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The fossil localities of the Piedra Chamana Fossil Forest (Eocene, Peru): a prospectus for research and conservation

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ABSTRACT. The fossil plants of the Piedra Chamana Fossil Forest in northern Peru occur in volcaniclastic rocks of the Huambos Formation dated at 39 Ma (late Middle Eocene). Studies to date have focused on the fossil leaves and woods in ashfall and overlying ashflow tuffs near the town of Sexi. Additional fossiliferous strata occur in tuffs and sedimentary deposits over a large area near Sexi and the adjacent community of Cunyac. These largely unstudied fossil exposures include locations with in situ vertical trees in growth position associated with paleosols. The paleoflora, dominated by taxa related to lowland Amazonian clades and including a few Asian components and a mangrove, suggests a seasonally flooded lowland tropical forest and more dry-adapted interfluvial vegetation growing under warm conditions. Associated paleosols also suggest distinct wet-dry cycles as they are highly weathered with mottling and show evidence of freshwater influence, landscape heterogeneity, and intense weathering. At present, the integrity of the fossil sites is compromised by mining, illegal collecting, and inadequate site protections, all of which have contributed to a significant loss of fossil material. Conservation and protection of these important paleontological sites and their development as a resource for education and tourism will benefit both science and the local community.

KEYWORDS: fossil woods and leaves, in situ forest, T^0 assemblage, paleosols, paleoenvironment, lowland tropical forest, fossil forest conservation

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INTRODUCTION

The Huambos Formation in northern Cajamarca, Peru, comprises a sequence of volcaniclastic and volcaniclastic-derived rocks dated at 39 Ma (late Middle Eocene; Woodcock et al., 2009). Strata within the middle of this sequence preserve the fossil plants of the Piedra Chamana Fossil Forest (woods and leaves) that have been the subject of numerous studies (Woodcock et al., 2017, 2019; Woodcock and Meyer, 2020; Allen et al., 2023; Woodcock, 2024). The scientific significance of the site rests on: a) the fossils, which provide a record of the vegetation and environment of South America early in the history of the New World lowland tropical forests and include in situ low-elevation (<500 m) forests with vertical trees in growth position; and b) the tectonic history of the site and paleotopographic constraints that place the area at low elevation at a time when there were already high elevations in adjacent areas (Scherrenberg et al., 2016; Boschman, 2021) and provide a maximum age for the 2400–2600 m uplift of the Western Cordillera to its present elevation, with remarkably little deformation of the fossiliferous strata, during later Andean mountain building. The objectives of this paper are to: 1) summarize the geologic context and stratigraphic relationships of the Huambos volcanics; 2) document the range of fossil localities occurring in the area near Sexi; 3) summarize our understanding of the paleoflora and paleoenvironment; 4) present results of preliminary analyses of the in situ forest trees and paleosols; 5) outline the conservation history of the fossils and fossil sites; and 6) provide a prospectus for research and conservation.

MATERIALS AND METHODS

The fossil woods and leaves were studied using standard methods described in detail elsewhere (Woodcock et al., 2017; Allen et al., 2023). The fossils are reposited in the collections of the Museum of Natural History (MUSM) of the Universidad Nacional Mayor San Marcos in Lima. We have photographically inventoried and monitored the fossil localities over the past ~20 years, and some photos in the figures include the dates taken in order to document loss of fossil material and site disturbance over time.

Paleosol analysis involved excavation of trenches at three locations near the in situ trees to document soil structure, roots, colors, mottling, and mineralogy. Samples were collected for mineralogical, geochemical and petrographic analyses. Micromorphology was studied by means of petrographic thin sections. Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) was used to establish the elemental composition of the samples for determination of the intensity of ancient soil formation, and x-ray diffraction analysis was used to determine clay mineral composition (Moore and Reynolds, 1997). The paleosols at Sites 1 and 2 have a close relation to the fossil trees (Sites 1 and 2). A third trench was excavated at a different stratigraphic level (Site 3) in order to characterize potential variability in paleoenvironments and soil types.

GEOLOGIC CONTEXT

The Piedra Chamana fossil site is located on a 2500–4000 m, low-relief plateau along the western escarpment of the Western Cordillera of Northern Peru (Fig. 1A, B). This plateau, which extends for over 300 km, archives the Paleogene volcano-sedimentary rocks deposited in the retroarc Calipuy Basin. Radiometric ages from volcanic materials associated with the fossil forest are similar to those of the basal Tablachaca/Huambos Formation (Table 1; Prudhomme et al., 2019) of the Pativilca Magmatic Arc (Mamani et al., 2010).

Table 1. Current/previous stratigraphic treatments for the area near Sexi and inferred relationships to Calipuy Basin sequences to the south (*fossiliferous strata)

Sexi Plateau 6°30′–6°35′S		Calipuy Plateau-Basin 7°50′–8°40′S
Navarro et al. (2012)	[1]Noble et al. (1990); [2]Woodcock et al. (2009)	Prudhomme et al. (2019)
		Calipuy Group Volcanics 12 ± 0.4 Ma–30.2 ± 1.2 Ma
		Tablachaca Formation volcano-sedimentary sequence
*Incahuasi volcanic center rocks (Grupo Calipuy)	*Huambos Volcanics (Grupo Calipuy) [1]39.3 ± 1.0, 39.4 ± 1.0 Ma [2]39.35 ± 0.21, 39.52 ± 0.11 Ma	… basal Tablachaca Formation conglomerates 40.1 ± 2.6 Ma, 40.6 ± 0.6 Ma
Inca II unconformity	[1]Incaic II unconformity?	Middle Eocene Erosional Surface 44.8 ± 3.7 Ma
Chancay Volcanic Sequence Rocks	Llama Formation Volcanics [1]54.8 ± 1.8 Ma	Huaylas Formation

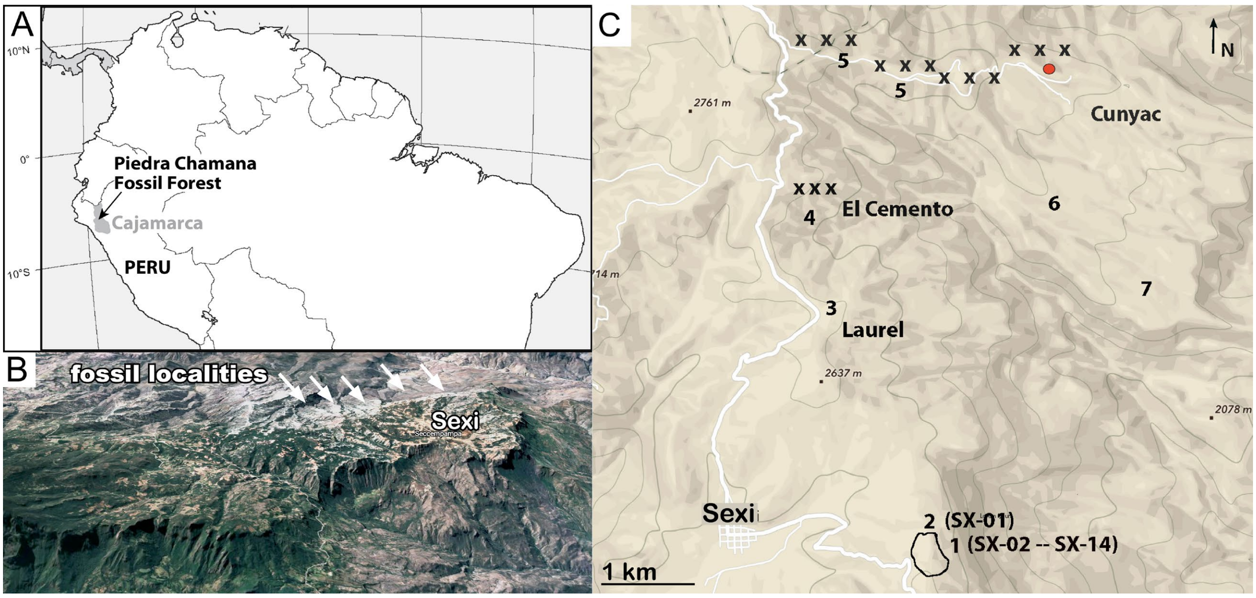

Figure 1. **A**. The location of the fossil forest in northern South America; **B**. The Sexi plateau, looking east. From Google Earth (https://earth.google.com/web/); **C**. Map showing fossil localities near the communities of Sexi and Cunyac in Cajamarca. X's denote areas of pozzolana extraction. Red dot indicates location of open pit mine

The Huambos/Tablachaca Formation and overlying volcanics post-date the early Eocene Incaic Orogeny (Mégard, 1984; Noble et al., 1990) and overlie a regional middle Eocene (~41 Ma) erosional surface (Noble et al., 1990), which separates them from the underlying 44–55 Ma old volcanic deposits of the Llama Formation (Mourier et al., 1988) and the Cretaceous-Paleocene intrusive rocks of the Costal Batholith (Martínez-Ardila et al., 2023).

