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Fossil forests in the Austral Basin (Argentina) marking a Cenomanian heterogeneous forced regressive surface

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ABSTRACT

The mid-Cretaceous greenhouse period in the southern Patagonia Argentina (Austral Basin) is represented by the Mata Amarilla Formation. It is composed of three informal sections which were deposited in littoral and continental environments. The boundary between the lower and middle sections of the Mata Amarilla Formation shows a drastic reduction in accommodation/sediment supply (A/S) ratio, interpreted as a forced regressive surface. This surface is characterized by a well-developed palaeosol, associated with the extensive preservation of a podocarp-dominated fossil forest over a vast area (more than 5400 km^2). Sedimentological and palaeopedological analyses, in conjunction with forest structure, tree density and growth ring analyses, indicate that the mid-Cenomanian forced regression can be distinguished as a non-uniform surface developed over a short period of time. This sequence boundary is recognized through a heterogeneous regional surface, delimited in the western part of the study area by an erosional surface generated by a large lateral channel migration recorded by sheet-like channel deposits with transported logs. By comparison, towards the eastern part of the study area, it appears as a paraconformity bounded by a very mature vertic Alfisol, which may have taken 40–100 ky to develop, and the preservation of a fossil forest in life position with a minimum age of 337 years. It is concluded that the extensive presence of these fossil forests at the same stratigraphic level in a vast region respond to changes in A/S ratio in a forced regressive surface at basin scale.

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INTRODUCTION

Forced regression refers to the process of seaward migration of a shoreline in response to a relative sea-level fall (Posamentier & Morris, 2000; Schwarz *et al.*, 2006; García-García *et al.*, 2011; Li *et al.*, 2011). In recent years, there has been an increase in the number of studies focused on forced regressive deposits due to their importance as hydrocarbon reservoirs (Posamentier & Morris, 2000; Schwarz *et al.*, 2006; García-García *et al.*, 2011; Li *et al.*, 2011; among others). The origin of forced-regressive wedge system tracts (*sensu* Hunt & Tucker, 1992) has been extensively debated in sequence stratigraphy (see historical perspective in Plint & Nummedal, 2000). Most documented Cretaceous forced-regressive wedges are located in the Western Interior Seaway of North America; in contrast, there is relatively little documentation of forced-regressive wedges in other Cretaceous worldwide successions (Schwarz *et al.*, 2006; Veiga *et al.*, 2008; García-García *et al.*, 2011).

Multidisciplinary studies concerning the biotic response and preservation factors related to the important changes in the accommodation space/sediment supply conditions (A/S ratio) are scarce (Gastaldo *et al.*, 2004; Gastaldo &

Demko, 2011). In this regard, the boundary between the lower and middle sections of the Mata Amarilla Formation shows a drastic reduction in A/S ratio and an important increase in the degree of amalgamation of fluvial channel deposits, occurring together with the extensive fossilized trees in a large area of the basin (5400 km^2 of exposed outcrops; Varela, 2015). In the north-eastern sector of the Austral Basin, this surface preserves fossil forests with silicified stumps in life position associated with a very mature palaeosol level. In turn, in the western sector, the same surface is characterized by transported logs within sandy sheet-channel deposits (Varela *et al.*, 2012a).

In this paper, this key surface is analysed by integrating observations on the fossil forest and associated palaeosol. The purpose of this study is to identify how changes in depositional environments and forest preservation can be explained within the framework of a mid-Cretaceous forced regressive non-uniform surface at basin scale.

GEOLOGICAL SETTING

The Austral Basin (also known towards the south as the Rocas Verdes Marginal Basin + Magallanes Basin) is located on the south-western edge of South America (Fig. 1A). It extends over the southernmost end of Argentina and Chile, and is surrounded to the east by the Deseado Massif (Macizo del Deseado) and to the west by the Patagonian-Fuegian Andes (Fig. 1A). Three main tectonic stages of the Austral Basin have been identified (Biddle *et al.*, 1986; Rodríguez & Miller, 2005; Richiano *et al.*, 2012; Varela *et al.*, 2012b): a rift stage, a stage of thermal subsidence, and, finally, a foreland stage. The Mata Amarilla Formation displays the best outcrops of the lower Upper Cretaceous deposits in the Austral Basin, thus marking both the closure of the previous Marginal Rocas Verdes Basin and the beginning of the foreland stage of the Austral Basin (Varela *et al.*, 2012b, 2013). This unit shows a maximum thickness towards the south of the study area (Fig. 1B) of ~350 m. It is composed of grey and blackish siltstones and claystones, alternating with beds of 1–10 m consisting of white and yellow–grey fine- to medium-grained sandstones, deposited in littoral and continental environments (Russo & Flores, 1972; Russo *et al.*, 1980; Arbe, 2002; Poiré *et al.*, 2004; Varela *et al.*, 2011). The Mata Amarilla Formation crops out on the southern margin of the Shehuen River (also known as 'Chalía River'), and on both margins of the Leona River (Fig. 1B). This unit overlies the Piedra Clavada Formation with a transitional contact and is unconformably covered by the marine deposits of the La Anita Formation (Fig. 2). The

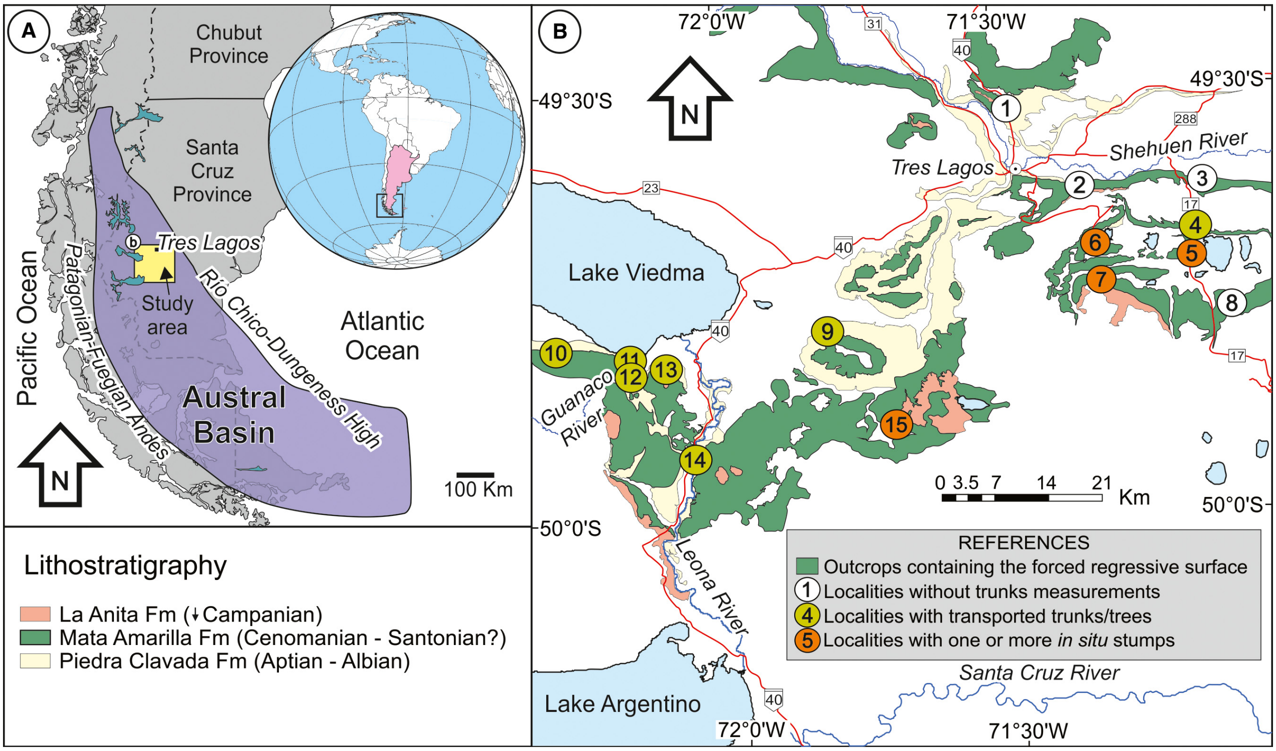
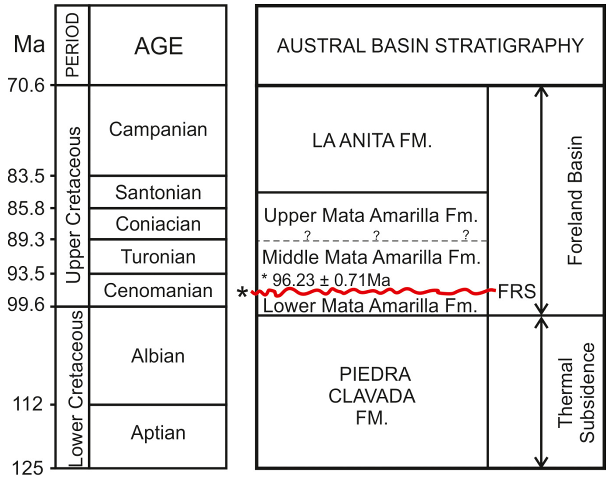


Fig. 1 (A) Geological setting of the Austral Basin and location of the study area. (B) Geological map of the study area showing the Cretaceous units of the Austral Basin (modified from Varela *et al.*, 2012a). Localities named in this work: (1) Waring Hill; (2) La Regina Farm; (3) Mata Amarilla Farm; (4) MAFer locality; (5) María Elena; (6) La Urbana Farm; (7) Pari Aike Farm; (8) Bajada de los Orientales Farm; (9) Índice Hill; (10) La Marina Outpost; (11) South of Lake Viedma; (12) Mouth of Guanaco River; (13) Hornos Hill; (14) Fortaleza Hill and (15) La Blanca Farm.



* Varela *et al.*, 2012b

Fig. 2 Stratigraphic scheme of the mid-Cretaceous of the Austral Basin modified from Varela *et al.* (2012b).

middle section of the Mata Amarilla Formation yields a U-Pb laser ablation concordia age of 96.2 ± 0.71 Ma (middle Cenomanian), which confirms that the Mata Amarilla Formation was deposited during the early Late Cretaceous (Fig. 2; Varela *et al.*, 2012b), in the context of a greenhouse period which began in the late Albian to the early Cenomanian (Huber *et al.*, 1995; White *et al.*, 2001; Royer, 2010).

On the basis of facies analysis, Varela *et al.* (2012a) divided the Mata Amarilla Formation into three sections: lower, middle and upper (Fig. 2). The section boundaries are clearly defined by dark marker horizons and a larger proportion of fine-grained sediments in the upper and lower sections, while the middle section shows a whitish colour due to a preponderance of sand-grained sediment. The lower section of the Mata Amarilla Formation is characterized by mudstones with subordinate sandstones in the west attributed to distal fluvial environments, whereas towards the east it consists of a fining-upward succession of mudstones, heterolithic sediments with mixed-structures and sandstones with herringbone cross-bedding assigned to littoral environments (Fig. 3). The middle section is characterized by conglomerates to coarse-grained sandstones with subordinate mudstones in the west, whereas towards the east, it consists of medium- to coarse-grained sandstones with subordinate mudstones (Fig. 3). Finally, the upper section is also characterized by mudstones with subordinate fine- to medium-grained sandstones (Varela *et al.*, 2013). The Mata Amarilla Formation is distinguished by an extensive development of stacked palaeosols, which display characteristics of hydromorphic soils and could be grouped within the gleysols (Varela *et al.*, 2012a). The lower and upper sections are composed of histosols, histosols with acid sulphate properties and hydromorphic vertisols associated with the low-gradient coastal environments (Fig. 3; Varela *et al.*, 2012a). The onset of the middle section is marked by the occurrence of mature vertic Alfisols and the rest of the middle section is characterized by the presence of vertisols and inceptisols related to the palaeotopographic relief, that is their relative position within the fluvial environment (Fig. 3; Varela *et al.*, 2012a).

