Journal of South American Earth Sciences 28 (2009) 40–53

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Latest Carboniferous–earliest Permian transgressive deposits in the Paganzo Basin of western Argentina: Lithofacies and sequence stratigraphy of a coastal-plain to bay succession

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ARTICLE INFO

Keywords:
Tupe Formation
Paganzo Basin
Transgression
Late Paleozoic
Sequence stratigraphy

ABSTRACT

The upper Paleozoic rocks of Gondwana record a complex paleoclimatic history related to the migration of the supercontinent over high latitudes. Changes in climate and relative sea level can be traced through detailed sedimentologic and sequence-stratigraphic analysis. Our study focuses on transgressive deposits of Stephanian–Early Permian age in the lower member of the Tupe Formation with the objective of characterizing lithofacies and sedimentary environments within a sequence-stratigraphic framework in order to achieve a better understanding of the sedimentary history of the Paganzo Basin and the nature of transgressive deposits.

Sixteen lithofacies grouped in eight assemblages were defined and arranged in two complete sequences. A sequence boundary (SB) is identified at the base of the Tupe Formation. Coastal-plain deposits capped by marine embayment lithofacies are included within sequence 1. A relative sea-level fall (SB) is recorded by an abrupt change into braided alluvial-plaine deposits (LST). The beginning of the TST is characterized by the appearance of coal and deltaic lithofacies. Late TST deposits occur above a ravinement surface and comprise bay-margin to distal-bay deposits forming a retrogradational stacking package. These lithofacies are replaced upwards by HST deposits. A relative sea-level fall (SB) is recorded by the presence of fluvial deposits overlying marine lithofacies.

The Tupe Formation illustrates the transition of a coastal-plain to a marine embayment. The detection of a transgressive surface within the coastal-plain deposits of sequence 1 expanded significantly the volume of deposits now included as part of the latest Carboniferous–earliest Permian transgression, and underscores the importance of searching for transgressive signatures in non-marine environments. The presence of two sequences supports a punctuated shoreline trajectory with an overall retrogradational stacking pattern. An abrupt relative sea-level fall and increased aridity is recorded at the end of the transgressive event.

1. Introduction

Upper Paleozoic rocks of Gondwana record a complex paleoclimatic history related to the movement of the supercontinent over high latitudes (López Gamundí et al., 1992). Three glacial and deglaciation events are recorded in different basins of South America, South Africa, Antarctica, Australia and India. After each of these glaciations, post-glacial transgressions were triggered. Because of detailed sedimentologic and sequence-stratigraphic analysis, changes in climate, tectonics, and relative sea level can be detected over different areas of Gondwana. This paper deals with transgressive deposits which span the Carboniferous–Permian boundary within Cuesta de Huaco, San Juan, western Argentina.

As a response to transgressions, sedimentary successions tend to display a retrogradational stacking pattern (Posamentier and Allen, 1999). The recognition of an overall landward migration of the shoreline and/or deepening-upward trends in the succession is crucial for the identification of transgressive deposits (Cattaneo and Steel, 2003). However, within continental successions transgressive signatures have to be sought reflecting a landward advancing shoreline.

The transgressive surface (TS) is a point on the relative sea-level curve where a sedimentary environment suffers a shift after the end of regression (Catuneanu, 2006). The identification of this surface (TS) does not necessary imply a lithofacies change from non-

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doi:10.1016/j.jsames.2008.10.003

marine to marine rocks or from shallow-marine to deep-marine lithofacies.

Historically, transgressions have been identified by the presence of marine fossils (trace and body fossils) and certain physical sedimentary structures (e.g., tidal bedding), rather than by the stacking pattern of sedimentary successions. This led to location of many transgressions at a higher stratigraphic position than where they would be placed within a sequence-stratigraphic framework.

The transgression represented in the lower member of the Tupe Formation in the western sector of the Paganzo Basin (western Argentina) illustrates some of these problems. This transgression was first identified by Cuerda (1965), who described an interval bearing marine invertebrate fossils.

This paper focuses on several aspects of the latest Carboniferous–earliest Permian transgression into the western area of the Paganzo Basin, namely: (1) documentation and interpretation of its lithofacies within a sequence-stratigraphic framework, (2) the role of paleogeography as a controlling factor in the distribution and characteristic of transgressive deposits, and (3) location of transgressive surfaces in non-marine environments.

2. Regional setting

During the late Paleozoic, three diachronic glacial events occurred over different regions of Gondwana (López Gamundí et al., 1997). The first, Late Devonian–Early Carboniferous in age, is recorded in the Solimões and Amazonas basins in Brazil, and in the Lake Titicaca region of Bolivia. The second, Late Carboniferous, is represented in the Tarija Basin of Bolivia and northwestern Argentina and the Paganzo and Calingasta-Uspallata basins of western Argentina. The third glaciation took place in the Late Carboniferous–Early Permian in different basins in the southeastern region of South America (Paraná, Sauce Grande and Malvinas basins), Antarctica, South Africa, India and the western basins of Australia. The aftermaths of these glacial periods were characterized by transgressions recorded by the establishment of lakes and fjord embayments, and subsequent climatic amelioration (e.g., López Gamundí, 1989; Buatois and Mángano, 1994, 1995; Holz, 1999; Limarino et al., 2002). Our study focuses on deposits of latest Carboniferous–earliest Permian age in the western margin of the Paganzo Basin.

The Paganzo Basin is one of the most extensive late Paleozoic continental depositional areas of Argentina. It is a pericratonic foreland basin, tectonically influenced by the effects of the accretion of a terrane to the western margin of Gondwana during the Late Devonian–Early Carboniferous (Chanic Orogeny) (Ramos et al., 1986). As a response to this event, a positive element, known in the geologic literature as the Proto-Precordillera, emerged between the Calingasta-Uspallata and Paganzo basins (Amos and Rolleri, 1965; Turner and Méndez, 1975; Ramos and Palma, 1996). According to López Gamundí et al. (1992), the Protoprecordillera divided the drainage between the two basins during the Early and early Late Carboniferous. However, during early Late Carboniferous, an embayment (Guandacol Embayment) around its northern tip connected the mostly non-marine sedimentation in the Paganzo Basin with the marine sedimentation on the Calingasta-Uspallata Basin. During the Late Carboniferous–Early Permian, an extensive breach in the Protoprecordillera at the latitude of our study area would have already existed, allowing the development of marine lithofacies on the western margin of the Paganzo Basin (López Gamundí et al., 1992).

The deposits on the western margin of Paganzo Basin consist of a thick sedimentary succession formally included in the Paganzo Group (Azcuy and Morelli, 1970). Limarino et al. (1986) proposed Cuesta de Huaco as a stratotype of reference for this sector of the basin. These authors recognized three formations within the Paganzo Group: Guandacol, Tupe, and Patquía. The Guandacol Formation consists of coarse-grained diamictite formed in subaqueous outwash environments (Limarino et al., 2002). These beds are replaced upwards by shale, mudstone, and varve-like bedsets containing dropstones, marine invertebrates (Martínez, 1993) and microplankton (Ottone, 1991), interpreted as postglacial transgressive deposits in a fjord environment (Gutierrez and Limarino, 2001; Limarino et al., 2002; Pazos, 2002). The upper interval of the Guandacol Formation mainly consists of sandstone and records the progradation of a Gilbert Type delta (Limarino et al., 2002).

The Tupe Formation consists of sandstone, conglomerate, mudstone, and coal that unconformably overlie the Guandacol Formation. The Tupe Formation mostly records deposition in continental environments. However, in some localities this continental succession is punctuated by a marine interval containing an invertebrate fauna which belongs to the *Tivertonia jachalensis-Streptorhynchus inaequiornatus* Biozone (Sabattini et al., 1990). Recently, this biozone has been considered to be Early Permian in age (Cisterna et al., 2002, 2006; Archbold et al., 2004; Simanauskas et al., 2003). Palynologic and paleofloristic data (Vergel and Fasolo, 1999; Gutiérrez et al., 2005) from different localities in the western zone of the Paganzo Basin (La Herradura Creek, La Delfina Creek, La Ciénaga, and Paslean) allow restricting the transgression to the latest Carboniferous–earliest Permian interval (Cisterna et al., 2005). Lithofacies analyses have been performed in these deposits (Bossi and Andreis, 1985; Ottone and Azcuy, 1986; Limarino et al., 1986; Pazos, 1994), but a detailed analysis of the associated transgressive stratigraphy is still lacking. The Patquía Formation consists of conglomerate, sandstone, and evaporite developed in an arid to semiarid settings. The Patquia Formation records the development of fluvial, eolian and playa-lake environments (Limarino et al., 1986).

3. Lithofacies analysis

A detailed sedimentologic and high-resolution sequence-stratigraphic analysis in the lower member of the Tupe Formation between the localities of Mina La Ciénaga and Quebrada La Delfina (Fig. 1) allows us to describe and analyze the most landward expression of the Stephanian–Lower Permian transgression in the Paganzo Basin (Figs. 1 and 2). Sixteen lithofacies were recognized (Table 1). In the proposed lithofacies code, the capital letter indicates the lithology, whereas the subindex broadly refers to the dominant sedimentary structure, and/or other relevant attributes. Additional criteria for lithofacies identification include bed geometry and bed boundaries. Geometry is based on the scheme proposed by Friend et al. (1979). The environmental framework of MacEachern and Gingras (2007) for bay successions is adopted in this study. Lithofacies are grouped in seven assemblages taking into account their field relationship and environmental significance. Ichnologic analysis also provides valuable information. The distribution of the lithofacies assemblage over the different localities is shown in Fig. 3.

