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# The Upper Carboniferous postglacial transgression in the Paganzo and Río Blanco basins (northwestern Argentina): facies and stratigraphic significance

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**Abstract**

During the early Late Carboniferous (Namurian–early Westphalian), an important postglacial transgression took place in the basins of western Argentina. The regional distribution, lithological characteristics, facies arrangement, and age of the transgression are analyzed herein. The postglacial transgressive event was studied in the Río Blanco and Paganzo basins. Seven regionally extensive facies were recognized. Laminated mudstones were deposited during the maximum flooding stage, including some thin marls and black limestone beds interpreted as condensed levels. Laminated mudstones with dropstones facies, due to iceberg melting, point out to deglaciation processes. Bouldery and pebbly diamictites mainly represent gravity flow deposits, which, in some cases, are associated with interbedded sandstones and mudstones sequences interpreted as turbidites. Sandstones with large-scale cross-bedding represent high constructive Gilbert-type deltas. Finally, coarsening and thickening upward sequences result from the progradation of mouth bars deposited in delta-front environments. On the basis of the facies arrangement, three major postglacial facies associations were recognized: open marine, transitional, and continental-dominated. Palynological assemblages suggest a Namurian to early Westphalian age for the postglacial transgression. © 2002 Published by Elsevier Science Ltd.

*Keywords:* Carboniferous; postglacial marine deposits; Namurian

## 1. Introduction

During the Late Paleozoic, the Gondwana supercontinent was affected by a paleoclimatic episode known as 'Gondwanic glaciation.' Glacial deposits related to this event have been reported from Bolivia on the west margin (Helwig, 1972; Díaz Martínez et al., 1993) to Australia on the eastern side of Gondwana (Veevers et al., 1994), including Argentina (González, 1982; López Gamundí, 1987; González Bonorino, 1992; López Gamundí and Espejo, 1993), Brazil (Rocha Campos, 1967, 1981), Uruguay (Ferrando and Andreis, 1990), South Africa (Visser and Hall, 1985), Antarctica (Collinson et al., 1994; Isbell et al., 1997), and India (Laskar and Mitra, 1976; Suttner and Dutta, 1986). This paleoclimatic episode was not synchronous in Gondwana; the age depends on the paleolatitudinal position of the region (Powell and Li, 1994; López Gamundí et al., 1994; González Bonorino and Eyles, 1995; López Gamundí, 1997). Consequently, the oldest records in western Gondwana probably correspond to the Lower Carboniferous in Bolivia and Argentina (Díaz Martínez et al., 1993; Eyles et al., 1995; González Bonorino and Eyles, 1995), whereas the youngest ones, located in South Africa, may be of Lower Permian age.

The Gondwanic glaciation includes three major events of Devonian–Early Carboniferous, early Late Carboniferous, and late Late Carboniferous–Early Permian ages (López Gamundí, 1997). Considering that one of the more prominent Gondwanic postglacial features is the presence of transgressive facies (Veevers and Powell, 1987; López Gamundí, 1989; González Bonorino and Eyles, 1995), at least three marine flooding events would be expected. If this hypothesis is correct, a study of each of the transgressive

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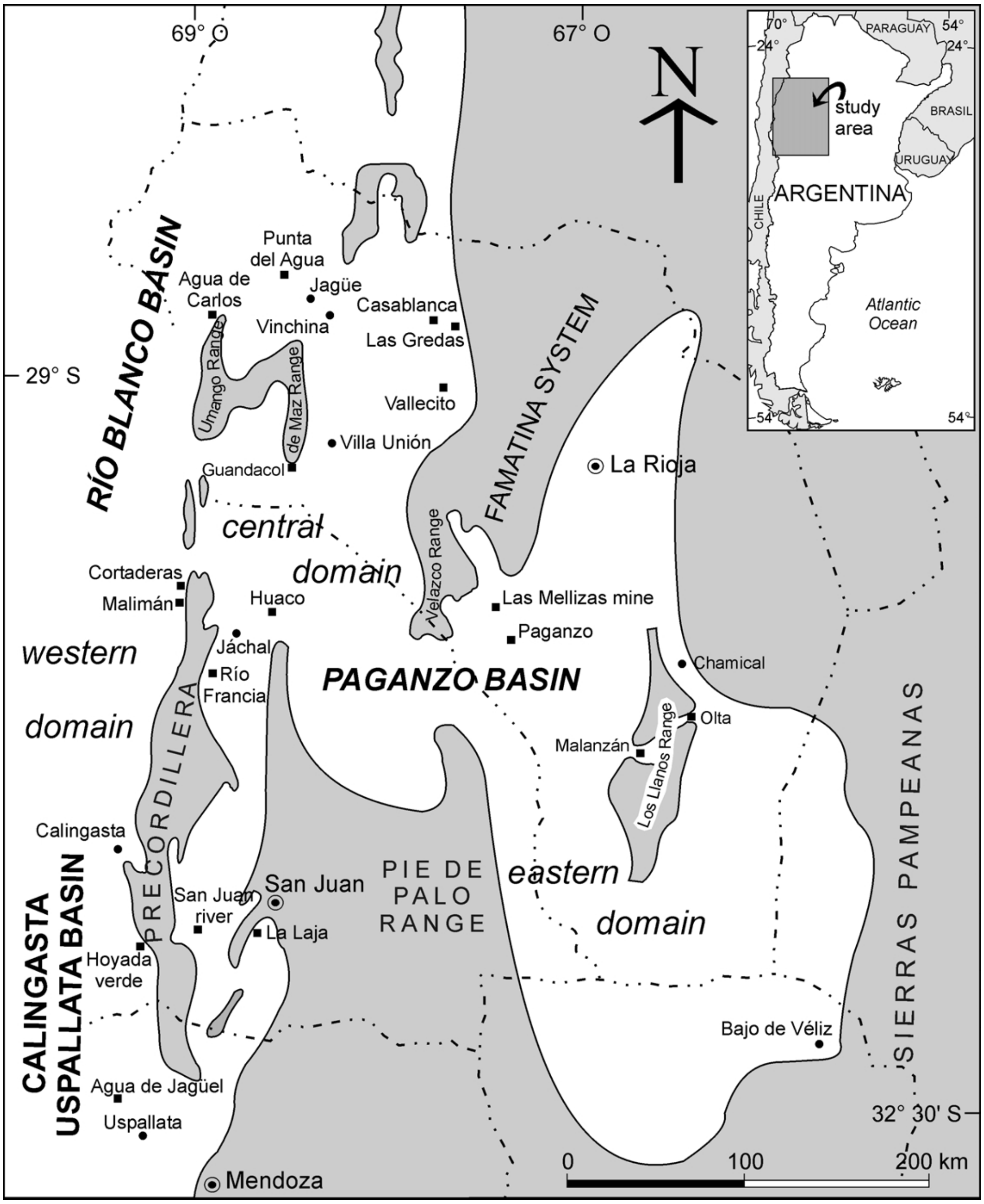


Fig. 1. Location map of the Pagazo, Río Blanco, and Calingasta-Uspallata basins in northwest Argentina showing structural elements and localities referred in the text.

episodes becomes critical for chronostratigraphic intercontinental correlation.

To shed light on this problem, we analyze the age, regional extent, and stratigraphic signature of the early Late Carboniferous (Namurian–early Westphalian) transgressive event registered in the Paganzo and Río Blanco basins of Western Argentina (Fig. 1). To the west of the studied area, this level has been interpreted as a postglacial transgression in the Calingasta-Uspallata basin (López Gamundí, 1989).

## 2. Regional setting

During the Carboniferous, the Río Blanco and Paganzo basins acted as subsiding foreland basins (González Bonorino and Eyles, 1995; González Bonorino, 1991; López Gamundí et al., 1994) bounded to the east by the Sierras Pampeanas cratonic area and to the west by an orogenic belt composed of folded Lower Paleozoic–Lower Carboniferous units (Fig. 1).

