PLANT TAPHONOMY AND PALEOENVIRONMENT OF THE BAHÍA LAURA COMPLEX, MIDDLE–LATE JURASSIC, AT THE LAGUNA FLECHA NEGRA LOCALITY (SANTA CRUZ PROVINCE, ARGENTINA)

ANA JULIA SAGASTI¹,²
DIEGO M. GUIDO¹,²
JUAN L. GARCÍA MASSINI¹,³
KATHLEEN A. CAMPBELL⁴

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Studied assemblage is ascribed to a mixed Onslow–Ipswich palynoflora.

Preservation of a Jurassic flora is determined by associated volcanic and geothermal system.

The henricosborniid *Nanolophodon tutuca* is newly described from the Itaborai Basin.
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ANA JULIA SAGASTI1, 2, DIEGO M. GUIDO1, 2, JUAN L. GARCÍA MASSINI1, 3, AND KATHLEEN A. CAMPBELL4

1Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). anajusagast@gmail.com; anajusagasti@fcnym.unlp.edu.ar
2Instituto de Recursos Minerales (INREM-U NLP), 64 no 3, B1904AMC La Plata, Buenos Aires, Argentina. diegoguido@yahoo.com
3Centro Regional de Investigaciones Científicas y Transferencia Tecnológica de La Rioja (CRILAR-CONICET), CONICET-Provincia de La Rioja-UNLaR-SEGMAR-UNCa, Entre Ríos y Mendoza s/n, 5301 Anilaco, La Rioja, Argentina. massini112@yahoo.com.ar
4School of Environment, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand. kia.campbell@auckland.ac.nz

Abstract. Taphonomic studies were carried out at Laguna Flecha Negra locality (Bahía Laura Complex, Middle–Late Jurassic), Santa Cruz Province, Argentina. Sedimentary facies and preservational styles were defined to recognize plant taphofacies in the studied sequence. Eleven taphofacies were identified and plant sources within a volcanic and geothermal system are proposed. Plant remains are of autochthonous to para-autochthonous origin and best preservation was found in distal facies of siliceous hot spring (sinter) systems. Lateral and vertical taphonomic differences were found in the studied sequence. These are due to changes in the sedimentary input and distance to the geothermal fluids. Results enable the reconstruction of the depositional history of this region of the Deseado Massif geological Province. We infer formation of a hot-spring (sinter) system that was subsequently destroyed by a phreatic eruption process at the margin of an andesitic effusive dome in partially reworked fall pyroclastic subfacies. After the destruction of the geothermal system, a fluvial and lacustrine epiclastic subfacies developed preserving a plant community typical of the Middle–Late Jurassic of Gondwana. Later, volcanic activity produced pyroclastic subfacies, with thick ash-fall and flow deposits from different sources and separated by a time gap that promoted fossilization of an in situ forest. Taphonomic studies of these plant communities allowed reconstruction of a chain of geological events and how these processes have influenced the preservation of a Jurassic flora from Patagonia, thus contributing to an understanding of the paleoecology of the Deseado Massif geological province.

Key words. Paleobotany. Taphonomy. Geothermal wetlands. Volcaniclastic deposits. Paleoenvironmental reconstruction. Deseado Massif.

Resumen. TAFONOMÍA DE PLANTAS y PALEOAMBIENTE DEL COMPLEjo BAHÍA LAURA, JURÁSICO‒MEDIO‒SUPERIOR, EN LA LOCALIDAD LAGUNA FLECHA NEGRA (PROVINCIA DE SANTA CRUZ, ARGENTINA). Se realizó el estudio tafonómico de la Localidad Laguna Flecha Negra (Complejo Bahía Laura, Jurásico Medio‒Superior), Provincia de Santa Cruz, Argentina. Se reconocieron las facies sedimentarias y los estilos preservacionales para definir las tafofacies en la secuencia estudiada. En este trabajo se identifican once tafofacies para plantas y se proponen las fuentes de aporte de material vegetal dentro de un marco geológico de sistema volcánico y geotermal. Los restos corresponden a plantas autóctonas a parautóctonas, y su mejor preservación se observa en facies distales de sistemas geotérmicos silíceos. Se encontraron variaciones tafonómicas laterales y verticales en la secuencia estudiada. Estas diferencias se atribuyen a cambios en el aporte sedimentario y a la distancia a las emanaciones geotermicas. Los resultados obtenidos permiten reconstruir la evolución geológica en esta región del Macizo del Deseado. Se interpreta la generación de un sistema de hot-spring silíceo que fue destruido subsecuentemente por una erupción freática en el margen de un domo andesíctico en facies de flujo piroclástico parcialmente retrabajado. Luego de la destrucción del sistema geotermal, se desarrollaron subfacies epiclásticas fluviales y lacustres en las cuales se produjo la fosilización de una comunidad vegetal jurásica. La actividad volcánica de la región dio origen a subfacies piroclásticas, con potentes depósitos de caída y flujo piroclásticos con distintas procedencias, y separados por un hiato temporal que promovió la fosilización de un bosque in situ. Los estudios tafonómicos de estas comunidades vegetales permitieron reconstruir una serie de eventos geológicos y cómo estos procesos influenciaron la preservación de una flora Jurásica de Patagonia. Con este trabajo se contribuye al conocimiento de la paleoecología de la provincia geológica del Macizo del Deseado.

Palabras clave. Paleobotánica. Tafonomía. Humedales geotérmicos. Depósitos volcániclásticos. Reconstrucción paleoambiental. Macizo del Deseado.