3.1. Assemblage I: interbedded medium- to fine-grained sandstone, siltstone, and coal lithofacies

3.1.1. Description

This lithofacies assemblage comprises the lowermost interval of the studied sections in both localities. It consists of medium- to fine-grained sandstone (St, Sp, Sr, Sl) occurring in packages of 0.5 m to 16 m, encased in heterolithic lithofacies of interbedded siltstone, mudstone (Fl), very-fine-grained sandstone (Sl, Sr), and

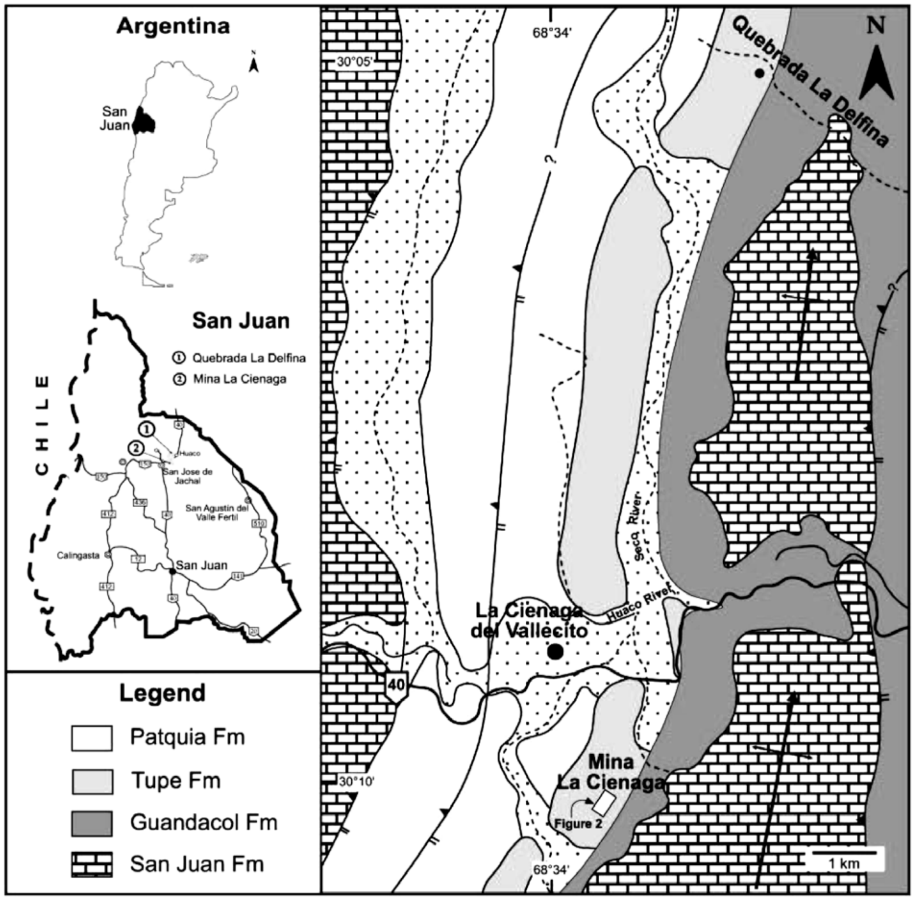

Fig. 1. Simplified geological map and location of the studied outcrops. Mina La Ciénaga and Quebrada La Delfina.

coal (C) lithofacies. The sandstone occurs in erosionally based, normally-graded, laterally continuous packages of sheet-like geometry, internally showing lateral-accretion surfaces (Fig. 4). The fine-grained lithofacies are grouped in a heterolithic assemblage that sharply or gradationally overlies the sandstone units. These are characterized by thinly interlaminated siltstone and mudstone with plant fragments along the bedding planes (Fl, Fr), very-fine-grained sandstone (Sr, Sl, Sm), and coal (C). The thickness of the individual beds forming these packages is only a few centimeters, but bedsets vary between 0.2 m and 11 m thick. The coal beds are thicker towards the upper section of this assemblage, reaching up to 1 m. Rhizoliths occur within this lithofacies. Fining-upward cycles were detected throughout this assemblage comprising normally graded, erosionally based sandstone bodies at the base, and fine-grained heterolithic lithofacies at the top of each cycle. Trace fossils occur in the heterolithic lithofacies, which includes *Helminthopsis abeli*, *Treptichnus pollardi,* and undetermined grazing trails.

3.1.2. Interpretation

This assemblage is considered to have been deposited in a coastal-plain environment, dissected by meandering-fluvial channels, and with extended and temporally inundated floodplains and waterlogged soils. Sandstone packages are interpreted as channel fills, and the lateral-accretion surfaces and normal grading reflect the lateral migration of their axes. Associated floodplains and waterlogged soils are represented by the heterolithic lithofacies. During the flooding stages of the fluvial system, relatively thin beds of sandstone (Sr, Sl, Sm) and siltstone were deposited as the river flow extended outside the main channels, and covered the floodplains. Silt and mud settled down from suspension, while floodplains were still inundated. Small temporary water bodies also formed, as inferred from thinly-laminated claystone deposits. The presence of rhizoliths, high amounts of fossil plants, and coal evidence extended vegetated areas, where peat was able to develop. The upward increase in thickness of the coal beds is related to an increase in accommodation space.

3.2. Assemblage II: interbedded chlorite mudstone and sandstone lithofacies

3.2.1. Description

At the top of the Assemblage I in Mina La Ciénaga, the chlorite mudstone and siltstone lithofacies (Pc) is interbedded with tabular, fine- to medium-grained sandstone bodies. These sandstone packages internally show a set of different lithofacies (Sl, Sm, Sr) which alternate without any evidence of scouring or breaks in sedimentation (Fig. 5). Climbing ripples and horizontal lamination gradationally alternate, both laterally and vertically, within the same bed. Massive sandstone beds occur locally. These bodies only show signatures of scouring or internal erosion surfaces when the grain size is coarse sand.

3.2.2. Interpretation

Mudstones were deposited from suspension fallout in a coastal lagoon environment. The fine- to medium-grained sandstone bodies display transitional fluctuations between climbing-ripple cross-lamination, horizontal lamination and massive intervals, which are interpreted as river-fed density currents or quasi-steady turbidity currents, and hyperpicnial flows (Mulder and Alexander,

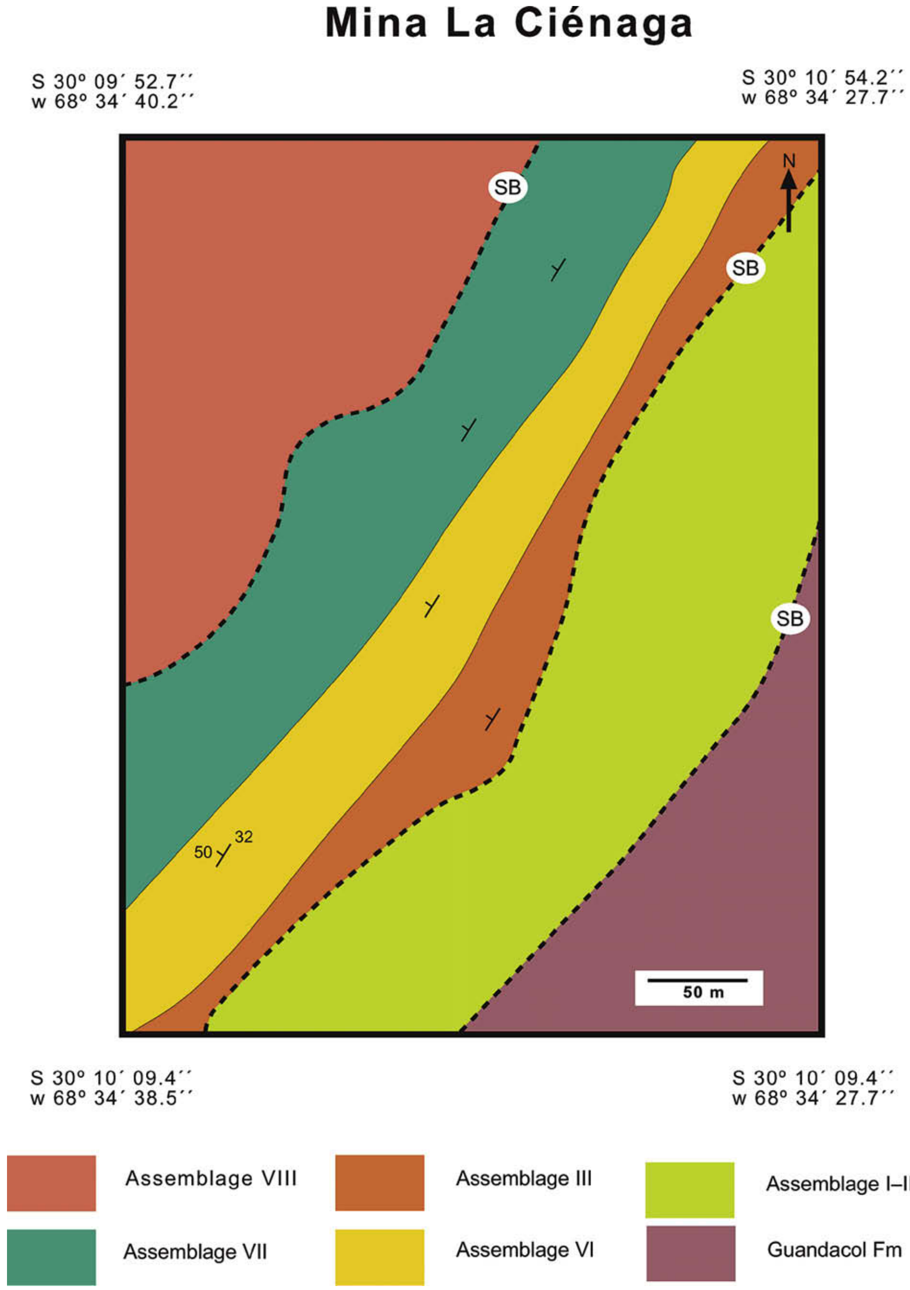

Fig. 2. Distribution of the different lithofacies assemblages in Mina La Ciénaga.

