

Late Paleocene leaf macroflora from a destroyed outcrop of the Marcelina Formation, Paso Diablo Mine, Venezuela: a rescue record

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Abstract

In 2016, a production blast at a mining face of the Paso Diablo Mine (Guasare Basin, northwestern Venezuela) exposed a level rich in fossil leaves of the Marcelina Formation (late Paleocene), located between coal seams 4O and 4M. The material was removed as overburden by a mining shovel a few hours after it was documented. We present the first published record of leaf macroflora from this formation at the mine, based on 25 blocks recovered from the blast debris (27 leaves or fragments) and 8 photographic records of unrecovered specimens documented at the mine face. The leaves are preserved in two facies: carbonaceous shales with leaves accumulated as leaf litter, and massive sandstones with scattered leaves and woody debris. These facies are interpreted as recording a low-energy swamp plain interrupted by a higher-energy event that rapidly buried the leaf litter, between two long-lived peat-forming episodes. Six informal morphotypes are recognized on the basis of leaf architecture, without assignment to family. Elliptic pinnate leaves predominate, followed by broad leaves with numerous straight, parallel secondary veins; a leaf with palmate venation, a small lamina, a leaf with ascending secondaries and monocot remains are also recorded. All laminae with an observable margin are entire. Some leaves show perforations, marginal notches and areas lacking the carbonaceous film that are compatible with insect damage, although they could also result from the blast or from diagenetic processes. The paleoflora is consistent with that of the Cerrejón Formation, ~43 km away on the other side of the Sierra de Perijá, and a resemblance of the broad leaves to *Menispermites guajiraensis*, limited to the pattern of the secondary veins, is proposed as a hypothesis. Photographs and specimen metadata are available on Zenodo.

Keywords: Paleocene; Marcelina Formation; Guasare Basin; Venezuela; fossil leaves; leaf architecture; taphonomy; rescue paleontology; Cerrejón.

1. Introduction

The history of terrestrial vegetation spans about 470 million years: from the first plants that colonized the land during the Ordovician, through the diversification of vascular plants in the Silurian, the appearance of the first forests in the Devonian, the spread of the extensive swamp forests of the Carboniferous and the dominance of gymnosperms, particularly conifers, during much of the Mesozoic, to the expansion of angiosperms in the Cretaceous. In this context, the Cretaceous–Paleogene (K–Pg) boundary event marked the last major turning point in the history of continental floras. At a global scale, however, the response of vegetation was not uniform. In the Northern Hemisphere, particularly in North America, the initial recolonization of disturbed landscapes was dominated by ferns, a phenomenon known as the "fern spike" (Tschudy et al., 1984), a pattern also recorded in New Zealand (Vajda et al., 2001). In Patagonia, by contrast, the palynological record shows a marked drop in diversity but low extinction rates and a post-boundary predominance of conifers of the family Cheirolepidiaceae (Barreda et al., 2012), suggesting that southern high latitudes acted as floristic refugia, although macrofloral records nonetheless indicate significant species-level extinction (Stiles et al., 2020). In northern South America, the event reduced plant diversity by about 45%, and recovery was a prolonged process that took about 6 million years, giving rise to forests very different in composition and structure from those of the Cretaceous, characterized by the dominance of angiosperms, an increase in legumes, a marked reduction of conifers in the lowlands and the development of more closed and stratified canopies. These features laid the foundations of present-day Neotropical rainforests (Carvalho et al., 2021).

Paleocene paleobotanical records from northern South America therefore offer a privileged window into how vegetation recovered and reorganized after the K–Pg extinction, and how Neotropical rainforests, today the most diverse terrestrial ecosystems on the planet, originated. The best known of these paleofloral records is that of the Cerrejón Formation, in La Guajira, Colombia, regarded as the oldest evidence of a Neotropical rainforest (Wing et al., 2009). This formation and the Marcelina Formation, in the Guasare Basin, have been correlated with the Cuervos Formation of the Cesar sub-basin (Ayala-Calvo et al., 2009), and their sandstones show similar petrofacies, although those of the Marcelina Formation contain more carbonate fragments (Bayona et al., 2007). However, the paleoflora of this same Paleocene coastal plain in the Venezuelan sector, in the Guasare Basin, remains virtually undocumented from macrofossils.

At the Paso Diablo Mine, ~43 km east of Cerrejón, coal mining in the Marcelina Formation periodically exposes levels with plant remains that are removed without documentation. In 2016, one of these levels was exposed by a blast and was documented and partially rescued by the author a few hours before its removal.

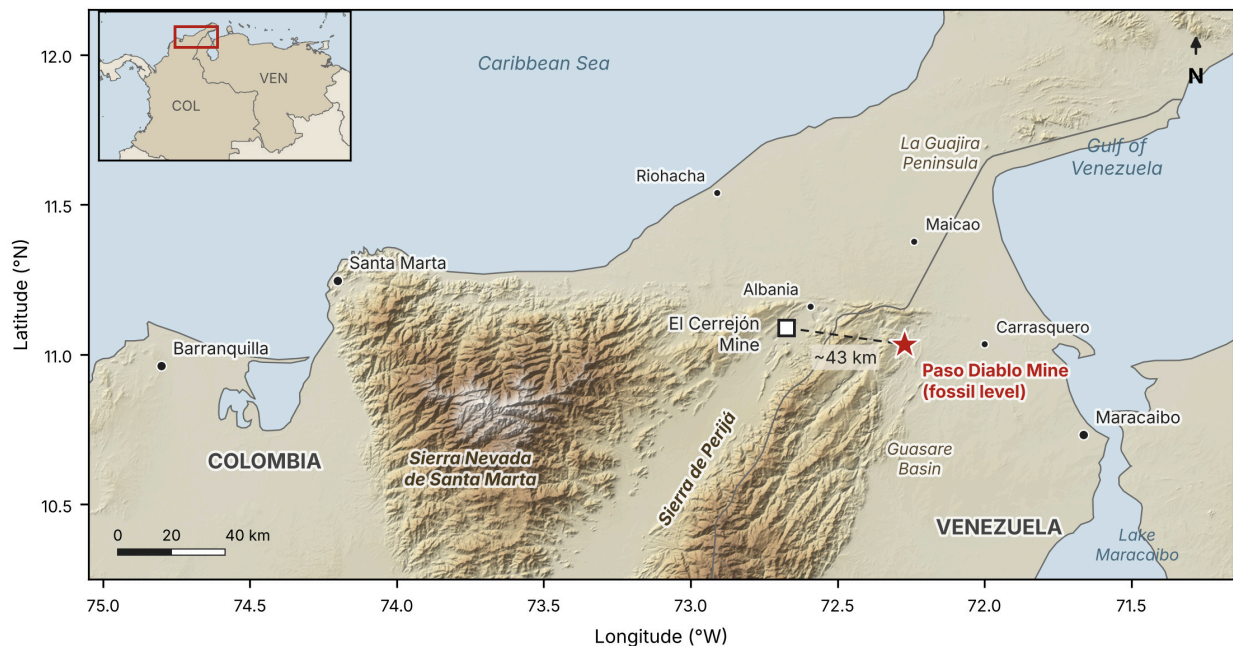
The aims of this work are (1) to document the stratigraphic and taphonomic context of the fossil-bearing level; (2) to describe the leaf morphotypes recognizable in the rescued material and in the field photographic records; and (3) to compare them preliminarily with the paleoflora of the Cerrejón Formation.

2. Geological setting

2.1 Location. The Paso Diablo Mine is an open-pit coal mine located in Mara Municipality, Zulia State, northwestern Venezuela, in the Guasare Basin, approximately 43 km east of the El Cerrejón Mine (La Guajira, Colombia) (Fig. 1).

2.2 Marcelina Formation. Coal at the mine is extracted from the Marcelina Formation, of late Paleocene age (Hackley & Martínez, 2007). The unit consists of gray micaceous and carbonaceous sandstones interbedded with dark gray to black shales, numerous coal seams and, locally, siltstones, sandy limestones and red siliceous porcellaneous shales (Sutton, 1946; L xico Estratigr fico de Venezuela, 1997). It conformably overlies the Guasare Formation and is unconformably overlain by Eocene sandstones of the Misoa Formation, and it reaches about 540 m in thickness along the Guasare River. Its coals accumulated in raised, rain-fed peat mires isolated from clastic input, in a foreland basin whose relatively slow subsidence is associated with the advance of the Lara nappes during the oblique collision between the Caribbean and South American plates (Hackley & Mart nez, 2007).

