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Changes in the architecture of fluvial deposits in the Paganzo Basin (Upper Paleozoic of San Juan province): an example of sea level and climatic controls on the development of coastal fluvial environments

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ABSTRACT

Paganzo Group exposures (Tupe Formation) in the Huaco area provide an excellent opportunity for assessing the role of sea level and climatic changes on the morphology and nature of coastal fluvial systems deposited in areas of limited tectonic activity. The paleogeographic position of Huaco, close to a coastal region within the Paganzo Basin, allows identification of the effects of sea level change on fluvial architecture. Despite the fact that the Huaco area was dominated by coastal fluvial systems, three marine incursions flooded this part of the basin during the Namurian, Early Pennsylvanian and Late Pennsylvanian respectively. During deposition of the Paganzo Group, climatic conditions evolved from glacial (Namurian) to hot and dry (Late Cisuralian).

Five types of fluvial deposits were recognized on the basis of architectural element analysis, lithofacies distribution and type of fluvial bounding surfaces present. Fluvial system 1 (FS1) constitutes the lower part of the Tupe Formation and consists of stacked multi-storey channel-fill complexes formed on large braided alluvial plains dominated by channel-avulsion processes. FS2 consists of multi-storey channels alternating with floodplain deposits including coal beds and organic-rich mudstones. This fluvial system is interpreted as the deposit of an anastomosed network of sandy channels. FS3 occurs between the Early Pennsylvanian and Late Pennsylvanian marine transgressions and consists of sandstones and some conglomerates that form stacked channel complexes. Sporadically, very fine-grained sandstone and mudstone floodplain deposits appear as thin intercalations. FS3 likely formed on braided alluvial plains with channels dominated by transversal bars. FS 4 corresponds to an anastomosed fluvial system that was dominated by two types of braided channel belts that were separated by narrow floodplains. Finally, FS5 is composed of fining-upward cycles ranging from gravely sandstones at the bottom of channels to muddy floodplain deposits at the top. The whole FS5 succession was deposited by high-sinuosity meandering rivers.

Detailed stratigraphic analyses clearly suggest that both, sea level and climate changes were first-order controls on fluvial system configurations. In this way, braided systems belonging to FS1 correspond to a low-accommodation system tract. Whereas, coal beds of FS2, which resulted from high water-tables, correspond to a high accommodation system tract that was likely associated with advanced stages of the Late Pennsylvanian transgression. A significant change in the nature of fluvial deposits took place prior to the Late Pennsylvanian sea level rise when braided fluvial systems (FS3) with very scarce floodplain deposits prevailed. Towards the top of the Late Pennsylvanian transgressive deposits, a high relief fluvial incision surface was carved into the underlying marine deposits. This surface was later mantled by anastomosed rivers (FS4) corresponding to low-accommodation deposits formed in a lowstand or during the early stages of the ensuing sea level rise. In later phases of this transgression, high accommodation conditions prevailed and fluvial sedimentation was dominated by high-sinuosity rivers (FS5). These fluvial deposits are considered as an inland equivalent to the shallow-marine deposits exposed in the neighboring Agua Negra Formation located to the west.

KEYWORDS **Fluvial architecture. Sea level changes. Climatic changes. Late Paleozoic. Sequence stratigraphy.**

INTRODUCTION

The effects of sea level and climate change on the morphology of fluvial systems has been highly debated (Shanley and McCabe, 1994; Wright and Marriot, 1993; Dalrymple et al., 1998; Blum and Tornqvist, 2000; Blum and Aslan, 2006). In particular, during the 1980's and 1990's, the successful results obtained using sequence stratigraphy in marine deposits encouraged interpreting fluvial stratigraphy and channel-body stacking patterns as the consequences of eustacy. However, any attempt to establish a direct and univocal relationship between changes in sea level and specific configurations of alluvial systems, must address the fact that other allocyclic controls (e.g., climate, tectonics or subsidence) also exert an important role in the development of fluvial deposits (Miall, 1991, 2002, 2006; Leckie, 1994; Blum and Price, 1998; Dalrymple et al., 1998; Legarreta and Uliana, 1998; Feldman, et al., 2005). The relative importance of each allocyclic control depends upon several factors, which include such factors as: distance of the fluvial system from the sea, climatic history, tectonic activity in and adjacent to the basin, and basinal subsidence rates (Miall, 1991, 1996; Dalrymple et al., 1998). The aim of this paper is to analyze the effect of sea level, climatic, and tectonic changes on fluvial systems located close to coastal areas.

The strata examined here correspond to a relatively thick fluvial succession (up to 375m thick) that represents the stratigraphic transition from the lower (Early Pennsylvanian) to the upper (Late Pennsylvanian) sections of the Paganzo Group (Bodenbender, 1912; Azcuy and Morelli, 1970). Even though the Paganzo Group corresponds to an essentially continental succession, at least three marine transgressions flooded the western portion of the basin producing substantial changes in the balance of the equilibrium profiles of the fluvial systems. The Paganzo Group also exhibits a complex climatic history, showing the transition from Early Pennsylvanian postglacial humid and temperate conditions to a drier and hotter Early Permian climate.

For this paper, the Paganzo Group was studied at several exposures along the Huaco anticline (Fig. 1). The Huaco area (Fig. 2) was chosen because: 1) it is one of the classic localities of upper Paleozoic strata in northwest Argentina, 2) its paleogeographic location, close to the paleo-coastline, allows for the recognition of, at least, three marine incursions, and 3) Late Carboniferous paleoclimatic signatures are extensively preserved in these outcrops. The aim of this paper is to analyze the evolution of the fluvial systems of the Tupe Formation (Figs. 2 and 3).

METHODOLOGY

Strata of the Tupe Formation (Pennsylvanian), exposed on the western flank of the Agua Hedionda anticline (Figs. 2 and 3), are described and interpreted in this paper. In particular, the characteristics of fluvial deposits and their relationship with marine transgressions and climatic conditions are analyzed in detail. Fluvial intervals were characterized on the basis of a hierarchy of bounding surfaces and an arrangement of architectural elements following the methodology of Miall (1985). This approach allowed for

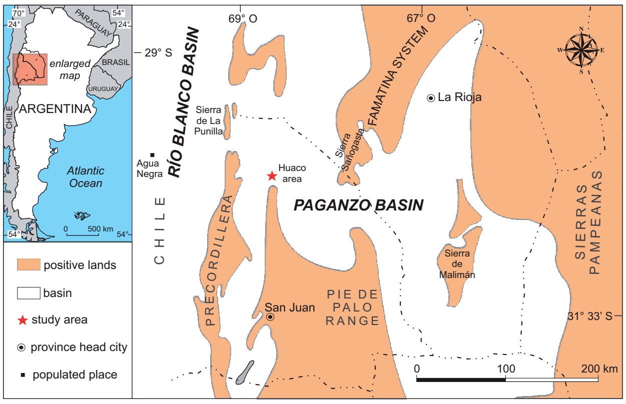


FIGURE 1 | **Late Paleozoic paleogeography of the Paganzo Basin showing the location of the Huaco area (modified from Salfity and Gorustovich, 1984).**

the recognition of five types of fluvial deposits referred to as fluvial systems (FS). Relationships between the deposits of the fluvial systems, as well as with associated marine strata, were studied in the field using different observation scales. First, photo-panoramic cross-sections allowed for establishing lateral continuity of fluvial and marine intervals, thus allowing for an estimate of lateral changes in thickness. Second, three sections, about 300m each, spaced out across the Late Paleozoic sequences were measured to record the type of fluvial systems present and the nature of their bounding surfaces. Third, the distribution of the fluvial systems and marine deposits were surveyed and mapped in detail .

STRATIGRAPHIC SETTING

During the Late Paleozoic, thick sedimentary successions were formed in the western Andean basins of Argentina (for a review see Archangelsky, 1996 and Limarino et al., 2006). The paleogeography of this region is shown in Fig. 1 (Salfity and Gorustovich, 1983), where the “Protoprecordillera” mountain belt separated two main depositional areas, an eastern region dominated by continental sedimentation (Paganzo Basin) and a western one where marine deposition prevailed (Río Blanco Basin). The Paganzo Basin (Fig. 1) is one of the best known Late Paleozoic basins in Argentina. It exposes a continuous stratigraphic record from Serpukhovian to the Late Guadalupian or Early Lopingian (Fig. 2, 3). Upper Paleozoic rocks from this basin were grouped in the Paganzo Group, which was further divided in two stratigraphic intervals (Bodenbender, 1912; Azcuy and Morelli, 1970). In the study area, the lower interval of the Paganzo Group, Late Carboniferous in age, is represented by the Guandacol and Tupe Formations, while the Permian interval corresponds to the Patquía Formation (Fig. 3). The lowermost strata of the Guandacol Formation are composed of resedimented diamictites and true tillites deposited during the Late Carboniferous glacial event (López Gamundí and Martínez, 2000; Marenssi et al., 2005). The glacigenic deposits were covered by fjord-like successions comprising transgressive shales (Namurian postglacial transgression, Limarino et al., 2002) and estuarine and deltaic deposits, which form the upper Guandacol Formation. The depositional environment, deltaic or estuarine, depended on the relative position of the last unit in the basin.

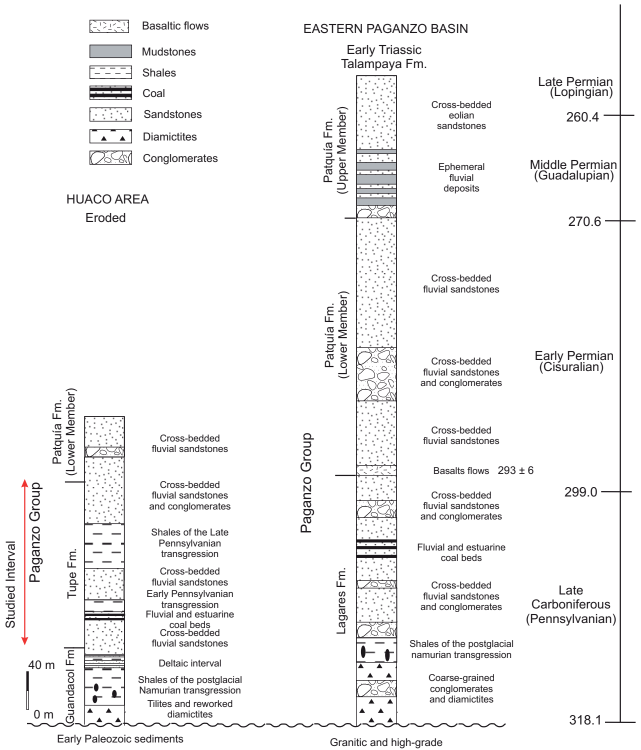


FIGURE 2 | **Stratigraphy of the Paganzo Group in the Huaco area (left) and in the eastern portion of the Paganzo Basin (right).**

The overlying Tupe Formation is almost entirely fluvial, although, two marine transgressions interrupted fluvial sedimentation during the Early Pennsylvanian and the Late Pennsylvanian (Fig. 3, Desjardins et al. 2009). Finally, the Patquía Formation represents a classical red-bed succession dominated by fluvial strata in the lower interval and eolian and ephemeral lacustrine deposits in the upper interval (Fernández Sevesso and Tankard, 1995; Caselli and Limarino, 2002).

