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Evidence of Neogene wildfires in central Chile: Charcoal records from the Navidad Formation

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ABSTRACT

Mediterranean-type climate (MTC) ecosystems are characterized by recurrent wildfires. Although the majority of wildfires are human-ignited, non-anthropogenic (i.e., natural) wildfires are common in all MTC regions except central Chile. The low frequency of natural wildfires in this Chilean region is explained by the scarcity of non-anthropogenic ignition sources, basically thunderstorm-induced lightning and volcanic activity. However, from a geological perspective, the current relative absence of non-anthropogenic wildfires in central Chile is a recent phenomenon. In the transition from the Early to Middle Miocene, the climate in the region was likely warm and seasonally dry. Such climate conditions would allow the growth of fuel during the spring, becoming flammable during the dry season. This fire-prone landscape would likely have been ignited by the high volcanic activity that concomitantly occurred with the orogeny of the Andes. To evaluate this hypothesis, we sampled rocks from the three locations at the Navidad Formation, considering the fossil plant evidence deposited during this warm and seasonally dry period. We found a high concentration of charcoal in Playa Navidad, coinciding with the global warming event reported between 17 and 15 Ma. The predominance of microscopic charcoal particles (between 125 and 250 μm) only allows us to infer the occurrence of Neogene fires at a regional scale. The fused cell walls preserved in the charcoal anatomy likely suggest that such fire events were highly severe. The presence of pumice associated with the high charcoal concentrations supports the hypothesis of volcanic ignition sources. Very little charcoal was found in Punta Perro (Late Oligocene – Early Miocene) or in Cerro Los Pololos (late Middle Miocene), where fire may have been limited by fuel humidity and ignition sources respectively, although changes in the depositional environment would also help explain differences in the fire record throughout the Navidad Formation. In conclusion, our results provide the first quantitative Neogene charcoal record for South America. The evidence of fire occurrence in central Chile during the Neogene will contribute to understanding the evolution of the Mediterranean-type flora.

1. Introduction

Regions with a Mediterranean-type climate (MTC) host sclerophyllous woody vegetation generally characterized by crown wildfires that occur every 10 to 60 years (Keeley et al., 2012). This fire regime is explained by the annual climate seasonality (Batllori et al., 2013), where the mild temperatures (12 °C) occurring during the rainy season (with a cumulative precipitation of 320 mm) provide the conditions for the growth of plant biomass that becomes highly flammable during the warm and dry summers (22 °C and 50 mm; Keeley et al., 2012). Currently, anthropogenic ignition is responsible for most of the wildfires in MTC regions, due to their high population density (Keeley et al., 2012). However, there are lightning-initiated wildfires in all MTC regions except for central Chile (30°–37°S), where they are practically negligible (1.3% for the 2003–2015 period cf. Chilean National Forestry Agency, CONAF; see also Montenegro et al., 2003). The scarcity of non-anthropogenic (i.e., natural) wildfires in central Chile is explained by the low regional thunderstorm-induced lightning activity, which is five times lower in central Chile than in California and almost 13 times lower than in the Australian MTC region (René Garreaud, com. pers., based on the World Wide Lightning Location Network for the 2009–2012 period). Despite the almost total absence of natural wildfires in the region, many plant species are able to regenerate after being burnt, mainly by resprouting (e.g., Montenegro et al., 2003). This has been used as an argument against the role of fire in the evolutionary origin of fire adaptive traits in the Chilean plants and, by

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extension, in species from other regions (Valiente-Banuet et al., 1998; Lloret et al., 1999; Bradshaw et al., 2011).

However, the current absence of recurrent natural wildfires in central Chile is a recent phenomenon at a geological time-scale (Heusser, 1990; Villa-Martínez et al., 2003). Specifically, periods of frequent fires have been recorded in Laguna Tagua-Tagua (34°30′S) at the end of the Pleistocene (between 53,800 and 28,500 year BP), before the arrival of humans to the region, which dates back to 11,380 year BP (Heusser, 1990 and references therein). Similarly, fires detected in Laguna Aculeo (33°S50′S) between 5500 and 2500 year BP are not necessarily attributable to human activity, considering that the oldest archaeological site in the Laguna Aculeo watershed dates from 2000 year BP (Villa-Martínez et al., 2003; Sanhueza et al., 2007). In both cases, the pollen record concomitant with fire occurrence indicates annual rainfall seasonality and warm conditions (Heusser, 1990; Villa-Martínez et al., 2003).

The current sclerophyllous flora of central Chile is derived from a Neogene Subtropical Paleoflora that through most of the Miocene occupied the central areas of Chile and Argentina, under a warm climate with high seasonal precipitation (Hinojosa and Villagrán, 2005; Hinojosa et al., 2011). Given such warm climatic conditions, with abundant vegetation growing during spring and becoming dry during summer, the landscape was probably highly fire-prone in the presence of an ignition source (e.g., see Pyne et al., 1996 and Pausas and Keeley, 2009 for a general discussion on fire drivers). In this sense, it has been proposed that both thunderstorm-initiated lightning and/or volcanism would have triggered wildfires in the past in central Chile (Fuentes and Espinosa, 1986; Keeley et al., 2012).

In this work, we hypothesize the occurrence of wildfires in the MTC region of Chile during the transition from Early to Middle Miocene, triggered by the warm conditions, the marked annual seasonality in precipitation and the co-occurrence of a variety of ignition sources. To test this hypothesis, we explored the existence of charcoal particles of the fossil record in the Navidad Formation, located on the west side of the Coastal Range in central Chile, considering the fossil plant evidence deposited here during this warm and seasonally dry period.

2. Geological and palaeontological setting

Several basins of differing size developed along the Chilean continental shelf between 33 and 45°S; they are filled with Cretaceous to Miocene sequences in discrete depocenters bounded by basements highs that segment individual basins (Melnick and Echtler, 2006). The northernmost of these sedimentary units is the Navidad Basin (Cecioni, 1980; Fig. 1). First described by Darwin (1846), its stratigraphic extent and subdivision has been controversial. For this study, we follow Encinas et al. (2006), who divided the sedimentary deposit between Valparaíso (~33°00′S) and Punta Topocalma (~34°30′S) into four Formations: Navidad, Licancheu, Rapel and La Cueva. The Navidad Formation extends from the mouth of the Rapel River (in Punta Perro beach) to the Matanzas locality, being 250 m thick on average