TAPHONOMY is the science that examines the processes affecting organism remains during fossilization, burial, and exhumation (Brenchley & Harper, 1998). It is a term forged by Efremov (1940) to refer to the history of fossilized remains. Traditionally, taphonomy includes two aspects: biostratinomy and fossil diagenesis. Biostratinomy includes the
sedimentological history of the organic remains, up to and including burial (Gee & Gastaldo, 2005). This includes abra-
sion, fragmentation, dislocation, reorientation and sorting, collectivity a set of processes that can be recognized in the
fossil record (Speyer & Brett, 1988; Fernández-López & Fernández-Jalvo, 2002). Fossil diagenesis includes those
processes that start after the burial of an organism or a portion of the organism, which convert the organism into a fossil
(e.g., compression, recrystallization, replacement) (Gee & Gastaldo, 2005). These processes lead to physical and
chemical balance between the plant remains and the sedimentary environment (Martín-Closas & Gómez, 2004). Burial
of organic remains may lead to the loss of information (e.g., due to the selective preservation of different organs), but at
the same time may provide additional information, since each type of fossil is indicative of the depositional environ-
ment in which these remains have been accumulated, as well as subsequent history. Fossilization might favor the
appearance of preservational modifications, which may therefore increase the available taphonomic information
(Fernández-López, 1991). In such circumstances, the taphonomic history of organic remains may be strongly correlated
to the environmental conditions and sedimentary environment, as reflected in various taphonomic attributes (Speyer
& Brett, 1988; Allison & Bottjer, 2011).

Taphonomic facies, or taphofacies, consist of suites of sedimentary rock characterized by combinations of preser-
vational features of the contained fossils (Brett & Baird, 1986; Brett & Speyer, 1990). The concept of taphofacies
describes the different types of preservation found through a sedimentary succession, and the different types of preser-
vation and modes of occurrence of different fossil taxa within individual horizons (Speyer & Brett, 1986, 1988).
These differences allow recognition of patterns of temporal and spatial distribution of fossil remains in fossil assem-
blages; they are the basis to integrate information about species distributions and process-product associations of
the fossil remains (Speyer & Brett, 1988). The taphonomic properties of a taphofacus (i.e., a group of remains that
were buried together) are the product of specific environmental conditions (Brett & Baird, 1986); specifically, tapho-
facies are generated by an interdigitated mosaic of environmental conditions. In this sense, taphofacies models
describe the distributions of taphonomic conditions that have a direct correspondence with environmental phenom-
ena that can be empirically determined (Speyer & Brett, 1988). In plants, taphonomic studies incorporate the com-
plexity of different organs (e.g., roots, branches, leaves, seeds) behaving differently under the same environmental
processes and conditions (Colombi & Parrish, 2008; Bodnar, 2010), and the same organ behaving differently when en-
vironmental conditions change (Bodnar, 2010). In this sense, taphonomic studies of plants are a potent tool for
paleoenvironmental and paleoclimatic reconstructions (Bodnar, 2010).

The Middle-Late Jurassic Bahía Laura Complex in Santa Cruz Province hosts fossil-rich deposits formed in or at the
margins of geothermal systems (Channing et al., 2007; Guido & Campbell, 2009, 2011, 2012, 2017, 2019; Guido et
al., 2010, 2019; García Massini et al., 2012a, 2016; Sagasti et al., 2016, 2018, 2020). These are comparable to the
famous Devonian Rhynie Chert (e.g., Channing et al., 2011; García Massini et al., 2012a, 2016); however, the deposits
from Bahía Laura Complex crop-out in large geothermal fields that have experienced low to none post-depositional
disturbance (i.e., tilting, faulting). Plant fossils from the Deseado Massif paleo hot springs are distributed over
different geothermal sub environments, presumably following specific ecological preferences (Channing et al.,
2007, 2011; Guido et al., 2010; García Massini et al., 2012a, 2016; Sagasti et al., 2016). Silicification processes affecting
these environments have also lead to fossilization of interactions between plants, arthropods, fungi and other
microorganisms (García Massini et al., 2012b, 2016; Sagasti et al., 2018). In this paper, we provide the first description
and interpretation of plant taphofacies in the Bahía Laura Complex at the Laguna Flecha Negra locality, Santa Cruz
Province, Patagonia, Argentina. We integrate these taphofacies with depositional models for siliceous hot
spring deposits, or sinters, volcanic and volcaniclastics rocks, intending to reconstruct the paleoenvironmental
settings in which the fossil plant assemblages were preserved.

Institutional abbreviations. MPM PB, Museo Padre Jesús Molina, Paleontological Collection, Santa Cruz Province,
Argentina.
MATERIAL AND METHODS

Field methods included a detailed sedimentological logging of the outcrops taking into consideration grain size, color, composition, primary sedimentary structures, and geometry of the horizons, as well as contacts and vertical passage between successive rock beds (Selley, 2000). During logging we identified the fossil-bearing levels mentioned in an initial report of this locality (Channing et al., 2007). For each fossil horizon a detailed description of the fossil remains in situ was made (i.e., type of organs, sorting, degree of fragmentation, density, and spatial distribution).

Sedimentary facies were defined following the criteria of Walker (1992), Reading and Levell (1996), Scasso and Limarino (1997) and Miall (2006). Walker (1992) defines the concept of facies as a rock body characterized by a particular combination of lithology and physical and biological structures that generate an aspect (=facies) that is different from the adjacent rocks. The characterization of clastic rocks requires an initial identification of the lithology in terms of composition, texture, sedimentary structures, the geometry of the bedding, paleocurrents, and fossil content (Scasso & Limarino, 1997). Detailed analysis of these features allows the definition of facies present in a rock sequence, which, along with the application of Walther’s Law, is essential to recognize the genesis of sedimentary deposits and paleoenvironmental changes through time. The analysis and interpretation of the facies association were made following the criteria of Guido (2004). The sedimentological section was illustrated using CorelDraw 2019, with a scale of 1:250.