PENNSYLVANIAN SEA LEVEL CHANGES

During the Pennsylvanian, several marine transgressions took place along the western margin of Gondwana, forming distinct marine intervals that alternated with continental or transitional strata (Rivano and Sepúlveda, 1985; Starck et al., 1993; López Gamundí, 1997; Díaz Martinez et al., 2000; Limarino et al., 2002). In the specific case of the Paganzo Basin, the western part shows a complete record of three different transgressive events (Fig. 4). The oldest event corresponds to the Lower Pennsylvanian (Namurian) postglacial marine deposits described by Limarino et al. (2002) for different Late Paleozoic basins in Argentina. The postglacial transgression entirely flooded the Paganzo Basin, resulting in a continuous interval of fine-grained deposits dominated by shales with dropstones, thin intercalations of resedimented diamictites, fine-grained sandstones and marls. Strata deposited during this transgression overlie an irregular postglacial surface displaying considerable relief. Where the transgression flooded glacial valleys, the post-glacial strata form a fjord-like successions (Buatois and Mángano, 1995; Kneller et al., 2004). Regionally, the post-glacial package can be divided into a transgressive and a regressive systems tracts (using terminology of Embry and Johannessen, 1992). The base of the transgressive interval corresponds to an irregular surface cut into the glacial diamictites and glacial-related deposits. Three major intervals are recognized in the deposits of the transgressive system tract. The lower interval consists of interbedded fine-grained sandstones, dropstone-bearing shales and thinly-bedded resedimented diamictites. Marine invertebrate fossils commonly occur in this interval. The middle part is mainly composed of shales with dropstones up to 40cm in diameter and thin (centimetric) intercalations of resedimented diamictites. Finally, the upper section contains monotonous successions of shales without dropstones. The maximum flooding surface is marked by marl beds that are associated with highly bioturbated mudstone units. The regressive system tract shows important differences according to its paleogeographic position. In the major part of the Paganzo Basin, progradational deltaic successions are currently interpreted as highstand deposits (Limarino et al., 2006). However, to the west, in the neighboring Río Blanco Basin, the same stratigraphic interval consists of thin erosionally-based fluvial deposits that probably represent subsequent falling stage and lowstand system tracts. During the regressive phase, the Paganzo Basin may have experienced a much higher sediment supply than that of the Río Blanco Basin. The resolution of this issue requires additional analyses.

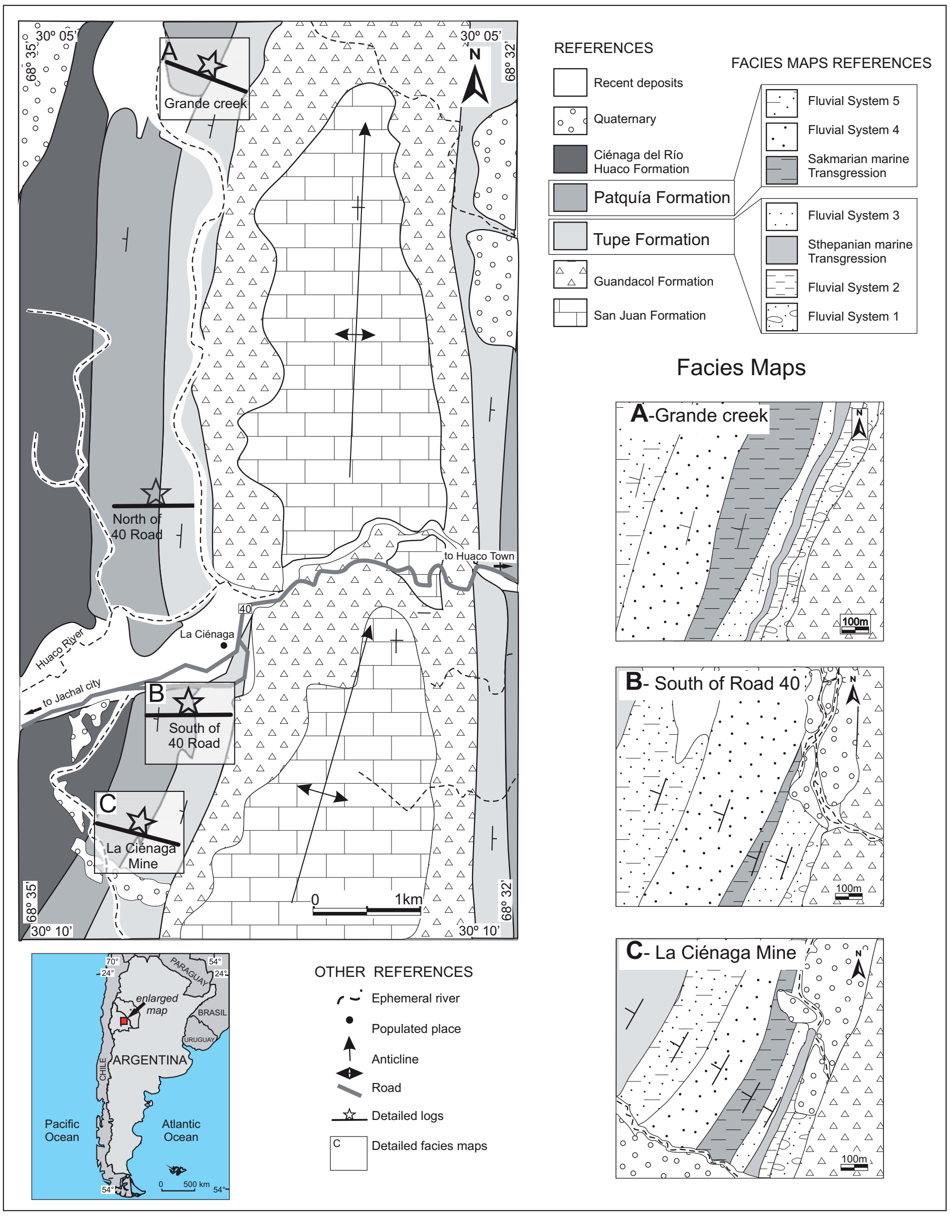


FIGURE 3 | **Geologic map of the Huaco area. A, B and C indicate the position of the detailed facies map showing the distribution of fluvial systems and incision surfaces. Stars indicate the location of sections studied in this paper and shown in figure 9.**

In the Paganzo Basin, marine sediments have yielded scarce remains of fossil invertebrates that lack stratigraphic significance (Martínez, 1993). However, in the neighboring Calingasta-Uspallata and Río Blanco basins, the postglacial marine deposits contain an important fauna belonging to the Lower-Middle Pennsylvanian brachiopod *Levipustula* Biozone (Fig. 4; Archangelsky et al., 1996). Moreover, palynological assemblages obtained from marine shales contain palynomorphs of the Lower Pennsylvanian *Rastrickia densa-Convolutispora muriornata* Biozone (Césari and Gutierrez, 2000).

A second transgressive event occurred during the Late Carboniferous, but in this case only the westernmost part of the Paganzo Basin was flooded (Fig. 4). In the Huaco area, marine deposits (up to 30m thick, Fig. 5A) are included in the middle part of the Tupe Formation (Limarino et al., 1987; Desjardins et al., 2009). The transgressive facies, forming a fining-upward succession, is composed of very fine-grained horizontally-laminated sandstones, shales and medium-grained cross-bedded sandstones. This interval represents sedimentation in estuarine tidal flats and in tidal channels with well-developed tidal bars (Fig. 5C). Highstand deposits were almost entirely eliminated in the western Paganzo Basin by a subsequent regional-scale fluvial incision event. Marine shales yield invertebrate fossils of the Late Pennsylvanian *Tivertonia-Streptorhynchus Biozone* (Archangelsky et al., 1996).

Finally, the youngest marine incursion recognized in Huaco occurs at the upper part of the Tupe Formation (Fig. 4). These marine deposits form a relatively thick succession (up to 70m, Figs 5A and 5B) of shales, mudstones and very fine-grained sandstones (Limarino et al., 1987) deposited in a distal-bay environment, were the sandstones represent tempestites (Desjardins et al., 2009). The transgressive systems tract is composed of horizontal-laminated and low-angle cross-bedded, medium- and fine-grained sandstones likely deposited in foreshore and backshore environments (up to 15m thick). This interval is replaced upwards by shoreface fine-grained sandstones and offshore shales including isolated sandy storm deposits (up to 40m thick). Highstand facies comprise coarsening-upward, muddy to sandy successions probably related to the progradation of open shorelines and strandplains. The thickness of the highstand deposits is highly variable because they have been truncated by a regional subaerial unconformity formed by fluvial incision. Despite the fact that fossils are not found in this interval in Huaco, the stratigraphic relations suggest a Late Pennsylvanian age for the marine flooding event.

LATE CARBONIFEROUS – EARLY PERMIAN PALEOCLIMATES

Glacial conditions in Gondwana were favoured by the location of parts of this supercontinent around the southern Pole during the Late Paleozoic (Geuna et al., 2010).