The Huambos/Tablachaca Formation consists of basal coarse-to-fine conglomerates overlain by sedimentary and volcanic/volcaniclastic rocks, and the Sexi fossil forest lies within the basal segment of the formation. Indications of a low relief, low-elevation setting (Prudhomme et al., 2019; Baby et al., 2025) include interbedded sedimentary rocks with charophytes consistent with lacustrine conditions (Rivera et al., 2005) and the fossil forest described here, which includes a mangrove and lowland tropical forest taxa (Woodcock et al., 2017; Woodcock and Meyer, 2020).

The uplift of the basin to its modern position was controlled by the Western Andean Escarpment Thrust (WAET) (Prudhomme et al., 2019), a major crustal-scale west-verging fault system that uplifted the western segment of the Western Cordillera as a whole block and passively transported it to the east, with no major internal deformation (Baby et al., 2025). The thick-skin deformation associated with the WAET, and its deep crustal detachments, explains why there are fossil trees still standing vertically even after more than 2000 m of surface uplift during Andean orogeny. Minor internal deformation within the basin can be seen in the regional eastward tilting of the Plateau and in the several NW-trending faults that traverse the fossil area (Woodcock et al., 2009). For instance, Navarro et al. (2013) recognized the area near Location 7 (Fig. 1C) as representing a displaced fault block.

The Sexi plateau with its cap of Incahuasi volcanics is oriented N–S; it is sharply truncated to the west and southwest and less steeply dissected in the east (Fig. 1B). Elevations are 2500 to 3000 m and are lower (1900–2000 m) where these volcanic rocks extend eastward. The soft volcanic rocks of the plateau are highly erodible and subject to slumping, creating significant geologic hazards (Núñez et al., 2006; Núñez, 2007) and are mined for the cement additive pozzolana; two mining concessions near Sexi coincide with important fossil localities.

The Sexi volcanic rocks are part of the Huambos Formation described by Noble et al. (1990) and have their type area near Sexi and the town of Huambos to the northeast. Stratigraphic sequences near Sexi (Location 1 in Fig. 1C) correspond to at least two eruptive events (Navarro et al., 2013). At the base of the first sequence, volcanic strata with a thickness of ~50 m were formed by lahars and pyroclastic flows and fining upward volcaniclastic sediments likely deposited in a low energy fluvial and/or lacustrine environment. A radiometric date of 39.52 ± –0.11 Ma was obtained from a ~150-m thick tuff from this sequence interpreted as an ignimbrite (Woodcock et al., 2009) that likely corresponds to the regional unit described by Noble et al. (1990). The top of this sequence at the main fossil site near Sexi is marked by erosional surfaces associated with paleosols and in situ trees.

The second eruptive sequence overlies the in situ forests and associated paleosols and includes an ~1 m thick ashfall tuff and overlying crystal-rich lapilli tuffs containing abundant accretionary lapilli and fossil woods. The presence of accretionary lapilli may indicate eruption in a phreatomagmatic pyroclastic environment or occurrence of meteoric precipitation during eruption. Plagioclase from the ash layer has an Ar/Ar date of 39.35 ± 0.21 Ma (Woodcock et al., 2009). The deposits overlying the ash layer have been interpreted variously as lahars or the lateral facies of a pyroclastic flow originating several kilometers to the north-northwest (Cereceda, 2008; Woodcock et al., 2009; Navarro et al., 2013). These deposits are referred to here as ashflow tuffs. A south/southeasterly direction of flow is also suggested by the preferred NW/SE orientation of the logs (Woodcock et al., 2009). The ashflow deposits were likely emplaced a short time after the ashfall since there is no evidence of paleosol formation at the contact. There are tabular strata of pyroclastics and colluvial deposits at the top of the section in some areas, which also contain fossil wood (Navarro et al., 2013).

Mapping studies of the Calipuy volcanics in northern Peru have identified many of the volcanic centers (Table 1) and demonstrate the eastward migration of the volcanic arc since the Paleogene (Cereceda, 2008; Navarro, 2013). The typical eruptive sequence is described as involving effusive eruptions of pyroclastic flows and lahars followed by (often explosive) emissions of pyroclastic flows in significant volumes (Rivera et al., 2005). The Incahuasi Volcanic Center is estimated at ~4 km northeast of the Sexi plateau (Cereceda, 2008). The stratigraphic record at Sexi appears typical of volcaniclastic depositional sequences distal to a volcanic source, which characteristically have fine-grained tephra falls and thick sequences of lahar and fluvially reworked sediments (Major, 2022).

The lapilli-rich airfall tuff at Location 1 may correspond to similar units at the locations to the north that are also associated with fossils or fossiliferous strata, as for example at Location 5 (Fig. 1C). In the case of the ashflow and sedimentary deposits with fossil wood and the paleosols, it is more difficult to ascertain lateral continuity and correspondences.

FOSSIL LOCALITIES

Location 1 – Ashfall and tuff deposits with leaves and fossil woods (elevation 2580–2620 m). At Location 1 (Fig. 1C; field sites SX-02 to SX-14), two ashflow tuffs are the source of fossil woods that are scattered over the surface and can also be seen weathering out of the rocks (Fig. 2A, B). The lower of these ashflow deposits contains abundant woods and lapilli; the lapilli are more common in the upper part of the deposit and occur in nearly undeformed layers. The upper ashflow deposit has smaller fossil specimens and fewer lapilli (Woodcock et al., 2009). Most of the described woods are associated with the tuffs at Location 1; these woods are generally well preserved (Woodcock et al., 2017, 2019). Specimens range from small to large (3–4 to 75 cm diameter) axes or trunks, and both monocot and non-monocot angiosperms are represented.

Underlying the ashflow tuffs at Location 1 is an ash layer from which fossil leaves have been recovered (Allen et al., 2023; Fig. 2C, D). The ash is approximately 1 m thick with a crystal-rich layer at the base and lapilli that are more common in the upper portion; it is interpreted as a primary ashfall deposited at some distance from the source volcano (Woodcock et al., 2009). The small leaf flora was excavated from one location along an outcrop where the ash is loosely consolidated and breaks irregularly. The leaves do not occur in clear bedding planes, indicating rapid deposition and resulting in specimens that are often fragmentary when collected. The ashfall deposit is underlain by fining upward ash-rich sediments that show paleosol development at the ashfall contact. There are also vertical trees extending through the ash. The ashfall deposit is also exposed in one location along the southern escarpment (Fig. 5D).

