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Sequence stratigraphic analysis of Cenomanian greenhouse palaeosols: A case study from southern Patagonia, Argentina

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ABSTRACT

The aim of this contribution is to analyse extrinsic (*i.e.*, tectonics, climate and eustasy) and intrinsic (*i.e.*, palaeotopography, palaeodrainage and relative sedimentation rates) factors that controlled palaeosol development in the Cenomanian Mata Amarilla Formation (Austral foreland basin, southwestern Patagonia, Argentina). Detailed sedimentological logs, facies analysis, pedofeatures and palaeosol horizon identification led to the definition of six pedotypes, which represent Histosols, acid sulphate Histosols, Vertisols, hydromorphic Vertisols, Inceptisols and vertic Alfisols.

Small- and large-scale changes in palaeosol development were recognised throughout the units. Small-scale or high-frequency variations, identified within the middle section are represented by the lateral and vertical superimposition of Inceptisols, Vertisols and hydromorphic Vertisols. Lateral changes are interpreted as the result of intrinsic factors to the depositional systems, such as the relative position within the floodplain and the distance from the main channels, that condition the nature of parent material, the sedimentation rate and eventually the palaeotopographic position. Vertical stacking of different soil types is linked to avulsion processes and the relatively abrupt change in the distance to main channels as the system aggraded.

The large-scale or low-frequency vertical variations in palaeosol type occurring in the Mata Amarilla Formation are related to long-term changes in depositional environments. The lower and upper sections of the studied logs are characterised by Histosols and acid sulphate Histosols, and few hydromorphic Vertisols associated with low-gradient coastal environments (*i.e.*, lagoons, estuaries and distal fluvial systems). At the lower boundary of the middle section, a thick palaeosol succession composed of vertic Alfisols occurs. The rest of the middle section is characterised by Vertisols, hydromorphic Vertisols and Inceptisols occurring on distal and proximal fluvial floodplains, respectively.

The palaeosol succession for the Mata Amarilla Formation can be analysed within a sequence stratigraphic scheme considering changes in depositional environments in relation to accommodation/supply conditions. The results contrast with classical models, mainly in that the palaeosols of the Mata Amarilla Formation are relatively well-developed throughout the whole sequence, including transgressive periods of relatively high aggradation rate. Also, even when during regressive episodes, when a thick palaeosol succession that marks the sequence boundary is developed in the classical models, the lack of incised valleys in this succession led to the preservation of thick palaeosol successions during lowstand conditions. The vertical and lateral palaeosol distribution identified in the Mata Amarilla Formation could be eventually extrapolated to other sequences deposited during climate optimums.

1. Introduction

Palaeosols or fossil soils are the remains of ancient soils that may have been buried by subsequent deposits, or exposed over long time intervals without any pedogenic activity (Retallack, 2001). These soils are generally not in equilibrium with the present soil-forming factors, that is, they are soils which developed under conditions which differ from the ones now prevailing. Soil formation always depends on five 'soil-forming factors', namely, (1) parent material, (2) climate, (3) topographic relief, (4) organisms and (5) time (Jenny, 1941; Leckie et al., 1989; Retallack, 2001) and therefore the precise definition of palaeosol features may provide important information on the conditions prevailing during the accumulation of ancient sequences. It should be noted that soil-forming factors do not act separately but simultaneously. Thus, none of the factors is individually responsible for the characteristics of the soil, as it is the combined influence of all of them that determines the formation of a certain soil type.

The Mata Amarilla Formation is one of the most representative units of the early Upper Cretaceous of the Austral Basin, southwest Patagonia, Argentina. In this unit, successions of up to nearly 300 m of stacked palaeosols have been recorded (Varela, 2011). The excellent quality of

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the outcrops and the absence of an important degree of diagenesis made it possible to study both lateral and vertical palaeosol variations, as well as their palaeoenvironmental correlation and relationships within the sequence stratigraphic framework. Various authors have highlighted the importance of palaeosols in the definition of sequence stratigraphic examples, both theoretically (Wright and Marriott, 1993) and in the rock record (Aitken and Flint, 1996; McCarthy and Plint, 1998; McCarthy et al., 1999, among other authors). More recently the contributions on palaeosols have focused mainly on descriptive and genetic studies (Wright et al., 2000; Kraus and Hasiotis, 2006; Kraus and Riggins, 2007; Krause et al., 2010) or on the application of classical sequence stratigraphic models (Mack et al., 2010).

In general terms, the palaeosols of the Mata Amarilla Formation display characteristics of hydromorphic soils and they can be classified as Gleysols or gley soils according to the classification by Mack et al. (1993). This name refers to their typical grey, greenish-grey to olive green colouration, caused by the reduced state of the iron oxides. Despite the fact that the outcrops of the Mata Amarilla Formation are located at 50° S latitude, these palaeosols display characteristics which are compatible with warm temperate climates. This is consistent with the beginning of the Cenomanian greenhouse period, which lasted throughout the Upper Cretaceous and most of the Palaeogene (Royer, 2010). The Cenomanian is an important period in the evolution of vegetation in South America, as a floral change from mesophytic groups to floras dominated by angiosperms occurred at this time (Iglesias et al., 2007, 2009).

The aim of this contribution is to study the relative influence of extrinsic (*i.e.*, tectonics, climate and eustasy) and intrinsic (*i.e.*, palaeotopography, palaeodrainage and relative sedimentation rate) factors in the development of the early Upper Cretaceous palaeosols in southern Patagonia on the basis of the description and interpretation of macroscopic and microscopic pedogenic features. Thus, the spatial distribution of palaeosols, both lateral and vertical, is interpreted in terms of the predominance of autocyclic and allocyclic factors that controlled the sedimentation and pedogenesis. Moreover, the implications of the results obtained in the study of the Mata Amarilla Formation are discussed, especially those concerning the development of a model of palaeosol evolution within a sequence stratigraphic context during climate optimum conditions.

2. Geological setting

The Austral Basin (Fig. 1), also known as the Magallanes Basin, is located on the southwestern edge of the South American Plate, and it is bounded to the south by the Scotia Plate. It covers an area of approximately 230,000 km^2 which extends over the southernmost end of the Argentine and Chilean territories. With an elongated shape in a north–south direction, and a depositional eastern edge running parallel to the Chico River (Río Chico), it extends to the sea in the Río Chico High (Dorsal de Río Chico), also known as Dungeness High (Dorsal de Dungeness), which separates it from the Malvinas Basin. Its tectonic western edge is constituted by the Patagonian–Fuegian Andes (Andes Patagónico–Fueguinos; Fig. 1). The study area is located in the southwest of the Santa Cruz Province, Argentina, near the locality of Tres Lagos (Fig. 1).

The Mata Amarilla Formation marks the transition between the marginal basin stage and the foreland stage of the Austral Basin (Varela, 2009, 2011; Varela et al., 2012). This formation has a maximum thickness of approximately 350 m in outcrop, and it is composed of grey and blackish siltstones and claystones, alternating with 1 to 10 m thick units constituted by whitish and yellowish-grey fine- to medium-grained sandstone, deposited in littoral and continental environments (Russo and Flores, 1972; Arbe, 1989, 2002; Poiré et al., 2004; Varela and Poiré, 2008; Varela et al., 2008; Varela, 2009, 2011). The Mata Amarilla Formation overlies the Piedra Clavada Formation with transitional contact and it is unconformably covered by the La Anita Formation (Varela and Poiré, 2008; Varela, 2009, 2011). On the basis of facies analysis, Varela (2009, 2011) also divided the Mata Amarilla Formation into three sections, according to the different conditions of accommodation space creation with respect to sediment supply (Fig. 2). These changes were induced by relative sea-level oscillations in response to the tectonic evolution of the Austral fold and thrust belt (Varela, 2009, 2011; Varela et al., 2012).

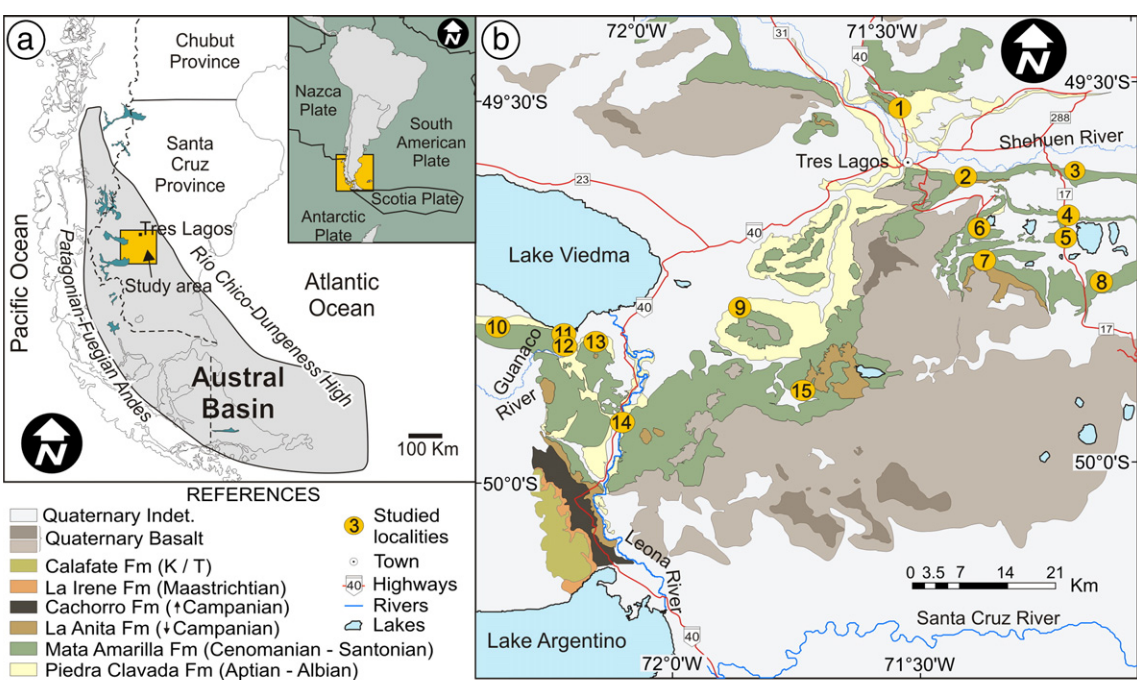

Fig. 1. (a) Geological setting of the Austral Basin and location of the study area. (b) Geological map of the study area showing the Cretaceous units of the Austral Basin (after Varela, 2011). Localities: (1) Cerro Waring; (2) Estancia La Regina; (3) Estancia Mata Amarilla; (4) MAFer; (5) CME; (6) Estancia La Urbana; (7) Estancia Pari Aike; (8) Estancia Bajada de los Orientales; (9) Cerro Índice; (10) Puesto La Marina; (11) South of Lago Viedma; (12) Mouth of Río Guanaco; (13) Cerro Hornos; (14) Cerro Fortaleza and (15) Estancia La Blanca.