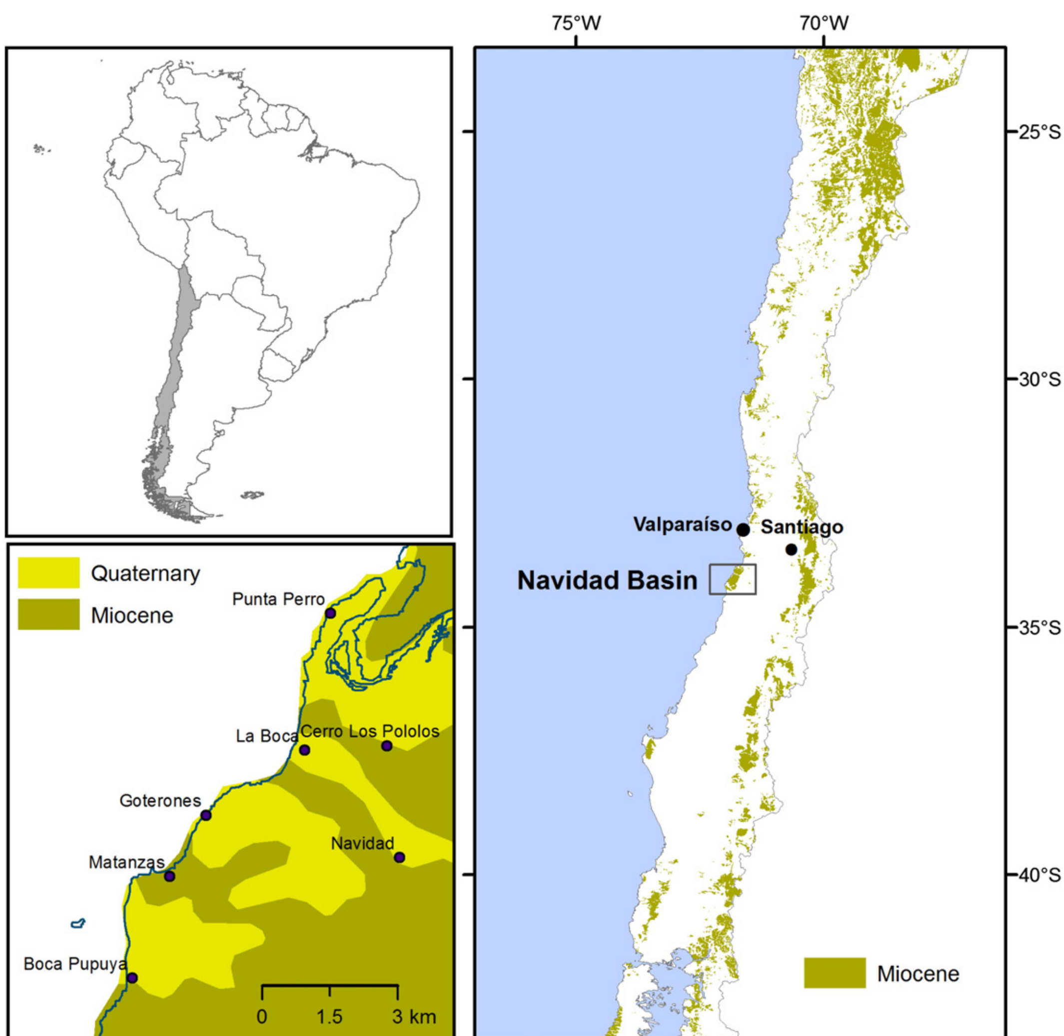

Fig. 1. Map of the geographical location of the study site. Upper left panel showing Chile in South America, right panel the Navidad Basin in Chile using the geological map from SERNAGEOMIN 1:1.000.000, and the down left panel the study site and references inside the text.

(Gutiérrez, 2011). The base of the Formation is located at Punta Perro, over Paleozoic monzogranite (289 ± 7 Ma cf. K—Ar dating of biotites and biotite-amphibolite granodiorites; Hervé et al., 1988). The lithology consists of a conglomerate level at the base (3 m thickness), overlaid by alternating sandstones with mudrock lenses (Encinas et al., 2006; Gutiérrez, 2011).

The Navidad Formation includes an assemblage of a suite of different fossils in excellent preservation conditions, ranging from leaves and palynomorphs to marine micro- and macrofossils (e.g., Martínez-Pardo, 1990; Troncoso, 1991; Suárez et al., 2006; Finger et al., 2007; Nielsen and Glodny, 2009; Gutiérrez, 2011). Strontium dating along the Navidad Formation conducted on 95 shells (mostly mollusks) yield $^{87}Sr/^{86}Sr$ ages between 31.5 and 11.5 Ma (Encinas, 2006; Nielsen and Glodny, 2006, 2009; Gutiérrez et al., 2013). Radiometric dating by K—Ar and $^{40}Ar/^{39}Ar$ methods on volcanic scoria and pumice clasts yield ages between 22.2 and 11.06 Ma (Encinas, 2006; Gutiérrez et al., 2013). All these data, along with the revision of other age-dating tools based on the interpretations of the fossil assemblages (e.g., biostratigraphic correlation), consistently indicate an age within the Late Oligocene to Middle Miocene interval (Nielsen and Glodny, 2009; Gutiérrez et al., 2013; Finger et al., 2013; Finger, 2013).

Some authors interpret the depositional environment of the Navidad Formation as a middle bathyal continental slope, based on sedimentological evidences (e.g., large channels or rip-up clasts, both typical of deep marine environments), the presence of deep water benthic foraminifers, and trace fossils (e.g., psychrospheric ostracod species) (Encinas, 2006; Encinas et al., 2008; Finger et al., 2007, 2013; Finger, 2013). On the contrary, other authors propose a shallow coastal to outer continental shelf as its depositional environment, considering the presence of wave ripple marks in sandstones and well-preserved fossils, including both terrestrial or shallow water invertebrates (some of them partially articulated), as well as abundant terrestrial palynomorphs and complete leaves (Gutiérrez, 2011; Gutiérrez et al., 2013; Le Roux et al., 2013). In any case, regardless of the depositional environment of the Navidad Formation, the abundance of highly preserved continental and marine fossils (e.g., Le Roux et al., 2013) do not suggest a taphonomic bias in the preservation of charcoal particles originated by local and regional fires on the continent.

The Navidad Formation contains some of the best-preserved Neogene fossil floras in central Chile that permits the reconstruction of changes in the vegetation through the Miocene in this region. Two fossil floras have been described at the bottom of the Navidad Formation, the first located in Los Goterones-Matanzas area (Troncoso, 1991; Troncoso and Romero, 1993; Hinojosa et al., 2015). Strontium dating on shell material yielded $^{87}Sr/^{86}Sr$ ages of 23 Ma at Goterones and 22.0–23.5 Ma at Matanzas (Hinojosa and Villagrán, 2005; Gutiérrez et al., 2009; Gutiérrez et al., 2013). They corresponded to Mixed Paleoflora (sensu Hinojosa and Villagrán, 1997), composed of Antarctic-Australasian and Neotropical elements. Podocarpacae, Myrtaceae, Berberidaceae, and *Nothofagus* are the prevailing morphotaxa in such assemblages (Troncoso, 1991; Troncoso and Romero, 1993; Hinojosa et al., 2015). Palaeoclimate reconstructions from leaf physiognomic analyses (i.e., on the basis of leaf margin and size) indicate that such Mixed Paleofloras, grew under mesotherm climatic conditions, with mean annual temperatures between 15.6 °C and 16.2 °C, and annual precipitation between 762 and 1149 mm (data for Los Goterones and Matanzas, respectively; Hinojosa and Villagrán, 2005; Hinojosa et al., 2015). A second fossil flora was described at Boca Pupuya, biostratigraphically dated to the transition from Early to Middle Miocene (Troncoso, 1991; Troncoso and Romero, 1993; Encinas, 2006). It comprises lower number of *Nothofagus* morphotaxa and higher subtropical elements (particularly, Neotropical Myrtaceae and Pantropical Lauraceae) compared to Mixed Paleofloras, and thus it was classified as Neogene Subtropical (Villagrán and Hinojosa, 1997; Hinojosa et al., 2006). Using the same leaf physiognomic analysis mentioned above, the estimated mean annual temperature was 21.4 °C and the annual precipitation 931 mm (Hinojosa and Villagrán, 2005). The growing season in Boca Pupuya was noticeably much wetter than in Los Goterones (estimated mean growing season precipitations of 1280 and 800 mm, respectively), but they did not significantly differ in dry season rainfall (200 and 172 mm for Boca Pupuya and Goterones, respectively; Hinojosa and Villagrán, 2005). Another fossil flora was described at the top of the Navidad Formation, particularly at the locality named Cerro Los Pololos (Hinojosa et al., 2015). Radiometric dating at Cerro Los Pololos yielded an $^{40}Ar/^{39}Ar$ age of 12.87 Ma (Gutiérrez et al., 2009; Gutiérrez et al., 2013). It was also described as Neogene Subtropical, and the climate reconstruction from leaf physiognophy yielded similar temperature and precipitation data as that calculated for Boca Pupuya (21.4 °C mean annual temperature and 908 m of annual precipitation; Hinojosa et al., 2015).

The change from Mixed Paleoflora to Neogene Subtropical assemblages has been associated with a climatic shift which occurred from the Early to Middle Miocene, when the climate became warmer, with wet growing seasons and dry summers (Hinojosa and Villagrán, 2005; Hinojosa et al., 2015). In fact, on the basis of global deep-sea oxygen and carbon isotopes, a global warming event has been described for the transition from the Early to Middle Miocene, with an optimum between 17 and 15 Ma (the Mid-Miocene Climatic Optimum, MMCO; Zachos et al., 2001). In Chile, the MMCO has been recorded by both planktonic foraminifera (Martínez-Pardo, 1990), and through leaf physiognomic analysis (Hinojosa et al., 2011; Hinojosa et al., 2015). In summary, the climate at the site of the Navidad Formation changed from temperate and humid at the Late Oligocene – Early Miocene, to warm and highly seasonal in precipitation towards the Middle to Late Miocene. During this last period, the warm temperatures and high rainfall in the growing season would have increased the primary productivity, thus providing fuels that became dry (and thus available to burn) at summer.