2.3 Fossil-bearing level. The material comes from an interval approximately 15 m thick, located between coal seams 4M (8.45 m) and 4O (3.65 m; thicknesses in well PBN-134, according to Carbones del Zulia, 2014, in Montiel, 2014), at the base of the coal-bearing sequence mined at the site (~200 m thick, seams 4 to 9), within the middle part of the Marcelina Formation (Fig. 2). The interval consists mainly of shales interbedded with coal layers, siltstones and fine- to medium-grained sandstone beds of variable thickness and alternation, among which there is a thicker, competent bed of gray, massive and dense, fine- to medium-grained sandstone. The level was exposed in a faulted transition pit of panel T7, between elevations -48 and -60 m a.s.l. The fossil area, of about 700 m², is centered at UTM zone 18N E 798,142, N 1,221,037 (WGS84; 11.0334 N, 72.2715 W); these coordinates were obtained in the field with surveying instruments and later checked in the mine planning software (Mincom MineScope). The level was removed by the shovel in July 2016, a few hours after it was documented.



Relief: Copernicus GLO-30 DEM (ESA), via OpenTopography; boundaries: Natural Earth

Fig. 1. Location map of the Paso Diablo Mine (star; center of the fossil area, 11.0334 N, 72.2715 W) and the El Cerrej n Mine (square), ~43 km apart, at the northern end of the Sierra de Perij , which separates the Guasare (Venezuela) and Cesar-Rancher  (Colombia) sedimentary basins. The Sierra Nevada de Santa Marta and the main cities of the region are shown. Inset: location in northern South America. Shaded relief (vertical exaggeration  2, illumination from the northwest) from the Copernicus GLO-30 digital elevation model (European Space Agency, 2021; distributed by OpenTopography), resampled to ~200 m; boundaries and coastlines: Natural Earth (public domain).

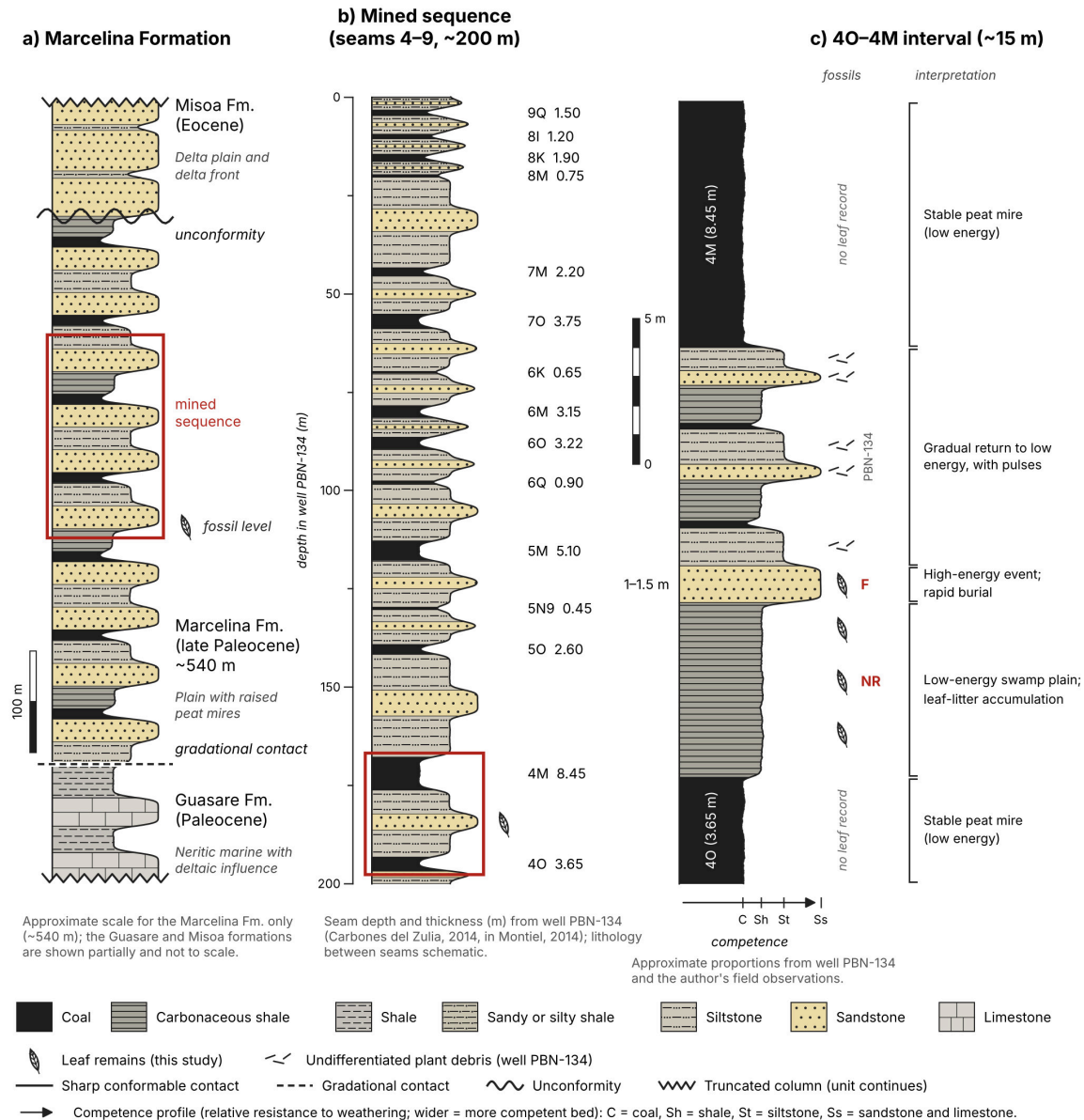


Fig. 2. Stratigraphic columns. (a) Schematic position of the mined sequence and the fossil-bearing level in the middle part of the Marcelina Formation (~540 m; approximate scale), between the Guasare (Paleocene) and Misoa (Eocene, unconformable) formations, with the depositional environment interpreted for each unit: neritic marine with deltaic influence (Guasare; *Léxico Estratigráfico de Venezuela*, 1997), plain with raised peat mires (Marcelina; Hackley & Martínez, 2007), and deltaic plain and front (Misoa; van Veen, 1971). (b) Sequence mined at the Paso Diablo Mine (seams 4–9, ~200 m thick), with the fossil-bearing interval 4O–4M boxed; depth and thickness of the seams according to well PBN-134 (Carbones del Zulia, 2014, in Montiel, 2014); depths approximate, read from the original figure; lithology between seams schematic. (c) Detail of the 4O–4M interval (~15 m), with fossil column and interpretation of environments according to Section 4.4. In the fossil column, NR: non-recovered records in carbonaceous shale; F: recovered specimens in sandstone; undifferentiated plant remains in siltstones and sandstones according to the description of well PBN-134; there is no leaf record in seams 4O and 4M. Approximate proportions according to well PBN-134 and the author's field observation. The width of the beds represents their relative competence (resistance to weathering). Lithologic patterns according to the FGDC standard (USGS, 2006), assigned from the descriptions in the *Léxico Estratigráfico de Venezuela* (1997): coal; carbonaceous shale (pattern 624) in the Marcelina Fm.; shale (620) in the Guasare Fm., whose shales are marine and are not described as carbonaceous; sandy or silty shale (619) in the Misoa Fm., whose shales are "micaceous, sandy to silty"; siltstone (616); sandstone (607); limestone (627). In panel a, only the Marcelina Fm. is at approximate scale; only the upper part of the Guasare Fm. (limestones and shales) is shown, and only the base of the Misoa Fm., beginning with a sandstone body (the contact is placed below the lowest composite sandstone; *Léxico Estratigráfico de Venezuela*, 1997), both without scale and with a zigzag cut (truncated column). Contacts: gradational between Guasare and Marcelina (dashed line; *Léxico Estratigráfico de Venezuela*, 1997), unconformable between Marcelina and Misoa (wavy line), and sharp conformable within Marcelina (solid line). Format of scale bars and interpretation column after Doria et al. (2008).