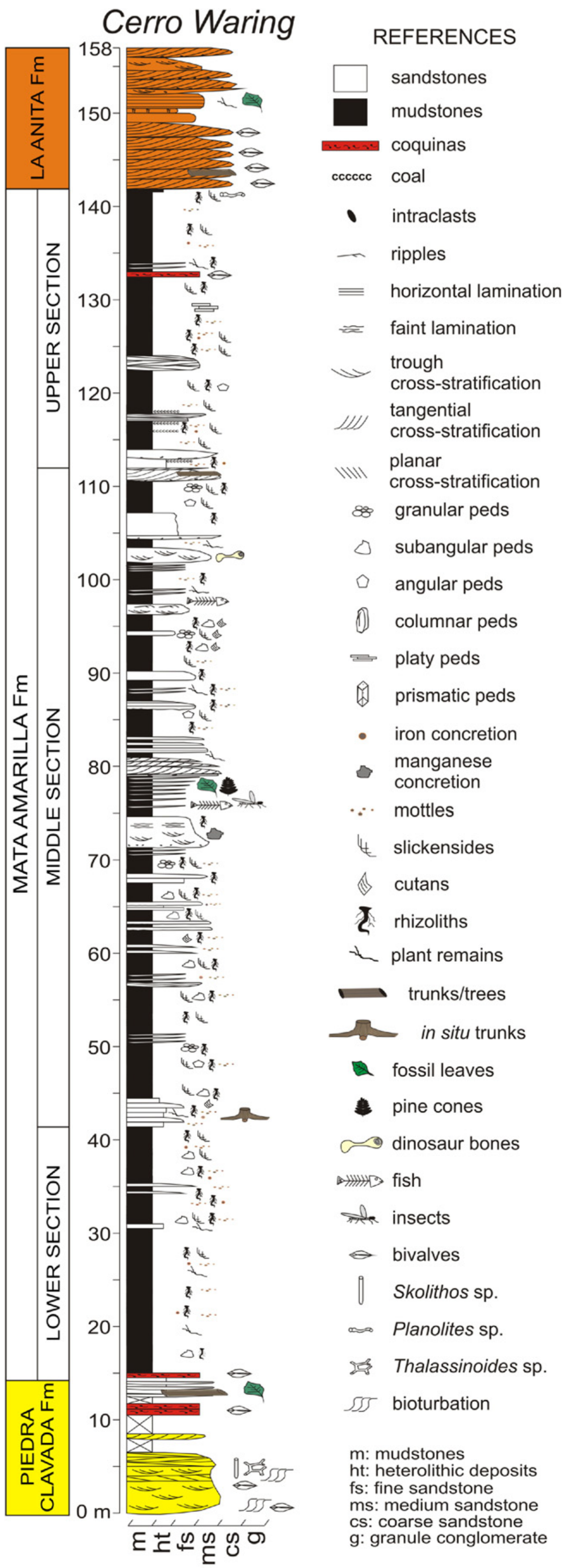

Fig. 2. Sedimentological section of the Mata Amarilla Formation at Cerro Waring, showing vertical distribution of sedimentary facies.

A sedimentological log of the Cerro Waring locality (Fig. 2) shows that the lower section of the Mata Amarilla Formation consists of fine-grained intervals with palaeosol development interbedded with laminated shale and coquinas, corresponding to coastal plain and lagoon palaeoenvironments (Varela et al., 2011). The middle section of the Mata Amarilla Formation is characterised by sandstones and siltstones, which represent low-sinuosity meandering fluvial channels and crevasse splay deposits (Varela, 2011), intercalated with fine-grained floodplains, mostly subaerial with palaeosol development and subordinate lacustrine deposits (Varela, 2011). The upper section of the Mata Amarilla Formation is also dominated by fine-grained deposits, which are related to distal fluvial channels. The palaeoenvironments correspond, as they do in the lower section, to coastal plain and lagoon settings with high organic matter preservation and palaeosol development (Varela, 2011).

3. Methodology

The Mata Amarilla Formation palaeosols were studied in 15 localities (Fig. 1), where the detailed description of pedogenic features and soil horizons was used to interpret palaeosol development processes (following the criteria described by Retallack, 1988, 1994). Colour of the palaeosol matrix, as well as for other features as mottles, nodules concretions and cutans was determined using the Munsell colour chart (Munsell® Soil Color Chart, 2000). Field analysis was combined with the description of 26 thin sections in which micromorphological features were identified adopting the terminology suggested by Bullock et al. (1985) and Stoops (2001).

The mineralogy of mudstones, mottles, concretions, nodules and rhizoliths was obtained by X-ray diffraction (XRD) analysis. Clay mineralogy was determined from diffraction patterns obtained using samples that were air-dried, ethylene glycol-solvated and heated to 550 °C (Brown and Brindley, 1980). The mineralogy of sandstones was determined in thin-sections, following Gazzi–Dickinson's method (Ingersoll et al., 1984), in which 400 points were assessed using a point counter (Varela, 2011).

Pedogenic feature identification (both at meso and microscale), together with the definition of soil horizons, allowed the identification of pedotypes that were interpreted and classified following the most widely used system in pedology (Soil Taxonomy: Soil Survey Staff, 1998). Palaeosol analysis of the Mata Amarilla Formation was also combined with palaeoenvironmental studies available for these sections obtained through detailed facies and architectural element analysis (Varela, 2011).

The excellent 3D exposures of the Mata Amarilla Formation in the study area allowed a detailed analysis of the lateral and vertical relationships of the identified pedotypes. Photomosaics of selected outcrops were obtained in order to map the lateral changes between pedotypes. Vertical changes between different types of palaeosols were also recorded at two different scales, through sedimentary logs of the whole unit and detailed vertical logs of selected intervals in order to capture high-frequency vertical changes in different pedotypes.

4. The Mata Amarilla Formation pedotypes

The description of the macro- and micromorphological pedofeatures, together with the differentiation of soil horizons served as the basis for the identification of six different pedotypes for the Mata Amarilla Formation in the study area (Pedotypes 1 to 6; Fig. 3). These pedotypes were classified according to present-day soil classifications (Soil Taxonomy: Soil Survey Staff, 1975, 1998) as suggested by Retallack (1993, 2001) in order to stimulate the comparison between present-day soils and palaeosol studies.

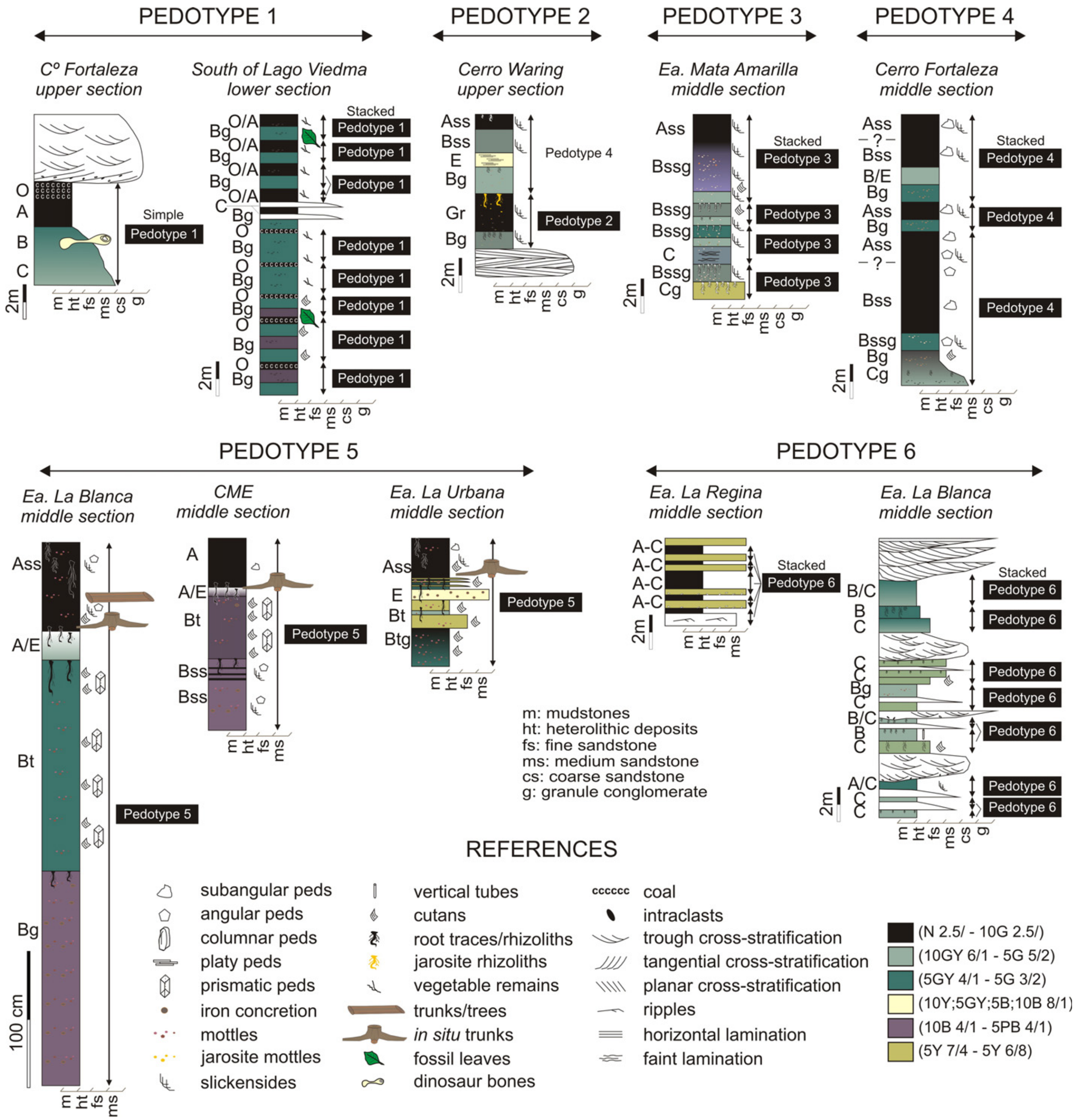

Fig.3. Different pedotypes identified in the Mata Amarilla Formation. For location see Fig. 1.

4.1. Pedotype 1

Pedotype 1 is found in the lower and upper sections of the Mata Amarilla Formation. This type of palaeosols is characterised by abundant pedogenic features such as mottles, slickensides and rhizoliths. There are two types of mottles in Pedotype 1: purplish-blue mottles (10B 3–2.5/1 and 5PB 3–2.5/1), which indicate iron oxides in a ferrous state and abundant organic matter; and dark grey to black mottles (N 2.5/0), corresponding to minute carbonaceous remains disseminated throughout the palaeosol matrix. Slickensides are generally abundant and they are covered by cutans composed of organic matter, manganese oxides (mangans) and clays (argillans). Rhizoliths in Pedotype1 include greenish-grey rhizoliths and fossil roots preserved as carbonaceous material. Greenish-grey rhizoliths are 10 to 60 cm in length, and generally have a main axis with radiating lateral or adventitious rhizoliths (taproots). Fossil roots preserved as carbonaceous material perfectly preserve all the characteristics of the root, even the original plant tissue (Fig. 4c). Disseminated organic remains are common in these pedotypes; they have equidimensional to elongate shapes and are dark to black in colour. Less frequently, very well-preserved carbonised tissue fragments (~1.5 mm in length) are present, in which even the original cell walls can be distinguished (Fig. 4d).