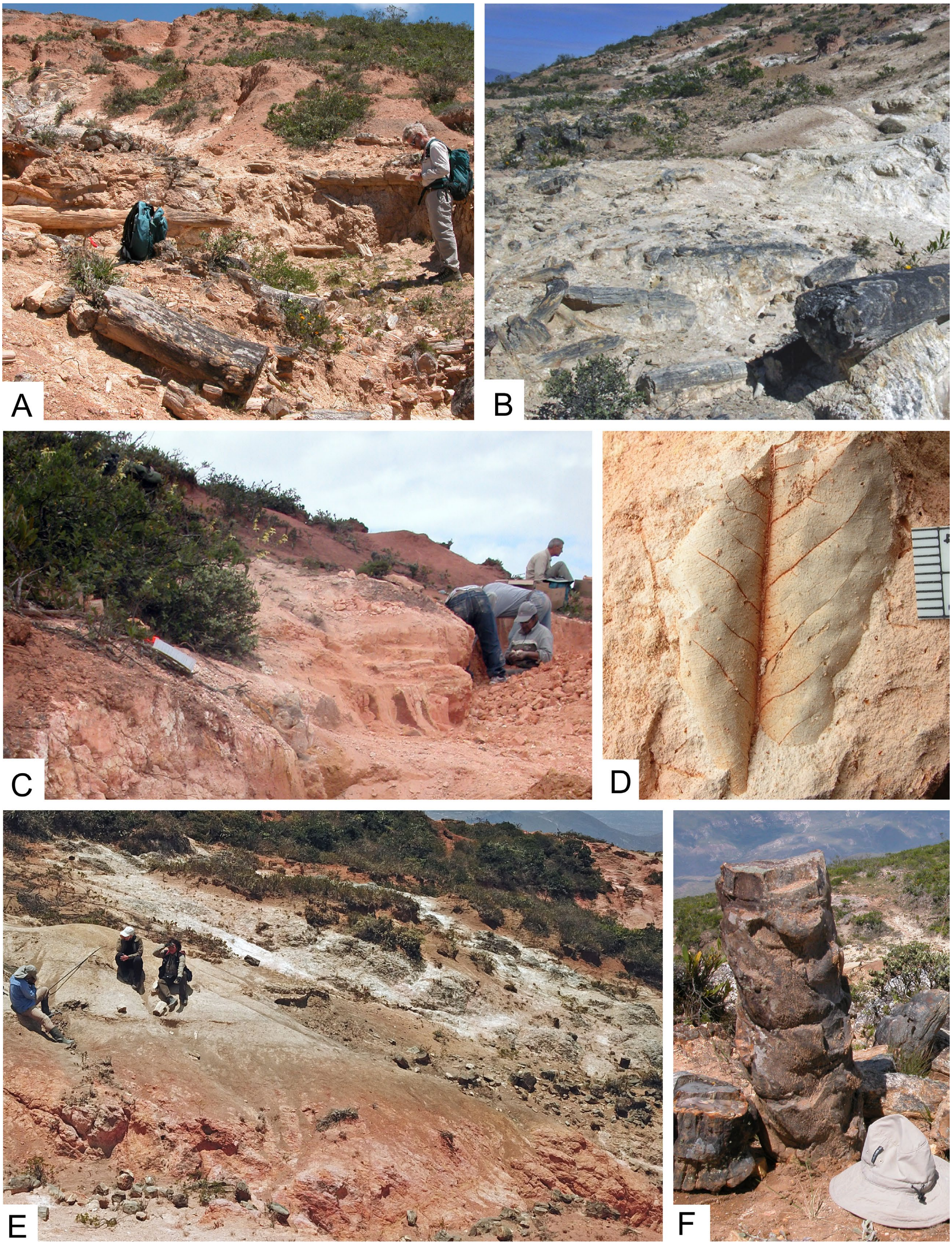

Figure 2. **A**, **B**. Fossil woods associated with the ashflow deposits at Location 1 (SX-02-SX-14), where a large volume of wood has weathered out of the rocks and is on the surface (photos 2005); **C**. Site where leaves were excavated from the underlying ashfall deposit (photo 2007); **D**. Fossil leaf embedded in ash showing the typically incomplete state of the specimens; **E**, **F**. Fossil woods in sedimentary deposit at Location 2. The specimen in F is a large palm trunk with persistent leaf bases now in the site museum in Sexi (photos 2024, 2010)

Location 2 – Sedimentary deposits with fossil wood (elevation 2520 m). Fossil woods occur in a volcaniclastic sequence at Location 2 (Fig. 2E, F; Field Site SX-01). These woods are particularly well preserved and include many monocots. Several eudicot woods have also been described from this location (Woodcock et al., 2017, 2019). The large palm stem with preserved leaf bases shown in Fig. 2F is now in the site museum in Sexi.

Location 3 – Fossil woods (elevation 2600–2610 m). A significant quantity of fossil woods occurs at Location 3, an area known as Laurel (Figs 1B, 3A–C). The woods are associated with tuffs containing accretionary lapilli. The correlation of these woods with Location 1 deposits is not yet well established, but they both belong to the same unit. The fossil trunks include large diameter specimens and also specimens with a characteristically ellipsoidal shape (Fig. 3A, B). The woods at this location are generally dark brown and show minimal anatomical detail. Occurring among these woods are specimens with banding giving the appearance of growth rings. This wood type is seen elsewhere in the assemblages; detailed study has shown affinity with the mangrove genus *Avicennia* L. – Acanthaceae (Woodcock et al., 2017). The woods of this type recovered from this location are not very well preserved but show this distinctive pattern.

Location 4 – Fossil woods (elevation 2600–2620 m). In 2011 we observed fossil woods that had been discarded at a site where pozzolana was being mined (Fig. 3D).

Location 5 – Fossil woods (elevation 2580–2650 m). At this location along the road to Cunyac, we observed fossil woods, including small specimens appearing to be in situ elements (Fig. 3E) in an ashfall deposit with sparse accretionary lapilli. These deposits may no longer be intact owing to mining activities. The fossil wood in Fig. 3F is at the base of a channel deposit underlying an ash layer. The coarse sandstone deposits seen here and elsewhere near Cunyac are 1–2 m thick and with lateral accretion sets and are interpreted as the channel facies of meandering river systems. These channel deposits range from beige to dark purple in color, which may be an expression of redox conditions associated with their original environment. The greenish sediments below are laminated/bedded, and likely not a paleosol.

Location 6 – Fossil woods in sedimentary deposits (elevation 2250–2400 m). At Location 6 in Cunyac (Fig. 1C), fossil woods occur in sediments that are likely also a channel deposit (Fig. 4A and 4A3) but have a different lithology from those at Location 5. These woods, which appear to be well preserved and include a diversity of taxa, have not been studied. Woods that likely weathered out of this deposit also occur on the surface of lacustrine strata extending to the west (Fig. 4A1, 2). The lacustrine deposits show desiccation features in many places, with small to large mud crack polygons, some suggestive of cryptalgal features. Locations 6 and 7 (Fig. 1C) are at a lower elevation than the other sites; this general area was interpreted as a displaced fault block by Navarro et al. (2013).

Location 7 – Fossil woods in ashflow tuff (elevation 2240–2320 m). At Location 7 (Fig. 1B), an area known as Palanganas, there is a tuff deposit containing fossil wood (Fig. 4B). The deposit has a more indurated appearance than the ashflow deposits at Location 1. These woods have not been studied.

Fossils eroded out of overlying deposits. At many locations on the Sexi plateau, there are fossils occurring at the surface near the above-described fossil localities. An example are the small wood fragments (up to 2–3 cm in diameter) associated with highly oxidized colluvial sediments shown in Fig. 4C; these occur south of Location 1 and at some other locations. Isolated larger specimens have been found at various locations on the western and southern periphery of the plateau and appear to have weathered out of overlying strata no longer intact locally. Often these specimens are palms, which may be especially resistant to weathering and breakdown owing to their high silica content.

SUMMARY OF THE PALEOFLORA

Thirty-two taxa of fossil wood have been described from the site (Woodcock et al., 2017, 2019, 2020; Woodcock and Meyer, 2020; Woodcock, 2024). Most are associated with the ashflow tuffs at Location 1 (Fig. 2). The majority of the woods (26 of 32 taxa) show affinity with modern South American lowland tropical forest taxa, particularly vegetation associated with the várzea (whitewater) and seasonally flooded