Late Paleozoic successions found in the Paganzo Basin show a paleoclimatic evolution from glacial to arid (hot) conditions (Fig. 4, for reviews see López Gamundí et al., 1992 and Limarino et al., 1997). A glacial climate prevailed during the Namurian in the Upper Paleozoic basins of Argentina. This extreme climate led to the widespread deposition of diamictites bearing faceted and striated clasts and shales with dropstones (González, 1982; López

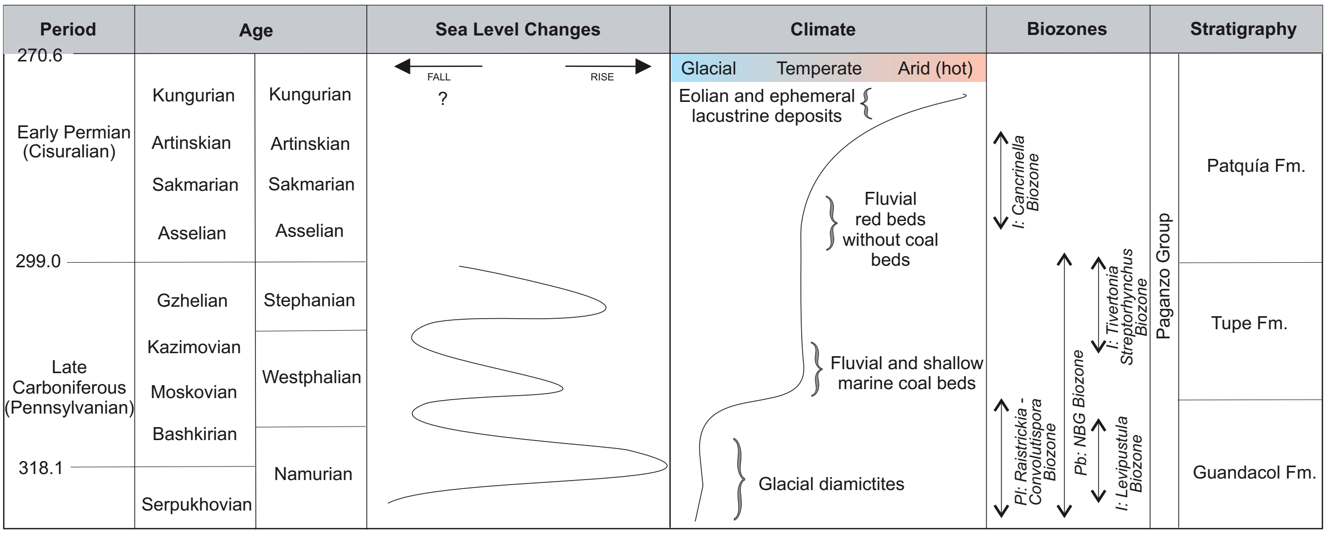


FIGURE 4 | **Late Paleozoic sea level and climatic changes in Huaco and in neighboring areas. Pb: paleofloristic, Pl: palynological and I: invertebrate biozones.**

Gamundí, 1989; López Gamundí et al., 1992; González Bonorino, 1992; Marenssi et al., 2005). These diamictites correspond to two different genetic types. On the one hand, there are true tillites showing massive stacked beds of breccias and paraconglomerates (Limarino and Gutiérrez, 1990; Marenssi et al., 2005) that in some cases rest on striated pavements (González, 1982; Marenssi et al., 2005). On the other hand, there is a suite of stratified diamictites that, though resulting from different kinds of resedimentation processes, was derived from a glacial source (López Gamundí, 1989, 1997).

Climate amelioration during the Early Pennsylvanian resulted in the decline of glacial conditions and the onset of a postglacial transgression. A postglacial cold and wet climate was inferred by López Gamundí et al. (1992) on the basis of the disappearance of glacial deposits, formation of carbonaceous mudstones and the occurrence of paleoflora dominated by lycophytes.

Towards the Middle-Late Pennsylvanian, wet and temperate conditions were conductive to the formation of coal (Fig. 4), carbonaceous shales and kaolinitic mudstones that were derived from intense K-feldspar weathering in soils (López Gamundí et al., 1992; Limarino et al., 1997; Net et al., 2002). Moreover, in this stratigraphic interval, vegetated paleosols are associated with abundant fossil floras composed of lycophytes, sphenophytes, pteridosperms, progymnosperms and *Calamites,* which suggest wet temperate conditions. These fossil plants belong to the Pennsylvanian Nothorhacopteris- Botryphyllum- Ginkgophyllum Flora (NBG, a classical Gondwana flora; Archangelsky, 1996).

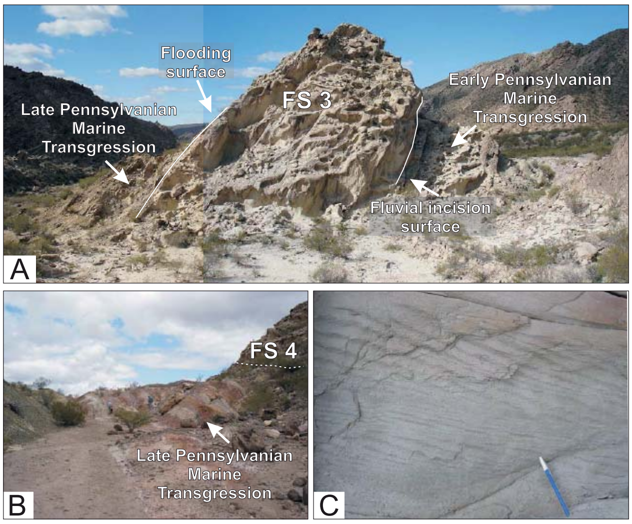


FIGURE 5 | **A) Stratigraphic position of the Early Pensylvanian and Late Pensylvanian marine transgressions. Both are separated by fluvial deposits belonging to FS3. B) Highly weathered Late Pensylvanian marine deposits eroded by fluvial deposits of FS4. C) Detail of tidal bar deposits showing inclined heterolithic stratification (IHS) in estuarine deposits associated with the Early Pennsylvanian transgression.**

A progressive decrease in humidity and a correlative increase in temperature is currently assumed to have occurred during the Late Pennsylvanian to Early Permian (López Gamundí et al., 1992; Limarino et al., 1997). Under these conditions, coal and carbonaceous shales became very rare (Fig. 4), and vegetated paleosols were progressively replaced by calcrete-type ones. The Lower Permian biological record is composed of scarce remains of the *Glossopteris* flora. Detailed phytoecological studies carried out by Cúneo (1986) suggest a temperate-dry, locally humid climate.

Finally, arid or semi-arid climates dominated during the Middle and probably Late Permian (Fig. 4), as suggested by the occurrence of widespread eolian deposits and ephemeral lacustrine facies (Limarino and Spalletti, 1986; Limarino et al., 1991; López Gamundí et al., 1992).

The fluvial systems reported in this paper correspond to the Upper Carboniferous, which comprises intermediate climates between glacial and hot-arid conditions (Fig. 4). Thus, the fluvial deposits might have been formed under two major climatic stages, first a humid and temperate climate, (Early to Middle Pennsylvanian) and a later drier and probably hotter climate (Late Pennsylvanian).

LATE CARBONIFEROUS – EARLY PERMIAN TECTONIC SETTING

During the late Paleozoic, the westernmost part of Gondwana was a tectonically active margin where two major types of basins are recognized: arc-related and retroarc basins (Limarino and Spalletti, 2006). Arc-related basins, including the Río Blanco Basin (Figs. 1 and 6), formed the proto-Pacific margin of Gondwana that experienced important tectonic and volcanic activity during the latest Devonian-Early Carboniferous and from the Middle Permian to the Early Triassic (Llambías and Caminos, 1987; Breitkreuz, et al., 1989; Caminos and Azcuy, 1996; Ramos, 1999; Limarino et al., 2006).

The retroarc basins, including the Paganzo Basin, occur between the highly deformed arc-related area and the pericratonic upland region of the Sierras Pampeanas (Figs. 1 and 6). In this area, volcanic and tectonic activities were more limited than in the arc-related basins. Diverse interpretations have been proposed for the Paganzo Basin. López Gamundí and Breitkreuz (1997) and López Gamundí et al. (1994) considered the Paganzo as a foreland basin while Fernández-Sevesso and Tankard (1995) interpreted it as a suite of discrete fault-controlled depocenters that originated as transtensional pull-apart basins. Although this last model can be applied to the early evolutionary stages of the Paganzo Basin (Late Mississippian), a more robust interpretation has been suggested by Ramos and Palma (1996) who described the Paganzo as a composite basin divided into two sectors: a western foreland region and an eastern pericratonic area. More recently, Limarino et al. (2006) discussed subsidence in the Paganzo Basin and proposed at least two different subsidence mechanisms: 1) extension in the back-arc region related to the subduction of the paleo-Pacific plate, or 2) extension related to the collapse of the Protoprecordillera Orogen, which resulted in mass transfer towards the east and a consequent increase in subsidence in the Paganzo area.

Stratigraphic studies clearly show that the Paganzo Basin is a polyhistory basin, showing three main evolutionary stages (Limarino et al., 2006). The oldest corresponds to the foreland basin stage developed in an embryonic “proto-Paganzo Basin” throughout the Protoprecordilleran orogeny (Late Devonian-Early Carboniferous, A in figure 6). The Protoprecordillera was formed during the Middle Devonian to the earliest Carboniferous accretion of the Chilenia Terrain to the western margin of Gondwana (Ramos et al., 1984, 1986; López Gamundí et al., 1994; Limarino et al., 2006). This collision promoted the formation of a fold and thrust belt (Protoprecordillera) separating the western Río Blanco Basin from the foreland area of the Paganzo Basin (A in figure 6).

From the beginning of the Pennsylvannian to the earliest Permian, tectonic and magmatic activity was low in the Paganzo Basin and post-orogenic sedimentation dominated in the area formerly corresponding to both arc-related and retroarc basins (Caminos and Azcuy, 1996; Limarino et al., 2006, B in figure 6). Provenance analyses in the Paganzo Basin, based on detrital modes of sandstones (Net and Limarino, 2006), show an important decrease in the input of lithic sediments from the Protoprecordillera during the Pennsylvanian, which suggests low tectonic activity and subdued topographic relief in the Protoprecordillera area (Fig 6). Low tectonic activity in the Paganzo Basin during the Late Carboniferous-Early Permian was also pointed out by Fernández-Seveso and Tankard (1995) who considered that low and uniform regional subsidence rates occurred during this interval.

During the Middle Permian, subduction was re-established in the westernmost part of the arc-related basins, which were partially covered by widespread volcanic rocks (C in figure 6). During this time, tectonic deformation was concentrated in the Andean region while widespread red bed successions accumulated in retroarc areas (Paganzo Basin).

In summary, the strata analyzed in this paper (Pennsylvanian) records no stratigraphic or provenance evidence for significant tectonic activity in the Paganzo area. This time interval is considered to be a time of post-orogenic sedimentation (Fernández-Seveso and Tankard, 1995; Caminos and Azcuy, 1996; Limarino et. al., 2006) and relative tectonic quiescence.

