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Sedimentary evolution of Neogene continental deposits (Ñirihuau Formation) along the Ñirihuau River, North Patagonian Andes of Argentina

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ABSTRACT

The sedimentary evolution of the Ñirihuau Formation (late Oligocene–middle Miocene) was studied along the southern margin of the Ñirihuau River, in the North Patagonian Andes. The 1300-m-thick section includes 15 epiclastic and volcaniclastic lithofacies which are grouped into five lithofacies associations: deep lacustrine, shallow lacustrine, fluvial channels, subaerial floodplains and volcaniclastic flows (lahar). Syn-eruptive and inter-eruptive stages are recorded along the Ñirihuau River section. The former consist of highly aggradational packages several tens of meters thick of ash-fall beds and lahar deposits. During inter-eruptive periods sedimentation took place mostly in shallow and deep lacustrine environments, with four cycles of lake expansion and contraction, and a minor proportion of fluvial deposits. Sedimentary supply originated from the northeast and northwest in the lower part of the unit through low to moderate sinuosity fluvial systems, flowing into a lake with high-gradient margins, and forming Gilbert-type deltas. The younger sections were sourced from the northeast, east and southeast, indicating changes in the basin morphology. Basic and intermediate volcanic rocks similar to those of the Ventana Formation (Oligocene) are interstratified at the beginning of the sedimentation. The syn-orogenic nature of the Ñirihuau Formation is evidenced by the changes in the basin shape, but mainly by the differences in styles and intensities of deformation between the Ñirihuau River section and the overlying outcrops of La Buitrera Hill, both separated by a folded unconformity.

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RESUMEN

Se presenta un estudio sobre la evolución sedimentaria de la Formación Ñirihuau (Oligoceno tardío - Mioceno medio) en la margen sur del río Ñirihuau, en los Andes Nordpatagónicos. Los 1300 m de potencia de la formación permiten la identificación de quince litofacies epiclásticas y volcaniclásticas, agrupadas en cinco asociaciones de litofacies: lacustre profunda, lacustre somera, de canales fluviales, de planicie de inundación y de flujos volcaniclásticos (lahares). Se reconocen en la sección del Río Ñirihuau estadíos Sin-eruptivos e Inter-eruptivos. Los estadíos Sin-eruptivos consisten de paquetes dominantemente agradacionales de ceniza volcánica de decenas de metros de potencia y depósitos de lahar. En los estadíos Inter-eruptivos la sedimentación tuvo lugar en ambientes lacustres somero y profundo, con cuatro ciclos de expansión y contracción del lago, y en menor proporción sedimentos de ambiente fluvial. En la mitad inferior de la unidad el aporte sedimentario provino desde el noreste y noroeste a través de sistemas fluviales de baja a moderada sinuosidad, desembocando en un lago con márgenes de alto gradiente, y formando deltas tipo Gilbert. Las secciones superiores tienen sus aportes desde el noreste, este y sureste, indicando cambios en la morfología de la cuenca. Durante los inicios de la sedimentación se registran rocas volcánicas básicas e intermedias, que caracterizan a la Formación Ventana (Oligoceno). La naturaleza sin-orogénica de la Formación Ñirihuau está evidenciada por los cambios en la forma de la cuenca, y principalmente por las diferencias de estilo e intensidad en la deformación tectónica que presenta la sección del río Ñirihuau y los depósitos que los cubren en el cerro La Buitrera, ambos separados entre sí por una discordancia plegada.

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1. Introduction

The sedimentary evolution of foreland basins located in areas proximal to volcanic centers show a complex relationship between tectonic subsidence (Allen et al., 1986; Jordan, 1995; DeCelles and Giles, 1996; Catuneanu, 2004), processes related to the evolution of the volcanic arc (Kuenzi et al., 1979; Vessell and Davies, 1981; Cas and Wright, 1987; Fisher and Smith, 1991; Riggs et al., 1997; Smith et al., 2002), and climatically controlled processes of reworking of volcanic detritus during eruptive and inter-eruptive stages (Smith, 1987, 1991). Those processes are commonly linked and full understanding of the evolution of basins involve detailed analysis of periods of magmatic-volcanic activity, temporal-spatial changes in style and intensity of tectonic processes, and stratigraphic studies (Walton, 1986; Turbeville, 1991; Bahk and Chough, 1996; Smith et al., 2002; Zanchetta et al., 2004; Martina et al., 2006). Sedimentation also preserves evidence of how those processes have changed, and are better preserved in basins with a high subsidence rate, which favors the development of lacustrine or marine settings (Ravnas and Steel, 1998; Einsele, 2000; Gawthorpe and Leeder, 2000; Catuneanu, 2004).

The Ñirihuau–Collón Curá Basin is a relatively small N–S trench, covering an area of roughly 200 km by 30–50 km. Its geometry is strongly asymmetric in a W–E cross-section, displaying an active deep margin to the west, and an unaffected eastern margin where Tertiary units show a characteristic onlap pattern (Giacosa et al., 2005). The basin has two main depocenters: the Ñorquinco depocenter in the southern sector of the basin with ~2000 m of thickness and the Ñirihuau depocenters, exposed around S.C. de Bariloche (Fig. 1B) with maximum thickness between 2000 and 2500 m (Spalletti, 1981; González Bonorino and González Bonorino, 1978). The basin was filled by the Ñirihuau and Collón Curá Formations (Cazau et al., 1989) from Late Oligocene to Middle Miocene. Most of the infill was preserved in alluvial, fluvial and lacustrine environments, with minor proportion of aeolian, brackish and marine deposits (Cazau, 1972; González Bonorino and González Bonorino, 1978; Spalletti, 1981).

The aim of this research is to present the results of a detailed sedimentological analysis carried out in the type-section of the Ñirihuau depocenter along the southern riverbank of the Ñirihuau River (41° 15′ S; 71°15′W), to investigate the patterns of sedimentary deposition and to understand the tectonic and volcanic controls on sedimentation.

2. Geological framework

The Tertiary infilling of the Andean North Patagonian region is distributed in two basins originally connected, and then separated during the Andean compression (Giacosa and Heredia, 1999). To the west, Late Eocene to Early Miocene sedimentary rocks (Chiesa and Camacho, 2001; Barreda et al., 2003) were deposited in marine and continental environments (Feruglio, 1941; Ramos, 1982) in the surrounding areas of El Bolsón city, conforming the El Bolsón Basin (*sensu* Giacosa and Heredia, 1999, 2004a). Complex structural relationships and paleoenvironment variability of the El Bolsón Basin have led to ambiguity in its stratigraphic nomenclature; "marine Patagoniense and Estratos con Nothofagus" (González Bonorino, 1944), Lutitas del Río Foyel (Bertels, 1980), Rincón de Cholila Formation (Cazau, 1972), Río Foyel Formation (Phote de Baldis, 1984), Ñorquinco Formation (González Díaz and Zubia, 1980) and Mallín Ahogado Formation (Giacosa et al., 2001). Asensio et al. (2005) review the stratigraphy of the El Bolsón Basin, identifying four formations and defining the El Foyel Group.

During the Oligocene up to 2000 m of bimodal, volcanic rocks of the Ventana Formation (Rapela et al., 1988) accumulated in the area, and they are part of the basement of the Ñirihuau Basin. Their

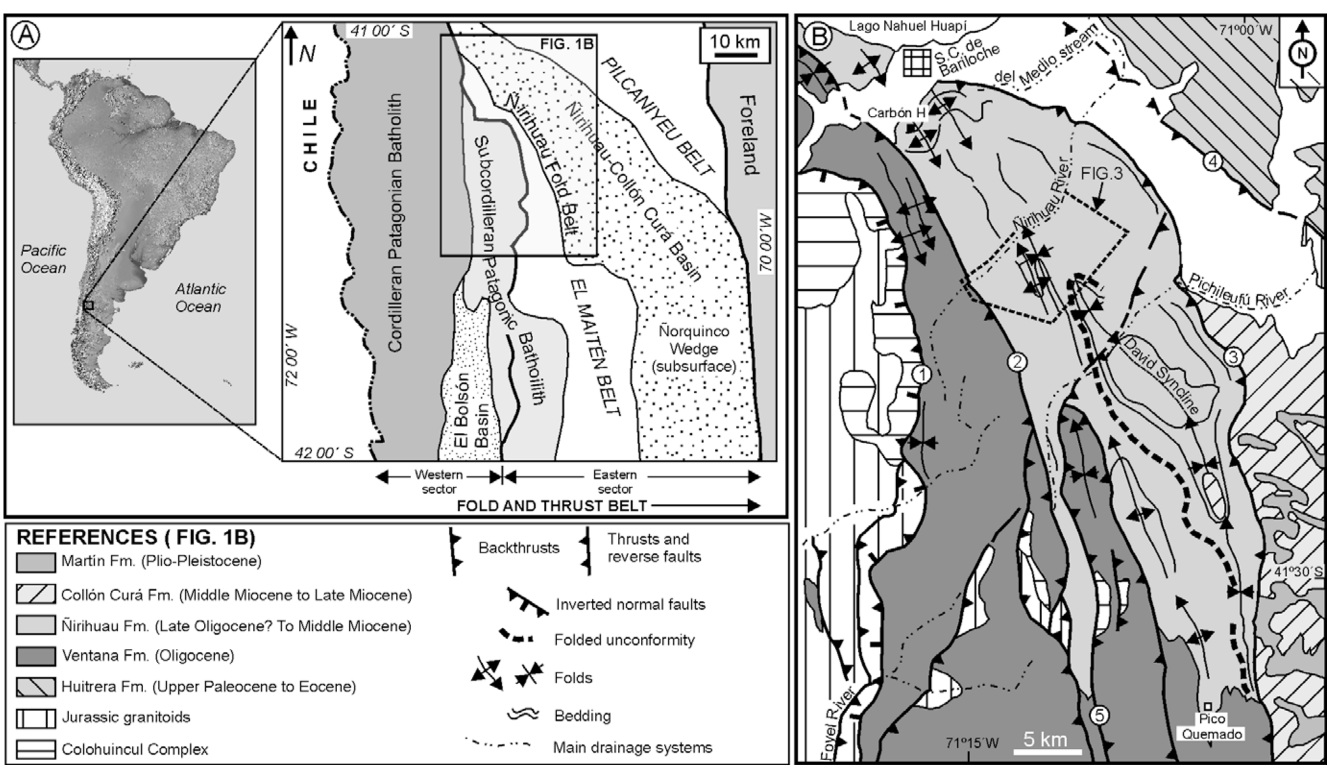

Fig. 1. Location maps. (A) Location of the Ñirihuau–Collón Curá in southern South America, with indication of main tectomagmatic and tectosedimentary regions of northern Patagonia. (B) Simplified geologic map of the northern sector of the Ñirihuau–Collón Curá Basin in the Ñirihuau Fold Belt. (1) Ventana-Catedral thrust, (2) Otto thrust, (3) Pantanoso thrust, (4) Río Chico thrust, (5) El Maitén backthrust. Based in Giacosa and Heredia (2004b) and Giacosa et al. (2005).