METHODOLOGY

Sedimentological and palaeopedological analysis

The study area is located to the south-west of the Santa Cruz province, Patagonia, Argentina (Fig. 1A). Fifteen localities were studied (Fig. 1B) and detailed sedimentary logging was undertaken (Fig. 4A). To incorporate forest multiproxy studies, a detailed description of the Mata Amarilla Formation palaeosols was carried out using a detailed description of pedogenic features. Palaeosols

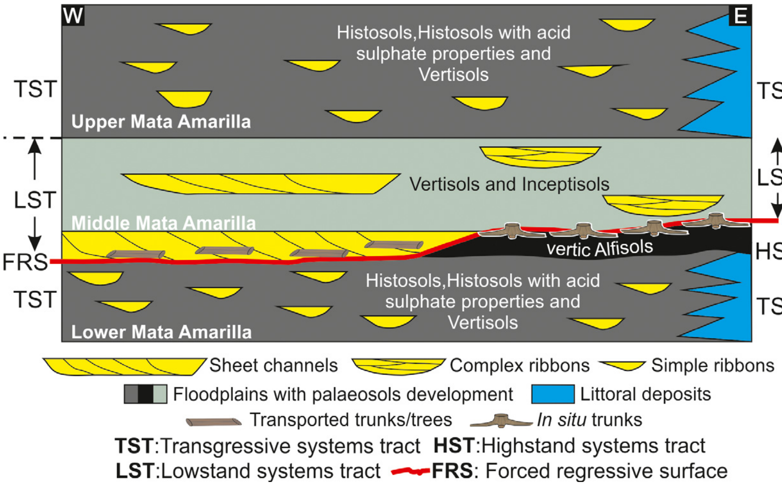


Fig. 3 Schematic cross-section showing the regional large-scale association between palaeosol types, depositional environments and sequence stratigraphy of the Mata Amarilla Formation. Vertical scale is between 100 and 350 m depending on the location in the basin. Modified from Varela *et al.* (2012a).

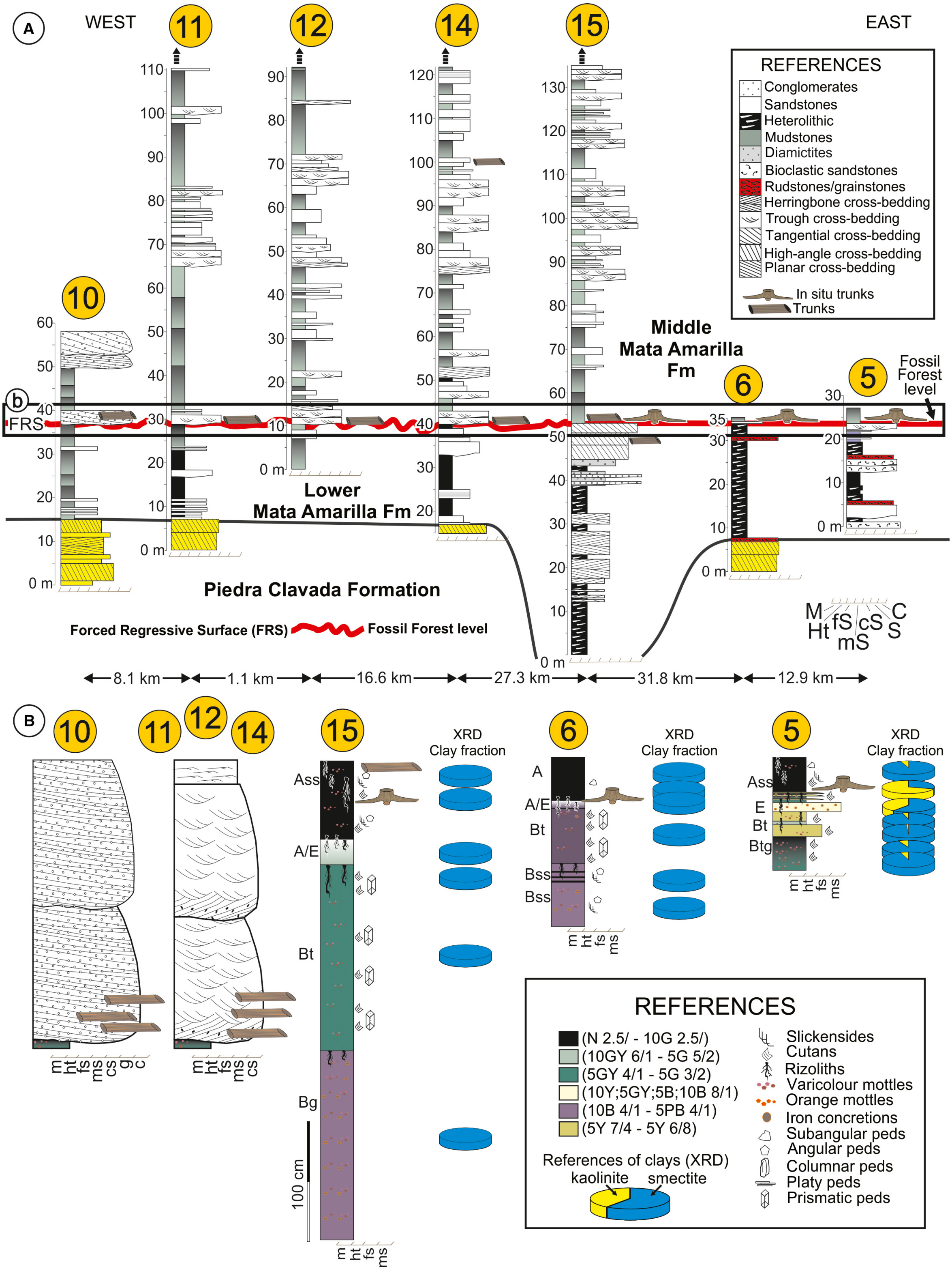


Fig. 4 (A) Sedimentological section showing vertical and lateral distribution of sedimentary facies in the Mata Amarilla Formation. (B) Detailed sedimentological section of the forced regressive surface. Localities as in Fig. 1.

horizons were used to interpret soil development processes (following the criteria described by Retallack, 1988, 1994). The colour of the palaeosol matrix, as well as of other pedogenic features (such as mottles, nodules, concretions and cutans), was determined using the Munsell colour chart (Munsell Soil Color Chart, 2000) in fresh rock samples. Field analysis was combined with thin-section description, and the micromorphological features observed under the microscope were identified following the terminology by Bullock *et al.* (1985) and Stoops (2001).

The mineral composition of mudstones, mottles, concretions, nodules and rhizoliths was obtained by X-ray diffraction (XRD) analysis at the Centro de Investigaciones Geológicas of the Universidad de La Plata. Pedogenic feature identification at both meso- and microscale, together with the definition of soil horizons, was used for soil taxonomy (Soil Survey Staff, 1998). Palaeosol analysis of the Mata Amarilla Formation was also combined with the palaeoenvironmental development of the *in situ* fossil forest.

Forest reconstruction

More than 45 permineralized stems with excellent preservation of the secondary xylem were analysed. All of them were sampled from the same level of the Mata Amarilla Formation, corresponding to the forced regressive surface (Varela, 2015). Standard cross-sections, as well as tangential longitudinal and radial longitudinal sections, were used to anatomically describe the fossil wood at microscale. Log samples were saved in the Repository of the Museo Provincial Padre Molina (Santa Cruz province) with the numbers MPPM-PB-1549 to -1568, and wood thin sections were placed in the micro-slides repository of the Palaeobotany Division of the Museo de La Plata (Universidad Nacional de La Plata) with the numbers pmLPPB-1919 to -1929. Anatomical terms used in this paper follow the recommendations of the List of Microscopic Features for Softwood Identifications (IAWA Committee, 2004), the terminology developed for Mesozoic conifer-like woods by Philippe & Bamford (2008) and the standardized wood measurements established by Chattaway (1932). All fossil wood was identified using wood identification keys for extant woods and fossil descriptions (Greguss, 1955; Tortorelli, 1956; Grosser, 1986; Bamford & Philippe, 2001; García Esteban *et al.*, 2002, 2004; Gulbranson *et al.*, 2012).

To determine the deciduousness on the forests, based on the method described by Falcon-Lang (2000), the radial diameters of successive tracheid cells were measured across each growth increment. Four parameters were calculated: skew of the cumulative sum deviation from the mean (CSDM) curves, percentage of latewood, and percentage of cell diminution in ring increments and Ring Markedness Index (RMI). Taking into account that deciduous conifers give CSDM curves which are dominantly left-skewed or symmetrical while evergreen conifers have dominantly right-skewed CSDM curves, the habit for the Mata Amarilla Formation trees was inferred.

Predictive models applied to extant conifers allows the forest strata reconstruction based on the relationship between stem diameter and tree height (Niklas, 1994a). Fossil logs rarely preserve the complete diameter of the original tree (e.g. no preservation of the outermost cortical region), resulting in an underestimation of height in fossil trees. This is a common problem that depends on the degree of fossil preservation. Most of the *in situ* forests of the Mata Amarilla Formation have an excellent preservation of logs without any sign of structural compression, avoiding any problems when using the field-measured diameter. The log diameters of the trees in life position were measured as high as possible, where the diameter is more constant (~100 cm), avoiding the basal part where diameter may be increased by the roots. For the compressed logs at Localities 11 and 13 (Fig. 1B), an alternative formula proposed by Philippe *et al.* (2009) was used to reconstruct the original basal log diameter $D = 4a/\pi$. Where a is the major axis radius, and the formulae can be summarized as n $D{\sim}1.27{*}a$.

Using the basal diameter (D) of fossil stumps, Niklas (1994a,b) estimated the critical buckling height (H_{crit}) of trees, as the height at which the mechanical structure of the wood fails, leading to collapse. Because trees actually never reach H_{crit}, estimated tree heights (H_{est}) are calculated on the basis of log diameter to height ratios observed in living trees (Niklas, 1993, 1994a,b) using the formula: $H_{est} = 27.8\ D^{0.430}$. Condensed explanations of this formula can be found in Artabe *et al.* (2007) and Brea *et al.* (2011). The use of this formula allows for comparisons of the Mata Amarilla Formation fossil forests with several other Mesozoic and Palaeogene fossil forests.

To estimate the ages of the trees and establish ranges of ages in the forest, we used the formulae from Veblen *et al.* (1981) obtained from wood rings measured from *Podocarpus nubigena* Lind logs, as follows: $\log_e Y = 3.0844 + 0.5717 \log_e X$ ($r = 0.68$; $P < 0.01$), where Y is the age of the tree and X is the log diameter. This equation was obtained from species adapted to cold temperate environments, which differs from the Mata Amarilla Formation palaeoenvironment. However, similar growth rates were observed in several planted native conifer trees in New Zealand (Lloyd, 1960; Bergin & Kymberley, 1992; Whitehead *et al.*, 2002). A lateral view of the locality 6 forest (La Urbana Farm, Fig. 1B) was reconstructed based on stump diameter and estimated tree height following a field transect.