FLUVIAL SEDIMENTATION

Bounding surfaces and architectural elements

The characterization of fluvial sedimentation is based on the identification and description of architectural elements within the studied strata (Allen, 1983; Miall, 1985, 1996; Sánchez Moya et al., 1996). A bounding surface nomenclature encompassing seven hierarchical categories based on Miall’s (1985, 1996) methods (Fig. 7) was used in this study. Thus, first and second-order bounding surfaces were used to characterize micro and mesoform dynamics, whilst third-order surfaces allow for describing the style of bar migration (Fig. 7). Fourth order surfaces correspond to the classical example defined by Miall (1985) as those limiting the preserved morphology of macroforms, frequently bars or architectural elements within floodplain deposits. Following DeCelles et al. (1991), two different

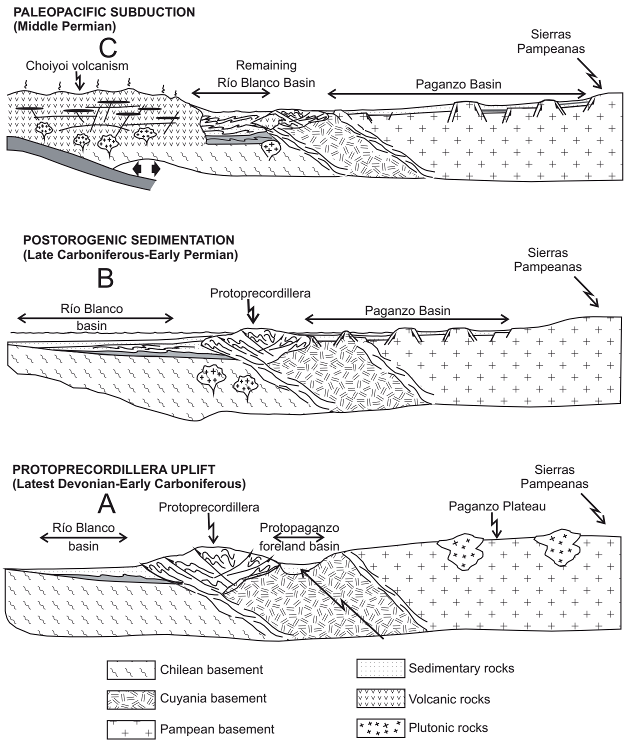


FIGURE 6 | **Tectonic evolution of the western margin of Gondwana during the Early Paleozoic.**

types of fourth-order surfaces were identified: accretionary (4a) and erosional (4e, Fig. 7). The accretionary surface bounds the upper part of macroforms characterized by low relief and flat or convex-upward geometry (Fig. 7). The 4e surface corresponds to the erosional base of channelized bodies. The DeCelles et al. proposal has been adopted because the distinction between two kinds of fourth-order surfaces ("a" and "e" types, Fig. 7) is useful not only to describe the internal characteristics of channel belts but also to characterize minor crevasse channels within floodplain deposits.

Fifth-order bounding surfaces consist of flat or low-relief erosional surfaces that define channel-fill complexes (Fig. 7). Characteristically, fifth-order surfaces show longer lateral continuity and exhibit lower relief than those enclosed in erosive fourth-order surfaces. The sixth-order surfaces recognized here show low-relief and bound stacked channel complexes, forming slightly irregular or flat erosive surfaces rather than erosive incisions (Fig. 7). Finally, seventh-order surfaces appear as incision surfaces that, in some cases, form small paleovalleys (Fig. 7).

On the basis of the arrangement of bounding surfaces and lithofacies distribution, a total of 10 architectural elements have been identified in the fluvial deposits. In-channel architectural elements include: single channels (CHs), channel-fill complexes (CHm), lateral-accretion macroforms (LA), downstream accretion macroforms (DA) and sandy bedforms (SB). In floodplain areas, muddy floodplain fines (FF), sandy overbank sediments (SO), swamp (SW), crevasse splay (CS), crevasse channel (CR) and levee (LV) elements were recognized.

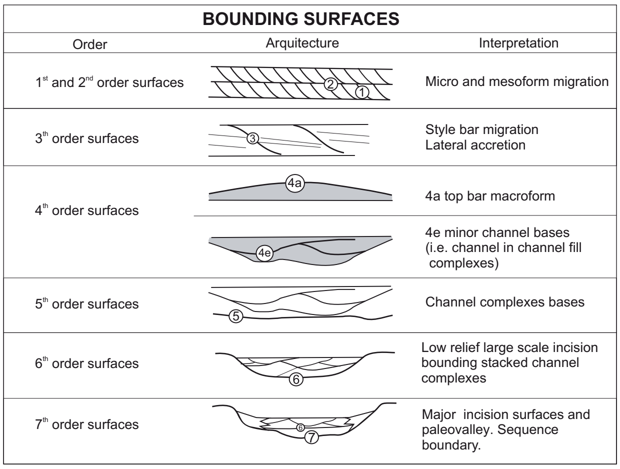


FIGURE 7 | **Bounding surfaces and architectural elements used in this paper (slightly modified from Miall, 1996).**

Fluvial systems

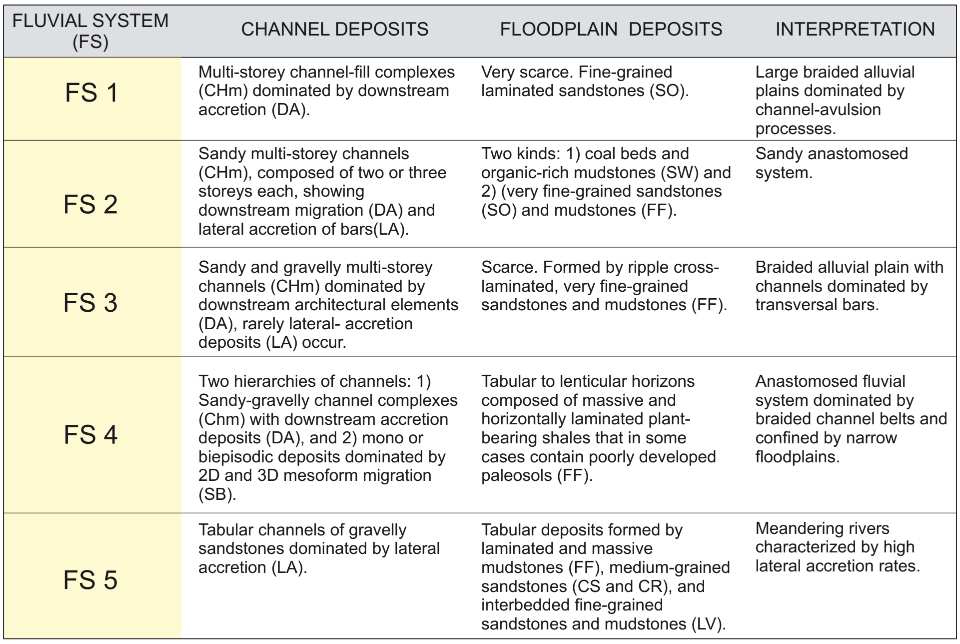
The different architectures of channel and floodplain deposits allows for the differentiation of five types of fluvial systems (FS) in the Tupe Formation (Figs. 2 and 8). The stratigraphic position of the fluvial systems and associated marine deposits in the four different sections located along the western flank of the Huaco anticline are shown in figure 9.

Fluvial system 1 (FS 1)

FS 1 occurs in the lower part of the Tupe Formation and rests on a low-relief seventh-order surface carved into shallow marine and deltaic deposits of the upper Guandacol Formation (Fig. 2 and 9). FS1 consists of stacked lenticular channels forming multi-storey channel-fill complexes (up to 8m thick) bounded by low relief fifth-order bounding surfaces (CHm architectural element, Figs. 9 and 10a). Internally, the channel-fill complexes were divided into single channel units (CHs architectural element), which were bounded by concave upward high- to moderate-relief e-type fourth-order surfaces. The bottom of each channel body is made up of a thin, massive, sandy gravel veneer representing a channel lag deposit (Fig. 9 and 10a). This interval is followed by sandy bar deposits composed of horizontal or low-angle tabular cross-bedded sets laterally bounded by third-order surfaces, forming the DA architectural elements (Miall, 1985). Bar top deposits, which are made up of centimeter-scale intervals of horizontal-laminated medium to fine-grained sandstones, commonly are partially eroded.

Although fine-grained floodbasin deposits are very scarce in this unit, some discontinuous intervals of laminated fine-grained sandstones are believed to represent sedimentation on the alluvial plain during flood events (SO architectural element, Fig. 11).

FS1 is interpreted as originating on large braided alluvial plains (Miall, 1996) dominated by channel-avulsion processes (Fig. 11). Fifth-order bounding surfaces, indicating the base of channel complexes, probably formed during periods of alluvial-plain erosion that were not important enough to promote significant incision of previously formed deposits. Channels were probably dominated by low-relief longitudinal bars that favored the formation of horizontal or low-angle tabular cross-bedded sets (Fig 11 and 10a). Restricted formation of alluvial plain deposits similar to those described by Reinfelds and Nanson (1993) could be represented by fine-grained laminated sandstones of the SO architectural element. However, the distinction between alluvial plain and bar top deposits is frequently problematic.



FLUVIAL SYSTEM (FS)	CHANNEL DEPOSITS	FLOODPLAIN DEPOSITS	INTERPRETATION
FS 1	Multi-storey channel-fill complexes (CHm) dominated by downstream accretion (DA).	Very scarce. Fine-grained laminated sandstones (SO).	Large braided alluvial plains dominated by channel-avulsion processes.
FS 2	Sandy multi-storey channels (CHm), composed of two or three storeys each, showing downstream migration (DA) and lateral accretion of bars(LA).	Two kinds: 1) coal beds and organic-rich mudstones (SW) and 2) (very fine-grained sandstones (SO) and mudstones (FF).	Sandy anastomosed system.
FS 3	Sandy and gravelly multi-storey channels (CHm) dominated by downstream architectural elements (DA), rarely lateral- accretion deposits (LA) occur.	Scarce. Formed by ripple cross-laminated, very fine-grained sandstones and mudstones (FF).	Braided alluvial plain with channels dominated by transversal bars.
FS 4	Two hierarchies of channels: 1) Sandy-gravelly channel complexes (Chm) with downstream accretion deposits (DA), and 2) mono or biepisodic deposits dominated by 2D and 3D mesoform migration (SB).	Tabular to lenticular horizons composed of massive and horizontally laminated plant-bearing shales that in some cases contain poorly developed paleosols (FF).	Anastomosed fluvial system dominated by braided channel belts and confined by narrow floodplains.
FS 5	Tabular channels of gravelly sandstones dominated by lateral accretion (LA).	Tabular deposits formed by laminated and massive mudstones (FF), medium-grained sandstones (CS and CR), and interbedded fine-grained sandstones and mudstones (LV).	Meandering rivers characterized by high lateral accretion rates.