2001; Zavala et al., 2006). The upward increase in sandstone thickness is interpreted as the result of fluvial progradation. The clay mineralogy of these deposits, as well as those from assemblage VII, are related to a source area to the west of the studied localities, thus representing transgressive episodes (Net et al., 2002).

3.3. Assemblage III: pebbly and coarse-grained to medium-grained amalgamated sandstone lithofacies

3.3.1. Description

This lithofacies assemblage is present in both localities, albeit with some differences. It consists of amalgamated units of pebbly coarse- to medium-grained sandstone (St, Sp, Sl, Gt, Gp, Gh) and pebbly conglomerate lenses. These sandstone lithofacies comprise laterally continuous, amalgamated lenticular multi-storey packages (Fig. 6). Individual beds vary in thickness between 0.6 m and 4 m. The total thickness of this assemblage in Quebrada La Delfina is 50 m, while in Mina La Ciénaga is only 12 m. Internally these bodies are highly variable, showing large trough and planar cross-stratification, and massive medium- to coarse-grained sand matrix-supported pebbly conglomerate (Gh), conglomerate lenses, clay-chips of relatively small size, and coal fragments.

3.3.2. Interpretation

The establishment of a braided-type fluvial system in the area is inferred for this assemblage. The large cross-stratified beds were deposited as longitudinal and lateral bars grew, and migrated along the course of the braided system (Miall, 1996). Trough cross-stratified sandstone and the gravel lenses are interpreted as channel-fill deposits. The Gh lithofacies represents concentrated flows during megaflood stages of the river system. The absence of floodplain deposits and the multi-storey character of these

Table 1
Lithofacies chart.

Lithofacies	Lithology and sedimentary structures	Sedimentary processes and depositional conditions	Sedimentary environments	Distribution
Gt	Trough cross-stratified, gravelly very coarse-grained sandstone. Each set generally comprises a sharp and erosive base. Clay-chips are common	Tractive bed load deposition from unidirectional currents as channel fills	Braidplain and ephemeral fluvial	Assemblages: III, VIII
Gp	Planar cross-stratified, gravelly very coarse-grained sandstone. Each set is limited by a sharp and planar base and top. Clay-chips are common	Tractive bed load deposition from unidirectional currents as longitudinal bars and/or channel fills	Braidplain and ephemeral fluvial	Assemblages: III, VIII
Gh	Matrix supported conglomerate. Well rounded clasts scattered in a medium- to coarse-grained sandstone	Deposition from a concentrated density flows	Braidplain and ephemeral fluvial	Assemblages: III, VIII
St	Trough cross-stratified, moderate to well sorted, medium- to coarse-grained sandstone. Sharp and erosive bases; sharp or gradational tops	Tractive bed load deposition from unidirectional currents	Braidplain, coastal plain, delta, bay-margin and ephemeral fluvial	Assemblages: I, III, IV, V, VI, VIII
Sp	Planar cross-stratified, moderate to well sorted, very fine- to medium-grained sandstone. Erosive and sharp bases; sharp tops	Tractive bed load deposition from unidirectional currents in channels	Braidplain, coastal plain and ephemeral fluvial	Assemblages: III, IV, VIII
Sl	Horizontally laminated, well sorted, very fine- to medium-grained sandstone. Sharp to gradational bases and tops. Locally interbedded within thin layers of silt and clay	Bed load + suspension load deposition from unidirectional currents.	Braidplain, coastal plain, lagoon, prodelta and ephemeral fluvial	Assemblages: I, II, III, IV, V, VIII
Sr	Climbing ripple cross-laminated, very well sorted, fine- to very fine-grained sandstone. Gradational and sharp bases and tops. Occasionally interbedded within thin layers of silt and clay	Continuous traction + suspension fallout deposition from turbulent currents	Coastal plain, lagoon and prodelta	Assemblages: I, II, IV, V, VIII
Sh	Planar to low-angle cross-stratified, well sorted, medium- to fine-grained sandstone. Sharp bases and tops. Parting lineation is present	Sediment rework by waves in the surf zone under upper-flow regime	Bay-margin	Assemblages: VI
Swr	Wave-ripple cross-laminated and low-angle cross-laminated, very well sorted, very fine- to fine-grained sandstone. Sharp bases and tops	Sediment deposit and/or reworked by oscillatory currents	Bay-margin and distal-bay	Assemblages: VI, VII
Srd	Very well sorted, normally graded, fine to very fine-grained sandstone. Sharp erosive base and dome shaped tops	Traction + suspension fallout from turbidity currents and high-energy waves	Distal-bay	Assemblages: VII
Sm	Massive, well sorted, medium-to very fine-grained sandstone. Gradational and sharp bases and tops	Continuous traction + suspension fallout deposition from turbulent currents	Coastal plain, lagoon and delta	Assemblage: I, II, VI
Fl	Fine horizontally laminated mudstones, siltstone and, very fine-grained sandstone. Sharp bases and tops	Suspension fallout, in times alternating with traction + suspension fall out from turbulent currents	Coastal plain, braidplain, prodelta and ephemeral fluvial setting	Assemblages: I, III, IV, V, VIII
Fr	Fine horizontally laminated to massive rooted mudstone and siltstone. Sharp bases and tops	Soil development on alluvial and coastal-plain deposits	Coastal plain and braidplain	Assemblages: I, VIII
Pc	Fine laminated chloritic mudstones and siltstones. Sharp bases and tops	Suspension fallout	Lagoon	Assemblage: II
Pm	Massive and fine laminated marine mudstone. Sharp bases and tops	Suspension fallout	Distal-bay	Assemblages: VI, VII
C	Coal and carbonaceous mudstone. Sharp bases and tops	Organic material accumulation forming in setting with very low clastic sediment input	Peat	Assemblages: I, IV

deposits reflect that the channels shifted at high rates, precluding preservation of floodplain deposits.

3.4. Assemblage IV: interbedded coarse- to fine-grained sandstone and coal lithofacies

3.4.1. Description

This lithofacies assemblage is observed only in Quebrada La Delfina. It consists of coarse- to medium-grained sandstone (Sp, St, Sl) forming sharp-based, normally graded packages of variable thickness (0.3–2.5 m). Conglomerate lags lie on surfaces, scouring into relatively thick coal lithofacies (1.5 m), and siltstone lithofacies bearing large amounts of plant fragments (Fig. 7A and B). The coal lithofacies differs from that of Assemblage I in the absence of associated thick packages of heterolithic fine-grained lithofacies. No rhizoliths or evidence of paleosols were detected. The coals occur as sharp-based packages on top of sandstone, with irregular tops on which coarse-grained sandstone lithofacies lie. The total thickness of this assemblage is 15 m.

3.4.2. Interpretation

Sandstone lithofacies in Assemblage IV may have formed in a similar setting to those of Assemblage II. However, the presence of thick coal lithofacies and floodplain deposits suggests an increase in accommodation for peat development, and a decrease in sediment supply. Assemblage IV is interpreted as a braidplain associated to coal peats and water bodies (Assemblage V).

3.5. Assemblage V: interbedded medium- to fine-grained sandstone and mudstone lithofacies

3.5.1. Description

This assemblage occurs above Assemblage III and is also only present in Quebrada La Delfina. It consists of laminated mudstone containing small plant fragments along their bedding planes, and slightly erosionally based, tabular fine-grained sandstone packages (Sl, Sr) and amalgamated bodies of medium- to fine-grained sandstone (Sl, Sr, Sp, St) that contain numerous reactivation surfaces (Fig. 7C and D). The mudstone lithofacies ranges from 1 m to 5 m thick, the tabular sandstone units are up to 1.5 m, while the amalgamated packages are up to 8 m thick.

