AMEGHINIANA
A GONDWANAN PALEONTOLOGICAL JOURNAL

Submitted: September 8th, 2020 – **Accepted**: November 11th, 2020 – **Posted online**: November 18th, 2020

To link and cite this article:

doi: 10.5710/AMGH.11.11.2020.3395

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

TAFONOMÍA DE PLANTAS Y PALEOAMBIENTE DEL COMPLEJO BAHÍA LAURA, JURÁSICO MEDIO-SUPERIOR, EN LA LOCALIDAD LAGUNA FLECHA NEGRA (PROVINCIA DE SANTA CRUZ, ARGENTINA)

ANA JULIA SAGASTI[1, 2], DIEGO M. GUIDO[2, 3], JUAN L. GARCÍA MASSINI[3, 4]; AND KATHLEEN A. CAMPBELL[5]

[1]Becaria Posdoctoral Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). anajusagasti@gmail.com anajusagasti@fcnym.unlp.edu.ar

[2]Instituto de Recursos Minerales (INREMI-UNLP), 64 nro 3, B1904AMC, La Plata, Buenos Aires, Argentina.

[3]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Godoy Cruz 2290, CABA, Argentina.

[4]Centro Regional de Investigaciones Científicas y Transferencia Tecnológica de La Rioja (CRILAR-CONICET), Provincia de La Rioja, UNLaR, SEGEMAR, UNCa, CONICET, Entre Ríos y Mendoza s/n, 5301, Anillaco, La Rioja, Argentina.

[5]School of Environment, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand.

36 pages (text + references), 4 illustrations, 2 Tables

Running Header: SAGASTI *ET AL.*: PALEOENVIRONMENTAL RECONSTRUCTION AT LAGUNA FLECHA NEGRA

Short description: Taphonomic studies allow reconstructing the depositional history and plant fossilization pathways in a hot-spring (sinter) system in the Deseado Massif.

Corresponding author: Ana Julia Sagasti anajusagasti@gmail.com

anajusagasti@fcnym.unlp.edu.ar

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.

Keywords. 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 para-autóctonas, 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 geotermales. 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 andesítico 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 reconocer 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 volcaniclásticos. 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 abrasion, fragmentation, dislocation, reorientation and sorting, collectively 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, and which convert the organism into a fossil (e.g. compression, re-crystallization, replacement) (Gee & Gastaldo, 2005). These processes lead to physical and chemical balance between the plant remains and the sedimentary environment (Martín-Closas & Gomez, 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 environment 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 preservational 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 preservation and modes of occurrence of different fossil taxa within individual horizons (Speyer & Brett, 1986; Speyer & Brett, 1988). These differences allow recognition of patterns of temporal and spatial distribution of fossil remains in fossil assemblages; 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 taphocenosis (i.e. a group of remains that were buried together) are the product of specific environmental conditions (Brett & Baird, 1986); specifically, taphofacies 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 phenomena that can be empirically determined (Speyer & Brett, 1988). In plants, taphonomic studies incorporate the complexity 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 environmental 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; García Massini *et al.*, 2012a, 2016; Guido & Campbell, 2009, 2011, 2012, 2017, 2019; Guido *et al.*, 2010; 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; García Massini *et al.*, 2012a, 2016; Guido *et al.*, 2010; 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 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; Guido & Campbell, 2011; Guido *et al.*, 2019) 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 km^2 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; which 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 My (Féraud *et al.*, 1999; Pankhurst *et al.*, 2000). Figure 1

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 of 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. 1.1, 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.

Table 1

The lowest part of the Bahía Laura Complex at Laguna Flecha Negra comprises an andesitic lava dome (Ld facies at Figs. 1.1, 2). 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.

Figure 2

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).

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 Caída 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 volcaniclastic 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(IC)**]; (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

256 with imprints and casts of small branches [**Tm(I)**].Taphofacies 1 to 6 are found in
257 stratigraphic horizon 2, taphofacies 7 and 8 in stratigraphic horizon 3, and taphofacies 9
258 to 11 in stratigraphic horizon 4 (Fig. 2).

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

267 Figure 3

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

274 *Taphofacies Scm(Cw).* This taphofacies consists of tabular bodies of massive,
275 white colored, coarse sandstone with an orange mottled surface, and is characterized by
276 the presence of preservational style Cw: fragments of carbonized wood (Fig. 3.4).
277 Charcoalified wood fragments are small, with a maximum size of 10 cm long and 15 cm
278 wide. Wood fragments appear in small groupings, randomly distributed, and parallel to
279 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 50 cm to 1.5 meters. 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 m to 1.5 m and are up to 2 meters 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. 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. Figure 1.1–2 shows 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 for at the top of the sequence, which 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 a moderate temperature (~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

379 settings are abundant, most frequently addressing plants of the Rhynie chert (*e.g.*,
380 Channing, 2001, 2003; Channing & Edwards, 2009 a, b; Edwards & Selden, 1993;
381 Edwards *et al.*, 1998; Kenrick & Crane, 1997; Taylor & Berbee, 2006; Trewin, 2001).
382 These show how preservation status varies according to environmental conditions and
383 speed of silicification. Plants growing in the most humid habitats of Rhynie, are usually
384 the best-preserved, whilst others that grew on better-drained substrates have their soft
385 tissues decayed or missing (Kerp, 2018). Plants preserved within the cherts of Laguna
386 Flecha Negra present various states of decay, some preserving soft parenchymatous
387 tissues whilst others are only fragments of woody material. This disparity in decay
388 states and the abundance of plant material that appears randomly to parallel to
389 stratification oriented suggest that these fossils correspond to plant litter and fragments
390 that were rapidly silicified by hydrothermal fluids . Preservation of cellular detail is
391 consistent with low temperature fluids (*e.g.*, Channing & Edwards, 2009a, b, 2013,
392 Channing, 2017), which supports the interpretation of silica gel-dominant, distal sinter
393 facies affected by fluvial deposits that concentrated the transported vegetal material.
394 In the coarse sandstone horizon that contains the chert lenses in the northwestern
395 part of the study area, fossil remains of unknown affinity correspond to stems preserved
396 as casts, impressions and charcoal. In this same region, *in situ* permineralized roots, and
397 gymnosperms stems and branches occur in close proximity to each other. The presence
398 of angular volcanic lithics is indicative of a volcaniclastic source for these sediments.
399 Weathered feldspar crystals indicate a proximal source and scarce transport for these
400 sediments, that would have derivate from the underlying Bajo Pobre lava dome
401 (Channing *et al.*, 2007). Geothermal activity associated with this volcanic event would
402 have favored the development of mineral rich fluids that flowed following the