Ten preservational styles have been defined at the Laguna Flecha Negra locality: (1) individual permineralization of roots (Rp), (2) stem casts (Cs), (3) carbonized wood (Cw), (4) massive siliceous permineralizations (Ch), (5) individual permineralizations of stems (Ps), (6) impressions of leaves, leafy twigs and reproductive structures (I), (7) impression-compressions (IC), (8) vertical silicified stems and stumps (Sv), (9) horizontal to oblique silicified stems and stumps (Sh), and (10) compressions of plant debris (D). Different types of fossils were classified following the criteria of Archangelsky (1970), Willis and McElwain (2002) and Taylor et al. (2009). For the definition of taphofacies, a combination of codes of letters for the preservational styles and lithofacies was applied following the criteria of Speyer and Brett (1986, 1988), Guido (2004), Colombi and Parrish (2008) and Bodnar (2010). The attributes used are as follow: sedimentary facies, types of fossils, density, and degree of fragmentation. Comparisons were made with models of sedimentation in geothermal environments of the Deseado Massif (Guido et al., 2010, 2019; Guido & Campbell, 2011) and with modern geothermal systems (Channing & Edwards, 2013; Channing, 2017).

Geological setting

The Deseado Massif, Santa Cruz Province (southern Patagonia), is a geological province with a 60,000 km² areal range, that is characterized by extensive Middle to Late Jurassic bimodal volcanic rocks, including calc-alkaline rhyolites and minor andesites and dacites (Guido & Campbell, 2011). Jurassic volcanic units recognized in the province are included in the Bahía Laura Complex which encompasses: The Bahía Laura Group (La Matilde and Chon Aike formations), represented by the extensive acid volcanic rocks (Guido, 2004), and the andesites of the Bajo Pobre Formation; these are genetically related units that appear intercalated in several localities in Santa Cruz Province (Guido & Campbell, 2011). Bahía Laura volcanic rocks and related hydrothermal mineralization of the Deseado Massif were formed due to extension, magmatism, and a high thermal gradient from Middle to Late Jurassic (Guido & Campbell, 2011). Radiometric analysis estimate that volcanism and crustal extension occurred between 177.8 and 153.4 Ma (Féraud et al., 1999, Pankhurst et al., 2000). Studies were conducted at the Laguna Flecha Negra locality, in a region located around 69° 48' W and 47° 55’ S, in the Deseado Massif geological province, approximately 100 km NNE from Gobernador Gregores, in Santa Cruz, Argentina (Fig. 1). This locality is included in the topographic chart 4669-I (Gobernador Gregores) at a 1:250,000 scale (Panza & Marín, 1998). The Laguna Flecha Negra locality records a fossil flora contained in rhyolitic, pyroclastic and epiclastic (fluvial) deposits with chert lenses located in the western edge of a 400 m diameter dry lagoon (Figs. 1, 2) (Channing et al., 2007; Sagasti, 2018; Sagasti et al., 2018, 2020). The outcrop sequence of Laguna Flecha Negra has been attributed to Middle-Late Jurassic Chon Aike and Bajo Pobre formations based on lithological characteristics and stratigraphic relationships with the units of the Bahía Laura.
Group (Channing et al., 2007). The Bajo Pobre, Chon Aike and La Matilde formations intercalate variably along Santa Cruz Province, thus we prefer the use of volcanic facies within the Bahía Laura Complex stratigraphic unit, as proposed by Echeveste et al. (2001) and Guido et al. (2006). Table 1 summarizes the facies defined for the Laguna Flecha Negra outcrops.

The lowest part of the Bahía Laura Complex at Laguna Flecha Negra comprises an andesitic lava dome (Figs. 1.1, 2, Ld facies). These lavas contain angular basic xenoliths and evidence of hydrothermal and weathering alteration such as degraded biotites and blue-green coloration. The margins of the outcrops of the lava have been weathered to an orange residue.

Stratigraphically above this unit is an unconformity overlain by a 12.5 m thick horizon of coarse, massive, white-colored volcanic sandstone (Figs. 1.1, 2.1–2, Scm facies). Weathering at this stratigraphic level is evidenced by an orange-mottled surface. The sandstone comprises angular volcanic lithic clasts and eroded feldspar crystals. The sandstone level contains fossil plants preserved as impressions, casts, compressions, small carbon pieces, and permineralizations. Two chert lenses (Figs. 1.1, 2.2, facies Ch) of 20 cm thickness each are contained within the sandstone.

Conformably overlying the white sandstone is five meters of interbedded fine sandstone and dark siltstone (Figs. 1.1, 2.3, facies SfSc). Bed thicknesses increase upwards to 10–35 cm, each with upward-fining sand to silt internal structure. These beds are initially cross-bedded and then transition upwards to parallel bedding. Bedding surfaces contain heavily weathered volcanic clasts, ash particles and mica flakes. A well-preserved flora was collected from SfSc facies (Sagasti et al., 2020).
TABLE 1. Facies code for the outcrops of Laguna Flecha Negra locality.