3. Material and methods

3.1 Discovery and recovery of the material. The fossil-bearing level was discovered in July 2016 by the author, then Drilling and Blasting Supervisor of the operation, during the routine inspection of rock fragmentation after the blast of a mining face, prior to loading of the material with a P&H electric rope shovel. According to personnel with long experience at the mine, leaf remains had occasionally been observed in previous blasts but were never documented, because continuity of production took priority (A. Alvarado, pers. comm.). Abundant carbonized leaf impressions were observed among the fragmented blocks. Within a few hours, before the material was removed by the electric rope shovel as overburden above coal seam 4O, the author photographed in the field, at the mine face after the blast, the largest or non-transportable specimens, and collected from the blast debris, which was to be hauled away later, those fragments that could be carried by hand because of their size and weight. The material had been fragmented and disturbed by the blast but had not been transported, so it comes from the level exposed at the face. Selection favored specimens with the best visible preservation; the material is therefore not a representative sample of the relative abundance of taxa in the deposit. The recovered specimens come mainly from gray to beige, dense and compact, fine- to medium-grained sandstones, whose competence allowed them to be carried. Specimens preserved in gray, carbonaceous, fissile shales, which are fragile and difficult to extract without breaking, were documented only by photography at the mine face and are designated as non-recovered records (NR). Consequently, the physical collection is biased toward the sandstone facies.

3.2 Transport, preparation and custody. The fragments rescued before being removed or broken up by the electric rope shovel were grouped and selected according to their ease of handling and the space available in the operations vehicle, and taken to the facilities of the Drilling and Blasting department, where they were carefully examined and reduced to hand specimens with hammer and chisel, taking care not to damage the leaf impressions. The specimens were later moved to the author's residence in Venezuela, where they were stored carefully wrapped in layers of paper inside plastic boxes, without alteration or chemical treatment, to preserve their surfaces. Their deposit and preservation in a Venezuelan institutional collection is in progress.

3.3 Photographic documentation. The recovered specimens were photographed on 2 July 2017 by M. Chalita, photojournalist and architect, with his Nikon D3100 digital SLR camera. A photographic set was arranged in the courtyard of the author's residence in Venezuela, with cloth and white card backgrounds, combining sunlight and artificial light. Each specimen was photographed next to a 2 × 2 cm checkerboard scale printed on card, placed in some shots on the table (L-shaped scale) and in others directly on the rock, at the level of the leaf (vertical ruler). Dimensions were measured on the photographs from the included scale and were used to classify leaf size according to the categories of Ellis et al. (2009) and to compare it with the paleoflora of the Cerrejón Formation (Wing et al., 2009). Specimen codes (F- followed by a number, e.g., F-70) correspond to the numbering of the photographic sequence (file Fosiles-70.jpg); some specimens were photographed more than once and received two numbers, so they are recorded with combined codes (e.g., F-46/F-47). The non-recovered records (NR) were photographed by the author at the mine face after the blast, in July 2016, with a mobile phone camera, using as scale an Estwing E3-24BLC flat-tip (chisel-edge) hammer (24 oz head; 28.6 cm overall length according to the manufacturer). All images are available on Zenodo (Solano Nava, 2026; <https://doi.org/10.5281/zenodo.23264877>).

3.4 Description and assignment of morphotypes. In the absence of previous records of fossil macroflora at the mine and of available local specialists, the specimens were described by the author from the photographs, following the leaf architecture characters of Ellis et al. (2009): lamina shape and size, length:width ratio, margin, apex, base, and primary, secondary and tertiary venation

pattern. Measurements were taken on the photographs using the included scale. Specimens with similar combinations of characters were grouped into informal morphotypes (A, C, D, E, F and G). Possible family-level affinities were explored by comparison with published descriptions and figures of Neotropical Paleocene floras, particularly from the Cerrejón Formation (Doria et al., 2008; Herrera et al., 2008; Gómez-Navarro et al., 2009; Wing et al., 2009), and with the present-day vegetation. As a first reference for the latter, the flora inventory of the mine in use in 2016, prepared by its Department of Ecology and Environment as part of the waste-dump reforestation plan (internal, unpublished document), was consulted; it consists of a list of native species recorded in undisturbed areas. Based on that list, photographs and dimension data of herbarium specimens were sought in the online catalog of the United States National Herbarium (US, Smithsonian Institution), against which the venation patterns and dimensions of the morphotypes were compared. Lowland specimens from the region closest to the study area were prioritized: *Nectandra* and *Ocotea* (Lauraceae) and *Annona*, *Duguetia*, *Guatteria*, *Oxandra* and *Xylopia* (Annonaceae) from Zulia State and the Sierra de Perijá; *Abuta*, *Anomospermum*, *Disciphania* and *Odontocarya* (Menispermaceae) from Zulia State, including a specimen of *Disciphania* collected ~13 km from the fossil area, in the Guasare River basin; and *Sterculia apetala* (Malvaceae) from the Colombian Caribbean coast (Table S1). For *Magnolia* and *Talauma* (Magnoliaceae), no specimens were found from Zulia State or from the neighboring Colombian departments (La Guajira, Cesar and Magdalena); the available records come from mountainous regions of central and eastern Venezuela and from the Colombian Andes. As exploratory support, general-purpose artificial intelligence tools with image analysis were used to suggest candidate families; these suggestions were checked against the observed characters and the literature and were not used as an identification criterion. Several initial assignments were discarded after this review, and no comparison allowed a reliable assignment; the morphotypes are therefore kept without family assignment, and their taxonomic affinity requires cuticle analysis and review by specialists.

4. Stratigraphic context and taphonomy

4.1 Sequence. According to the mine stratigraphic column and the author's observations, the ~15 m interval between seams 4O (base) and 4M (top) consists, from base to top, of: (1) carbonaceous shales or siltstones in contact with the roof of seam 4O; (2) a sandstone bed 1–1.5 m thick, of variable thickness along the walls exposed by mining, in contact with the underlying shales; and (3) interbedded shales, thin coal layers and sandstone beds, passing upward into seam 4M. From field observation, the author infers that the shale specimens come from the shale package in contact with the roof of seam 4O, and the specimens recovered in sandstone from the predominant competent bed in the exposed facies sequence. This succession is consistent with that recorded in well PBN-134, located ~1.3 km north of the fossil area, where the interval between seams 4O and 4M (~15–17 m) shows dark gray siltstones with plant remains above seam 4O, an intermediate sandstone, and interbedded siltstone and sandstone up to seam 4M (Carbones del Zulia, 2014, in Montiel, 2014) (Fig. 2c).

4.2 Provenance of the material. The specimens were not collected in situ but from among the blocks fragmented and scattered by the blast. It is therefore not possible to assign each specimen to a specific bed; their provenance is constrained to the interval between seams 4O and 4M by georeferencing of the area in the mine planning model and by the mine stratigraphic column. Within that interval, the matrix lithology allows the source bed to be inferred: the recovered specimens, preserved in compact fine- to medium-grained sandstones, would come from the 1–1.5 m sandstone bed, the main sandy interval of the package according to the mine column, whereas the non-recovered records in fissile carbonaceous shale would come from the shales in contact with the roof

of seam 4O. This assignment is an inference based on lithological correspondence and not on observation of the specimens *in situ*.

4.3 Fossil-bearing lithologies and mode of preservation. The leaves are preserved as carbonized compressions and impressions in two main lithologies. (a) In gray, fissile carbonaceous shales, the leaves occur in some blocks concentrated and overlapping on bedding planes, as leaf litter (Fig. 3A). (b) In gray to beige, compact and massive, fine- to medium-grained sandstones without visible lamination, the leaves occur scattered and accompanied by fragments of stems and trunks, which were not observed in the shales (Fig. 3B). One specimen (F-89) is preserved in reddish porcelanite, a lithology reported for the formation (Léxico Estratigráfico de Venezuela, 1997) but different from the facies observed in the package; the author therefore infers that it could be a fragment thrown by the blast from levels above the area where the other specimens were found.

