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Age and tectonostratigraphic significance of the Upper Carboniferous series in the basement of the Andean Frontal Cordillera: Geodynamic implications

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Abstract

The age and tectonosedimentary environment of the Palaeozoic sediments on the Frontal Cordillera is not well known and earlier studies have been unable to satisfactorily explain the geological history of the basement of the Andes.

In the vicinity of the old Castaño Viejo mine crop out various levels of partially metamorphosed microbialite limestones, which alternate with thin marly–lutitic interstrata. These levels contain abundant palynomorph remains, which allow the series to be dated as Silurian–Devonian. These data, together with the presence of warm climate fossils, lend support to the hypothesis of a major allochtony of the Chilenia Terrane (of which the Frontal Cordillera formed part), relative to the Cuyania Terrane (which included the Precordillera), prior to their amalgamation.

Upper Carboniferous palynomorphs found during this study occur in association with resedimented palynomorphs and chitinozoa, of possible Devonian age. This demonstrates the equivalence of both fossiliferous series and their location within the upper part of the Upper Carboniferous Agua Negra Fm. The Silurian–Devonian elements, deformed during a phase prior to the Gondwanic orogeny, were eroded and transported to the foreland basin during the Upper Carboniferous.

The palynomorph associations found in all samples correspond to the Ancistrospora palynological zone and to the *Raistrickia densa–Convolutispora muriornata* Biozone, which are indicative of Upper Carboniferous times. Characteristic forms such as *Ancistrospora verrucosa* and *C. muriornata*, both indicative of an Upper Carboniferous age, were found in samples from the Castaño Viejo area.

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Earlier interpretations of the Frontal Cordillera attributing the sedimentation to a palaeo-latitude at some distance from Gondwana, were based on the presence of Silurian–Devonian hot water stromatolithic limestones. Our results suggest that Cuyania and Chilenia were not necessarily separated by a great distance before their amalgamation. This in turn means that a large ocean was not necessarily consumed in the process.

Keywords: Palynomorphs; Sedimentology; Basin analysis; Chilenia terrane; Late Palaeozoic; Andes

1. Introduction

The study area is located (Fig. 1) in the San Juan province of Argentina, within the morphostructural unit known as the Andean Frontal Cordillera (Groeber, 1938). The palaeozoic basement of the Andean Frontal Cordillera crops out on its easternmost margin, where it meets the Rodeo-Calingasta basin.

In the Quebrada de las Animas of the Castaño Viejo area (Fig. 2), there are some outcrops of limestones in the palaeozoic succession. These limestones were named such as San Ignacio Fm (Rodríguez Fernández et al., 1996, 1997) and were dated as Silurian–Lower Devonian by Pöthe de Baldis et al. (1987). The warm water characteristics of the limestones (low palaeolatitude) and the results of some authors (Ramos, 1988) have been used to demonstrate the major allochtonia of Cuyania (Precordillera) with respect to Chilenia Terranes (Frontal Cordillera). These limestones are absent in the Precordillera and the sedimentary rocks of the same age are mainly siliciclastic and were laid down in cold waters (high palaeo-latitude). According to this interpretation, prior to the Devonian amalgamation, the two land masses were separated by an extensive area of ocean which was progressively consumed during the time leading up to their collision.

The rest of the palaeozoic series are represented by the Agua Negra Fm (Polanski, 1970), of Upper Carboniferous–Permian age (Aparicio, 1969). This is made up of alternating sandstones, lutites and conglomerates, with limestones in the upper part. The Agua Negra Fm was laid down, (Heredia et al., 2002), during the Gondwanic Orogenic cycle. Different tectonic settings have been deduced for the two successions: one is preorogenic and of Carboniferous–Permian age, and the other is synorogenic and dating from the Permian.

This study focuses on the age, and the regional and tectonostratigraphic significance of the Palaeozoic sequence of the Castaño Viejo area. A detailed study of the main lithofacies was carried out in an attempt to complete our understanding of the geological and geodynamic evolution of this region. Further, an analysis was made of the age of the samples of palynomorphs taken along the whole length of the Quebrada de las Animas and Quebrada de las Ñipas, near the Castaño Viejo mine. The results of this analysis suggest a more precise age, Upper Carboniferous, for this series than that have been indicated by previous studies.