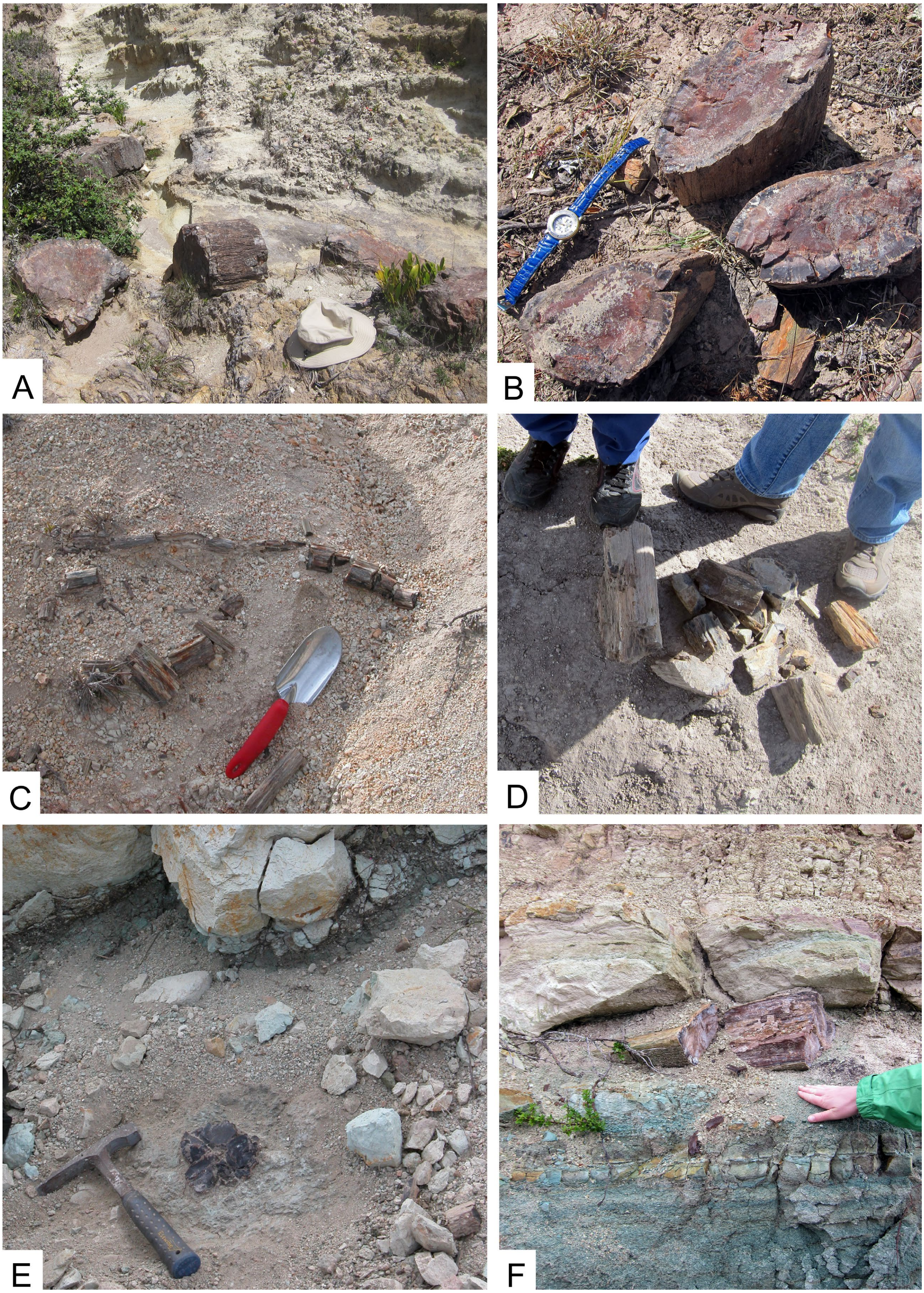

Figure 3. **A–C**. Fossil woods at Location 3 (photos 2011); **A**. Large trunks; **B**. Smaller trunks showing typical compressed shape; **C**. Trunk or branch in ash; **D**. Fossil woods discarded at Location 4 near mine site (photo 2011); **E**. Small in situ stem at Location 5 (photo 2005). This site likely no longer exists due to extractive activities; **F**. Channel sandstone with fossil wood overlain by ash at Location 5 (photo 2018)

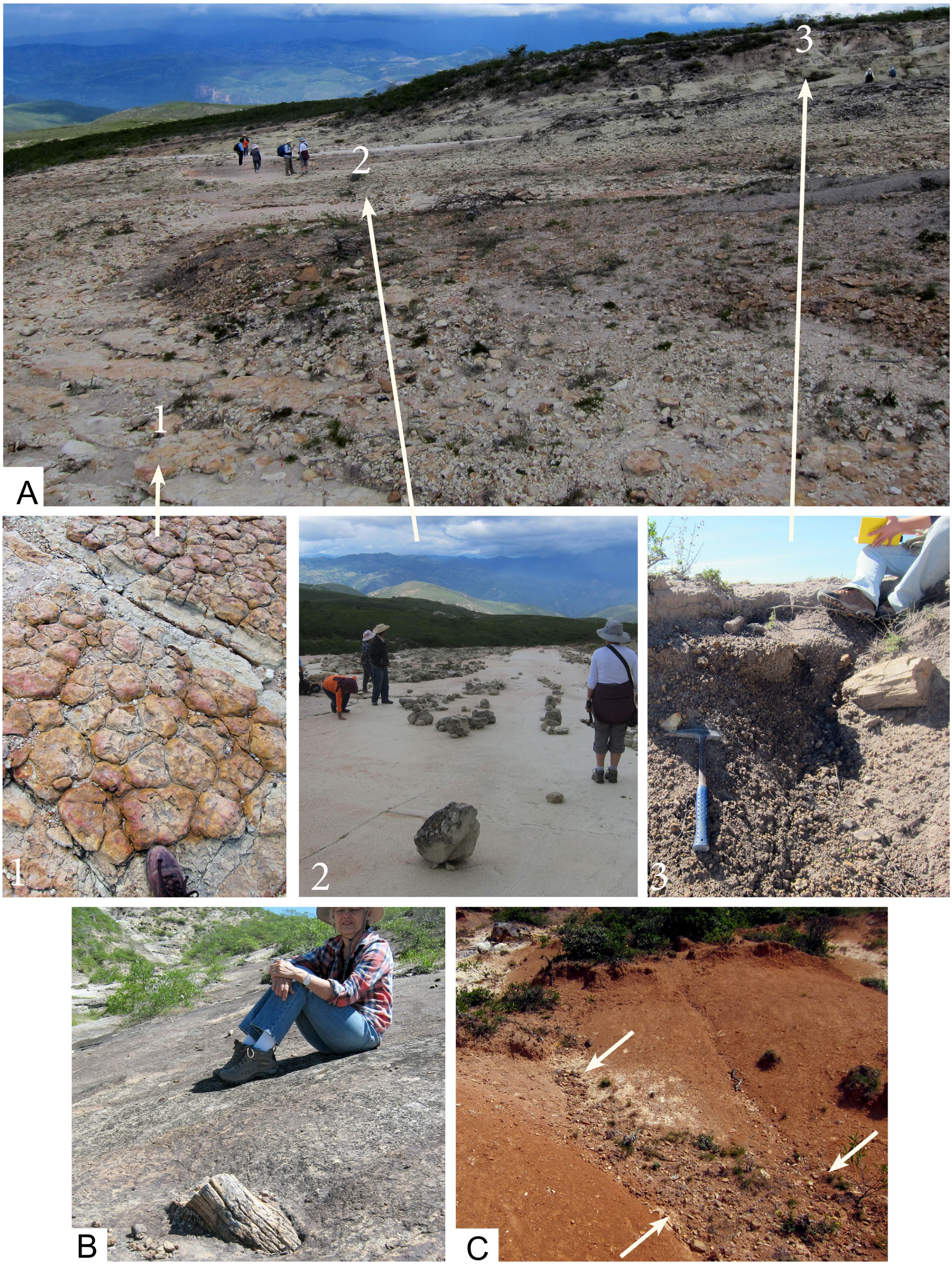

Figure 4. Fossil sites at Locations 6 and 7 near Cunyac. **A**. Overview of stratigraphic sequence at Location 6. View is looking south-southeast. The fossil woods are in a likely channel deposit in an overlying position at 3. Lacustrine sediments, in places with polygonal mudcracks, occur at 1 and 2; detrital woods are found in these areas (photo 2018); **B**. Indurated ashflow deposit containing fossil wood at Location 7 (photo 2011); **C**. Colluvium with small pieces of fossil wood (photo 2011)

forests of the Western Amazon. Represented taxa encompass genera of emergent forest trees including *Cariniana* Casar. (Lecythidaceae), *Ceiba* Mill. (Malvaceae – Bombacoideae), *Cynometra* L. (Fabaceae); a wood showing close affinity with *Prioria* Griseb. (Fabaceae), which has one neotropical representative in seasonally flooded coastal forests; lianas (cf. *Thiloa* – Combretaceae); understory elements – *Tabernaemontana* Plum. ex L. (Apocynaceae), *Miconioidea* Woodcock, Meyer et Prado (Melastomataceae); a mangrove taxon – *Avicennia*; a diverse array of malvaceous taxa including well-known elements of the neotropical flora (*Ochroma* Sw., *Sterculia* L., *Ceiba* Mill. species); and a diversity of palms as well as non-palm monocots – all consistent with a diverse, lowland tropical forest in a near-coastal location. However, the assemblage also includes woods with Asian affinities – *Lagerstroemia* L. (Lythraceae) and *Grewia* L. and *Grewinium* (Bande et Srivastava) Srivastava et Guleria (Malvaceae) – and/or with relatives currently very rare in Amazonia. An example of the latter is cf. *Pseudomonotes* A.C.Londoño, E.Alvarez et Forero, in a family, Dipterocarpaceae, typical of Southeast Asia. Several of the woods – *Dalbergia* L.f. (Fabaceae), *Cordia* L. (Cordiaceae), *Lagerstroemia* L. species – are semi-ring-porous, an anatomical pattern uncommon in New World tropical forests. The Asian and semi-ring-porous component of the vegetation suggests a more dry-adapted plant association occupying interfluvial areas and adapted to a markedly seasonal precipitation regime without an analog in the modern South American tropics. The presence of Asian elements has been noted in both Neotropical and North American temperate latitude Cenozoic fossil floras (e.g. Wheeler and Dillhoff, 2009; Martinez et al., 2013, 2024; Herrera et al., 2024).