Pedotype 1 shows the palaeosol profiles with O–A–Bg successions (Fig. 3), and occurs in isolation (simple Pedotype 1) or stacked

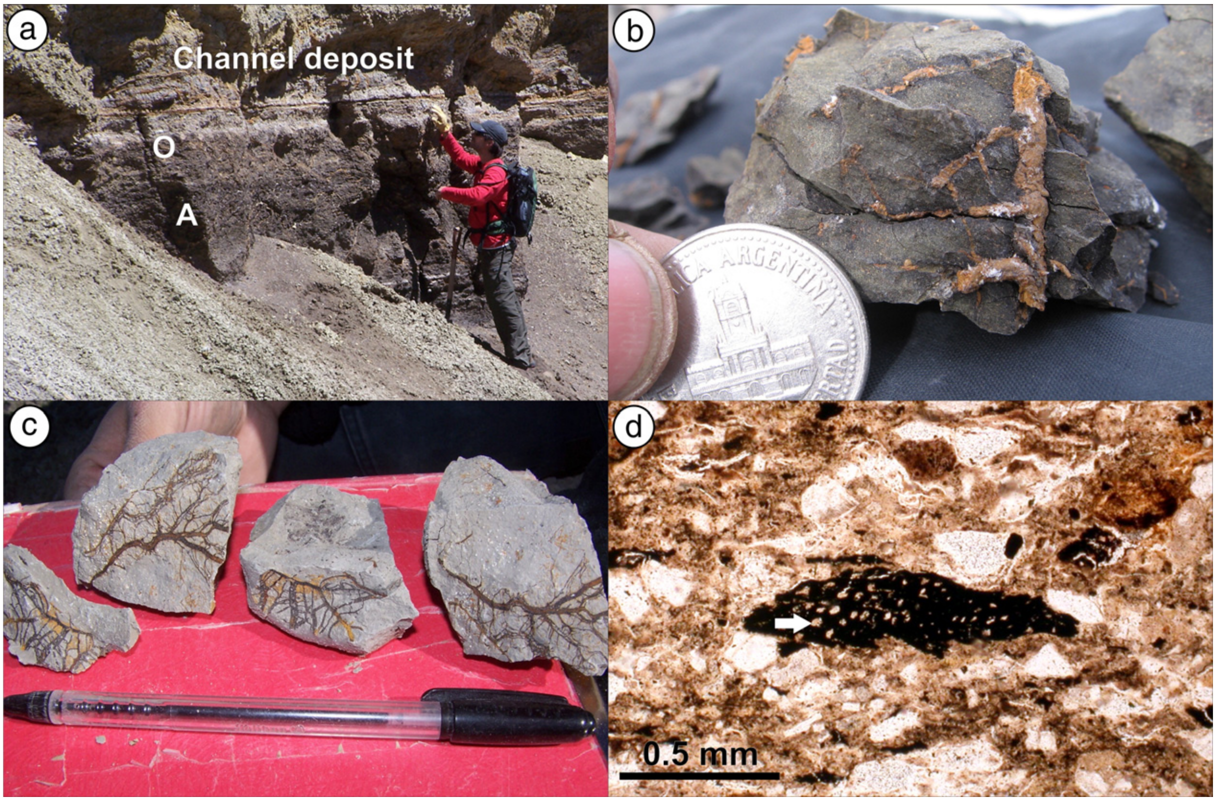

Fig. 4. Macroscopic and microscopic features of Pedotypes 1 and 2. (a) Simple Pedotype 1 at Cerro Fortaleza. Person is 1.80 m tall. (b) Jarosite rhizoliths from a Gr horizon of Pedotype 2. Coin is 2.4 cm in diameter. (c) Root traces preserved as carbonaceous material, produced by the anoxic environment resulting from a high water table. Pen is 14.5 cm long. (d) Microscopic view of vegetable remains in A horizon, even plant cells (white arrow) can be distinguished.

Pedotype 1 (Fig. 3). They are characterised by an O histic epipedon (N 3/0; N 3/0 and10G 2.5/1) composed of abundant carbonised plant fragments. The thickness of O horizons ranges between 5 and 20 cm and they are transitional to an A horizon (10Y 3/1–2.5/1) with relatively less organic matter content and variable thickness (Fig. 4a). Gley-coloured subhorizons (Bg) are generally present, with low chromas (10GY 5/1 to N 5/0) and thicknesses ranging from 80 to 160 cm. This Bg horizon is usually characterised by the presence of mottles (both types identified), cutans and slickensides. Fossil roots are restricted to A horizon, whereas greenish-grey rhizoliths appear in both A and Bg horizons.

4.1.1. Classification

The presence of the histic epipedons, abundant well-preserved carbonised plant fragments, and fossil roots preserved as carbonaceous material, as well as purplish-blue and dark grey to black mottles allows classifying the Pedotype 1 soil as a Histosols (Soil Survey Staff, 1975, 1998; Retallack, 1993, 2001). Histosols usually occur in topographically low areas, with very poor drainage conditions. The high degree of preservation of organic matter in this pedotype could indicate rapid burial or anoxic conditions (McCabe and Parrish, 1992). Accordingly, the presence of carbonaceous fossil roots is generally associated with hydromorphic palaeosols (McSweeney and Fastovsky, 1987; McCarthy et al., 1998).

4.2. Pedotype 2

Pedotype 2 is found only in the lower and upper sections of the Mata Amarilla Formation and shows similar pedogenic features as Pedotype1 such as abundant well-preserved carbonised plant fragments, fossil roots preserved as carbonaceous material, as well as purplish-blue and dark grey to black mottles. However, this pedotype is characterised by a profusion of mottles and rhizocretions preserved in jarosite, which are characteristically orange in colour (10YR 8/6 and 7/6), similar to the ones described by Kraus (1998). Most jarosite rhizoliths are taproots with variable shapes and sizes, both long thin roots and short thick ones (Fig. 4b). Horizons with abundant mottles and rhizocretions preserved in jarosite were referred to as Gr horizons by Kraus (1998; Fig. 3), although sometimes the differentiation from O horizons is very difficult because both have abundant carbonised fragments and dark colour (N 3/0; N 3/0 and10G 2.5/1). In terms of horizon development this pedotype is characterised by O–Gr–Bg or Gr–Bg profiles.

4.2.1. Classification

The profusion of pedogenic features preserved in jarosite in Pedotype 2 palaeosols indicates characteristics of acid soils and they are called 'potential acid sulphate soils', following the criteria of Brinkman and Pons (1973) and Kraus (1998). Jarosite [$KFe_3(OH)_6(SO_4)_2$] is usually formed from pyrite when the soil drainage conditions make oxidation possible, which leads to an increase in soil acidity (Miedema et al., 1974; Van Breeman, 1982; Kraus, 1998). The presence of jarosite confirms that the palaeosols have been flooded or waterlogged almost the whole year, causing permanent reducing conditions with organic matter preservation, iron reduction and pyrite precipitation. Yet, a high concentration of sulphates is necessary for pyrite precipitation to occur, which is why this type of poorly drained soils is typical of coastal areas and estuaries (Miedema et al., 1974; Van Breeman, 1975). In short, Pedotype 2 palaeosols are classified as Histosols with potential acid sulphate properties. Histosols with potential acid sulphate properties are usually related to very low-gradient, topographically low areas with very poor drainage conditions and they appear in the Mata Amarilla Formation in successions associated with distal fluvial systems or the upper reaches of lagoon and estuarine environments (Varela, 2011).

4.3. Pedotype 3

This pedotype is one of the most abundant palaeosol types in the Mata Amarilla Formation and it is widely represented throughout the whole unit. It is characterised by a homogenisation of the soil profile due to pedogenesis and the most typical morphological features are slickensides (Fig. 5b) and microslickensides (Fig. 5c). The horizons with a profusion of friction structures (*e.g.*, Ass and Bss) are characterised by the development of angular peds (Fig. 5b). Rhizoliths associated with this pedotype are of two types: yellowish rhizoliths (7.5YR–10YR), composed of goethite and in a smaller proportion hematite; and greenish-grey rhizoliths (5GY; 10GY; 5G at value of 4–5/1), in which the iron oxides are in a ferrous state (Fe^{2+}; Fig. 5d). Both rhizolith types can be observed as root casts (*i.e.*, sediment-and/or cement-filled root moulds), rhizotubules, rhizocretions and/or rhizohaloes. Some horizons show mottles which are yellowish to brownish (7.5YR–10YR) and bluish grey in colour (10B 4–6/1 and 5PB 4–6/1), disseminated in a greenish grey matrix with low chromas (5GY, 10GY, 5G and 10G), together with some iron and manganese concretions and nodules. The nodules are yellowish to dark brown (7.5YR 6/6 up to 7.5YR 5/8), between 0.5 and 20 mm in diameter, and composed of smectite, quartz and iron oxides, as well as small quantities of calcite and siderite (Fig. 5e).

Pedotype 3 most commonly shows an Ass–Bssg–Bssg–Cg profile (Fig. 3). The Ass superficial vertic horizons are in average 1 m thick, dark in colour (10Y 2.5/1; 5GY 2.5/1), and occasionally –when the palaeosol tops are eroded– they may be absent. B horizons (10GY 6/1 to 5G 5/1) can be subdivided in up to six parts with different colours or properties (Bss, Bg or Bssg). The thickness of each part may vary between 40 cm and over 1.5 m (Fig. 5a). C or Cg horizons are usually present, with a thickness between 60 cm and over 1 m, except in the case of cumulate soils in which these C horizons are absent (Fig. 5a).

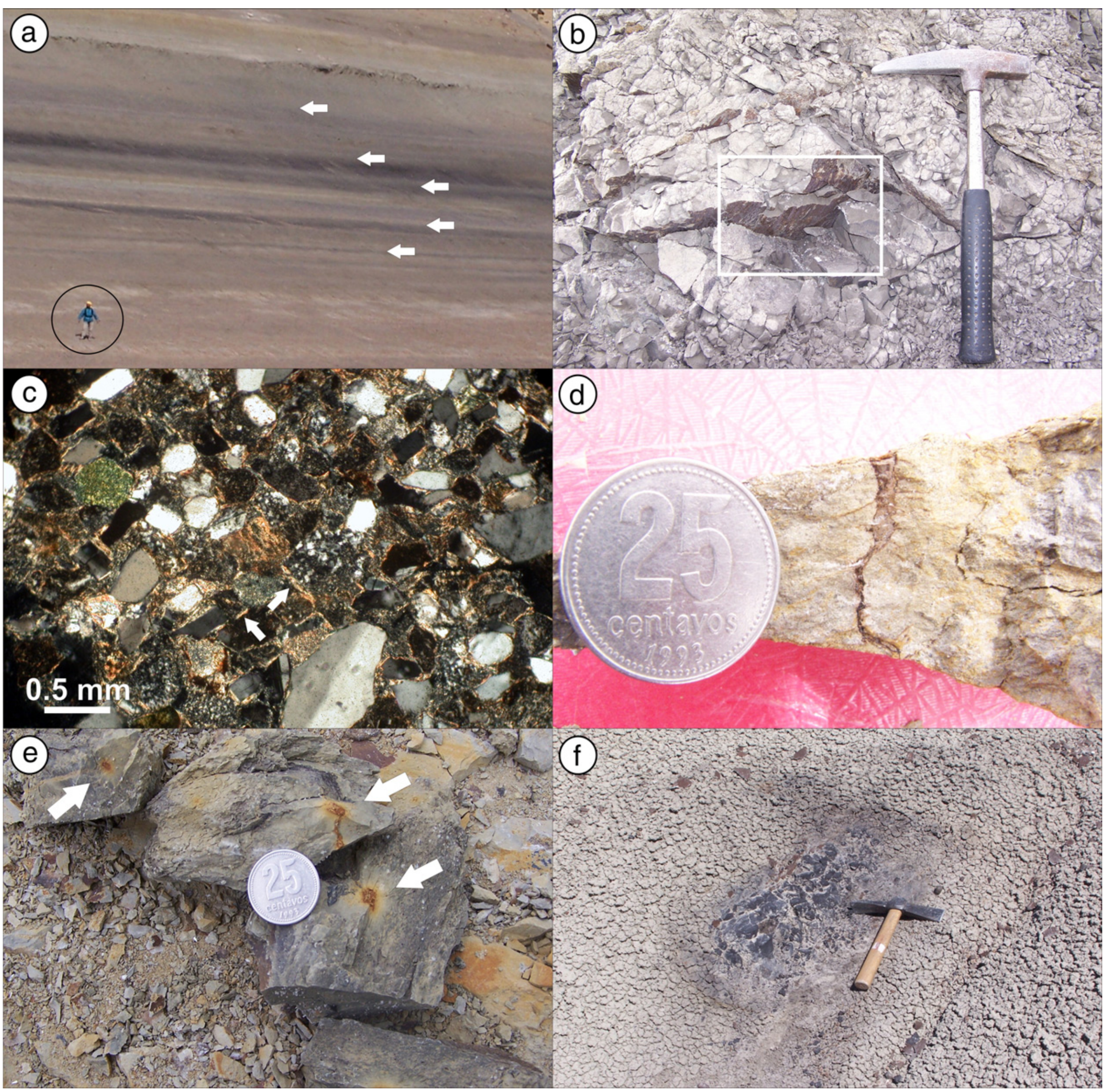

Fig. 5. Macroscopic and microscopic features of Pedotypes 3 and 4. (a) Stacked Pedotypes 3 and 4 at Cerro Waring. White arrows show the top of each palaeosol profile. Person is 1.75 m tall. (b) Slickensides and angular peds, produced by the shrinking and swelling of smectites during alternating episodes of soil wetting and drying. Hammer is 33 cm long. (c) Photomicrograph of micro-slickensides with polarised light. The A-axis of the clasts is oriented in two directions forming an angle of ~45°. (d) Gley root trace in a Bssg horizon. Coin is 2.4 cm long in diameter. (e) Iron nodules surrounded by grey haloes (*i.e.*, iron depletion zones) (white arrows). Coin is 2.4 cm long in diameter. (f) Manganese–iron concretion from Bssg horizon of Pedotype 4 at Estancia Mata Amarilla. Hammer is 50 cm long.