Sedimentation in the Paganzo basin (Fig. 2) started at the

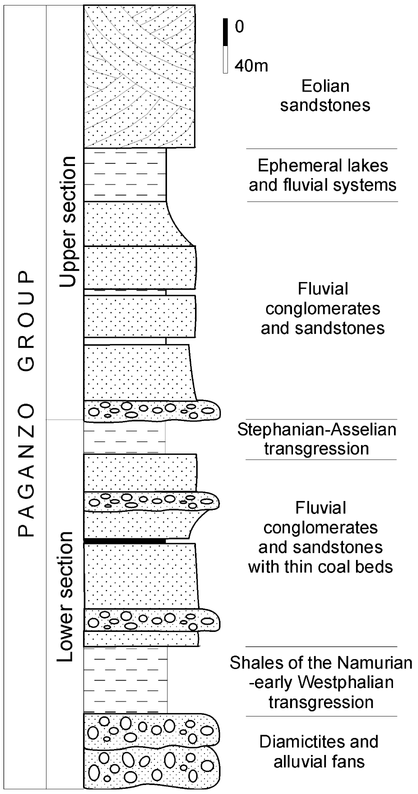


Fig. 2. Schematic profile of the Paganzo Group in the Paganzo Basin.

beginning of the Late Carboniferous (probably Namurian; Limarino and Gutierrez, 1990; Césari and Gutierrez, 2000) and lasted until probably Middle to Late Permian (Limarino and Césari, 1987). Sedimentation during the Late Carboniferous occurred mainly in continental settings, beginning with coarse-grained alluvial fan sediments (Andreis et al., 1986) and tillites covered by shales, mudstones, and varve-like sediments that originally were interpreted as 'glacio-lacustrine' facies (Limarino and Césari, 1988). More recently, the glaciolacustrine deposits yielded marine invertebrates (Martínez, 1993) and microplankton (Ottone, 1991), which suggests marine transgressions in a fjord environment (Buatois and Mángano, 1995; Kneller et al., 2000; Gutierrez and Limarino, 2001). These deposits pass to conglomerates and sandstones originating in several fluvial settings, including braided, meandering, and anastomosing rivers (Limarino, 1987; Net, 1999). Carboniferous sedimentation ended with mudstones, marls, and very fine-grained sandstones that correspond to a Late Carboniferous–Early Permian transgressive event. Near Permian times, sea levels fell, and sedimentation proceeded exclusively in arid and semiarid continental environments, including thick eolian sequences (Limarino and Spalletti, 1986; López Gamundí et al., 1992).

In the Rio Blanco basin, two tectosedimentary cycles are present (Fig. 3). The oldest corresponds to the Early Carboniferous and is represented by the Angualasto Group (Limarino and Césari, 1993). This unit is made up of marine shales, mudstones, and fine-grained sandstones intercalated

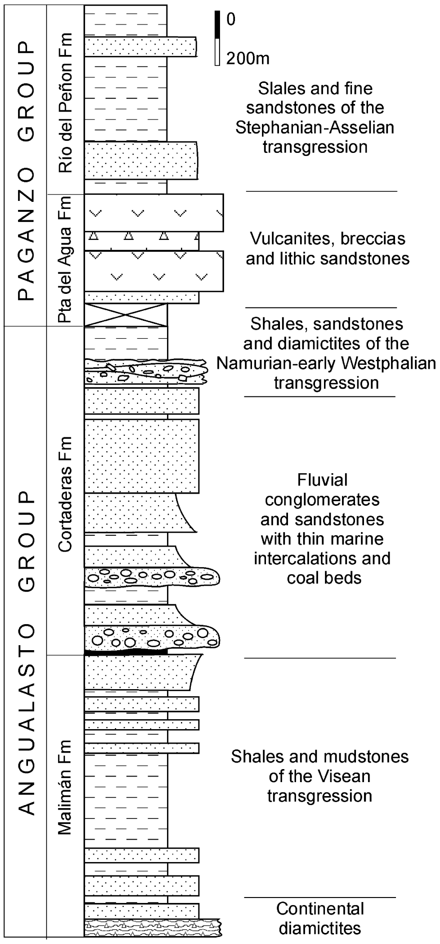


Fig. 3. Schematic profile of the Angualasto and Paganzo Groups in the Río Blanco basin.

with conglomerates and cross-bedded, coarse-grained sandstones deposited in fan deltas and fluvio-deltaic environments. To the top of the Angualasto Group, glaciomarine tillites are covered by marine transgressive shales containing dropstones and Namurian fossil remains (Limarino et al., 1993). The second tectosedimentary cycle (Fig. 3) corresponds to the Lower Carboniferous–Early Permian Punta del Agua and Río del Peñón Formations (González and Bossi, 1986), which consist of a complex interfingering of volcaniclastic, shallow marine, and fluvial deposits.

## 3. Carboniferous transgressions in northwestern Argentina

The chronology and importance of sea level changes during the Carboniferous and Permian in the western basins of Argentina have not received detailed study. Limarino and Césari (1993) provided some references to Early Carboniferous sea level changes and recognized two main transgressive events within the Angualasto Group in the Río Blanco basin (Cortaderas and Malimán creeks, Fig. 1).

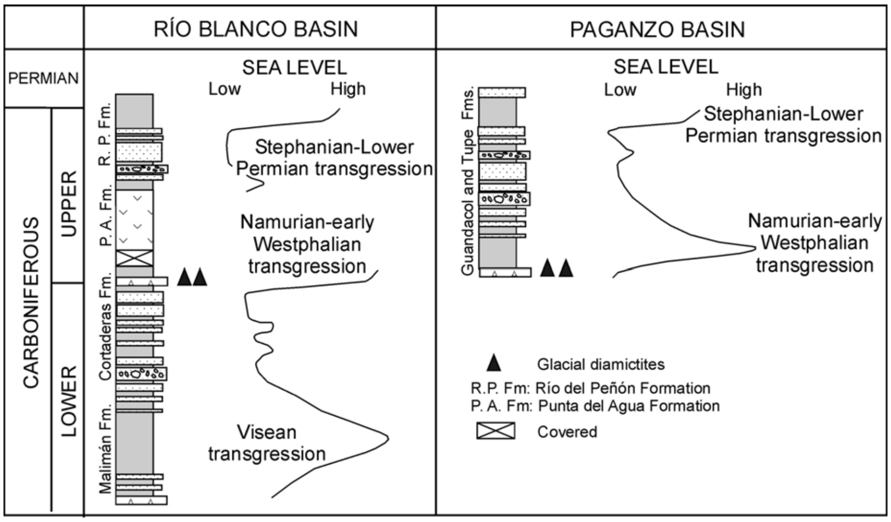


Fig. 4. Comparative chart showing sea level changes in the Río Blanco and Paganzo Basins.

The oldest, Visean in age, corresponds approximately to the middle section of the Malimán Formation (C and D levels of Limarino and Césari, 1993), whereas the youngest (Namurian) is represented in the upper member of the Cortaderas Formation (Limarino and Césari, 1993). The latter event includes glaciomarine tillites (iceberg-dump till deposits) and resedimented diamictites related to the Gondwanic glaciation (Limarino et al., 1993).

To the south in the Calingasta-Uspallata basin (Hoyada Verde locality, Fig. 1), transgressive deposits lie on the glacigenic section of the Hoyada Verde Formation (López Gamundí 1989). This rise in sea level was attributed to glacioeustatic changes due to deglaciation processes. Marine invertebrates of the upper carboniferous *Levipustula* zone have been found in that transgressive level (González, 1982; Archangelsky et al., 1996b).

In the Paganzo basin, two major transgressive episodes are recognized. The oldest (Namurian–early Westphalian; Limarino and Gutierrez, 1990; Archangelsky et al., 1996a; Césari and Gutierrez, 2000; Gutierrez and Limarino, 2001) covers glacial or gravity-resedimented diamictites and is represented in the Guandacol, Agua Colorada, and Malanzán Formations. In the Guandacol Formation (Huaco, Fig. 1), Martínez (1993) reported marine brachiopods and bivalves in black shales covering the diamictitic levels near the base of the Guandacol Formation. To the east, the Agua Colorada and Malanzán Formations rest in a more landward paleogeographic setting into the Paganzo basin. For the first unit (Las Gredas locality, Fig. 1), Limarino and Gutierrez (1990) reported shales and mudstones overlying diamictitic facies originally interpreted as glaciolacustrine deposits. These fine-grained rocks yielded an interesting palynological assemblage composed of spores and pollen grains. Furthermore, Gutierrez and Limarino (2001) recently reported marine microplankton (*Leiosphaerindia* sp., *Greinervillites* sp., *Cymatiosphaera* sp., and *Navifusa variabilis*) in the Malanzán Formation (Olta creek, Fig. 1), which extends the Namurian–early Westphalian transgression into the easternmost part of the Paganzo basin.