2. Geological setting

This sector of the Frontal Cordillera presents a polycyclic structure with an eastwards vergency. Owing to variations in structural style, lithology and tectonic structures, two different groups can be differentiated in the study area (Rodríguez Fernández et al., 1997; Heredia et al., 2002): a Palaeozoic basement composed of Devonian and Permo-Carboniferous marine sedimentary rocks, intruded by Permo-Triassic granitoids, and an Andean Mesozoic–Tertiary cover intruded by Mesozoic and Tertiary granitoids.

In the basement, the Devonian rocks were affected by the Late Devonian Chanic phase of the Famatinian orogenic cycle (Ramos et al., 1984, 1986). Several folds with chevron geometries and western vergency can be recognised in the Agua Negra valley (Heredia et al., 2002). The presence of a sharp unconformity between the Devonian and Carboniferous–Permian rocks confirms the occurrence of the Chanic event in this zone.

The most important Palaeozoic structures are related to the Gondwanic Orogeny of Permian age.

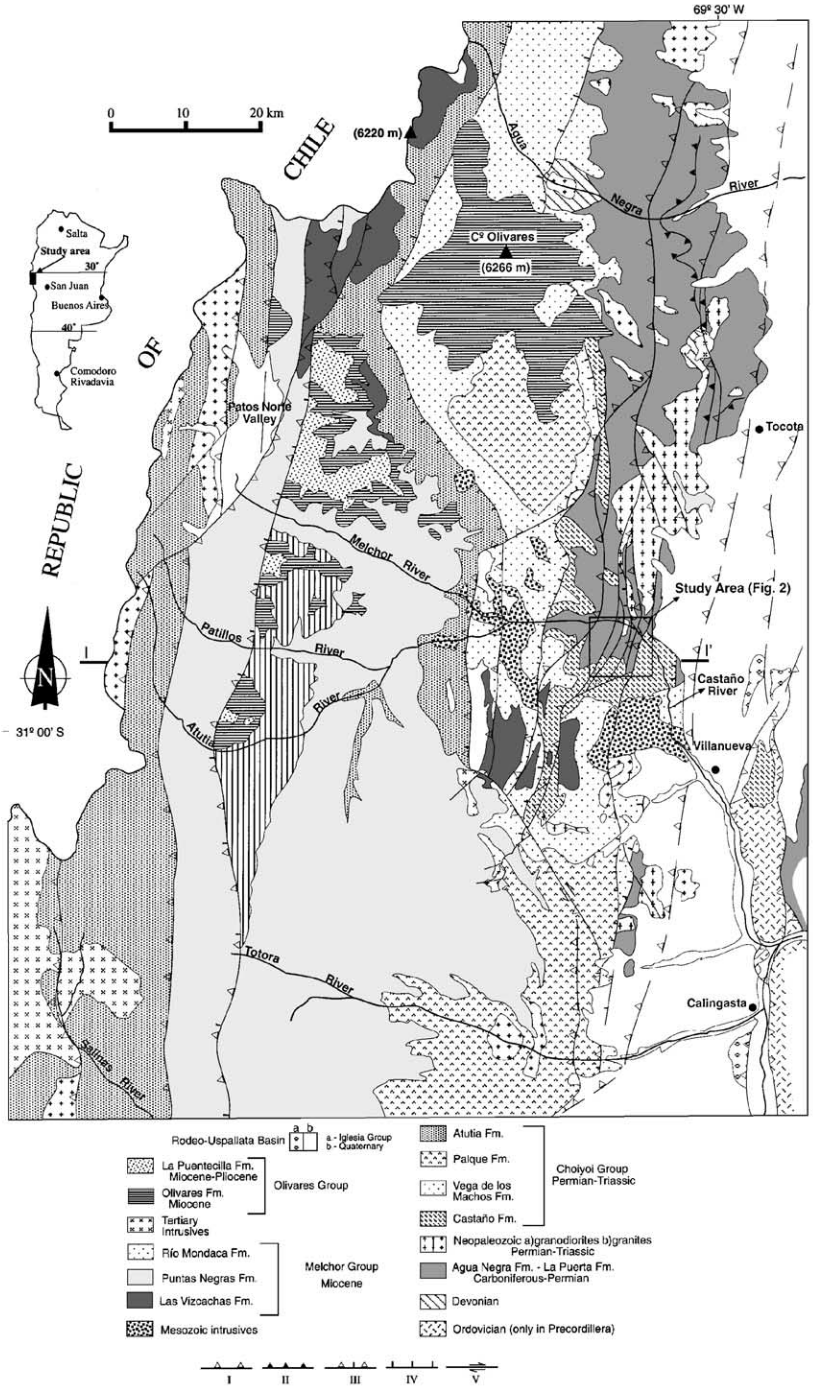