4.4 Interpretation. The concentration of leaves on bedding planes of carbonaceous shales is compatible with the accumulation of leaf litter under low-energy conditions, in quiet waters of the swamp environment. The association of scattered leaves with woody debris in massive sandstones without visible lamination suggests, instead, transport and rapid burial during episodes of higher hydraulic energy, such as overbank floods or deltaic advances over the swamp plain, consistent with the deltaic progradation events recognized in the formation. Considering that about 11 m of peat are required to form 1 m of bituminous coal (Ryer & Langer, 1980), seams 4O and 4M represent prolonged periods of organic matter accumulation in low-energy environments. Using as a reference the duration estimated for the Wyodak coal, also of late Paleocene age (~414,000 years for 18.3 m of coal; Large et al., 2003), seam 4O (3.65 m) would have required about 40 m of peat and on the order of 80,000 years of accumulation, and seam 4M (8.45 m) about 90 m of peat and on the order of 190,000 years. These figures are only order-of-magnitude estimates that assume uniform accumulation and compaction rates, but they indicate that the peat mires remained stable for tens of thousands of years, which is consistent with the relatively slow subsidence proposed for the basin (Hackley & Martínez, 2007; Large et al., 2021). The interval separating the two seams records a progressive adjustment of the depositional environments: at the base, the accumulation of organic matter under low-energy conditions, represented by the carbonaceous shales with leaf litter, is interrupted by a high-energy event that supplied coarser sediment and suddenly swept in and buried plant remains, allowing the preservation of the leaves contained in the sandstone. This event was followed by a gradual return to low-energy regimes, with small pulses recorded in the interbedded shales, siltstones, thin coals and sandstones, until the establishment of the peat mire that formed seam 4M. This pattern suggests a rhythmic alternation of increases and decreases in the energy of the system. These alternations, on a scale of tens of thousands of years, could reflect orbital climate cycles such as those recognized in coeval coals (Large et al., 2003), or processes inherent to the deltaic system, such as crevasse splays that interrupt peat accumulation and introduce sands rich in organic matter into coal-bearing sequences (Dziamara et al., 2023), in a context of foreland subsidence associated with the oblique collision between the Caribbean and South American plates and the emplacement of the Lara nappes (Escalona & Mann, 2003; Hackley & Martínez, 2007). This interpretation is preliminary, since the relationships between beds could not be observed directly in the fossil area.

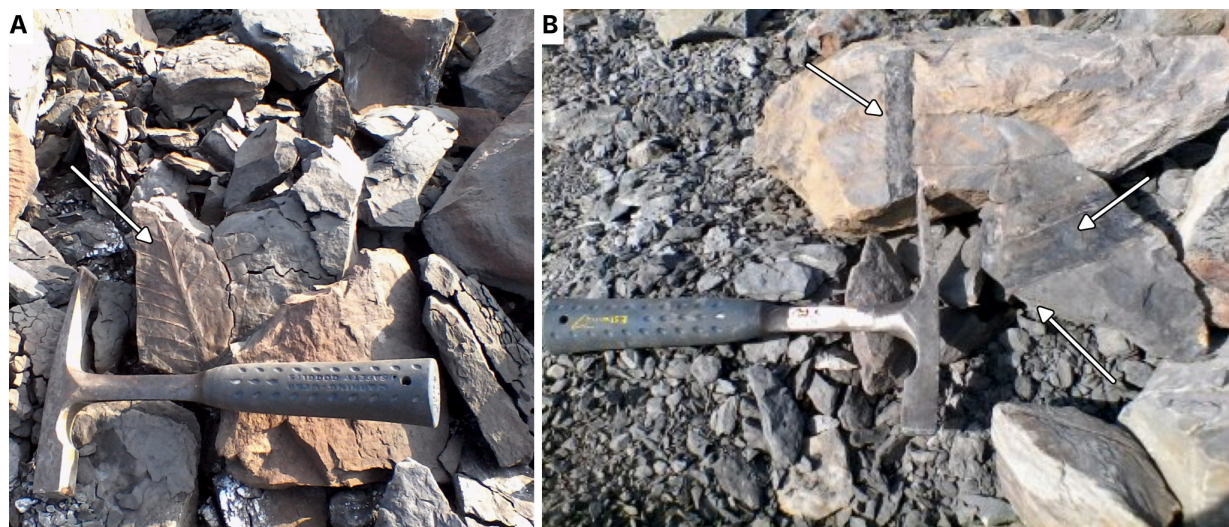


Fig. 3. Field views of the two fossil-bearing lithologies of the 4O–4M interval, Paso Diablo Mine (July 2016). Both show rock fragments moved by the blast, not outcrops in original position. (A) Fragments of gray fissile shale; on the surface of one of them, a leaf of morphotype A with visible midvein and secondaries (NR-1, arrow). (B) Blocks of massive fine- to medium-grained sandstone, weathered to beige, with elongate black remains of embedded carbonized stems (arrows). Scale: Estwing E3-24BLC flat-tip hammer (28.6 cm overall length). Photographs by C. Solano Nava, unretouched (cropping only; A rotated to leave the hammer handle horizontal); B reproduced from the only available file, of low resolution (400 × 300 pixels). Originals on Zenodo (Solano Nava, 2026). Plate format after Doria et al. (2008).

5. Results

5.1 Composition of the material. The collection comprises 25 recovered blocks, containing 27 leaves or leaf fragments documented in the laboratory, and 8 field photographic records of non-recovered specimens (NR-1 to NR-8). Several specimens were photographed more than once and are recorded with combined codes (e.g., F-41/F-46/F-47). Six informal morphotypes are recognized (A, C, D, E, F and G), defined by leaf architecture characters independent of size (lamina shape, base, margin and venation pattern). The letters are kept for continuity with the data archive (Solano Nava, 2026); morphotypes B and H of preliminary versions were discarded after revision. No morphotype is assigned to a family. All laminae with an observable margin have an entire margin. Measurements, taken on the photographs from the included scale (see 3.3), are used as comparative values to classify leaf size and compare it with the paleoflora of the Cerrejón Formation.

5.2 Description of the morphotypes

Morphotype A. Simple leaves, elliptic to oblong, with acute apex and acute to cuneate base; margin entire; venation pinnate, with regular secondaries at $\sim 45^\circ$ that curve toward the apex near the margin (brochidodromous to eucamptodromous). L:W ~ 2 –2.5. Approximate size between ~ 6 and ~ 17 cm long. This is the most frequent morphotype: 15 laboratory specimens (F-3, F-5/F-10, F-16, F-21, F-29/F-110, F-38/F-40, F-41/F-46/F-47, F-69, F-75, F-86, F-88, F-94/F-118, F-97, F-102/F-103, F-114/F-115) and 4 field records (NR-1, NR-2, NR-3, NR-7; cf. NR-5). Present in both sandstone and carbonaceous shale. Illustrative specimen: F-41/F-46/F-47 (~ 16 – 17×7 cm), whose block also preserves a leaf fragment (F-41b) with finely preserved reticulate higher-order venation (Fig. 4).

Morphotype C. Leaf with palmate (actinodromous) venation: at least four to five primary veins diverge from a basal point, with reticulate minor venation between them. Outline possibly lobed, not determinable because of the fragmentation of the lamina. ~ 9 cm from the base to the tip of the longest segment. Single specimen: F-32, in reddish sandstone (Fig. 6A). It is the only morphotype with palmate primary venation in the collection.

Morphotype D. Small lamina (~4 cm), with regular and strongly marked pinnate secondaries; apex and base not preserved. Because of its size it could correspond to a leaflet of a compound leaf. Single specimen: F-1/F-2, in fine-grained gray sandstone (Fig. 6B, C).

Morphotype E. Broad leaves, medium to large in size; midvein robust; secondaries numerous, straight, regular and parallel, arising from the midvein at an acute angle and curving toward the apex near the margin; margin entire. Reference specimen: F-70 (~12 × 11 cm visible), which preserves the apex, where the secondaries curve and converge, and one complete lateral margin, but not the base; the shape of the base and the presence of basal veins are therefore unknown. The base is not preserved either in the specimens tentatively assigned (cf. E) photographed in the laboratory. Assigned by the secondary-vein pattern: F-106. Tentatively assigned (cf. E), because they share the pattern of straight, parallel secondaries in broad leaves but are incomplete or of insufficient resolution: F-56, F-61, F-79, F-119/F-121, NR-6 and NR-8. Present in sandstone and carbonaceous shale. The angle of the secondaries varies between ~45° and ~70° among specimens (Fig. 5).

Morphotype F. Leaf with pinnate venation, with long, straight, parallel and widely spaced secondaries ascending from the midvein at an acute angle (~30–35°); margin entire in the visible portion. Single specimen: F-63/F-65/F-82 (fragment, ~14 cm visible), in fine-grained gray sandstone (Fig. 6D). It differs from morphotype A in the angle and course of the secondaries.

Morphotype G. Monocot leaf remains, with fine, linear, parallel striations, without midvein or reticulate venation. Specimen: the upper right block of NR-1 (weathered reddish sandstone, with impressions of striate laminae compatible with palm leaves). A comparison with Arecaceae (palms) is possible but cannot be confirmed without additional features (Fig. 6E).