3. Material and methods

The study area is located in the Navidad locality (~33°50′S/71°50′W), on the coast of the Bernando O′Higgins region, in central Chile (Fig. 1). We collected 19 samples from 6 levels, distributed along the stratigraphic column of the Navidad Formation between 60 and 120 m asl (hereafter Playa Navidad; Fig. 2). One sample was collected in a sandstone level with mudrock lenses. The other samples were collected in medium to thick middle layers of fine-grained sandstones, clear ochre in color. More sampling effort was conducted in thicker strata. The age of the sampled stratigraphic levels at Playa Navidad (Fig. 2 and Supplementary materials) comprises the MMCO described in the transition from Early to Middle Miocene (Zachos et al., 2001). To compare charcoal records in Playa Navidad with those of previous and later periods within the Navidad Formation, we also collected samples at the localities of Punta Perro (4 samples from one level located at ~4 m asl) and Cerro Los Pololos (2 samples from one level at ~160 m asl), respectively. Isotopic dating of the sampled level at Punta Perro indicated ages corresponding to the Late Oligocene – Early Miocene, and that at Cerro Los Pololos to the late Middle Miocene (see also Fig. 1 and Supplementary materials).

For each sample, an aliquot of known volume was disaggregated with warm, distilled water. Because the rocks were not cemented, treatment of the samples with HF or HCl to disaggregate them was unnecessary (Scott, 2010). Then, we carefully washed the samples through a sequential series of sieves with increasing mesh size: 125 μm, 250 μm and 1 mm sieves. This methodology (i.e., wet sieving) is habitually used to quantify macroscopic fossil charcoal in non-laminated sediments (Whitlock and Larsen, 2001; Scott, 2010). After the last sieving, charcoal particles bigger than 1 cm were manually separated. No charcoal particle bigger than 5 cm was found. Therefore, we sorted the charcoal samples into four size classes:]125 μm–50 μm],]250 μm–1 mm],]1 mm–1 cm], and]1 cm–5 cm] (hereafter >125 μm, >250 μm, >1 mm,

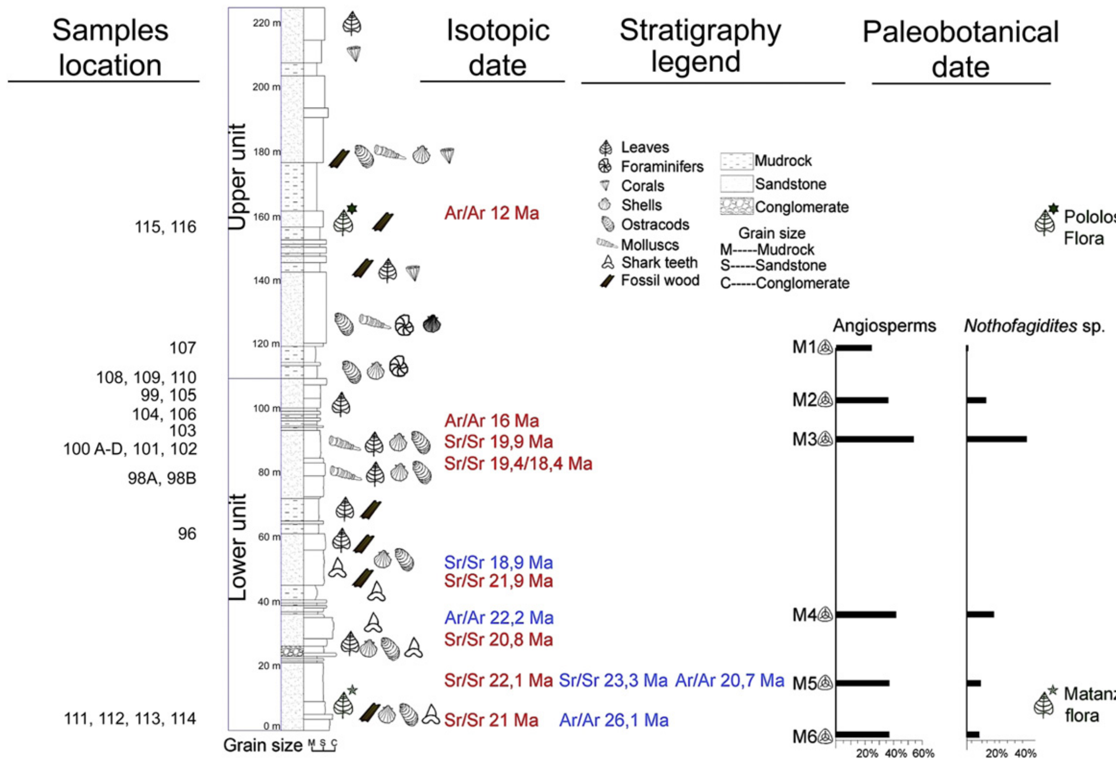

Fig. 2. Stratigraphy of the Navidad Formation (cf. Gutiérrez et al., 2013), showing isotope dates from Encinas (2006; blue) and Gutiérrez et al. (2013); red), paleobiota (cf. Gutiérrez et al., 2013) and sample locations. Elevation above present-day sea level is indicated.

and >1 cm). Following Scott (2010), the first two size classes correspond to microscopic charcoal, whereas the last two are considered macroscopic charcoal. Then, charcoal particles from each size class were counted under a stereomicroscope, except for the biggest size class, which was counted by naked eye. Charcoal presence was then expressed as the number of particles per volume in each sample. Identification of charcoal particles was conducted following the scheme proposed by Scott (2010). Specifically, particles were classified as charcoal when they were totally black, with splintery fracture, silky lustre, and preserved anatomical structure (Fig. 3A and B). Coal is also black, but with very bright lustre, conchoidal fracture and the anatomical plant structure is not discernible (Fig. 3C and D). Fossil organic matter (i.e., non-charcoalified) can be distinguished by its brown color, irregular fracture and degraded anatomical structure (Fig. 3E and F). To ensure correct charcoal determination under the stereomicroscope, charcoal particles from eight of the 25 studied samples were observed under scanning electronic microscopy (SEM). These samples comprised one from Cerro Los Pololos (S115), one from Punta Perro (S113), and six from Playa Navidad (S107, S105, S99, S104, S102, S96). Five charcoal particles per sample (between 250 μm and 1 cm in size) were studied, except for the sample S113, from which only one charcoal particle was available for SEM studies. For this purpose, particles were gold coated with the Ion Coater IB-2 (Eiko Engineering Co. Ltd., Ibaraki, Japan) and observed under the LEO 420 (LEO Electron Microscopy Ltd., Cambridge, England), located at the Microscopy Service of the Universidad Austral de Chile. For each of these charcoal particles, charring severity was estimated by observing the cell wall structure. Specifically, three categories were established following the results of experimental charring of plant tissues (Jones and Chaloner, 1991; Vaughan and Nichols, 1995; McParland et al., 2007): moderate severity, if the cell wall lamella was identifiable; high severity, if cell walls were homogenized and the middle lamella was not recognized; very high severity, when cracking appeared along the site of the middle lamella or individual cells pulled apart. For each sample, the presence of coal and organic matter was registered. The correct determination of this type of material was checked by means of SEM as done for charcoal particles (ten particles of coal and five of fossil organic material).

To support the hypothesis of volcanism as an ignition source, presence/absence of pumice was recorded for each sample. We evaluated the relationship between charcoal concentration and presence/absence of pumice by means of one-way ANOVA. This analysis was conducted considering each charcoal size class separately. Charcoal concentration was log-transformed prior to the analysis in order to meet normality and homoscedasticity assumptions.

4. Results

Charcoal particles were found in all collected samples from Playa Navidad, Punta Perro and Cerro Los Pololos, although their abundance and size distribution was not homogeneous along the sequence (Fig. 4). Whereas charcoal concentrations in Playa Navidad ranged between 87 and 41,699 particles ml^{-1}, charcoal particles were very scarce in samples from Punta Perro (on average 55 particles ml^{-1}) and Cerro Los Pololos (on average 671 particles ml^{-1}). The charcoal concentration at Playa Navidad, in particular, reached its maximum between 90 and 95 m asl, with values up to 35,450 and 6,145 particles ml^{-1} for particle sizes >125 and >250 μm, respectively. The smallest charcoal fraction (>125 μm) gathers at least 70% of the total charcoal concentration in many samples (63%), including those with most charcoal particles. The largest charcoal fraction (>1 cm) was almost negligible, except in S99 (105 m asl), for which 2.9 particles ml^{-1} were recorded (none bigger than 5 cm). In Punta Perro and Cerro Los Pololos, most charcoal particles correspond to the >250 μm size class (100% and 62% respectively; Fig. 4).