A second marine episode in the Paganzo, Río Blanco, and Calingasta-Uspallata basins has been informally known as the 'Stephanian transgression.' It is well represented in the upper part of the Tupe (Limarino et al., 1986), Río del Peñón (Scalabrini Ortiz, 1972; González and Bossi, 1986), and Agua de Jagüel (González and Bossi, 1986) Formations. This transgressive horizon has provided marine invertebrates of the Late Carboniferous–Lower Permian *Tivertonia–Streptorhynchus* Zone (Sabattini et al., 1991).

Accordingly, three main Late Paleozoic transgressions have been identified in western Argentina (Fig. 4): (1) an Early Carboniferous (Visean?) transgression stratigraphically located several hundred meters below glacial diamictites, (2) a Namurian–early Westphalian transgression that rests on the glacial diamictites, and (3) a Stephanian–Lower Permian transgression located some hundred meters above the diamictitic level (Fig. 4). This paper deals with the Namurian–early Westphalian transgression that overlies the glacial diamictites.

## 4. Postglacial marine deposits: facies description

Seven facies of regional importance have been identified in the Namurian–early Westphalian transgressive deposits (Fig. 5, Table 1): (1) laminated mudstones (FL), (2) laminated mudstones with dropstones (FD), (3) bouldery diamictites (BD), (4) pebbly diamictites (PD), (5) interbedded sandstones and mudstones (SF), (6) large-scale cross-bedded sandstones (SP), and (7) coarsening and thickening upward sequences of interbedded mudstones and sandstones (CUS). Lithofacies codes are after Miall (1977) and Eyles et al. (1985).

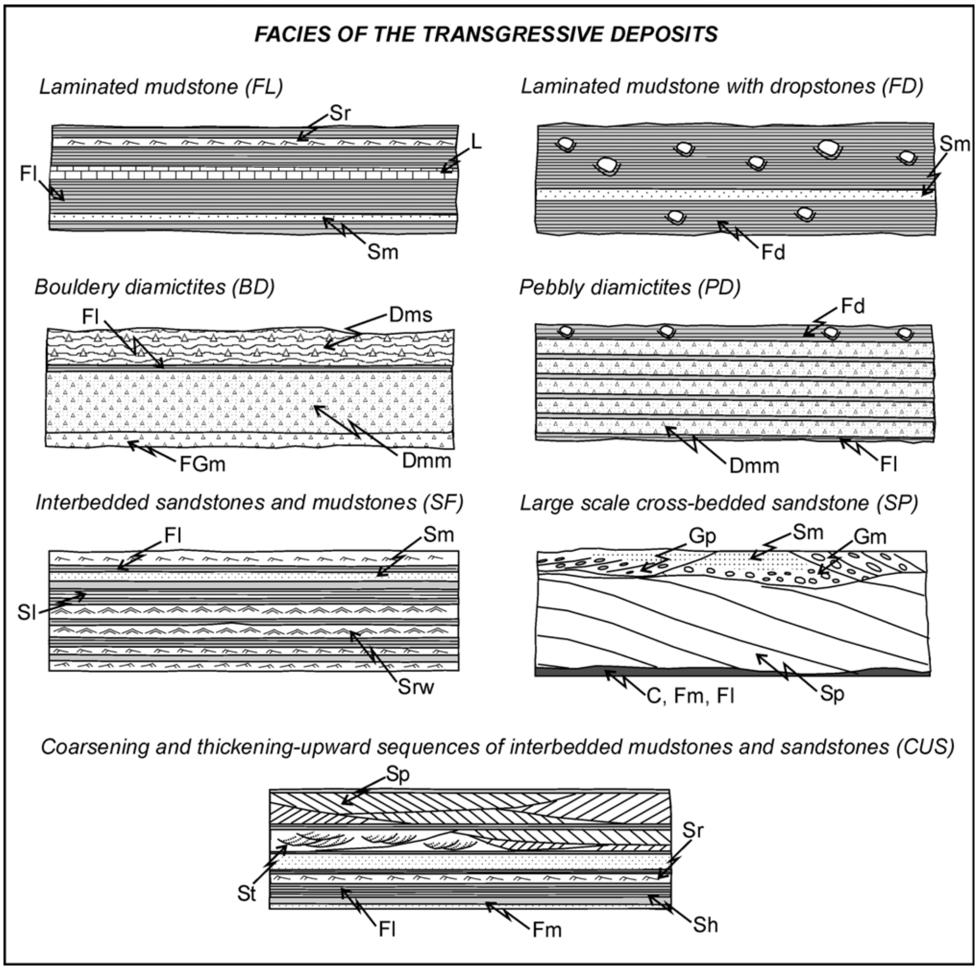


Fig. 5. The seven marine postglacial facies, with characteristic lithofacies and geometry.

### 4.1. Laminated mudstones

This facies consists of rhythmically stratified, dark colored, greenish gray to black laminated claystones and siltstones (FL lithofacies) arranged in monotonous sequences of variable thickness (Fig. 6a). In the western domain, it can reach from 10 to 100 m thick (see the upper member of the Cortaderas Formation), whereas in the central domain, it reaches only 40 m (see Huaco). Farther inland in the eastern domain, the sequences span from a few meters thick in Paganzo to 30 m in the Malanzán Formation (Malanzán paleovalley).

Two different types of lamination have been recognized. The more frequent is produced by parallel orientation of clay minerals imparting fissility, is very common in all the domains, and results from the settling of fine-grained particles. A second type, present only in the eastern domain, shows subtle textural changes within layers that originate varve-like rhytmites characterized by alternating layers of claystones (dark term) and sandy siltstones (light term). Although these rocks probably correspond in part to annual rhytmites (true varves as in Las Gredas, Limarino and Gutierrez, 1990), we suggest that most are non-annual rhytmites originated by underflows in bodies of water (Limarino and Césari, 1988).

Massive or ripple laminated very fine sandstones (Sm and Sr) and thin tabular layers of marls and black limestones (L) are occasionally intercalated in laminated mudstone sequences. Sandstones conform in 1–6 cm thick tabular beds that frequently show isolated sets of current-ripple lamination with sharp but nonerosive bases (Fig. 6b). Laminated mudstones (FL) correspond to the maximum flooding stage, whereas intercalated current-ripple laminated sandstones (Sr) are distal density currents. These deposits may be tied to the peak of the transgressive event, at which marls (L) associated with bioturbated levels represent condensed horizons.

### 4.2. Laminated mudstones with dropstones

FD facies is composed of a monotonous sequence of laminated mudstones similar to FL facies but with dropstones (Fig. 6c) from few centimeters to 0.45 meters in diameter. Dropstones frequently show pentagonal forms, sometimes faceted surfaces, and occasionally striae and nails. Although dropstones appear isolated, they usually

Table 1
Facies and lithofacies code (percentages point out the approximate relative participation of each lithofacies within each facies)

| Facies | Major lithofacies | Relative participation (%) |
|---|---|---|
| Laminated mudstones (FL) | Fl: laminated mudstones | 90 |
| | Sr: current ripple laminated sandstones | 4 |
| | Sm: massive sandstones | 4 |
| | L: marls and black limestones | 2 |
| Laminated mudstones with dropstones (FD) | Fd: laminated mudstones with dropstones | 95 |
| | FGI: laminated pebbly mudstones | 5 |
| Bouldery diamictites (BD) | Dmm: massive matrix-supported diamictites | 65 |
| | Dms: stratified matrix-supported diamictites | 25 |
| | FGm: massive pebbly mudstones | 6 |
| | FGl: laminated pebbly mudstones | 4 |
| Pebbly diamictites (PD) | Dmm: massive matrix-supported diamictites | 80 |
| | Fd: laminated mudstones with dropstones | 15 |
| | Fl: laminated mudstones | 5 |
| Interbedded sandstones and mudstones (SF) | Sl: parallel-laminated sandstones | 20 |
| | Sr: current ripple laminated sandstones | 20 |
| | Srw: wave ripple laminated sandstones | 15 |
| | Sm: massive sandstones | 10 |
| | Sg: micrograded sandstones | 5 |
| | Fl: laminated mudstones | 20 |
| | Fm: massive mudstones | 10 |
| Large-scale cross-bedded sandstones (SP) | Sp: large-scale cross-bedded sandstones | 65 |
| | Sm: massive sandstones | 10 |
| | Sr: current ripple cross-laminated sandstones | 8 |
| | Gp: cross-bedded conglomerates | 5 |
| | Sh: horizontally laminated sandstones | 5 |
| | Fl: laminated mudstones | 5 |
| | Fm: massive mudstones | 2 |
| | C: coal | $<1$ |
| Coarsening-and thickening upward sequences of mudstones and sandstones (CUS) | Sr: current cross-laminated sandstones | 30 |
| | Sh: laminated sandstones | 25 |
| | Fl: laminated mudstones | 20 |
| | Fm: massive mudstones | 20 |
| | Sp: planar cross-bedded sandstones | 3 |
| | St: trough cross-bedded sandstones | 2 |

concentrate in beds or sets of beds and in some cases grade to laminated pebbly mudstones (FGl). Dropstones are recognized by impact structures marked by the bending or rupture of underlying laminae (Thomas and Connell, 1985). FD facies is located above tillites and resedimented diamictites and covered by the FL facies. We interpret FD facies as formed by the melting of icebergs corresponding to the initial stage of the transgression (early transgressive systems track, López Gamundí, 1997).