The tree density of the fossil forests was obtained using only permineralized stumps that were recognized to be in life position (*in situ*) with the complete root systems in the palaeosol. This type of preservation occurs only at localities 5, 6 and 15 fossil forests (Fig. 1B). In other localities where the forced regressive surface was found (Varela, 2015), only logs in a horizontal arrangement were identified, preventing the analysis of the original position of the trees in the forests. The density at locality 6 fossil forest (La Urbana Farm, Fig. 1B) was measured using both the point-centred quarter method (Cottam & Curtis, 1956) and the distance to its nearest neighbour. The point-centred quarter method is also used in modern forests and has proven to produce the most conservative values using several techniques, including spatial statistics (Cottam & Curtis, 1956; Artabe *et al.*, 2007). At locality 5 fossil forest (Fig. 1B), density was measured only based on distance to its nearest neighbour due to the reduced extension of the area and the scarcity of *in situ* stumps (i.e. only four).

SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHIC FRAMEWORK OF A FORCED REGRESSIVE SURFACE

The palaeogeography of the lower section of the Mata Amarilla Formation was proposed as a large embayment with a shallow marine coast and smooth continental relief (Varela *et al.*, 2011, 2013). The middle section of the Mata Amarilla Formation is characterized by conglomerates, sandstones, siltstones, and mudstones with palaeosol development (Varela *et al.*, 2012a). In the western part, four facies associations (FAs) are defined: gravelly sheet bodies, sandy sheet bodies, tabular mudstones and fine-grained sandstones, and fine-grained deposits. They are interpreted as a gravel-bed braided fluvial system in the west that transitions towards the east to a sandy high-sinuosity meandering (HSM) fluvial system. In the eastern part of the basin, six FAs were recognized: large-scale complex ribbon bodies, small-scale simple ribbon bodies, tabular mudstones and fine-grained sandstones, lobe-shaped bodies, fine-grained deposits and heterolithic deposits with continental fossils: plants, insects, freshwater fishes and dinosaurs (Iglesias *et al.*, 2007; Petrulevičius *et al.*, 2014). They are part of a low-sinuosity (LSM) fluvial system with aggradation (Varela, 2015).

The braided fluvial system transitionally changes eastward to a HSM fluvial system with a sandy bedload. The HSM fluvial system characterizes localities 9, 11, 12, and 13 (Fig. 1B), while locality 14 shows the transition to a LSM fluvial system with aggradation. The HSM fluvial system is a tributary of the LSM fluvial system. The LSM is the main fluvial system within the drainage network and has a north-east–south-west orientation, flowing towards the basin depocentre in the south-west (Varela *et al.*, 2013; Varela, 2015).

The sequence stratigraphic scheme of the Mata Amarilla Formation was proposed by Varela (2015) based on the accommodation/sediment supply conditions. A relatively high aggradation rate has been inferred for the lower section, evidenced by isolated channels in the floodplain deposits. This was correlated with the development of marginal marine systems in the eastern area, suggesting the development of a transgressive systems tract (TST; Fig. 3). The boundary between the lower and middle sections of the Mata Amarilla Formation was interpreted as a response to a drastic reduction in accommodation/sediment supply condition, which is evidenced by a significant increase in the degree of amalgamation of fluvial channels, together with the onset of fluvial sedimentation across the whole area. This boundary is a non-uniform surface which is also characterized by the presence of a strongly developed palaeosol level associated with the extensive preservation of horizontal and *in situ* fossil trees within a large area (an outcropping surface of more than 5400 km^2). Fossil trees are preserved in life position to the east (localities 5, 6 and 15; Figs 1, 3 and 4) and as transported logs within amalgamated sheet-like channel deposits to the west (localities 11, 13 and 14; Figs 1, 3 and 4). These pieces of evidence point to the development of a forced regressive surface, which represents a sequence boundary (SB) within a sequence stratigraphic framework (*sensu* Catuneanu *et al.*, 2009; Fig. 3). The upper part of the middle section is dominated by the accumulation of sheet sandstones in the western sector and by complex ribbon sandstone bodies in the eastern sector, which was interpreted as the subsequent lowstand systems tract (LST; Fig. 3). Finally, the upper section of the Mata Amarilla Formation is characterized by isolated channels within fine-grained deposits with abundant hydromorphic palaeosols that represent a high A/S ratio. Thus, the upper section was interpreted as a second transgressive systems tract (Varela, 2015; TST, Fig. 3).

DISTRIBUTION OF FOSSIL LOGS IN THE SHEET-LIKE CHANNEL DEPOSITS

In this section we describe the preservation, disposition and distribution of the fossil forest at the western part of the study area where the logs are found within gravelly and sandy sheet-like channel deposits. Gravelly sheet channels consist of tabular bodies which are 5 m thick and more than 250 m wide, and internally characterized by large-scale tangential cross-bedding, low-angle planar cross-bedding and less frequently trough cross-bedding (locality 10; Fig. 4B). This channel fill was interpreted as longitudinal downstream accretion bars from a braided fluvial system (Varela, 2015). The logs are located isolated in the channel bars deposits as basal lags (Fig. 4B), without any clear relation with the channel axes. Sandy sheet channels are composed by bodies of 1–8 m thick and more than 250 m wide. Internally they show large-scale inclined surfaces perpendicular to the main channel orientation, which are filled with trough cross-bedding and less abundant planar cross-bedding with mud intraclasts (localities 11, 12 and 14; Fig. 4B). These deposits were interpreted as 3D and less frequently 2D bedform migrations in a high-sinuosity fluvial system with lateral accretion (Varela, 2015). The logs are preserved in a random isolated way within the bedform at the bottom of these channel deposits, mostly as basal lags (Fig. 5). In general they have parallel and subperpendicular orientation with respect to the bedform. Sometimes, logs were found lying on sheet-channel deposits with their stumps and root system preserved (Fig. 5A), possibly denoting limited transportation from the original growing site (Gastaldo, 2004; Gastaldo & Degges, 2007).

PALAEOPEDOLOGY OF THE FORCED REGRESSIVE SURFACE

Description of palaeosol macromorphology

The palaeosols associated with the localities 5, 6 and 15 fossil forests level show thick, well-developed horizons, and palaeosol profiles with A-A/E-Bt-Bss or Ass-E-Bt- Btg successions (Figs 4B and 6A–C), although in many cases they can show eroded tops, and Ass and A/E horizons are absent. Ass horizons are dark to black in colour (N 2.5/0 to 5GY 2.5/1) and their thickness varies from 30 cm to 1 m (Fig. 6A and 6C). In turn, A/E albic horizons (5B 8/1 to 10B 8/1) are poorly defined and vary between 10 and 20 cm thick (Fig. 6A). The Bt argillic horizons are characterized by the presence of illuvial clay (argillans) and vary between 50 cm and 1.5 m thick, occasionally reaching 2 m (Fig. 6C). They range from purplish grey to greenish grey colours (10G; 5BG; 10BG; 5B; 10B and 5PB) at values 3/1 to 5/1. There is usually an underlying Bg or Bss horizon with gley colours (10GY 3/1 to 5/1; 5G 3/1 to 5/2), 50 to 80 cm thick, and occasionally a C horizon with variable colouration and thickness is present. These palaeosols are characterized by the presence of cutan or argillan coatings, as well as prismatic peds (Fig. 6D). Argillans were observed both with the naked eye (Figs. 6E and F) and in thin sections at the lab (see below), where the oriented clays filling cavities and channels, as well as the clay coatings around detrital grains or rhizoliths, were identified (Fig. 6G). This type of palaeosol is also characterized by the presence of vertic and hydromorphic features, including slickensides (Fig. 6H), wedge-shaped peds, gley colours and mottles. These mature palaeosols are only present in the eastern localities and at the same stratigraphic level (the forced regressive surface located at the beginning of the middle section of the Mata Amarilla Formation; Fig. 6B), and always associated with the conspicuous fossiliferous level of trees in life position corresponding to the localities 5, 6 and 15 fossil forests (Zamuner *et al.*, 2004, 2006). The *in situ* fossil trees show shallow root systems with well-developed horizontal roots and minimal development of vertical roots (Fig. 6A–C). The horizontal roots display towards their ends a webbed shape, like duck's feet (Fig. 6C).

Description of palaeosol micromorphology

At a micromorphological level, the palaeosols recognized at the forced regressive surface of the Mata Amarilla Formation show A and Ass horizons with clay loam to silty clay particle size classes (Fig. 7A–B); the coarse/fine material (c/f) ratio is 1/8 to 3/8 with porphyric c/f related distribution which varies from simple/double spaced porphyric (Fig. 7B, D) to open porphyric (Fig. 7A, C). Groundmass of A horizons present undifferentiated b-fabric (Fig. 7A) whereas Ass horizon are characterized by

Fig. 5 (A) Short-transported podocarp logs at Hornos Hill (locality 13), person for scale is 1.75 m tall. (B) podocarp log at Fortaleza Hill (locality 14). (C) podocarp log at South of Lake Viedma (locality 11). (D) podocarp log at South of Lake Viedma (locality 11).

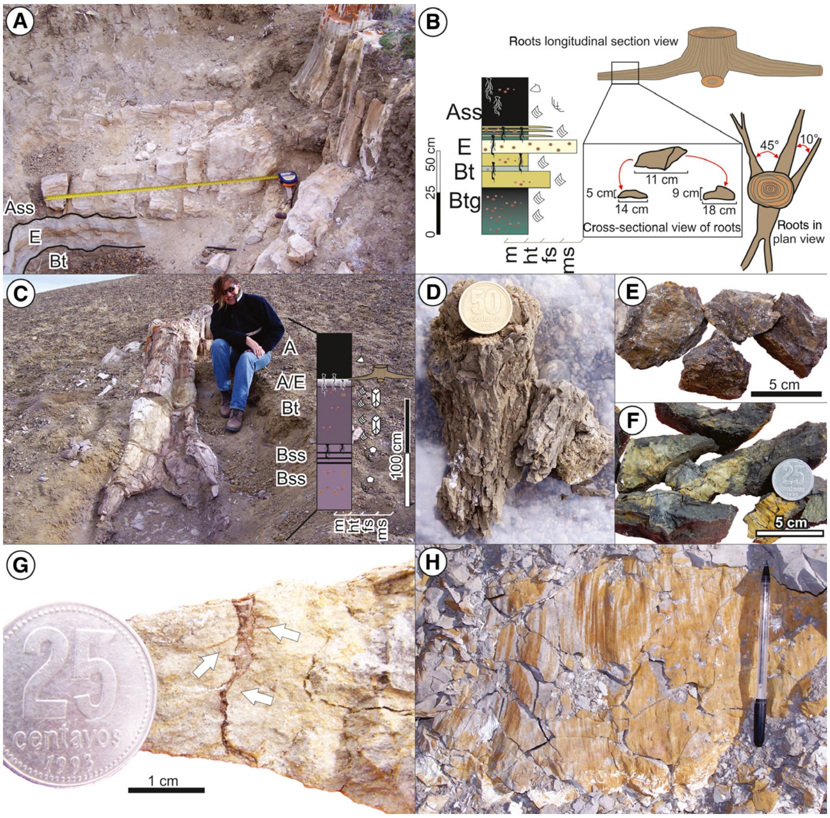


Fig. 6 (A) General view of a vertic Alfisol with *in situ* fossil tree roots at La Urbana Farm (locality 6). (B) Detailed vertic Alfisol log and detail of *Podocarpoxylon garciae* roots in life position (longitudinal, cross-sectional and plan views) from La Urbana Farm (locality 6), for log references see Fig. 4. (C) General view and detailed log of a vertic Alfisol with a tree in life position at María Elena (locality 5), for log references see Fig. 4. (D) Prismatic peds from Bt horizon, coin is 2.5 cm in diameter. (E) Subangular blocky peds with argillans and mottles, characteristic of a Bt horizon. (F) Subangular blocky peds with overprinted cutans and slickensides from Bt horizon. (G) Illuviated clays filling root cavities in a Bssg horizon. (H) Slickensides from a Bss horizon, pen is 14 cm long.