FIGURE 8 | **Chart summarizing the major characteristics of the fluvial systems described in this paper. In brackets are marked the architectural elements of channel and floodplain deposits.**

Fluvial system 2 (FS 2)

Fluvial system 2 occurs above deposits of the FS 1 and is overlain by marine strata deposited during the Early Pennsylvanian transgression (Fig. 9). The contact between FS 1 and FS 2 is transitional and is marked by an increase in the abundance of cross-bedded sets within channel deposits and by the occurrence of fine-grained floodbasin deposits. The upper bounding surface separating FS2 and the overlying marine deposits is gradational without evidence of significant marine erosion.

FS 2 channel deposits comprise multi-storey channels (CHm) up to 1.5m thick, each composed of two or three storeys (Fig. 11). The bottom of the channel deposits is dominated by massive coarse-grained sandstones showing dispersed pebbles. Bar deposits, which form the major part of each channel fill, are made up of coarse and medium-grained sandstones containing both tabular and trough cross-bedded sets (up to 40cm thick, Fig. 11). Bar top deposits, up to 20cm thick, consist of parallel laminated and ripple-cross laminated fine-grained sandstones, locally including mudstones. Cross-bedded units yield westward paleocurrent orientations.

Two different types of third-order surfaces have been identified in these strata (Fig. 11). The first consists of convex-upward inclined surfaces that bound medium-scale cross-bedded sets and cosets formed by the downstream migration of bars (DA). The other type is composed of concave-upward surfaces defining lateral accretion units (LA).

Probably, one of the most conspicuous features of FS 2 is the existence of two different kinds of floodplain deposits (Fig. 11). First, coal beds and organic-rich mudstones with abundant remains of fossil plants form the SW architectural element. This type of deposit exhibits lenticular beds that are a few hundred meters wide and up to 1.5m thick. They are commonly overlain by muddy floodplain accumulations (Fig. 12 A).

A second type of floodplain accumulation corresponds to meter-scale successions of interbedded very fine-grained sandstone and mudstone (SO and FF architectural elements, Fig. 11). The former occurs as heterolithic or ripple-cross laminated micaceous-rich beds (up to 30cm thick, Fig. 12B), while mudstones (commonly organic-rich) are mainly massive or show pedotubules, root trace fossils and other soil structures. Lateral and vertical transitions between coal beds (SW) to interbedded sandstones and mudstones (FF) occur locally (Fig. 12A).

A network of sandy anastomosed channels is hypothesized as the best scenario to explain the depositional style for strata included in FS 2 (Miall, 1996; Makaske, 2001- Fig. 11). In this context, channels may have been dominated not only by downstream migration of in-channels bars (DA) but also by lateral accretion of point bars (LA, Fig. 11). However, the multi-storey character of the channels clearly suggests that they were relatively stationary on their floodplains with a low rate of lateral migration. As shown in figure 11, channel belts were separated by broad, vegetated and, in some cases, poorly-drained floodplains. Swamp areas (SW), prob-

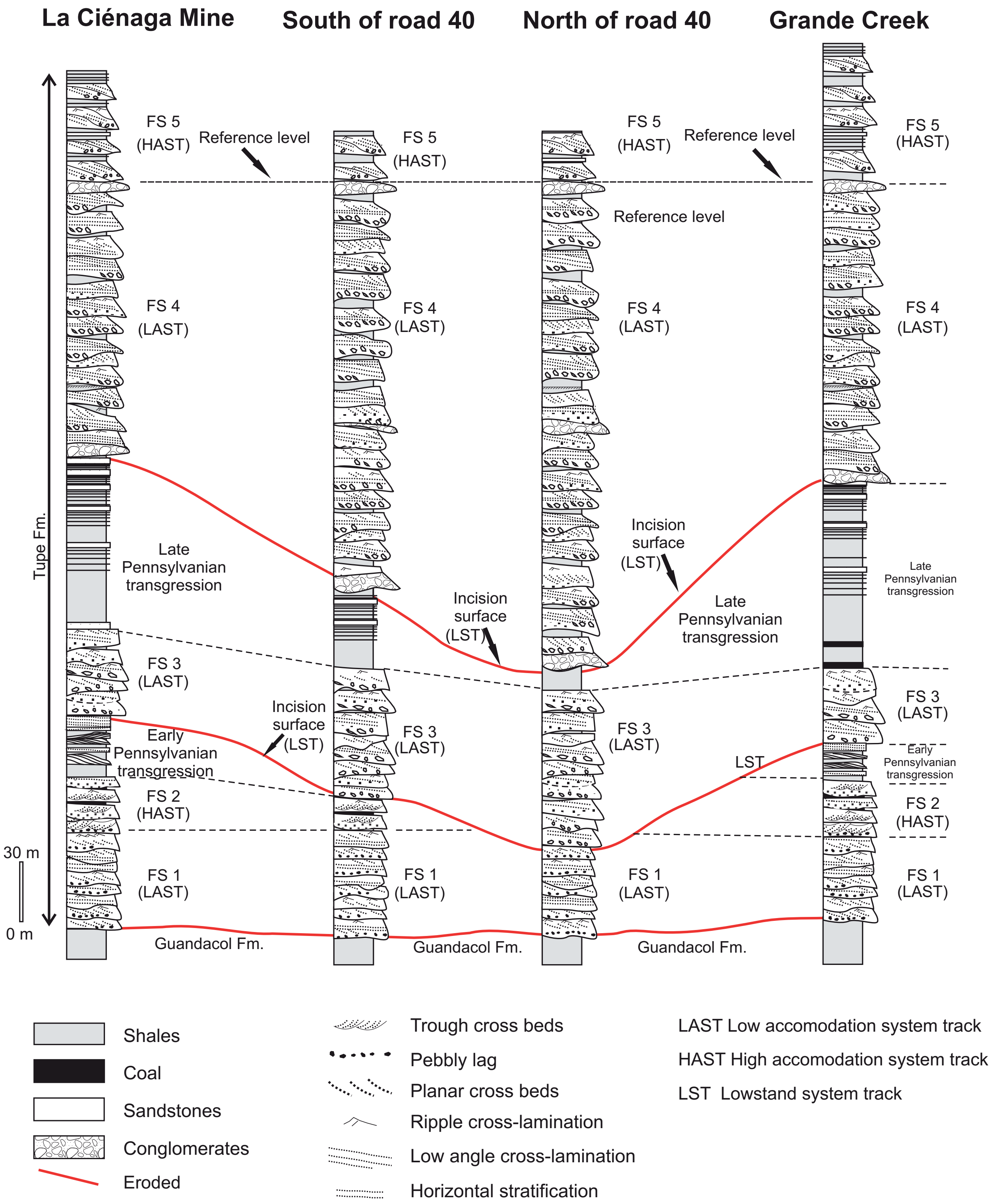


FIGURE 9| **Stratigraphic positions of marine and fluvial systems along the western flank of the Huaco anticline. Note that marine deposits are missing or partially removed in some sections due to fluvial incisions during sea level fall (for location of the sections see figure 3).**

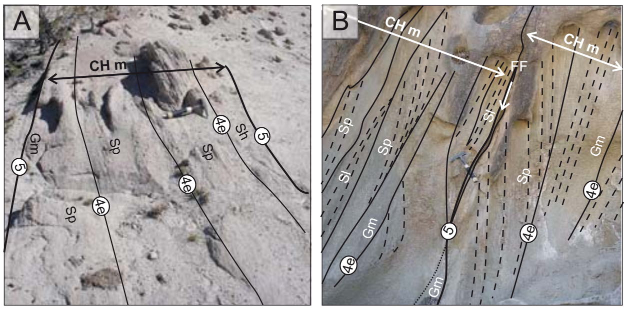


FIGURE 10 | **A) CHm architectural element of FS1 with massive conglomerates, planar cross- bedded sandstones and horizontal bedded fine-grained sandstones; B) CHm and FF architectural elements of FS3 showing five order bounding surfaces that enclose minor channels limited by 4e bounding surfaces.**

ably related to abandoned channels, passed laterally into low-gradient and better-drained floodplains (FF).

Fluvial system 3 (FS 3)

FS 3 is intercalated between two marine transgressive successions (Fig. 2 and 9) and it is almost entirely composed of coarse-grained sandstones with subordinate conglomerate units. The base of FS 3 is marked by a moderate to high-relief erosional surface cut into marine deposits related to the Early Pennsylvanian transgression (seventh-order bounding surface, Fig. 9). The importance of this surface can be easily deduced in a North-South transect from La Ciénaga Mine (South) to Grande Creek (North, Figs. 3 and 9). At the southern end of the transect, the incision surface separates marine units related to the Early Pennsylvanian transgression below from FS3 sandstones above. Southward (North of road 40 outcrops, Fig. 9), the incision surface has not only cut out all of the marine deposits of the Early Pennsylvanian transgression, but it also truncates sandstone deposits of FS 2, including coal beds and carbonaceous mudstones, characteristic of that fluvial system (Fig. 9). Further North (Grande Creek in Fig. 3), Early Pennsylvanian marine deposits and coal beds of the FS 2 re-appear as the erosion surface rises up within the stratigraphic succession (Fig. 9) pointing out the irregular relief on the incision surface.

FS 3 deposits are overlain by shales of the Late Pennsylvanian transgression and rest on an erosion surface with a minimal relief that is locally covered by a thin interval of marine reworked fluvial sandstones.

Channel deposits within FS3 consist primarily of sandstones with minor accumulations of conglomerates. These deposits form channel complexes consisting of multi-storey channels (CHm) up to 3m thick (Fig. 11 and 10b). Each channel complex is bounded by a flat fifth-order bounding surface, but in some cases channel complexes are amalgamated and fifth-order bounding surfaces can not be clearly identified. A distinctive feature of FS3 is the presence of slightly erosive sixth-order bounding surfaces that bound three or four stacked channel complexes similar to the "groups of channels" described by Miall (1996). In this case, the low relief of the surfaces is believed to have been caused by short-term stabilization of the alluvial plains associated with brief periods of erosion rather than long-term incision and the formation of paleovalleys (Zaitlin et al., 2002).

Pebble conglomerates and massive coarse-grained sandstones with dispersed gravel-size clasts form the lower part of the channel complexes. Intraformational mudstone and coal clasts (up to 25cm in diameter) are common in the lower portion of FS3. The intraformational clasts represent erosion of underlying FS2 and Early Pennsylvanian marine strata. The remainder of the channel fill consists of sandy bar deposits that exhibit tabular cross-bed (up to 40cm, fig. 10b) with minor occurrence of trough cross-bedded sets. Inclined third-order surfaces bound downstream architectural elements (DA) that dominate over rare lateral-accretion deposits (LA, Fig. 11). Paleocurrent orientations indicate westward and southwestward sediment transport.