5.3 Indeterminate material. The following are recorded as indeterminate: two leaf fragments from blocks with other specimens (F-3b, F-41b) and an impression of a large leaf in the field (NR-4; visible midvein ~18–22 cm), whose outline is masked by fractures and whose lamina shows fine parallel lines that could correspond to dense secondary venation. In addition, fragments of stems and trunks were documented in sandstone (Fig. 3), not observed in the shales. Finally, F-89, preserved in reddish porcelanite, shows a surface with oblique, striate marks that could correspond to bark or a stem, possibly of a palm; lacking additional diagnostic features, it is recorded as an indeterminate axial remain (Fig. 6F).

5.4 Possible damage to the lamina. Several specimens (e.g., F-3, F-41/F-46/F-47, F-70, F-88, F-102/F-103) show areas with rounded edges lacking the carbonaceous film, perforations and marginal notches. These features are compatible with insect damage, but may also result from loss of the carbonaceous film during fragmentation of the rock by the blast or from diagenetic processes; their interpretation requires review by specialists (see Discussion).

Table 1. Summary of morphotypes.

Morphotype	Diagnostic features	Lab.	Field	Lithology
A	Elliptic; secondaries ~45° curving toward the apex	15	4 (+1 cf.)	Sandstone and shale
C	Palmate venation	1	—	Reddish sandstone
D	Small lamina; marked secondaries	1	—	Sandstone
E	Broad; secondaries numerous, straight and parallel; base unknown	2 (+4 cf.)	2 cf.	Sandstone and shale
F	Secondaries ascending at an acute angle	1	—	Sandstone
G	Monocot; parallel striations	—	1	Weathered sandstone
Indet.	Leaf fragments; axial remain (F-89)	3	1	Sandstone, shale, porcelainite

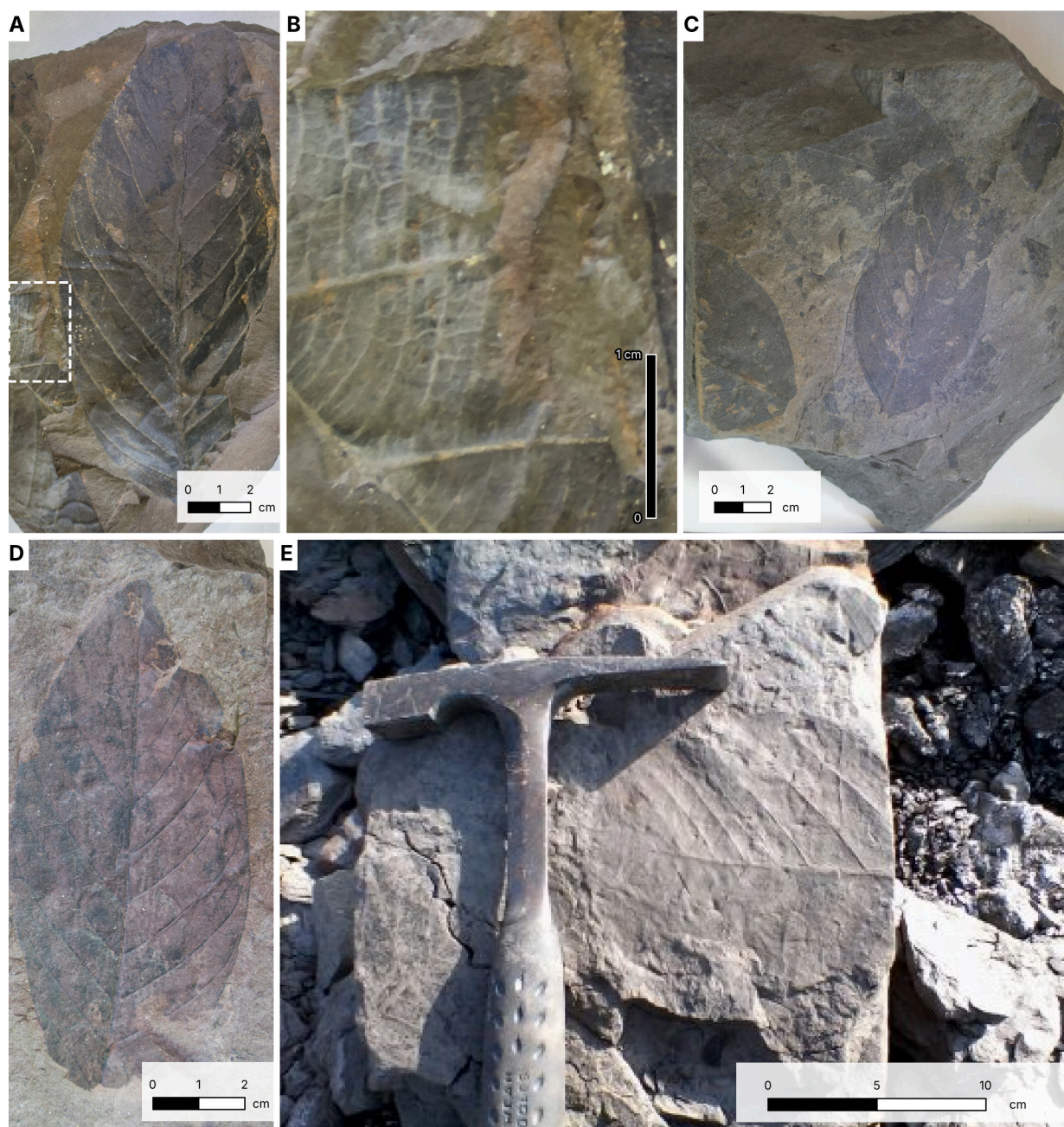


Fig. 4. Morphotype A from the Marcelina Formation, Paso Diablo Mine. Unretouched photographs (cropping only; C and D rotated to leave the apex up). (A) F-41/F-46/F-47, illustrative specimen: elliptic leaf with entire margin, acute apex and regular secondaries that curve toward the apex near the margin; the dashed box indicates the area enlarged in B. (B) F-41b, enlargement of the boxed area in A (lower left part of the same block): leaf fragment with finely preserved reticulate higher-order venation. (C) F-3, block with several accumulated leaves and leaf fragments (leaf litter); central leaf of morphotype A with light patches on the lamina (possible herbivory or loss of the carbonaceous film) and, on the left, F-3b (indeterminate). (D) F-16, complete elliptic leaf in beige sandstone with reddish tones, with brochidodromous secondaries. (E) NR-7, non-recovered field record in gray carbonaceous shale, photographed at the mine face after the blast with a mobile phone (low resolution); Estwing E3-24BLC flat-tip hammer (28.6 cm overall length) for reference. A–D in fine- to medium-grained sandstone. Graphic scales in centimeters: in A–D, calculated from the 2 × 2 cm scale included in each photograph (in C the ruler lies on the table and not at the level of the leaf, so the scale is approximate); in E (10 cm), estimated from the length of the hammer head (~16.7 cm, measured as a proportion of its overall length in another photograph of the same hammer), so it is also approximate. Original photographs on Zenodo (Solano Nava, 2026). Plate format after Doria et al. (2008).