403 topography to generate the chert lenses found at the margin of the Laguna Flecha Negra
404 lagoon.
405 The absence of chert lenses in the rest of the locality also contributes to the
406 interpretation of chert lenses as distal facies within a localized geothermal system. In
407 this area, sandstones have a higher content of silica cement, contain a well-preserved
408 flora of impressions, and have no evidence of geothermal influence. Overlying these
409 sandstones, the sequence is volcaniclastic in origin. In the southwestern area of the
410 locality the association of taphofacies SfSc(IC) and SfSc(D) occurs in horizons that
411 range from 10 to 35 cm thickness. This is the thinnest level of the sequence, and points
412 to a later reworked stage of the volcanic event. It is also the clastic level with the
413 greatest abundance of organic material. Horizons preserve both, an autochthonous and
414 para-autochthonous flora that shows well-preserved organs and abundant plant debris.
415 Presence of cross- to parallel lamination, plant debris, and texture of the rocks could
416 indicate a fluvial to lacustrine origin.
417 Depositional environments determine the accuracy with which a fossil
418 community reflects the composition and structure of the original vegetation (DiMichele
419 & Falcon-Lang, 2011). In subaqueous settings, and under reducing conditions,
420 decomposers activity is limited and, thus, plant material is slow to decay, whereas, in
421 superficial and oxygenated environments, organic decay occurs rapidly (Trewin &
422 Fayers, 2016). Volcanic ash-falls can bury and preserve *in situ* vegetation almost
423 instantly, allowing preservation of horizontal structure of plant communities over a vast
424 area around a volcanic building (Johnson, 2007; DiMichele & Falcon-Lang, 2011).
425 Taphocenosis preserved in the same spatial conformation as in life, and which have
426 undergone little or no biostratinomic filtering following plant death, are called "T_0
427 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 T_0 assemblage (DiMichele & Falcon-Lang, 2011). Landscapes buried faster preserve the vegetation structure with greater fidelity (Johnson, 2007). Fossil forests such as the one preserved in Laguna Flecha Negra are an example of T_0 assemblage since it preserves *in situ* stems and stumps that were 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.*, Ballhaus *et al.*, 2012; Dawson, 1877; DiMichele & Falcon-Lang, 2011; Liesegang & Gee, 2020; Walton, 1935; Wnuk & Pfefferkorn, 1984). 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

453 geothermal activity in the geological record. The evolutionary history of this locality
454 may be reconstructed (Fig. 4) because of the structurally undisturbed nature of Jurassic
455 deposits in this region (Guido & Campbell, 2011). The detailed taphonomic and genetic
456 study described herein indicate spatial and topographic relationships amongst
457 preservational styles, source of siliceous-rich fluids and volcanic and volcaniclastic
458 input.

459 Guido (2004) analyzed the Bahía Laura Complex sequences and studied the
460 lithofacies subdivisions of the Jurassic volcanic and volcaniclastic deposits from the
461 Deseado Massif. In that work, two facies were defined (volcaniclastic and effusive) and
462 several subfacies within them. The volcaniclastic facies comprise all the fragmentary
463 volcanic deposits and include both pyroclastic and reworked volcanic rocks. Pyroclastic
464 rocks formed by explosive processes and were grouped in three subfacies: flow, fall and
465 surge deposits. The reworked volcaniclastic rocks are included in the subfacies
466 epiclastic; they appear interstratified, which prevents recognizing divisions within them
467 (Guido, 2004).

468 The effusive facies includes coherent, non-fragmented rocks, which were
469 formed by cooling and solidification of magma, without the involvement of explosive
470 events (Guido, 2004). Two subfacies can be recognized within the effusive facies:
471 extrusive lava rocks that form flows and domes (grouped in the lava subfacies), and
472 hypabyssal rocks that were consolidated in the subsurface (grouped in the sub-volcanic
473 subfacies).

474 Facies defined for the outcrops at Laguna Flecha Negra can be analyzed within
475 the context of depositional models for the Bahía Laura Complex (Table 2). Facies Ld is
476 interpreted as an effusive deposit of the lava subfacies. These andesitic domes represent
477 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).

Table 2

Channing *et al.* (2007) identified the presence of cross-cutting 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).

Fig. 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-

503 bedding, finning upwards), as well as preservational styles observed (i.e. impression-
504 compressions of leaves and compressions of plant debris).
505 Figure 4
506 Facies Ch and SfSc can be correlated to the epiclastic subfacies as they are
507 composed of volcaniclastic and vegetal debris transported by water, as is indicated by
508 their sedimentary structures.
509 Facies Tm correspond to an explosive stage of the Middle-Late Jurassic
510 volcanism from the Bahía Laura Complex. It can be assigned to a fall pyroclastic
511 subfacies and is related to the volcanic center proposed by Echeveste *et al.*, (2001),
512 located to the west of this locality. This explosive fall stage was so intense that it did not
513 preserve plants but the hiatus in volcanic activity after this eruption favored the
514 development of a forest at the top of the sequence (Fig. 4.3).
515 The extraordinary preservation of the *in situ* forest is explained by the rapid
516 burial produced by Ir pyroclastic flow subfacies (Fig. 4.4), named Ignimbrita Flecha
517 Negra by Echeveste *et al.* (1999). Direction of emplacement and thinning of the
518 ignimbrite suggests a vent to the North.
519 **Geothemal environments of the Deseado Massif**
520 To date, 23 paleo-hot spring sites are known for the Deseado Massif. Five of these were
521 studied in detail to generate sedimentary models, namely San Agustín, Cerro Negro, El
522 Macanudo, La Marciana and Claudia (Guido & Campbell, 2011). Cerro Negro and El
523 Macanudo correspond to calcareous sinters or travertines and, thus, present a different set of
524 facies than those formed in siliceous sinters (Guido & Campbell, 2011, 2012, 2017). At La
525 Marciana, proximal facies of a siliceous sinter are preserved (Guido & Campbell, 2009). Apron
526 sinter facies have poorly preserved plant stems; however, this locality has not yielded much
527 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; Garcia 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 fluvio-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 & Campbell (2011), but its geology and paleontology has been preliminary analyzed (García Massini *et al.*, 2016; Nunes et al., 2020). At La Bajada, a series of lineament occur, between which The Valentina breccia appear 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 Ignimbrita 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.