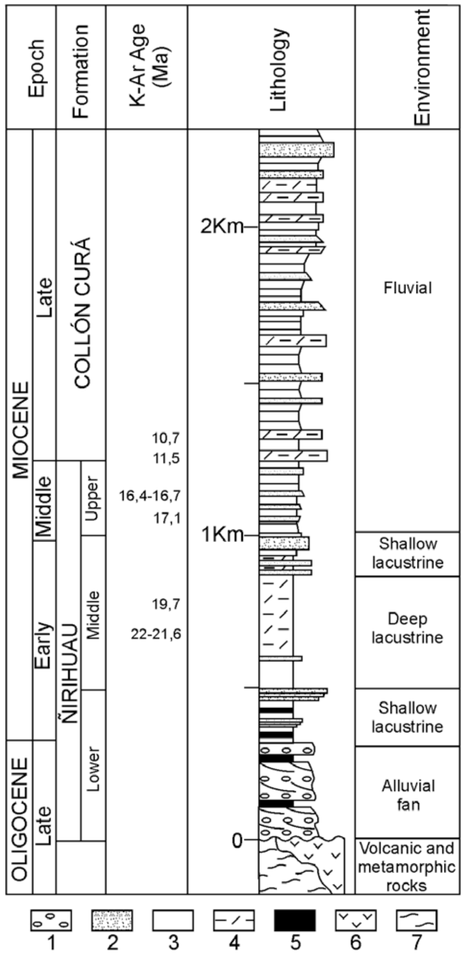

Fig. 2. Schematic stratigraphic section of the Ñirihuau–Collón Curá Basin, based on Mancini and Serna (1989) and Cazau et al. (1989). (1) Conglomerates and fanglomerates, (2) sandstones, (3) shales and siltstones, (4) tuffs and tuffaceous sandstones, (5) coal, (6) volcanic rocks, (7) metamorphic rocks.

outcrops are widely exposed in the western part of the basin, also identified in the subsurface at 1.264 m depth in the Ñorquinco $x-1$ well bore. Igneous-metamorphic rocks of the Cushamen Formation (Volkheimer, 1964) are also part of the basement of the basin, being found at 2.300 m depth in the Horqueta $x-1$ well bore. Toward the Andean sector metamorphic rocks are assigned to the Colohuincul complex (Turner, 1965).

The Ñirihuau Basin is located to the east of the El Bolsón Basin, infilled by Upper Oligocene to Middle Miocene volcanosedimentary rocks (Fig. 1A). The Ñirihuau Basin has been alternately interpreted as a pull-apart basin (Spalletti and Dalla Salda, 1996) and as an extensional basin in a back-arc setting (Mancini and Serna, 1989; Cazau et al., 1989). Ramos and Cortés (1984) and Giacosa and Heredia (1999, 2000) interpret it as a foreland basin with the formation of the main depocenters related to the eastward migration of the orogenic front. Recently, Giacosa et al. (2005) suggested that in some sectors of the basin the deposition of the lower member of the Ñirihuau Formation was influenced by late-stage extension associated with Oligocene volcanism.

Several studies (Ramos, 1982; Cazau et al., 1989; Mancini and Serna, 1989; Giacosa et al., 2005) suggest sedimentation began during the Late Oligocene, with ages of 22–21 Ma (Early Miocene) for the medium member and 17–16 Ma (Early-to-Middle Miocene) for the upper member of the Ñirihuau Formation (Fig. 2). The Collón Curá Formation, according to isotopic and paleontological data (Giacosa et al., 2001) is considered to be Early-Middle to Early-Late Miocene (Langhiane–Tortoniane).

Spalletti and Dalla Salda (1996) determined three stages of Ñirihuau Basin in-filling: the initial stage consists of fan-delta and lacustrine deposits with fining-upward arrangement and important thickness variations (lower member and most of the medium member of the Ñirihuau Formation), the intermediate stage is composed of high-sinuosity fluvial systems and lacustrine deposits with uniform distribution into the basin (upper member of the Ñirihuau Formation), and the final stage (Collón Curá Formation) contains pyroclastic and volcanoclastic materials reworked by fluvial and aeolian processes and deposited onlapping previous relief.

2.1. The Ñirihuau Formation

The Ñirihuau Formation, formally defined by González Bonorino (1973), was initially described by Roth in 1922. Its relationship with the underlying Ventana Formation has been interpreted as concordant (Ljungner, 1931), unconformable (Groeber, 1954) or variable depending on the location in the basin (González Bonorino and González Bonorino, 1978). Feruglio (1941), based on the presence of marine fossils, divided the unit into the basal "marine Patagoniense" and the upper "continental Patagoniense" or "Capas con Nothofagus". González Bonorino and González Bonorino (1978) interpreted the marine layers as part of the Ventana Formation. The concordant relationship of the Ñirihuau Formation with the Ventana Formation and the volcaniclastic character of both units led González Bonorino and González Bonorino (1978) to define the Nahuel Huapí Group, composed of the Ventana and Ñirihuau Formations. Cazau et al. (1989) and Mancini and Serna (1989) used the concordant contact and general sedimentary arrangement to integrate the Ñirihuau and Collón Curá formations into a unique sedimentary cycle. A recent review of the evolution of the El Bolsón and Ñirihuau basins (Cazau et al., 2005) proposed a tectono-sedimentary scheme with four main stages from late Paleocene to Pliocene. Their last stage (lower Miocene to Pliocene) includes the syn-orogenic deposition of the Ñirihuau Formation.

A complete section of the unit was divided by González Bonorino and González Bonorino (1978) into eight distinctive packages, containing three levels of volcanic rocks. They recognized a basal part where fluvial environments were supplied from the northwest, a section with calcareous rocks of brackish environment and finally fluvial environments sourced from the northwest. The Las Bayas River section is the most complete section of the Ñirihuau depocenter (Cazau et al., 1989), where three Members were defined: the lower member (alluvial fan and lacustrine associations); the middle member (deep and shallow lacustrine environments); and the upper member (entirely fluvial environments). A north–south correlation based on outcrop and subsurface data (Cazau et al., 1989, their Fig. 7) shows that the Ñirihuau River section is mainly fluvial, with lacustrine associations in the middle member. Spalletti (1981) studied the sections of the Otto and Carbón Hill (832 m thick) considered by González Bonorino (1973) as a continuous section of the basal part of the Ñirihuau Formation. They identified alluvial fans, low-and-high sinuosity fluvial systems, lacustrine bodies, subaqueous deltaic platforms and probable transitional environments with tidal control. The vertical analysis (Spalletti, 1981, their Fig. 4) shows three major prograding and retrograding cycles. In the area of Bariloche–Ñirihuau River, Spalletti (1983) recognized the predominance of deltaic deposits, prograding from the north and east–northeast. The clastic sedimentary components were probably derived from the erosion of Cretaceous and Tertiary volcanic rocks of varied composition (Spalletti and Matheos, 1987) and pyroclastic materials (Cazau et al., 1989, 2005), with a minor contribution of granitic and metamorphic rocks.

Paleobotanical studies in the Ñirihuau Formation (Rassmus, 1922; Feruglio, 1941; Aragón and Romero, 1984) recognized the predominance of components of the Fagaceae family, including an abundance of *Nothofagus* and associated flora (Romero, 1978). Romero and Dibbern (1984) correlated the small size of the leaves and the prevalence of Fagaceae with temperate to temperate-warm climates in the lower parts of the Ñirihuau Formation. Younger sections lack subtropical taxi, show leaf size reduction and suggest temperate-cold conditions and climatic seasonality. Thick coal-bearing layers in the basal section of the Ñirihuau Formation (Aragón and Romero, 1984) and aeolian deposits in upper sections (Spalletti, 1981) also indicate a process of aridity throughout the unit.

The numerous studies carried out in the Ñirihuau Formation were mostly motivated by the exploratory interest in coal and hydrocarbons. Main coal accumulations are located in the lower member and conform the Pico Quemado coal basin, which contains about 3,000,000 tons of coal and more than 20 abandoned mines. Bergmann (1984) presented a synthesis of the knowledge, distribution and main characteristics of the coal mines of this basin. The presence of liquid hydrocarbons in the Arroyo de la Mina was recognized from the beginning of the past century (Willis, 1914; Feruglio, 1941). Mancini and Serna (1989) note that potential hydrocarbon reservoir rocks are associated to shallow lacustrine successions of the uppermost lower member. The source rocks are claystones and siltstones of deep lacustrine environments of the middle member. Exploratory wells and thermal maturation studies of the organic matter (Mancini and Serna, 1989) indicate the absence of accumulations of interest or feasibility (Robles, 1984; Cazau et al., 1989). However, the recent increase of oil prices renewed the interest for developing studies in this basin.

3. Methodology

Geologic and structural mapping, using aerial photography at 1:50.000 scale, were used to locate partial stratigraphic sections and major structural features. Partial stratigraphic sections (scale 1:1.000) were completed in the field and then compiled in a general section. The lower section (Section 0) was studied south of the junction point between Tristeza Creek and the Ñirihuau River, but no detailed stratigraphic sections were measured due to limited exposures. The intermediate sections (Sections 1; 2a,b) were located to the west and east of the Puesto Riquelme and Puesto Crespo (see Fig. 3). Younger outcrops of the Ñirihuau Formation were observed at Estancia El Desafío (Sections 3 and 4). Correlations between different stratigraphic sections were based on regionally extensive volcaniclastic marker beds or characteristic fine-grained tuff deposits. Paleocurrents and structural measurements were corrected using a declination angle of 9° E. The lithofacies analysis follows the classifications and lithofacies definitions of Miall (1996), Bridge (1993) and Talbot and Allen (1996), as well as necessary modifications for volcaniclastic environments (Mathisen and Vondra, 1983; Smith, 1987; Cas and Wright, 1987). The assignment of the lower, middle and upper members of the Ñirihuau Formation are used in agreement with Cazau et al. (1989) and Mancini and Serna (1989).