Floodplain deposits are scarcely represented. They occur sporadically as thin intercalations of ripple cross-laminated, very fine-grained sandstones and mudstones (FF). They are more common in the upper part of FS3.

FS 3, probably formed on a wide braided, alluvial plain (Miall, 1996) with channels dominated by transversal bars (Fig. 11). Recurrently, the alluvial plain might have been stabilized and partially eroded, promoting the formation of low relief sixth-order surfaces that limited groups of channel complexes. Fine-grained floodplain deposits are volumetrically less significant.

Fluvial system 4 (FS 4)

Marine deposits related to the Late Pennsylvanian transgression are abruptly overlain by pebble conglomerates and medium-grained sandstones, here constituting the base of FS 4 (Fig. 9). An incision surface beneath these fluvial deposits truncates most of the underlying Late Pennsylvanian marine deposits (south and north of the road 40 stratigraphic sections, Fig. 11). Locally, a deeply weathered claystone and siltstone interval (up to 15m thick), containing paleosols bearing metallic and carbonate concretions, occurs at the top of the marine deposits. These paleosols suggest prolonged subaerial exposure of the marine deposits following sea level fall.

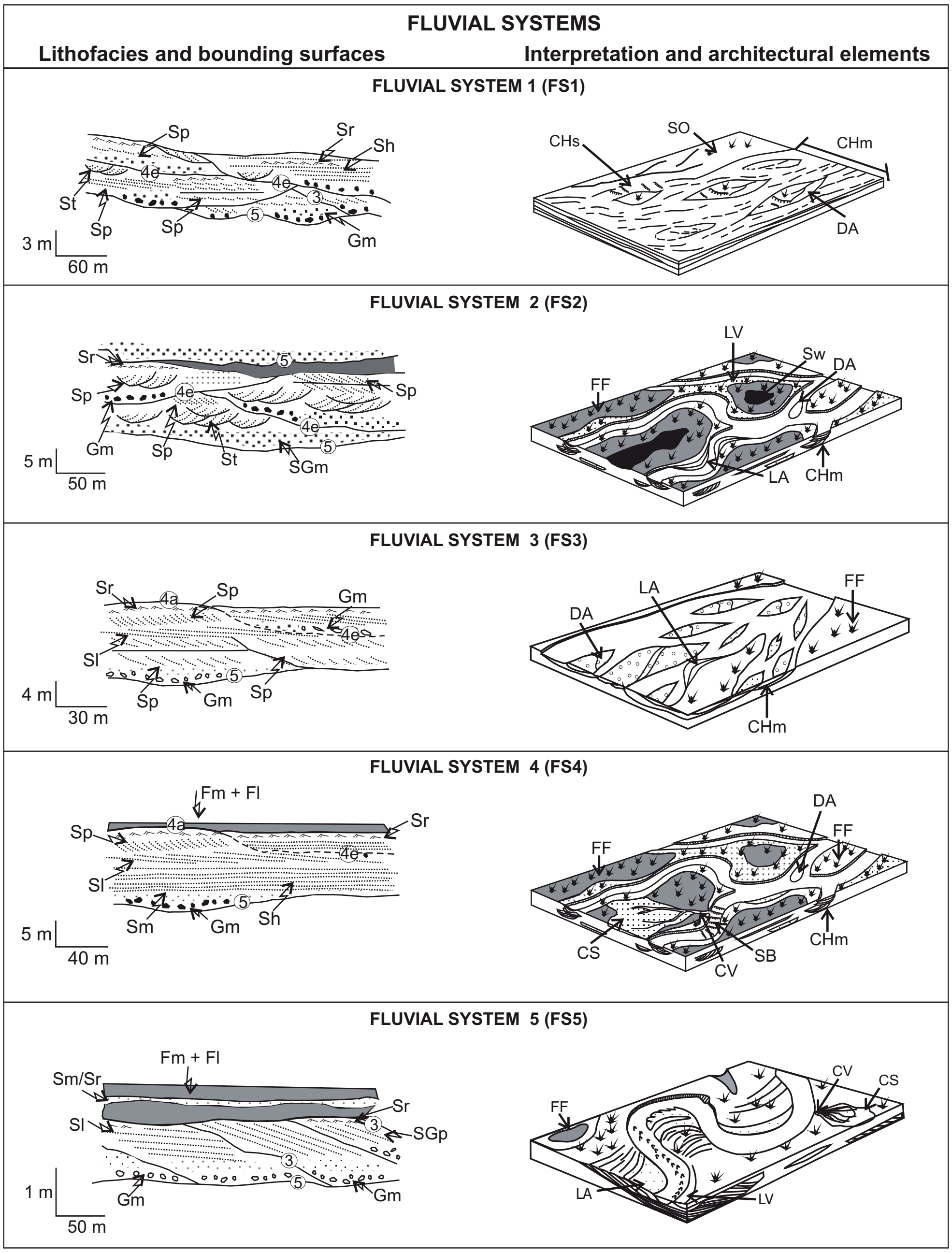


FIGURE 11 **Lithofacies, bounding surfaces, architecture and interpretation of the fluvial systems. Gm: massive conglomerate, SGm: massive pebble sandstone, SGp: planar cross-bedded pebble sandstone, Sl: low angle laminated sandstone, Sm: massive sandstone, St: trough cross-bedded sandstone, Sp: planar cross-bedded sandstone, Sh: horizontal laminated sandstone, Sr: ripple laminated sandstone.**

A conspicuous feature of the strata of FS 4 is the occurrence of two different types of channel deposits (Fig. 11). The first type consists of thick channel complexes (4 to 6m thick, CHm) commonly bounded by a low-relief fifth-order bounding surface mantled by intraformational mudstone clasts (up to 20cm in diameter). This basal interval is overlain by cross-bedded, pebble conglomerates, which in turn, are overlain by coarse and medium-grained trough and tabular cross-bedded sandstones. Concave upward 4e-order surfaces bound individual channels, while 4a-order inclined and convex-upward surfaces bound downstream accretion (DA) architectural elements interpreted as bars.

The second type of channel deposits consists of mono or bi-episodic deposits (up to 70cm thick) dominated by 2D and 3D mesoform migration (SB architectural element, Fig. 11). In some cases, these channel fills occur within fine-grained floodplain deposits and consist of a thin basal lag of coarse and medium-grained sandstones draped by ripple cross-laminated fine-grained sandstones or by massive muddy sandstones. Paleocurrent orientations display relatively high dispersions and indicate westward to southward paleo-flow directions. The southward-oriented paleocurrents are likely to be the result of fluvial systems flowing parallel to the Protoprecordillera belt while westward

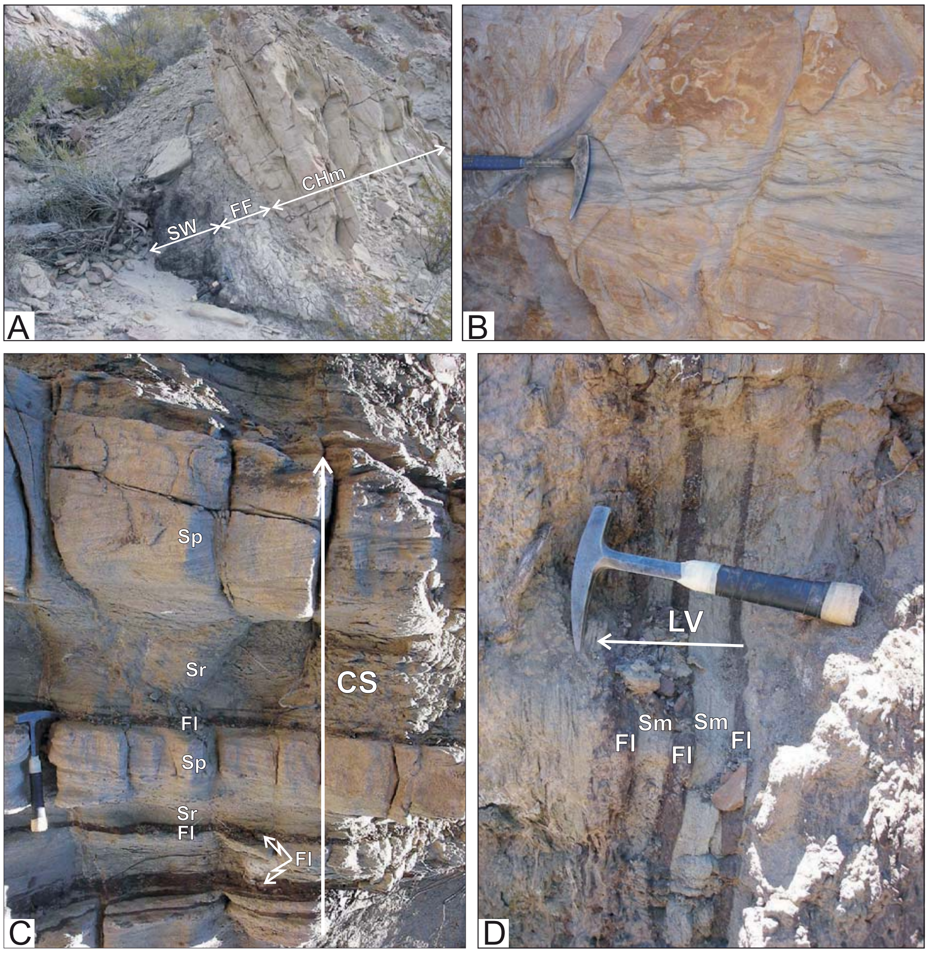


FIGURE 12 **A) Lenticular coal beds (SW architectural element) contained in muddy floodplain deposits (FF) of FS2, B) Heterolithic ripple cross-laminated fine-grained sandstone (SO) deposited in sandy alluvial plains (FS2), C) Levee deposits (LV) consisting of fine-grained sandstones and mudstones of FS5 d. Interbedded fine- or medium-grained sandstones and mudstones deposited in crevasse splays areas (CS) of FS5.**

paleoflows are more consistent with the regional drainage pattern in the Paganzo Basin.

Floodplain deposits form tabular to lenticular horizons 10 to 30cm thick. The overbank sediments are composed of massive and horizontally laminated plant-bearing shales that in some cases contain poorly developed paleosols (FF). These floodplain sediments are commonly interbedded with ripple cross-laminated and heterolithic fine-grained sandstones, and were probably formed by low-energy floods across interchannel areas.