| Code | Lithology          | Fossil content                                      | Thickness | Geometry | Main features                                                                 |
|------|--------------------|-----------------------------------------------------|-----------|----------|--------------------------------------------------------------------------------|
| Ld   | Andesitic lava     | –                                                   | ?         | Dome     | Angular mafic xenoliths. Alteration from degraded biotites to green-blue lavic fragments. Intense weathering at the margins. |
| Scm  | White volcanic sandstone | Permineralized roots, impressions and casts of stems, permineralized stems of medium size | 12.5 m    | Tabular  | Coarse grain angular volcanic clasts and eroded feldspar crystals. Massive.     |
| Ch   | Chert              | Abundant Permineralized plant fragments             | 20 cm     | Lenticular | Chert lenses with abundant vegetal detritus distributed in a massive silica matrix, some appear parallel to the chert limits. |
| SfSc | Dark sandstone and siltstone | Well preserved fossil flora of impressions and impression-compressions | 10–35 cm  | Tabular  | Fine grain. Stratification surfaces with strongly weathered volcanic clasts, ash particles and mica flakes. Fining upwards from fine sandstone to siltstone. Cross-lamination that goes parallel at the top of the horizons. |
| Tm   | White tuffs        | In situ permineralized forest                        | 15 m      | Tabular  | Coarse to fine grain. Massive, with an upward-finning tendency. End-up in thin lapilli horizons. |
| Ir   | Pink rhyolitic ignimbrite | –                                                      | 12.5 m    | Tabular. Thinning to the south                                           | Eutaxitic. Massive structure |

Figure 2. Stratigraphic column of the volcaniclastic succession studied at Laguna Flecha Negra. Modified from Sagasti et al. (2018). 1, Lithofacies Scm with permineralized roots (white arrows); 2, Lithofacies Scm and Ch; 3, Lithofacies SfSc; 4, Lithofacies Tm.
Conformably overlying the dark siltstone and sandstone beds are 15 meters of massive white tuffs, which have been identified as volcanic ash fall deposits named Tobas de Caida El Fénix unit by Echeveste et al. (2001) and Channing et al. (2007). The tuffs fine upward from coarse to fine, with lapilli-rich horizons at the top. The uppermost part of this stratigraphic section constitutes an in situ permineralized forest that extends for about 1 km on a paleo-slope, and contains sparse twig impressions embedded within the tuffaceous sediments (Figs. 1.1, 2.4, Tm facies).

The fossiliferous strata are covered to the north and west by a 12.5-meter-thick, pink rhyolitic ignimbrite lying unconformably over the volcanlastic sediments (Figs. 1.1, 2, facies Ir). This corresponds to the Ignimbrita Flecha Negra unit of Echeveste et al. (2001) and represents the youngest member of the Bahía Laura volcanic Complex in this locality.

RESULTS
Taphofacies

Eleven taphofacies were identified at the Laguna Flecha Negra locality: (1) white coarse sandstone with individual permineralized roots [Scm(Rp)]; (2) white coarse sandstone with stem casts [Scm(Cs)]; (3) white coarse sandstone with carbonized wood [Scm(Cw)]; (4) chert lenses with plant fragments [Ch(Ch)]; (5) white coarse sandstone with individual permineralized stems [Scm(Ps)]; (6) white coarse sandstone with impressions of leaves, leafy twigs and reproductive structures [Scm(I)]; (7) fine sandstone and cross-laminated siltstone with impressions-compressions of leaves, leafy twigs and reproductive structures [SfSc(II)]; (8) fine sandstone and cross-laminated siltstone with impressions-compressions of plant debris [SfSc(D)]; (9) massive tuffs with vertical permineralized stems and stumps [Tm(Sv)]; (10) massive tuffs with horizontal and oblique permineralized stems and stumps [Tm(Sh)]; (11) massive tuffs with imprints and casts of small branches [Tm(I)]. Taphofacies 1 to 6 are found in stratigraphic horizon 2, taphofacies 7 and 8 in stratigraphic horizon 3, and taphofacies 9 to 11 in stratigraphic horizon 4 (Fig. 2).

Taphofacies Scm(Rp). This taphofacies consists of tabular bodies of massive, white colored, coarse sandstone with evidence of subaerial exposure above an orange mottled surface, and is characterized by the presence of preservational style Rp (Figs. 3.1–2), which comprises individual permineralized roots. Individual roots are non-ramified fragments that range from 0.5 to 3 cm diameter and are up to 60 cm long that have undergone silicic permineralization. Roots are set perpendicular, oblique, or parallel to the stratification surface; they occur in small groupings and have a somewhat clumped distribution within host sediments.

Taphofacies Scm(Cs). This taphofacies constitutes tabular bodies of massive, white colored, coarse sandstone with an orange mottled surface. It is characterized by the presence of preservational style Cs: stem casts (Fig. 3.3). Casts are three-dimensional, 30 cm long, 10 cm wide, and have a striated surface which usually appears to be superficially oxidized. Casts are positioned almost parallel to the stratification surface and close to the occurrence of carbonized wood material (Cw, below).

Taphofacies Scm(Cw). This taphofacies consists of tabular bodies of massive, white colored, coarse sandstone with an orange mottled surface, and is characterized by the presence of preservational style Cw: fragments of carbonized wood (Fig. 3.4). Charcoalified wood fragments are small, with a maximum size of 10 cm long and 15 cm wide. Wood fragments appear in small groupings, randomly distributed, and parallel to the stratification surface.

Taphofacies Ch(Ch). This taphofacies comprises two lenticular chert levels (Fig. 3.5–6), of up to 20 cm thick and 3 meters
of outcrop length, contained within white coarse sandstone in the northwestern part of the Laguna Flecha Negra locality. The siliceous matrix contains abundant plant remains of variable sizes, many of which are preserved parallel to the stratification surface (Fig. 3.5). Some fragments display good anatomical detail and almost intact morphologies (Fig. 3.6).
Taphofacies Scm(Ps). This taphofacies is typified by tabular bodies of massive, white colored, coarse sandstone with siliceous cement and an orange mottled surface. Plant fossils comprise permineralized plant axes of preservational style Ps (Fig. 3.7). Fragments of silicified plant axes range from 4.4 cm to 11.7 cm in diameter and from 2.2 to 6.7 cm long. These occur in high concentrations, always parallel to the stratification surface. Preservation is good to poor, allowing anatomical studies (Sagasti, 2018).