### *4.3. Bouldery diamictites*

Different types of diamictites, such as massive matrix-supported (Dmm), stratified matrix-supported (Dms), and pebbly mudstones (FGm and FGl), are included in this facies. Dmm deposits include clasts of up to 80 cm maximum diameter (Limarino et al., 1993) embedded in a silty or clayey matrix. This kind of diamictite forms lensoid or irregular beds from 0.4 to 1.5 m in thickness (Fig. 6d), sometimes amalgamated and intercalated with thin levels of FL and FD lithofacies.

Dms lithofacies is very common in some sections and is made up of coarse matrix-supported paraconglomerates with maximum clast sizes of 30 centimeters. These rocks form lenticular beds characterized by a crude planar fabric defined by the horizontal orientation of their clast's larger axes and, in some cases, by a thin, inversely graded basal interval.

Two different types of pebbly mudstones have been recognized. Lenticular beds of massive pebbly mudstones (FGm), with few pebbles floating in a muddy matrix, and laminated pebbly mudstones (FGl), usually containing dropstones of up to 20 cm, show penetrative deformation of the underlying beds. When the number of gravel-sized clasts decreases, FGl lithofacies gradually pass into FD lithofacies.

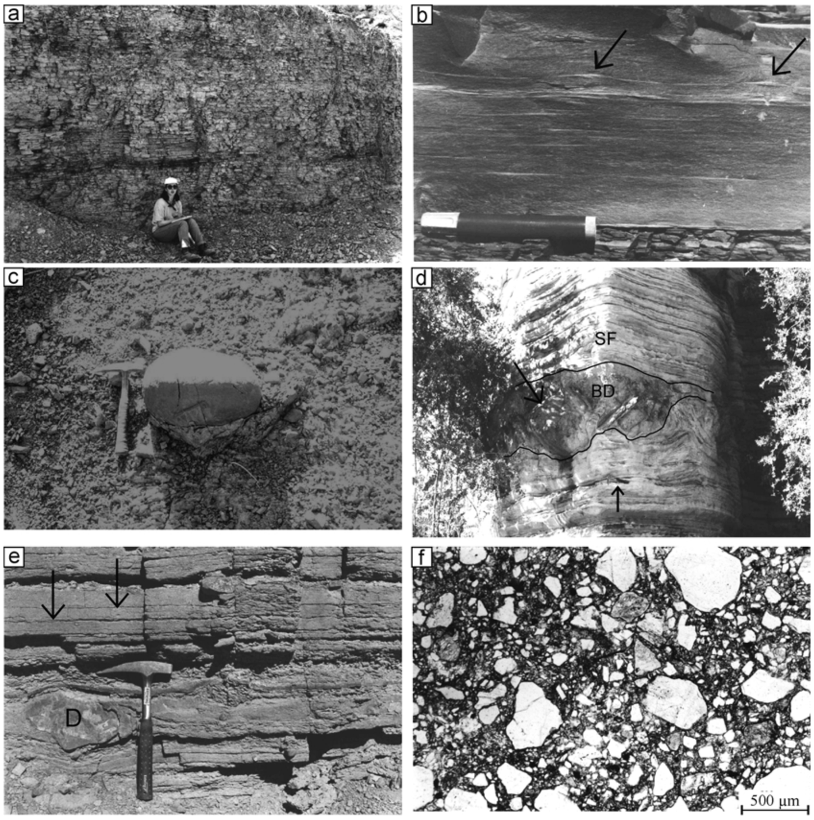


Fig. 6. Views of the transgressive facies: (a) laminated mudstones facies (FL) in Malanzán Formation (Malanzán paleovalley); (b) detail of starving ripples (arrows) in the FL facies, Guandacol Formation (Huaco); (c) laminated mudstones with dropstones facies (FD) in the Cortaderas Formation (Cortaderas creek); (d) bouldery diamictites (BD facies) intercalated between wavy bedded sandstones and mudstones of the SF facies in the Malanzán Formation (Olta paleovalley)—note the extraordinary size of boulders (large arrow) and the deformation at the base of the bed (rock pick for scale indicated by the small arrow)—(e) detail of the pebbly diamictites (PD facies) with a dropstone (D) in the Guandacol Formation; arrows mark thin mud streaks that separate distinct mudflow events (Huaco); and (f) photomicrograph of the pebbly diamictites facies (PD) in the Guandacol Formation (Huaco) showing its characteristic extremely poor sorting and floating and chaotic fabric (parallel nicols, × 40).

Stratified diamictites (Dms) have been observed in Paganzo and Río Blanco basins and can be genetically interpreted as having been formed by gravity flow processes. In this sense, López Gamundí (1987) presents an interesting discussion of reworking processes in relation to Gondwanic glaciation in three basins of Argentina (Tarija, Calingasta-Uspallata, and Tepuel Genoa). In contrast, some levels of massive diamictites (Dmm) may represent true tillites, as described by Limarino and Gutierrez (1990) in the Agua Colorada Formation. In some cases, Dmm facies can result from gravity flows or ice rafting mechanisms that produce iceberg-dump till deposits (Thomas and Connell, 1985). This latter possibility has been suggested for the diamictites and pebbly mudstones found in the upper member of the Cortaderas Formation (Limarino et al., 1993).

The massive pebbly mudstones (FGm) probably result from subaqueous debris flows and therefore represent a lateral equivalent of the stratified diamictites (Dms). In contrast, laminated pebbly mudstones with dropstones (FGl) point to the simultaneous settling of fine particles and ice rafting processes.

### 4.4. Pebbly diamictites

This facies is composed of pebbly, matrix-supported diamictites (Dmm), including clasts of up to 7 cm in diameter, very commonly associated with FD and FL lithofacies. Diamictites consist of pebbly, massive para-conglomerates with clasts of limestones, granites, and sedimentary rocks set in a sandy, muddy matrix. These rocks form tabular massive beds of up to 10 cm in thickness (Fig. 6e,f). The contact between diamictite beds is sharp, generally planar, and less commonly undulated and shows thin mud streaks (Fig. 6e). Although most of the diamictitic beds are massive, in some cases, a poorly defined grading develops, as does a crude planar fabric of clasts. Oversized clasts of up to 15 cm are present (Fig. 6e); they frequently show pentagonal forms and cause the deflection or rupture of the mud streaks.