ACKNOWLEDGMENTS

We thank the Culture Bureau of Santa Cruz Province for supporting our research and granting us the research permits to study the Bahía Laura Complex deposits in the Deseado Massif. Partial funding for this project comes from UNLP (Proy. Inc. N/807), PICT 2014-3496 (JGM and DG), PIP 2011-2013 (JGM) and the National Geographic Society. The paper benefited greatly from the constructive comments and suggestions of Scientific Editor of Ameghiniana Dr. Adriana Mancuso, as well as two referees.

REFERENCES

Allison, P. A., & Bottjer, D. J. (2011). *Taphonomy: Process and Bias Through Time*. Second edition. (612 pp) Springer.

Archangelsky, S. (1970). *Fundamentos de Paleobotánica*. Facultad de Ciencias Naturales y Museo, Universidad Nacional de la Plata, Serie técnica y Didáctica 10, 347 pp.

605 Ballhaus, C., Gee, C. T., Bockrath, C., Greef, K., Mansfeldt, T., & Rhede, D. (2012).
606 The silicification of trees in volcanic ash–an experimental study. *Geochimica et*
607 *Cosmochimica Acta, 84,* 62–74.
608 Bodnar, J. (2010). *La paleoflora triásica de la Formación Cortaderita en la quebrada*
609 *homónima, Cuenca de Barreal-Calingasta, Provincia de San Juan, Argentina.*
610 Unpublished Thesis. 291 pp.
611 Brenchley, P. J., & Harper, D. A. T. (1998). *Palaeoecology: Ecosystems, environments*
612 *and evolution*. Chapman and Hall. London, United Kingdom. 407pp.
613 Brett, C. E., & Baird, G. C. (1986). Comparative taphonomy: a key to
614 paleoenvironmental interpretation based on fossil preservation. *Palaios 1*, 207–
615 227.
616 Brett, C. E., & Speyer, S. E. (1990). Taphofacies. In: Briggs, D. E. G., & Crowther, P.
617 R. (Eds.). *Palaeobiology: a synthesis* (pp. 258–262) Blackwell Science.
618 Cady, S. L., & Farmer, J. D. (1996). Fossilization processes in siliceous thermal springs:
619 trends in preservation along thermal gradients. In *Ciba Foundation Symposium*.
620 (pp. 150–173) John Wiley and Sons Ltd.
621 Channing, A. (2001). *Processes and environments of vascular plant silicification.*
622 Unpublished Doctoral Thesis. Cardiff University (United Kingdom) 352pp.
623 Channing, A. (2003). The Rhynie chert early land plants: palaeoecophysiological and
624 taphonomical analogues. *Transactions of the Institution of Mining and*
625 *Metallurgy (Section B: Applied Earth Science) 112*, 170–171.
626 Channing, A. (2017). A review of active hot-spring analogues of Rhynie: environments,
627 habitats and ecosystems. *Philosophical Transactions of the Royal Society B 373*,
628 20160490. DOI: 10.1098/rstb.2016.0490

629 Channing, A., & Edwards, D. (2009a). Silicification of higher plants in geothermally
630 influenced wetlands: Yellowstone as a Lower Devonian Rhynie analog. *Palaios*
631 *24*, 505–521.
632 Channing, A., & Edwards, D. (2009b). Yellowstone hot spring environments and the
633 palaeo-ecophysiology of Rhynie chert plants: towards a synthesis. *Plant Ecology*
634 *& Diversity 2*, 111–143. DOI: 10.1081/17550870903349359
635 Channing, A., & Edwards, D. (2013). Wetland megabias: ecological and
636 ecophysiological filtering dominates the fossil record of hot spring floras.
637 *Palaeontology* 1–34. doi:10.1111/pala.12043.
638 Channing, A., Edwards, D., & Strutevant, S. (2004). A geothermally influenced wetland
639 containing unconsolidated geochemical sediments. *Canadian Journal of Earth*
640 *Sciences. 41*, 809–827.
641 Channing, A., Zamuner, A. B., Edwards, D., & Guido, D. M. (2011). *Equisetum*
642 *thermale* sp. nov. (Equisetales) from the Jurassic San Agustín hot spring deposit,
643 Patagonia: anatomy, paleoecology, and inferred paleoecophysiology. *American*
644 *Journal of Botany 98*, 680–697.
645 Channing, A., Zamuner, A. B., & Zuñiga, A. (2007). A new Middle-Late Jurassic flora
646 and hot spring chert deposit from the Deseado Massif, Santa Cruz Province,
647 Argentina. *Geological Magazine 144*, 401–411.
648 Colombi, C. E., & Parrish, J. T. (2008). Late Triassic environmental evolution in
649 Southwesterns Pangea: plant taphonomy of Ischigualasto Formation. *PALAIOS*
650 *23*, 778–795.
651 Dawson, K. W. (1877). Note on a specimen of *Diploxylon* from the coal formation of
652 Nova Scotia. *Quarterly Journal of the Geological Society of London, 33*, 836–
653 842.

DiMichele, W. A., & Falcon-Lang, H. J. (2011). Pennsylvanian <<fossil forest>> in growth position (T° assemblages): origin, taphonomic bias and palaeoecological insights. *Journal of the Geological Society, 168*, 585–605.

DiMichele, W. A., Falcon-Lang, H. J., Nelson, W. J., Elrick, S., & Ames, P. R. (2007). Ecological gradients within a Pennsylvanian mire forest. *Geology, 35*, 415–418.

DiMichele, W. A., & Gastaldo, R. A. (2008). Plant paleoecology in deep time. *Annals of the Missouri Botanical Garden 95*, 144–198.

DiMichele, W. A., Nelson, W. J., & Elrick, S. D. (2006). Spatial patterns in the final forest of a drowned peat mire, Springfield coal (Middle Pennsylvanian), Illinois Basin. *Geological Society of America, Abstracts with Programs 38*, 380.

DiMichele, W. A., Nelson, W. J., Elrick, S., & Ames, P. R. (2009). Catastrophically buried middle Pennsylvanian *Sigillaria* and calamitean sphenopsids from Indiana, USA: What kind of vegetation was this? *Palaios, 24*, 159–166.