Taphofacies Scm(I). This taphofacies constitutes tabular bodies of massive, white colored, coarse sandstone with an orange mottled surface. The rocks are strongly cemented with silica. Plant fossils are characterized by preservational style I: impressions of leaves, leafy twigs and reproductive structures (Fig. 3.8) with variable degrees of fragmentation, and with some displaying oxidized surfaces. Fossils occur parallel to the stratification surface within the plant-bearing levels. Plant organs are widely distributed in the sediments and can be extracted as individual units.

Taphofacies SfSc(IC). This taphofacies consists of tabular bodies of fine sandstone and dark siltstone. Rock beds fine upwards from fine sandstone to siltstone. Beds are cross-laminated at the base and shift to parallel laminated towards the top (Fig. 2). Volcanic lithics appear strongly weathered over the stratification surface, occurring with ash particles and mica flakes. Plant fossils are characterized by preservational style IC: impressions-compressions (Fig. 3.9). This preservational style comprises leaves, leafy twigs and reproductive structures in the form of an amorphous carbonaceous film that does not preserve anatomical features and has no associated cuticles. Fossils are abundant within the plant-bearing level and occur parallel to the stratification surface. There is no significant superimposition of organs, allowing the isolated extraction of samples.

Taphofacies SfSc(D). This taphofacies constitutes tabular bodies of fine sandstone and dark siltstone. The rocks fine upwards from fine sandstone to siltstone, are cross-laminated at the base, and parallel laminated towards the top. Volcanic lithics are strongly weathered on bedding planes and co-occur with ash particles and mica flakes. Plant fossils are characterized by preservational style D: plant debris (Fig. 3.12). This preservational style consists of finely comminuted and compressed, individually unidentifiable plant fragments in layers set parallel to the bedding plane.

Taphofacies Tm(Sv). This taphofacies comprises tabular bodies of white tuff, fining upwards from coarse to fine grain sizes, with thin horizons of lapilli; it is characterized by the presence of preservational style Sv: vertical stems and stumps (Fig. 3.10). Stumps are attached at the base to their roots contained in the rock. The diameters of stems and stumps range from 0.5 to 1.5 m. Stems and stumps are silicified, occur perpendicular to slightly oblique to the stratification surface and in moderate to high concentrations.

Taphofacies Tm(Sh). This taphofacies is made up of tabular bodies of white tuff, fining upwards from coarse to fine grain sizes, with thin horizons of lapilli. It is typified by the presence of preservational style Sh: horizontal stems and stumps (Fig. 3.11). Fallen trees are preserved attached to their respective bases (Fig. 3.11). Diameters of trees range from 0.3 to 1.5 m and are up to 2 m long. Stems and stumps are silicified and appear in high concentrations, parallel to the stratification surface.

Taphofacies Tm(I). This taphofacies comprises tabular bodies of white tuff, fining upwards from coarse to fine grain sizes, with thin horizons of lapilli. It is characterized by the presence of preservational style I: impressions. This preservational style consists of impressions of fragments of twigs that are oriented parallel to the stratification surface.

Spatial distribution of taphofacies

The sequence studied at Laguna Flecha Negra preserves effusive lavas and volcaniclastic rocks of the Bahía Laura Complex. Figures 1.1–2 show the spatial distribution of litho- and taphofacies at the Laguna Flecha Negra locality. Close to the lagoon edge, the sandstone contains taphofacies Scm(Rp), Scm(Cs), Scm(Cw), Ch(Ch), Scm(Ps), and, in minor abundance, Scm(I). In the southern part of the locality there is a greater representation of taphofacies Scm(I), whilst taphofacies Scm(Rp), Scm(Cs), Scm(Cw), Scm(Ps), and Ch(Ch) are absent. Taphofacies SfSc(IC) and SfSc(D) are distributed along the cliffs that bound this sequence. The sandstone and siltstone unit is overlain by massive tuffs, which lack fossils in most of their vertical distribution, except at the top of the sequence, where it hosts taphofacies Tm(Sv), Tm(Sh) and Tm(I). The volcaniclastic sequence ends with the Ignimbrita Flecha Negra, a lithofacies that does not preserve any type of fossil.
DISCUSSION
Incorporation pathways for plant material

The study of modern terrestrial geothermal systems with subaerial siliceous thermal spring-aprons and geothermally influenced wetlands allow division into three general areas along a discharge gradient: proximal near-vent, with high temperatures (>59°C); mid-slope apron, with moderate temperatures (~59° to 35° C); and distal slope apron, with low temperatures (<35°C) (Fig. 4.1 inset) (e.g., Walter, 1976; Cady & Farmer, 1996; Channing et al., 2004). Fluid composition and mineralization processes along these gradients generate recurring biological and textural associations that allow comparisons with fossil systems (Guido & Campbell, 2011).