3.5.2. Interpretation

Laminated mudstone was deposited as fine-grained particles fell from suspension in a prodelta environment. Tabular sandstone

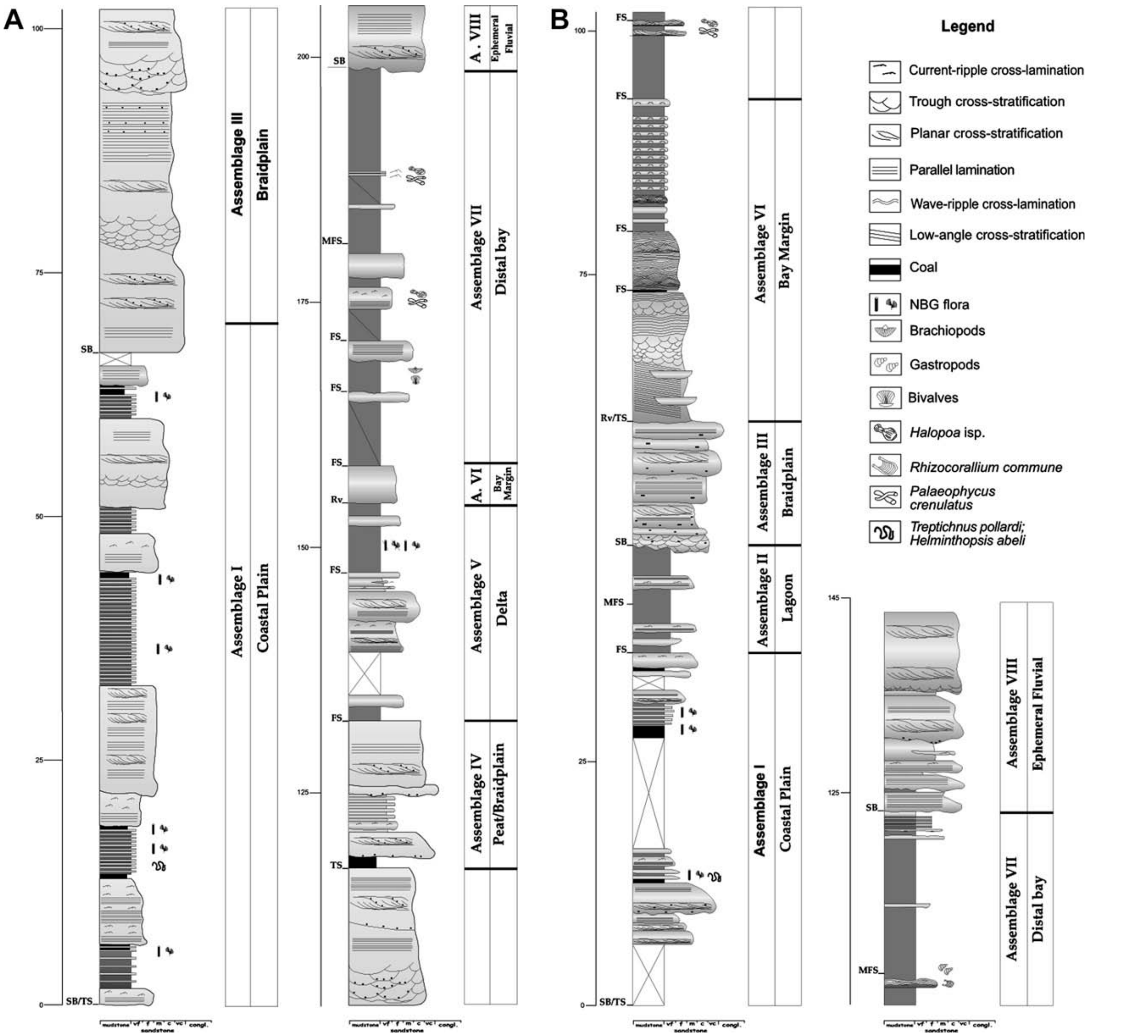

Fig. 3. Distribution of lithofacies, lithofacies assemblages and sedimentary environments within the studied stratigraphic sections. (A) Quebrada La Delfina; (B) Mina La Cienaga.

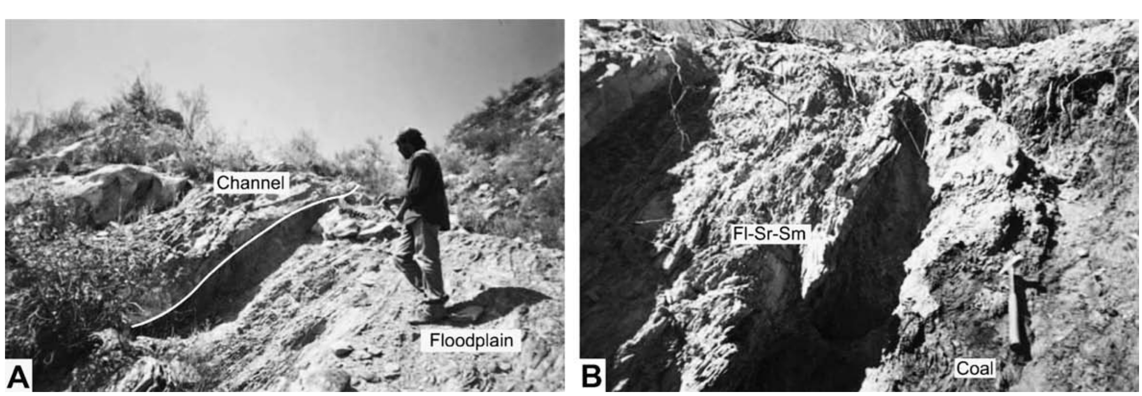

Fig. 4. Assemblage I: Coastal-plain deposits. (A) Contact between two successive fining-upward cycles (Quebrada La Delfina). (B) Coal and heterolithic deposits (Fl, Sr and Sm lithofacies) (Mina La Ciénaga). Rock hammer = 35 cm.

packages within the prodelta are interpreted as high-density currents that originated during flooding stages of associated river systems. The amalgamated sandstone bodies represent the progradation of a delta front.

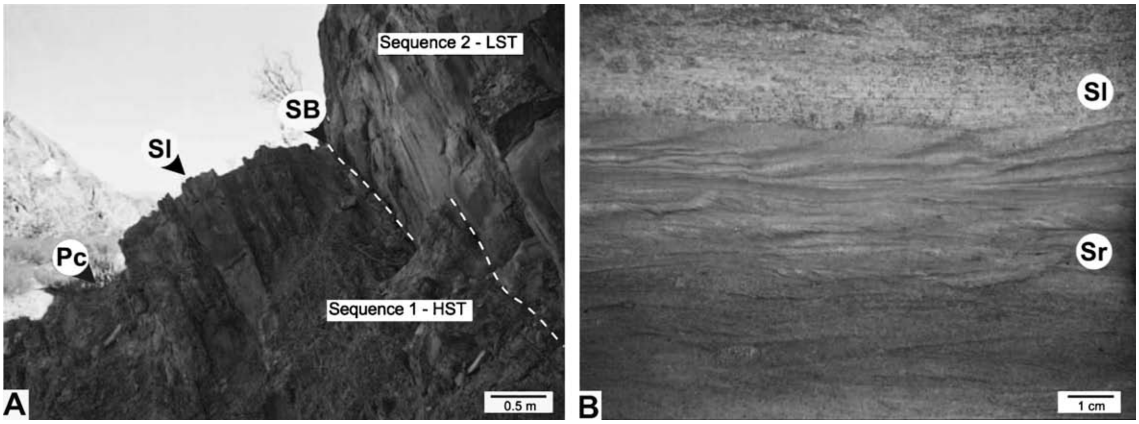

Fig. 5. Assemblage II: Lagoon deposits. (A) Relatively tabular sandstone (Sl lithofacies) layer interbedded with chloritic mudstone (Pc lithofacies). The sequence boundary (SB) is placed at the base of the Assemblage III interval. (B) Internal view of sandstone deposits (Sr and Sl lithofacies). Notice fluctuation in grain size and sedimentary structures. These lithofacies are interpreted as deposited from a quasi-steady turbidity flow.

3.6. Assemblage VI: medium- to very fine-grained sandstone and heterolithic lithofacies

3.6.1. Description

The lithofacies comprising this assemblage are observed in both localities, albeit with some differences. In Mina La Ciénaga, planar to low-angle cross-stratified, medium- to fine-grained sandstone lithofacies (Sh) unconformably overlies the coarse-grained lithofacies of Assemblage II (Fig. 8). This lithofacies is interbedded with erosionally based lenses of coarse-grained sandstone which are 0.1–1 m thick. Overlying this lithofacies, low-angle cross-stratified, wave-ripple cross-laminated and current-ripple cross-laminated fine-grained sandstone lithofacies occur (Sh, Swr, St) for more than 18 m of section (Fig. 8B). The sedimentary succession continues in this locality with 11.5 m of heterolithic lithofacies, consisting of current-ripple cross-laminated, wave-ripple cross-laminated and massive, very fine- to fine-grained sandstone, and horizontally laminated mudstone. A thin layer of carbonaceous shale is observed at the top of this assemblage at this particular locality. In Quebrada La Delfina, this assemblage comprises only massive, fine-grained sandstone (Sm) (Fig. 3).

3.6.2. Interpretation

The Sh lithofacies scoured by lenses of coarse-grained sandstone is interpreted as formed within a high-energy bay margin. The coarse-grained sandstone represents ephemeral flows within small channels cutting through a beach. On top of these deposits, low-angle cross-stratified, wave-ripple cross-laminated and current-ripple cross-laminated, fine-grained sandstone (Sh, Swr, Sr) are interpreted as the product of longshore currents and wave action. The absence of mud indicates that these lithofacies were deposited in a relatively high-energy environment above the fair-weather wave base. The heterolithic lithofacies observed in Mina La Ciénaga represent a more distal position within a bay margin because the mudstone layers suggest periods of low energy. A similar process was interpreted for these lithofacies by Pazos (1994). In Quebrada La Delfina, the massive sandstone packages also represent a bay-margin environment.