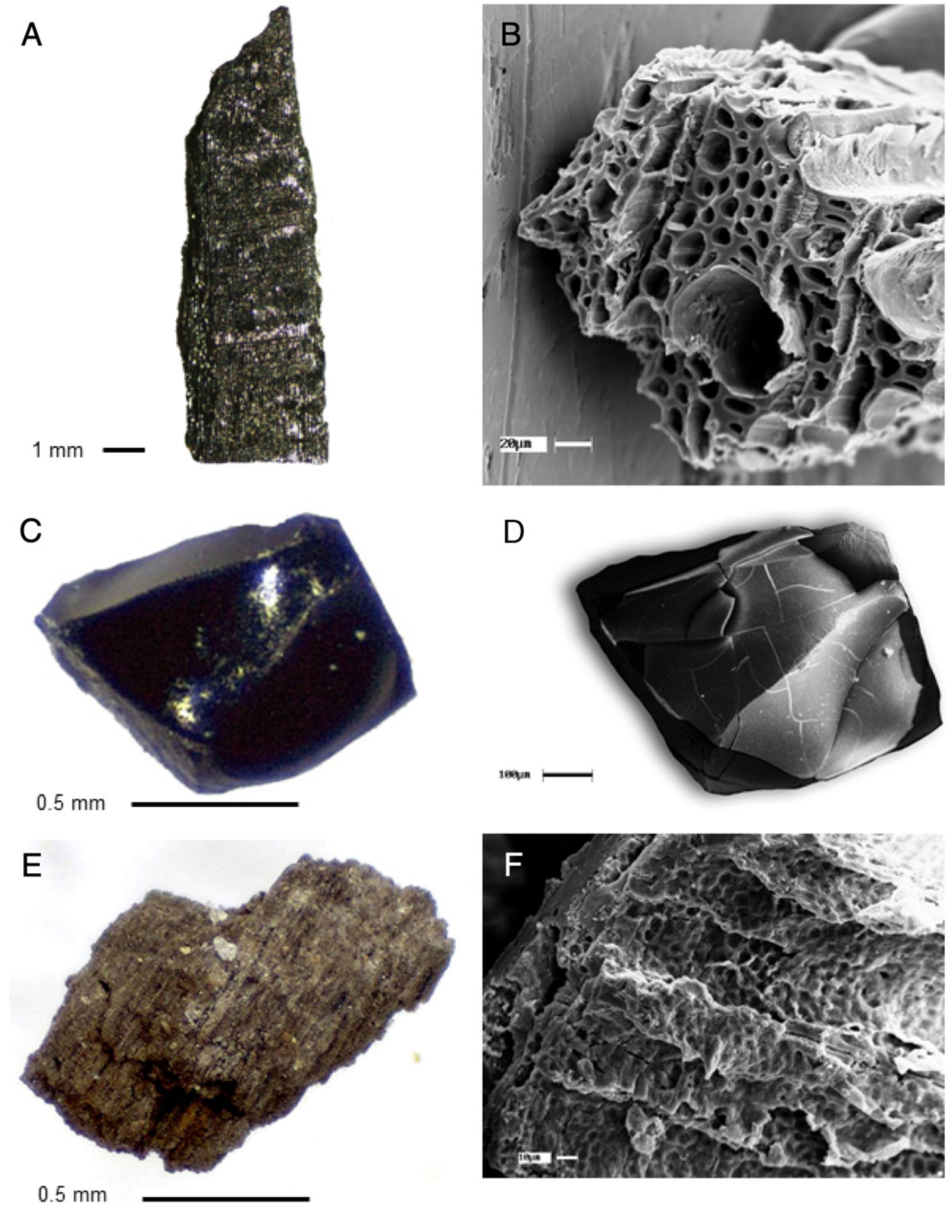

Fig. 3. Images of the different particle types studied. A) Stereomicroscope image of a charcoal particle from Playa Navidad (Early to Middle Miocene), showing black color, silky lustre and fibrous structure. B) SEM image of a charcoal particle; different cell types of the secondary xylem (vessels and parenchyma) are discernible. C) Stereomicroscope image of a coal particle from Punta Perro (Late Oligocene – Early Miocene), showing black color, bright lustre and conchoidal fracture. D) SEM image of the same particle shown in C; notice that the anatomical structure is not discernible. E) Stereomicroscope image of uncharred wood from the Navidad Formation corresponding to Late Oligocene – Early Miocene (4 m asl); notice the brown color, non lustre and fibrous structure. F) SEM image of the same particle shown in E; xylem elements in longitudinal section are discernible, but the cell walls are irregularly degraded.

We found pumice in most samples of Playa Navidad, and low representation of organic matter and coal. Contrastingly, pumice was not recorded in samples from Punta Perro and Cerro Los Pololos, but we found organic matter in both cases. In Punta Perro, we also found coal, which was more abundant than charcoal in this stratigraphic level (Fig. 4). Further, charcoal concentration in the studied stratigraphic levels of the Navidad Formation was positively associated with the presence of pumice for particles >125 μm (Table 1, Fig. 5). A similar pattern was found for charcoal particles >250 μm and >1 mm, but differences were marginally significant ($P < 0.1$; Table 1). For the largest charcoal particles (>1 cm), charcoal concentration did not differ between samples with or without pumice (Table 1). Residuals were normally distributed ($P > 0.05$ in the Shapiro–Wilk test) and the dispersion between groups homogeneous ($P > 0.05$ in the Breusch-Pagan test) for all comparisons, except in the case of the largest particles (>1 cm). However, considering the robustness of the ANOVA test to violations of the normality and homoscedasticity assumptions when the samples size are similar (as in this case; see Table 1), and the P-value obtained (>0.05), the probability of Type I error is very low (Zimmerman, 2004).

From a total of 121 SEM images of charcoal particles analyzed, we found that the highest charring severity was detected in sample S102 (90 m asl), which was the sample with the highest total charcoal concentration (41,699 particles ml^{-1}). The SEM image shows small fissures in the cell walls at the middle lamella (Fig. 6A). Similar modifications of the ultrastructure were detected in sample S99 (105 m asl), the sample with the highest concentration of the largest charcoal particles (>1 cm). In the remaining samples, cell walls are homogenized (i.e., the middle lamella is not discernible) and porous, but not fractured or fissured (Fig. 6B).

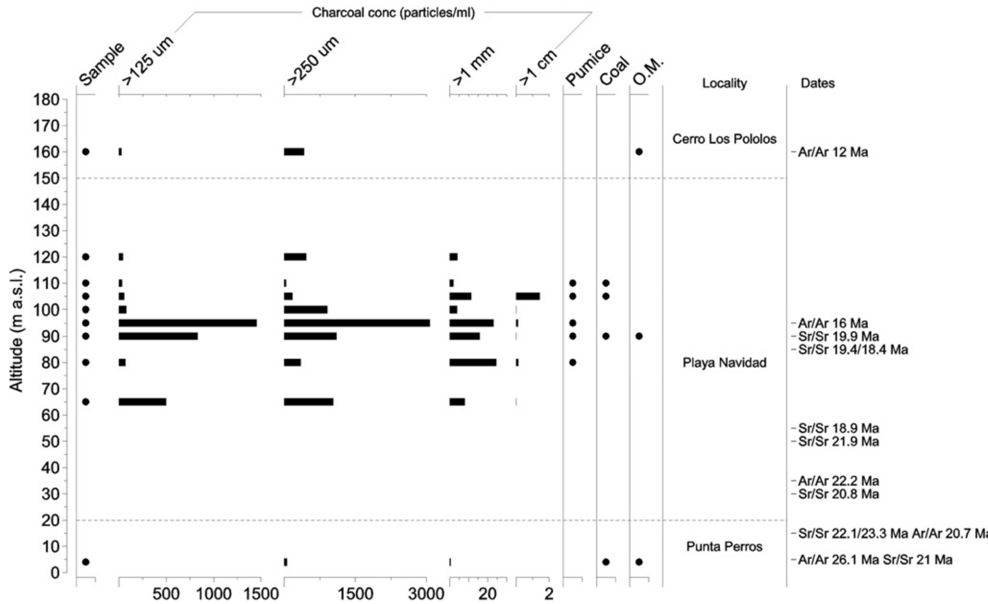

Fig. 4. Average charcoal concentration (particles ml^{-1}) in the studied levels of the Navidad Formation. For each particle size and each elevation (above the present-day sea level), charcoal concentration was averaged. Presence/absence of pumice, coal and organic matter (O.M.) are shown in black dots. Isotopic dates (cf. Gutiérrez, 2011, Gutiérrez et al., 2013) and sampling location are specified.