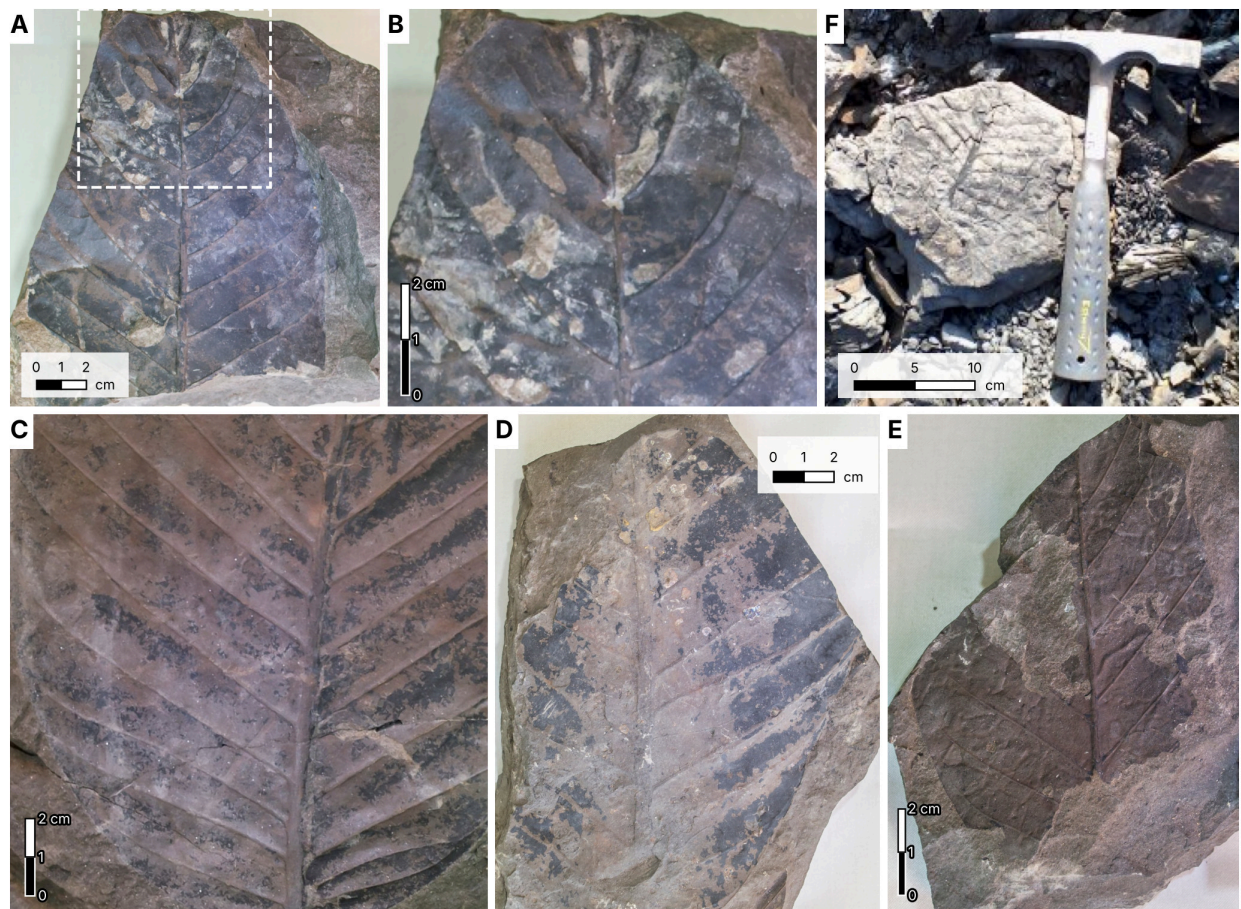


Fig. 5. Morphotype E from the Marcelina Formation, Paso Diablo Mine. Leaves oriented with the apex up; unretouched photographs (cropping and rotation only). (A) F-70, reference specimen: broad leaf with robust midvein and numerous, straight, parallel secondaries; the apex (top) and one lateral margin are preserved, but not the base, which is truncated by the edge of the block; the dashed box indicates the area enlarged in B. (B) F-70, enlargement of the apex: the secondaries curve and converge toward the apex near the margin. (C) F-106, straight, parallel and regular secondaries that curve toward the apex near the margin; base not preserved. (D) F-79 (cf. E), broad leaf with spaced secondaries. (E) F-119/F-121 (cf. E), straight, parallel secondaries; base not preserved. (F) NR-8 (cf. E), non-recovered field record in carbonaceous shale, photographed in the field on a block moved by the blast, with a mobile phone (low resolution); Estwing E3-24BLC flat-tip hammer (28.6 cm overall length) for reference. A–E in fine- to medium-grained sandstone. Graphic scales in centimeters: in A–E (2 cm), calculated from the 2 × 2 cm scale included in each photograph; in F (10 cm), estimated from the length of the hammer, so it is approximate because of the perspective of the shot. Original photographs on Zenodo (Solano Nava, 2026; <https://doi.org/10.5281/zenodo.23264877>). Plate format after Doria et al. (2008).

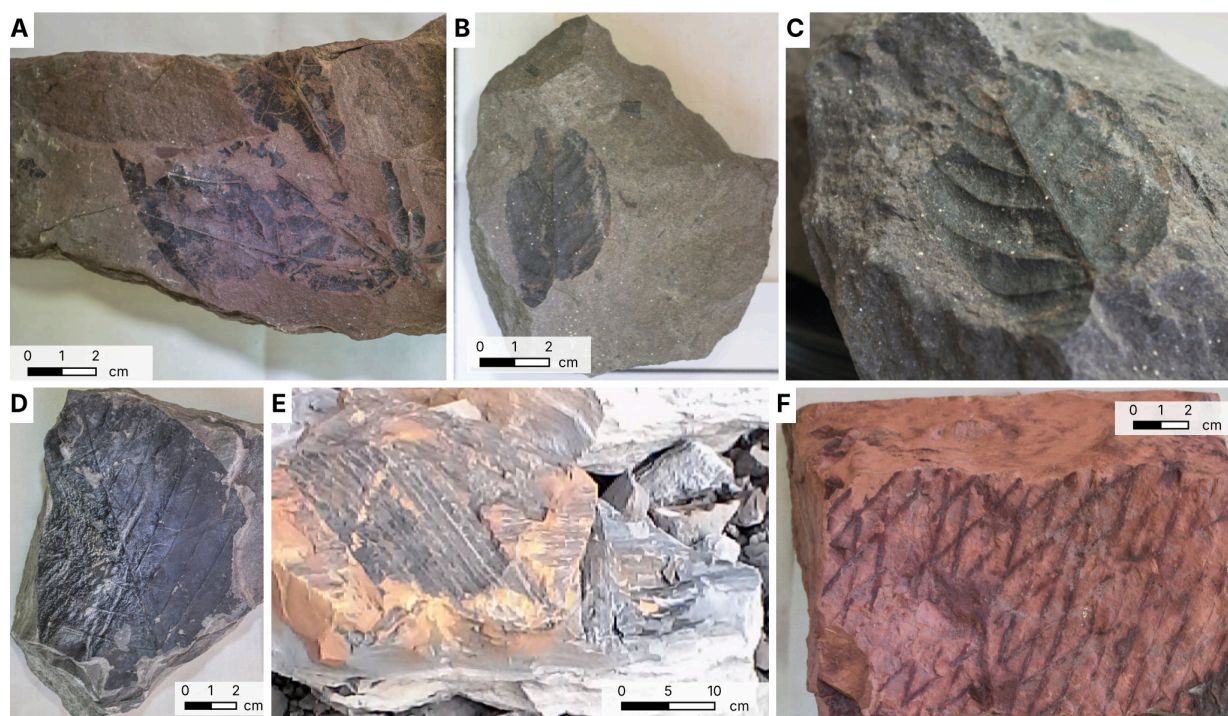


Fig. 6. Morphotypes C, D, F and G and indeterminate axial remain from the Marcelina Formation, Paso Diablo Mine. Unretouched photographs (cropping and rotation only). (A) Morphotype C, F-32: palmate (actinodromous) venation, with four to five primary veins diverging from a basal point (on the right) and reticulate minor venation; reddish sandstone. (B) Morphotype D, F-1/F-2 (view F-2): small lamina (~4 cm) with marked pinnate secondaries; fine-grained gray sandstone. (C) The same specimen in oblique view (F-1), highlighting the relief of the secondaries; no scale. (D) Morphotype F, F-63/F-65/F-82 (view F-65): fragment with long, straight, parallel and spaced secondaries ascending at an acute angle; fine-grained gray sandstone. (E) Morphotype G, NR-1 (upper block of the field photograph): laminae with fine, linear, parallel striations, compatible with monocot leaves (cf. *Arecaceae*), in weathered sandstone; field photograph with a mobile phone (low resolution). (F) F-89, indeterminate axial remain in reddish porcelanite, with oblique, striate marks (possible bark or stem, possibly of a palm). Graphic scales in centimeters: in A, B, D and F, calculated from the 2 × 2 cm scale included in each photograph (in B the ruler lies on the table, so the scale is approximate); in E (10 cm), estimated from the length of the Estwing E3-24BLC flat-tip hammer (28.6 cm overall length) in the same photograph, so it is approximate. Original photographs on Zenodo (Solano Nava, 2026). Plate format after Doria et al. (2008).

6. Discussion

6.1 Value of the record. The documented material comes from a level that was removed as overburden a few hours after its exposure, so these photographs and specimens are the only testimony of its fossil content. To our knowledge, there are no published descriptions of leaf macroflora from the Marcelina Formation at the Paso Diablo Mine; previous studies of the interval have focused on the organic petrography of its coals (Hackley & Martínez, 2007). Although modest, the collection documents the vegetation of the middle part of the formation at a stratigraphically constrained point (between seams 4O and 4M), precisely georeferenced, and remains publicly available for review (Solano Nava, 2026). The case also illustrates the recurrent loss of paleontological information at active mining faces, where fossil remains are known to the personnel but are not documented.