The fossil leaves comprise 31 non-monocot angiosperms and multiple monocot fragments (Allen et al., 2023). This number of morphotypes is notable considering that the entire leaf assemblage consists of just 210 specimens. The leaves were excavated from the ashfall deposit in the southwestern part of the in situ assemblage from Location 1 (Fig. 2C, D, our field site SX-08). They were found above the paleosol/ashfall contact in the ash layer underlying the ashflow deposits. The leaves may also have been damaged by falling ash and accretionary lapilli during deposition in the coarse ash. It is likely that the ashfall stripped the leaves from the trees, depositing them in the immediate vicinity, and that the leaf flora represents a highly localized sampling of the vegetation. The thicker, more sclerophyllous leaves are more likely to have been preserved and also more readily recovered. The most common morphotype has characteristics consistent with extant *Avicennia* L.; however, many taxa, especially tropical species, have similar leaf architecture so other affinities cannot be excluded (Allen et al., 2023).

The leaf flora is notable for the small size of the leaves (primarily in the microphyll and notophyll size categories) and the prevalence of untoothed margins (leaves are 100% entire margined). Floral assemblages dominated by these leaf sizes are anomalous in the modern-day tropics but occur in the Esmeraldas flora (late Middle Eocene of Colombia, Martínez et al., 2021). Univariate analysis of the leaf characters suggests warm conditions with precipitation lower than that in the present-day tropical rainforests; these estimates are consistent with those derived from analysis of the woods (Woodcock and Meyer, 2020; Allen et al., 2023).

THE IN SITU FORESTS

Fossil assemblages with trees still in growth position include the two in situ forests at Location 1 (Fig. 1C) and others occurring elsewhere in the area. These assemblages capture a snapshot of the paleovegetation and paleoenvironment at a specific time and place in the past. The in situ forests in Sexi are both critical to the paleoecological interpretations and of significant scientific importance for what they can say about South American forest history and the evolution of specific plant taxa and clades. Moreover, they provide unequivocal evidence of low, near sea-level elevation areas in the Eocene, which is crucial for reconstructing the topographic history of the Andes. Assessment of these assemblages and associated paleosols is ongoing.

IN SITU TREES

The in situ trees near Sexi occur over a ~300 × 100 m^2 area due east of town (field sites SX-05 to SX-09) and also at one location to the southeast (SX-12) along the southern escarpment of the plateau (Fig. 1C). They are associated with the ashfall deposits (about 1 m thick) and paleosols that underlie the thick lapilli tuff containing the largest volume of fossil wood (Woodcock et al., 2009). Included are vertical elements and also trunks oriented more horizontally. Along the outcrop that runs through this part of the site, there are vertically oriented trees that can be seen to be rooted in the lowermost paleosol (Fig. 5A, C, D). Trees associated with the upper paleosol have not been documented thus far, but their occurrence seems likely given the leaves that have been recovered from the ashfall deposit. There are also fossil trees that protrude above the ash layer (Fig. 5B) and appear to have been broken off at or above the ashfall-ashflow contact. Both monocots (palms) (Fig. 5C) and non-monocot angiosperms are represented. We have noted the presence of spreading root systems in some specimens (Fig. 5A) but have only limited information regarding spacing and root structure. The in situ trees have diameters up to 30 cm; none reaches the size of the largest trunks in the overlying lapilli tuff (up to 0.75 m in diameter). The in situ trees are generally less well preserved than the ashflow woods and show different permineralization features (Woodcock, 2024).

In one area (SX-06, Fig. 1C) where paleosols can be traced laterally across the landscape, there are small to medium-sized trees with preserved root systems that can be seen to be spreading at/near the surface of the lower paleosol (Fig. 5A). The wood of one of these trees shows features indicating affinity with *Qualea* Aubl. (Vochysiaceae – Myrtales) and has been named as new species of *Qualeoxylon* (Woodcock, 2024). The vertically oriented lacunae lined with chalcedony (cryptocrystalline quartz) seen in this wood may represent decay attributable to white rot fungi and preservational conditions different from the ashflow woods. The *Qualea* + *Ruizterania* clade of Vochysiaceae, with approximately 60 species, occurs in a range of vegetation types in the lowland tropics of the New World. It includes tall canopy trees in terra firme Amazon forests and shorter-statured trees or treelets of the Cerrado or South American Dry Diagonal (Fern, 2018). Aspects of the anatomy (diameter of the vessels) of the fossil correspond to that seen in many of the drier-adapted species (subclade *Qualea* I of Gonçalves et al. (2020)). The spreading root structure seen in this specimen is often seen in wet areas or where there is substrate instability, as would have been the case with these volcaniclastic substrates. These trees also appear to be relatively small-statured and could be components of more open vegetation.

A second in situ tree was collected from an exposed ashfall tuff at a short distance from the other in situ trees on a southern escarpment of the plateau (Fig. 5D). On the basis of the wood characteristics, this small (7.5 cm diameter) tree or treelet has been referred to the genus *Dodonaea* Mill., which is in a subfamily of Sapindaceae (Dodonaeoideae) with a center of diversity in the New World and commonly occurs in dry areas and as strand/littoral elements (Woodcock et al., 2019). It is notable that *Dodonaea viscosa* Jacq. occurs worldwide in the tropics and subtropics and can also be found growing at the fossil sites, where it is an important pioneer species adapted to the volcanic-derived soils.

There are also places along the ash exposure where small stems can be seen embedded in the ash in both vertical and horizontal position (Fig. 5E, F). These appear to be nonwoody (herbaceous) elements with good preservation but are fragile and require care to study. We cannot provide a definite characterization of these specimens; however, their presence shows the kind of detail about the plant communities that is potentially obtainable with further study.

PALEOSOLS

Trenched exposures near the in situ forest trees show the presence of paleosols formed on fining upward sequences of volcaniclastic materials (Fig. 6) (Terry et al., 2019, 2022; Yeago, 2023). Apart from the in situ trees and associated large rooting structures, most roots are only several millimeters in diameter and are preserved as a combination of downward branching clay infills and drab haloed traces, some of which are associated with intense reddish orange staining. Zones of mottling are preserved as reddish-orange discolorations that occur at different levels in each profile. Evidence of seasonal wet/dry conditions and associated water table fluctuations are seen in thin sections as translocated clay in root voids mixed with redoximorphic staining (Fig. 7D). These soils have low bases:alumina ratios; predominance of kaolinite and quartz in the clay