Echeveste, H., Fernández, R., Bellieni, G., Tessone, M., Llambías, E., Schalamuk, I., Piccirillo, E., & De Min, A. (2001). Relaciones entre las Formaciones Bajo Pobre y Chon Aike (Jurásico medio a superior) en el área de Estancia El Fénix-Cerro Huemul, zona centro-occidental del Macizo del Deseado, provincia de Santa Cruz. *Revista de la Asociación Geológica Argentina 56 (4)*, 548–558.

Echeveste, H., Fernández, R., Llambías, E., Tessone, M., Schalamuk, I., Bellieni, G., Piccirillo, E., & De Min, A. (1999). Ignimbritas tardías de alto grado en la Formación Chon Aike (Jurásico), Macizo del Deseado, Santa Cruz. *XIV Congreso Geológico Argentino, Actas II* 182–185.

Edwards, D., Kerp, H., & Hass, H. (1998). Stomata in early land plants: An anatomical and ecophysiological approach. *Journal of Experimental Botany, 49*, 255–278.

678 Edwards, D., & Selden, P. A. (1993). The development of early terrestrial ecosystems.
679 *Botanical Journal of Scotland 46*, 337–366.
680 Efremov, J. A. (1940). Taphonomy: a new branch of paleontology. *Panamerican*
681 *Geology 74*, 81–93.
682 Falcon-Lang, H. J., Nelson, J., Elrick, S., Looy, C., Ames, P., & DiMichele, W. A.
683 (2009). Incised channel-fills containing conifers imply that seasonally-dry
684 vegetation dominated - Pennsylvanian tropical lowlands. *Geology 37*, 923–926.
685 Féraud, G., Alric, V., Formari, M., Bertrand, H., & Haller, M. (1999). $^{40}Ar/^{39}Ar$ dating
686 of Jurassic volcanic province of Patagonia: migrating magmatism related to
687 Gondwana break-up and subduction. *Earth Planet. Sci. Lett. 172*, 83–96.
688 Fernández López, S. (1991). Taphonomic concepts for a theoretical biochronology.
689 *Revista Española de Paleontología 6*, 37–49.
690 Fernández-López, S. R., & Fernández-Jalvo, Y. (2002). The limit between
691 biostratinomy and fossildiagenesis. In: De Renzi, Pardo Alonso, Belinchón,
692 Peñalver, Montoya, & Márquz-Aliaga (Eds.) *Current Topics on Taphonomy and*
693 *Fossilization.* Ayuntamiento de Valencia. Valencia, Spain. 27–36.
694 García Massini, J. L., Escapa, I. H., Guido, D. M., & Channing, A. (2016). First glimpse
695 of the silicified hot spring biota from a new Jurassic chert deposit in the Deseado
696 Massif, Patagonia, Argentina. *Ameghiniana 53 (2)*, 205–230.
697 García Massini, J. L., Channing, A., Guido, D. M., & Zamuner, A. B. (2012a). First
698 report of fungi and fungus-like organisms from Mesozoic hot springs. *Palaios*
699 *27*, 55–62.
700 García Massini, J. L., Falaschi, P., & Zamuner, A. B. (2012b). Fungal-arthropod-plant
701 interactions from the Jurassic petrified forest Monumento Natural Bosques

Petrificados, Patagonia, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology, 329–330,* 37–46.

Gee, C. T., & Gastaldo, R. A. (2005). Sticks and mud, fruits and nuts, leaves and climate: Plant taphonomy comes of age. *PALAIOS 20,* 415–417.

Guido, D. M. (2004). Subdivisión litofacial e interpretación del volcanismo jurásico (Grupo Bahía Laura) en el este del Macizo del Deseado, provincia de Santa Cruz. *Revista de la Asociación Geológica Argentina 59 (4),* 727–742.

Guido, D. M. & Campbell, K. A. (2009). Jurassic hot-spring activity in a fluvial setting at La Marciana, Patagonia, Argentina. *Geological Magazine 146 (4),* 617–622.

Guido, D. M., & Campbell, K. A. (2011). Jurassic hot spring deposits of the Deseado Massif (Patagonia, Argentina): characteristics and controls on regional distribution. *Journal of Volcanology and Geothermal Research 203*, 35–47.

Guido, D. M., & Campbell, K. A. (2012). Diverse subaerial and lacustrine hot spring settings of the Cerro Negro epithermal system (Jurassic, Deseado Massif), Patagonia, Argentina. *Journal of Volcanology and Geothermal Research 229–230,* 1–12.

Guido, D. M., & Campbell, K. A. (2017). Upper Jurassic travertine at El Macanudo, Argentine Patagonia: a fossil geothermal field modified by hydrothermal silicification and acid overprinting. *Geological Magazine,* doi:10.1017/S0016756817000498

Guido, D. M., Campbell, K. A., Foucher, F., & Westall, F. (2019). Life is everywhere in sinters: examples from Jurassic hot-spring environments of Argentine Patagonia. *Geological Magazine* https://doi.org/10.1017/S0016756819000815

Guido, D. M., Channing, A., Campbell, K. A., & Zamuner, A. (2010). Jurassic geothermal landscapes and fossil ecosystems at San Agustín, Patagonia, Argentina. *Journal of the Geological Society, London 167*, 11–20.

Guido, D., Escayola, M., de Barrio, R., Schalamuk, I., & Franz, G. (2006). La Formación Bajo Pobre (Jurásico) en el este del Macizo del Deseado, Patagonia: vinculación con el Grupo Bahía Laura. *Revista de la Asociación Geológica Argentina 61 (2),* 187–196.

Harper, C. J., Walker, C., Schwendemann, A., Kerp, H., & Krings, M. (2020). *Archaeosporites rhyniensis* gen. et. sp. nov. (Glomeromycota, Archaeosporaceae), from the Lower Devonian Rhynie chert- a fungal lineage morphologically unchanged for more than 400 million years. *Annals of Botany* mcaa113, DOI: 10.1093/aob/mcaa113.

Herbst, R. (1966). Revisión de la flora liásica de Piedra Pintada, provincia de Neuquén, Argentina. *Revista del Museo de La Plata 5,* 27–53.