6.2 Comparison with the Cerrejón Formation. The Cerrejón Formation, mined ~43 km to the west, hosts the best-studied Neotropical Paleocene flora, regarded as the oldest record of Neotropical rainforest (Wing et al., 2009; Jaramillo et al., 2007). Its proximity, its late Paleocene age and its correlation with the Marcelina Formation through the Cuervos Formation (Ayala-Calvo et al., 2009) make it the natural framework of comparison for Paso Diablo. Three aspects of the Paso Diablo paleoflora are consistent with that of Cerrejón:

(a) *Entire margins and large leaves.* All Paso Diablo fossils in which the margin is visible show well-defined, entire margins, and morphotype E includes medium to large leaves. At Cerrejón, about three quarters of the leaf types are large and entire-margined, a feature associated with warm, humid tropical climates (Wing et al., 2009). The number of morphotypes at Paso Diablo is too low to yield quantitative paleoclimatic estimates; however, given their geographic proximity (~43 km), similar age and comparable coastal-plain setting with peat mires, it is proposed as a hypothesis that the climatic conditions recorded in the Cerrejón Formation could be extrapolated to Paso Diablo.

(b) *Monocots.* The presence of leaf remains with parallel striations (morphotype G) and of a possible palm stem or bark (F-89) is compatible with the palms and other monocots abundant at Cerrejón (Herrera et al., 2008; Gómez-Navarro et al., 2009), although the material does not allow a more precise assignment.

(c) *A possible affinity with Menispermaceae (hypothesis).* Morphotype E recalls *Menispermites guajiraensis* Doria, Jaramillo & Herrera, described from the middle part of the Cerrejón Formation (Doria et al., 2008), in two observable features: large, entire-margined leaves and several pairs of secondaries arising from the midvein at an acute angle, with a straight to gently curved course toward the margin. This secondary-vein pattern, which according to Doria et al. (2008) distinguishes *M. guajiraensis* from the other species of the genus, matches the numerous, straight, parallel secondaries of morphotype E (F-70, F-106). The comparison is, however, very limited, because the preserved parts do not overlap: F-70 preserves the apex and one lateral margin but not the base, whereas in *M. guajiraensis* the apex is unknown and the diagnosis rests on the cordate base and the 5–7 actinodromous basal veins, which cannot be evaluated in the Paso Diablo material. Nor is it possible to confirm the brochidodromous pattern, the opposite percurrent tertiary venation or the areolation. Because the pattern of straight, parallel secondaries occurs in several angiosperm families, it does not by itself allow the morphotype to be assigned to Menispermaceae. The resemblance is therefore proposed only as a working hypothesis, which requires specimens with the base preserved, observation of F-70 under a stereomicroscope, and cuticle analysis.

6.3 Taphonomy and collection biases. The collection records two modes of preservation: leaves accumulated on bedding planes of carbonaceous shales, compatible with leaf litter deposited in quiet waters, and scattered leaves with woody debris in massive sandstones, compatible with transport during higher-energy episodes (Section 4). Notably, the detonation of the blast fragmented the rock, so that only the fossils contained in the most competent lithology survived. This first bias was compounded by that of collection, which favored specimens in sandstone, more resistant to transport by vehicle, and those with the best visible preservation; the leaves in shale were documented only photographically and at lower resolution. Therefore, the relative frequency of the morphotypes does not represent the composition of the original vegetation, and the actual diversity of the level was probably higher.

6.4 Possible insect damage. Several leaves show areas lacking the carbonaceous film with rounded edges, perforations and marginal notches (Section 5.4). At Cerrejón, insect feeding damage is abundant but of low diversity and produced mainly by generalist herbivores (Wing et al., 2009). The features observed at Paso Diablo could correspond to similar damage, but no damage types or causal agents are assigned here, since they may be confused with loss of the carbonaceous film caused by the blast or by diagenetic processes. Their evaluation requires direct examination of the specimens by specialists.

6.5 Limitations and outlook. The descriptions are based exclusively on photographs, without cuticle analysis or observation under magnification, and the specimens were not collected in situ. Priorities for future studies are: (1) deposit of the specimens in a Venezuelan institutional collection; (2) direct

review by paleobotanists, with emphasis on the higher-order venation of morphotypes E and C; (3) cuticle analysis, if preservation allows; and (4) evaluation of the possible insect damage. In addition, the Paso Diablo case suggests the value of simple protocols for documenting paleontological finds at the active coal mines of the Guasare Basin.

7. Conclusions

1. The first published record of leaf macroflora from the Marcelina Formation (late Paleocene) at the Paso Diablo Mine is documented, from a level between seams 4O and 4M that was destroyed by mining in 2016.
2. The leaves are preserved in two facies: carbonaceous shales with leaf-litter accumulations, and massive sandstones with scattered leaves and woody debris, which record higher-energy episodes within the swamp environment.
3. Six informal morphotypes defined by leaf architecture are recognized. Elliptic pinnate leaves predominate (morphotype A), followed by broad leaves with numerous, straight, parallel secondaries (morphotype E). All laminae with an observable margin are entire.
4. The paleoflora is consistent with that of the Cerrejón Formation in the predominance of entire margins and in the presence of large leaves and monocots. A resemblance of morphotype E to *Menispermites guajiraensis*, based only on the secondary-vein pattern, is proposed as a hypothesis.
5. The material, publicly available, requires institutional deposit and review by specialists to establish its taxonomic affinities at family level and, where preservation allows, at genus level, as well as to evaluate the possible evidence of insect damage.

Data availability

Photographs of all specimens and the metadata table are available on Zenodo: Solano Nava, C.E. (2026). Photographic archive of late Paleocene leaf macrofossils, Marcelina Formation, Paso Diablo Mine, Guasare Basin (Venezuela) [Data set]. <https://doi.org/10.5281/zenodo.23264877>

Acknowledgments

The author thanks Miguel Chalita for the photography of the specimens; Professor Zaima Montaña (Universidad Tecnológica de Maracaibo) for facilitating contact with specialists; Jorge D. Carrillo-Briceño (Paleontological Institute and Museum, University of Zurich) and Carlos Jaramillo (Smithsonian Tropical Research Institute) for their guidance on the material; Armando Alvarado, Drilling and Blasting Supervisor at the Paso Diablo Mine, for sharing his first-hand knowledge of the presence of fossil-bearing levels at the mine, which led the author to pay closer attention during post-blast inspections; and the personnel of the Paso Diablo Mine for the information provided. The author also thanks his family, especially his mother and his uncles and aunts, for putting up with the mess that living with a pile of rocks in their homes sometimes meant; his girlfriend, for her love and motivation; and his sister, his sister-in-law and his closest friends, for their constant support.

Statement on the use of artificial intelligence. During the preparation of the manuscript, artificial intelligence tools were used as support for the initial exploration of affinities, the organization of the text and the translation; all content was reviewed by the author, who takes full responsibility for it.

Competing interests. The author declares no competing interests. The author derives no financial benefit from the find, and the specimens have not been sold; they are intended for a Venezuelan institutional collection.

Funding. This work received no funding. It was carried out on the author's own initiative, and the author covered the costs of research, transport and storage of the material.

Author contribution. C. E. Solano Nava made the discovery, carried out the field documentation and rescue of the material, described and interpreted the specimens, prepared the figures and wrote the manuscript.

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Supplementary material

Table S1. Herbarium specimens of extant genera consulted for the morphological comparison (Section 3.4). United States National Herbarium (US), Smithsonian Institution, National Museum of Natural History, Department of Botany; online catalog consulted in October 2026 (<https://collections.nmnh.si.edu/search/botany/>). Lowland specimens from the region closest to the study area were selected; *Magnolia* and *Talauma* (Magnoliaceae) are not included, as there are no specimens from Zulia State or from La Guajira, Cesar or Magdalena. The comparison does not imply taxonomic assignment.