4. The Rio Ñirihuau exposures

The Río Ñirihuau section is located on the easternmost tectonic sheet of the Ñirihuau Fold Belt, a characteristic structure of the sub-Andean region of the North Patagonian Andes (Giacosa and Heredia, 2004b). The N–NW trending fold belt has a NNW direction, is nearly 60 km long and 25–30 km wide, and is composed of two main tectonic sheets. The western sheet contains volcanic rocks of the Ventana Formation and the eastern sheet is composed of sedimentary rocks of the Ñirihuau Formation, with some units of the Collón Curá Formation (Fig. 1B). The western sheet is bounded to the west and east by the Ventana–Catedral and Otto thrusts, while the eastern sheet is part of the uplifted folded block related

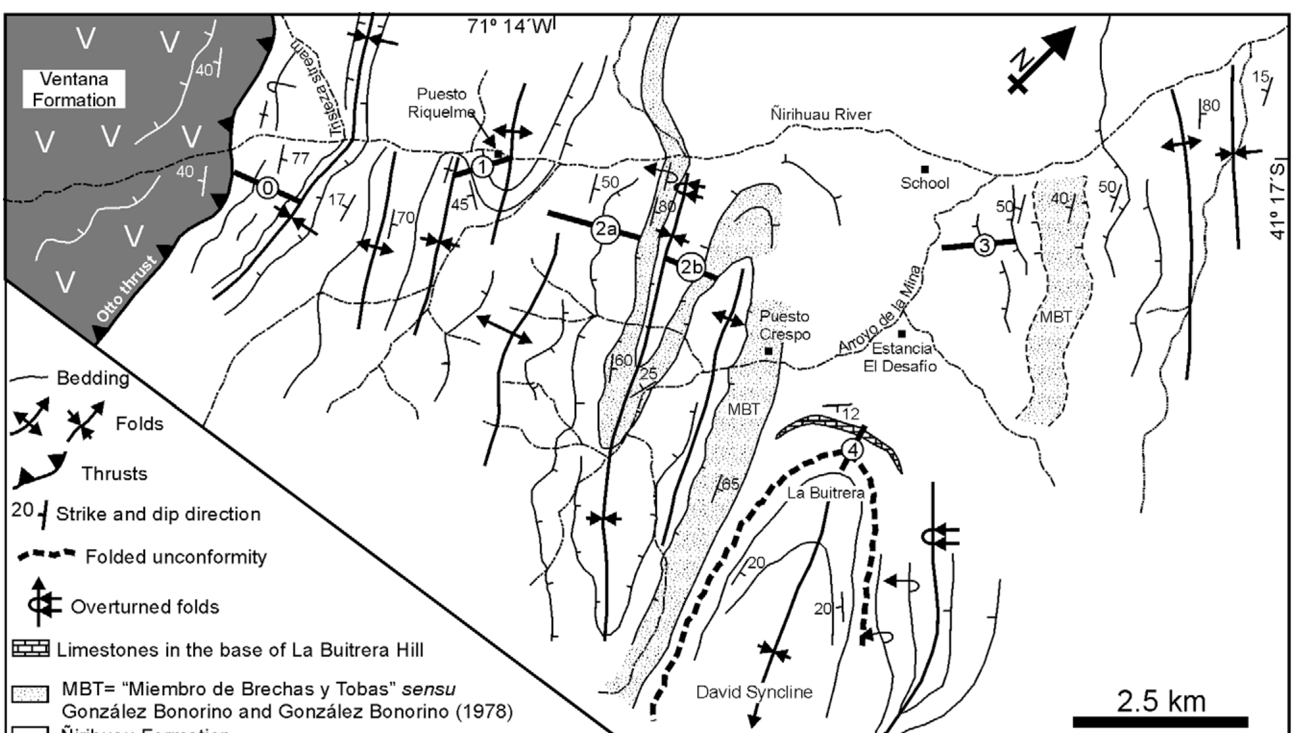

Fig. 3. Geologic map of the southern margin of the Ñirihuau River (location in Fig. 1B). Encircled numbers refer to the location of the partial sections, as in Fig. 5. Outcrops exposed along the Ñirihuau River show intense folding, but the La Buitrera beds are part of a wide, less deformed syncline. Only a synthetic stratigraphic section of Section 0 was carried out due to poor quality of the exposures (Fig. 7).

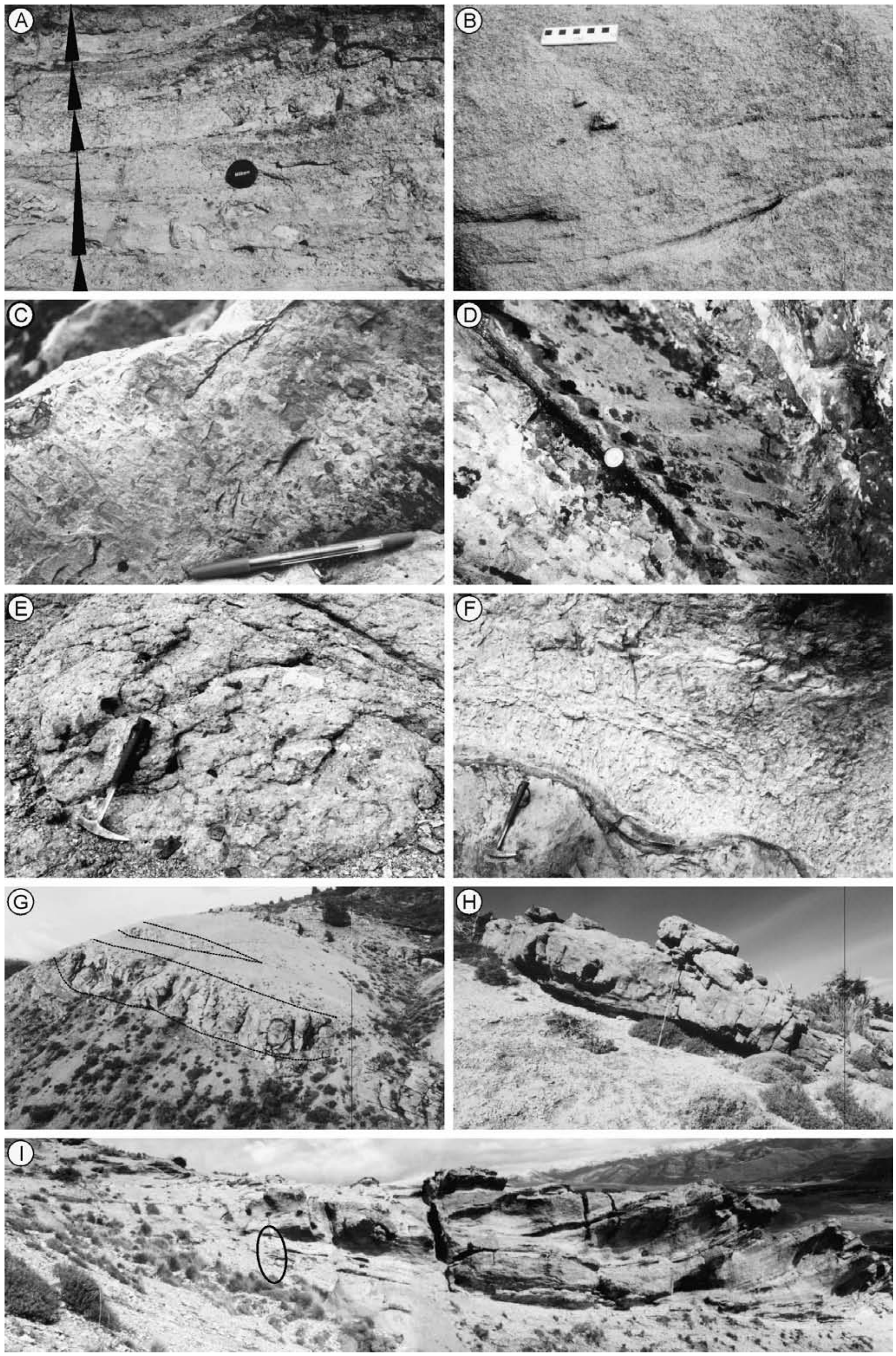

Fig. 4. Details of the lithofacies identified in the outcrops of the southern margin of the Ñirihuau River. (A) Fine gravels to coarse sandstone sequences with fining-upward arrangement, located in the bottomset of a migrating macroform (LF8). Large clasts are located at the base of the sets and display matrix supported fabric, but the finer parts are better selected and clast supported. The scale is 6 cm in diameter. (B) Coarse and medium sandstones displaying low-angle cross-bedding (LF6), the larger clasts (medium gravels) are volcanic in origin and show no vertical grading of size clasts. The scale is graduated in centimetres. (C) Fine-grained strata containing plant remains in the bedding planes (LF5). (D) Medium to fine-grained sandstones with straight-crested, symmetrical ripples (LF8). The coin is 13 mm in diameter. (E) Matrix-supported gravels (LF12) with occurrence of faceted clasts. Note the poor selection of the material and the absence of current structures. The hammer is 30 cm long. (F) Fine tuffaceous sandstones with undulated (deformed) base; it contains parallel lamination and low-angle cross-lamination (LF 13). Black dots are altered lithics of pyroclastic rocks. (G) Lenticular bodies filled by massive and cross-laminated tuffs (LF15), interpreted as the infilling of drainage systems during pyroclastic events. On the left of the picture there are stratified tuffs deposited on the adjacent floodplain. The maximum thickness of the main lenticular channel is 5.50 m. (H) Trough cross-bedded sandstones and gravels (LF6) in erosive contact on grey, massive shales and siltstones (LF10). They represent the infilling of fluvial channels and distal floodplain deposits, respectively. The length of the Jacob stick is 1.50 m. (I) Inclined foreset and asymptotic bottomset, part of a shallow lacustrine Gilbert-type delta. In the circle there is a Jacob stick.