Pebbly diamictites (Dmm) are interpreted as subaqueous mudflow deposits, probably related to the reworking of bouldery diamictites (BD facies) during deglaciation. The sharp contacts between diamictite beds indicate that each corresponds to a distinct sedimentation event separated by periods of quiescence in which thin mud

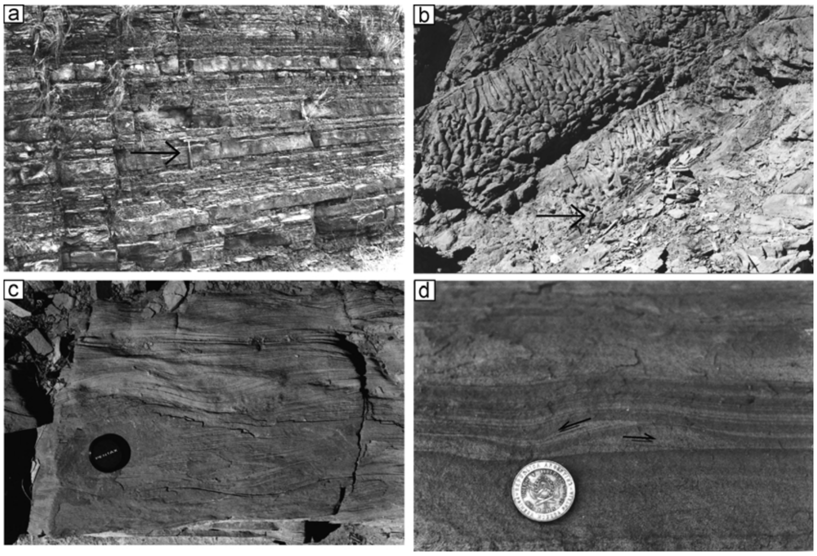


Fig. 7. Views of the marine postglacial facies: (a) interbedded sandstones and mudstones (SF facies) interpreted as turbiditic sequences in the Malanzán Formation, rock pick (arrow) for scale (Malanzán paleovalley); (b) flute marks at the base of the turbiditic sequences (SF facies) in the Guandacol Formation, rock pick (arrow) for scale (Huaco); (c) microhummocky structure in tempestite beds (SF facies) of the Guandacol Formation (Huaco); and (d) detail of the tidally influenced SF facies showing foresets oriented in opposite directions (Olta paleovalley).

streaks were deposited. Oversized clasts are considered dropstones.

### 4.5. Interbedded sandstones and mudstones

Sequences of interbedded sandstone and mudstone (SF) are common throughout the analyzed area and generally appear above the transgressive maximum (FL facies). On the basis of the sand/mud ratio and type of sedimentary structure, three kinds of SF facies can be differentiated. Sandstone–mudstone pairs are interpreted as turbidites (Limarino, 1987; Limarino and Césari, 1988) that show partial to complete Bouma (1962) sequences (Fig. 7a). Each cycle begins with a sharp and erosional base that contains flute marks, sole marks, and load casts (Fig. 7b). The Ta interval corresponds to massive (Sm) and occasionally graded (Sg) sandstones passing upward into parallel-laminated medium to fine-grained sandstones of the Tb interval (Sl). Tb is overlain by current-ripple and climbing-ripple laminated (Sr) fine to very fine sandstones (Tc division). Turbidite muddy beds comprise horizontal laminated mudstones (Fl, including irregular sands layers, Td) and massive mudstones (Fm) of the Te interval. Thick-bedded (15–30 cm) turbidites show complete Ta–Te cycles with well-developed flute, prod, and chevron marks at the base of the beds. Thin-bedded (less than 5 cm) turbidites, however, are only composed of Tc–Te intervals. The sandy term (Tc) shows neither scour nor tool marks and frequently exhibits isolated levels of rippled fine-grained sandstones (Sr).

A second type of SF facies corresponds to sequences with a high sand/mud ratio and small-scale dome structures (microhummocky, Fig. 7c). The sandy term resembles the Tc interval of the turbidites but shows evidence of oscillatory flows, such as chevron-like lamination, off-shoots, and bundle-wise building of the cross-laminated units (Srw). In some rare cases, triangular flute and small groove marks are present at the lower surface of the beds. We suggest that the described deposit represents sandy tempestites deposited during storms, followed by a fallout of fine particles during fair weather sedimentation.

Finally, the third kind of SF facies is formed by thin beds (up to 5 cm) of alternating mudstones and very fine sandstones that show heterolitic structures (flaser and wavy bedding). Lenses of ripple cross-laminated sandstones with foreset oriented in opposite directions are common and suggest tidal current action (Fig. 7d).

### 4.6. Large-scale cross-bedded sandstones

This facies is characteristic of sections from the eastern part of the Paganzo basin (Sierras Pampeanas and Famatina). It is made up of large-scale sets of cross-bedded sandstones (Sp) and conglomerates (Gp) that form Gilbert-type clinoforms (Fig. 8a). Superb examples of these rocks (up to 13 m thick) come from the lower member of the Agua Colorada Formation (Vallecito locality, Fig. 1). Gilbert-type deltas can be divided into three sections: (1) the lower section, which corresponds to the prodelta, is composed of very fine laminated or massive sandstones (Sh, Sm) interbedded with laminated (or massive) mudstones (Fl–Fm); (2) the middle section, which forms the foresets of the delta-front, is made up of ripple cross-laminated (Sr) or massive (Sm) fine-grained sandstones with thin intercalations of laminated mudstones (Fl); and (3) the upper section, which includes large-scale cross-bedded sandstones (Sp), massive conglomerates (Gm), and some lenticular beds of

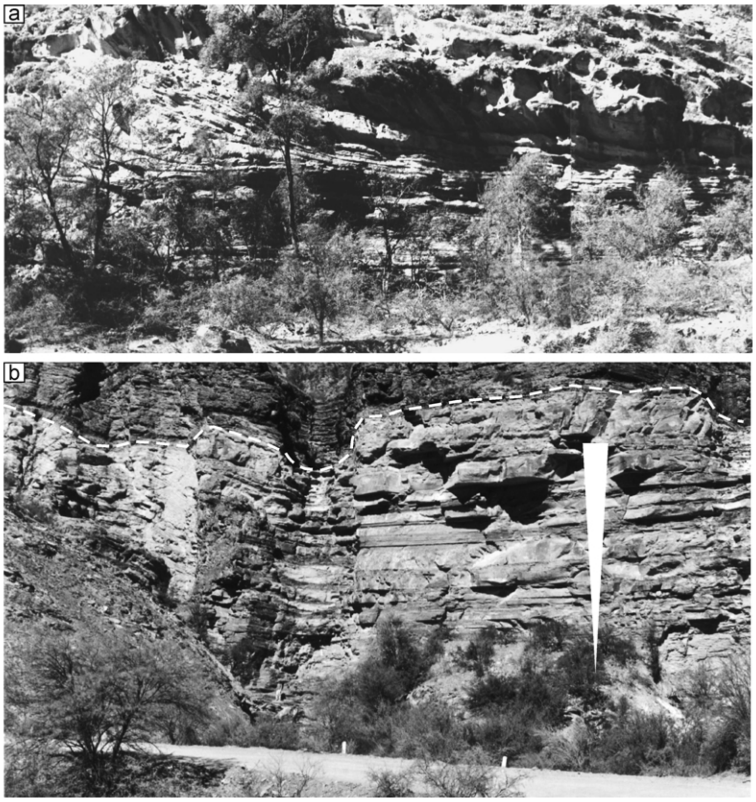

Fig. 8. Field views of (a) large-scale, cross-bedded sandstones (SP facies) corresponding to a Gilbert-type delta in the Malanzán Formation (Olta paleovalley) and (b) coarsening and thickening upward mudstones and sandstones sequences (CUS facies) in the Guandacol Formation (Huaco).

carbonaceous mudstones and coals (C), belongs to the subaerial delta plain.

Other excellent exposures of Gilbert-type deltas in the eastern domain also have been described in the Lagares and Malanzán Formations (Limarino, 1987; Sterren and Martínez, 1996). In both units, as well as in the Agua Colorada Formation, Gilbert-type delta deposits (SP facies) cover laminated mudstones with dropstones (FD) and laminated mudstone (FL) facies.

### *4.7. Coarsening and thickening upward sequences of interbedded mudstones and sandstones*

Coarsening and thickening upward sequences of mudstones and sandstones are frequent in the upper part of the postglacial marine event, especially in the west of the Paganzo basin (Fig. 8b). This facies conforms to sequences from 40 to 90 m thick in the Huaco and Guandacol sections (Fig. 1), where it appears as several stacked cycles of strongly prograding sequences.

Ideally, each cycle begins with thinly interbedded mudstones and sandstones resting on top laminated mudstones (FL facies) or thin-bedded turbidites (SF facies). Sandstones are very fine-grained and highly micaceous and present parallel (Sh) or climbing-ripple lamination (Sr). Mudstones are mainly laminated (Fl) and less frequently massive (Fm). Sandstone bed thickness and frequency increases upward, and at the same time, cosets of cross-bedded medium- and coarse-grained sandstones (Sp, St) become dominant. These mudstone–sandstone couplets are interpreted as distributary mouth bars deposited in front of highly constructive deltas. Fine-grained sandstones and mudstones of the middle and lower part of the prograding cycles are assigned to distal mouth bars, whereas the coarse-grained, cross-bedded sandstones correspond to proximal bars.