Johnson, K. R. (2007). Palaeobotany: Forest frozen in time. *Nature 447*, 786–787.

Kenrick, P., & Crane, P. R. (1997). The origin and early evolution of plants on land. *Nature 389*, 33–39.

Kerp, H. (2017). Organs and tissues of Rhynie chert plants. *Philosopical Transactions of the Royal Society B 373*, 20160495. http://dx.doi.org/10.1098/rstb.2016.0495

Knoll, A. H. (1985). Exceptional preservation of photosynthetic organisms in silicified carbonates and silicified peats. *Philosophical Transactions of the Royal Society of London B 311,* 111–122.

Liesegang, M. & Gee, C. T. (2020). Silica entry and accumulation in standing trees in a hot-spring environment: cellular pathways, rapid pace and fossilization potential. *Palaeontology 63* (4), 651–660.

Martín-Closas, C., & Gomez, B. (2004). Taphonomie des plantes et interpretations paléoécologiques. Une sinthése. *Geobios 37*, 65–88.

Matysová, P., Rössler, R., Götze, J., Leichmann, J., Forbes, G., Taylor, E. L., Sakala, J., & Grygar, T. (2010). Alluvial and volcanic pathways to silicified plant stems (Upper Carboniferous–Triassic) and their taphonomic and palaeoenvironmental meaning. *Palaeogeography, Palaeoclimatology, Palaeoecology 292*, 127–143.

Mencl, V., Matysová, P., & Sakala, J. (2009). Silicified woods from the Czech part of the Intra Sudetic Basin (Late Pennsylvanian, Bohemian Massif, Czech Republic): systematics, silicification and palaeoenvironment. *Neues Jahrbuch für Geologie und Paleontologie, Abhandlungen 252*, 269–288.

Miall, A. D. (2006). *The geology of fluvial deposits. Sedimentary facies, basin analysis and petroleum geology.* 4th edition. (582pp) Springer.

Nunes, C. I., García Massini, J. L., Escapa, I. H., Guido, D. M., & Campbell, K. (2020). Conifer root nodules colonized by arbuscular mycorrhizal fungi in Jurassic geothermal settings from Patagonia, Argentina. *International Journal of Plant Sciences 181*, 196–209.

Opluštil, S., Pšenička, J., Libertín, M., Bek, J., Dašková, J., & Šimunek, Z. (2009). Composition and structure of an in situ Middle Pennsylvanian peatforming plant assemblage buried in volcanic ash, Radnice Basin (Czech Republic). *Palaios 24*, 726–746.

Pankhurst, R. J., Riley, T. R., Fanning, C. M., & Kelley, S. P. (2000). Episodic silicic volcanism in Patagonia and the Antarctic Peninsula: Chronology of magmatism associated with the Break-up of Gondwana. *Journal of Petrology 45*, 605–625.

Panza, J. L., & Marín, G. (1998). Hoja Geológica 4969-I Gobernador Gregores. Escala 1:250.000, Provincia de Santa Cruz. SEGEMAR. Boletín *211*,77p

Reading, H. G. & Levell, B. K. (1996). Controls on the sedimentary rock record. In H. G. Reading (Ed.) *Sedimentary environments: processes, facies and stratigraphy*. (pp. 5–36). Blackwell Science.

Sagasti, A. J. (2018). *Estudio paleobotánico, paleoecológico y paleoambiental en la localidad de Laguna Flecha Negra, Macizo del Deseado, Jurásico Superior, Provincia de Santa Cruz, Argentina.* Unpublished Thesis. 253pp.

Sagasti, A. J., García Massini, J., Escapa, I. H., Guido, D. M., & Channing, A. (2016). *Millerocaulis zamunerae* sp. nov. (Osmundaceae) from Jurassic, geothermally influenced, wetland environments of Patagonia, Argentina. *Alcheringa: An Australasian Journal of Palaeontology* DOI: 10.1080/03115518.2016.1210851.

Sagasti, A. J., García Massini, J. L., Escapa, I. H., & Guido, D. M. (2018). Multitrophic interactions in a geothermal setting: Arthropod borings, actinomycetes, fungi and fungal-like microorganisms in a decomposing conifer wood from the Jurassic of Patagonia. *Palaeogeography, Palaeoclimatology, Palaeoecology* doi:10.1016/j.palaeo.2018.09.004

Sagasti, A. J., García Massini, J. L., Escapa, I. H., Guido, D. M., & Morel, E. M. (2020). Middle-Late Jurassic megaflora of Laguna Flecha Negra locality in Santa Cruz Province, Patagonia, and floristic assemblages of the Bahía Laura Complex. *Journal of South American Earth Sciences 100.* https://doi.org/10.1016/j.jsames.2020.102564

Scasso, R. A., & Limarino, C. O. (1997). *Petrología y diagénesis de rocas clásticas.* Asociación Argentina de Sedimentología, Publicación Especial Nro. 1. Capital Federal, Argentina. 258pp.

Selley, R. C. (2000). *Applied sedimentology* (2nd Edition). Academic Press. London, 523 pp.

800 Speyer, S. E., & Brett, C. E. (1986). Trilobite taphonomy and Middle Devonian
801 taphofacies. *Palaios 1*, 312–327.
802 Speyer, S. E., & Brett, C. E. (1988). Taphofacies models for epeiric sea environments:
803 middle Paleozoic examples. *Palaeogeography, Palaeoclimatology,*
804 *Palaeoecology 63*, 225–262.
805 Taylor, J. W., & Berbee, M. L. (2006). Dating divergences in the fungal tree of life:
806 Review with some new analyses. *Mycologia 98*, 838–849
807 Taylor, T. N., Hass, H., Krings, M., Klavins, S. D., & Kerp, H. (2004). Fungi in the
808 Rhynie chert: a view from the dark side. *Transactions of the Royal Society of*
809 *Edinburgh: Earth Sciences 94*, 457–473.
810 Taylor, T. N., Taylor, E. L., & Krings, M. (2009). *Paleobotany, The Biology and*
811 *Evolution of Fossil Plants, Second Edition*, (pp. 1230) Academic Press.
812 Trewin, N. H. (2001). The Rhynie chert. In: Briggs, D.E.G., & Crowther, P. (Eds.)
813 *Palaeobiology II*. (pp. 342–346) Blackwell Science.
814 Trewin, N. H. & Fayers, S. R. (2016). Macro to micro aspects of the plant preservation
815 in the Early Devonian Rhynie cherts, Aberdeenshire, Scotland. *Earth and*
816 *Environmental Science Transactions of the Royal Society of Edinburgh 106,* 67–
817 80.
818 Trewin, N. H., & Kerp, H. (2017). The Rhynie and Windyfield cherts, Early Devonian,
819 Rhynie, Scotland. In: Fraser, N. C., & Sues, H. D. (Eds.) *Terrestrial*
820 *conservation lagerstätten. Windows into the Evolution of Life on Land.* (pp. 1–
821 38). Dunedin Academic Press.
822 Walker, R. G. (1992). Facies, facies models and modern stratigraphic concepts. In
823 Walker, R. G., & James, N. P. (Eds.) *Facies models, response to sea level*
824 *changes*.1–14. Geological Association of Canada.