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to the Pantanoso thrust. The Otto thrust brings up thick volcanic rocks of the Ventana Formation over strongly folded layers of the Ñirihuau Formation (Fig. 3).

The eastern sheet is structurally characterized by: (a) strongly asymmetric tight folds, overturned toward the east, especially in the vicinity of the Otto thrust and (b) the concentric and symmetric, 50-km-long David syncline, formed in response to flexion over the ramp of the Pantanoso thrust. The contact between the two kinds of structures is a folded unconformity (Giacosa et al., 2005).

East of the Pantanoso thrust, the Ñirihuau and Collón Curá Formation form in subsurface a triangular sedimentary wedge pointing to the foreland, which displays a typical onlap seismic fabric (Giacosa and Heredia, 2004b).

5. Sedimentology

Sediment composition, grain size, sedimentary structures and vertical lithofacies changes were used to identify 15 lithofacies in the Ñirihuau Formation; their characteristics and hydrodynamic significance are summarized in Table 2. Lithofacies were grouped into five genetically significant lithofacies associations: deep lacustrine, shallow lacustrine, fluvial channels, subaerial floodplains and volcaniclastic flows. The Ñirihuau River sections are compiled in Fig. 5 (scale 1:1.000), and a synthetic representation of the lithofacies associations are presented in Fig. 6.

5.1. LA1: deep lacustrine lithofacies association

Description: This association consists of interbedded, plane-laminated or massive claystones and siltstones (LF1, see Table 2), occasionally with thin lenses of medium- to fine-grained, fining-upward sandstone (LF2) or fine-grained sandstone with planar base and convex-up top (LF3). Green and grey colors are dominant, limonitized lithic crystals (oxidized pyrite) are common and variable thickness in varve-like laminae are observed in the finer deposits. This lithofacies is characterized by its fine-grained clastic composition and the absence of trace fossil assemblages. Their thickness varies from a few meters to 45 m, with repetitive alternation of fine-grained lithofacies.

Interpretation: Its fine grain size, preservation of fine laminations, laterally continuous strata and relationship with other lithofacies associations suggest this lithofacies association was deposited from suspension in offshore zones of a lacustrine environment (Glenn and Kelts, 1991). Pyrite relicts and lack of preservation of fossil traces could indicate stressful conditions for living communities, and probably anoxia (Davison, 1993). Preservation of sand-sized strata in this environment is related to occasional high-energy flows that transported channelized and non-confined clastic material to the offshore (Talbot and Allen, 1996).

5.2. LA2: shallow lacustrine lithofacies association

This lithofacies association consists of coarse-grained deposits of fine gravels and sandstones with common occurrence of debris plants. According to their internal arrangement, two sub-types were recognized: (a) Gilbert-type deltas, and (b) delta front and distributary channels.

5.2.1. LA2.a: Gilbert-type deltas

Description: This sub-association consists of fine gravels and coarse- to medium-grained sandstones. This sub-association is characterized by the development of steeply dipping foresets (~20°) with concave-up geometries and thickness variations from 7 to 1.5 m (Fig. 4I). It grades down-dip to gently inclined bottomsets (<5°), where individual strata are thinner, better sorted and of finer grain size. Foresets are composed of poorly organized gravelly lithofacies, with clast or matrix supported fabric and fining upward trend; the occurrence of outsized, imbricated clasts is also common. Individual beds are planar, non-graded or fining upward (Fig. 4A) and contain low-angle cross stratification (LF8). They are frequently amalgamated in packages up to 7 m thick defining a coarsening-upward succession. Between individual beds, fine sandstones with symmetrical ripples are present (LF5), with plant fragments on bedding surfaces (Fig. 4C).

Interpretation: The strata geometries and coarse grain size of the foresets are indicative of the development of a Gilbert-type delta (Nemec, 1990; Prior and Bornhold, 1990). These deltas are typical of relatively deep lakes with high gradient margins, dominantly supplied by coarse gravels (Talbot and Allen, 1996; Sohn et al., 1997).

5.2.2. LA2.b: delta front and distributary channels

Description: This sub-association shows a tabular appearance at outcrops and displays a basal transition to LA1 (deep lacustrine

Table 1
References of the stratigraphic sections.

REFERENCES OF THE SECTIONS		
Laminated and massive Shales	Low-angle cross-bedding	Steams and trunk fragments
Siltstones	Parallel bedding	C Coal blades and carbonaceous debris
Tuffaceous siltstones	Sigmoidal cross-bedding	Disturbed bedding
Tuffs	Frontal accretion	Paleocurrents and number of datas
Fine gravels to fine sandsones	Asymmetrical ripples	Axis of symmetrical ripples
Volcaniclastic breccias	Symmetrical ripples	Tuffaceous and pumiceous intraclasts
Limestones	Antidune cross-bedding	Carbonaceous nodules
Ignimbrite	Parallel lamination	Lenticular geometry
Basic volcanic rocks	Leaves and plant remains	Angular unconformity
Volcanic breccia	Prograding cycle	Trough cross-bedding
	Retrograding cycle	
GRAIN SIZE SCALE 1. Shale, 2. Siltstone, 3. Fine sandstone, 4. Medium sandstone, 5. Coarse sandstone, 6. Fine gravel, 7. Coarse gravel		

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lithofacies association). It is composed of planar-tabular packages several tens of meters thick integrated by multiple coarsening-upward cycles. Individual coarsening upward successions are composed of fine gravels and coarse- to medium-grained sandstones with large-scale trough cross-bedding (LF4) interbedded with sandstone strata of plane base and convex-up top (LF3). Many strata show fining-upward arrangement and vertical reduction in the scale of cross bedding from base to top. Medium- to fine-grained sandstone beds commonly show symmetrical ripples (LF5, Fig. 4D). These coarsening-upward successions are commonly truncated by lenticular bodies with scoured bases and fining-upward arrangement. The latter are composed of coarse sandstones with trough cross bedding (LF6) and medium- to fine-grained sandstones with symmetrical ripples (LF5), with leafs and wood fragments on bedding surfaces. The lenticular sandbodies are individually up to 2 m thick and 10–40 m in true width. Cross bedding on channelized strata show palaeocurrents roughly parallel to those obtained in clinoforms of the LA2.a sub-association, but they are oriented at high angle in relation to rippled sandstones that belong to the coarsening upward succession. Fine-grained shales containing an abundance of leaves and small fragments of wood and carbonaceous remains (LF7) can be found in upper parts of coarsening-upward successions.

Interpretation: The coarsening upward succession is interpreted as a delta front of a wave-dominated delta prograding into a standing body of water. Tabular and lobate bodies are part of a bar complex in the mouth of the delta system (Link and Osborne, 1978). Lenticular sandbodies represent low-sinuosity, distributary channels. The overlying shales with abundance of plant remains can be considered as part of an interdistributary bay (Harms et al., 1982). Although it is difficult to state what type of bar complex is represented, their geometries, stratigraphic position and palaeocurrents suggest they are most likely lacustrine bars deposited broadly parallel to the shoreline, locally crossed by distributary channels.

5.3. LA3: fluvial channels lithofacies association

Description: This lithofacies association consists of lenticular to tabular bodies with erosional base, in-filled with tuffaceous gravels and sandstones. The sandbodies are encased in pale-grey to brownish, fine-grained rocks and in pyroclastic-rich successions (LA4, see below) and generally show higher consolidation than surrounded rocks (Fig. 4H). A typical lithofacies succession consists of a basal lag of fine gravels and coarse sandstones (LF6), occasionally containing thin lenses of inversely graded gravel and sandstones (LF14) that grade up to trough cross-bedded (Fig. 4B), medium-grained sandstones or medium to fine-grained sandstones with low angle cross-bedding and/or antidune stratification (LF13). These vertical successions are nongraded or they fine-upward, and can be amalgamated in multistory sandbodies that reach lateral extensions and thicknesses of up to 250 and 15 m, respectively. No lithofacies related to waning stages were preserved (e.g. rippled sandstones). Palaeocurrents show unidirectional and unimodal distribution of measurements, and show low standard deviation (<30° around the mean). This lithofacies association has been separated from the distributary channels sub-association due to the lack of either evidences of oscillatory flows or preservation of plant remains, and also by the characteristics of the surrounded, fine-grained rocks.

A low proportion of lenticular sandbodies were preserved into highly aggrading, tabular successions of fine tuffs. These sandbodies are in-filled with fine, massive tuffs and fine tuffaceous sandstones (LF11) that upward develop plane-parallel lamination, low-angle cross-bedding and antidune cross-bedding (Fig. 4G). These sandbodies are generally of finer grain size and have dimensions (thickness, lateral extent) lower than those previously described, being also common the development of secondary porosity due to alteration of pumice or lithic fragments, with limonitized patines and cavities.

Interpretation: A fluvial origin is assigned to this lithofacies association due to their lenticular geometry, absence of oscillatory flows, superposition of fining-upward cycles in multistory sandbodies, unidirectional palaeocurrents and lateral relation with other lithofacies associations (Miall, 1996). The low dispersion of palaeocurrent measurements inside individual channels, dominance of coarse material in the infilling and the absence of lateral accretion surfaces suggest a low-sinuosity of the channelized system (Bridge et al., 2000). Absence of sedimentary structures generated during low-stage flood flows are related to erosion produced during subsequent increments of flow or sediment supply, and indicate rapid shifting of the channel position by avulsion during high-flood stages (Smith et al., 1989).

Fluvial channels developed during or immediately after periods of intense deposition of ash-fall strata on the floodplain (syn-eruptive stages *sensu* Smith, 1991) are identified by their finer grain size, pyroclastic composition, and smaller scale.

5.4. LA4: floodplain lithofacies association

This lithofacies association represents a low proportion of the sections, and can be subdivided in proximal and distal sub-associations.

5.4.1. LA4.a: proximal floodplain

Description: It consists of sparsely bioturbated, massive mudstones and plane-laminated siltstones, interbedded with erosively-based lenses (<1 m thick) of medium- to fine-grained cross-bedded sandstones that fine upward, or convex-up packages of plane-laminated sandstones (LF10). The entire succession displays coarsening-upward or fining upward trend, but is commonly truncated by the occurrence of channel sandbodies. Mottling of sediment is common, with rare preservation of rhizoliths.