There are three main paths for the incorporation of plant material in modern hot-spring systems (Channing & Edwards, 2013): (1) allochthonous and para-autochthonous organs that fall from the local vegetation, both within the hot spring system, and at its margins, (2) autochthonous communities that are fossilized by progradation of aprons and geothermal wetland margins, and (3) herbaceous communities that replace arboreal components after long periods of flooding, and which are permineralized in life position. In Laguna Flecha Negra, taxonomical analyses of the taphocenosis have shown that paleocommunities were dominated by microphyllous conifers of the families Araucariaceae, Cheirolepidiaceae, Cupressaceae (s.l) and Podocarpaceae, as well as leafy branches with no definite familiar affinities (Sagasti, 2018; Sagasti et al., 2020). Cycadeoids were also abundant, whilst ferns and possible pteridosperms had lower diversity and abundance (Sagasti, 2018; Sagasti et al., 2020). Horizontal distribution of different organs is consistent with preservational biases that affect fossilization processes of plant parts. Woody organs are concentrated in sediments with high porosity and influence of mineral-rich fluids, whilst laminar organs and reproductive structures become preserved as impressions and compressions in rocks with lower porosity and without geothermal influence.

Within the chert lenses of Laguna Flecha Negra, there are abundant plant remains showing variable degrees of fragmentation. Gymnospermous leafy twigs with anatomical details, fern petioles, fragmented pinnulae, roots, and leaves with multiple vascular bundles are preserved. Studies of silicified fossil plants from geothermal settings are abundant, most frequently addressing plants of the Rhynie chert (e.g., Edwards & Selden, 1993; Kenrick & Crane, 1997; Edwards et al., 1998; Trewin, 2001; Channing, 2001, 2003; Taylor & Berbee, 2006; Channing & Edwards, 2009a, 2009b). These show how preservation status varies according to environmental conditions and speed of silicification. Plants growing in the most humid habitats of Rhynie are usually the best-preserved, whilst others that grew on better-drained substrates have their soft tissues decayed or missing (Kerp, 2018). Plants preserved within the cherts of Laguna Flecha Negra present various states of decay, some preserving soft parenchymatous tissues whilst others are only fragments of woody material. This disparity in decay states and the abundance of plant material that appears randomly to parallel to stratification oriented suggest that these fossils correspond to plant litter and fragments that were rapidly silicified by hydrothermal fluids. Preservation of cellular detail is consistent with low temperature fluids (e.g., Channing & Edwards, 2009a, 2009b, 2013; Channing, 2017), supporting the interpretation of silica gel-dominant, distal sinter facies affected by fluvial deposits that concentrated the transported vegetal material.

In the coarse sandstone horizon that contains the chert lenses in the northwestern part of the study area, fossil remains of unknown affinity correspond to stems preserved as casts, impressions and charcoal. In this same region, in situ permineralized roots, and gymnosperms stems and branches occur in close proximity to each other. The presence of angular volcanic lithics is indicative of a volcanioclastic source for these sediments. Weathered feldspar crystals indicate a proximal source and scarce transport for these sediments, that would have originated from the underlying Bajo Pobre lava dome (Channing et al., 2007). Geothermal activity associated with this volcanic event would have favored the development of mineral rich fluids that flowed following the topography to generate the chert lenses found at the margin of the Laguna Flecha Negra lagoon.

The absence of chert lenses in the rest of the locality also contributes to the interpretation of chert lenses as distal facies within a localized geothermal system. In this area, sandstones have a higher content of silica cement,
contain well-preserved impressions of flora, and have no evidence of geothermal influence. Overlying these sandstones, the sequence is volcaniclastic in origin. In the southwestern area of the locality the association of taphofacies SfSc(IC) and SfSc(D) occurs in horizons that range from 10 to 35 cm thickness. This is the thinnest level of the sequence, and points to a later reworked stage of the volcanic event. It is also the clastic level with the greatest abundance of organic material. Horizons preserve both, an autochthonous and para-autochthonous flora that shows well-preserved organs and abundant plant debris. Presence of cross- to parallel lamination, plant debris, and texture of the rocks could indicate a fluvial to lacustrine origin.

Depositional environments determine the accuracy with which a fossil community reflects the composition and structure of the original vegetation (DiMichele & Falcon-Lang, 2011). In subaqueous settings, and under reducing conditions, decomposers activity is limited and, thus, plant material is slow to decay, whereas in superficial and oxygenated environments organic decay occurs rapidly (Trewin & Fayers, 2016). Volcanic ash-falls can bury and preserve in situ vegetation almost instantly, allowing preservation of horizontal structure of plant communities over a vast area around a volcanic building (Johnson, 2007; DiMichele & Falcon-Lang, 2011).

Taphocenosis preserved in the same spatial conformation as in life, and which have undergone little or no biotrinomic filtering following plant death, are called “T0 assemblages” (DiMichele & Gastaldo, 2008; DiMichele & Falcon-Lang, 2011; Channing & Edwards, 2013). The rate of accumulation of sediment plays a major role in the preservation of a T0 assemblage (DiMichele & Falcon-Lang, 2011). Landscapes buried faster preserve the vegetation structure with greater fidelity (Johnson, 2007). Fossil forests such as the one preserved at Laguna Flecha Negra are an example of T0 assemblage since stems and stumps were preserved in situ covered by ash-fall deposits. These type of fossil assemblages allow studies of paleoecological parameters such as forest layers, density and age structure (e.g., DiMichele et al., 2006, 2007, 2009; Opluštil et al., 2009; Sagasti, 2018). Permineralization of erect trees has been recorded mostly in dryland settings (Mencl et al., 2009), in regions with abundant volcanic sediment input (Matysová et al., 2010), and in regions with carbonate or silica availability (e.g., Dawson, 1877; Walton, 1935; Wnuk & Pfefferkorn, 1984; DiMichele & Falcon-Lang, 2011; Ballhaus et al., 2012; Liesegang & Gee, 2020). Different kinds of anatomy of the entombed trees have different preservational potentials and are most likely to appear in distinct physical environmental settings (DiMichele & Falcon-Lang, 2011). In addition, fossil forests are likely to represent only a fragment of the ecological community (Falcon-Lang et al., 2009). This is evidenced at Laguna Flecha Negra by the limited amount of impressions associated with the in situ forest. Permineralized stems and stumps appear in taphofacies Tm(Sv) and Tm(Sh), closely related to impressions of unidentifiable plant fragments of taphofacies Tm(I). Facies Tm of the outcropping sequence of Laguna Flecha Negra preserves only the arboreal component of the plant community, whilst herbaceous understory is absent, which suggest the rapid burial by the Ir ignimbrite facies.