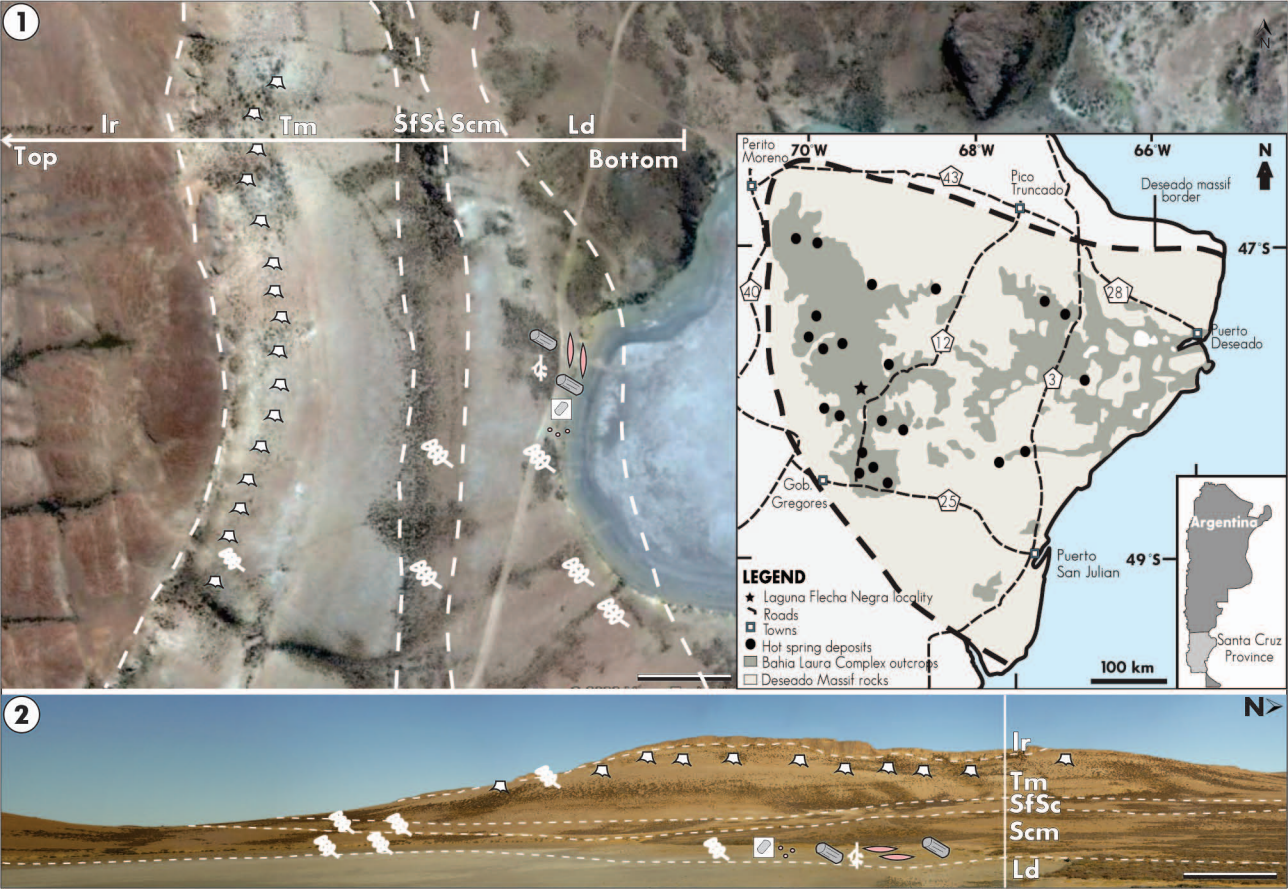
825 Walter, M. R. (1976). Hot-spring sediments in Yellowstone National Park. In: Walter,
826 W. R. (Ed.) *Stromatolites: Developments in Sedimentology*, 20. (pp. 489–498)
827 Elsevier.
828 Walton, J. (1935). Scottish Lower Carboniferous plants: the fossil hollow trees of Arran
829 and their branches (*Lepidophloios wunschianus* Carruthers). *Transactions of the*
830 *Royal Society, Edinburgh 58*, 313–337.
831 Willis, K. J., & McElwain, J. C. (2002). *The Evolution of Plants.* (378pp) Oxford
832 University Press.
833 Wnuk, C., & Pfefferkorn, H. W. (1984). The life habits and paleoecology of Middle
834 Pennsylvanian medullosan pteridosperms based on an *in situ* assemblage from
835 the Bernice Basin (Sullivan County, Pennsylvania, U.S.A.). *Review of*
836 *Paleobotany and Palynology 41*, 329–351.
837 **Figure captions**
838 **Figure 1. 1,** Aerial view of the Laguna Flecha Negra locality showing the distribution
839 of lithofacies. Modified from Maxar Technologies2020; Google EarthPro 2020,
840 accessed January 2020. Scale: 100 m. Inset: Map of the Bahía Laura outcrops in the
841 Deseado Massif. Black dots point to geothermal localities. Laguna Flecha Negra
842 locality is marked with a black star. Modified from Sagasti *et al.* 2016. **2,** Panoramic
843 view of the Laguna Flecha Negra cliffs in which the studied succession crops-out. Areal
844 distribution of taphofacies is marked. Scale: 100 m
845 **Figure 2.** Stratigraphic column of the volcaniclastic succession studied at Laguna
846 Flecha Negra. Modified from Sagasti et al. (2018). **1,** Lithofacies Scm with
847 permineralized roots (white arrows). **2,** Lithofacies Scm and Ch. **3,** Lithofacies SfSc. **4,**
848 Lithofacies Tm.