## 5. Postglacial facies associations

The Namurian–early Westphalian transgression has been identified in several localities and can be grouped into three main paleogeographic domains (Fig. 1): (1) the western domain, presently in the western Precordillera, where the transgression is represented by open marine facies (López Gamundí, 1987); (2) the central domain, located in the central and eastern Precordillera, where transitional, fjord-type environments prevail; and (3) the eastern domain, mainly within the Sierras Pampeanas, where transgressive facies have been described as glaciolacustrine deposits or very shallow marine facies.

On the basis of facies arrangement, architecture, and paleogeographic distribution of these deposits, three main postglacial facies associations were recognized: open marine, transitional, and continental-dominated. Each characterizes the previously noted western, central, and eastern domains (Figs. 9 and 10).

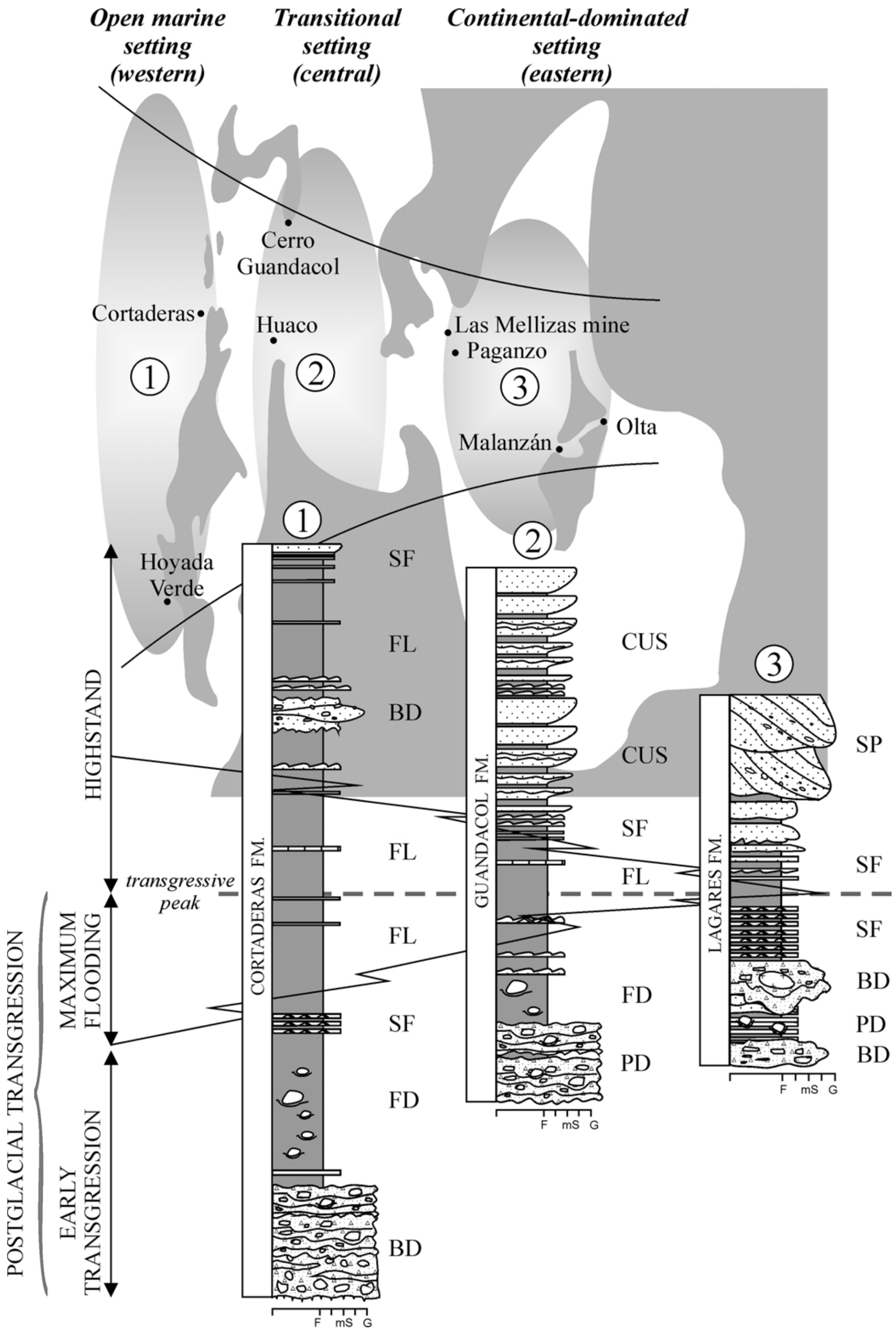


Fig. 9. General scheme of the Namurian–early Westphalian transgression facies distribution in open marine (western), transitional (central), and continental-dominated (eastern) settings for the Paganzo and Río Blanco basins.

*5.1. Postglacial facies associations in open marine settings*

Open marine postglacial deposits are characteristic of the western domain (Fig. 9). They correspond to the Jagüe, Cortaderas, Hoyada Verde, and Agua de Jagüel Formations (Río Blanco and Calingasta-Uspallata basins, Fig. 1). These units exhibit similar arrangements of their postglacial transgressive facies (Figs. 9 and 10). A sharp contact highlighting the beginning of the postglacial event separates glaciomarine tillites below from shales containing dropstones (FD facies) above. Laterally, these shales grade into lenticular beds of bouldery diamictites (BD) and

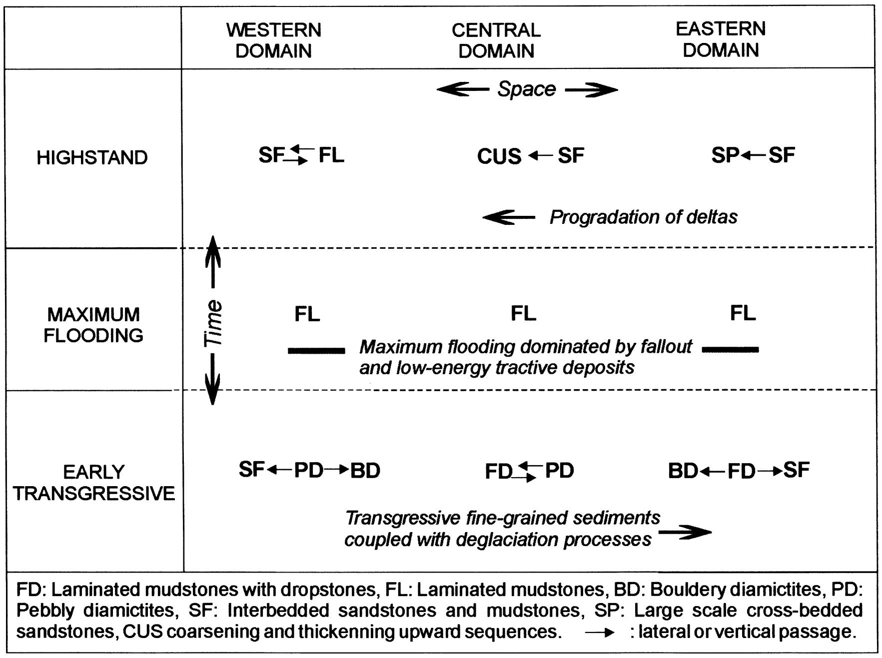


Fig. 10. Distribution of the postglacial facies association in time and space.

interbedded sandstone and mudstone sequences (SF). These facies are covered by dropstone-free shales (FL facies) that correspond to the maximum flooding stage (Fig. 9) or the late transgressive system tract of López Gamundí (1997). During the subsequent high stand phase, laminated mudstones (FL facies) and discrete episodes of turbiditic currents (López Gamundí, 1989) (SF facies) dominated. In the Cortaderas and Hoyada Verde localities (Fig. 1), these high stand sediments are separated from coarse-grained fluvial sandstones that contain plant debris (Carrizo, 1990) by a sharp surface.