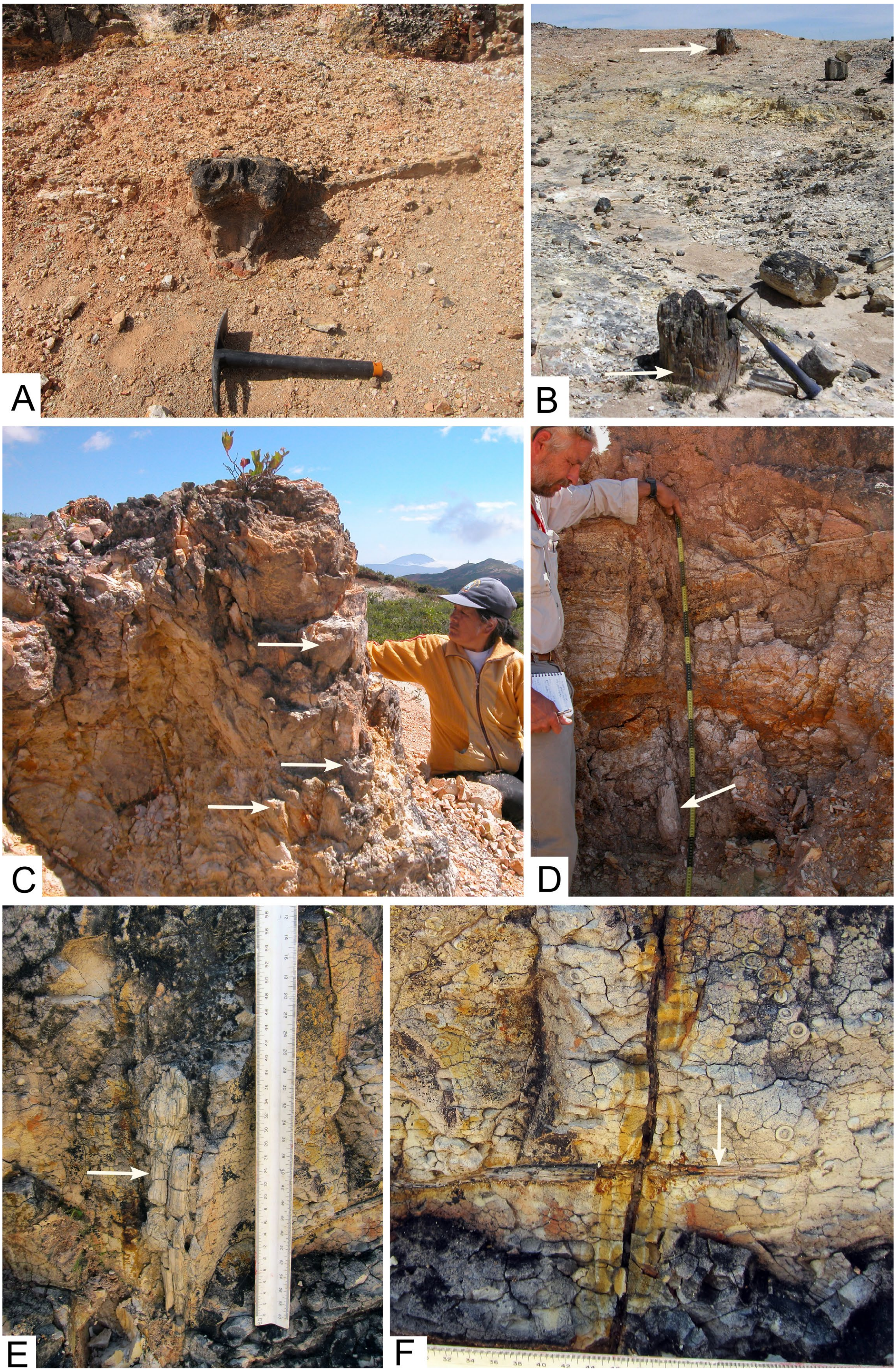

Figure 5. The in situ forest at Location 1. **A**. Small tree with extended root system associated with a paleosol (6°33′55.8″S 79°02′02.8″W); **B**. In situ trees (arrows) extending through the ash layer and appearing to be broken off near the ashflow contact (photo 2005); **C**. Palm with persistent leaf bases (arrows) (photo 2009); **D**. Small tree extending upwards from the paleosol in the lower part of the ash. A cast of this tree can be traced through the upper part of the ash. This specimen has been referred to the genus *Dodonaea* (Sapindaceae, Woodcock et al., 2019) (photo 2005); **E**, **F**. Small in situ elements. Note accretionary lapilli and ashfall/paleosol contact along the bottom of the photos (photos 2018); **E**. Small herbaceous plant in growth position in the ashfall; **F**. Small horizontal stem or root

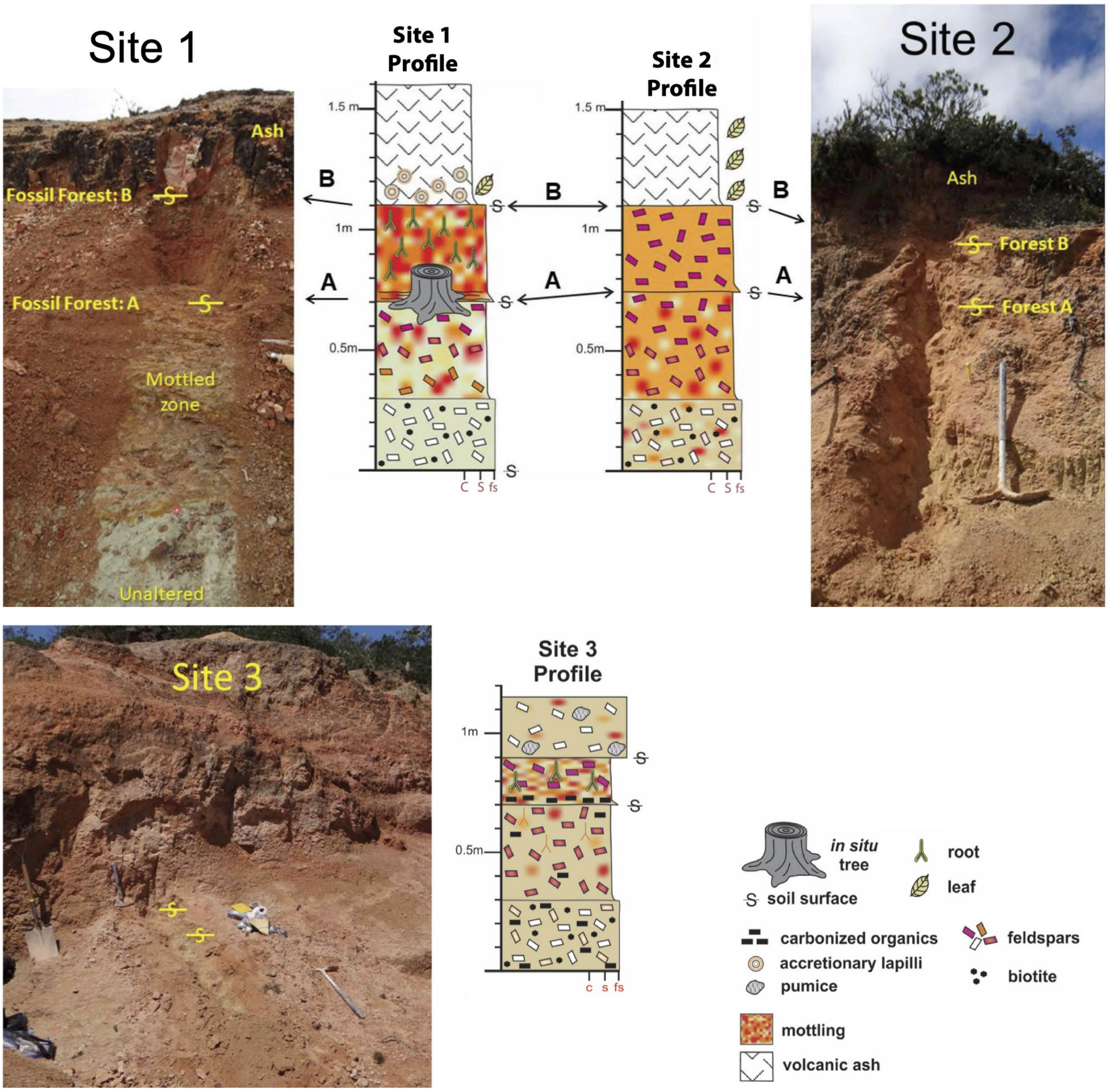

Figure 6. Soil profiles at three locations near the in situ forest trees. Paleosol Sites 1 and 2 are approximately 200 m apart. The paleosols at these sites are associated with an overlying ashfall layer and interpreted as representing the same paleolandscape. Paleosol Site 3 profile occurs ~20 m below Sites 1 and 2

mineral profiles; and low strontium:barium values (Fig. 7A–C) (Yeago, 2023). Bases:alumina ratios and clay mineralogy suggest intense stripping and weathering of paleosol profiles, consistent with humid-tropical conditions. These properties are consistent with highly weathered soils occurring in a seasonal climate with a fluctuating water table and freshwater rather than brackish or saline conditions, in agreement with the reconstruction of seasonally flooded and drier forest associations based on the macrofossils.

