceae? and Arecaceae with an understory composed of Zingiberales and Poaceae.

The integrated study of the clay mineral and paleofloristic assemblages of the Peñas Coloradas and Las Flores formations reveals that the climatic conditions exerted an effective control on the early Paleogene deposits of Golfo San Jorge basin, which may have changed from temperate-warm and humid conditions, with highly seasonal precipitation to warmer subtropical-tropical conditions with more year-round rainfall.

Nonetheless, an improved geochronological resolution by using radiometric dating is essential to precise the exact duration of the global the Paleocene-Eocene warming interval in Central Argentinean Patagonia.

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