Depositional history of the Jurassic Laguna Flecha Negra locality

Laguna Flecha Negra provides an opportunity to assess the impact of depositional and post-depositional history on fossil plant assemblages affected by volcanism and geothermal activity in the geological record. The evolutionary history of this locality may be reconstructed (Fig. 4) because of the structurally undisturbed nature of Jurassic deposits in this region (Guido & Campbell, 2011). The detailed taphonomic and genetic study described herein indicates spatial and topographic relationships amongst preservational styles, source of siliceous-rich fluids and volcanic and volcaniclastic input.

Guido (2004) analyzed the Bahía Laura Complex sequences and studied the lithofacies subdivisions of the Jurassic volcanic and volcaniclastic deposits from the Deseado Massif. In that work, two facies were defined (volcaniclastic and effusive) and several subfacies within them. The volcaniclastic facies comprise all the fragmentary volcanic deposits and include both pyroclastic and reworked volcanic rocks. Pyroclastic rocks formed by explosive processes and were grouped in three subfacies: flow, fall and surge deposits. The reworked volcaniclastic rocks are included in the subfacies epiclastic; they appear interstratified, which prevents recognizing divisions within them (Guido, 2004).
The effusive facies includes coherent, non-fragmented rocks, which were formed by cooling and solidification of magma, without the involvement of explosive events (Guido, 2004). Two subfacies can be recognized within the effusive facies: extrusive lava rocks that form flows and domes (grouped in the lava subfacies), and hypabyssal rocks that were consolidated in the subsurface (grouped in the sub-volcanic subfacies).

Facies defined for the outcrops at Laguna Flecha Negra can be analyzed within the context of depositional models for the Bahía Laura Complex (Table 2). Facies Ld is interpreted as an effusive deposit of the lava subfacies. These andesitic domes represent a late stage of volcanism and have their source to the east of the Laguna Flecha Negra lagoon (Echeveste et al., 2001; Channing et al., 2007). These effusive andesitic deposits were covered by proximal ash fall volcanic and fluvial reworked volcaniclastic deposit present at Scm facies. This lithofacies also preserved, but only proximal to the Laguna Flecha Negra lagoon, plant-rich chert horizons representing distal siliceous hot spring facies (Figs. 1–2).

Channing et al. (2007) identified the presence of crosscutting NW-SE striking chalcedony veining with minor carbonate mineralization to the north-western edge of the Laguna Flecha Negra lagoon. Stratigraphic relationship between veining and chert beds was not established although they shared mineral composition and trace elements (Channing et al., 2007). We hypothesize the presence of surface geothermal springs forming sinter close to the NW oriented fault containing the chalcedony veins. The spring drainage would have followed the paleoslope preserving vegetal debris in its way and driving extensive permineralization. The influence of these geothermal fluid flow would have promoted the preservation of roots and conifer axes as loci of permineralization that occur in the coarse sandstones (facies Scm) and which contain the chert lenses of the sequence.

Ld and Scm and Ch facies were interpreted as formed almost simultaneously, with not preserved hot-spring sinter terrace deposits forming at the edge of the hydrothermally altered andesitic domes, close or at the actual location of the Laguna Flecha Negra lagoon (Fig. 4.1).

Figure 4.2 shows an interpretation for the lack of the sinter apron as a result of hydrothermal eruption breccia event in the lagoon whose crater area is covered by modern sediments. A fluvial and lacustrine setting was established after the eruption, which is evidenced by sedimentary structures of facies SfSc (i.e., parallel to cross-bedding, finning upwards), as well as preservational styles observed (i.e., impression-compressions of leaves and compressions of plant debris).

Facies Ch and SfSc can be correlated to the epiclastic subfacies as they are composed of volcaniclastic and vegetal debris transported by water, as is indicated by their sedimentary structures.

Facies Tm corresponds to an explosive stage of the Middle–Late Jurassic volcanism from the Bahía Laura Complex. It can be assigned to a fall pyroclastic subfacies and is related to the volcanic center proposed by Echeveste et al. (2001), located to the west of this locality. This explosive fall stage was so intense that it did not preserve plants but the hiatus in volcanic activity after this eruption favored the development of a forest at the top of the sequence (Fig. 4.3).

The extraordinary preservation of the in situ forest is explained by the rapid burial produced by Ir pyroclastic flow subfacies (Fig. 4.4), named Ignimbrita Flecha Negra by Echeveste et al. (1999). Direction of emplacement and thinning of the ignimbrite suggests a vent to the North.