cross striated b-fabric with two sets of birefringent clay orientation forming angles of ~45° (Fig. 7D). The A horizons are distinguished by the presence of voids forming galleries, usually having iron or manganese oxide cementation (Fig. 7A, C). Voids are open and lined with organic matter (Fig. 7C) or filled by high luminescence clay minerals (Fig. 7B). Albic horizons (E-A/E) are poorly defined, and in locality 5, has a sandy particle size class with monic c/f related distribution and the presence of typic amiboidal shape nodules of iron oxides (according to Bullock *et al.*, 1985; Fig. 7E). These mature palaeosols are characterized by the presence of a Bt argillic horizon (Soil Survey Staff, 1975, 1998, Retallack, 1994). Bt horizons present sandy clay (Fig. 7F, G) silty clay (Fig. 7H, I) to clay (Fig. 7J) particle size classes, and the c/f ratio varies from 2/3 (Fig. 7F, G) to 1/10 (Fig. 7J) with chitonic-gefuric (Fig. 7F–I) to open porphyric c/f related distribution (Fig. 7J). The typical feature of the Bt subsurface horizons is the presence of illuvial clay. It is present as laminated, dense, incomplete clay and organic matter infilling (Fig. 7F), as microlaminated dense complete limpid and impure illuvial clays infilling (Fig. 7G) or as hypo-coating of rizholith voids composed of a mixture of organic matter, clay and Fe-Mn oxides (Fig. 7J). Occasionally, rhizoliths with partially preserved roots and thick argillans coating their walls are also present (Fig. 7H–I).

Palaeosol interpretations

Based on the presence of well-developed horizons and abundant illuviated clay in some horizons (Bt), Varela *et al.* (2012a) assigned these palaeosols to Alfisols (*sensu* Soil Survey Staff, 1975, 1998). Micromorphological evidence of illuvial clay in the palaeosols of the Mata Amarilla Formation was recognized based on the presence of cutan or argillan coatings and hypo-coatings. These clay minerals were elluviated from a type A surface horizon and illuviated into a B horizon (White, 1997). Furthermore, the presence of vertic features, such as slickensides, and wedge-shaped peds, allows a further classification of this type of soils as vertic Alfisols (Soil Survey Staff, 1975, 1998; Varela *et al.*, 2012a). Slickensides and microslickensides are formed in soils by periodic expansion and contraction of expansive clay minerals associated with strongly seasonal precipitation (White, 1997; Retallack, 2001; Driese *et al.*, 2003). In thin-section the presence of cross striated b-fabric also indicates shrinking and swelling processes related to seasonal contrast (Hussein & Adey, 1998; Driese *et al.*, 2003; Kovda & Mermut, 2010; Di Celma *et al.*, 2015). The Alfisols from the Mata Amarilla fossil forests also have hydromorphic features, such as the presence of gley colours, mottles and nodules in the Bg and E horizons. Nodules are 0.5–20 mm in size, surrounded by haloes of a light

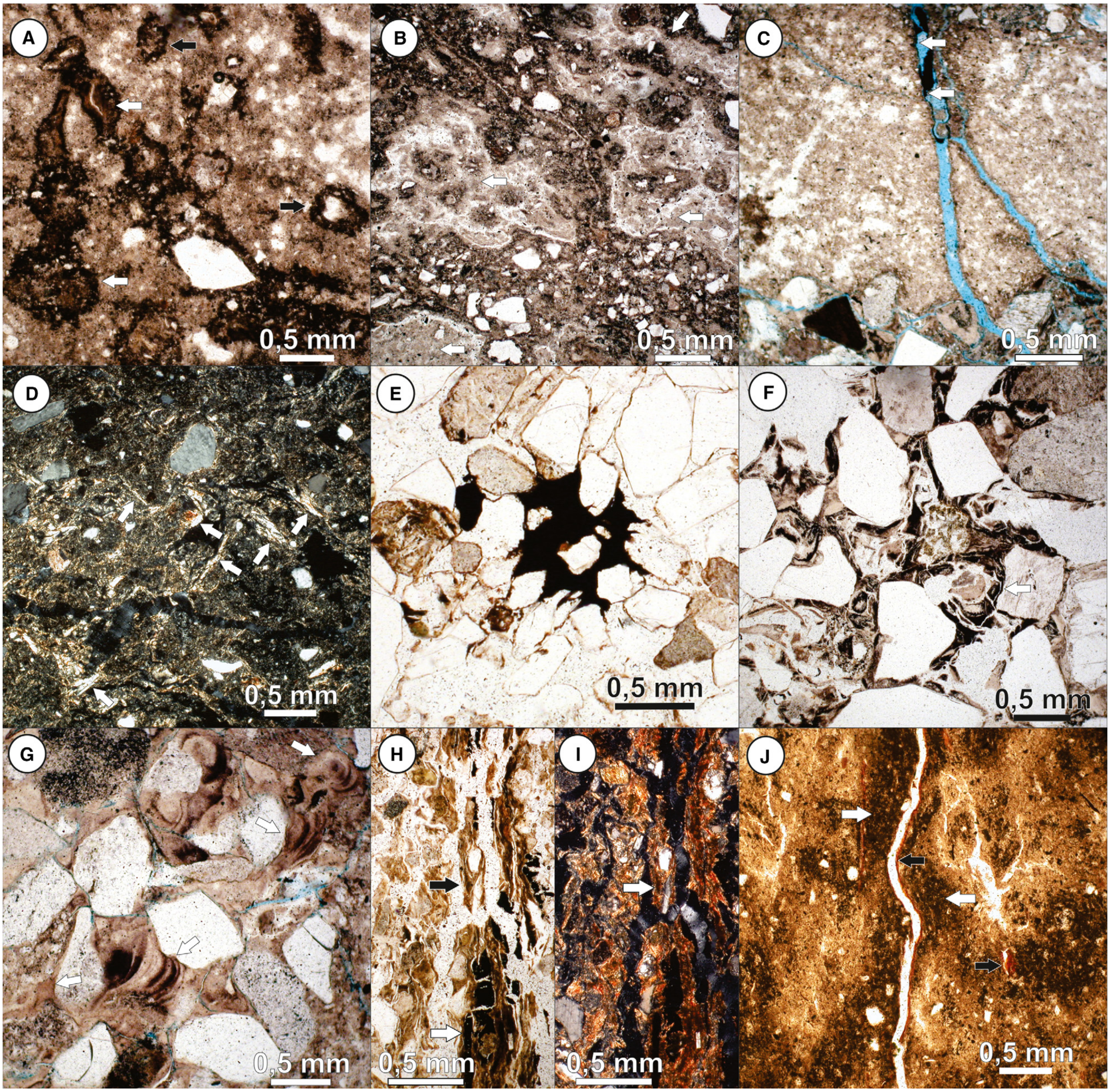


Fig. 7 Detailed of vertic Alfisols micromorphology (A) Photomicrograph from A horizon at locality 6, showing groundmass with undifferentiated b-fabric and the presence of voids forming galleries (white arrows) and voids in cross-sectional views (black arrows), showing cementation of iron and manganese oxides, PPL. (B–C) Photomicrographs from A horizon at locality 6 (B) simple to double spaced porphyric c/f related distribution and voids filled by high luminescence clay (white arrows), PPL. and (C) open porphyric c/f related distribution and open voids lined with organic matter and forming galleries (white arrows), PPL. (D) Photomicrograph of Ass horizon at locality 6, showing groundmass with cross striated b-fabric with two sets of birefringent streaks clay orientation forming an angle of ~45° (micro-slickensides), the c/f ratio is 1/8 with double spaced to open porphyric c/f related distribution, XPL. (E) Photomicrograph of E horizon at locality 5 showing monic c/f related distribution with a typic amiboidal shape nodule composed of iron oxide, PLL. (F) Photomicrograph of Bt horizon at locality 5, the c/f ratio is 2/3 with a chitonic-gefuric c/f related distribution showing laminated dense incomplete illuvial clay and organic matter infilling (cutans; white arrow). (G) Photomicrograph of Bt horizon at locality 5, showing chitonic-gefuric related distribution, the c/f ratio is 2/3 and microlaminated dense complete limpid and impure illuvial clays infilling (argillans; lines of clay illuviation in white arrows). (H and I) Plane polarized light (PPL) and crossed polarized light (XPL) photomicrographs of Bt horizon at locality 6, showing a rhizolith with partially preserved root (white arrow) and cutans (i.e. argillans) that cover the walls of rhizoliths (black arrow), noted double spaced porphyric c/f related distribution with a c/f ratio of 1/8. (J) Photomicrograph from Bt horizon at locality 15, showing a groundmass with undifferentiated b-fabric; and a rhizolith with a hypo-coating composed of a mixture of organic matter, clay and Fe-Mn oxides (white arrows) and thin coating of limpid clay (black arrows).

yellowish colour. The hydromorphic features suggest a fluctuating water table and/or alternating periods of waterlogging, both caused by rainfall seasonality (Duchaufour, 1992; Vepraskas, 2004; Lindbo *et al.*, 2010). The voids and cavities are often interconnected by galleries (Fig. 7A and B), and sometimes lined with organic matter, which could be attributed to bioturbation by worms (Fig. 7C). The time required to form strongly developed Bt horizons of clay texture is between 40 and 100 ky (Harden, 1982; Harrinson *et al.*, 1990; Duchaufour, 1992). Pedogenic features, such as mottles, slickensides, nodules and iron/manganese oxide concretions, are in accordance with a warm temperate climate with a pronounced seasonality caused by rainfall (among others, Duchaufour, 1992; White, 1997; Hussein & Adey, 1998; Retallack, 2001; Kovda & Mermut, 2010).

FOSSIL FORESTS OF THE FORCED REGRESSIVE SURFACE

Wood taxonomy and growth ring analysis

Order CONIFERALES
Family PODOCARPACEAE Endlicher, 1847
Genus *Podocarpoxylon* Gothan, 1905
Type species *Podocarpoxylon juniperoides* Gothan, 1905
Species *Podocarpoxylon garciae* Del Fueyo, 1998

Material examined

Thirteen stumps in life position at locality 6 (La Urbana Farm) (MPM-PB-1549 to MPM-PB-1561) and thin sections (pmLPPB-1919 to -1930). Five stumps at locality 5 (María Elena) (MPM-PB-1562 to MPM-PB-1566 and microscope slides pmLPPB-1931 to pmLPPB-1935), twelve logs at locality 11 (South of Lake Viedma) (MPM-PB-1567 and pmLPPB-1936) and seven logs at locality 13 (Hornos Hill) (MPM-PB-1568 and pmLPPB-1937).

Description

Silicified stumps and stems of 10–120 cm in diameter (Table 1). Generally dark yellow to orange-yellow in external colours without evidence of compression, except at locality 13 (Hornos Hill), where they are dark black externally and laterally compressed (Fig. 5A).