3.7. Assemblage VII: interbedded mudstone and fine-grained bioturbated sandstone lithofacies

3.7.1. Description

Assemblage VII occurs in both localities and its environmental significance is of paramount importance in our study. It consists of thick packages (0.5–11 m) of massive mudstone (Pm) in which erosionally based, relatively thin tabular bodies (0.3–0.8 m) of fine- to very fine-grained sandstone occur (Srd) (Fig. 9). These sandstone packages display normal graded bedding and internally show horizontal lamination which grades upwards into wave-ripple cross-lamination. A fragmentary and scarce marine fauna of the *Tivertonia jachalensis-Streptorhynchus inaequiornatus* Biozone occurs within mudstone deposits in Quebrada La Delfina, including brachiopods, bivalves, gastropods, and a few crinoids. In Mina La Ciénaga, the only body fossil fauna occurs as coquina composed of large gastropods. Trace fossils occur in the sandstone packages in both localities, including the ichnogenera *Rhizocorallium, Palaeophycus, Planolites*, and *Halopoa.*

3.7.2. Interpretation

This assemblage records sedimentation within a distal-bay environment. The mudstone records mud settling from suspension below the fair-weather wave base, while the tabular, lateral continuous sandstone packages are interpreted as tempestites. During exceptional storms, sand was removed from nearshore areas and transported seaward as a turbidity flow, to be deposited as normally-graded, tabular packages of sandstone (Walker and Plint, 1992).

3.8. Assemblage VIII: interbedded pebbly and coarse-grained sandstone and siltstone lithofacies

3.8.1. Description

This lithofacies assemblage unconformably overlies Assemblage VII. It consists of thickly interbedded pebbly conglomerate (Gt, Gp), very coarse- to fine-grained sandstone (Sp, St, Sl, Sm), and siltstone lithofacies (Fl, Fr). The conglomerate, and sandstone lithofacies occur in erosionally based, laterally continuous multi-storey, and ribbon-like bodies that vary in thickness from 0.5 m to 16 m (Fig. 10A). The packages internally display a variety of sedimentary structures, and multiple reactivation and lateral-accretion surfaces. An impressive feature of these bodies is the abundance of large (up to 1 m) clay-chips distributed through the unit (Fig. 10B). The siltstone lithofacies are essentially massive, although horizontal lamination occurs in some beds. Rhizoconcretions are locally observed.

3.8.2. Interpretation

This assemblage is considered to have been deposited in an ephemeral fluvial system under a semi-arid climate (Net et al., 2002). The sandstone units are interpreted as channel fills, which include different lithofacies (Sp, St, Sl, Sr). The numerous reactiva-

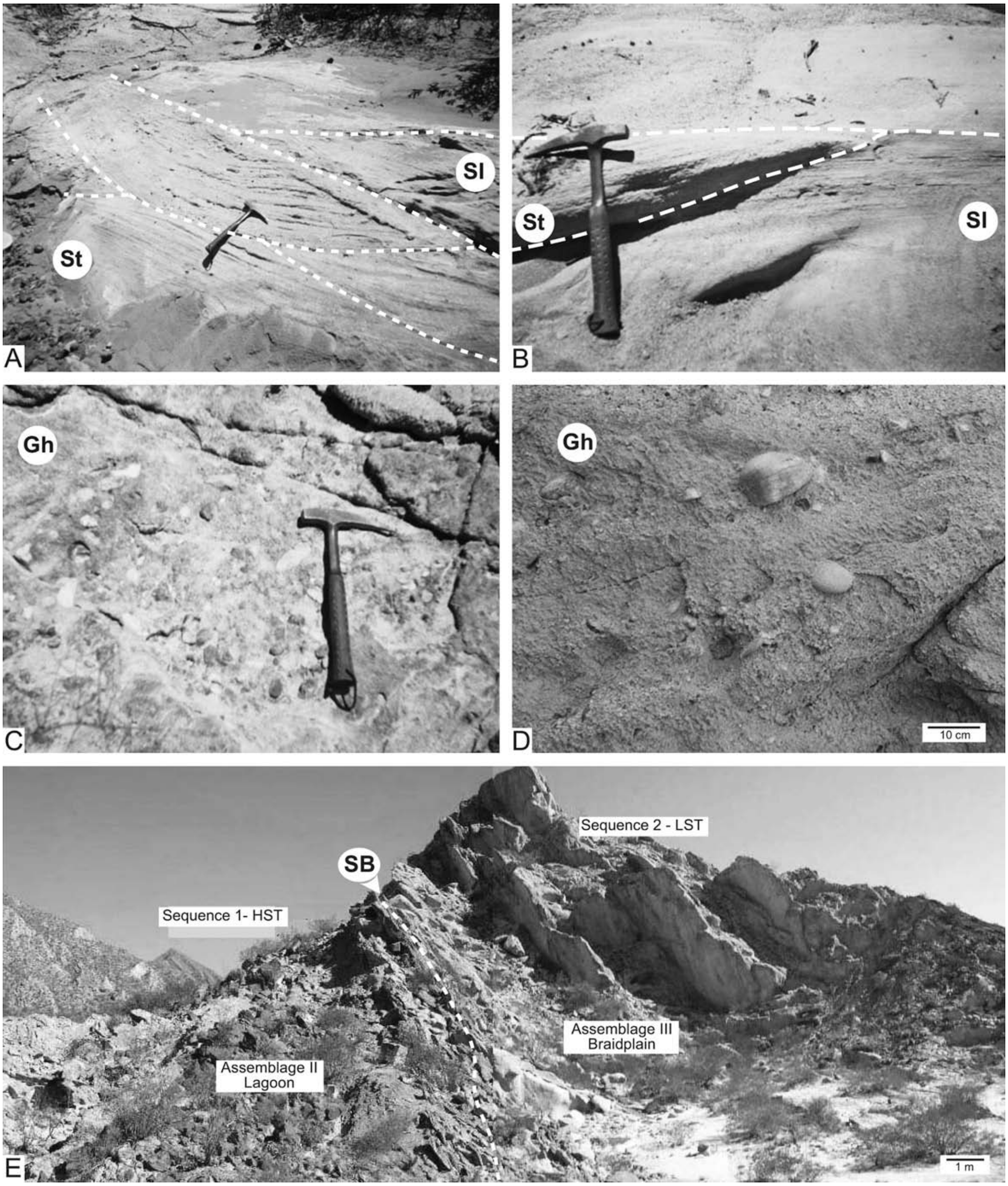

Fig. 6. Assemblage III: Braidplain deposits. (A) Arrangement of sandstone deposits within a channel (St and Sl lithofacies). Rock hammer = 35 cm (Quebrada La Delfina). (B) Reactivation surfaces in sandstone (St and Sl lithofacies) (Quebrada La Delfina). (C) Conglomerate lag at the base of a channel deposit (Gh lithofacies) (Mina La Ciénaga). (D) Matrix-supported conglomerate (Gh lithofacies) (Mina La Ciénaga). (E) Panoramic view of lenticular sandstone bodies of Assemblage III above a sequence boundary (SB).

tion and lateral-accretion surfaces reflect the autocyclic dynamic of this fluvial system (Miall, 1996). During flooding stages of the fluvial system, large amounts of material were eroded from the floodplains and incorporated to the flow as mud chips.

4. Stratigraphic response to marine transgressions

Marine transgressions can be identified in the stratigraphic record from the recognition of a systematic or irregular movement of the shoreline towards the land, reflected by an overall retrogradational stacking pattern (Cattaneo and Steel, 2003). The shoreline trajectory concept was introduced by Helland-Hansen and Gjelberg (1994) to illustrate the shoreline path along the depositional dip. The shoreline trajectory is controlled by fluctuations in relative sea level and sediment supply.

Three general types of transgressive shoreline trajectories (Fig. 11) are considered: non-accretionary, accretionary, and punctuated (Helland-Hansen and Gjelberg, 1994; Cattaneo and Steel, 2003). However, a shoreline trajectory may show different paths at different areas of a transgressed sedimentary environment, or basin. Local paleogeography and the inherited physiography of a basin (see Cattaneo and Steel, 2003) play a major role in determining which areas will tend to prograde, retrogradate or agradate. This interaction of an existent topography with transgressive sedimentary processes is reflected in variable thicknesses of along-strike correlative deposits.