4.3.1. Classification

The main characteristics of Pedotype 3 are wedge-shaped angular or subangular peds, slickensides or stress cutans, and the homogenisation of the soil matrix. These features, together with patterns of mounds and depressions (Gilgai microrelief) are the diagnostic features of Vertisols (Soil Survey Staff, 1975, 1998). In this sense, Pedotype 3 palaeosols are classified as Vertisols in which the dominant process of pedogenesis or pedoturbation is the shrinking and swelling of expansive clays (White, 1997; Retallack, 2001).

4.4. Pedotype 4

Pedotype 4 is also one of the most abundant pedotypes and is present in the three section of Mata Amarilla Formation. It shows similar pedologic features as Pedotype 3, but with more abundance of redoximorphic features. This pedotype is characterised by the profusion of pedofeatures such as mottles, nodules and concretions, as well as haloes in a light greyish colour (Fig. 5e). These palaeosols show manganese concretions with jet black colour (10B 2.5/1), spherical to cylindrical in shape with diameters between 20 cm and over 60 cm (Fig. 5f). Pedotype 4 develops Ass–Bss–Bssg–Bg–Cg successions (Fig. 3). The Ass superficial vertic horizons are in average 1 m thick, dark black in colour (N 2.5/0), and sometimes it is very difficult to differentiate them from an underlying dark Bss horizons (N 2.5/0 to 10Y 2.5/1). B horizons are also characterised by redoximorphic and/or vertic features and can be subdivided based on these properties or differences in colourations (Bss, Bg or Bssg). The thickness of each part may vary between 40 cm and over 2 m (Fig. 5a), giving rise to B horizons up to 5 m thick. Occasionally, the presence of a light coloured albic horizon B/E (10Y 8/1 to 5GY 7/1) is recorded. C or Cg horizons are also present, with a thickness up to 1 m (Fig. 5a).

4.4.1. Classification

Pedotype 4 has important hydromorphic characteristics and redox-type features, that is, some of the horizons have been exposed to alternating oxidation and reduction conditions. Large manganese concretions have been attributed to root systems or tree stumps (Kraus and Hasiotis, 2006) associated with very poor drainage conditions (Retallack, 2001; Stiles et al., 2001; Kraus and Hasiotis, 2006). This pedotype is classified according to the abundance of vertic and redoximorphic features as hydromorphic Vertisols (Aquerts; Soil Survey Staff, 1975, 1998). These hydromorphic Vertisols (Aquerts) are usually associated with a depressed topography with a high water table and/or impeded to inefficient drainage conditions, being waterlogged throughout part of the year (Imbellone et al., 2009). Pedotype 4 palaeosols are darker in colouration, have better developed horizons and more abundance of redoximorphic features than Pedotype 3 (Vertisols).

4.5. Pedotype 5

Pedotype 5 is not abundant in the Mata Amarilla Formation, and is always associated with the María Elena Petrified Forest (Zamuner et al., 2004, 2006), which marks the transition between the lower and middle sections of the unit. In the localities within the eastern sector of the study area there are petrified trees in life position associated with this type of soil (Fig. 6a); whereas in the rest of the localities trunks are lying on channel beds with their stumps preserved, which indicates limited transport from its original position (Fig. 6g). These *Podocarpaceae* tree stumps (Zamuner et al., 2004, 2006) have typical adaptations that provide anchorage in partially waterlogged zones, as horizontal root growths with endings in the webbed shape of duck's feet (Fig. 6h).

Pedotype 5 is characterised by the presence of cutans or argillan coatings, as well as prismatic peds (Fig. 6b). Argillans can be observed both in hand specimens (Fig. 6c and d) and in thin sections. In the latter, oriented clay filling cavities and channels, as well as clay coatings around detrital grains or rhizoliths are identified (Fig. 6e and f). This type of palaeosol is also characterised by the presence of vertic and hydromorphic features, including slickensides, wedge-shaped peds, gley colours and mottles. Pedotype 5 shows thick and well-developed horizons, and profiles with Ass–A/E–Bt–Bss or (Bg) successions (Figs. 3 and 6a), although in many cases they can show eroded tops and the surface horizons Ass and A/E are not present. 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. In turn, A/E albic horizons (5B 8/1 to 10B 8/1) are poorly defined and between 10 and 20 cm thick. The Bt argillic horizons are characterised by the presence of illuvial clay (argillans) and are between 50 cm and 1.5 m thick, occasionally reaching 2 m. Their colours range from purplish grey to greenish grey (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), between 50 and 80 cm thick, and occasionally a C horizon with variable colouration and thickness is present.

4.5.1. Classification

Based upon the presence of well-developed horizons and abundant illuviated clay in some horizons (Bt), Pedotype 5 palaeosols are comparable to Alfisols (Soil Survey Staff, 1975, 1998). Although argillic horizons can also characterise Ultisols, the presence of weatherable or chemically unstable grains, such as feldspars (33%, in average), indicates a high base status (Retallack, 1988, 1993). 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).

4.6. Pedotype 6

This pedotype is present in the middle section of the Mata Amarilla Formation, vertically and laterally associated with Pedotypes 3 and 4 (Fig. 7a). The most frequent pedogenic features of Pedotype 6 are rhizoliths, with less frequent mottles and concretions. The rhizoliths occurring in this type of palaeosol are mainly yellowish to brownish in colour, composed of goethite and in a smaller proportion hematite, and have different shapes and sizes. Yellowish mottles and nodules (7.5YR 6/6 up to 7.5YR 5/8), 0.5 to 20 mm in diameter, are common in the subsuperficial horizons, surrounded by haloes of a lighter yellowish colour (Fig. 7b). In thin section, these features have a subrounded to ameboidal shape (Fig. 7c). On occasion, there is evidence of manganese and iron oxide crusts or micropans (Fig. 7d). Above these crusts, precipitation of iron oxide stringers in a dendritic pattern as a result of the capillary action within the pore spaces of the palaeosol can be observed. Pedotype 6 shows thin and poorly developed profiles (mainly A/C, A–C, Bg–B/C–C or B–C). The upper horizons (A or A/C) have gley colouration (from 10Y to 5G) and variable thicknesses, generally less than 1 m (Figs. 3 and 7a). On the other hand, C horizons are sandy, light yellowish–green in colour (5Y 8/3 to 7/8) with thicknesses varying from 40 cm to 1 m.

4.6.1. Classification

The lack of noticeable soil horizon differentiation (*i.e.*, A–C or B–C profiles) together with clear evidence of pedoturbation or pedogenesis (rhizoliths, mottles, *etc.*) suggests that Pedotype 6 may represent Inceptisols (Soil Survey Staff, 1975, 1998). Inceptisols are incipient or poorly developed soils, which share characteristics with other soil orders, but without diagnostic features (Soil Survey Staff, 1975, 1998). Their B horizons are usually labelled as cambic horizons of the Bw type, but in this study the ‘w’ suffix was not used due to the difficulty in determining weathering characteristics in fossil soils. Iron oxide stringers found in Bg horizons, may indicate former water table positions in which the pH and Eh conditions changed abruptly (Bullock et al., 1985; Retallack, 2001).

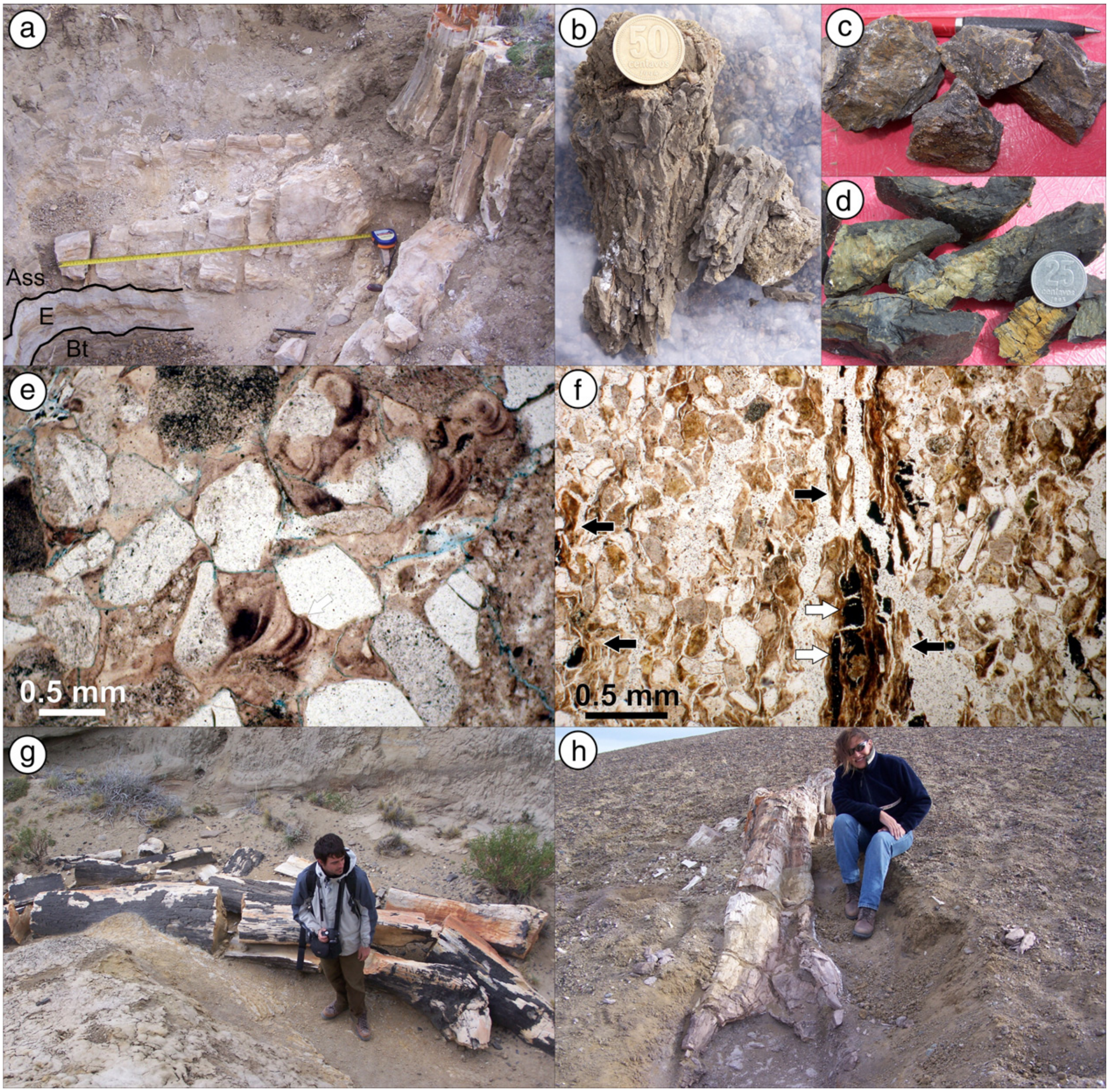

Fig. 6. Macroscopic and microscopic features of Pedotypes 5. (a) General view of a Pedotype 5 with *in situ* petrified tree at Estancia La Urbana. Tape measure is 95 cm long. (b) Prismatic peds from a Bt horizon. Coin is 2.5 cm in diameter. (c) Subangular blocky peds with mottles and argillans, characteristic of a Bt horizon. Pen is 14 cm long. (d) Subangular blocky peds with overprinted cutans and slickensides from a Bt horizon. Coin is 2.4 cm in diameter. (e) Photomicrograph of cutans (*i.e.*, argillans), showing lines of clay illuviation (white arrow). (f) Photomicrograph of a rhizolith showing a partially preserved root (white arrows) and cutans (*i.e.*, argillans) that cover the walls of rhizoliths (black arrows). (g) *Podocarpaceae* pseudo-transported trunk at Cerro Hornos. Person is 1.75 m tall. (h) *Podocarpaceae in situ* tree from the María Elena Petrified Forest at CME locality, showing roots adaptation for anchorage (webbed duck's feet). Person is 1.75 m tall.