In cross-section, wood shows smooth-marked growth rings, with 3 mm in mean thickness (1.7–3.8 mm in range). The transition from earlywood to latewood is thin, composed by few layers of tangentially compressed thick-walled tracheids (Fig. 8A and B). Tracheids are quadrangular to rectangular in shape (Fig. 8C). The earlywood is constituted by tracheids with a mean radial diameter of 39 μm (79–14 μm) and a tangential diameter of 33 μm (41–25 μm), whereas the latewood tracheids have a mean radial diameter of 25 μm (57–4 μm) and a tangential diameter of 20 μm (39–4 μm). The latewood is narrow, with 4–19 regular radial rows of tracheids (Fig. 8C). The mean number of tracheids that separate the rays is 4, with a range between 1 and 8. Intercellular axial spaces are

Table 1 Diameters and taphonomic characters for each fossil forest locality

Locality of the Fossil Forest	Log n°	Diameters, cm	Taphonomic position
Locality 4	T1	86	Horizontal stump
Locality 5	T1	120	*In situ*
Locality 5	T2	100	*In situ*
Locality 5	T2′	100	*In situ*
Locality 5	T3	26	Horizontal stump
Locality 5	T3′	50	*In situ*
Locality 5	T4	92	Horizontal stump
Locality 5	T5	65	Horizontal stump
Locality 6	T1	–	*In situ*
Locality 6	T2	56	*In situ*
Locality 6	T3	66	*In situ*
Locality 6	T4	120	Horizontal stump
Locality 6	T5	–	*In situ*
Locality 6	T6	70	Horizontal log
Locality 6	T7	–	Roots in life position
Locality 6	T8	112	*In situ*
Locality 6	T9	70	*In situ*
Locality 6	T10	–	Roots in vita
Locality 6	T11	–	Horizontal stump
Locality 6	T12	–	Roots in vita
Locality 6	T13	–	*In situ*
Locality 7	T1	–	*In situ*
Locality 7	T2	70	Horizontal stump
Locality 7	T3	45	Horizontal log
Locality 11	T1	74	Horizontal stump
Locality 11	T2	49	Horizontal log
Locality 11	T3	48	Horizontal log
Locality 11	T4	79	Horizontal stump
Locality 11	T5	64	Horizontal log
Locality 11	T6	62	Horizontal log
Locality 11	T7	52	Horizontal log
Locality 11	T8	65	Horizontal log
Locality 11	T9	58	Horizontal log
Locality 11	T10	80	Horizontal stump
Locality 11	T11	57	Horizontal log
Locality 11	T12	10	Horizontal log
Locality 13	T1	53	Horizontal stump
Locality 13	T2	38	Horizontal log
Locality 13	T3	57	Horizontal stump
Locality 13	T4	35	Horizontal log
Locality 13	T5	105	Horizontal stump
Locality 13	T6	72	Horizontal stump
Locality 13	T7	48	Horizontal log
Locality 14	T1	–	Horizontal log
Locality 14	T2	–	Horizontal log
Locality 14	T3	–	Horizontal log
Locality 14	T4	–	Horizontal log
Locality 15	T1	89	Horizontal stump
Locality 15	T2	72	Horizontal stump
Locality 15	T3	–	Horizontal log
Locality 15	T4	–	Horizontal log
Locality 15	T5	–	Horizontal log
Locality 15	T6	120	*In situ*
Total	53	69.34	

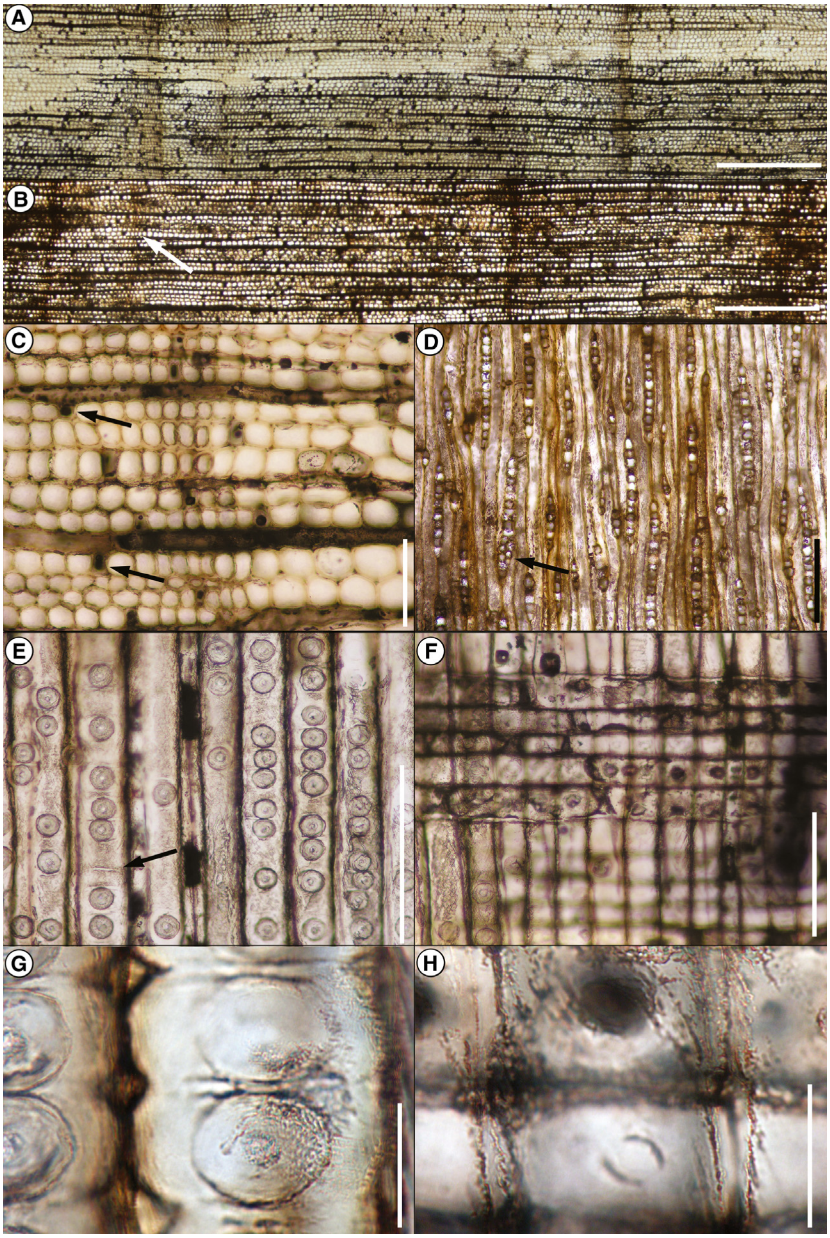


Fig. 8 Wood anatomy of *Podocarpoxylon garciae* at the forced regressive surface. (A–C) Cross-section of grow rings of locality 6 (La Urbana Farm) *in situ* fossil woods. (A) pmLPPB-1927 (MPM-PB-1557), scale 0.4 mm. (B) pmLPPB-1923 (MPM-PB-1552), white arrow denoting a false grow ring. Scale 0.4 mm. (C) Closer view at a grow ring, note quadrangular and smaller cells at late wood (left). Black arrow at diffuse axial parenchyma (pmLPPB-1923), scale 0.1 mm. (D) Tangential longitudinal section showing uniseriate rays. Black arrow showing a partial biseriate ray (pmLPPB-1927), scale 0.2 mm. (E–H) Radial longitudinal section in pmLPPB-1931 (MPM-PB-1552). (E) Uniseriate large pits (abietinoid type wood) and Sanio bars (black arrow), scale 200 µm. (F) Cross-field pitting of cupressoid type (1–2 oval to circular pits), scale 200 µm. (G) Closer view of pitting at radial tracheid walls showing Sanio bars, scale 20 µm. (H) Closer view at two cross-field pitting of cupressoid type, scale 20 µm.

present (Fig. 8C), and probably trabeculae as well. The axial parenchyma is scarce and diffuse (Fig. 8A–C).

In radial longitudinal section, the tracheid pitting is recognized as the abietinoid type. Pits are circular, areolate, spaced or contiguous, uniseriate or rarely with biseriate portions; when biseriated, pits are opposite or alternate (Fig. 8E). In radial tracheid walls, transversal thickening as bars of Sanio occurs (Fig. 8E and G). The mean size of the pits is 1.9 µm (2.5–1.5 µm). The aperture of pits is circular or oval, 0.3–0.5 µm in diameter. The cross-field pitting is of the cupressoid type, with 1–2 oval to circular pits (1–1.6 µm in size). Pits have large apertures and thin, weakly defined borders (Fig. 8H). The tangential and transverse walls of the parenchyma ray cells are smooth.

In tangential longitudinal section, the radial system is homogeneous (homocellular rays). Uniseriate low rays with 2–3 cells in height are most common with a mean of 6 (2–17) cells in height. Occasionally, uniseriate rays with a small biseriate portion (Fig. 8D) occur. There is an absence of pits in tangential walls, when the ray cell walls are smooth.

Comparison

The abietinoid pitting with cross-field pits (mostly 1–2 per field), the presence of homocellular rays, and ray cells with smooth walls and scarce axial parenchyma in the wood anatomy allows the assignment of the fossils to genus *Podocarpoxylon* Gothan, 1905 (Petriella, 1972; Del Fueyo, 1998; Bamford & Philippe, 2001; Gnaedinger, 2007; Philippe & Bamford, 2008). The fossils were compared with diverse *Podocarpoxylon* species that have axial parenchyma (see Table 1 in Gnaedinger, 2007; Table 2 in Franco & Brea, 2015). The wood fossil described for the Meso-Cenozoic of Gondwana with axial parenchyma are: *P. mazzonii* (Petriella) Müller-Stoll & Schultze-Motel (1990), *P. speciosum* (Ramanujam) Trivedi & Srivastava (1989), *P. mahabalei* (Agashe) Trivedi & Srivastava (1989), *P. schmidianum* Sahni (1931), *P. paralatifolium* Vozenin-Serra & Grant-Mackie (1996), *P. austroamericanum* Gnaedinger (2007), *P. trichinopoliense* (Varma) Bose & Maheshwari (1974), *P. umzambense* Schultze-Motel (1966), *P. stokesii* Thayn & Tidwell (in Bamford & Corbett, 1995) *P. mahabalei* Agashe (1969) and *P. garciae* Del Fueyo (1998). The anatomy of the Mata Amarilla Formation woods show uniseriate radial wall pits, scarce and diffuse axial parenchyma, cross-field pitting of the cupressoid type with 1–2 circular pits, usually uniseriate and rarely biseriate rays, low rays 1–15 cells in height (most commonly 2–3 cells high), smooth tangential and transverse walls of the parenchyma cells, and frequent intercellular axial spaces, indicating placement within *Podocarpoxylon garciae* Del Fueyo (Del Fueyo, 1998; Gnaedinger, 2007). The specimens describe here as *P. garciae* differs from *P. mahabalei*, *P. speciosum*, *P. mahabalei*, *P. austroamericanum*, and *P. umzambense* in the number of pits per cross-field. *P. mazzonii* and *P. schmidianum* differ in the type of the radial pitting and ray height. *P. paralatifolium* and *P. trichinopoliense* have uniseriate rays. *P. stokesii* differs in the ray height, the number of pits per cross-field and it has abundant axial parenchyma.