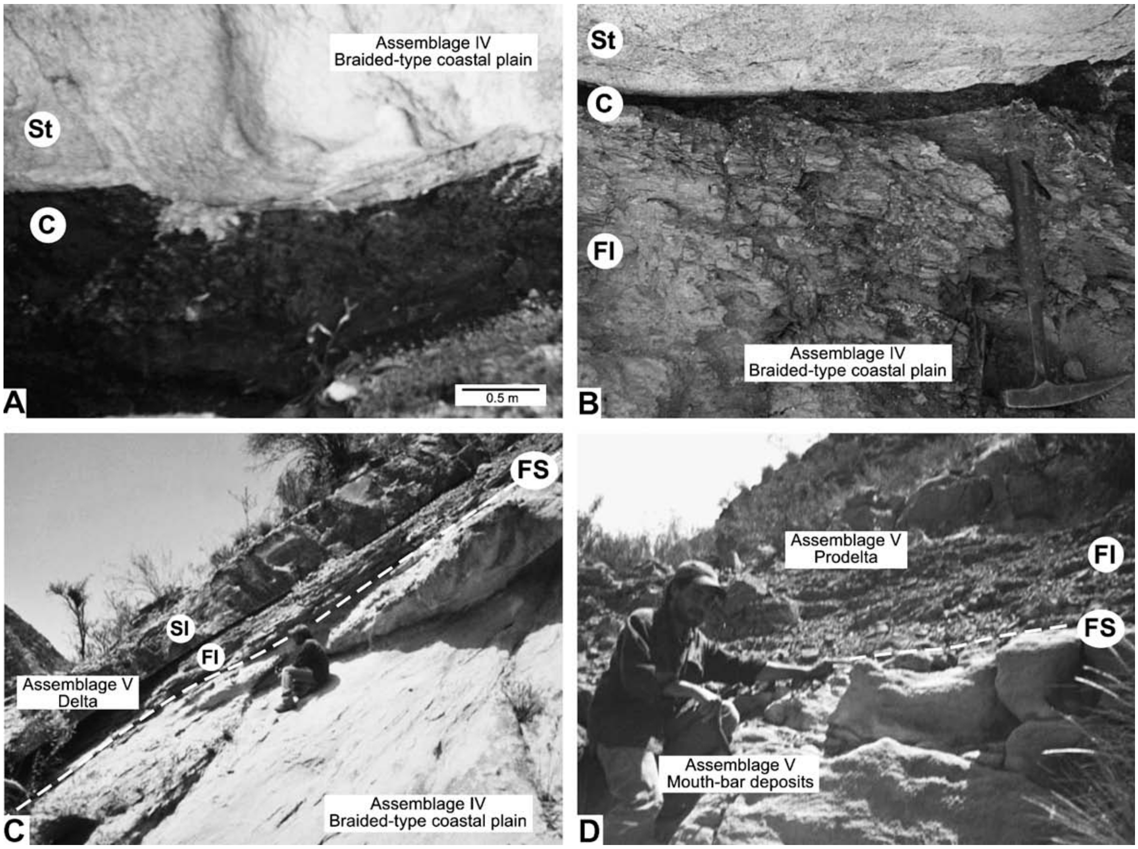

Fig. 7. Assemblage IV–V: Braidplain and deltaic deposits. (A) Base of Assemblage V. (B) Channel (St), floodplain (Fl) and peat (C) deposits. Rock hammer = 35 cm. (C) Flooding Surface (FS) separating braidplain from prodelta deposits (Fl). The tabular sandstone body (Sl) is interpreted as a density-flow deposit in a prodelta environment (Quebrada La Delfina). (D) Delta-front and prodelta deposits. (Quebrada La Delfina).

Bohacs and Suter (1997) analyzed the sequence stratigraphy of paralic settings, and the distribution and thickness of coal lithofacies within these environments. These authors pointed out the importance of the position, rate, and direction of change of the water-table during different segments of the relative sea-level curve. The position of the water-table determines the rate of production and accumulation of peats. If the water-table drops or is low (below a theoretical threshold), no continuous peat accumulates. Rising ground waters provide a suitable scenario for the formation of laterally continuous coals. Only if accommodation increases and balances or slightly exceeds organic productivity, peat expands vertically, allowing the formation of coal deposits. However, if the water-table is much above the surface, the mires became stressed and are eventually inundated. In this scenario, lacustrine deposits tend to replace coal deposits.

5. Sequence stratigraphy of the latest Carboniferous–earliest Permian transgression

The contact between the Guandacol and Tupe formations corresponds to a surface of sequence-boundary hierarchy. The sequence boundary can be easily traced throughout this area of the basin. In Mina La Ciénaga, coastal-plain deposits of the Tupe Formation erosionally overlie delta mouth-bar deposits of the Guandacol Formation, while in Quebrada La Delfina the coastal-plain developed on top of distal front-delta lobes. Two complete sequences are detected (Fig. 12).

5.1. Sequence 1

5.1.1. Lowstand systems tract

The lowermost deposits of the Tupe Formation (Assemblage I) record the evolution of a coastal plain characterized by meandering channels and extended floodplains deposits. Sheet-like, fining-upward sandstone packages, commonly displaying lateral-accretion surfaces (Assemblage I), record the channel lateral migration. Interbedded sandstone, siltstone, mudstone, and coal lithofacies were formed in floodplains, peat, and associated water bodies. A freshwater ichnofauna, including *Helminthopsis abeli*, *Treptichnus pollardi*, and undetermined grazing trails occur towards the top of this systems tract.

5.1.2. Transgressive systems tract

Towards the top of the deposits included within Lithofacies Assemblage I, an increase in coal thickness from 1–4 cm to 1 m is observed. The thicker coal bed at the top indicates an increase in accommodation for peat production and accumulation. The thickness and areal distribution of the coal lithofacies in a paralic setting is a function of the position, rate, and direction of change of the water-table (Bohacs and Suter, 1997). In these settings, sea-level fluctuations can have a great effect on the water-table position. During a transgression, the water-table tends to rise in order to accommodate to its new equilibrium profile, increasing the accommodation space available for the production and accumulation of peat. In Mina La Ciénaga, coastal-lagoon deposits cap a coastal-plain interval. The transgressive surface is located at the

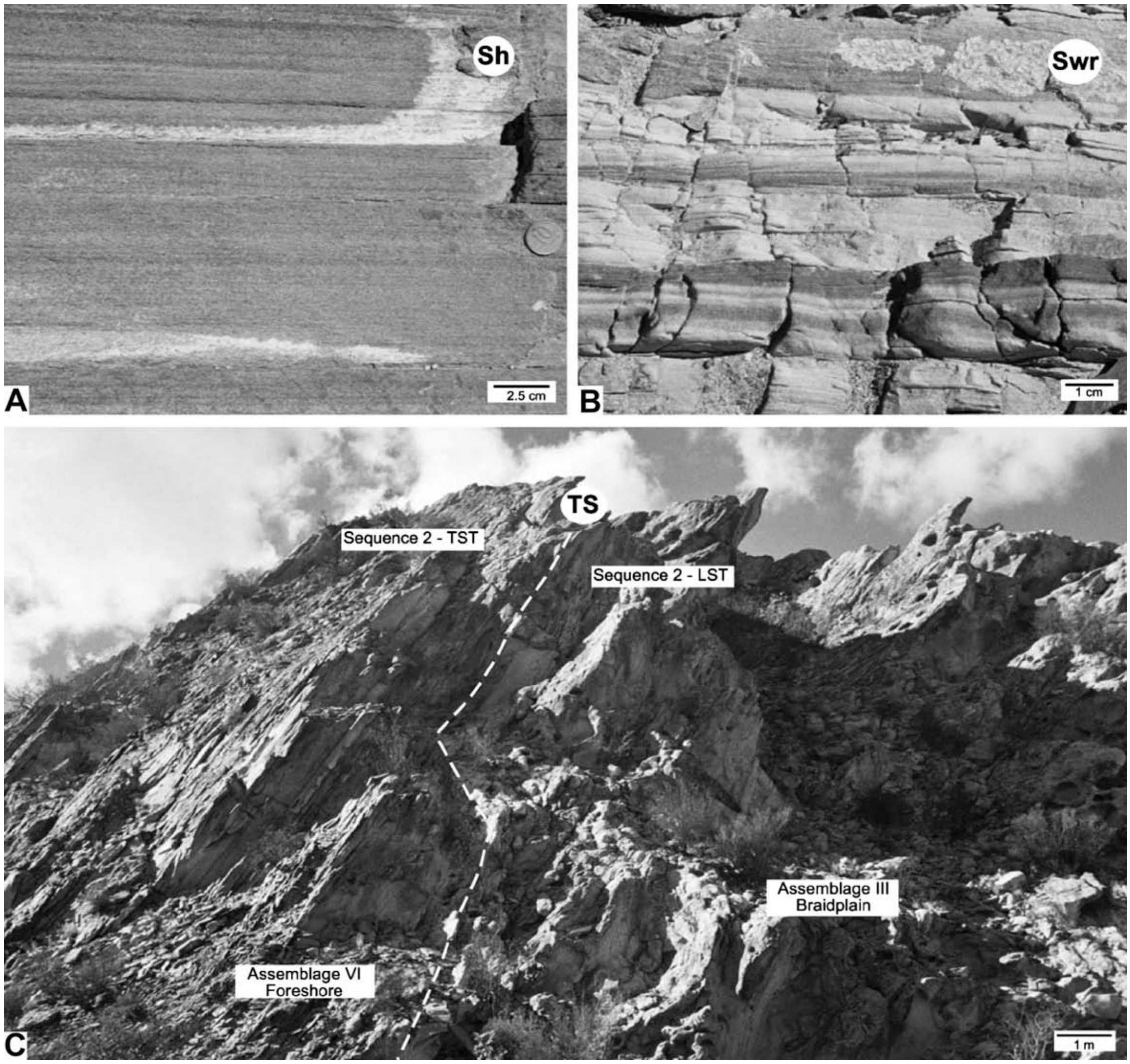

Fig. 8. Assemblage VI: Bay-margin deposits. (A) High-energy deposits (Sl lithofacies) (Mina La Ciénaga). (B) Low-angle and wave-ripple cross-laminated sandstone lithofacies (Swr) (Mina La Ciénaga). (C) Transgressive surface (TS) between lowstand systems tract and transgressive systems tract deposits of sequence 2 (Mina La Ciénaga).