5. Spatial distribution of palaeosols

5.1. Large-scale vertical variations in palaeosols

Considering the different types of palaeosols identified in the Mata Amarilla Formation, a large-scale, consistent stacking can be described for the whole unit, intimately related to changes in depositional environments that allowed defining three sections for this unit. The lower section of the Mata Amarilla Formation has a predominance of mudstones. In the eastern sector of the study area, the lower section represents coastal palaeoenvironments and in the western sector fine-grained successions of distal fluvial system occur (Varela, 2011). Pedotypes 1 and 2 (Histosols and acid sulphate Histosols), and few Pedotype 4 palaeosols (hydromorphic Vertisols) are found in the western area (Fig. 8).

In the middle section of the Mata Amarilla Formation, sandy facies predominate over muddy deposits (Fig. 8). The María Elena Petrified Forest is developed in the lower part of this interval (Zamuner et al., 2004, 2006). In the eastern sector of the study area, the fossil trees are in life position and are associated with a low-sinuosity meandering fluvial system (Varela, 2011; Fig. 8). Towards the west, the fossil trunks with their stumps preserved are associated with a high-sinuosity meandering fluvial system (Varela, 2011; Fig. 8). Associated with the María Elena Petrified Forest a horizon with Pedotype 5 palaeosols (vertic Alfisols) occurs. The rest of the middle section is dominated by palaeosols of Pedotypes 3 (Vertisols), 4 (hydromorphic Vertisols) and 6 (Inceptisols) related to distal and proximal floodplain deposits of both high- and low-sinuosity fluvial systems (Fig. 8).

Finally, the upper section of the Mata Amarilla Formation resembles the lower section (Varela, 2011). Muddy facies (Fig. 8), related

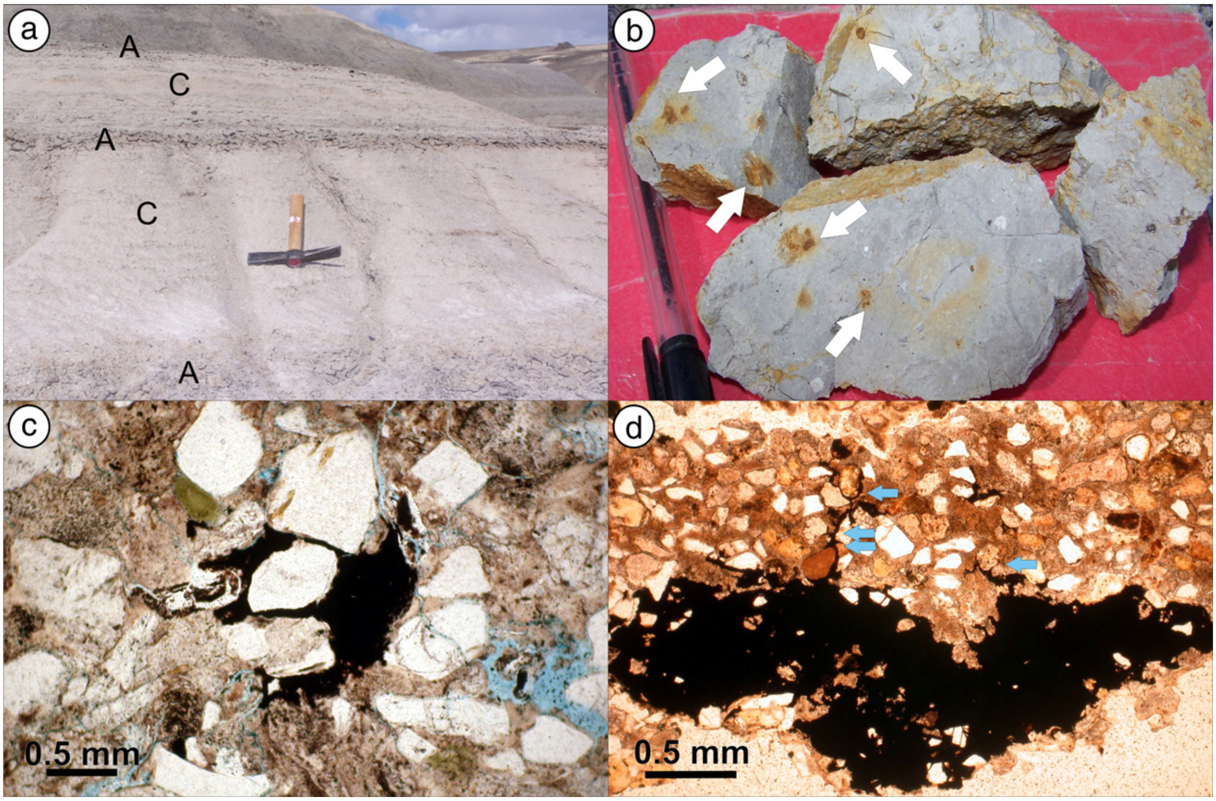

Fig. 7. Macroscopic and microscopic features of Pedotypes 6. (a) General view of stacked Pedotype 6 at Estancia Mata Amarilla. Hammer is 50 cm long. (b) Iron oxide nodules (white arrows) from a Bg horizon. Pen is 14 cm long. (c) Photomicrograph of an ameboidal nodule composed of iron oxide. (d) Microscopic view of a micropan or crust composed of iron and manganese oxide. Blue arrows show the upward precipitation of oxides in a dendritic pattern, produced by capillary effect.

to coastal lagoon and estuary deposits occur in the eastern sector of the study area (Varela, 2011). Associated with these deposits, hydromorphic palaeosols were developed (*i.e.*, Pedotypes 1, 2 and 4) related to low-gradient coastal plain areas and a relatively high water table, similar to the ones developed in the lower section of the Mata Amarilla Formation (Fig. 8).

5.2. Small-scale lateral variations in palaeosols

In the lower and upper sections, lateral variations in the type of palaeosol developed are regional in scale, and are mainly linked to the variations in the sedimentary palaeoenvironment. Marginal-marine successions developed in the eastern part of the study area do not develop thick palaeosol successions, while in the western sector Histosols (Pedotypes 1 and 2) and hydromorphic Vertisols (Pedotype 4) are developed related to distal fluvial successions. In contrast, the middle section of the Mata Amarilla Formation shows lateral variations at outcrop scale (on the order of 100–200 m), associated with their relative position within the fluvial environment. In the photo panel of Estancia Mata Amarilla (Mata Amarilla Farm; Fig. 9), lateral variation in palaeosols from Pedotype 4 (hydromorphic Vertisols) with a large quantity of organic matter to Pedotype 6 (Inceptisols) as they get closer to the channel facies can be clearly recorded. Inceptisols are found close to the channel sandstone and formed on silt to medium-grained sand, while Vertisols are located farther from the channel sandstone and developed on muddy silt and mud (Fig. 9). In this sense, the palaeosols developed closer to the channel show signs of oxidation and the surface horizons have scattered organic matter (Inceptisols; Fig. 9). The palaeosols farther from the channel are, in turn, grey to olive green in colour, with gley Bg and Cg horizons, as they were developed near or below the water table and mainly subjected to reducing conditions (Duchaufour, 1982; Kraus and Aslan, 1999). As the distance from the channel increases, palaeosols show progressively more hydromorphic characters (transition from Pedotype 3 to Pedotype 4) suggesting poorly drainage conditions. This could be related to a lower topographic position as sedimentation rate diminishes away from the channels (Pizzuto, 1987) giving rise to differential aggradation rates, and to the decrease in grain size in the same direction resulting in less permeable sediments in the distal floodplain (Kraus and Aslan, 1999; Varela et al., 2006; Fig. 9).

5.3. Small-scale vertical variations in palaeosols

High-frequency, vertical variations in the type of palaeosol developed were also identified in the middle section of the Mata Amarilla Formation (Fig. 10). Sequences a few metres thick show the superimposition of Inceptisols and Vertisols bounded by relatively sharp surfaces and intercalated with channel sandstones. For example, Fig. 10 shows hydromorphic Vertisols (Pedotype 4) overlain by Inceptisol (Pedotype 6), which are in turn covered by Pedotype 3 Vertisols. This palaeosol stacking is sharply overlain by coarse-grained channel deposits. Considering the lateral distribution of palaeosols described in the previous section, the properties of the palaeosols reflect how distal or proximal they were to the channel at a given time and may give an idea on the high-frequency changes within the fluvial plain.

The vertical stacking of different palaeosol types is occasionally gradual, for instance from Inceptisols (Pedotype 6) to Pedotype 3 Vertisols (Fig. 10) as both reflect relatively proximal conditions related to the main feeder channel. On the other hand, sometimes there is a more important change in palaeosol characters, for example from hydromorphic Vertisols (Pedotype 4) to Pedotype 6 Inceptisols (Fig. 10), which develop relatively close to the main channels; or from Vertisols (Pedotype 3) to channel deposits (Fig. 10).