Fig. 1. Geological sketch map of the Andean Frontal Cordillera between 30°00′ and 31°30′ S latitude (Provincia de San Juan, Argentina). The study area appears in box. I–I′ cross-section represented in Fig. 3. After Heredia et al. (1996, 2002), Espina et al. (in press), Cardo et al. (in press), Ragona et al. (1995) and Rodríguez Fernández et al. (1996). (I) Andean thrust, (II) Gondwanic thrust, (III) inverted normal fault, (IV) Andean normal fault, (V) strike–slip fault.

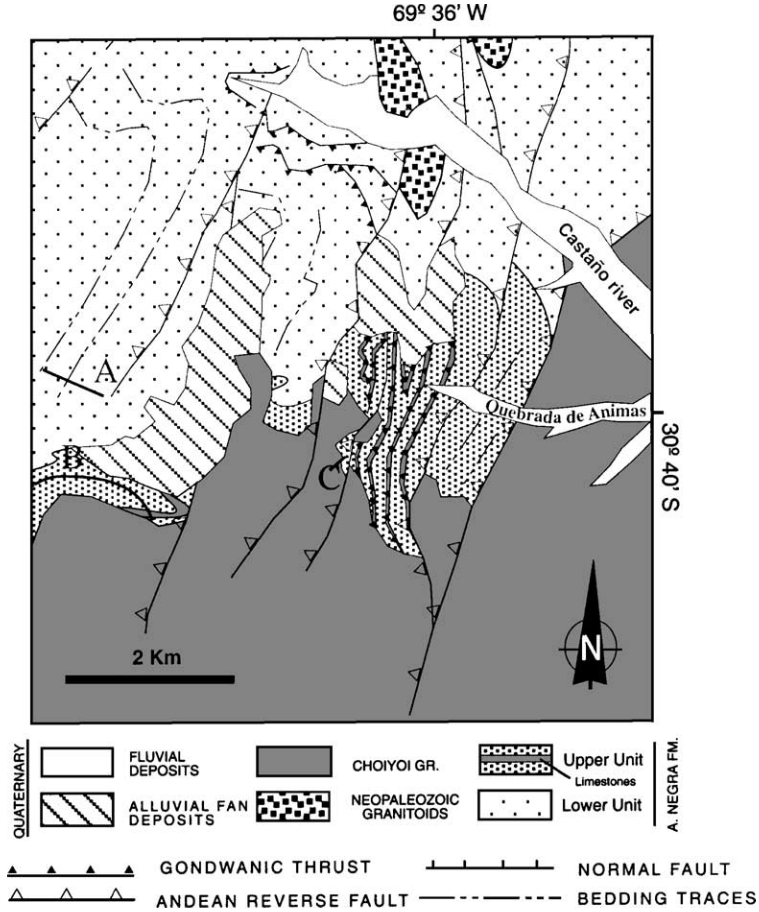

Fig. 2. Geological sketch map of the Quebrada de las Ñipas and Quebrada de las Animas (Heredia et al., 2002). Palynomorph samples were collected in the areas A (Animas section), B (Ñipas section), C (Animas section).

These include east-vergent thrusts and related folds (Fig. 2) that record a large-scale shortening.

A volcanic and volcanoclastic cover (Choiyoi Group: Permian and Triassic) unconformably overlies the Palaeozoic basement (Figs. 1–3). This unit is affected by normal faults, such as, the Las Leñas Fault (Fig. 3) with downthrown western blocks, and intruded by Jurassic granodioritic rocks. The faults in this unit affect the basement in a typical thick-skinned tectonic style and are grouped in swathes with a N–S strike (Fig. 1).