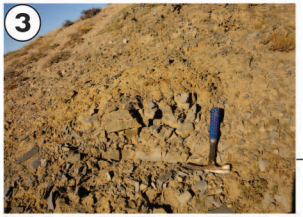
Figure 3. Preservational styles recognized in the Bahía Laura Complex at Laguna Flecha Negra locality. **1,** Individual permineralization of roots in coarse sandstone. MPM PB 15896. Scale: 2 cm **2,** Transverse section of permineralization of individual roots in coarse sandstone. Scale: 2cm **3,** Stem casts in white tuffs. MPM PB 16028. Scale: 4 cm. **4,** Carbonized wood in coarse sandstone. MPM PB 15898. Scale: 1 cm. **5,** Massive siliceous permineralization (=cherts). Scale: 15 cm. **6,** Fragments of plants found in the chert levels. Scale: 2 cm. **7,** Individual permineralization of stems in coarse sandstone. Scale: 15 cm. **8,** Impressions of leaves in coarse sandstone. Leafy twigs and reproductive structures also occur preserved as impressions. *Scleropteris vincei* Herbst (1966). MPM PB 16008. Scale: 0.1 cm. **9,** Impressions-compressions of recognizable plant organs in laminated silts. *Sphenopteris* cf. *nordenskioeldii*. MPM PB 15886. Scale: 0.5 cm. **10,** Vertical silicified stems and stumps in massive tuffs. Stem 056. Scale: 20 cm. **11,** Horizontal to oblique silicified stems and stumps in massive tuffs. Stem 003. Scale 30 cm. **12,** Compressions of plant debris in laminated silts. MPM PB 15894. Scale: 1 cm.

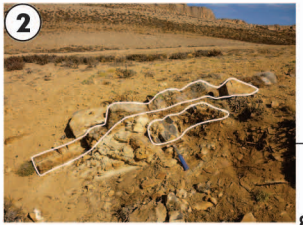
Figure 4. 1–4, Schematic W–E cross-section along Laguna Flecha Negra locality outcrops and their evolution during Middle–Late Jurassic. Details in text.

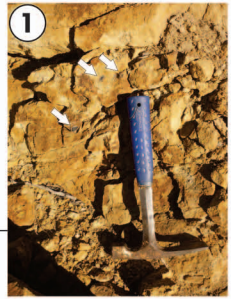
Table 1. Facies code for the outcrops of Laguna Flecha Negra locality.

Table 2. Lithofacies subdivision of the acid Jurassic volcanism of the Deseado Massif. Modified from Guido (2004).


1
Ir
Tm
SfSc
Scm
Ld
Top
Bottom
N
Perito Moreno
70°W
68°W
66°W
N
43
Pico Truncado
Deseado massif border
47°S
40
28
12
3
Puerto Deseado
Gob. Gregores
25
Puerto San Julian
49°S
LEGEND
Laguna Flecha Negra locality
Roads
Towns
Hot spring deposits
Bahia Laura Complex outcrops
Deseado Massif rocks
100 km
Argentina
Santa Cruz Province
2
N
Ir
Tm
SfSc
Scm
Ld







5 m

Horizon | Facies | Lithology | Tapho-facies | clay | silts | VF F M C VC sandstones

5 Ir

4 Tm — Tm(Sv), Tm(Sh), Tm(l)

3 SfSc — SfSc(D), SfSc(IC)

2 Scm Ch — Scm(l), Scm(Cs), Scm(Cw), Scm(Ps), Ch(ch), Scm(Rp)

1 Ld Scm

Legend

Sedimentary structures

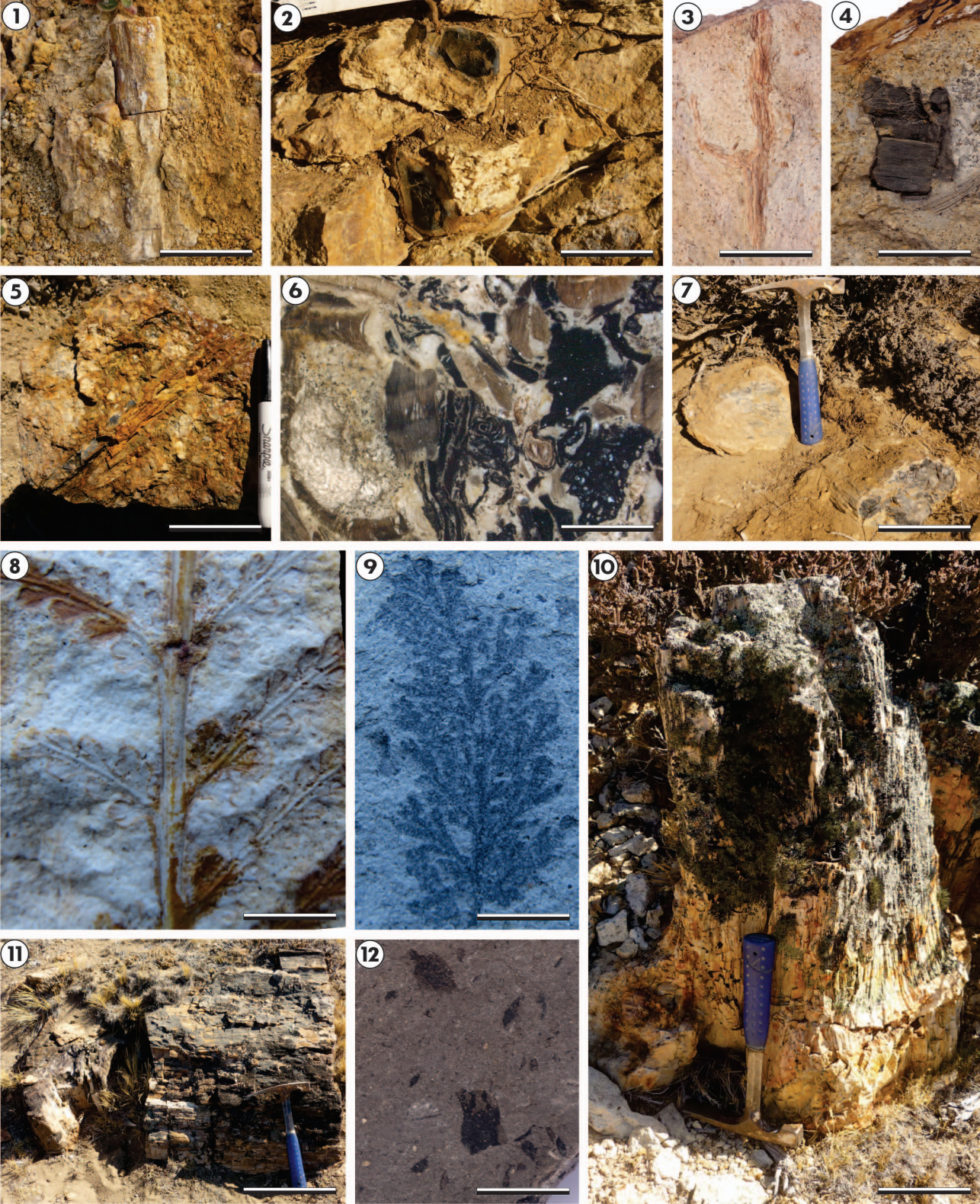
- Massive
- Cross lamination
- Flat lamination
- Chert lenses
- Surface oxidized and mottled