5. Discussion

5.1. Contribution to the Pre-Quaternary fires database in South America

While Quaternary charcoal has been reported consistently in South America (e.g., Whitlock et al., 2007), pre-Quaternary charcoal records are not frequent. From the Paleozoic, charcoal records in South America are restricted to the Permian, most of them reported at the Paraná Basin, Brazil (Jasper et al., 2013; Manfroi et al., 2015 and references therein). There is some charcoal evidence from the Mesozoic in central western Argentina (Colombi and Parrish, 2008; Mancuso, 2009; Late and Middle Triassic, respectively) and, recently, in the Takutu Basin, north Brazil (dos Santos et al., 2016; Early Cretaceous). Charcoal records are very rare during the Cenozoic in South America, with all occurrences being reported for central Chile. The first Cenozoic charcoal record was described for the Ranquil Formation, located on the Arauco Basin (37°12′S, 73°29′W; Schöning and Bandel, 2004), which is contemporaneous to the Navidad Formation (Finger, 2013). Specifically, a charcoalified wood fragment of an Anacardiaceae was found within volcanoclastic sediment. Burnt wood fragments were also previously reported at the Navidad Formation, within parallel-laminated sandstones, although the levels where they were found were not specified (Encinas et al., 2008). These charcoal particles co-occur with abundant pumice clasts that the authors interpreted as the result of catastrophic pyroclastic flows that were transported from the Andean volcanoes to the coast along paleorivers. Our results point that the Cenozoic charcoal records previously reported in central Chile were not the result of occasional fires, but of multiple fire events occurred in the region during the Miocene.

The scarcity of terrestrial charcoal records over much of the Cenozoic in South America occurs also on a global scale (Bond, 2015). In this sense, it has been proposed that the apparent shortage of terrestrial charcoal records over much of the Cenozoic would be due to a taphonomic bias related to changes in fuel types (from woody to herbaceous; Bond, 2015). However, it probably also reflects the low research effort conducted to identify charcoal particles, traditionally overlooked despite its relevance in paleoenvironmental reconstructions (Scott, 2010; Hamad et al., 2012).

Table 1
ANOVA results evaluating the relationship between charcoal concentration (for each size class) and pumice presence in the studied levels of the Navidad Formation. Charcoal concentration was log-transformed prior to the analysis. From the 25 studied samples, 14 presented pumice.

	df	*SS*	*MS*	*F*	*P*
Charcoal > 125 μm					
Pumice	1	10.40	10.40	8.34	0.008
Residuals	23	28.70	1.25		
Explained variance (%)		26.60			
Charcoal > 250 μm					
Pumice	1	3.32	3.319	3.15	0.089
Residuals	23	24.21	1.053		
Explained variance (%)		12.06			
Charcoal > 1 mm					
Pumice	1	1.27	1.268	3.78	0.064
Residuals	23	7.73	0.336		
Explained variance (%)		14.10			
Charcoal > 1 cm					
Pumice	1	0.00	0.004	0.26	0.618
Residuals	23	0.32	0.014		
Explained variance (%)		1.10			

5.2. Ignition sources

The tight association between pumice presence and high charcoal concentration suggests that volcanic activity would have provided the ignition source for fire initiation. Actually, a variety of volcanic clasts (pyroclasts, pumice, ash, and scoria) has been previously recorded through the Navidad Formation, indicating high volcanic activity during the Neogene (Encinas et al., 2008; Gutiérrez, 2011). In fact, the Navidad Formation is located in the south edge of the Southern flat-slab region of the Nazca plate that was distinguished by high volcanic activity during the Oligocene and Early Miocene. This volcanic activity decreased through the Miocene, being nearly nil by 10 Ma (Gregory-Wodzicki, 2000).

The absence of charcoalified logs and large trunks in the area (Gutiérrez, pers. obs.) indicates that the charcoal was not originated by lavas, which entombed vegetation, but by wildfires ignited by volcanic activity (Scott, 2010). Accordingly, explosive eruptions forming abundant (and ardent) pyroclastic flows, such as those that currently occur in our study area, tend to produce viscous lavas that do not spread long distances (Rittmann, 1962; Stern et al., 2007). Therefore, lightning

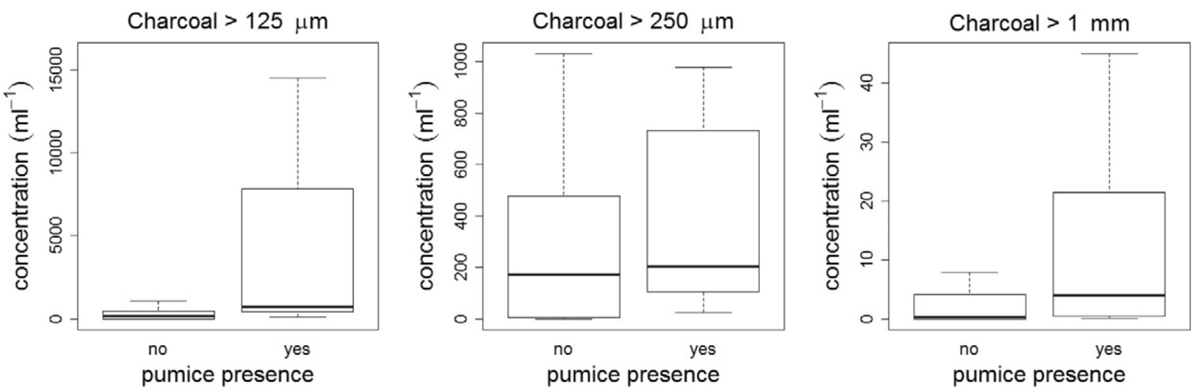

Fig. 5. Boxplot of charcoal concentration (by particle size class) in relation to pumice presence. Only the size classes with significant differences between groups ($P < 0.1$) are shown. Samples from Punta Perro, Playa Navidad and Cerro Los Pololos were pooled. Note differences in y-axis scale.

strikes, pyroclastic flows and/or the high temperatures reached during eruptions could have generated wildfires, similar to those occurring currently in different regions worldwide (Kozlowski and Ahlgren, 1974; Blong, 1984; Tunison et al., 2000; Pausas, 2016), including Chile (Fuentes and Espinosa, 1986).

Regarding lightning-initiated fires, it has been proposed that they were more frequent during the Middle Miocene in central Chile, when a smaller Andes range did not block the convective summer thunderstorms that develop east of the mountain range, as currently do (Keeley et al., 2012). Multiple proxies of elevation (oxygen isotopic composition, Δ_{47} isotopologs, and fossil leaf physiognomy) indicate that the central Andean plateau reached no more than half of its present elevation between ca. 25 and 10 Ma (up to 2.3 km; Garzione et al., 2008). Similarly, towards the southern part of the central Andes (28°–33°30′S), the mountain range had only two thirds of the current elevation between 24 and 16 Ma (35–40 km), as indicated by the geochemical analyses of volcanic rocks, particularly the relationship between light and heavy rare earth elements (Gregory-Wodzicki, 2000, and references therein). However, simulation studies on the evolution of the Andean topography do not fully support the existence of summer thunderstorms in central Chile during the Miocene (Garreaud et al., 2010). Particularly, such experiments suggest that the Andean uplift had little effect on the summer rainfall for the west coast of subtropical South America, but it was a key factor in extending convective precipitation over the Amazon Basin.