### 5.2. Postglacial facies associations in transitional settings

To the east in the central domain, transitional conditions between open marine and very shallow terrestrial-influenced settings prevail (Fig. 9). In the Guandacol, Volcán, Agua Colorada, and Jejenes Formations, the postglacial marine deposits show some differences from the western domain, particularly during the high stand stage (Fig. 10). First, the laminated mudstone interval (FL facies) is thin, and pebbly diamictites (PD facies) prevail over bouldery ones (BD facies). Second, interbedded sandstones and mudstones (SF facies) in the central area show frequent evidence of oscillatory currents (microhummocky structures), which are probably related to storm episodes. Third, the top of the high stand stage is marked not by a sharp contact (as occurs in the western area) but by noticeable coarsening and thickening upward sequences (CUS facies) of delta-front environments.

### 5.3. Postglacial facies associations in continental-dominated settings

In the most inland part of the Paganzo Basin, postglacial sedimentation proceeded in continental-dominated settings. Thus, fjord-like conditions developed in the Malanzán, Lagares, and Agua Colorada Formations (Fig. 9). Transgressive deposits form the thinnest intervals (from 8 to 30 m thick), as compared with the western and central domains. Facies arrangement in this area (Fig. 10) includes a thin basal interval of mudstones with dropstones (FD facies) that covers glacially influenced diamictites and alluvial fan deposits. Thin intervals of tidally influenced deposits (SF facies), as well as bouldery diamictites (BD), appear closely associated with the dropstone-bearing shales (FD) (Figs. 9 and 10). During the maximum flooding stage, only a thin interval of laminated mudstones (FL facies) was deposited. In the high stand, fine-grained sediments were progressively replaced by sequences of alternating sandstones and mudstones (SF facies) that correspond to turbidites or distal storm deposits. The most characteristic feature of the high stand stage in the inner part of the Paganzo basin is the progradation of Gilbert-type deltas (SP facies), as favored by a high sediment supply rate coupled with limited wave and tidal action.

## 6. Stratigraphic position and age of the postglacial transgression

A synthesis of the regional stratigraphy and biostratigraphic data of the three different facies associations is now presented.

### 6.1. Western domain

In the western domain, the transgression has been observed in at least four localities (from north to south): Agua de Carlos, Malimán, Hoyada Verde creek, and Agua de Jagüel creek (Fig. 1).

In the Precordillera of the La Rioja Province, Fauqué and Limarino (1990) found glaciomarine deposits in the Jagüe Formation (Agua de Carlos, Fig. 1) composed of matrix-supported, massive diamictites with striated, faceted, and elongate pentagonal clasts. These glaciomarine deposits are covered by offshore marine facies composed of shales with dropstones of up to 0.45 m in diameter (Fauqué and Limarino, 1990). Although the transgressive shales yielded no fossils, Azcuy and Carrizo (1995) reported plant remains of the Visean *Archaeosigillaria–Frenguellia* zone several meters lower in continental preglacial deposits. Moreover, these marine shales are unconformably covered by fluvial conglomerates, sandstones, and mudstones containing paleofloristic elements of Late Westphalian–Stephanian age (Carrizo and Azcuy, 1995). These stratigraphic relationships assign the transgressive level to the Namurian–early Westphalian.

At the Sierra de La Punilla (Cortadera creek, Fig. 1), the transgressive deposits are located in the upper member of the Cortaderas Formation. They are made up of 150 m of greenish gray, very fine sandstones and mudstones with several levels of thick-bedded, matrix-supported, massive and stratified paraconglomerates, pebbly mudstones, and shales with dropstones (Limarino et al., 1993). These rocks have provided abundant spores and marine acritarchs, such as *Maranhites*, *Navifusa*, *Dictyotidium*, *Verhyachium*, *Michrystridium*, *Exochoderma*, and *Duvernaysphaer* (Fig. 11), dated as latest Early Carboniferous (Césari and Limarino, 1992). In contrast, strata above the glaciomarine level contain elements of the Upper Carboniferous NBG biozone (Carrizo, 1990). Therefore, a Namurian–early Westphalian age is suggested for the transgressive facies of the Cortaderas Formation (Césari and Limarino, 1992).

A similar situation occurs to the south in the Sierra de Barreal (Hoyada Verde, Fig. 1), where the Hoyada Verde Formation can be divided into two sections. The lower section is made up of tillites, gravity-resedimented diamictites (debris flows), shales with dropstones, and a pavement of striated boulders (González, 1982; López Gamundí and Martínez, 2000), all interpreted as glaciomarine sediments (González, 1982; López Gamundí, 1983). A monotonous section of laminated mudstones corresponding to the transgressive level studied herein composes the upper section (López Gamundí, 1983), where brachiopods, bivalves, and crinoids of the Namurian–Westphalian Levipustula zone (Archangelsky et al., 1996b) were found.

Finally, in the Paramillos de Uspallata area (Agua de Jagüel, Fig. 1), the base of the Agua de Jagüel Formation presents diamictites with striated and faceted clasts covered by shales with dropstones and laminated mudstones of the transgressive facies (Bercowski and Vallecillo, 1996). In the laminated mudstones of this locality, Martínez et al. (2001) found brachiopods and gasteropods of probable late Late Carboniferous age.

### 6.2. Central domain

In the central domain, the Precordillera represents the transition between open marine environments (western domain) and thin flooding facies typical of the Sierras Pampeanas (eastern domain). The transgression is well exposed in at least five localities (Fig. 1), namely, Huaco, Río Francia, San Juan River Valley, Quebrada de Las Lajas, and Quebrada Grande.

In the Huaco anticline area (Fig. 1), the Guandacol Formation presents transgressive mudstones resting directly atop gravity-resedimented diamictites and probably terrestrial tillites (Bossi and Andreis, 1985; Martínez, 1993; Net, 1999; Pazos, 2000; López Gamundí and Martínez, 2000). These rocks originally were interpreted as lacustrine, but in recent years, the discovery of marine invertebrates (Martínez, 1993) and marine palynomorphs (Ottone, 1991) has compelled a review of this interpretation. Whereas Martínez (1993) reported finding a marine fauna composed of brachiopods, pectinid bivalves, indeterminate gastropods, fish scales, and jawbone remains in black shales resting atop diamictites, Ottone (1991) highlighted the great number of spores and pollen grains together with low percentages of marine Chlorophyte algae such as *Maranhites* and *Tasmanites*. Both sources of information associate the Guandacol Formation with a shallow marine environment.

The Río Francia section (Fig. 1) constitutes another locality in the Central Precordillera where the transgression is represented. Césari et al. (1991) identified abundant palynofloras dominated by spores, monosacate pollen, and acritarchs in the laminated mudstones containing dropstones that belong to the lower part of the Guandacol Formation.

From their work in the San Juan River Valley, Milana and Bercowski (1993) described glacial striated pavements covered by different types of resedimented diamictites and probably tillites. This glacially influenced interval passes upward to dropstone-bearing laminated mudstones and shales, which are interstratified with sandstones. These deposits are interpreted as corresponding to the postglacial transgression.

The carboniferous transgression is also registered in the lower part of the Jejenes Formation, which outcrops in Quebrada de Las Lajas (Fig. 1). The transgressive deposits are composed of mudstones, shales containing dropstones, and massive pebbly mudstones. At these levels, Césari and Bercowski (1998) reported palynofloras dominated by spores and monosacate pollen grains, along with subordinated marine acritarchs of Namurian age. Moreover, marine microfossils represented by abundant *Prasinoficeae* algae and few *Veryhachyum* specimens (Fig. 11a) enabled them to envisage a marine depositional environment close to the