The skew of the cumulative sum deviation from the mean (CSDM) curves for *P. garciae* are right-skewed with a mean skew percentage of +38.98, with a range from +9.09 to +76.19% (Fig. 9 and Table 2), which indicates an evergreen habit. In New Zealand, living podocarps have given skew ranges of +30.8 to +40.0% and +40.0 to +52.4%, based on *Podocarpus totara* Don ex Hook and *Prumnopitys ferruginea* (Benn ex Don) de Laub. respectively (Falcon-Lang, 2000). Among other Patagonian fossils, podocarps have shown ranges as broad as +38.8 to +48.39% (average of +40.23%) in the early Palaeocene (Brea *et al.*, 2011). These results indicate that in the Mata Amarilla Formation, the *P. garciae* ring boundaries and ring increments are comparable to those of extant conifers with long leaf retention times (LRTs) ranging between 2 and 6 years (Falcon-Lang, 2000; Table 2).

Podocarp forest structure and tree density

The spatial distribution of the stumps at locality 6 (La Urbana Farm, Fig. 1B), made it possible to measure the forest density, using both the point-centred quarter method and the nearest neighbour method (Fig. 10A–B). At locality 5 (Fig. 1B), tree density was measured based only on distance to the nearest neighbour due to the reduced size of the area and scarcity of *in situ* stumps (Table 1). In other fossil forest localities it was impossible to measure forest density due to the fact that the real position of trees could not be identified, and some of them show signs of short transportation (parautochthony).

The point-centred quarter and nearest neighbour methods are known to give different density values (Cottam & Curtis, 1956) that should not be used as absolute values for cross comparisons. However, they are very useful to compare both fossil and modern forests using the same methods (Fig. 10A–B; Table 3). Mean distance to the nearest neighbour method gives values as low as 16.24 and 36.73 trees per hectare (mean distance of 12.41 m for locality 6 and 16.5 m the locality 5). The obtained maximum value of 114 trees per hectare (Table 3) still corresponds to a forest type with low tree density (Fig. 10C).

Comparisons with other podocarp-dominated extant forests

The tree density values obtained for the Mata Amarilla Formation fossil forests are comparable to recent forests with old podocarp trees in which large forest gaps occur, generating multiple open spaces that are used by more competitive species (Blakely & Dinham, 2008). In mixed temperate rainforests in South America, *Podocarpus nubigenea* can reach a height of up to 25 m tall (1–2 m in diameter) and is found as a tolerant species in advanced ecological succession, with <30 trees per hectare (Veblen

Table 2 Range of values obtained for ring markedness parameters (RMI) and CSDM curves (Fig. 11) in five *Podocarpoxylon garciae* trees at locality 6 (La Urbana Farm) using Falcon-Lang (2000) method. Average are obtained from four measures in different grow rings at each fossil wood. Percentages of skew are similar to evergreen podocarp forest from New Zealand with a leaf retention time of 2–6 years

Thin section wood sample	Percentage Latewood	Percentage diminution	Ring markedness index (RMI)	Percentage skew
pm-LPPB-1923	14.28–33.93	84.14–89.45	12.16–28.55	+16.36–+76.19
pm-LPPB-1927	4.21	73.90	5.70	+51.57
pm-LPPB-1930	19.67–25.81	81.13–90.81	17.08–21.04	+31.15–+51.67
pm-LPPB-1931	17.04–17.30	82.43–84.78	14.26–14.40	+9.09–+63.63
Average	20.92	85.56	17.85	38.98

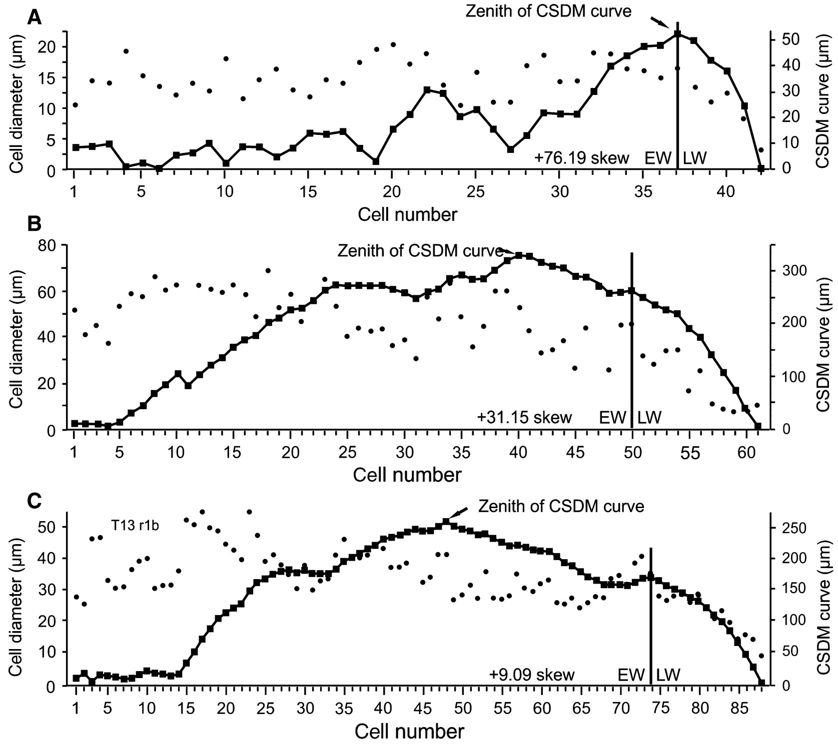


Fig. 9 Right-skewed CSDM curves and growth ring increment of three wood specimens from locality 6 (La Urbana Farm). The distance where CSDM curve reaches the zenith represents the percentage of skew in relation with the total distance between the centre (mediana) of the CSDM curve. Positive skew are oriented to the right of the centre, according to evergreen habit (Falcon-Lang, 2000). Circles represent cell diameter and squares represent positive value in the summatory with respect to the mean tracheid diameter in the CSDM curve. EW: early wood, LW: late wood. (A) pmLPPB-1923, (B) pmLPPB-1930, and (C) pmLPPB-1931.

et al., 1981). *Saxegothaea conspicua* Lindl., which has a similar ecological pattern to *P. nubigenea* in the southern Andes, can reach up to 20 m tall (2 m in diameter) with a homogeneous age range in the forests. However, due to the regenerative property of the trees, they can reach up to 3 m in diameter (Veblen *et al.*, 1981). The other two podocarps from the southern Andes, *Podocarpus saligna* Don. and *Prumnopitys andina* (Poepp. ex Endl.) de Laub., can reach up to 15–20 m tall (0.5–1 m in diameter), but are not a tolerant species and are uncommon in advanced ecological succession (Veblen *et al.*, 1981). In northern South America, *Prumnopitys montana* (Humb. & Bonpl. ex Willd.) de Laub. could reach 21 m (50 cm in diameter) in montane regions (Váquez Correa *et al.*, 2010). *Podocarpus guatemalensis* Standl. can reach 24 m (60 cm in diameter) in coastal areas, but most podocarp forests in South America are confined to montane environments.

Heath and peat podocarp forests with low-nutrient acidic sands and wet peaty soils are most commonly found at low altitudes in Borneo, Sumatra and Malaysia. Although they are characterized by seasonal waterlogging and low levels of mineral nutrient availability, they support high stem densities of small-diameter trees, typically 20–25 cm diameter breast height (dbh; Whitmore, 1984; Newbery *et al.*, 1986; Enright & Jaffré, 2011). This is not the case of the Mata Amarilla Formation forests, where Alfisols provided a rich mineral source and the total mean diameter is >60 cm, with the smallest tree being 26 cm in diameter (Table 1). Drought stress is thought to be a major driver of podocarp forest structure and composition, with shallow root systems (a response to seasonal waterlogging) leading to increased vulnerability during dry periods (Enright & Jaffré, 2011). This type of root system is similar to those observed in the fossil forest pits (Figs. 6A, B and 7C). Although forest understory was not recorded, diameters of fossil logs were used to recognize different vertical forest strata. For this purpose, not only trees in life position were used, but also a broad sampling from the same forest horizon of the Mata Amarilla Formation to obtain a better estimation of tree heights throughout the entire region. As shown in Table 1, mean diameters do not vary greatly among different localities.

From tree diameters and tree heights derived using Niklas (1994a,b), it is possible to recognize that all localities (including both *in situ* and horizontal logged forests, in groups or alone) show a greater percentage of large and old trees. The obtained estimation of 15–30 m in height for trees within Podocarpaceae is unusual. Most podocarp tree species attain heights between 15 and 20 m. Few species can reach more than 20 m, such as some species of *Dacrycarpus*, *Dacryidium* and *Prumnopitys*. *Retrophyllum comptonii* (Buchholz) Page reaches up to 30 m and *Dacrydium lycopodioides* Brongn & Gris reaches up to 20–25 m, both of which form the canopy layer or occur as emergent species in dense evergreen tropical forests in New Caledonia (Enright & Jaffré, 2011).