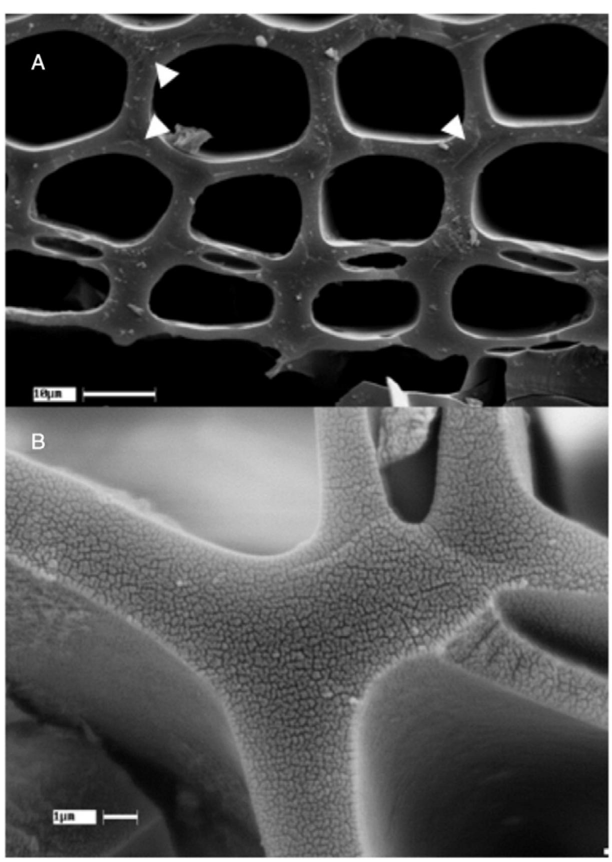

Fig. 6. SEM images of charcoal particles from the Navidad Formation. A) Detail of homogenized cell walls with slightly cracking along the middle lamella (arrows), suggesting very high charring severity. B) Detail of a homogenized and porous cell wall.

In addition, no fossil evidence of lightning (i.e., fulgurites, tubes of glasses formed by the rapid heating of the soil by a cloud-to-ground lightning strike; Pasek et al., 2012) has been reported for the Navidad Formation. However, we are aware that while the number of potential fulgurite-forming events is considered high globally, they are very rare in the geological record (Pasek and Block, 2009). Overall, there is not much evidence that allows us to determine the effect of the orogeny of the Andes in the lightning regime during the Miocene.

5.3. Spatial resolution and charring severity

Traditionally, charcoal size has been considered as a proxy for the accuracy in the spatial scale of fire inference. Microscopic charcoal (<1 mm cf. Scott, 2010) is easily wind-blown and transported far away from the burnt area. Consequently, the presence of microscopic charcoal only permits the inference of fire activity at a regional scale (Whitlock and Larsen, 2001). On the other hand, peaks of macroscopic charcoal (>1 mm cf. Scott, 2010) provide a record of local fires, at least for isolated basins (Clark, 1990; Whitlock and Larsen, 2001). The fact that most charcoal particles found in Playa Navidad corresponded to the smallest size classes (up to 1 mm) suggests that the charcoal record from this locality reflects regional fire data. In addition, some charcoal particles (even the macroscopic ones) could have been transported by water long distances, considering that the fusion of cell walls inhibits water penetration, thus increasing buoyancy (Vaughan and Nichols, 1995). Nevertheless, the concentration of the largest charcoal particles (>1 cm) was unrelated to pumice presence (Table 1), suggesting that other ignitions sources, such as occasional thunderstorm-initiated lightning, rockslides or spontaneous ignition, would be responsible for local wildfires that produced such large charcoal particles.

However, particle size would be more related to fire temperature than to transport. Specifically, the higher the charring temperature, the higher the charcoal brittleness (Belcher et al., 2005; McParland et al., 2007). Therefore, charcoal formed at high temperatures tends to break more easily during transport or burial, leading to smaller particles (Scott, 2010). In this sense, the homogenized cell walls in most of the charcoal particles studied by SEM suggest charring temperatures between 300 and 400 °C, a temperature range in which the charcoal begins to break apart (Jones and Chaloner, 1991; Vaughan and Nichols, 1995; McParland et al., 2007). The scarcity of very large charcoal particles (>1 mm) also give some support to the hypothesis of high fire severity, since fires charring at high temperatures tend to consume most of the aboveground biomass, including coarse fuel (Scott, 2010). Similarly, the fact that we found no charred herbaceous tissues suggests high charring temperatures (e.g., McParland et al., 2007). Therefore, the abundant microscopic charcoal found in Playa Navidad would not only reflect fires that occurred somewhere in the region, but also breakage (during transport and burial) of macroscopic charcoal formed at 300 °C or higher (Scott, 2010 and references therein).

Overall, the size and ultrastructure of the charcoal particles from Playa Navidad do not permit us to accurately determine the spatial scale of the fires. However, the volcanic sediments at the Navidad Formation allow us to make some inferences. Particularly, despite the observance of fine-grained pumice co-occurring with charcoal, there were no pumice-fall deposits, suggesting that the eruptions that likely triggered the fires did not directly affect the study site, but likely both pumice and charcoal traveled by wind or water transport to the catchment area (Rittmann, 1962). A similar hypothesis was proposed by Encinas et al. (2008) to explain charcoal and pumice co-occurrence at the Navidad Formation (see above). In any case, the uncertainty regarding the spatial resolution of fire reconstruction does not rule out our principle finding, that is, the presence of abundant Neogene charcoal in central Chile.

5.4. Fire activity during the Early to Middle Miocene

The Navidad Formation charcoal record documents natural fires occurring between 26.1 and 12.87 Ma in central Chile. Our quantitative charcoal analysis suggest a maximum in fire activity in the transition from Early to Middle Miocene, concomitant with the global warming event described between 17 and 15 Ma (Mid-Miocene Climatic Optimum, MMCO; Zachos et al., 2001). Regionally, this time span coincides with an increase of continental temperatures between 6 and 9 °C, as indicated by physiognomic analysis in the fossil flora of central Chile (Hinojosa and Villagrán, 2005; Hinojosa et al., 2015). In addition, changes in the topography and the oceanic circulation also led to annual seasonality in precipitation at this time (Hinojosa and Villagrán, 1997; Garreaud et al., 2010). Particularly, the Andes likely started to block moisture brought from the Amazon basin by eastern winds during summer, whereas the reinforcement of the Humboldt Current produced the northwards displacement of the subtropical south Pacific anticyclone in winter, permitting moist westerly winds to reach the Pacific coast of south-central Chile (Aceituno, 1988; Lenters and Cook, 1995; Insel et al., 2010). Under such warm conditions and an annual rainfall regime, fuel flammability likely increased during the dry season. Furthermore, the increased fire activity recorded in Playa Navidad is chronologically related to high volcanic activity in the area, as suggested by the higher charcoal concentration for samples with pumice (Figs. 4 and 5). In summary, the concurrence of abundant fuel, as a result of the warm and humid climate conditions during the growing season, the high fuel flammability during the warm and dry summers, and the frequent volcanic activity in the area, provide the perfect scenario for the spreading of wildfires during the MMCO.

The relative absence of charcoal in Punta Perro (Late Oligocene–Early Miocene) could be explained by the prevailing climatic conditions in southern South America since the Oligocene until the beginning of the Miocene (temperate and humid; Hinojosa and Villagrán, 2005; Hinojosa et al., 2015). At this time, the vegetation was composed of Antarctic-Australasian and Neotropical elements with a high affinity to the current temperate rainforest in southern South America (Troncoso, 1991; Troncoso and Romero, 1993; Hinojosa and Villagrán, 1997; Hinojosa et al., 2015). The current analogous vegetation, which develops under similar climatic conditions in central-south Chile, also shows very low fire activity, because fires are limited by the high-fuel moisture (Holz et al., 2012). Similarly, the scarce evidence of fires in Cerro Los Pololos (late Middle Miocene) could be explained climatically, and particularly by the decrease in global temperature (Zachos et al., 2001), that could diminish plant growth and/or flammability. Coupled to such changes in climate, our data confirm the reduction of volcanic activity in central Chile towards the end of Middle Miocene (Fig. 6), associated with changes in the subduction slope of the Nazca plate since ca. 20 Ma that virtually suppressed andesitic volcanism by 10 Ma (Gregory-Wodzicki, 2000).

Despite the fact that changes in fire activity documented through our charcoal record can be successfully explained by changes in climate, vegetation and ignition sources over time, we are aware that differences in the charcoal record between the studied localities can be also explained by differences in the facies. The lithology at Punta Perro is composed of gravel and granite pebbles, whereas alternating levels of middle to fine sandstones and mudrock lenses constitute the lithology at the upper level of the Navidad Formation (sensu Gutiérrez et al., 2013), which includes both Playa Navidad and Cerro Los Pololos (Gutiérrez, 2011; Gutiérrez et al., 2013). Independent of whether they were deposited in a middle bathyal continental slope or in a deltaic deposit with high horizontal variability (see “Geological and paleontological settings” for details), Punta Perro corresponds to a different facie than Playa Navidad or Cerro Los Pololos. Therefore, charcoal deposition and preservation could potentially differ between localities, not only due to changes in the fire drivers (climate, vegetation and ignitions sources) over time, but also due to changes in the depositional environment. However, the most interesting changes in charcoal concentration were observed within the samples collected at Playa Navidad (Fig. 6), all of them corresponding to the same facie (Gutiérrez, 2011).