The proposed model is that of an anastomosed fluvial system dominated by braided channel belts and confined by narrow floodplains (Fig. 11), which is similar to the one described by Makaske (2001). In this context, channel complexes are dominated by downstream architectural elements (DA), which correspond to the main channels of the alluvial belt. These channels were probably characterized by transversal bars. In contrast, simple channel deposits, made up of sandy mesoforms (SB), correspond to both secondary channels within the anastomosed belt (CHs) and/or crevasse channels within the floodplains (CR). Dominant processes in the floodplains include settling of fine-grained particles from suspension or by low-velocity flood currents rather than by the progradation of crevasse splays.

Fluvial system 5 (FS 5)

This fluvial system is composed of tabular beds of pebbly sandstones, coarse to medium-grained sandstones and mudstones. These deposits are transitional with underlying deposits of FS 4 (Fig. 9). Strata within this interval consist of fining-upward cycles, ranging from 1.5 to 3m in thickness. Channel deposits occur in the lower part of the cycle and are overlain by floodplain. Each cycle begins with a low relief erosional surface draped by a thin interval (up to 10cm) of massive pebbly sandstone. This interval is overlain by coarse to fine-grained trough cross-bedded sandstones that are laterally bounded by sloping convex-upward third-order surfaces (LA architectural element).

Channel sediments are covered by muddy overbank deposits (Fig. 11). Channel/overbank ratios range from 0.6 in the lower part of the section to 0.4 at the top, thus showing a progressive enrichment of floodplain deposits towards the top of FS5. Overbank deposits consist of parallel-laminated and massive claystones and siltstones (FF element) with centimeter scale intercalations (up to 8cm thick) of fine to medium-grained sandstone (Fig. 11). Despite the lack of preserved paleoflora, the existence of paleosols is suggested by the abundance of mottled structures, vertical tubes (pedotubules) and carbonate concretions probably related to calcrete-type paleosoils.

Fine-grained overbank deposits commonly pass laterally into interbedded fine or medium-grained sandstones and mudstones deposited as crevasse splay (CS architectural element, Fig. 12C). In some cases small feeder channels (CR element) with concentric or asymmetric fills (nomenclature from Gibling, 2006) are preserved. Crevasse splay medium-grained sandstones exhibit ripple cross-lamination, heterolithic bedding and, more rarely, horizontal bedding with parting lineation. Locally, thin intervals (up to 0.7m) of interbedded fine-grained sandstones and mudstones occur as levee deposits (LV element, Fig. 12D). The sandy units are composed of centimetre-scale beds of massive or ripple cross-bedded fine or very fine-grained sandstones, while mudstones appear as laminated, partially bioturbated or massive beds.

FS 5 is interpreted as originated from meandering rivers. Channels were characterized by high lateral accretion rates, and formed extensive point-bar deposits (Fig. 11). According to thickness and stratification types, point bars show moderate to low relief, low gradient and were dominated by downstream migration of in-channel bedforms (Miall 1991,1996). Lateral accretion of point bars is only shown by the presence of third-order bounding surfaces that point out periods of channel stabilization.

The progressive increase of muddy sediments towards the top of the FS 5 reflects an increase in the preservation of overbank deposits. During flood stage, sedimentation on the floodplain was probably dominated by two different mechanisms. The first is composed of thin intervals of ripple-cross and horizontal lamination with parting lineation and corresponds to the migration of sandy bedforms. These structures suggest relatively high velocity currents related to maximum flood stage. The second mechanism is the settling of fine-grained particles that produced laminated and massive muddy sediments (FF architectural element), which reflect the lowest velocity currents in the latest stages of flooding.

CONTROLS IN THE EVOLUTION OF FLUVIAL SYSTEMS

While sea level and climate seem to have been first-order controls influencing the evolution of the fluvial systems, neither significant tectonic activity nor changes in subsidence rates have been reported from Huaco and the surrounding areas (Limarino et al., 2006). Therefore, in the following discussion the effect of tectonism on the evolution of the fluvial depositional environments is considered to be secondary relative to sea level and climatic forcing.

During the Namurian, as a consequence of a global sea level fall, rivers showed a low stream equilibrium profile, favoring minor incisions into shallow marine deposits of the postglacial marine succession (top of Guandacol Formation, Figs. 13 and 14). Seemingly, large-scale incision surfaces are missing, or at least poorly developed in the western Paganzo Basin. Because of minimal relief, the contact between the Guandacol and Tupe Formations is frequently described as conformable. This fact is indicated not only by local-scale observation but also by a regional tendency of fluvial deposits of the Tupe Formation to overlie shallow marine and delta-top facies at the top of the Guandacol Formation. Holbrook (1996) showed that the formation of low relief incision surfaces resulted from fluvial progradation over a very flat coastal plain when fluvial depositional rates are high enough to keep pace with the rate of sea-level fall. In the case reported here, a similar context is suggested for the contact between Guandacol and Tupe Formations. Accordingly, the end of the glaciation, and a Namurian sea level rise, might have left large quantities of sediments stored in wide outwash plains, such as might have occurred in the easternmost part of the Paganzo Basin. During the regressive phase, following glaciation, large amounts of glacial detritus were reworked and transported from inland areas in the east to coastal plains in the west. Therefore, the high availability of sediment, may not only have promoted a decrease in the capacity of fluvial erosion, but it may also have maintained an equilibrium between sea-level fall and sediment supply, thus avoiding the formation of a high relief incision surface during sea level fall.

During the Westphalian, this low-relief topography might have been rapidly buried and smoothed by deposition of sandstones and conglomerates. Therefore, FS1 deposits first occurred as poorly confined braided stream systems and then as unconfined braid plains. It is not possible to establish unequivocally the exact relationship between the deposition of the FS1 and the position of the shoreline relative to the sea level curve. For this reason, we interpret FS1 deposits to have formed in a low-accommodation system tract (as defined by Catuneanu, 2006). In the study area, low-accommodation was mainly controlled by sea level. However, different situations can be envisaged within this context, including deposition during lowstand conditions and in the early phase of transgression (Fig. 14). The lack of an incision surface at the base of the FS1 suggests that fluvial sedimentation may have been continuous from the lowstand to the early stages of the transgressive system tract.

The braided stream deposits characterizing FS1 evolved into anastomosed fluvial deposits (FS2), which corresponded to a high-accommodation system tract. This change is here interpreted as linked to the Early Pennsylvanian transgression (Figs. 13 and 14). The anastomosed deposits included in FS2 were characterized by highly stabilized channels that were separated by both vegetated and poorly drained floodplains. Coal beds, organic-rich shales and stacked paleosols suggest that the equilibrium profile was elevated above the actual slope of the system. Such an elevated equilibrium profile favored aggradational processes in the low-gradient alluvial plains of FS 2. Accordingly, the accumulation and preservation of peat depend upon the balance between the rate of the creation of accommodation space rather than the rate of peat production (Bohacs and Suter, 1997). In particular, the existence of hydromorphic paleosols associated with coal beds points to high water-table positions during advanced stages of the Pennsylvanian transgression (Tandon and Gibling, 1994; Greb and Chesnut, 1996; Davies et al., 2006). Holocene mires show that, even in very wet climates, peat cannot accumulate more than 20m above the regional groundwater table (Bruenig, 1990; Davies et al., 2006). Finally, when the transgression reached this part of the basin, estuarine conditions replaced fluvial sedimentation (Fig. 13).

The boundary between the estuarine and shallow marine deposits related to the Early Pennsylvanian transgression and FS3 is a moderate to high-relief incision surface that progressively cut-out Early Pennsylvanian marine deposits towards the north (Figs. 9 and 13). This surface is easily identified in the field, as it is marked by a break from muddy shallow-marine to estuarine Early Pennsylvanian sediments below from fluvial coarse-grained arkoses above. Overlaying the incision surface coarse-grained sandstones and conglomerates belonging to FS3 were deposited by a braided-fluvial system (Fig. 13). This fluvial system is widely distributed along the western margin of the Paganzo Basin, separating the Early Pennsylvanian and

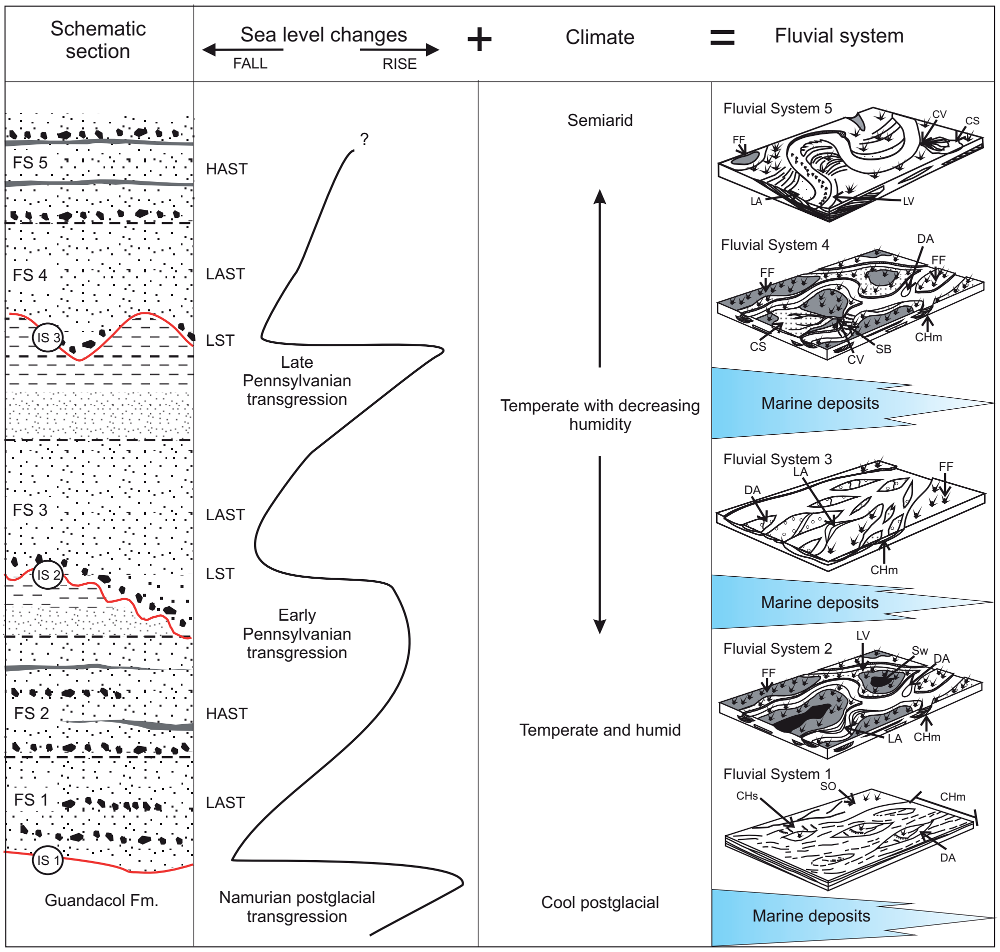


FIGURE 13 | **Schematic representation of sea level and climatic controls during the evolution of the fluvial systems described in the text. IS1: incision surface number 1, LAST: Low accommodation system tract, HAST: High accommodation system tract, LST: Lowstand system tract.**