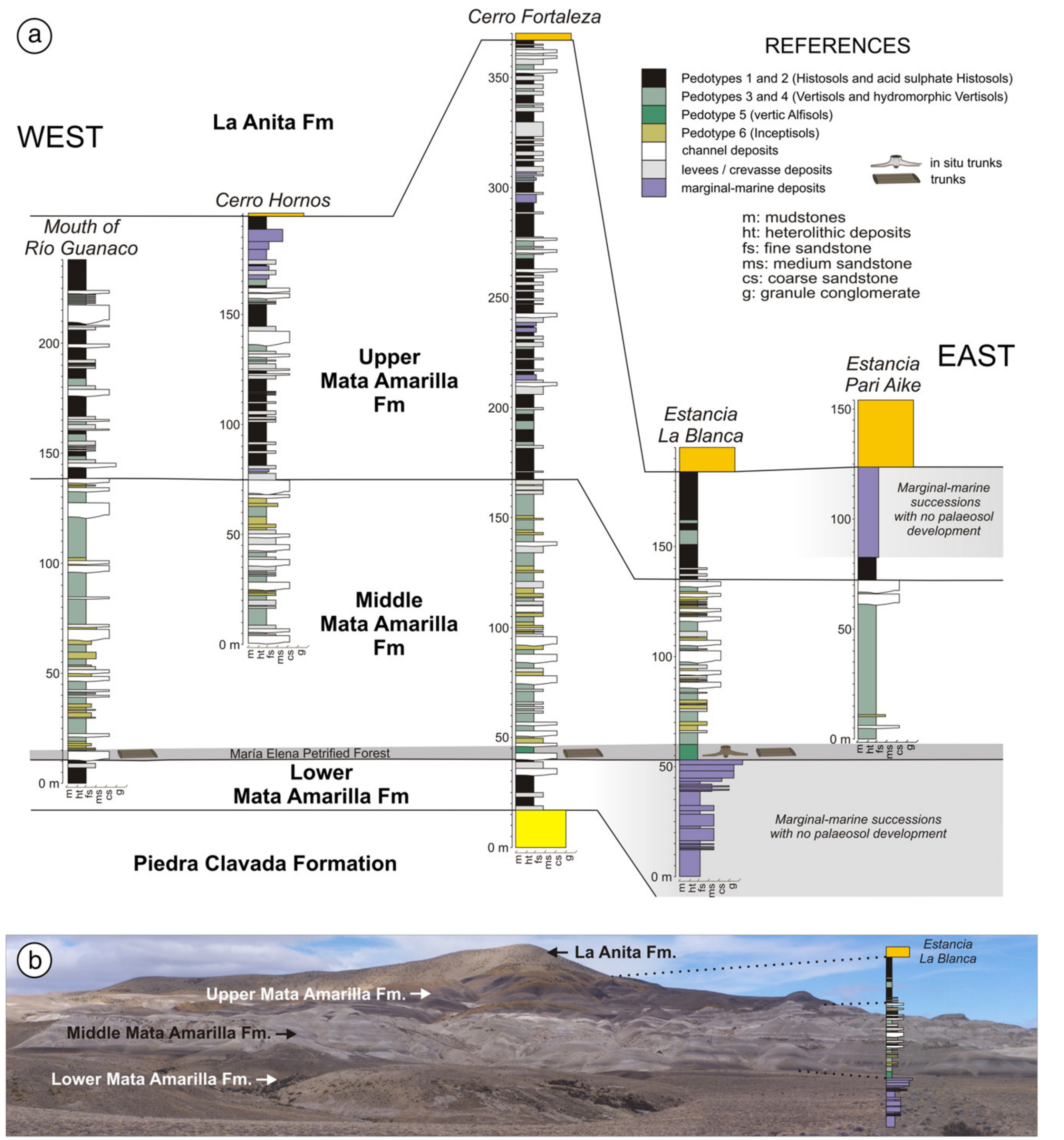

Fig. 8. (a) Large-scale vertical distribution of pedotypes identified in the Mata Amarilla Formation. The location of channel and splay deposits is also shown. In grey, areas related to marginal-marine accumulation with no palaeosol development. (b) Panoramic photograph of the Mata Amarilla Formation at Estancia La Blanca showing the large-scale distribution of palaeosols, identified by the different colouration. The lower and upper sections (dark-coloured) are predominantly fine-grained and correspond to coastal environments and distal fluvial settings with palaeosol development (mainly Pedotypes 1 and 2). The middle section of the Mata Amarilla Formation (light-coloured) has a higher proportion of sandstone deposits, and is characterised by high- and low-sinuosity meandering fluvial systems, in which Pedotypes 3, 4 and 6 are developed.

6. Discussion

Alluvial successions with stacked palaeosols commonly show sedimentary cycles that form in response to the combination of autocyclic and allocyclic processes (*e.g.*, Bridge, 1984, 2003; Wright and Marriott, 1993; Kraus, 1999, 2002; Kraus and Aslan, 1999). Cycles of alluvial aggradation ranging from tens to hundreds of metres thick are typically attributed to allocyclic factors, such as tectonics, eustatic changes, or climate changes (*e.g.* Wright and Marriott, 1993; Marriott, 1999; Kraus, 2002; Blum and Aslan, 2006; Cleveland et al., 2007). On the other hand, small-scale or high-frequency cycles are generally considered a response to autocyclic processes, such as avulsion or lateral migration of fluvial channels (Bridge, 1984, 2003; Kraus and Aslan, 1993, 1999; Cleveland et al., 2007). Accordingly, two scales of palaeosol variations were detected in the Mata Amarilla Formation, a small-scale or high-frequency variation and a large-scale or low-frequency variation, which are discussed below on the basis of the allocyclic and/or autocyclic factors controlling their development.

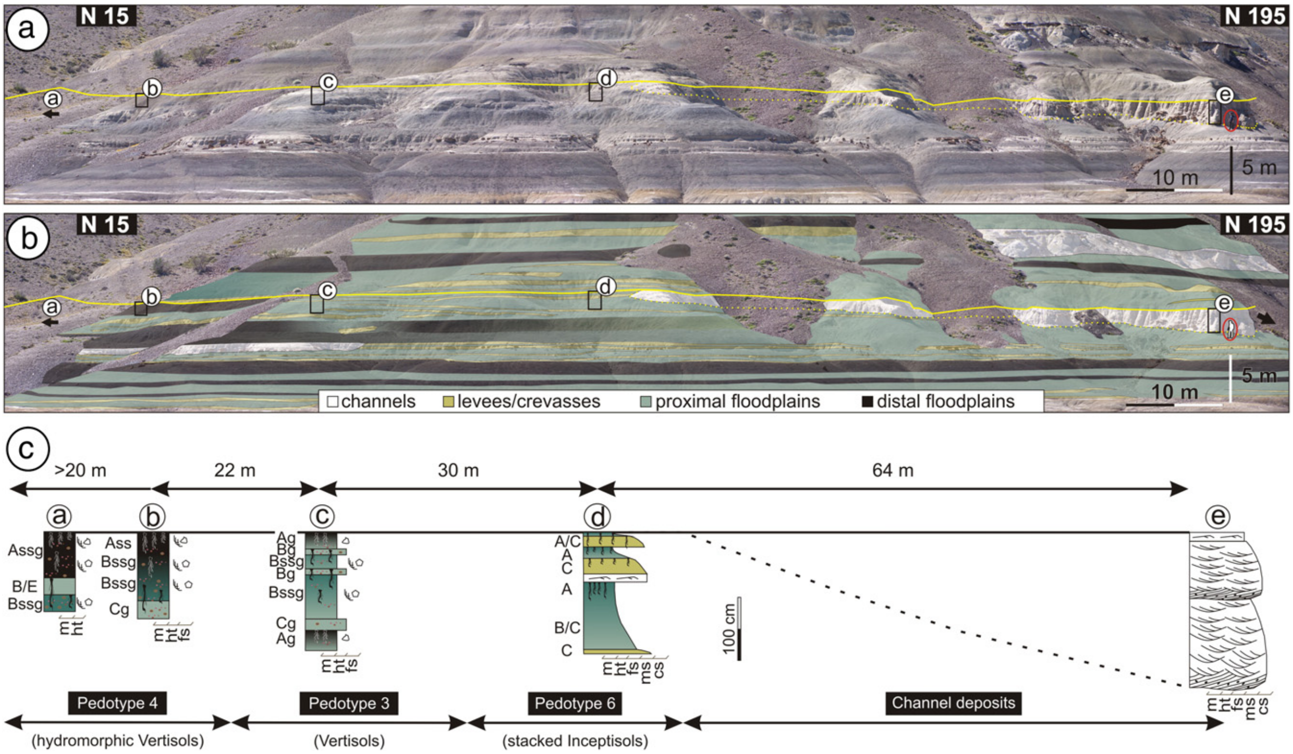

Fig. 9. Photomosaic of the middle section of the Mata Amarilla Formation at Estancia Mata Amarilla. Top panel (a) (without interpretation) and bottom panel (b) (interpreted) show lateral variations in the development of palaeosols and their relative position to channel deposits. Person for scale surrounded by red circle is 1.80 m tall. (c) Detailed vertical profiles of identified palaeosols (letters a to e show log position in panels). References as in Fig. 3.

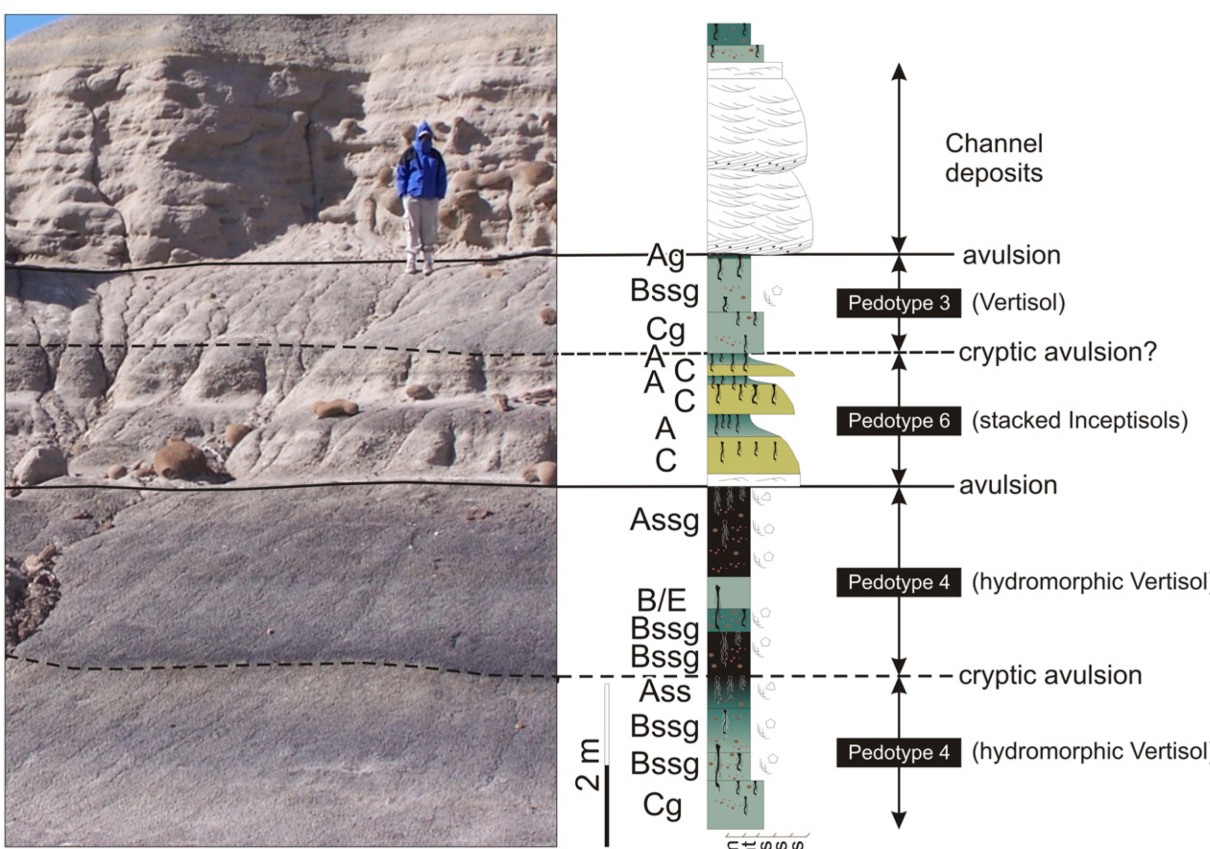

Fig. 10. Vertical, high-frequency changes in the development of palaeosols in the middle section of the Mata Amarilla Formation at Estancia Mata Amarilla. Note the sharp contact between palaeosol profiles, interpreted as the result of channel avulsions. The contact between Inceptisols and overlying Vertisols could be related either to an avulsion or to the abandonment of crevasse splay/avulsion deposits. References as in Fig. 3.