The profiles at Paleosol Sites 1 and 2 (Fig. 6), which are at a distance of ~200 m, are interpreted as representing the same paleo-landscape. Comparisons of the two profiles suggest slight differences in geomorphic position over this distance. Both sites preserve the same thickness of individual fining upward packages, but mottling is more pronounced in Site 1 (Figs 6, 7), suggesting a greater amount of hydromorphy and a lower position on the paleolandscape.

Paleosol Site 3 is located several tens of meters below Sites 1 and 2 and also represents pedogenic modification of a fining upward volcaniclastic sequence (Fig. 6). No trees were found at this site, but the same reddish-orange hydromorphic mottling is present toward the top of the profile. This profile is in most respects identical to the paleo-landscape of Sites 1 and 2 apart from the greater amount of coalified/charcoal plant remains disseminated throughout, and within a smaller overlying volcaniclastic interval with concentrations of carbonized plant remains at its base.

Although our studies have been limited in extent, observations of geologically older exposures near the fossil sites suggest a combination of fluvial and lacustrine environments with paleosols that formed along both low-lying and extremely well-drained geomorphic positions. These findings thus largely corroborate our earlier studies (Woodcock et al., 2019; Woodcock and Meyer, 2020) reconstructing the paleovegetation as a seasonally flooded tropical lowland forest.

DISCUSSION

The in situ forest assemblages of the Piedra Chamana Fossil Forest are examples of T^0, or time-zero, assemblages (DiMichele and Falcon-Lang, 2011). These types of fossil assemblages are particularly well documented in the late Paleozoic and provide unsurpassed information about past ecosystems and the biases influencing preservation that are important in interpreting the fossil record. Their study allows for whole plant reconstruction and determination of forest structure, changes

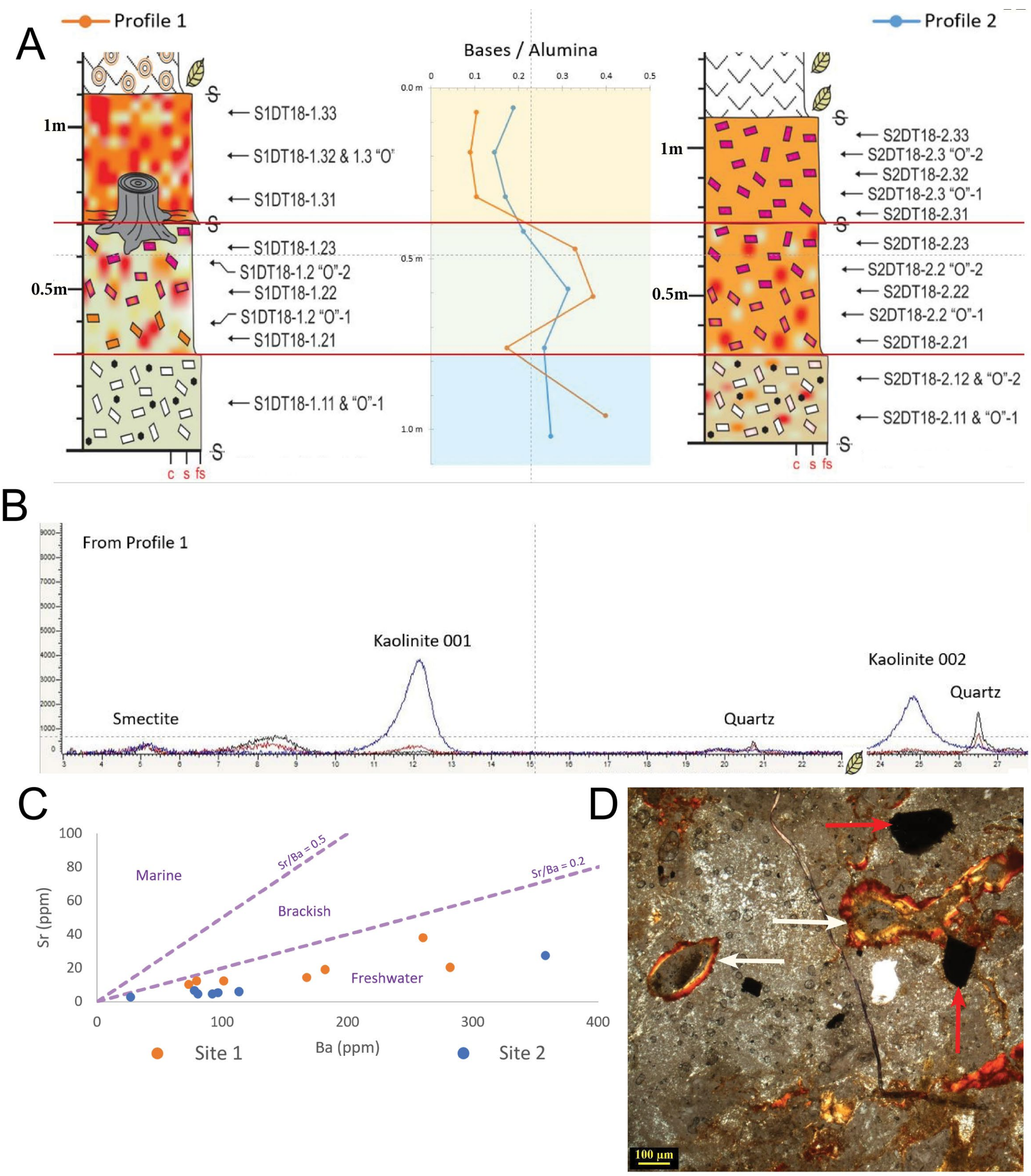

Figure 7. Results of paleosol analysis. **A**. Bases:alumina ratio sampled through the soil profiles at Paleosol Sites 1 and 2 (key in Fig. 6); **B**. X-ray diffractogram showing clay mineral composition of the paleosols. Values <1 are associated with acidic and/or highly weathered soils; **C**. Strontium:barium ratio for Paleosol Sites 1 and 2; **D**. Petrographic thin section showing iron oxide- and clay-lined voids (white arrows) and charcoal fragments (red arrows)

along environmental gradients, and many other aspects of the vegetation and paleoenvironmental context, information that would otherwise be impossible to obtain (DiMichele and Falcon-Lang, 2011). Rapidly deposited ashfalls like those preserving the fossils at the Piedra Chamana site can result in near-instantaneous burial and exceptionally detailed records and thus be particularly valuable.

The factors typically required for preservation of T^0 assemblages are relevant to interpreting the fossils and understanding their geologic, taphonomic, and paleogeographic context. These types of assemblages typically require rapid burial, existence of sufficient accommodation space for sediment accumulation, a position below the water table to protect from aerobic decay, and burial to a depth preventing erosion over longer time scales, conditions most likely to be met near regional base level or sea level in coastal locations (DiMichele and Falcon-Lang, 2011). The predominantly wetland settings in which T^0 assemblages occur have been related to high accommodation space associated with rise of regional base level in wetter conditions and also eustatic sea level rise (DiMichele and Falcon-Lang, 2011). In the case of the Eocene in situ forest in Sexi, many of these factors were likely present. The region was at very low elevation in a coastal/near-coastal setting (Woodcock et al., 2017, 2019; Woodcock and Meyer, 2020). Burial of the in situ trees in the ashfall was nearly instantaneous. A high water table is indicated by the mottling seen in the paleosols and the occurrence of flooded forest taxa. Protection from erosion over the near term and subsequent permineralization was favored by emplacement of overlying ashflow deposits and ignimbrites and locally high sedimentation rates linked to volcanic processes.

The Sexi region was part of the Pozo-system marine embayment that occupied western Amazon during this time in the Eocene (Custódio et al., 2023; Baby et al., 2025). This embayment is one of several Cenozoic marine incursions into western Amazonia and could be linked to eustatic sea level rises during times of high temperatures (Baby et al., 2025). The Pozo embayment, with its associated wetland, extended from Peru into Ecuador and Colombia and opened either to the Pacific in the area of the Gulf of Guayaquil and/or the Caribbean (Santos et al., 2008; Custódio et al., 2023; Baby et al., 2025).