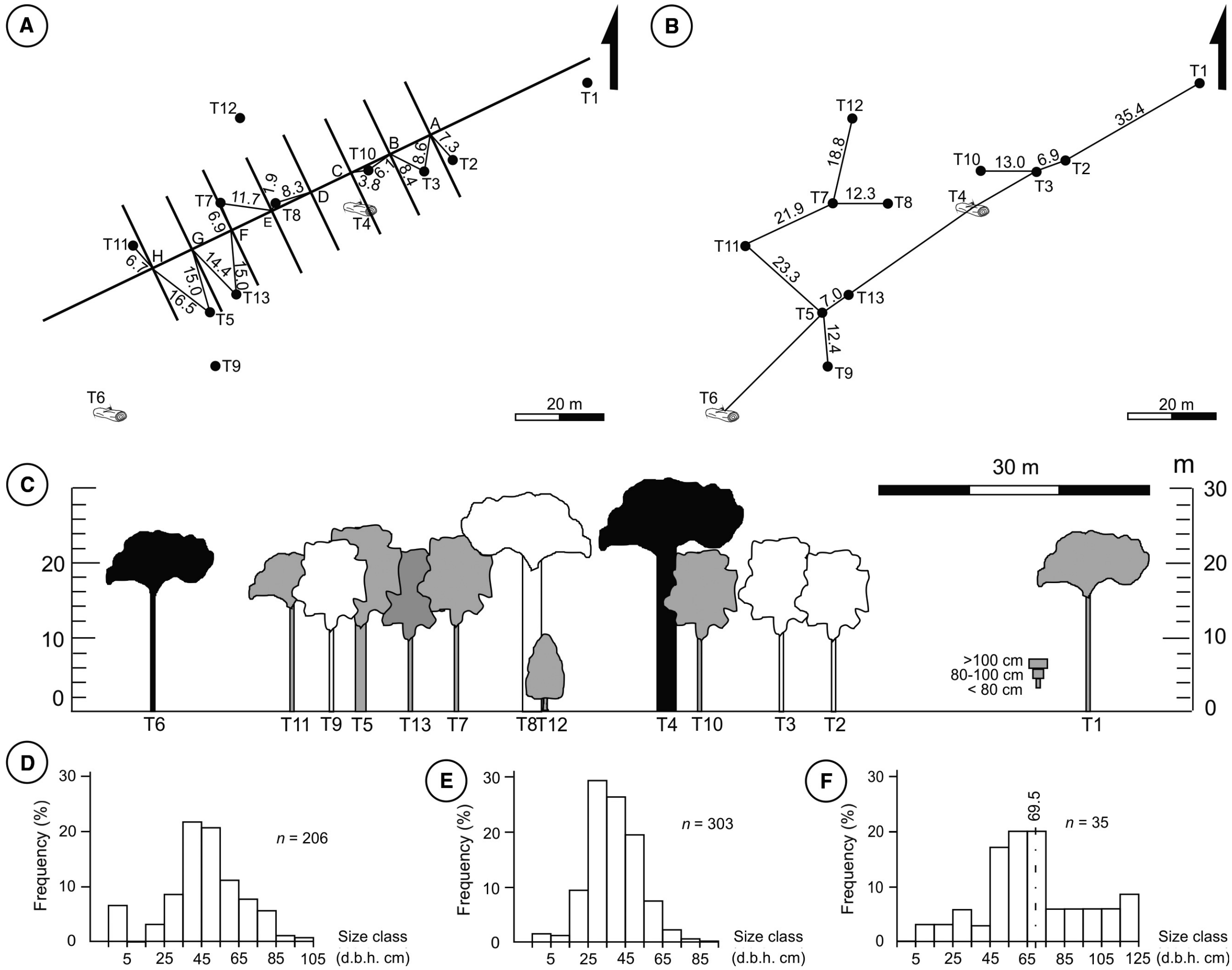


Fig. 10 (A) Transect used for point-centred quarter method (Cottam & Curtis, 1956) at locality 6 (La Urbana Farm), to estimate forest density and compare with other fossil forests. (B) Distance to its nearest neighbour at locality 6 (La Urbana Farm), used for compare modern forests density. (C) Fossil forest at locality 5 La Urbana (La Urbana Farm) reconstructed. Lateral view of the forest based on stump distribution (Fig. 8A), stump diameter and estimated tree highest. For a complete reconstruction, mean diameters from Table 1 was used to replacing those stumps where real diameters was impossible to measuring (trees in dark grey). The horizontal stumps at the field here are represented in life position based on the measured diameters and fallen tree reconstruction (streaked trees). Podocarp trees have cone like shapes when young, but tend to fall their lateral branches and develop profuse branching when old. The reconstruction demonstrates that the forest at locality 6 (La Urbana Farm) possessed large holes or spaces among very old trees. The trees reach heights similar to modern podocarp canopies. (D–E) Tree diameter frequency distribution of modern mixed podocarp forests with ~300 years old trees from New Zealand (Duncan, 1993). (D) Diameter frequency distribution of *Dacrydium cupressinum*. (E) Diameter frequency distribution of *Dacrycarpus dacrydioides*. (F) Tree diameter frequency distribution of *Podocarpoxylon garciae* using complete data of Mata Amarilla Formation fossil forests (Table 1).

Podocarp in lowlands

Podocarps are rare in tropical lowlands (Enright & Jaffré, 2011; Kitayama *et al.*, 2011). *Podocarpus neriifolius* Don, *Nageia wallichiana* (Presl.) Kuntze, *N. motleyi* (Malaysia), *N. fleuryi* (Vietnam) and *Sundacarpus amarus* (north-eastern Australia) are large, typically solitary canopy trees (up to 40 m in height and >100 cm dbh) in angiosperm-dominated lowland and lower montane forests (Enright & Jaffré, 2011). In Malaysian mountain cloud forests at 3000 m above sea level, emergent podocarps (*Dacrycarpus compactus* (Wasscher) de Laub. and *Podocarpus pilgeri* Foxw.) form an open canopy at around 25 m over a diverse angiosperm tree canopy (Enright & Jaffré, 2011). In Russell Forest in New Zealand, <25 podocarp trees (*Dacrydium cupressinum* Sol. and *Phyllocladus trichomanoides* Don.) larger than 20 cm in diameter (100 years old) per hectare were counted (Lloyd, 1960). Duncan (1993) demonstrated how in podocarp-dominated forests in New Zealand, the smaller trees greatly expand the number of specimens after they are affected by flood disturbances. This implies that once an area is disturbed, juvenile trees colonize the site and the numbers per hectare are higher until competition for light prunes their num-

Table 3 Tree density in fossil forest at localities 5 and 6 compared to modern podocarp forests. At locality 6 (La Urbana Farm), both nearest neighbour and point-centred quarter methods were used. (*) denoting that the main forest canopy is not only dominated by podocarps. (°) denoting that forest constituted by young individuals, <20 cm in diameter, from disturbed habitats

	Environment	Total Podocarp Density (trees per ha)	Source of Data
Locality 5	Lowland	36.73	This work (nearest neighbour)
Locality 6	Lowland	16.24	This work (nearest neighbour)
	Lowland	114.77	This work (point-centered quarter)
Orikaka, New Zealand	Lowland	14*	Blakely & Dinham (2008)
Rusell Forest, New Zealand	Lower montane	25*	Lloyd (1960)
Valdivia, Chile	Montane	6–46*	Veblen *et al.* (1981)
Mount Kinabalu, Malaysia	Montane	20–50*	Aiba *et al.* (2005)
Mount Kinabalu, Malaysia	Lowland	1055–1195°	Aiba & Kitayama (1999)
Mount Kinabalu, Malaysia	Lower montane	1624–4190°	Takyu *et al.* (2002)
Mount Kinabalu, Malaysia	Subalpine	3600–4383°	Aiba & Kitayama (1999)
Rusell Forest, New Zealand	Lower montane	2965*,°	Lloyd (1960)
South Westland, New Zealand	Lowland	250–831°	Duncan (1993)

bers. In the case of old forests, the podocarp population tends to have a tail towards larger and older trees, with low tree density and low percentage of specimens with a dbh of <20 cm (Fig. 10D and 10E). This suggests that the forced regressive surface in the Mata Amarilla Formation were developed before an old and well-established podocarp forest take place (Fig. 10F). In lowland areas from New Zealand, Dickinson & Mark (1999) recognized low soil pH values in the podocarp (*Dacrycarpus dacrydioides* (Rich.) de Laub. and *Dacrydium cupressinum*) rain forest association. These New Zealand forests are located above the estuary tidal range and are characterized by organic soils (50% organic matter), with low values for relative conductivity and the lowest bulk density among the podocarp communities. These stands are characterized by emergent podocarps up to 33 m tall, which closely match the 30 m maximum height inferred from the largest logs measured at locality 15 (Table 4).

In New Zealand, *D. dacrydioides* and *D. cupressinum* reach heights of 20 m in 80 years, whereas *Podocarpus totara* and *Phyllocladus trichomanoides* reach 18 m in 80 years (Bergin & Kymberley, 1992). These New Zealand forests are chiefly dominated by podocarps, although a well-developed main canopy of angiosperms occurs (*Weinmannia racemosa* and *Nothofagus menziesii*), together with relatively diverse small tree, shrub, herb, ground, liana and epiphytic strata (Dickinson & Mark, 1999). Angiosperm diversity is also high in the Mata Amarilla Formation (Iglesias *et al.*, 2007; Zamuner *et al.*, 2008), although the forest canopy seems to be dominated by podocarps due to the homogeneous spatial distribution and tree heights (Table 1).

Comparisons with other podocarp-dominated fossil forests

In a Palaeocene podocarp petrified forest in northern Patagonia, Brea *et al.* (2011) obtained values with a similar range of estimated heights. Although this Palaeocene forest was located in a lowland area close to the Atlantic open sea, it was parautochtonous and associated with a very different flora, where palms were abundant and an indurated hardground was associated with the coasts. The Palaeocene Szlápelis Petrified Forest in central Patagonia (Brea *et al.*, 2005) showed monotypic dominance to a tree related to the *Dadoxylon* type of wood. No diameters or heights were obtained, although the thickening of measured growth rings are similar to those of the Mata Amarilla Formation, and the CSDM curves analysed show values of an evergreen podocarp forest type with a high mean sensitivity (0.68).

Time of forest development

The formulae of Veblen *et al.* (1981) were used to infer tree age ranges (Table 4); the mean age of all forests is 230 years, with a range from 140 to 337 years old. These values are comparable to trees with a slower growth than in warmer climate environments (Enright & Jaffré, 2011) and, because fossil wood was not preserved completely (i.e.

Table 4 Mean diameters of trees per locality, mean high values obtained from diameters using Niklas (1993, 1994a,b) formulae, and age estimation using Veblen *et al.* (1981) in Mata Amarilla Formation forest at different localities. (*) denoting values with diameter correction for compressed horizontal fossil logs, following Philippe *et al.* (2009). Range values obtained from the minimum and maximum values measured in field

	Mean diameter (n° trees)	Mean height (m)	Age (Year)
Locality 5	0.79 m (7)	24.54	265
Locality 6	0.82 m (6)	25.31	271
Locality 11	0.58 m (12)	21.62	222
	0.37 m (12)*	17.81	172
Locality 13	0.58 m (7)	21.69	222
	0.37 m (7)*	17.87	172
Locality 15	0.94 m (3)	26.88	293
	0.60 m (3)*	22.14	227
Range	0.26–1.2 m (35)	15.58–30.0	140–337
Mean	0.59*–0.74 m (35)	21.5*–24.7	224*–230

cortex and most external xylem), the results should be taken as minimum values.

In New Zealand, the mean age of 15 m tall *Dacrydium cupressinum* (that reach up to 50 m and 1.5 m in diameter) and *Phyllocladus trichomanoides* (that reach up to 20 m and 1 m in diameter) trees, were measured by counting growth rings as 108 and 85 years old, respectively (Lloyd, 1960). Likewise, McCoy *et al.* (1999) suggested ages of up to 125 years for individuals approaching 20 cm dbh. These authors relate the low tree density with the presence of larger number of tall and old trees, and more homogeneous tree ages (Fig. 9). All of these characteristics coincide with most well-stabilized recent lowland podocarp forests in New Zealand. As noted by Wiser *et al.* (2011), podocarps are very long-lived; however, the forest ecology of these taxa requires relatively few juveniles to replace the current adults. Therefore, the development of the soil and forest of a podocarp community suggests more than 337 years in duration (Table 4).

Based on the above, we can conclude that the fossil forest preserved on the Mata Amarilla Formation forced regressive surface are evidence for podocarp-dominated large forests, with tall and old trees, co-occurring in association with vertic Alfisol palaeosol developed under warm temperate climate in southern South America (Patagonia). These podocarp-dominated fossil forests do not have modern analogue among South America. Forest density, tree heights and distribution of these fossil forests close match some New Zealand podocarp lowland forests. However, the vertic Alfisol where Mata Amarilla Formation forests developed is totally different than any modern soils where podocarp forests occurs.

Implications of the occurrence and the taphonomic fossil forest preservation in relation to the forced regressive surface

The preservation of a forest in a single stratigraphic level frequently occurs in the geological record (among others, Demko, 1995; Fielding *et al.*, 1997; Gastaldo, 2004; Demko *et al.*, 2004; Brea *et al.*, 2005, 2011; Artabe *et al.*, 2007; Gastaldo & Demko, 2011). This may be more a function of low-frequency external processes, rather than any other trigger factor (Gastaldo & Demko, 2011). Is important to discriminate both low- and high-frequency factors controlling the geological record before performing palaeoecological, palaeoclimatic and palaeobiologic interpretations (Gastaldo & Demko, 2011). In continental succession, special attention should be paid to the concept of 'base profile' (Quirk, 1996) as the state of equilibrium or disequilibrium of the fluvial system would condition the development and preservation of a forest in the geological record. Fluvial equilibrium is defined as a state when there is no significant erosion or deposition occurring in the fluvial systems (Quirk, 1996). Conversely, fluvial systems are in state of disequilibrium when they are depositing or eroding. Hence, disequilibrium states generate aggradation or degradation (downcutting) of the alluvial plain. Gastaldo & Demko (2011) suggest that the development and preservation of a petrified forest in the geological record is conditioned by: 1- low accommodation/sediment supply condition (low A/S ratio) and the equilibrium state of the fluvial systems that promote the development and evolution stage of the forest (Figs. 11 and 12A–C), followed by 2- a disequilibrium state of fluvial systems involved (aggradation) and an increase in the accommodation/sediment supply (high A/S) ratio to generate the conditions for taphonomic preservation stage of the forest (Fig 12D–E).