6.1. Small-scale, high-frequency changes in palaeosol development

Soil series or catenas are frequent associations between palaeosols and the palaeolandscape in which they are developed, for instance in the case of palaeosols developed near channels and those in more distal floodplains (Kraus, 1987, 1997; Kraus and Aslan, 1999). In this type of catena the best drained soils are developed near the channel margins (*i.e.*, levees and crevasse splays), which are associated to a higher position with respect to the neighbouring floodplains due to a higher aggradation rate related to flood affecting closer positions more frequently than in distal areas (Bridge and Leeder, 1979; Kraus and Aslan, 1999; Törnqvist and Bridge, 2002). Their closer position to the main channel also implies that they are usually developed on coarser sediments (*i.e.*, silts and fine sands), which are more permeable than the muddier deposits of the distal floodplains. In this respect, the palaeosols of the middle section of the Mata Amarilla Formation show systematic, small-scale lateral variations changes that can be directly related to their position relative to the main palaeochannels within the fluvial plain (Fig. 9). Proximal palaeosols show a low degree of development and are dominated by stacked Inceptisols. These soils were developed on relatively coarse material (fine sandstones) that might have favoured good drainage conditions. Therefore, hydromorphic features are absent in these palaeosols and horizon development is usually poor. As the distance from the channel increases, soils show better development with the presence of slickensides, wedge-shaped peds, and well developed horizons (Vertisols). Palaeosols located in the distal floodplain have even more mature features (*e.g.* darker colours, higher organic matter content, better developed soil horizons, typical of Pedotype 4 hydromorphic Vertisols). This could be the result of the decrease in the sedimentation rate accompanied by decrease in grain size and in drainage conditions as the distance from the channel increases. Different aggradation rates between proximal and distal parts of the floodplain (Bridge and Leeder, 1979; Mackey and Bridge, 1995; Törnqvist and Bridge, 2002) might have also resulted in changes in topographic position and therefore affecting local drainage and favouring temporal waterlogging in the distal floodplains.

Thus, the lateral palaeosol sequence, from the distal plain to the palaeochannel shows the transition from hydromorphic Vertisols, to typical Vertisols and eventually to stacked Inceptisols next to channel deposits (stage 1, Fig. 11). This change can be seen over distances between 100 and 200 m and is consistent with models recording the spatial variability within a palaeocatena (Kraus and Aslan, 1999).

Additionally, small-scale variations in palaeosol types are also observed in a vertical succession within the middle section of the Mata Amarilla Formation (Fig. 10). These changes can be quite evident, like the superimposition of stacked Inceptisols, developed relatively proximal to the main channel, sharply on top of distal, hydromorphic Vertisols (Fig. 10). If palaeosol type is strongly linked to the relative position within the floodplain relative to channels, these vertical changes may represent the result of an avulsion event (*i.e.* the abrupt changes in the position of the channels within the fluvial plain, stage 3, Fig. 11). The passages from Vertisols to channel deposit (Fig. 10) or the rapid abandonment of a channel also constitute the record of avulsion processes (stage 5, Fig. 11).

Although channels can change their position within the fluvial plain more gradually due to lateral migration (especially in high-sinuosity systems), this migration can be a relatively uniform process, gradually changing conditions of a certain location from distal to proximal, or vice versa. That would probably result in the gradual transformation of soil profiles and not necessarily in the vertical stacking of different soil types as observed in the studied section. For this to occur, a pause in soil formation and the reestablishment of floodplain aggradation is needed in order to develop a sharp boundary between soil types as seen in the Mata Amarilla Formation.

Still, some of these small-scale vertical changes can be more subtle and reflect the vertical superimposition of different soil types that are developed adjacent to each other within the floodplain or even the stacking of different soil profiles of the same type. For example, the lower portion of the section shown in Fig. 10 displays the vertical stacking of two hydromorphic Vertisol profiles. The presence of a sharp boundary between these two palaeosol profiles and the preservation of a superficial horizon (Ass) in the lower one indicates a relative break in sedimentation and pedogenesis and the subsequent development of a new soil profile, in this case as distal as the previous one (stage 2, Fig. 11). This subtle change in the rate of sedimentation and pedogenesis can also be related to changes in the position of main feeder channels and therefore regarded as a 'cryptic' avulsion within the fluvial system (Figs. 10 and 11). In this sense, 'cryptic' avulsions are avulsions which remain hidden within the traditional facies analyses and can only be revealed by means of detailed palaeosol analysis. Cryptic avulsions can also be interpreted in the case that Inceptisols are vertically replaced by typical Vertisols (Fig. 10). This change can also result from the avulsion of the main channel belt (stage 4, Fig. 11), although a similar vertical succession could be observed in the case of abandoned crevasse splay deposits or developed on top of avulsion deposits (Smith et al., 1989; Kraus and Aslan, 1993), away from the new channel position.

To summarise, small-scale lateral changes identified in the middle Mata Amarilla Formation are related to lateral changes within the floodplain and can represent mesoscale systems or palaeocatenas (sensu Kraus and Aslan, 1999). The systematic change in channel position within the alluvial plain due to avulsion process also resulted in the development of small-scale vertical sequences –a few metres thick– of different soil types and channel deposits. Both lateral and vertical changes can be associated to autocyclic processes, specifically to channel avulsion (Fig. 11).

6.2. Large-scale, low-frequency changes in palaeosol development

The described large-scale distribution of the Mata Amarilla palaeosols (Fig. 8) is intimately related to regional and temporal changes in the sedimentary environments (Fig. 12). The lower section of the Mata Amarilla Formation in the western sector is dominated by fluvial channels encapsulated in floodplain mudstones on which hydromorphic palaeosols developed (*i.e.*, Histosols, Histosols with acid sulphate properties and, in less proportion, hydromorphic Vertisols; Fig. 12). Towards the eastern sector, this lower section is characterised by estuarine facies with the development of Histosols and Histosols with acid sulphate properties in the upper estuary facies. These deposits are replaced, towards the eastern limit of the study area by outer estuary and marine deposits with no palaeosol development (Figs. 8 and 12). The onset of the middle section of the Mata Amarilla Formation is marked both by a change in depositional systems and also in the type of palaeosols developed. This boundary is characterised by a relatively sharp surface in the eastern area, where a thick succession of vertic Alfisols is developed associated to the *in situ* María Elena Petrified Forest (Fig. 12). The presence of tree trunks with little or no transport within amalgamated sheet-like channels in the western sector shows that the forest horizon – and therefore the vertic Alfisol level in which it was developed – was originally distributed across the whole study area, only that in the western sector it was not preserved due to fluvial erosion (Fig. 12). The middle section of Mata Amarilla Formation is characterised by fluvial deposits in the whole study area, although while in the western sector fluvial channels show sheet geometry, in the eastern sector complex sandy ribbons occur associated with muddy floodplains. Vertisols, hydromorphic Vertisols and Inceptisols developed in these floodplains, and as discussed in the previous section, the lateral distribution of these types of palaeosols is directly related to autocyclic processes (Fig. 12). Finally, the upper section of the Mata Amarilla Formation is characterised by channels encapsulated in fine-grained deposits with abundant hydromorphic palaeosols

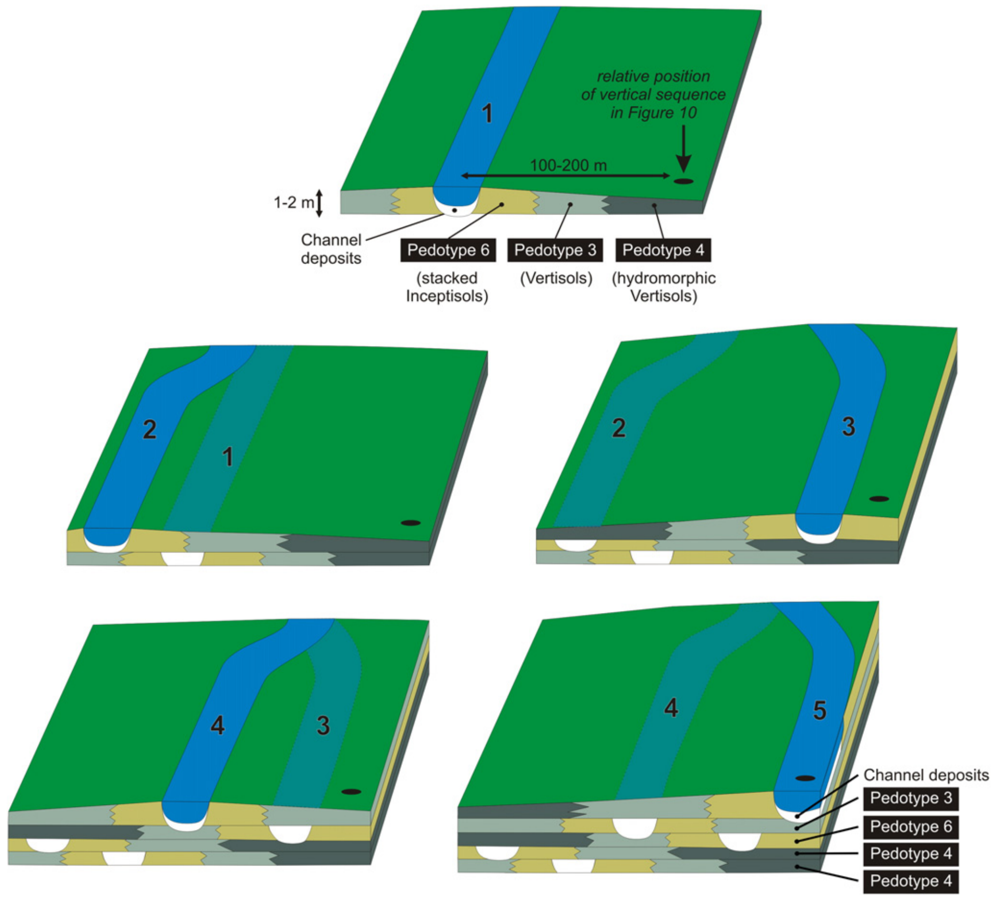

Fig. 11. Conceptual model showing the vertical and lateral changes in palaeosol development. The lateral variations are directly dependent on the position within the floodplain, *i.e.*, the distance from the palaeochannel, which determines the particle size, the sedimentation rate and therefore the palaeotopographic relief (stage 1). The vertical subsequent avulsions of the main channels (stage 2 to 5) result in the vertical stacking of different palaeosol types. Approximate location of vertical log in Fig. 10 is shown. Stage numbers are relative and show aggradation stages related to log in Fig. 10. However, the main channel could have switched position to a more distal location leaving no record in the studied vertical log (for example between stages 1 and 2).

(*i.e.*, Histosols, Histosols with acid sulphate properties and in less proportion hydromorphic Vertisols), which interfinger with estuarine facies towards the east (Fig. 12).

These large-scale changes in depositional systems and their relationship with different palaeosol types in the Mata Amarilla Formation (Fig. 12) can be attributed to low-frequency changes in allocyclic factors (*e.g.*, Wright and Marriott, 1993; Blum, 1994; Shanley and McCabe, 1994; Cleveland et al., 2007). In this sense, a sequence stratigraphic scheme can be constructed considering accommodation/sediment supply conditions for the three sections of the Mata Amarilla Formation

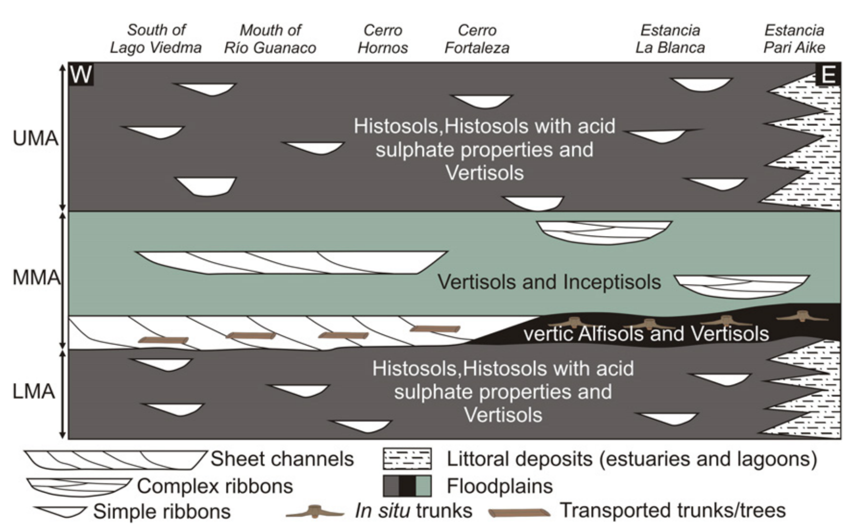

Fig. 12. Schematic cross-section showing the regional large-scale association between palaeosol types, depositional environments and stratigraphy of the Mata Amarilla Formation. LMA: Lower Mata Amarilla Formation, MMA: Middle Mata Amarilla Formation, UMA: Upper Mata Amarilla Formation. The relative position of studied localities is also shown (see Fig. 1 for distribution). Vertical scale is between 100 and 350 m depending on the location in the basin. No horizontal scale.