CONSERVATION ISSUES

The fossils of the Piedra Chamana Fossil Forest gained scientific attention in 1994, when specimens were brought to the Museo de Historia Natural in Lima and identified as plant fossils. The research staff of the museum (Guillermo Morales and Ysabel Prado) subsequently traveled to the site, explained the significance of the fossils to the community, and pursued protections for the fossils. In 1997 the fossils were declared cultural patrimony of Peru and commemorated with a postage stamp issued in 2000 featuring a photograph by the noted photographer Heinz Plenge. Unfortunately, protections pertained only to the fossils and not the site itself. Education and outreach efforts and paleontological resource assessment by our research team have received support from the US National Park Service (through Florissant Fossil Beds National Monument and The Friends of the Florissant Fossil Beds). A series of site plans beginning in 2005 included suggested routes for interpretive trails and recommendations for fencing of important areas and revegetation with native species to mitigate the high susceptibility of the soft volcanic rocks to erosion. The suggestion has also been made that the road extending down from the plateau to the south be moved away from the fossil sites. A site inventory and monitoring program was implemented in 2005; subsequent follow-up monitoring in 2018 documented disturbance and loss of fossil material, including significant specimens, over this period of time (Woodcock et al., 2020). The need for protection and conservation is mentioned in many scientific publications. Researchers have also advanced the idea that the scientific significance and natural beauty of the site merits recognition by the World Heritage program of UNESCO (Woodcock et al., 2020). Until recently the Peruvian Ministry of Culture had jurisdiction over the fossils. With the enactment in 2021 of Law No. 31204, the General Law of Paleontological Heritage of Peru, the Geological, Mining and Metallurgical Institute (INGEMMET) is designated as the governing body. This institution has conducted research related to the geology and paleontology of the fossil forest (Navarro et al., 2013; Tejada et al., 2013) and provided additional information emphasizing its scientific value as a Site of Paleontological Interest and supporting its designation and declaration as a Paleontological Zone of Peru.

Of the fossil localities described above and mapped in Fig. 1C, we are especially concerned about the lack of protections (fencing, site security) at Locations 1 and 2, which are easily accessible from the road and include the in situ forest assemblages, dense surface concentrations of fossil woods including some of the largest specimens, and the fossil leaf site. There is very little vegetation cover in this area, and significant erosion from El Niño related rains threaten the integrity of these sites. Also of particular concern are Locations 6 and 7 at Cunyac, where there is a diverse assemblage of well-preserved woods as yet unstudied; these sites are in close proximity to the 200-acre open pit mine where the cement additive pozzolana is mined. A substantial amount of fossil material has been lost due to extractive activities, and mining concessions cover almost the entire area where there are fossils. We note, however, that procedures could be implemented to recover and document fossils uncovered during the course of mining operations.

A common development model involves outreach, education, and empowerment of local communities to protect and develop significant sites like the Piedra Chamana Fossil Forest. This approach has many advantages, as evidenced by other sites worldwide where geotourism has been used to leverage economic sustainability, but it can also face significant obstacles. In the case of the fossil forest at Sexi, these include: complicated land tenancy in the fossil areas, which include communally owned lands; distance from the departmental capital and closer cultural and economic ties to Pacific coastal cities; and general lack of economic resources. Assistance to owners of communal shares and their descendants living in the area so they can develop economic opportunities based on geotourism, ecotourism, or marketing of local crafts rather than extractive activities or cattle ranching would have many benefits. The area is marginal for agriculture and experiences La Niña-related droughts and resulting shortages of potable water and forage for animals. Other important goals are to protect and restore modern soils, develop a management plan for the limited areas suitable for agriculture, and restore vegetation cover elsewhere. Stabilization and reforestation efforts would protect the fossil sites, as well as local water supplies and could be carried out in partnership with jurisdictions in the lower part of the Chancay Valley (Lambayeque, Chiclayo, Ferreñafe) to benefit their water security.

FUTURE PROSPECTS

RESEARCH

High priority needs to be given to further field surveys documenting the range of fossil sites and their stratigraphic context. This work will increase our understanding of the geological context and taphonomy of the fossils, the spatial continuity of the fossiliferous strata, and stratigraphic relationships. It will clarify many outstanding questions. For example, whether the deposits a) include strata that are sequential and can provide information about vegetational and environmental changes over time or b) are spatially extensive across the range of environments that might be expected in a near-shore, coastal flat setting with intermittent volcanic activity. Palynological survey work in 2024 did not recover palynomorphs with good preservation, but the potential still exists to tie the site to the Cenozoic pollen chronology being established for northern South America (Jaramillo et al., 2011, 2025). More information about the lacustrine and likely near-shore marine sedimentary deposits present in the area should also make it possible to correlate this major terrestrial fossil locality with the marine record of climate and global change.

At a finer scale, the in situ forests hold the promise of providing information about the vegetation and environments occurring at a specific place and time unprecedented in its detail and significance for our understanding of New World vegetational history. The work of describing the specimens now in collections also continues. In particular, the diverse monocot component of the vegetation is very incompletely documented. It is evident, however, that the material collected represents only a fraction of the biodiversity present and that there is a need for further collection and study of the permineralized specimens that are present at the site and vulnerable to disturbance and illegal collecting.

CONSERVATION

The stratigratigraphic survey work discussed above is also critical to conservation objectives and the protections that need to be enacted. We envision that this work will include an inventory and assessment along the lines of Arias et al. (2025) that have been successful in promoting geoheritage elsewhere in Peru. The approach taken involves 1) classification of potential geosites according to their scientific, educational, and touristic value, 2), evaluation of degradation risks and potential threats, and 3) recommendations on geosites selection. The benefits from this work will be considerable. It will help in site management by increasing our understanding of the geological hazards at the fossil site, which we know encompasses faults and areas prone to slumping. It will facilitate inclusion of fossil forest sites in local touristic circuits in this region of Peru; for example, the route extending from the coast and archeological and natural history sites in Lambayeque up the scenic Chancay Valley to the Monte Seco reserve (Bosques Nublados de Udima), the baths and protected area of Chancay Baños and Reserve Zone, and the fossil forest on the plateau just beyond. It will provide a framework for local planning and conservation efforts involving the community, municipal government, and governmental agencies. It will promote recognition of Peru's palaeontological heritage with the World Heritage framework. Peru already has one Global Geopark (Colca y Volcanes de Andagua), and there is one in Ecuador, one in Chile, and six in Brazil (unesco.org).

There is clearly a need for partnerships that will bring people together to realize shared goals and seek resources beyond those available locally. Organizational partners should include INGEMMET, which is the governing authority for palaeontological heritage, fossils, and palaeontological zones of Peru; the Universidad Nacional Pedro Ruiz Gallo, whose faculty and students have studied erosion, site stabilization, and land use in the fossil forest area; the Museo de Historia Natural of the Universidad Nacional Mayor San Marcos in Lima, where the fossils are archived; and government agencies at local, regional, and national levels. We also hope that the US National Park Service and Florissant Fossil Beds National Monument and its nonprofit affiliate The Friends of the Florissant Fossil Beds in Colorado will continue their longstanding involvement with research and education at the site. Ideally there should also be a scientific and resource advisory board including representatives from the local community to advise on research matters and protection and development of the site.

CONCLUSIONS

Our continued study of the fossils and fossil localities shows ever more clearly the importance of the fossils as an unparalleled source of information about South American geologic and paleobotanical history. The fossil assemblages document the Eocene occurrence of tropical lowland vegetation with floristic similarities to present day tropical forests along with some anomalous features and elements that may indicate an Eocene tropical climate without an analog in the modern South American tropics. The scientific importance of these sites rests on the highly detailed information obtainable from study of the fossil woods, the presence of fossil leaves as well as woods, the in situ forest assemblages still incompletely studied, and the range of vegetation types and environments represented. All indications are that scientific studies at this site will be ongoing well into the future. However, threats to the site, both natural and human-induced, jeopardize its scientific integrity and potential. We thus restate our hope that protections can be enacted, and the site developed in a way that benefits both local communities and future generations of scientists who will be interested in visiting the fossil forest and studying the fossils.

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ADDITIONAL INFORMATION

CONFLICT OF INTEREST. The authors have declared that no competing interests exist.

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