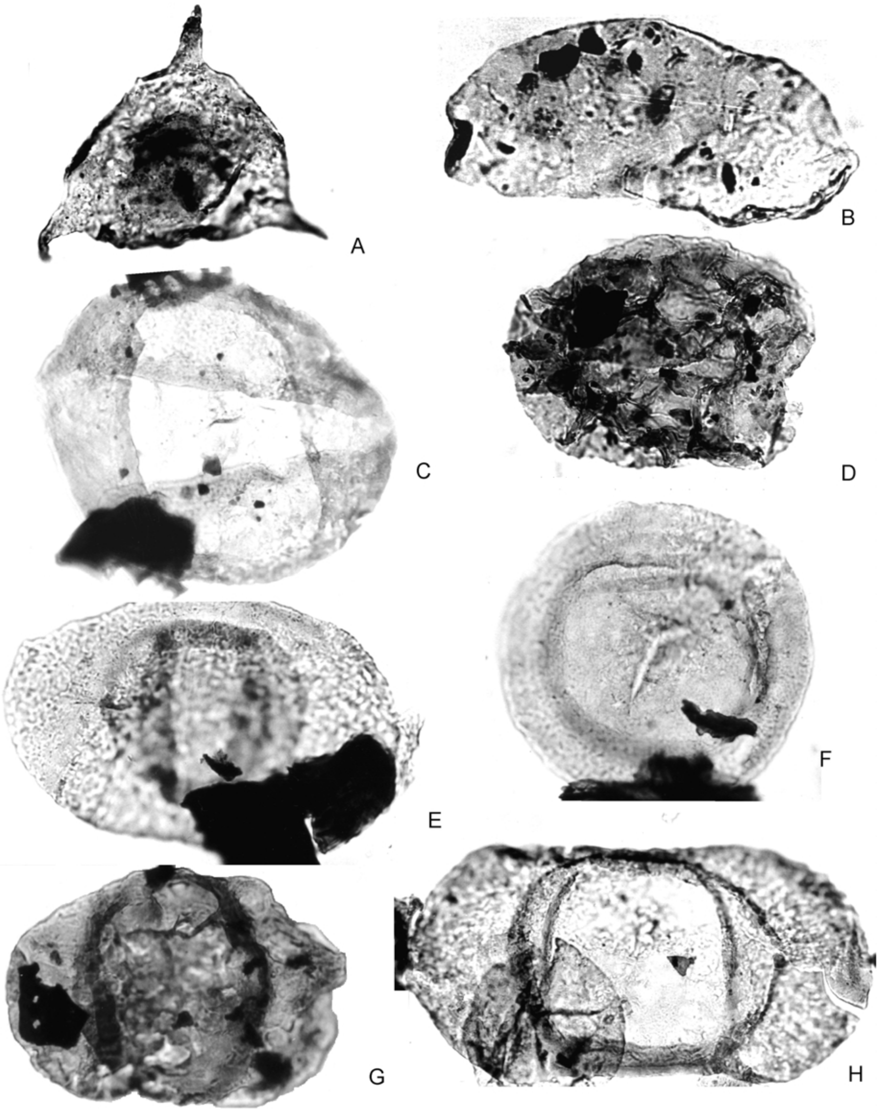


Fig. 11. Palynological species from the Jejenes (A) and Malanzán (B–H) Formations. (A) *Veryachium reductum* (Deunff) S and S emend. S and Sarjeant (×1000); (B) *Navifusa variabilis* Gutierrez and Limarino (×1000); (C) *Crucisaccites monoletus* Maithy (×1000); (D) *Greinervillites* sp. (×1000); (E) *Potonieisporites neglectus* Potonié and Lele (×1000); (F) *Plicatipollenites malabarensis* (Potonié and Sah) Foster (×1000); (G) *Limitisporites* sp. (×1000); and (H) *Limitisporites* sp. (×1000).

shore. In the same locality, Kneller et al. (2000) interpreted the depositional environment as a paleofjord.

### 6.3. Eastern domain

Several localities of Sierras Pampeanas show tillites or gravity-resedimented diamictites covered by fine sandstones and laminated mudstones with dropstones (Fig. 1), including Malanzán, Olta, Las Gredas, Paganzo, and Casa Blanca. These outcrops traditionally have been interpreted as fine-grained lacustrine deposits (Limarino et al., 1984; Limarino and Césari, 1988; Limarino and Gutierrez, 1990; Buatois et al., 1990). Furthermore, Buatois et al. (1990) suggested that these 'lakes' may have been formed due to a sea level rise related to carboniferous deglaciation. This lacustrine interpretation was recently challenged by Gutierrez and Limarino (2001), who recovered Namurian–Westphalian marine microplankton (*Cymathiosphaera* sp., *Greinervillites* sp., and *Navifusa variabilis*, Fig. 11b,d) from mudstones and shales of the Malanzán Formation.

In Sierra de Los Llanos, Andreis et al. (1986) considered the Malanzán Formation as deposited within a paleovalley of probable glacial origin. Thus, the valley fill began with diamictites and conglomerates of fluvial origin, which were covered by dropstone-bearing laminated mudstones and fine sandstones containing abundant pollen grains (Fig. 11c, e–h) and marine microplankton (Gutierrez and Limarino, 2001). In Olta locality, Sterren and Martínez (1996) described another glacial paleovalley filled up with bouldery diamictites and fanglomerates overlain by transgressive fine-grained sandstones and mudstones with dropstones. Although both the Malanzán and Olta paleovalley outcrops were interpreted as glaciolacustrine deposits by previous authors (Andreis et al., 1986; Limarino and Césari, 1988; Buatois et al., 1990; Sterren and Martínez, 1996; Net and Limarino, 1999), the presence of marine microplankton improves this interpretation to the inner part of a paleofjord environment.

To the north in Nevados del Famatina (Fig. 1), Limarino and Gutierrez (1990) described an interesting diamictite-bearing sequence in the lower part of the Agua Colorada Formation (Quebrada Las Gredas, Fig. 1). Diamictites were divided into two genetic types. One is composed of stratified, clast-supported paraconglomerates interpreted as resedimented debris flows, whereas the other is formed by matrix-supported, massive diamictites that are considered true tillites. Both diamictitic types are covered by shales with dropstones, mudstones, and some intercalations of very fine sandstones (Limarino and Césari, 1988; Limarino and Gutierrez, 1990). These rocks contain a conspicuous palynoflora composed of pollen grains (such as *Plicatipollenites malabarensis*, *Potonieistoporites neglectus*, and *Limitisporites hexagonalis*) and abundant spores (e.g. *Convolutispora muriornata*, *Raistrickia accinta*, *Anapiculatisporites argentinensis*) dated as Namurian (Limarino and Gutierrez, 1990).

In summary, despite paleogeographic differences, this transgressive level is clearly exposed in the three paleogeographic domains and overlies tillites, resedimented glacially influenced diamictites, or alluvial fan deposits. Thus, the fine-grained interval has chronostratigraphic significance and enables us to establish a regional correlation level. These transgressive shales contain marine invertebrates and acritarchs in the western and central domains and continental palynological assemblages associated with microplankton in the eastern domain. Taking into account the presence of abundant pollen grains, the interval cannot be older than early Namurian. This assumption is in agreement with the oldest known worldwide records of monossacate and bissacate pollen grains. In addition, the occurrence of spores and pollen grains belonging to the A subzone of the *Raistrickia densa-Convolutispora muriornata* Biozone (Césari and Gutierrez, 2000) indicates that this postglacial transgression ranges from Namurian to early Westphalian.

## 7. Conclusions

The marine postglacial transgression identified in the Calingasta-Uspallata (López Gamundí, 1989), Río Blanco (Limarino et al., 1993; Eyles et al., 1995), and Paganzo (Martínez, 1993) basins is the most widespread marine event in the Late Paleozoic Pacific basins of Argentina. Palynological data suggest a Namurian–early Westphalian age for this transgressive level and constrain to the Namurian the final stage of the glaciation in this part of Gondwana.

The Namurian transgression represents a key horizon for correlation among the Paganzo, Río Blanco, and Calingasta-Uspallata basins. The Malanzán Formation is correlated with the lacustrine interval of the Lagares Formation, the lower member of the Agua Colorada Formation, and the entire Guandacol Formation in the Paganzo basin. To the west, these units are equivalent in time to the upper sections of the Cortaderas (Río Blanco basin) and Hoyada Verde (Calingasta-Uspallata basin) Formations.

The postglacial mega-event can be divided into three major stages: (1) early transgressive, (2) maximum flooding ( = early transgressive and late transgressive systems tract; López Gamundí, 1997), and (3) high stand (Fig. 10). Early transgressive association is dominated by laminated mudstones with dropstones associated with bouldery and pebbly diamictites and thin intervals of heterolithic or cross-laminated sandstones and mudstones. The maximum flooding stage is characterized by dropstone-free laminated mudstones, which strongly suggests the complete melting of the ice masses. At the end of the glaciation, thin levels of marls probably represent condensed horizons. Finally, the high stand stage provides the most important lithological variabilities. In the eastern domain, conspicuous Gilbert-type deltas dominated, but in the central domain, coarsening and thickening upward sequences corresponding to the progradation of deltaic systems were deposited. The western domain does not indicate a clear development of progradational sequences; on the contrary, a pervasive surface of fluvial incision rests immediately above marine mudstones.

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