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**TABLE 2. Lithofacies subdivision of the acid Jurassic volcanism of the Deseado Massif.**

| Bahía Laura Complex | Facies volcaniclastic | Subfacies pyroclastic | Subfacies pyroclastic flow (Ir) |
|---------------------|-----------------------|------------------------|--------------------------------|
|                     | Fm                    | Subfacies pyroclastic  | Subfacies pyroclastic flow (Ir) |
|                     | Fm                    | Subfacies pyroclastic  | Subfacies pyroclastic flow (Ir) |
|                     | Fm                    | Subfacies pyroclastic  | Subfacies pyroclastic flow (Ir) |
|                     | Fm                    | Subfacies pyroclastic  | Subfacies pyroclastic flow (Ir) |
|                     | Fm                    | Subfacies pyroclastic  | Subfacies pyroclastic flow (Ir) |

Modified from Guido (2004).
To date, 23 paleo-hot spring sites are known for the Deseado Massif. Five of these were studied in detail to generate sedimentary models, namely San Agustín, Cerro Negro, El Macanudo, La Marciana and Claudia (Guido & Campbell, 2011). Cerro Negro and El Macanudo correspond to calcareous sinters or travertines and, thus, present a different set of facies than those formed in siliceous sinters (Guido & Campbell, 2011, 2012, 2017). At La Marciana, proximal facies of a siliceous sinter are preserved (Guido & Campbell, 2011).
Apron sinter facies have poorly preserved plant stems; however, this locality has not yielded much information about plant communities (Channing et al., 2007; Guido & Campbell, 2009).

The San Agustín siliceous sinter is characterized by subaqueous spring vent mounds, subaerial sinter aprons including some with deep pools, and geothermal wetlands with cooler margins (Guido et al., 2010). Of the hot spring-related sedimentary facies recognized at San Agustín, some were inferred as formed in perennially wet conditions, whilst others presented evidence of intermittent wet and dry conditions (Guido et al., 2010). This locality presents a complete geothermal landscape in which plants, fungi and animals are fossilized (Guido et al., 2010; Channing et al., 2011; García Massini et al., 2012a). The paleo-lake at San Agustín accumulated large volumes of volcanic materials, as well as geothermal inputs and offshore facies in which clastic sediments preserved compression fossils of plant fragments (Guido et al., 2010). Plant communities preserved at the margins of the hot spring system of San Agustín show a high affinity with those of Laguna Flecha Negra (Sagasti et al., 2020).

The Claudia hot spring system shows stratigraphic intercalation of sinter and travertine/silicified travertine deposits, and contains all the paleoenvironmental gradients from high temperature vent conduits to low temperature plant-rich facies (Guido & Campbell, 2014). Studies carried out at Claudia thus far have concentrated on sedimentary facies, biological signatures and depositional models (Guido & Campbell, 2011, 2014, 2019). In this geothermal field, fluvial sediments containing silicified tree trunks and lacustrine deposits have been recognized, but no paleontological study has been conducted yet. Permineralized plant remains are observed in plant rich chert from apron margins intercalated with fluviol-lacustrine strata (Guido & Campbell, 2014) that show the presence of wood fragments, young stems and seedlings of probable conifers (Sagasti, pers. obs.).

Jurassic volcanic rocks at La Bajada locality show a typical association between geothermal features, volcaniclastic fluvial or lacustrine reworked deposits and lava domes (García Massini et al., 2016). This locality was not part of the facies analysis carried by Guido and Campbell (2011), but its geology and paleontology has been preliminary analyzed (García Massini et al., 2016; Sagasti et al., 2016; Nunes et al., 2020). At La Bajada, a series of lineament occur, between which The Valentina breccia appears as a structurally controlled, phreatic breccia pipe that has been suggested as responsible for the destruction of the sinter terraces of the geothermal system (García Massini et al., 2016). La Bajada locality is probably the best analog to Laguna Flecha Negra between the known geothermal localities of the Deseado Massif.

CONCLUSIONS

The analysis of taphofacies carried out at Laguna Flecha Negra contributes to the interpretation of the evolutionary history of this sector of the Deseado Massif. Preservational styles Ps and Ch show the greater anatomical detail between the fossil remains studied at Laguna Flecha Negra. This is consistent with the presence of a siliceous hot-spring in this region. Presence of silicified roots is indicative of the formation of paleosoils and the establishment of a plant community. Progradation of aprons at the margins of geothermal wetlands promoted the fossilization of well-preserved stems and trunks (preservational style Ps), vegetal debris and branches (within preservational style Ch).

The absence of proximal sedimentary textures of hot-spring systems can be explained by a hydrothermal eruption breccia event that resulted in the absence of vent and apron features. The development of subsequent local fluvial and lacustrine facies is consistent with this interpretation since it is common the development of lagoons in craters produced by phreatic eruption.

Preservational styles Scm(I), SfSc(IC), and SfSc(D) are characterized by moderate to high loss of biological data through taphonomic loss. Fine sediments tend to preserve morphological characters with greater detail than coarser deposits. This is a feature normally observed in fossil fluvial and lacustrine settings. After this epiclastic event, a thick and rapid volcanic ash-fall event covered the landscape generating facies Tm with no plant preservation. On top of this ash deposit, a conifer forest was established and later entombed by the Igumnibrita Flecha Negra. It is interesting to note that although silica-rich fluids promoted the fossilization of stems and stumps, high temperatures associated to the pyroclastic flow led to cellular deformation and poor anatomic detail observed in fossils from taphofacies Tm(Sv) and Tm(Sh).
Taphonomic studies allow recognition of mechanisms that operate in the incorporation of plant remains to the fossil record. As mentioned, sedimentary input plays a fundamental role in the preservational potential of different organs. In this sense, volcaniclastic environments, especially those with the presence of geothermal fluids, constitute propitious settings for the preservation of plants in their different modes. Combining geologic, sedimentologic and taphonomic studies allows an integrated reconstruction of the sedimentary paleoenvironment and its relationship with the biota that inhabited it. In this way, more holistic reconstructions can be made and thus a better understanding of dynamics operating in sedimentary basins from the past is achieved.

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