Interpretation: A proximal floodplain environment is inferred due to alternation of fine-grained lithologies, the small scale of the interbedded sandstone bodies and their spatial association with fluvial channels. Deposition of mudstones and siltstones occurs from suspension in a low-energy environment; instead the sandstone strata are interpreted as crevasse channels or thin crevasse splays. Coarsening-upward successions reflect increasing of the involved flows arriving to a low-energy environment (Smith et al., 1989). Fining-upward trends are related to the increase of the distance to a main fluvial channel or gradual waning flow conditions. Mottling of the sediment is due to periodic waterlogging (Wright, 1999).

5.4.2. LA4.b: distal floodplain

Description: This sub-association is represented by the aggradational stacking of fine-grained rocks with gradual thickness variations. They include massive or rooted claystones and siltstones (LF9) or tabular strata of fine, massive to plane-laminated tuffs (LF15) occasionally containing symmetrical ripples on bedding surfaces. Pedogenic features include sparse rhizoliths, small carbonate concretions, mottling and vertically oriented excavations of *Skolithos* on the upper part of strata. Paleosols show no development of any typical or diagnostic horizon.

Interpretation: The fine grain size and gradual thickness variation of this lithofacies association evidence deposition from suspension in a low gradient setting (Miall, 1996). Carbonate concretions are related to changes in the position of ground-water table (Retallack, 1988). Poorly evolved paleosols can be considered Entisols (Soil Survey Staff, 1999). Low distal floodplain/channel ra-

Table 2
Recognized lithofacies of the Ñirihuau Formation.

Lithofacies and sedimentary features	Interpretatión
LF1: *Interbedded shales and siltstones, massive to plane-laminated*. Green and grey colours. Varve-like lamination. Bioturbarion absent. Oxidized pyrite crystals. Disturbed stratification and lamination. Carbonaceous concretions.	Suspension fallout deposition in relatively deep water setting. Poorly oxygenated lake bottom.
LF2: *Medium-to-fine sandstones, massive to horizontally-laminated*. Channelized, basal lag and crudely bedded sandstones, clast imbrications. Finer lithologies display parallel bedding and horizontal lamination.Carbonized trunk fragments and carbonaceous debris. Interbedded with LF1.	Transport of sediment supply to the offshore by high-energy currents.
LF3: Medium-to-fine sandstones, *plane base and convex-upward top*. Non-erosive base, convex-upward upper contact. Shale rip-up intraclasts, low-angle cross-bedding and horizontal bedding. Amalgamated, partially superposed sandbodies, which could contain lenses of laminated shales.	Low-relief depositional lobes. Represent distal deposits of the delta front or relatively deep sub-lacustrine fans.
LF4: *Fine gravels and coarse sandstones with large-scale cross-bedding*. Plane or erosive base. Nongraded sandbodies with sigmoidal geometry and amalgamation of partially superposed strata. Trough and low-angle cross-bedding. Meter-scale inclined surfaces with thin, laminated shales preserved in bedding surfaces. Trunk fragments and carbonaceous debris.	Migration of subaquatic bars in shallow lacustrine environment.
LF5: *Medium to fine sandstones with symmetrical ripples*. Plane or gradational base. Symmetrical ripples of straight axis and 4–7 cm of wavelength. Contain horizontal lamination, small scale cross-bedding and rare asymmetrical ripples. Laminated shales and siltstones are preserved in bedding planes, containing *Nothofagus* leafs and small trunk fragments.	Oscillatory currents in the lower flow regime during low-sediment discharge stages. Wave-influenced shallow lacustrine setting.
LF6: *Fine gravels and coarse-to-medium sandstones, fining upward*. Plane or erosive base. Amalgamated sandbodies with a basal lag and fining-upward trend. Trough and low-angle cross-bedding, their scale decrease to the top. Large-scale inclined surfaces dipping downstream (6–11°) or slightly upstream, these surfaces are mostly parallel to the paleocurrents.	Migration of subaqueous dunes in mobile channel belts or infilling of scours inside the channels (Jackson, 1976; Todd, 1996). Inclined surfaces are compound large-scale inclined strata (Lunt et al., 2004).
LF7: *Massive or plane-laminated shales*. Grey colors. Contain well preserved leaves on bedding planes and carbonaceous detritus. Frequently interbedded with	Deposition from suspension in a restricted environment, as an interdistributary bay.
LF8: *Fine gravels and coarse-to-medium sandstones, coarsening upward*.Planar base. Individual beds are nongraded or fining upward. Amalgamated beds present an overall coarsening-upward arrangement and tabular appearance. Could contain horizontal lamination or low-angle cross-bedding. Upward-concave foresets incline up to 20 degrees, they grades to gently inclined bottomsets (45–65 m long), where the beds are thinner and better sorted. Asymmetrical ripples with up-dip migration on top of the foresets.	Deposition from sedimentary gravity flow undergoing flow transformation upon a high-gradient foreset slope of a Gilbert-type shallow delta. Inclined foreset and bottomset association indicate rapid deposition in a high-gradient lake margin setting.
LF9: *Claystones, siltstones and tuffs with roots, mottling and carbonate concretions*. Plane base. Green and grey colours, minor reddish-light brown beds. Thin horizons with disperse carbonate nodules. Light brown-to-green and vertically oriented tubular mottles. Rare preservation of horizontal lamination, frequently sharp gradation to massive mudstones, with fine, vertical root traces. Limonitic oxides cover linear and vertical voids.	Immature paleosols (Stage 1 or 2 *sensu* Kraus, 1987). Light mottling is a result of periodic water-logging, and evidence a poor-drained floodplain. Weak develop of horizons indicate the presence of entisols (Retallack, 1988).
LF10: *Medium-to-fine sandstones interbedded with rooted shales and siltstones*. Plane or erosive base and lenticular geometry. Grey and white colored, low-consolidated sandstone beds, with fining-upward trend sizes. Low angle cross-bedding in the basal part, and horizontal lamination to the top, where fine root traces are common. Tuffaceous intraclasts.	Isolated lobes and crevasse channels deposited in the proximal floodplain. Scarce organic matter and bioturbation suggests rapid sedimentation and fluctuating water level.
LF11: *Tuffs with lenticular geometry and low-angle cross-bedding*. Plane base and lenticular geometry. Amalgamated, nongraded, massive beds. In the base matrix supported lapilli clasts. It grades to fine tuffs containing low angle cross-bedding, antidune stratification and horizontal lamination, which are interbedded with massive beds. Common lithic crystals, cavities and superficial patinas indicating alteration of original components.	Incorporation into local drainage systems of pyroclastic components, transportation in laminar or turbulent conditions, locally with characteristics of hyperconcentrated flood-flow deposits.
LF12: *Tabular, matrix supported medium-to-fine gravel beds*. Sharp base. Poorly sorted, nongraded, massive or crudely bedded, matrix supported beds with abundant matrix rich in coarse-to-fine pumice clasts. Could show reverse grading in the base or fining upward trend. Clasts are low rounded, volcanics and pyroclastics, until 20 cm in size. Amalgamated beds conforms regionally extensive packages more than 20 m thick.	Volcaniclastic flow (lahar) developed in rapidly aggrading conditions (Pierson, 1986). Laminar or in mass transport, but locally turbulence is reached due to flow transformation processes.
LF13: *Medium to fine sandstones with antidune cross-bedding*. Undulating bed boundaries. Weathered (oxidized) clasts and scarce, fine gravel clasts. Dome-shaped stratification, with amplitudes of 10–20 cm and wavelength de 1–2 m. The stoss and lee side angle in one measured antidune is 11° and 6°, respectively. Frequent low-angle cross-bedding and horizontal lamination.	High-sediment load and a high-sediment rate (Arnott and Hand, 1989) under upper-flow regime conditions (Alexander and Fielding, 1997).
LF14: *Fine gravels to fine sandstones, inversely graded*. Gradational or plane base. Horizontal or wedge-shaped shape. Massive or crudely stratified; sandstones could show horizontal bedding. Reworked pyroclastic clasts show poor grain-size selection. Tuffaceous clasts are moderate to well-rounded, inversely graded, and show matrix or clast-supported fabric. No vertical trend in lithic clasts was observed.	Inverse grading of the pyroclastic clasts is due to their intermediate density between that of the sandy matrix and the transporting water (Middleton, 1970; Maske et al., 1997).
LF15: *Massive or horizontal-laminated tuffs*. Plane base. Tabular, massive or laminated beds. Low consolidation and good-to-moderate grain size selection, containing oxidized volcanic clasts. Occasionally, interbedded with thin tuffaceous lenses containing low-relief, in-phase asymmetrical ripples.	Lapilli and ash-fall rain, subaereal or subaqueous (Mathisen and Vondra, 1983). Occasional deposition in very shallow water depth (Allen, 1968).