6. Conclusions

From the Navidad Formation charcoal record obtained in the present study we can draw the following conclusions:

- Our results document the first quantitative charcoal record from the Cenozoic in South America contributing to extend the pre-Quaternary fire database.
- Wildfires recurrently occurred in central Chile, coinciding with the global warming event reported between 17 and 15 Ma (Mid-Miocene Climate Optimum; MMCO).
- The concurrence of warm conditions, high seasonality in precipitation and very active volcanism likely explains the high fire activity recorded at Playa Navidad (Early to Middle Miocene).

Charcoal records in Navidad Formation indicate that despite the virtual absence of non-anthropogenic fires in central Chile at present, wildfires should be taken into account to evaluate the evolutionary drivers of many of the lineages currently occurring in this region considering that they are relicts from Neogene lineages, evolving at a time when the region was frequently on fire.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.palaeo.2016.06.036.

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References

Aceituno, P., 1988. On the functioning of the Southern Oscillation in the South American sector. Part I: Surf. Clim. Mon. Wea. Rev. 116, 505–524.
Batllori, L.E., Parisien, M.A., Krawchuk, M.A., Moritz, M.A., 2013. Climate change-induced shifts in fire for Mediterranean ecosystems. Glob. Ecol. Biogeogr. 22, 1118–1129.
Belcher, C., Collinson, M., Scott, A., 2005. Constraints on the thermal energy released from the Chicxulub impactor: new evidence from multi-method charcoal analysis. J. Geol. Soc. 162, 591–602.
Blong, R.J., 1984. Volcanic Hazards: A Sourcebook on the Effects of Eruptions. Academic Press, Sydney.
Bradshaw, S.D., Dixon, K.W., Hopper, S.D., Lambers, H., Turner, S.R., 2011. Little evidence for fire-adapted plant traits in Mediterranean climate regions. Trends Plant Sci. 16, 69–76.
Bond, W.J., 2015. Fires in the Cenozoic: a late flowering of flammable ecosystems. Front. Plant Sci 5, 1–11.
Cecioni, G., 1980. Darwin's Navidad embayment, Santiago region, Chile, as a model of the southeastern Pacific shelf. J. Pet. Geol. 2, 309–321.
Clark, J.S., 1990. Fire and climate change during the last 750 yr in northwestern Minnesota. Ecol. Monogr. 60, 135–159.
Colombi, C.E., Parrish, J.T., 2008. Late Triassic environmental evolution in southwestern Pangea: plant taphonomy of the Ischigualasto Formation. PALAIOS 23, 778–795.
Darwin, C., 1846. Geological observations on South America. Being the third part the geology of the voyage of the Beagle, under command of Capt. Fitzroy, R.N. during the years 1832 to 1836. Smith, Elder and Co., London.
dos Santos, Â.C.S., Holanda, E.C., de Souza, V., Guerra-Sommer, M., Manfroi, J., Uhl, D., Jasper, A., 2016. Evidence of palaeo-wildfire from the upper lower cretaceous (Serra do Tucano Formation, Aptian–Albian) of Roraima (North Brazil). Cretac. Res. 57, 46–49.
Encinas, A., 2006. Estratigrafía y sedimentología de los depósitos marinos mio–pliocenos del área de Navidad (33°00′–34°30′S), Chile Central. Implicaciones con respecto a la tectónica del antearco. Universidad de Chile, Santiago, Chile.
Encinas, A., Le Roux, J.P., Buatois, L.A., Nielsen, S.N., Finger, K.L., Fourtanier, E., Lavenu, A., 2006. Nuevo esquema estratigráfico para los depósitos marinos mio-pliocenos del área de Navidad (33°00′-34°30′S), Chile central. Rev. Geol. Chile 33, 221–246.
Encinas, A., Finger, K.L., Nielsen, S.N., Lavenu, A., Buatois, L.A., Peterson, D.E., Le Roux, J.P., 2008. Rapid and major coastal subsidence during the late Miocene in south-central Chile. J. S. Am. Earth Sci. 25, 157–175.
Finger, K.L., 2013. Miocene foraminifera from the south-central coast of Chile. Micropaleontology 59, 341–492.
Finger, K.L., Nielsen, S.N., DeVries, T.J., Encinas, A., Peterson, D.E., 2007. Paleontologic evidence of sedimentary displacement in Neogene forearc basins of central Chile. PALAIOS 22, 3–16.
Finger, K.L., Encinas, A., Nielsen, S.N., 2013. Comment on 'evidence for an Early-Middle Miocene age of the Navidad Formation (central Chile): Paleontological, paleoclimatic and tectonic implications' of Gutiérrez et al. (2013, Andean Geology 40 (1): 66–78). Andean Geol. 40, 571–579.
Fuentes, E.R., Espinosa, G., 1986. Resilience of shrublands in central Chile: a volcanism-related hypothesis. Interciencia 11, 164–165.
Garreaud, R.D., Molina, A., Farias, M., 2010. Andean uplift, ocean cooling and Atacama hyperaridity: a climate modeling perspective. Earth Planet. Sci. Lett. 292, 39–50.
Garzione, C.N., Hoke, G.D., Libarkin, J.C., Withers, S., MacFadden, B., Eiler, J., Ghosh, P., Mulch, A., 2008. Rise of the Andes. Science 320, 1304–1307.
Gregory-Wodzicki, K.M., 2000. Uplift history of the Central and Northern Andes: a review. Geol. Soc. Am. Bull. 112, 1091–1105.
Gutiérrez, N.M., 2011. Diversidad y cambios florísticos durante el Mioceno en Chile central. Facultad de Ciencias. Universidad de Chile, Santiago, Chile, p. 71.
Gutiérrez, N.M., Hinojosa, L.F., Le Roux, J.P., Pedroza, V., 2013. Evidence for an Early-Middle Miocene age of the Navidad Formation (central Chile): Paleontological, paleoclimatic and tectonic implications. Andean Geol. 40, 66–78.
Gutiérrez, N., Pedroza, V., Hinojosa, L.F., 2009. Edad de la Formación Navidad: Nuevos antecedentes para un viejo problema, XII Congreso Geológico Chileno. N°12, Actas 2: 10–18, Santiago (Chile). pp. 10–18.
Hamad, A.M.A., Jasper, A., Uhl, D., 2012. The record of Triassic charcoal and other evidence for palaeo-wildfires: signal for atmospheric oxygen levels, taphonomic biases or lack of fuel? Int. J. Coal Geol. 96, 60–71.
Hervé, F., Munizaga, F., Parada, M., Brook, M., Pankhurst, R., Snelling, N., Drake, R., 1988. Granitoids of the Coast Range of central Chile: geochronology and geologic setting. J. S. Am. Earth Sci. 1, 185–194.
Heusser, C., 1990. Ice age vegetation and climate of subtropical Chile. Palaeogeogr. Palaeoclimatol. Palaeoecol. 80, 107–127.
Hinojosa, L.F., Armesto, J.J., Villagrán, C., 2006. Are Chilean coastal forests pre Pleistocene relicts? Evidence from foliar physiognomy, palaeoclimate, and phytogeography. J. Biogeogr. 33, 331–341.
Hinojosa, L.F., Pérez, F., Gaxiola, A., Sandoval, I., 2011. Historical and phylogenetic constraints on the incidence of entire leaf margins: insights from a new South American model. Glob. Ecol. Biogeogr. 20, 380–390.
Hinojosa, L.F., Pérez, M.F., Rougier, D., Armesto, J., 2015. Flora y Vegetación de bosques de Chile: Legado histórico-biogeográfico. In: Montecinos, V., Orlando, J. (Eds.), Ciencias Ecológicas 1983–2013. Treinta años de investigaciones chilenas. Editorial Universitaria, Santiago, pp. 123–138.
Hinojosa, L.F., Villagrán, C., 1997. Historia de los bosques del sur de Sudamérica. I. Antecedentes paleobotánicos, geológicos y climáticos del Terciario del cono sur de América. Rev. Chil. Hist. Nat. 70, 225–239.