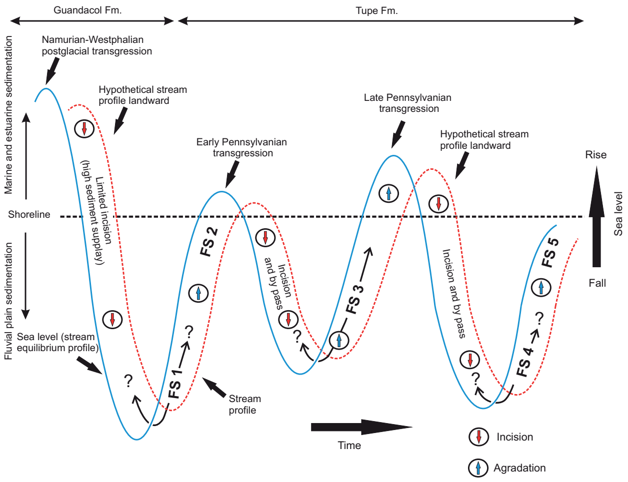


FIGURE 14 | **Idealized Upper Paleozoic sea level curve (solid line) and stream equilibrium profile (doted line). Note that when sea-level rise reaches the Huaco area, the stream profile line became a hypothetical projection landward.**

the Late Pennsylvanian transgressions. FS3 was dominated by multi-storey channels chiefly filled with transversal bar deposits. Amalgamated channel complexes of three or more stacked channel complexes are bounded by low relief sixth-order bounding surfaces. The origin of these surfaces is probably the result of local erosive episodes associated with high frequency sea-level falls within the larger-scale Late Pennsylvanian transgression. The presence of sixth-order surfaces corresponds to short-term falls in sea level that produced subtle temporary depressions in the stream equilibrium profile that resulted in short-term, small-scale erosional events. Later, the ensuing transgression allowed for the re-establishment of a high equilibrium profile that promoted aggradation in the fluvial system.

The lower part of the FS3 probably represents a vertical change from low-accommodation to high-accommodation conditions (as shown by the presence of floodplain deposits) associated with the Late Pennsylvanian transgression. In contrast to FS2, organic-rich fine-grained sediments and coals are missing from the top of FS3 despite the occurrence of high-accommodation conditions in both the fluvial systems. Such differences were probably result of different geomorphic settings. FS2 channels might have crossed low-gradient alluvial plains that drained into a low-energy estuarine system that favored the accumulation of organic matter. In contrast, FS3 was deposited by a more energetic, possibly higher gradient fluvial system, which passed laterally into a wave-dominated strandplain.

Differences in climatic conditions between FS2 and FS3 should also be considered. As illustrated in figure 4, climate during deposition of FS2 was wetter and temperate, which favored the accumulation of organic-rich sediment containing lycophytes, pteridosperms and progymnosperms plant fossils of the NBG flora. In comparison, FS3 was deposited under drier climatic conditions (López Gamundí et al., 1992; Limarino et al., 1997).

The most important fluvial incision took place at the top of the Late Pennsylvanian transgression succession (Figs. 9 and 13). Within the uppermost Late Pennsylvanian marine deposits, a thick (up to 15m) interval of highly weathered muddy sediments bearing different types of metallic concretions occurs. This horizon is used as a regional marker bed. The weathered horizon is exposed in at least two sites of the study area (Fig. 9). However it is missing in other places as detailed facies maps showed that this interval is eroded by the incision surface (Fig. 2). This scenario suggests that during sea-level fall, fluvial systems carved major valleys, more than 90m deep into the underlying marine sediments. Between these paleo-valleys, the uppermost marine deposits were preserved and probably remained exposed as terraces that experienced prolonged weathering and pedogenesis. Thus, these horizons represent sequence-bounding paleosols characterized by well-drained soil profiles, low water table positions, low sedimentation rates and prolonged exposure (Catuneanu, 2006). These conditions led to the formation of metallic concretions in highly lixiviated paleosols similar to “deeply-weathered soil profiles” (Blum and Aslan, 2006).

The incision surface was covered by pebble-conglomerates and sandstones belonging to FS4, which is interpreted as a low-accommodation system tract. These deposits are considered to reflect an anastomosed fluvial network that was dominated by braided channel belts (Figs. 11 and 13). This interval displays stream deposits dominated by downstream bar migration. The channel deposits are associated with thin overbank deposits composed of plant-bearing mudstones.

FS4 is transitionally overlain by pebbly sandstones and mudstones of FS5 that correspond to a high-accommodation system tract (Fig. 9). Deposits of this fluvial system are characterized by fining-upward cycles with channel-fills showing a high proportion of LA architectural elements. Fine-grained floodplain sediments (FF, CS and CV elements) progressively increase towards the top of each cycle with an overall increase in the ratio of floodplain to channel deposits occurring upward within the deposits of FS5. The increase in the abundance of floodplain deposits indicates that high-accommodation conditions and lower topographic gradients resulted in the progressive eastward displacement of the line separating erosion (or bypass) from deposition. This suggests that minimal tectonic activity occurred at that time.

It is interesting to speculate on the relationship between sea-level changes and FS4 - FS5 fluvial patterns. In the Cordillera de Los Andes region, 50km to the West, several

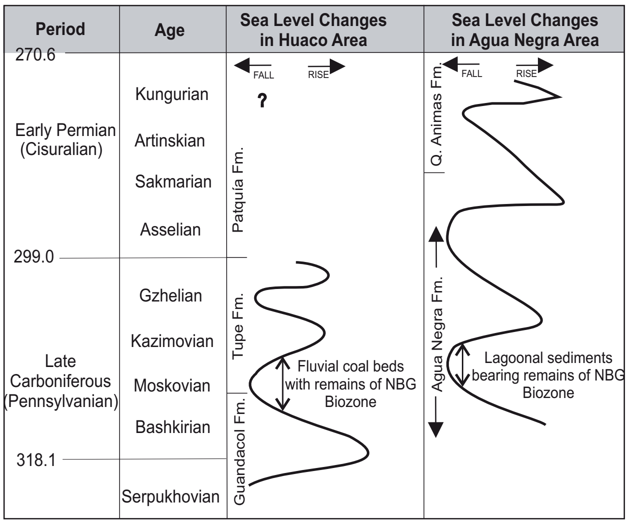


FIGURE 15 | **Schematic correlation between Huaco and Agua Negra areas using plant remains of the NBG Flora as key horizons.**

Late Paleozoic transgressive events have been reported in the Agua Negra Formation (Fig. 15). This primarily marine record, is a basinward equivalent to the FS4 and FS5 rocks in the Huaco area. Figure 15 displays a tentative correlation scheme between the Huaco and Andean areas using fossil plant-bearing beds of the NBG Zone as key units. Because this paleofloristic association occurs in both areas, it serves as a datum for regional correlation. The NBG flora in the Agua Negra Formation occurs in muddy sediments deposited in mainly lagoonal environments during a low-sea level stage. Interestingly, lagoonal deposits are sharply covered by transgressive shales, which, according to their stratigraphic position, should correspond to the Early Pennsylvanian marine deposits in the Huaco area (Fig. 15). If this assumption is correct, it suggests that the fluvial low-accommodation conditions that characterized FS4 in the Huaco area are correlative with a lowstand or the earliest portion of the transgressive system tract in the Agua Negra Formation. However, the high-accommodation systems tract of FS5 may represent a more advanced stage of the transgression (Figs. 13 and 14). This scheme allows the transitional shift from the anastomosed (FS4) to the meandering (FS5) fluvial network (Fig. 13) to be explained by an adjustment in accommodation space and equilibrium profile of the channels during a regressive-transgressive event.

CONCLUSIONS

To assume eustatic sea-level changes as the unique or even the major control in the evolution of fluvial systems often leads to erroneous conclusions, especially when other allocyclic controls are not considered. Several papers have clearly illustrated the role played by tectonics and climate over the evolution of an inland fluvial network, thus questioning the role of absolute sea-level change as the unique driving factor in the development of fluvial stratigraphy. To illustrate the role of sea-level and climate change, strata in the Huaco area were examined. These strata were deposited under constant tectonic subsidence rate. Under such conditions, the results of this study conclude that sea level fluctuations are, together climate, one of the first-order controls for fluvial systems within coastal plains.

The occurrence of multiple incision surfaces with different scales of incision, which separate marine deposits below from fluvial sediments above, suggests that several falls in sea level occurred during the Namurian – Late Pennsylvanian interval. Marine transgressive-regressive cycles during the Late Paleozoic might have been related to glacioeustatic sea level changes corresponding to different glacial events that occurred in Western Gondwana (Davydov et al., 2004).

The regressive phase in fluvial coastal areas appears to be represented by different degrees of incision surfaces and low-accommodation system tracts (Fig. 9). The relief of these surfaces does not necessarily reflect the magnitude of sea level fall. For instance, as mentioned above, high sediment flux can minimize the amplitude of incision. Accordingly, during the Westphalian, high amounts of postglacial sediments were available to allow fluvial progradation to keep pace with sea level fall. Furthermore, great volumes of transported sediments may have diminished the erosive capacity of the channel belts.

Low-accommodation systems tracts occur in three types of fluvial systems developed in the Huaco area (Figs. 13 and 14): poorly-confined and unconfined braided (FS1), unconfined braided (FS3), and/or low-sinuosity anastomosed (FS4) systems. Common features of these deposits are the presence of multi-storey channels dominated by downstream bar accretion (DA element) and scarce preservation of floodplain deposits. On the contrary, high-accommodation system tracts, probably related to transgressive events, are represented by anastomosed (FS2) and meandering (FS5) deposits. The increase in overbank facies towards the top of FS5 suggests a progressive sea-level rise favoring aggradation in coastal fluvial areas.

The effect of climate on fluvial systems is clearly shown by the nature of floodplain deposits. In this way, the formation of coal beds in FS2 was favored by a very humid and temperate postglacial climate, coupled with a high elevation of the water table (López Gamundí et al., 1992). In contrast, drier and probably hotter climates prevailed during FS5 deposition. Such conditions led to the formation of calcrete-type paleosols within a red-bed succession and then the formation of extensive eolian deposits during the Middle Permian (López Gamundí et al., 1992; Limarino et al., 1997).

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