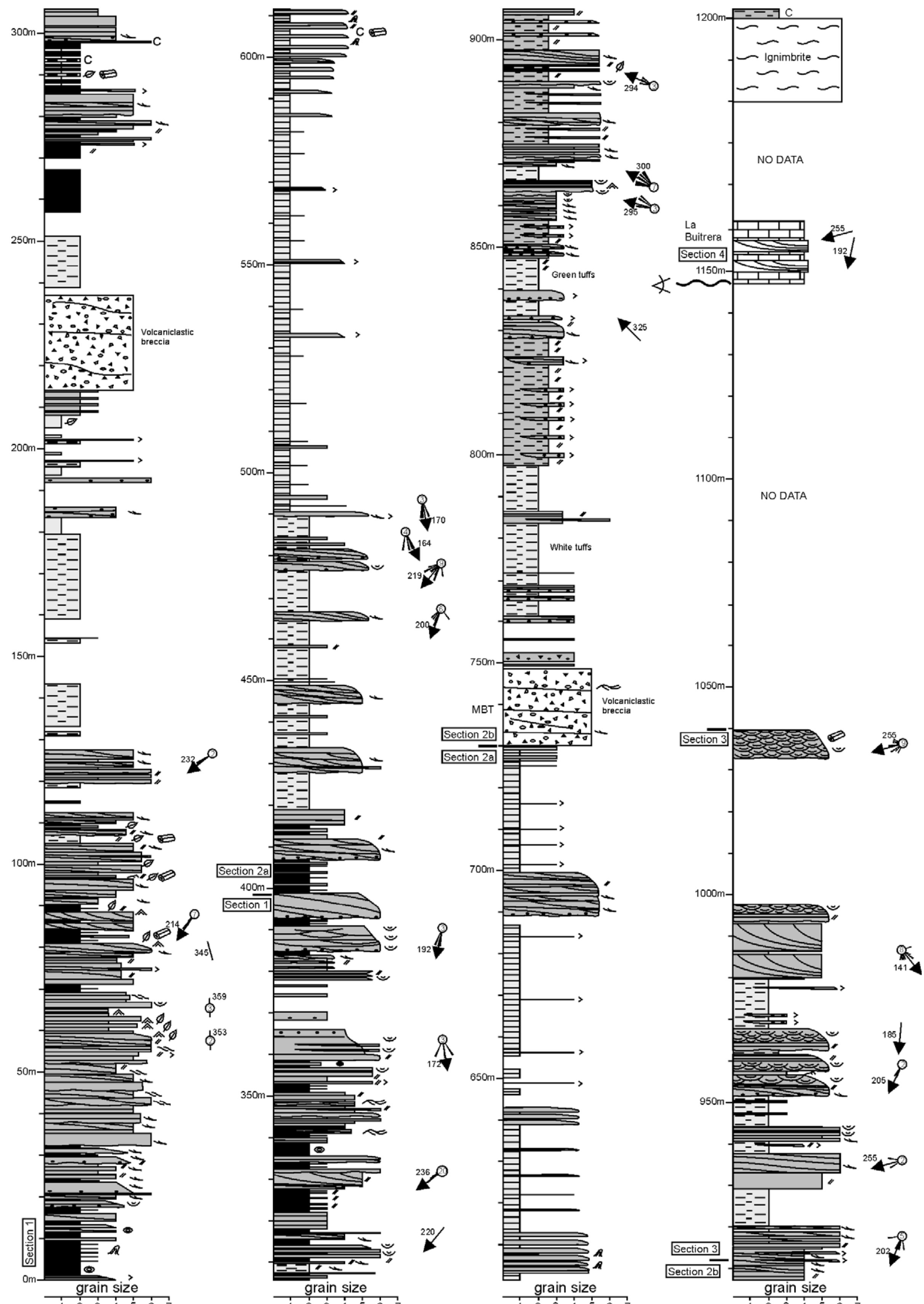

Fig. 5. Detailed stratigraphic section of the Ñirihuau Formation in the southern margin of the Ñirihuau River. The basal volcaniclastic succession exposed close to the Tristeza stream was omitted due to poor quality of the section (Section 0). Next to the sections the location of the partial sections (1, 2a, 2b, 3 and 4 in ascending order) is indicated, as in Fig. 3. References in Table 1.

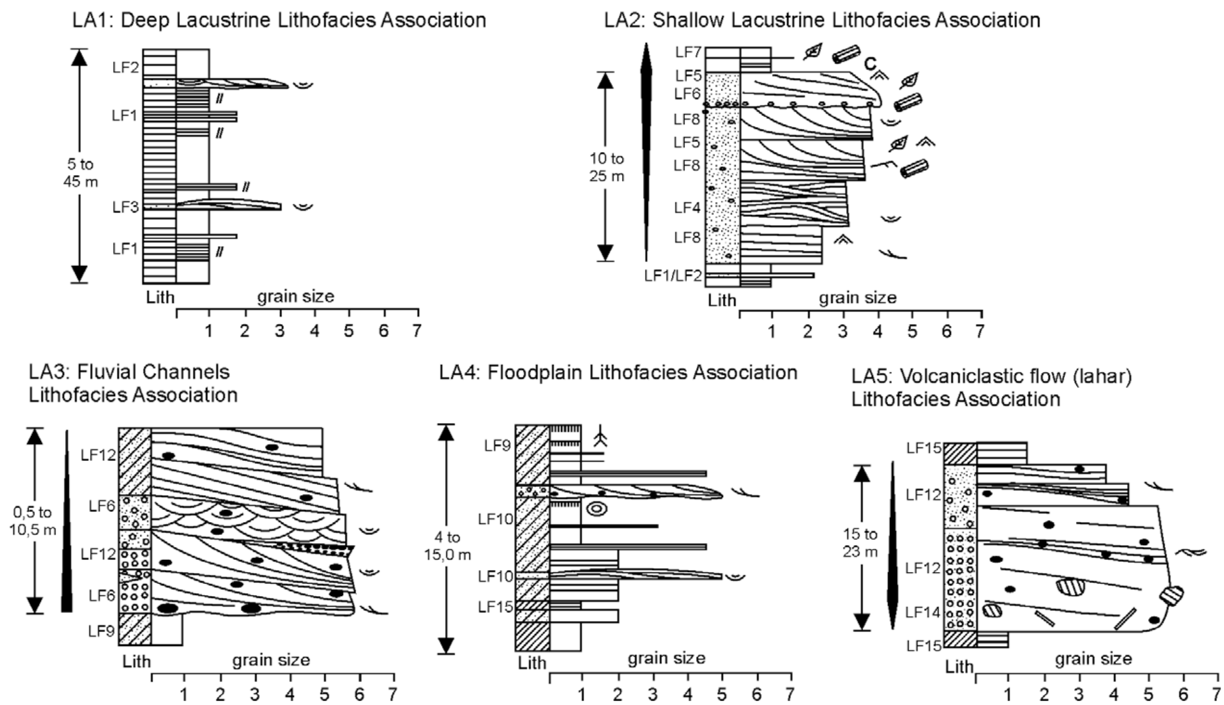

Fig. 6. Main lithofacies associations identified in the study area.

tio suggests relative instability of the floodplain (Kraus and Aslan, 1999; Kraus and Davies-Vollum, 2004), due probably to high mobility of the fluvial channels by avulsion. Rippled tuffs are related to the development of ephemeral, standing bodies of water adjacent to the main fluvial channels, probably in poorly-drained, ephemeral lakes.

5.5. LA5: volcaniclastic flow lithofacies association

Description: Two major volcaniclastic successions were identified (Figs. 5 and 7). Both consist of coarse-grained packages several tens of meters thick with lateral extension of thousands of meters. The packages show a highly aggradational appearance, and reach thicknesses from 15 to 23 m. The lithofacies association consists of matrix-supported medium- to fine gravels with volcanic and tuffaceous clasts until 20 cm in size, organized in individual strata 1.5–2 m thick with poorly defined boundaries and lack of internal organization (LF12). Clast/matrix ratio ranges from 0.2 to 0.4 of the exposed surface. Thin beds containing antidune cross-bedding (LF13), low-angle cross-bedding and reversely graded gravels (LF14) were recognized (Fig. 4F). Compositionally, the involved clasts are mostly of fine-grained volcanic rocks, ignimbrites and minor fine tuffs. Clasts are faceted to sub-rounded, and frequently contain a matrix of fine tuffs with random occurrence of out-sized clasts (Fig. 4E).

Interpretation: The volcanic and volcaniclastic composition, matrix supported texture and lack of internal organization are evidence of the development of a volcaniclastic debris flow (lahar) (Cas and Wright, 1987). Most of the lithofacies association was deposited from high-density flows, with attenuated turbulence due to a high concentration of particles into the flow (Coussot and Meunier, 1996). The occurrence of strata containing unidirectional structures indicates local dilution of the flow (Sparks, 1976), and the development of more turbulent flows (e.g. hyperconcentrated flood flows *sensu* Smith, 1986, 1987). The regional distribution and thickness of this association indicate a high instantaneous sedimentation rate, quickly aggrading geomorphic conditions and scarce reworking once the normal flow conditions were achieved.

6. Sedimentary evolution

A tectonic contact between the Ventana and Ñirihuau formations was recognized west of the junction between the Tristeza Stream and the Ñirihuau River, where the Otto thrust (González Bonorino and González Bonorino, 1978) uplifts volcanic rocks of the Ventana Formation over stratified sediments of the Ñirihuau Formation (Fig. 3). Therefore, it is possible that the basal section of alluvial fan origin recognized in the subsurface (Cazau et al., 1989; Mancini and Serna, 1989) could be tectonically suppressed in this locality.

The sedimentary evolution of the Ñirihuau Formation in the Ñirihuau Fold Belt commences with a basal stage identified 2.5 km to the west of the Puesto Riquelme and eastward of the Otto thrust (*Stage A*) that includes a 150 m thick section (minimum thickness) of channelized sandbodies of fluvial origin (LA3) interbedded with ignimbrites, volcanic breccias and basaltic rocks (Figs. 5 and 7). The quality of these exposures do not allow the detailed analysis possible in upper sections of the unit, but the recognized lithological types suggest the continuity of the volcanic processes that originated the Ventana Formation during the initial stages of deposition of the Ñirihuau Formation.

The basal stage is followed by the implantation of shallow lacustrine environments (*Stage B*), where Gilbert-type deltas (LA2.a) were active and migrated to the southwest (Fig. 5). Meanwhile, in gentle slopes of the lake, subaqueous channel and bar complexes were deposited containing abundant leaves, wood fragments and symmetrical ripples.