(Fig. 13a). A relatively high aggradation rate can be inferred for the lower section, evidenced by channels isolated in floodplain deposits. This can be correlated with the development of marginal marine systems in the eastern area suggesting the development of a transgressive system tract (TST; Fig. 13a). The boundary between the lower and middle sections of the Mata Amarilla Formation shows a drastic reduction in accommodation/sediment supply condition evidenced by an important increase in the degree of amalgamation of fluvial channels, together with the onset of fluvial sedimentation across the whole area. This boundary is also characterised by the presence of a strongly developed palaeosol level associated with the María Elena Petrified Forest with trees in life position to the east and transported trunks within amalgamated sheet-like channel deposits to the west (Fig. 13a). This evidence points to the development of a forced regression that, in a sequence stratigraphic framework represents a sequence boundary (SB) (sensu Catuneanu et al., 2009; Fig. 13b). The rest of the middle section is dominated by the accumulation of sheet sandstones in the western sector and complex ribbons sandstones in the eastern sector, which are interpreted as a lowstand system tract (LST; Fig. 13a). Finally, the upper section of the Mata Amarilla Formation is similar to the lower section and it is characterised by isolated channels within fine-grained deposits with abundant hydromorphic palaeosols which represent high accommodation/sediment supply condition. Thus, the upper section is also interpreted as a TST (Fig. 13a).

Several authors have highlighted the importance of palaeosol studies within a sequence stratigraphic framework, both theoretically (Wright and Marriott, 1993) and in field examples (Aitken and Flint, 1996; McCarthy and Plint, 1998). Wright and Marriott (1993) developed a model which predicts the degree of palaeosol development and drainage conditions of coastal plain palaeosols through the different stages of a eustatic cycle (Fig. 13b). This model suggests that during a relative sea-level fall or lowstand systems tract (LST) accumulation, strongly developed, well-drained soils occur on top of fluvial terraces, as the fall in the relative base-level of the fluvial systems generates incised valleys (Fig. 13b). When the relative sea level starts to rise – *i.e.*, during transgressive systems tracts (TST) – hydromorphic soils develop due to a relatively high water table triggered by the base-level rise. As the relative sea level continues to rise, the rate of accommodation creation increases together with sedimentation rate and giving rise to poorly developed palaeosols. Subsequently, at the beginning of relatively high sea-level periods or highstand systems tracts (HST), the aggradation rate decreases, resulting in an increase in the degree of soil development. Finally, when the sea level is at its maximum (late HST) the rate of accommodation creation is insignificant and strongly developed

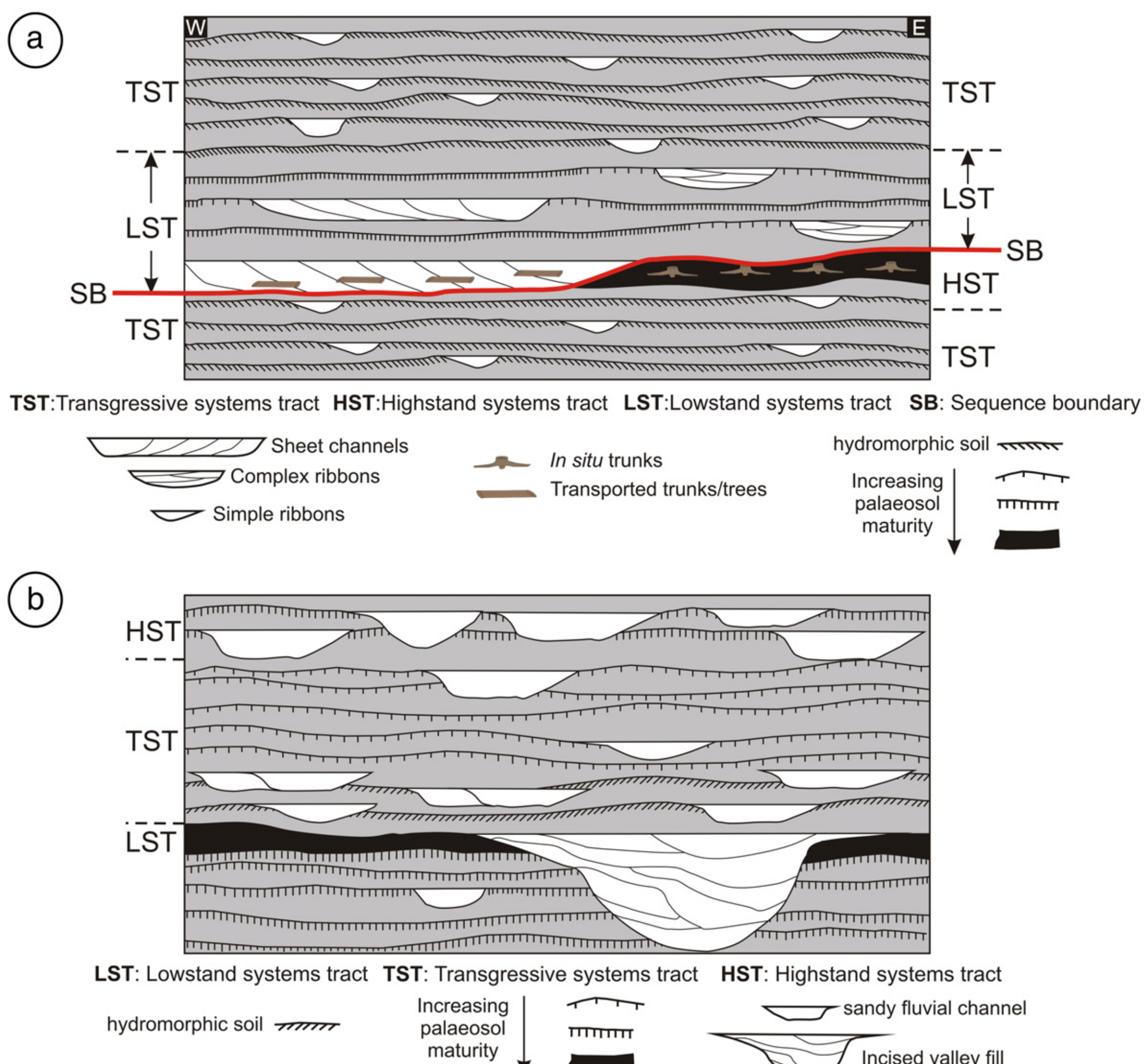

Fig. 13. Palaeosols and sequence stratigraphy. (a) Palaeosol sequence stratigraphic model of the Mata Amarilla Formation, based on outcrop data. Note the relatively high degree of development of palaeosols (except locally related to intrinsic factors) and the lack of incised valleys. This distribution is likely during greenhouse episodes when climate conditions are favourable for soil development and relative sea-level falls are less pronounced. (b) The classical palaeosol sequence stratigraphic model by Wright and Marriott (1993) that might be more applicable to icehouse periods.

palaeosol occurs. In spite of this, the preservation potential of the soils developed during this stage is limited, because the aggradation rate is too low and the fluvial systems would rework the floodplains. A characteristic of the model developed by Wright and Marriott (1993) is that, unlike other sequence stratigraphic models developed for marine environments (*e.g.*, Posamentier and Vail, 1998), it predicts high aggradation rates during transgressive periods, and low aggradation rates during the development of the HST. Consequently, the TST will show abundance of overbank deposits with poorly developed palaeosols, and in the HST the proportion of overbank deposits will decrease and the palaeosols will show a stronger degree of developed.

The sequence stratigraphic approach for the palaeosols of the Mata Amarilla Formation (Fig. 13b) contrasts with the classical theoretical model by Wright and Marriott (1993) in that there are no incised valleys, and the presence of lowstand wedges is the distinctive feature associated with the forced regressions. This is a character of sequence boundaries developed during greenhouse periods and has important implications in the elaboration of a predictive model for palaeosol development during these climate optimums. Even when during the forced regression, a thick strongly developed palaeosol level occurs in the Mata Amarilla Formation (vertic Alfisols), as it does in the theoretical model by Wright and Marriott (1993), the observations in the Mata Amarilla differ considerably from the classical models in which incised valleys and interfluve terraces are the main features that condition the physiography of the lowstand periods. In the studied unit palaeosols that range from weakly to strongly-developed are found in the upper part of the LST. As seen before, this difference is linked to the palaeotopographic location within the fluvial system and the relationship with channel deposits, but not to extrinsic factors. Also, in the theoretical model by Wright and Marriott (1993), palaeosols developed in the highstand deposits are strongly developed, while palaeosols of the Mata Amarilla Formation highstand are not preserved due to the nature of the lowstand wedge. Finally, during TSTs, the theoretical model predicts the development of hydromorphic, poorly developed soils. However, the Mata Amarilla Formation hydromorphic soils developed during the transgressive intervals could be assigned to well-developed palaeosols given the abundance of pedogenic features. Nevertheless, such a degree of palaeosol development is relative, because during climate optimums more favourable climatic conditions could significantly accelerate soil development processes resulting in an overall higher degree of palaeosol development throughout the whole sequence.

In summary, and although there is a strong link between the type of palaeosol developed and the large-scale sequence stratigraphic changes in the Mata Amarilla Formation, big differences can be observed from the classical theoretical models. This could be related to climatic conditions reigning during the Cenomanian, which may have favoured the development of well-developed palaeosols throughout the whole unit, and resulting in an increase in the relative importance of local soil forming factors such as parent material (in the case of levee-related palaeosols) or palaeotopography (in distal floodplain settings) rather than time. Also the classical models, in which palaeosol development during lowstands is related to the development of incised valleys, more likely during icehouse periods, may not be applicable in the Mata Amarilla Formation, as a relative important preservation of floodplain deposits is registered during the LST with the development of well developed, hydromorphic palaeosols. In this sense, the Mata Amarilla Formation example could be applied to other sequences occurring in middle latitudes during climate optimums in terms of predicting long-term palaeosol variability.

7. Conclusion

(1) In the Mata Amarilla Formation there is an extensive development of stacked palaeosols. Macroscopic and microscopic analyses led to the identification of six pedotypes that are grouped in four palaeosol orders: Histosols, Vertisols, Alfisols and Inceptisols.

(2) The palaeosols of the Mata Amarilla Formation display characteristics of hydromorphic soils and they could be grouped within the Gleysol order or gley soils, which are compatible with warm temperate climates. This is consistent with the beginning of the climate optimum or greenhouse period of the Cenomanian.

(3) The lower and upper sections of the Mata Amarilla Formation are characterised by the presence of Histosols, Histosols with acid sulphate properties and hydromorphic Vertisols associated with low-gradient coastal environments.

(4) The onset of the middle section of the Mata Amarilla Formation, which is of a fluvial nature, is marked by the occurrence of a thick, highly developed palaeosol level (*i.e.*, vertic Alfisols and Vertisols), associated with the María Elena Petrified Forest, which marks the sequence boundary. The rest of the middle section is composed of Vertisols and Inceptisols.

(5) The large-scale or low-frequency vertical variations in the type of palaeosol and the drainage conditions occurring in the three sections of the formation are related to extrinsic factors, whereas the lateral and vertical, small-scale or high-frequency variations within the middle section were the result of the influence of factors which are intrinsic to the depositional systems — such as the position within the floodplain and the distance from the main channels.

(6) Finally, a sequence stratigraphic model was developed for the palaeosol succession of the Mata Amarilla Formation, which could be applied to other sequences that deposited during climate optimums.

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