Taxon	Family	Collector and number	Locality	US Catalog No.	Barcode	Morphotype compared
<i>Nectandra bartlettiana</i> Lasser (type collection)	Lauraceae	H. F. Pittier 10978	Venezuela, Zulia: río Lora, forest between Camp 2 and the mouth of the río del Norte	1187508	00099273	A
<i>Nectandra globosa</i> (Aubl.) Mez	Lauraceae	G. Davidse 18810	Venezuela, Zulia, Distrito Colón: 9–20 km W of the junction of the road to río de Oro with the Maracaibo–La Fría highway (Hwy. 6)	3282936	03997768	A
<i>Nectandra lineata</i> (Kunth) Rohwer	Lauraceae	J. de Bruijn 1443	Venezuela, Zulia: río de Oro, ± 105 km WNW of Santa Bárbara (San Carlos del Zulia)	2837725	03997882	A
<i>Nectandra martinicensis</i> Mez	Lauraceae	E. Tejera 17	Venezuela, Zulia: vicinity of Perijá	897615	03997949	A
<i>Nectandra membranacea</i> (Sw.) Griseb.	Lauraceae	H. F. Pittier 10938	Venezuela, Zulia: río Lora, above Camp 2 of the Perijá Expl. Co	1187476	03998015	A
<i>Nectandra turbacensis</i> (Kunth) Nees	Lauraceae	Hno. Ginés 1558	Venezuela, Zulia: Perijá (label "Perina", to be verified)	2047163	03998249	A
<i>Nectandra turbacensis</i> (Kunth) Nees	Lauraceae	Hno. Ginés 99	Venezuela, Zulia: río Negro, west of Machiques, at the foot of the Sierra de Perijá	1950507	03998253	A
<i>Nectandra turbacensis</i> (Kunth) Nees	Lauraceae	J. de Bruijn 1322	Venezuela, Zulia: ± 35 km N of Santa Bárbara–San Carlos del Zulia; riparian forest near Ensenada Congo, Lake Maracaibo	2837742	03998248	A
<i>Ocotea cernua</i> (Nees) Mez	Lauraceae	J. de Bruijn 1402	Venezuela, Zulia: ± 30 km N of Santa Bárbara–San Carlos del Zulia; secondary forest along the río Bravo	2837998	03996219	A
<i>Ocotea guianensis</i> Aubl.	Lauraceae	J. A. Steyermark 99598 (VEN)	Venezuela, Zulia: 1 km W of the Machiques–Colón road, between the ríos Tokuko and Aricuiza, ~ 90 km S of Machiques	2860222	03996443	A
<i>Annona jahnii</i> Saff.	Annonaceae	E. Tejera 189	Venezuela, Zulia: vicinity of Perijá	1067443	03899113	F; F-79 (cf. E)
<i>Duguetia lucida</i> Urb.	Annonaceae	G. Davidse 18428	Venezuela, Zulia, Distrito Perijá: ~ 13 km NE of the crossing of the Maracaibo–La Fría highway (Hwy. 6) with the río Aricuaisá; seasonally flooded forest on mounds	3032536	03897029	F; F-79 (cf. E)
<i>Duguetia vallicola</i> J. F. Macbr.	Annonaceae	Veillon 132	Venezuela, Zulia: Chirimoyo, Aricuiza	2704806	03897096	F; F-79 (cf. E)
<i>Guatteria hirsuta</i> Ruiz & Pav.	Annonaceae	J. A. Steyermark 99763 (VEN)	Venezuela, Zulia, Sierra de Perijá: lower slopes, río Yasa, near Guasáma, above Kasmera (LUZ Biological Station), SW of Machiques	2813889	03897493	F; F-79 (cf. E)
<i>Oxandra espintana</i> (Spruce ex Benth.) Baill.	Annonaceae	E. Tejera 139	Venezuela, Zulia: vicinity of Perijá	1066110	03804670	F; F-79 (cf. E)

Taxon	Family	Collector and number	Locality	US Catalog No.	Barcode	Morphotype compared
<i>Oxandra venezuelana</i> R. E. Fr.	Annonaceae	J. A. Steyermark 99947 (VEN)	Venezuela, Zulia, Sierra de Perijá: lower slopes, evergreen lowland rainforest, quebrada Koshida, S of the Mistón de Los Ángeles de Tokuku, SW of Machiques	2813925	03804702	F; F-79 (cf. E)
<i>Xylopia amazonica</i> R. E. Fr.	Annonaceae	Veillon 100	Venezuela, Zulia: Aricuiza	2704802	04182106	F; F-79 (cf. E)
<i>Xylopia aromatica</i> (Lam.) Mart.	Annonaceae	H. F. Pittier 10590	Venezuela, Zulia: vicinity of Mene Grande, at the foot of the hills	1281357	03896724	F; F-79 (cf. E)
<i>Xylopia aromatica</i> (Lam.) Mart.	Annonaceae	J. de Bruijn 1155	Venezuela, Zulia, Distrito Perijá: ±5 km W of Machiques, hacienda El Capitán	2837395	03896730	F; F-79 (cf. E)
<i>Xylopia aromatica</i> (Lam.) Mart.	Annonaceae	E. Tejera 80	Venezuela, Zulia: vicinity of Perijá	897678	03896723	F; F-79 (cf. E)
<i>Xylopia aromatica</i> (Lam.) Mart.	Annonaceae	G. Ferrari 268	Venezuela, Zulia: Mene Grande area	2952360	04182110	F; F-79 (cf. E)
<i>Xylopia frutescens</i> Aubl.	Annonaceae	E. Ijász 77	Venezuela, Zulia: pasture between Caraquits and finca El Italiano, Perijá	2952361	03896787	F; F-79 (cf. E)
<i>Xylopia pittieri</i> Diels	Annonaceae	Veillon 119	Venezuela, Zulia: Aricuiza	2704803	04698390	F; F-79 (cf. E)
<i>Xylopia pittieri</i> Diels (isotype)	Annonaceae	H. F. Pittier 10990	Venezuela, Zulia: río Lora	1281358	00098782	F; F-79 (cf. E)
<i>Xylopia spruceana</i> Benth. ex Spruce	Annonaceae	J. de Bruijn 1466	Venezuela, Zulia: primary forest on the Machiques-Colón road, near the río Catatumbo, 85 km WNW of Santa Bárbara-San Carlos del Zulia	2837706	04698273	F; F-79 (cf. E)
<i>Abuta rufescens</i> Aubl.	Menispermaceae	G. Davidse, A. C. González & R. A. León 18447, 22 Jun 1980	Venezuela, Zulia, Distrito Perijá: ~13 km NE of the crossing of the Maracaibo-La Fría highway (Hwy. 6) with the río Aricuaisá; 9°26'N, 72°29'W; 40 m; forest on mounds, with channels between them subject to flooding	2938785	03578786	E
<i>Anomospermum reticulatum</i> (Mart.) Eichler	Menispermaceae	J. de Bruijn 1320	Venezuela, Zulia: ±35 km N of Santa Bárbara-San Carlos del Zulia; riparian forest near Ensenada Congo, Lake Maracaibo	2837743	03579190	E
<i>Disciphania ernstii</i> Eichler var. <i>ernstii</i>	Menispermaceae	J. A. Steyermark, G. Davidse & A. Stoddart 122961, 31 May 1980	Venezuela, Zulia, Distrito Mara: forest remnants among pastures, east of the río Guasare, 8 km (straight line) WSW of the Corpozulia Carichuano Camp; 10°59'30"N, 72°23'W (~13 km WSW of the fossil area); alt. ~600 m (label reading)	2858775	03579045	E
<i>Odontocarya tamoides</i> (DC.) Miers	Menispermaceae	A. H. Gentry 11041	Venezuela, Zulia: 11 km NE of Caja Seca	2788371	03579021	E
<i>Odontocarya</i> sp.	Menispermaceae	Hno. Ginés 2153	Venezuela, Zulia: Perijá	2047358	03579007	E
<i>Sterculia apetala</i> (Jacq.) H. Karst. var. <i>apetala</i>	Malvaceae	J. Giacometto 1055	Colombia, Magdalena: bank of the río Manzanares, near Santa Marta; moist clayey soils	1999285	00754835	C (F-32)
<i>Sterculia apetala</i> var. <i>apetala</i>	Malvaceae	H. H. Smith 1889	Colombia, Magdalena: Santa Marta	533768	03382321	C (F-32)
<i>Sterculia apetala</i> var. <i>apetala</i>	Malvaceae	H. M. Curran 41	Colombia, Bolívar: vicinity of Loba	537832	00754855	C (F-32)
<i>Sterculia apetala</i> var. <i>apetala</i>	Malvaceae	J. B. Zainúm 19 B0095	Colombia, "Bolívar" (Sinú region): swampy plain with lagoons, near Hacienda Martinica, 15 km from Montería (now Córdoba)	2103483	00754836	C (F-32)