These transitional environments were covered during the deposition of fine ash-fall strata and barely lithified, tabular, volcaniclastic flows (*Stage C*), which sometimes contain carbonaceous remains. This volcaniclastic stage reflects periods of increased volcanic activity, with production and delivery of large quantities of

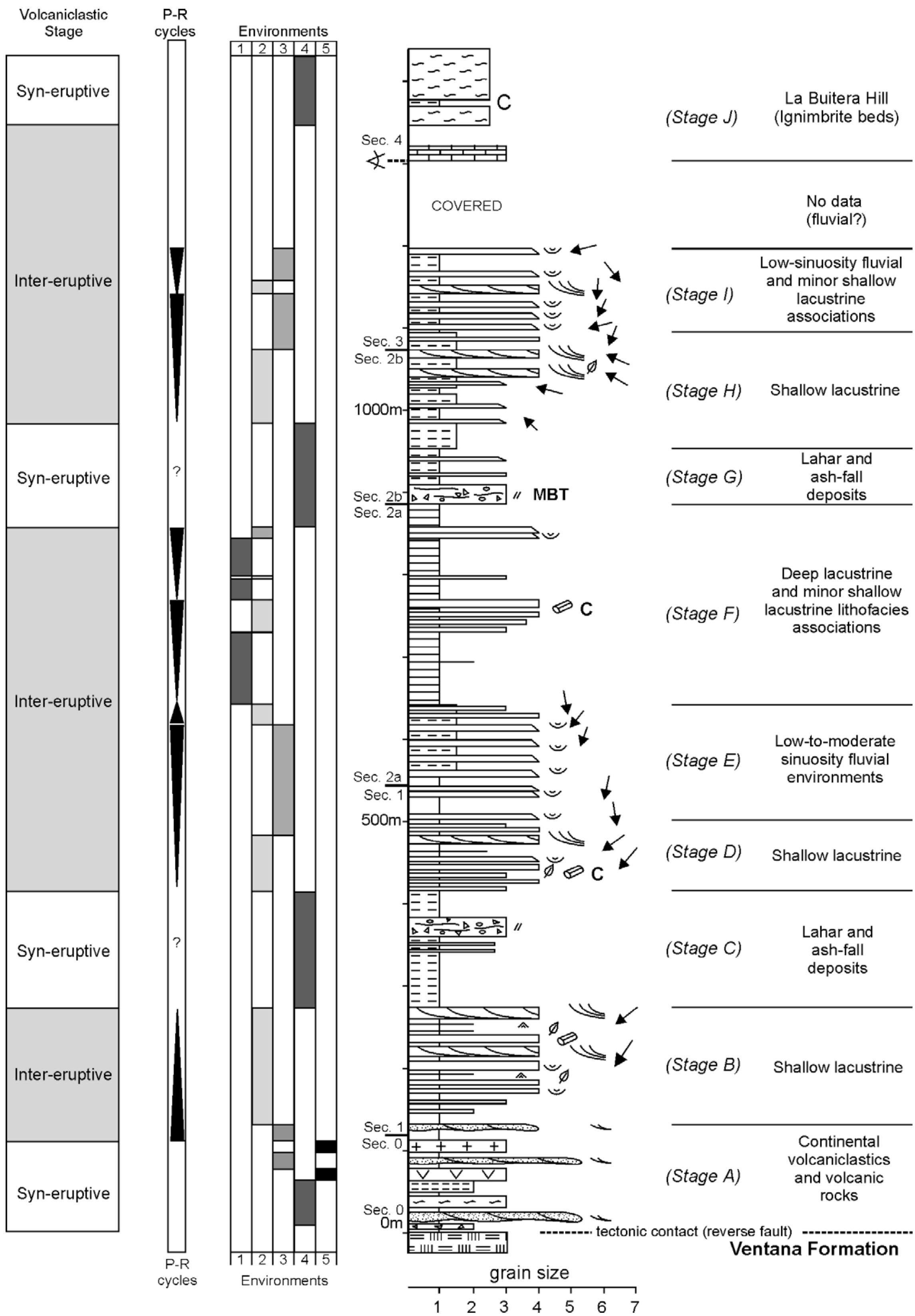

Fig. 7. Synthetic stratigraphic section of the Ñirihuau Formation along the Ñirihuau River section. Paleoenvironments and main stages in the sedimentary evolution, prograding–retrograding cycles and syn-eruptive and inter-eruptive periods are indicated. Paleoenvironments: (1) deep lacustrine, (2) shallow lacustrine, (3) fluvial, (4) pyroclastic and volcaniclastic, (5) volcanic rocks.

finely fragmented pyroclastics and reworking of pyroclastics by subaerial flows.

Once the pyroclastic delivery reduced, a shallow lacustrine environment occurred (*Stage D*), with Gilbert-type deltas prograding to the southwest. Gradual increasing of sediment supply or reduced rates of subsidence allowed the gradual upward transition to a 130 m thick section of low-sinuosity fluvial deposits (*Stage E*) draining to the southwest and southeast.

The previous fluvial succession is sharply covered by 230 m of shales and finely laminated siltstones (*Stage F*) deposited in deep lacustrine environments, and exposed 1 km to the east of Puesto Riquelme (Fig. 3). The fine-grained lithofacies are interbedded with shallow lacustrine channels and bars, some with plant remains and small wood fragments. In the topmost part of this stage, high-discharge events are recorded by the occurrence of thick and extensive channel associations (approx. 250 m wide and 15 m thick) encased into the mudstones.

A new pulse in the explosive volcanic activity and sudden incorporation of a large volume of volcaniclastic sediments to the basin (*Stage G*) is recorded into the Ñirihuau section. Volcanic breccias up to 23 m of thickness cover the entire study area and grade upward to a 50 m thick package of amalgamated white tuffs, deposited in subaerial and subaqueous conditions and interbedded with thin channels filled with reworked pyroclastics. This pyroclastic-rich stage was called by González Bonorino and González Bonorino (1978) as "Miembro de Tobas y Brechas", and some of the volcaniclastic strata were used as photographic geologic markers in the basin (e.g. Ramos, 1981).

The mainly pyroclastic succession continues in the surroundings of the Puesto Crespo, where it evolves to a 120 m-thick package of shallow lacustrine sediments (*Stage H*), with bars and deltaic lobes prograding to west–northwest and west–southwest. Fluvial environments are later developed in two progradational and retrogradacional cycles of 80 m thick (*Stage I*).

The upper part of the unit (around 150 m thick) is poorly exposed in the surroundings of Estancia El Desafío and in the base of the La Buitrera hill, but appears fluvial in origin with the presence of lenticular gravelly bodies and by correlation with published stratigraphic sections (Mancini and Serna, 1989; Cazau et al., 1989).

An angular unconformity at the base of the La Buitrera hill occurs, where laminated and brecciated limestones 12 m thick and ignimbrite deposits (*Stage J*) crop out with marked changes in attitude compared with the underlying rocks (Dessanti, 1972). The outcrops of the La Buitrera hill are part of the David Syncline and record the deposition of thick ignimbrite deposits (up to 70 m thick) interlayered with fine beds of tuffaceous sandstones with plant remains. The outcrops show the elongated shape of the basin during the last stages of the deposition of the Ñirihuau Formation. Previous studies considered the outcrops of La Buitrera as part of the Ñirihuau Formation (González Bonorino and González Bonorino, 1978) or to the Collón Curá Formation (Feruglio, 1941; Groeber, 1954; Dessanti, 1972) according to the interpreted structural relationship, but the lack of diagnostic sedimentary elements or radiometric age data disallow the assignment to either unit.

In the studied sections, there is a dominance of lacustrine deposits where four main shallowing upward sequences evolve from deep or shallow lacustrine environments to low-to-moderate sinuosity fluvial systems with a prograding arrangement (Fig. 5). Retrograding cycles have limited representation (Fig. 7). The paleocurrents obtained from dune and bedforms migration in fluvial channels and bar complexes preserved in shallow lacustrine environments indicate a source area located toward the northwest and northeast (see Fig. 5) for most of the unit, indicating that axial current transport was dominant. The sedimentary scheme for the deposition of the Ñirihuau Formation is substantially more complex than suggested by previous studies (e.g. Mancini and Serna, 1989 their Fig. 9) because the oscillation of the lake level and facies shifting are modified by the incorporation of huge volumes of pyroclastic rocks and volcaniclastic flows, which in turn are regulated by the intermittent activity of the volcanic arc.

Spalletti (1981) identified the presence of laterally extensive ignimbrite beds in the Otto and Carbón hills, suggesting a source area located toward the west. In this sense, the volcaniclastic layers recognized in the Ñirihuau River could be considered as lahars or distal co-ignimbrite deposits, due to the absence of evidence of deposition from a hot source. They are generally massive and suggest laminar (Sparks et al., 1978) or mass transport (Coussot and Meunier, 1996). In places the deposits share characteristics with hyperconcentrated flood-flow (Smith and Lowe, 1991; Cas and Wright, 1987) and evidence changes in density due to dilution of the flow head or water incorporation from local drainage systems.

In outcrops near S.C. of Bariloche, marine- and brackish-water sediments have been recognized (Feruglio, 1941; Mancini and Serna, 1989; Cazau et al., 1989, 2005). González Bonorino and González Bonorino (1978) noted the presence of *Turritella* shells in the hill located between the Arroyo del Medio and the Nahuel Huapí plain, and Aragón and Romero (1984) identified limestones with ostracod concentrations in easterly exposures (location 176) at the same stratigraphic level. These authors suggest incursion of marine conditions and occasional connections with a restricted sea. Nevertheless, we have found neither marine faunal or bioclastic associations in the studied sections, nor evidences of transitional, brackish or marine environments.

7. Discussion: external controls on the sedimentation

7.1. Tectonic control

The tectono-sedimentary interpretation of the Ñirihuau Formation must be considered in relation to the active uplifting of the Andean Ranges during the Neogene (Giacosa and Heredia, 2000). The distribution, geometry and syn-tectonic organization of the Ñirihuau–Collón Curá Basin indicate that the Ñirihuau Formation was deposited during the migration of the orogenic front toward the foreland (Giacosa and Heredia, 1999, 2000, 2004b; Giacosa et al., 2005). The Ñirihuau Formation represents the medium to distal part of a syn-tectonic sedimentary wedge, emplaced initially west of the El Bolsón valley (Giacosa and Heredia, 2004a). In the El Bolsón Basin, on top of materials considered as the upper part of the Mallín Ahogado Formation (Middle Eocene to Early Miocene), thick packages of massive conglomerates were unconformably deposited. These deposits were interpreted by Giacosa and Heredia (1999) as proximal facies of the orogenic wedge located to the west. Toward the east (foreland), these conglomerates could be correlated to the basal sections of the Ñirihuau Formation. The eastward advance of the orogenic front later produced the segmentation of the original basin, separating the El Bolsón and Ñirihuau–Collón Curá basins (Fig. 8).