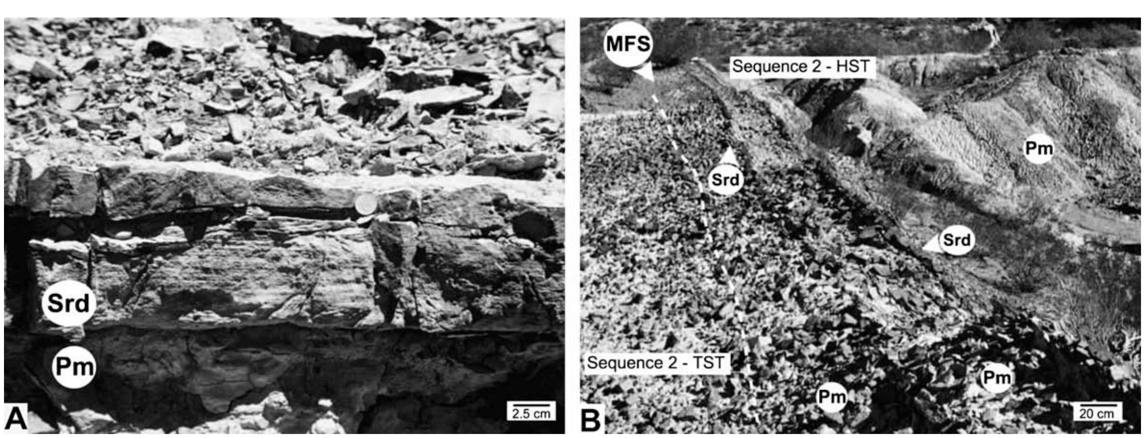

Fig. 9. Assemblage VII: Distal-bay deposits. (A) Close-up of the distal-bay sandstone (Srd lithofacies). (B) Interbedded mudstone (Pm lithofacies) and fine-grained sandstone (Srd lithofacies). The maximum flooding surface (MFS) separates the transgressive systems tract from the highstand systems tract in sequence B.

base of the first thick coal bed included in Assemblage I. The establishment of water bodies towards the top of this systems tract (Assemblage II) indicates that the relative sea-level rise exceeded the sediment influx, and peat production ceased. The maximum flooding surface is located within the coastal-lagoon lithofacies of Mina La Ciénaga. This systems tract highlights the proximity of the envisaged environments to the sea.

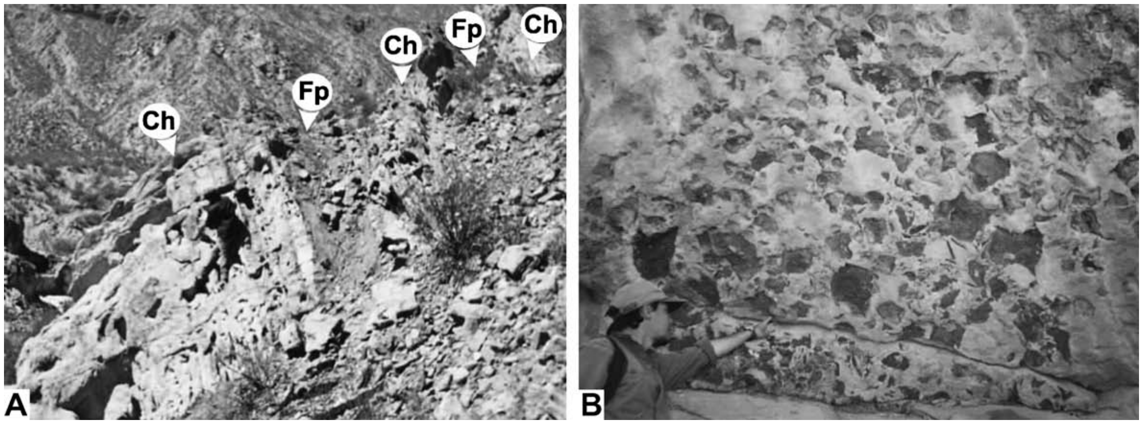

Fig. 10. Assemblage VIII: Fluvial deposits. (A) Different hierarchies of channel deposits (Ch) can be appreciated from in this picture. Fine-grained intervals (Fl and Fr lithofacies) represent floodplain deposits (Fp). (B) Clay-chips within channel deposits.

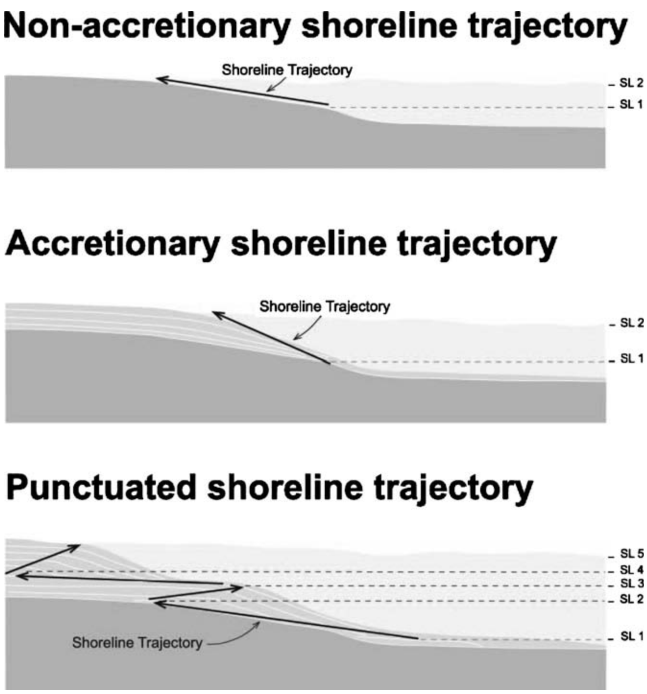

Fig. 11. Types of shoreline trajectories. (A) Non-accretionary: the shoreline trajectory coincides exactly with, or is at a lower angle than, the older surface being transgressed. (B) Accretionary: the shoreline trajectories diverge upwards from the transgressed topography. Sediments accumulate if the sediment influx from behind the shoreface is high. (C) Punctuated type: The shoreline trajectory has a complex zigzag pattern due to the occurrence of regressive intervals within the overall transgression. SL = sea level. Modified from Cattaneo and Steel (2003).

5.1.3. Highstand systems tract

This systems tract is represented by the progradation of a small delta system into a coastal-lagoon that was eventually filled. The progradation comprises thickening-upward tabular packages of sandstone deposited from river-fed quasi-steady turbidity currents. This systems tract is bounded at the top by a sequence boundary of regional extension. This surface shows some degree of incision over the area of study (Fig. 2) and mostly separates coastal-plain deposits (Assemblage I) from alluvial braided-type deposits (Assemblage III).

5.2. Sequence 2

5.2.1. Lowstand systems tract

The lowstand systems tract consists of coarse-grained lithofacies that were deposited in shifting multi-storey channels and bars within a braided-type alluvial plain (Assemblage III). This lithofacies assemblage is highly variable in thickness across the study area and is better represented in areas close to Quebrada La Delfina. No evidence of marine influence was detected.

Commonly lowstand deposits tend to be relatively thin if the by-pass of sediments is the dominant process taking place. This may be the case in Mina La Ciénaga, where this particular systems tract is represented only by 13 m of section. However, in Quebrada La Delfina lowstand deposits are up to 50 m thick. This suggests an irregular physiography within the basin, inherited not only from lowstand erosion, but from the older glacial paleogeography that existed during Guandacol times.

Towards the top of this systems tract in Quebrada La Delfina, a 1 m-thick coal bed and a decrease in sediment grain size (Assemblage IV) suggest a decrease in sediment supply and an increase in accommodation and water-table level. Overlying these deposits, a flooding surface is detected at the base of the deltaic lithofacies (Assemblage V). A transgressive surface is located at the base of the coal bed, from which a shift in the depositional setting is detected. In Mina La Ciénaga, the transgressive surface is located at the base of the bay-margin deposits (Assemblage VI) (Fig. 3).

5.2.2. Transgressive systems tract

The transgressive surface at the base of this systems tract has a different along-strike expression in the studied areas. In Quebrada La Delfina, floodplain deposits associated to peats and deltaic deposits (Assemblage IV, V) compose the lower part of this systems tract (Fig. 7C and D). Contrastingly, in Mina La Ciénaga bay-margin deposits overlie the transgressive surface.

Within the marine-embayment lithofacies assemblages, seven parasequences were identified. The first parasequence (P1) comprises bay-margin deposits that are capped by a thin layer of carbonaceous shale (Fig. 3). The associated lithofacies within this parasequence suggests the existence of an irregular shoreline. Parasequence 2 comprises bay-margin rippled-laminated and massive sandstone (Swr, Sr, Sm, Sh), and its upper boundary separates the bay-margin deposits from the distal-bay deposits. The succeeding five parasequences record deposition in distal areas of the Tupe marine embayment. A maximum flooding surface is located at a mudstone horizon within parasequence four (P4), containing fragmentary and scarce marine fauna of the *Tivertonia jachalensis-Streptorhynchus inaequiornatus* Biozone.