Contacts

- Net
- Unconformity

Fossils

- Impression/compressions
- Permineralized stems
- Carbonized wood
- In situ forest
- Silicified roots
- Casts


1
2
3
4
5
6
7
8
9
10
11
12

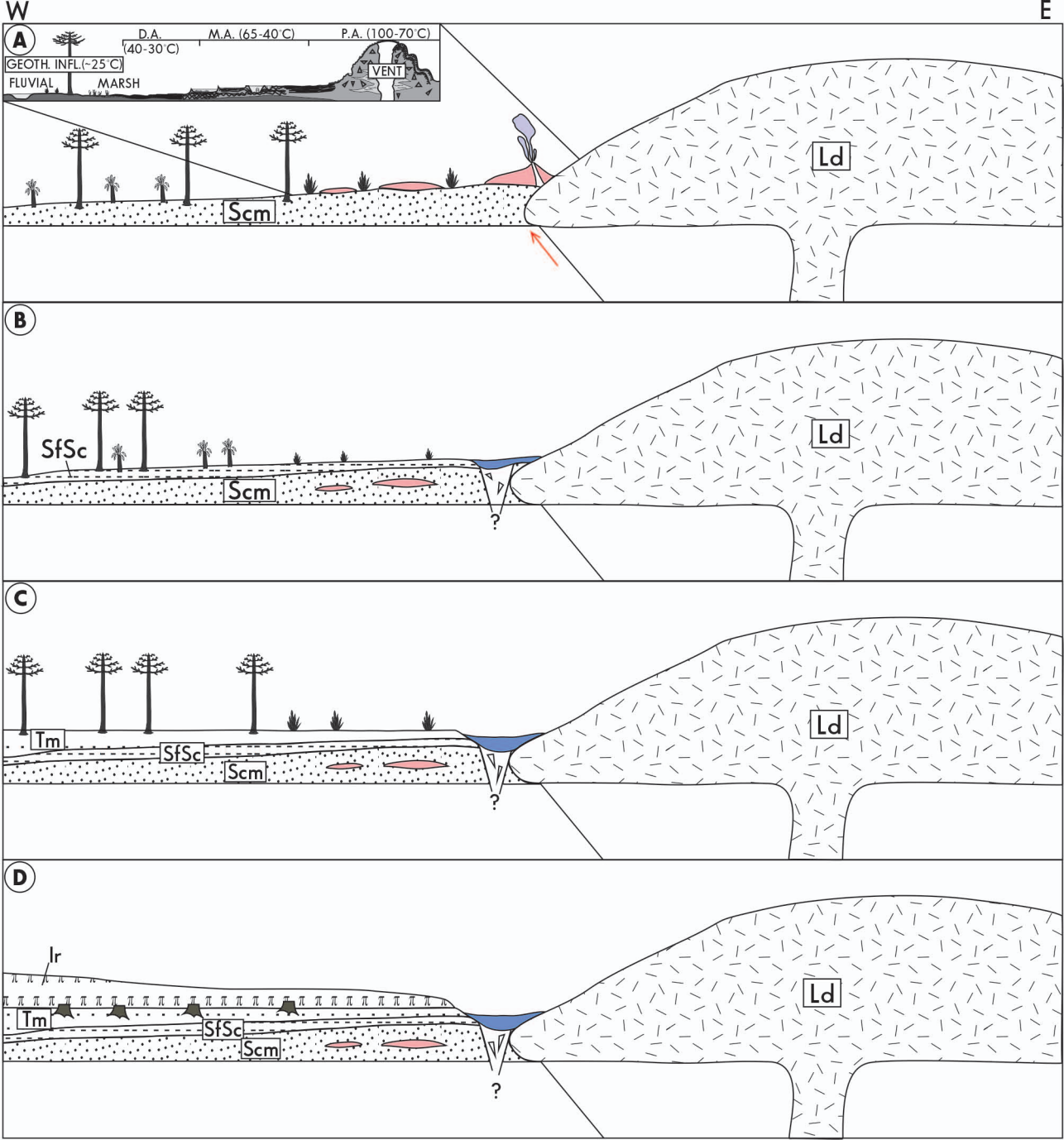

W
E
A
D.A.
M.A. (65-40°C)
P.A. (100-70°C)
(40-30°C)
GEOTH. INFL.(~25°C)
FLUVIAL
MARSH
VENT
Scm
Ld
B
SfSc
Scm
Ld
?
C
Tm
SfSc
Scm
Ld
?
D
Ir
Tm
SfSc
Scm
Ld
?

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 slitstone. 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 rhyolithic ignimbrite	–	12.5 m	Tabular. Thinning to the south	Eutaxitic. Massive structure

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

Bahía Laura Complex	Facies volcaniclastic	Subfacies pyroclastic	Subfacies pyroclastic flow (Ir) Subfacies pyroclastic fall (Scm; Tm) Subfacies pyroclastic surge
		Subfacies epiclastic (Ch; Scm; SfSc)	
	Facies effusive	Subfacies lavic (Ld)	
		Subfacies subvolcanic	

Modified from Guido (2004).