Structural observations in the Ñirihuau River and La Buitrera Hill regions show clear differences in the intensity of the deformation that affected both sectors. The outcrops of the Ñirihuau River display tight and east-vergent asymmetric folds (Fig. 3), while the outcrops of La Buitrera Hill are part of a wide syncline with open limbs (David syncline). The evidence allows interpretation of the base of the David syncline as a folded unconformity (Giacosa et al., 2005), indicating the beginning of the compressional deformation in the north sector of the basin during the latest stages of deposition of the Ñirihuau Formation (16–17 Ma). The sediment supply arrived to the Ñirihuau Basin mostly from the north, northeast and northwest, parallel to the axis of the basin, but transport from the east is also recorded. It depicts a closed shape for the basin during the deposition of the Ñirihuau Formation. This fact could indicate the beginning of the transport of the Ñirihuau–Collon Curá

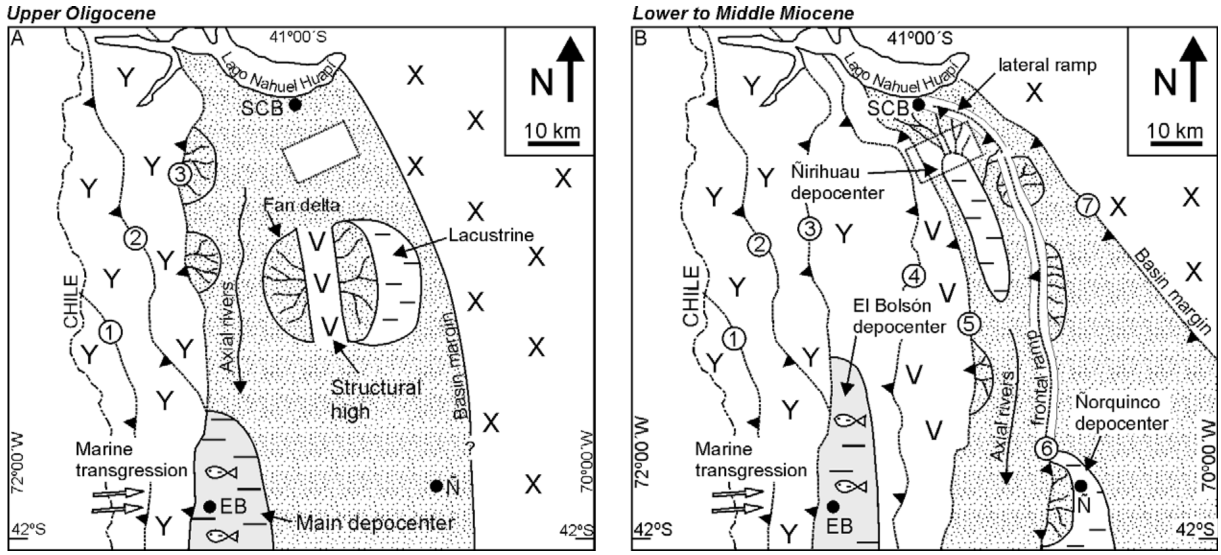

Fig. 8. Proposed tectosedimentary evolution of the Ñirihuau–Collón Curá Basin during the deposition of the Ñirihuau Formation, based on Giacosa and Heredia (1999, 2000, 2004a,b), Giacosa et al. (2005), Cazau et al. (1989), Mancini and Serna (1989), Spalletti and Dalla Salda (1996) and present results. (A) Early stages of deposition of the Ñirihuau Formation occurs during the upper Oligocene in a basin open to the west. The marine depocenter in the El Bolsón Basin and the continental succession of the Ñirihuau–Collón Curá Basin are connected. (B) The eastward migration of the orogenic front separates the original basin and originates the continental depocenters in the Ñirihuau–Collón Curá foreland basin during the lower Miocene. Some stratigraphic and structural features were omitted for clarity (e.g. Oligocene extensional structures). Keys: (1) Hielo Azul thrust, (2) Bolsón-Tronador thrust, (3) Lopez thrusts, (4) Ventana-Catedral thrust, (5) Otto thrust, (6) Pantanoso thrust, (6) Río Chico thrust. EB = El Bolsón city, SCB = San Carlos de Bariloche city, Ñ = Ñorquinco town. V = Ventana Formation (Oligocene) X = Huitrera Formation (upper Paleocene–Eocene), Y = pre-Tertiary basement rocks.

Basin on the Pantanoso thrust as a piggy-back basin and the creation of relief associated with the development of the lateral and frontal ramps of the Pantanoso thrust, located to the north and east, respectively (Fig. 8). The southerly tilting of the foreland basin could be due to the location of the lateral ramp to the north and a larger mass uplifted on the orogenic front in that direction. The continuous displacement of the Pantanoso thrust could also be the reason for the intense folding of the Ñirihuau Formation, the generation of the basal unconformity at the La Buitrera Hill, and the reduced intensity of the deformation of the younger units, as well as the later uplifting and erosion of the basin.

The upper member of the Ñirihuau Formation is poorly exposed from Las Minas Creek until the base of the La Buitrera Hill, and was studied in areas to the south by Cazau et al. (1989) and Mancini and Serna (1989), among others. They recognized the cessation of lacustrine sedimentation in the basin and a fluvial nature for this member (Spalletti and Dalla Salda, 1996), change that can be associated with the beginning of the uplifting and folding of the Ñirihuau Formation.

7.2. Volcanic control

Sedimentation in areas proximal to volcanic centers is strongly influenced by the activity of the volcanic arc. Studies on recent volcaniclastic areas allowed the recognition of syn-eruptive and inter-eruptive stages in the development of continental voclaniclastic sequences (Vessell and Davies, 1981; Smith, 1987, 1991). Developed facies models have shown that during syn-eruptive stages rapid aggradation of the topographical surface is achieved, flows are commonly hyperconcentrated to debris-flows and rivers frequently show a braided pattern, with a high proportion of primary pyroclastic components in their constitution. During inter-eruptive periods, incision and reworking of the poorly consolidated tephra by dilute flows take place, with smaller, low sinuosity to meandering rivers, and more diverse (volcanic and non-volcanic) lithologies (Smith, 1988, 1991; Critelli and Ingersoll, 1995; Bahk and Chough, 1996).

The Ñirihuau Formation contains primary and reworked volcaniclastic materials, and their location a few tens of kilometres from the source of volcanic rocks allows the analysis of their evolution using a volcaniclastic scenario. The Ñirihuau River section shows alterating packages of pyroclastic rocks interbeded with rocks preserved in lacustrine and fluvial environments, which represent syn-eruptive and inter-eruptive stages.

Syn-eruptive stages preserved in the Ñirihuau River section are characterized by highly aggradational packages of fine-grained tuffs transported and delivered to the basin by air currents. These strata are related to Plinian or Strombolian-type eruptions, where efficient fragmentation of magma occurs. The second group of syn-eruptive deposits are thick (up to 20 m) volcaniclastic breccias with aggradational appearance and matrix-supported texture. Their uniform thickness distribution evidences instantaneous delivery of large quantities of volcaniclastic detritus, and involves a huge incorporation of water to the flow to facilitate their movement. In spite of a lack of evidence of hot emplacement of lahars (e.g. degassing structures, fiammes) we suggest these cold lahars should be temporally related to hot lahars preserved to the west (e.g. Spalletti, 1981). Ash-fall deposits are interbedded with lahar deposits, which reflect changes in the rate of magma supply and variable mixing of pyroclasts with phreatic or external water.

Inter-eruptive stages preserved in the Ñirihuau River section are characterized by the reworking or previous and contemporary pyroclastic rocks in lacustrine and fluvial environments. Most of the section was deposited in lacustrine environments, that evidence an accomodation/supply ratio >1. The four retrograding-prograding cycles preserved show the interplay between climatically controlled delivery of detritus to the basin and tectonic subsidence. The lacustrine scenario is maintained even after the huge incorporation of volcaniclastic material during syn-eruptive stages (Fig. 7), suggesting high rates of subsidence of the basin. These conditions have changed during the deposition of the upper member of the Ñirihuau Formation (Cazau et al., 1989; Mancini and Serna, 1989; Spalletti and Dalla Salda, 1996) with the development of regionally distributed fluvial systems, but exposures of this member are sparse in the Ñirihuau River section. The La Buitrera Hill, located in the northern part of the David Syncline, consists of thick (up to 70 m) ignimbrite packages bedded with thin tuffs and shales containing coal beds and carbonaceous debris. The north–south elongation of the ignimbrite packages indicates the presence of longitudinal valleys and reflects the morphology of the basin during the final stages of deposition of the Ñirihuau Formation.

8. Conclusions

A 1300 m thick section of volcaniclastic and epiclastic, continental rocks of the Ñirihuau Formation were analyzed along the Ñirihuau River section. Fifteen epiclastic and volcaniclastic lithofacies were identified in these rocks, which were grouped into five lithofacies association: (1) deep lacustrine; (2) shallow lacustrine; (3) fluvial channels; (4) proximal to distal floodplain; and (5) volcaniclastic flow (lahar) deposits.

Syn-eruptive and inter-eruptive stages are recorded along the Ñirihuau River section. Syn-eruptive stages consist of highly aggradational packages several tens of meters thick of ash-fall beds and lahar deposits. During inter-eruptive periods sedimentation took place mostly in shallow and deep lacustrine environments, with four cycles of lake expansion and contraction, and a minor proportion of fluvial deposits.

In older exposures, there are intermediate to basic volcanic rocks and ignimbrites interbedded with fluvial channels associations. These deposits reflect the continued explosive volcanism of the Ventana Formation and mark the passage from the extensional conditions characteristics of the Ventana Formation (Oligocene) to the mostly syn-orogenic conditions that prevailed during the deposition of the Ñirihuau Formation (Lower Miocene). The younger sections of the Ñirihuau Formation are part of the middle and upper members, and consist of deep and shallow lacustrine associations, defining four shallowing-upward cycles, each covered by low-sinuosity fluvial associations. Sedimentary supply was from the northwest and northeast for most of the unit. Supply was much more variable for the younger section, sourced from the east and southeast. The changes in the transport direction suggest changes in the basin shape, related to the relief generation associated to lateral and frontal ramps of the Pantanoso thrust.

The outcrops of the Ñirihuau Formation along the Ñirihuau River show intense folding (tight or overturned anticlines and synclines) and the volcaniclastic beds of La Buitrera Hill are part of an open syncline, suggesting that the beginning of the uplifting, deformation and final organization of the basin took place during the deposition of the uppermost deposits of the Ñirihuau Formation.

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