5.2.3. Highstand systems tract

Above the maximum flooding surface, shallowing-upward distal-bay deposits occur. Four parasequences were identified. Each

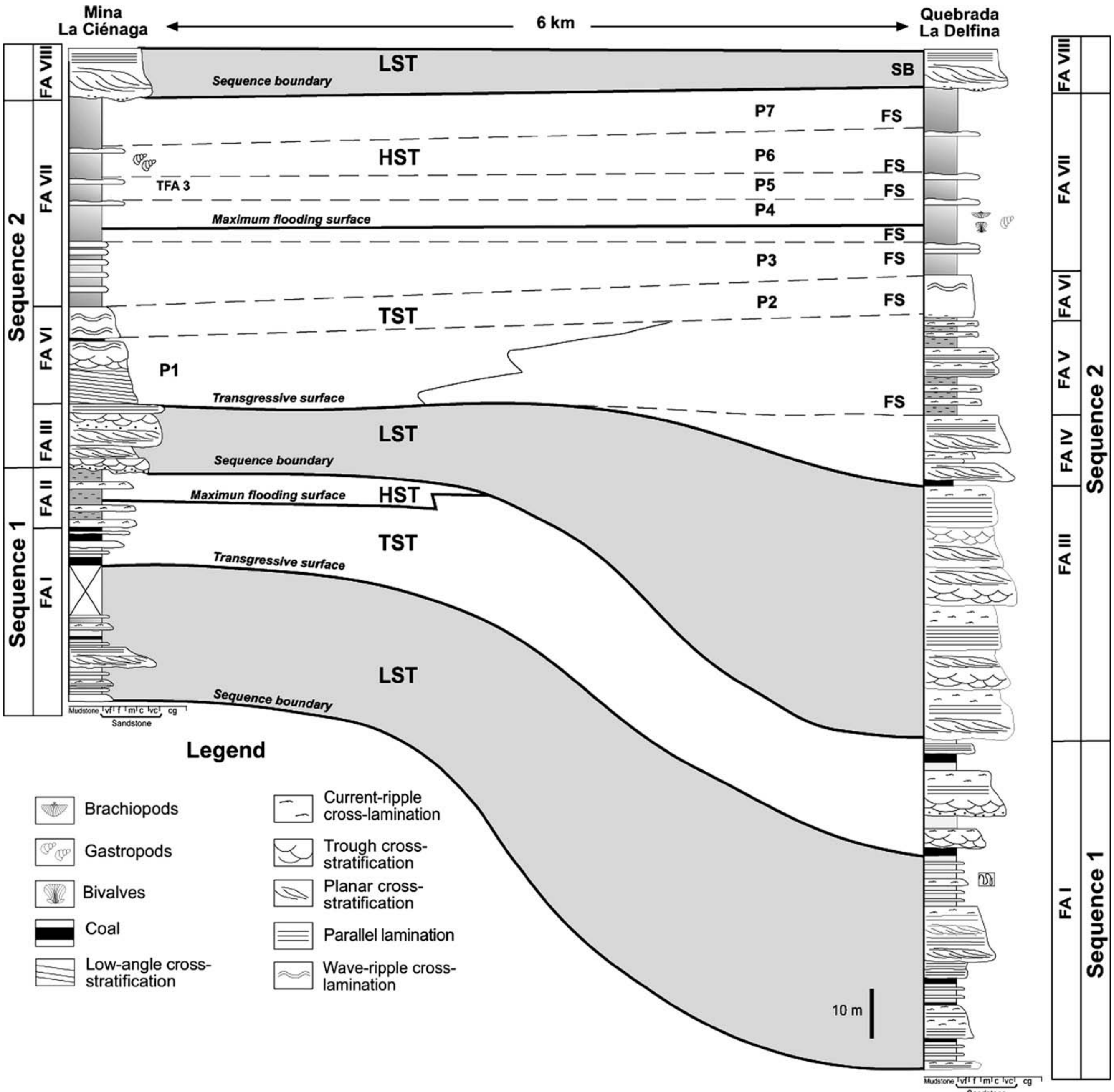

Fig. 12. Correlation between the studied sections and position of the sequence-stratigraphic surfaces, parasequences (P) and systems tracts. LST = lowstand systems tract. TST = transgressive systems tract. HST = highstand systems tract. The panel is oriented roughly parallel to the coastline.

parasequence starts with mudstone which is interbedded towards the top of the parasequence with relatively thin, tabular sand packages. The eroded sand from the shoreface was transported and deposited further into the bay by wave-influenced turbidity currents. Within this lithofacies (Srd), the ichnogenera *Palaeophycus*, *Halopoa*, *Planolites*, and *Rhizocorallium* are present.

Towards the top of this systems tract, deposits show a high degree of alteration, as indicated by their various colors. A discontinuous level with hematite nodules, phosphates, and traces of Cu and Mn oxides occurs in a sand-supported breccia formed by mud intraclasts (Pazos, 1994). The presence of clay fragments within these oxides reveals that they have been transported. A sequence boundary is located at the top of the distal-bay deposits (Fig. 3), revealing a sea-level drop and the passage to continental environments in a semiarid climate (Assemblage VIII).

6. Concluding remarks

The transgressive nature of the lowermost part of the Tupe Formation is evident from its overall retrogradational stacking pattern (Fig. 12). This succession records a transgressive period over the western margin of the Paganzo Basin during the latest Carboniferous–earliest Permian interval. Contemporaneous deposits from other basins of Gondwana share this transgressive nature, although in some cases with evidence of direct connection to ice masses (e.g. Paraná Basin). The final deglaciation phase in Gondwana over regions of South America (Paraná, Sauce Grande, and Malvinas basins), Antarctica, South Africa, India, and the western basins of Australia

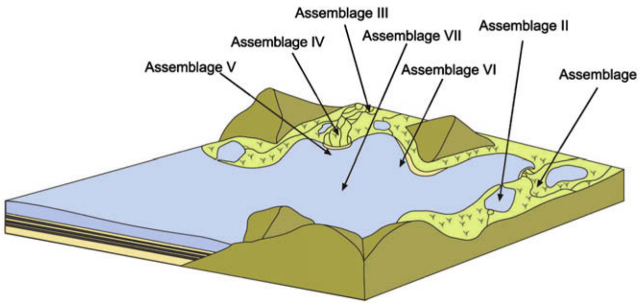

Fig. 13. Depositional model illustrating the environmental distribution of the lithofacies assemblages of the Tupe Formation during the Stephanian–Early Permian transgression. Assemblage VIII is not included in this figure as it corresponds to the subsequent lowstand system tract.

triggered transgressions that had an impact on coastal settings at higher latitudes. The Tupe Formation marine transgression records the flooding of a pericratonic basin by a distant, but rising postglacial sea (Fig. 13).

The Tupe transgression is characterized by an overall patchy distribution of its deposits and changes in thickness between adjacent localities. The inherited physiography from Guandacol glacial times and the paleogeographic characteristics of the Paganzo Basin played a major role in controlling the shape and trajectory of the shoreline and the location of depocenters. The thick lowstand deposits of sequence 2 are interpreted as the fill of an inherited previous topography. Also, remnants of the Protoprecordillera on the west margin (Fig. 13) of the basin could have acted as barriers, leading to the development of bays rather than an open sea. The scarcity of storm-related deposits and high-energy indicators within the bay-margin deposits also supports this environmental scenario. Although a marine invertebrate fauna was found at one level within the deposits of Quebrada La Delfina, trace-fossil evidence suggests a stressed environment. The ichnofauna is of much lower diversity than those that characterize fully marine environments. The marine fauna records maximum transgression.

The presence of two sequences with a retrogradational stacking pattern supports a punctuated shoreline trajectory, as evidence of proximity to the sea is detected within sequence 1 coastal-plain deposits. An increase in sediment supply is most likely to be responsible for the shift from a coastal plain with meandering channels (Sequence 1) to a braided plain of multi-storey channels (Sequence 2 – LST). Detailed study of the coastal-plain deposits from sequence 1 led us to locate the initial transgressive surface in a non-marine scenario.

The transgressive surfaces in both sequences are located at the first occurrence of thick coal beds within these nearshore environments. A rising water-table allowed the formation and preservation of coal lithofacies. The presence of lacustrine and lagoon deposits just above the coal lithofacies (Fig. 12) supports a rapidly advancing shoreline during rising sea level. This transgression illustrates the transition from a coastal-plain to a bay environment with development of peats, coastal lakes, and lagoons during transgressive systems tracts as a response to a retreating shoreline during relative sea level rise in a pericratonic setting without tidal signatures.

Acknowledgments

Financial support for this study was provided by the Argentinean Agency of Scientific Research, Natural Sciences and Engineering Research Council (NSERC) Discovery Grants and University of Saskatchewan Start-up funds awarded to Buatois. A special thanks to Ramiro Salvatierra for field work assistance. Comments by Juan Ponce, Oscar López Gamundí, Brian Pratt and an anonymous reviewer are greatly appreciated.

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