1 *Forest development and evolution stage:* The surface on which the forest developed corresponds to the contact between the lower and upper section of the Mata Amarilla Formation. This boundary is a heterogeneous surface, which in the western sector of the study area, generated erosion and degradation by lateral migration of a high-sinuosity fluvial system (Fig. 12A–B). To the eastern sector it was generated as a paraconformity due to conditions of relative balance or equilibrium of

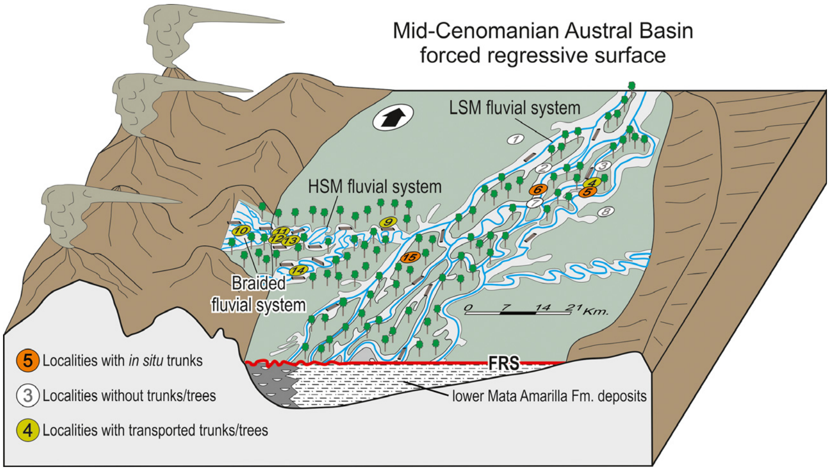


Fig. 11 Block diagram showing the mid-Cenomanian forced regression surface and their relationship with the palaeoenvironmental, palaeogeographic and palaeobotany context (Mata Amarilla Formation). HSM, high-sinuosity meandering; LSM, low-sinuosity fluvial system with aggradation.

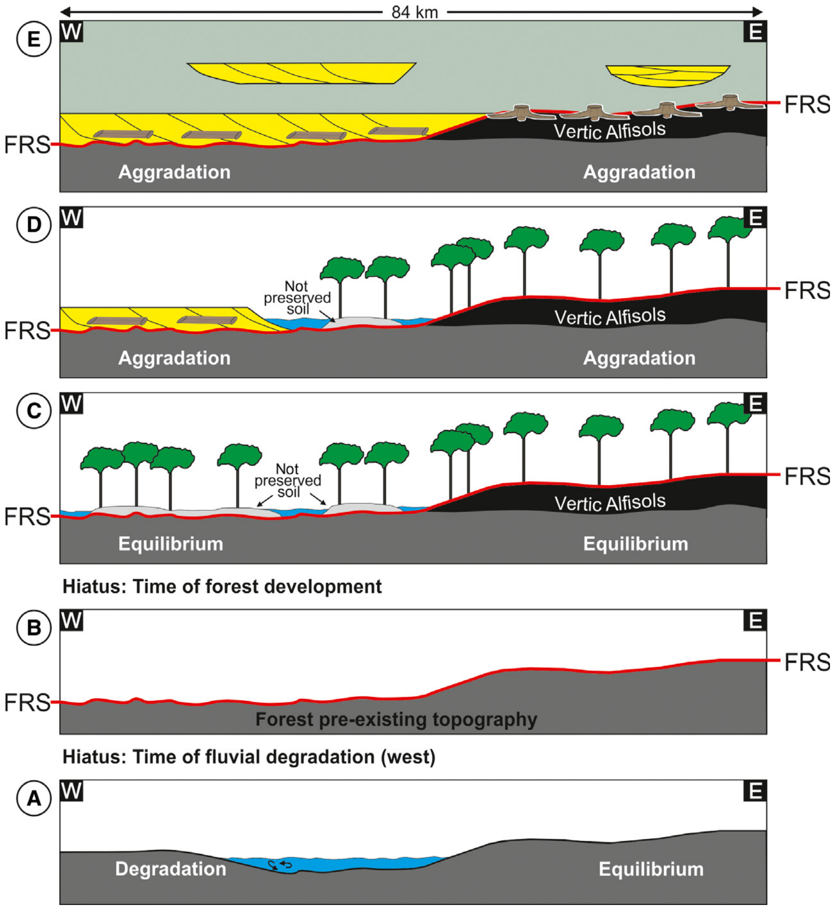


Fig. 12 Model of the Forced Regressive Surface (FRS) evolution in the Mata Amarilla Formation, adapted from Gastaldo & Demko (2011) and Varela *et al.* (2012a). (A) Development of the heterogeneous surface by degradation of the high-sinuosity fluvial system into the west and equilibrium of the low-sinuosity fluvial system into the east. (B) Pre-existing forest topography showing a heterogeneous surface is delimited by an erosional and irregular surface into the west and as a paraconformity into the west. (C) Time of equilibrium of the fluvial systems across the whole study area which promoted the development of the Podocarp fossil forest and their associated vertic Alfisols. (D) Onset of fluvial disequilibrium and landscape aggradation promotes floodplains reworking in the west, due to the migration of channels from the high-sinuosity fluvial system generating sheet-like channels deposits with forest trees as bed load. While to the east the low-sinuosity fluvial system favours the accumulation and preservation of floodplains. (E) Fluvial systems continued in aggradation status preserving westward logs within the sheet-like channels deposits, and eastward trees were preserved in life position within vertic Alfisols.

low-sinuosity fluvial system (Fig. 12A–B). These conditions occur in regressive system tract or lowstand wedges and are particularly pronounced in sequences boundaries (SB; Wright & Marriott, 1993; Catuneanu *et al.*, 2009; Varela *et al.*, 2012a), as in the case of forced regression of the middle section of Mata Amarilla Formation (Varela, 2015). A relative stability of the landscape is needed in which the forest reaches a stage of development of mature forest (Figs 11 and 12C). In other words, from a sedimentological point of view, a relatively low A/S ratio is required, and fluvial systems should have the peculiarity of being very close to the equilibrium profile, that is should not depositing or eroding (Shanley & McCabe, 1994; Quirk, 1996) (Fig. 12C). The Mata Amarilla Formation palaeosols display characteristics compatible with warm temperate climates (Varela *et al.*, 2012a) and have the necessary nutrients to support a mature podocarp forest development. However, vertic Alfisol has the limitation of vertic characteristics (i.e. the expansion–contraction soil) evidenced by slickensides, which are the product of a smectite clay mineral composition (Fig. 4B). These vertic pedofeatures, coupled with a high water table, prevent the development of deep vertical root systems by strangulation. Specimens of these Podocarpaceae have developed have developed subhorizontal shallow roots, as biological adaptation for anchoring system (Fig. 6A–C). This could be one of the reasons of monospecific genus of trees in this fossil forest.

2 *Taphonomic preservation stage:* The forest development and evolution stage is followed by the taphonomic preservation stage. During the preservation stage the conditions of accommodation/sediment supply (A/S ratio) were modified, as well as the fluvial systems became into a disequilibrium state dominated by aggradation (Fig. 12D–E). The difference in taphonomic preservation that trees have in the western and eastern sectors of the basin would be related to differences in sedimentary environments and more specifically to the type of fluvial system (Figs. 11 and 12D). In the western part of the basin, the fluvial systems developed were: braided fluvial system at locality 10 and high-sinuosity meandering at localities 11, 12 and 14 (Fig. 11), being characterized by the high mobility of the channels (Varela, 2015). During the aggradational disequilibrium state of the high-sinuosity meandering (HSM) fluvial system, reworking of unstable floodplains occurred due to the migration of channels. This generated sheet-like

channels deposits with forest logs as bed load (Fig. 12D). Conversely, in the eastern part of the basin, a low-sinuosity (LSM) fluvial system was developed at localities 4, 5, 6 and 15 (Fig. 11). The intrinsic dynamics of this LSM fluvial system, such as relatively fixed channels without lateral migration, generated the taphonomic conditions for the preservation of a large proportion of floodplain deposits and the *in situ* forest that were developed therein (Fig. 12D). Consequently, in eastward localities trees are preserved in life position associated with LSM fluvial system. Meanwhile, in western localities, logs are preserved as basal lags within sheet-like channel deposits from a HSM fluvial system (Figs 11 and 12D). In foreland basins, accommodation/sediment supply conditions are not constant throughout the basin, due to the typical geometry of a flexural basin (DeCelles & Giles, 1996). In the Austral Basin during the Late Cretaceous, A/S conditions were not constant throughout the basin, which favoured the difference between fluvial systems in the eastern and western parts of the basin (Varela, 2015).

To summarize, the sequence boundary of the Mata Amarilla Formation involves the time of heterogeneous surface generation, plus the time of forest and associated palaeosol development (Fig. 12A–D).

FINAL REMARKS

The drastic reduction in A/S ratio previously observed in the boundary between the lower and middle sections of the Mata Amarilla Formation occurs together with the extensive presence of fossil podocarp trees in a large area of the basin (5400 km^2 of exposed outcrops); this boundary is interpreted as a forced regressive surface (Varela, 2015). The Mata Amarilla Formation forest was living during the mid-Cretaceous greenhouse period. The presence of vertic Alfisols indicates that the climate was warm and humid with a pronounced rain seasonality. Pedogenic features, such as mottles, slickensides, nodules and iron/manganese oxide concretions, are in accordance with warm temperate climates. Root systems and the associated leaf macroflora recorded in the unit also indicate a wet lowland area in a context of warm temperate climate. Growth ring analysis in fossil woods gives a mean sensitivity and an age estimation that are commonly reached in podocarp forests. Similarly low forest density comprised of tall and old trees, are today only recorded at lowlands close to the sea in New Zealand.

The spatial distribution and preservation of the fossil trees can be explained by a burial during a lowstand wedge. The forced regressive surface is a sequence boundary (SB) distinguished as a non-uniform surface, which in the west is delimited by an erosional surface generated by a large lateral channel migration with transported logs as bed load. Towards the east, the SB appears as a paraconformity bounded by a strongly mature vertic Alfisol, and the extensive preservation of fossil forests in life position. Trees reached 337 years old, according to the growth ring analysis. It is noteworthy that the time required to form strongly developed Bt horizons of clay texture with abundant clay cutans is between 40 and 100 ky, which would limit the maximum development of the forced regressive surface. This study represents a remarkable example of how a forced regression in the sedimentary record left a heterogeneous regional surface also registered by the fossil record.

The presence of changes in the A/S ratio condition could generate the sedimentological and palaeopedological conditions for the development and preservation of a fossil forest at basin scale. Thus, the development and preservation of *in situ* fossil forests in the geologic record may be associated with sequence boundaries (SB), in which the conditions of accommodation/sediment supply are low. Hence, preservation of *in situ* fossil forest may not just be associated with eventual or catastrophic events such as lava flows, volcanic eruptions, and burial by ash fall or by flooding episodes. Furthermore, extrinsic factors (tectonics, climate and eustasy) could be triggers of exceptional preservation of forests such as the Mata Amarilla Formation and these concepts could be applied to other petrified forests around the world.

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