Hinojosa, L.F., Villagrán, C., 2005. Did South American Mixed Paleofloras evolve under thermal equability or in the absence of an effective Andean barrier during the Cenozoic? Palaeogeogr. Palaeoclimatol. Palaeoecol. 217, 1–23.
Holz, A., Kitzberger, T., Paritsis, J., Veblen, T.T., 2012. Ecological and climatic controls of modern wildfire activity patterns across southwestern South America. Ecosphere 3, art103.
Insel, N., Poulsen, C.J., Ehlers, T.A., 2010. Influence of the Andes Mountains on South American moisture transport, convection, and precipitation. Clim. Dyn. 35, 1477–1492.
Jasper, A., Guerra-Sommer, M., Hamad, A.M.A., Bamford, M., Bernardes-de-Oliveira, M.E.C., Tewari, R., Uhl, D., 2013. The burning of Gondwana: Permian fires on the southern continent—a palaeobotanical approach. Gondwana Res. 24, 148–160.
Jones, T.P., Chaloner, W.G., 1991. Fossil charcoal, its recognition and palaeoatmospheric significance. Glob. Planet. Chang. 5, 39–50.
Keeley, J.E., Bond, W.J., Bradstock, R.A., Pausas, J.G., Rundel, P.W., 2012. Fire in Mediterranean Ecosystems: Ecology, Evolution and Management. Cambridge University Press.
Kozlowski, T.T., Ahlgren, C.E., 1974. Fire and Ecosystems. Academic Press, New York.
Le Roux, J.P., Gutiérrez, N.M., Hinojosa, L.F., Pedroza, V., Becerra, J., 2013l. Reply to comment of Finger et al. (2013) on: 'evidence for an Early-Middle Miocene age of the Navidad Formation (Central Chile): Paleontological, Paleoclimatic and Tectonic implications' of Gutiérrez et al.(2013, Andean Geology 40 (1): 66–78). Andean Geol. 40, 580–588.
Lenters, J.D., Cook, K., 1995. Simulation and diagnosis of the regional summertime precipitation climatology of South America. J. Clim. 8, 2988–3005.
Lloret, F., Verdú, M., Flores-Hernández, N., Valiente-Banuet, A., 1999. Fire and resprouting in mediterranean ecosystems: insights from an external biogeographical region, the mexical shrubland. Am. J. Bot. 86, 1655–1661.
Mancuso, A.C., 2009. Taphonomic analysis in lacustrine environments: two different contexts for Triassic lake paleofloras from Western Gondwana (Argentina). Sediment. Geol. 222, 149–159.
Manfroi, J., Uhl, D., Guerra-Sommer, M., Francischini, H., Martinelli, A.G., Soares, M.B., Jasper, A., 2015. Extending the database of Permian palaeo-wildfire on Gondwana: charcoal remains from the Rio do Rasto Formation (Paraná Basin), Middle Permian, Rio Grande do Sul State, Brazil. Palaeogeogr. Palaeoclimatol. Palaeoecol. 436, 77–84.
Martínez-Pardo, R., 1990. Major Neogene events of the Southeastern Pacific: the Chilean and Peruvian record. Palaeogeogr. Palaeoclimatol. Palaeoecol. 77, 263–278.
McParland, L.C., Collinson, M.E., Scott, A.C., Steart, D.C., Grassineau, N.V., Gibbons, S.J., 2007. Ferns and fires: experimental charring of ferns compared to wood and implications for paleobiology, paleoecology, coal petrology, and isotope geochemistry. PALAIOS 22, 528–538.
Melnick, D., Echtler, H.P., 2006. Inversion of forearc basins in south-central Chile caused by rapid glacial age trench fill. Geology 34, 709–712.
Montenegro, G., Gómez, M., Díaz, F., Ginocchio, R., 2003. Regeneration potential of Chilean matorral after fire: an updated view. In: Veblen, T.T., Baker, W.L., Montenegro, G., Swetnam, T.W. (Eds.), Fire and Climatic Change in Temperate Ecosystems of the Western Americas. Springer New York, New York, pp. 375–403.
Nielsen, S.N., Glodny, J., 2006. The Middle Miocene Climate Optimum in Central and Southern Chile: 87Sr/86Sr Isotope Stratigraphy on Warm-Water Mollusks, XI Congreso Geológico Chileno. N° 11, Actas 2: 93–96, Antofagasta (Chile). pp. 93–96.
Nielsen, S.N., Glodny, J., 2009. Early Miocene subtropical water temperatures in the southeast Pacific. Palaeogeogr. Palaeoclimatol. Palaeoecol. 280, 480–488.
Pasek, M., Block, K., 2009. Lightning reduction of phosphate: implications for phosphorus biogeochemistry. Nat. Geosci. 2, 553–556.
Pasek, M.A., Block, K., Pasek, V., 2012. Fulgurite morphology: a classification scheme and clues to formation. Contrib. Mineral. Petrol. 164, 477–492.
Pausas, J.G., 2016. Flammable Mexico. Int. J. Wildland Fire 25, 711–713.
Pausas, J.G., Keeley, J.E., 2009. A burning story: the role of fire in the history of life. Bioscience 59, 593–601.
Pyne, S.J., Andrews, P.L., Laven, R.D., 1996. Introduction to Wildland Fire. John Wiley and Sons, New York.
Rittmann, A., 1962. Volcanoes and Their Activity. Interscience Publishers, New York.
Sanhueza, L., Cornejo, L., Falabella, F., 2007. Patrones de asentamiento en el período Alfarero Temprano de Chile Central. Chungará Rev. Antropol. Chil. 39, 103–115.
Schöning, M., Bandel, K., 2004. A diverse assemblage of fossil hardwood from the Upper Tertiary (Miocene?) of the Arauco Peninsula, Chile. J. S. Am. Earth Sci. 17, 59–71.
Scott, A.C., 2010. Charcoal recognition, taphonomy and uses in palaeoenvironmental analysis. Palaeogeogr. Palaeoclimatol. Palaeoecol. 291, 11–39.
Stern, C., Moreno, H., López-Escobar, L., Clavero, J., Lara, L., Naranjo, J., Parada, M., Skewes, M., 2007. Chilean volcanoes. In: Moreno, T., Gibbons, W. (Eds.), The Geology of Chile. The Geological Society, London, pp. 149–180.
Suárez, M.E., Encinas, A., Ward, D., 2006. An early Early Miocene elasmobranch fauna from the Navidad Formation, central Chile. S. Am. Cainozoic Res. 4, 3–18.
Troncoso, A., 1991. Paleomegaflora de la Formación Navidad, Miembro Navidad (Mioceno), en el área de Matanzas, Chile central occidental. Museo Nacional de Historia Natural de Chile, Boletín 42, 131–168.
Troncoso, A., Romero, E.J., 1993. Consideraciones acerca de las coníferas del mioceno de Chile Central Occidental. Bol. Mus. Nac. Hist. Nat. Chile 44, 47–71.
Tunison, J., D'Antonio, C., Loh, R., 2000. Fire and Invasive Plants in Hawai'i Volcanoes National Park. Proceedings, Invasive Plant Workshop: The Role of Fire in the Control and Spread of Invasive Species. Fire Conference, pp. 122–131.
Valiente-Banuet, A., Flores-Hernández, N., Verdú, M., Dávila, P., 1998. The chaparral vegetation in Mexico under nonmediterranean climate: the convergence and Madrean-Tethyan hypotheses reconsidered. Am. J. Bot. 85, 1398–1408.

Vaughan, A., Nichols, G., 1995. Controls on the deposition of charcoal: implications for sedimentary accumulations of fusain. J. Sediment. Res. 65, 129–135.
Villa-Martínez, R., Villagrán, C., Jenny, B., 2003. The last 7500 cal yr BP of westerly rainfall in Central Chile inferred from a high-resolution pollen record from Laguna Aculeo (34° S). Quat. Res. 60, 284–293.
Villagrán, C., Hinojosa, L.F., 1997. Historia de los bosques del sur de Sudamérica, II: Análisis fitogeográfico. Rev. Chil. Hist. Nat. 70, 1–267.
Whitlock, C., Larsen, C., 2001. Charcoal as a fire proxy. In: Smol, J.P., H.J.B.·Birks, Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 75–97.
Whitlock, C., Moreno, P.I., Bartlein, P., 2007. Climatic controls of Holocene fire patterns in southern South America. Quat. Res. 68, 28–36.
Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292, 686–693.
Zimmerman, D.W., 2004. A note on preliminary tests of equality of variances. Br. J. Math. Stat. Psychol. 57, 173–181.