Andean cover have also a volcanic and volcanoclastic nature and lie unconformably over the older units. In the Upper Miocene the older normal faults were inverted by the uplifting of the western block, deforming the lower and upper units during the compressional phase of the Andean Cycle.

3. Stratigraphy of the Agua Negra Formation

In the Frontal Cordillera, the Agua Negra Fm which has an estimated total thickness of approximately 2000 m, can be correlated by stratigraphic position and facies with the La Puerta Fm (Caballé, 1986), located to the NW of Calingasta (Fig. 1). It is Late Carboniferous–Early Permian in age (Aparicio, 1969; González, 1977).

On a regional scale, the lowest part of the Agua Negra Fm (Fig. 1), which does not outcrop in the Castaño Viejo area, contains an accumulation of

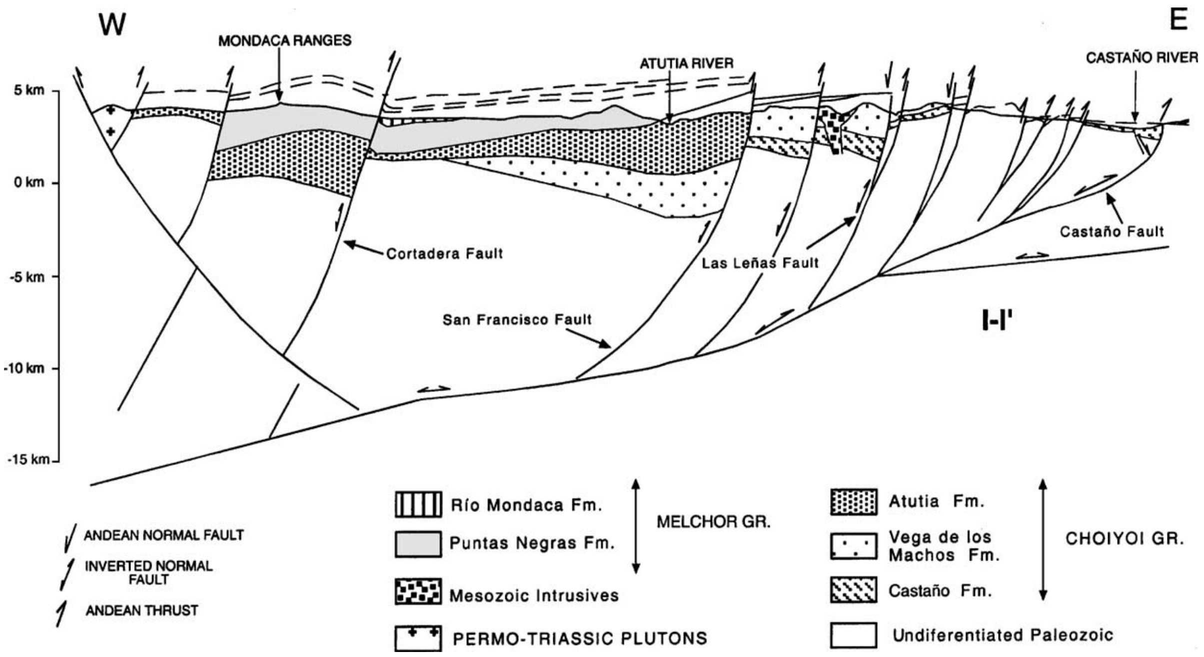

Fig. 3. General geological cross-section of the area. Location in Fig. 1 (Heredia et al., 2002).

black lutites with nodules and clasts. The poor sorting of the clasts and their rather disorderly distribution in some levels indicate that particular beds were deposited as a result of various types of massive flow processes.

In the middle of the stratigraphic succession there are terrigenous sandy levels which become progressively more abundant towards the top.

The uppermost sections of the Agua Negra Fm, which in the Castaño Viejo area correspond to the lowest stratigraphic outcrop, are mainly made up of sandy materials with various types of cross-bedding (Fig. 4). This suggests a high-energy environment in a shallow sub-aquatic context. In general, we propose that these correspond to barrier island beach deposits, which would have developed in this area as the result of significant drift currents that existed at the time of their accumulation.

In the Castaño Viejo area, the best Carboniferous outcrop appears in an anticlinal structure located at the head of the Quebrada de las Animas (Figs. 2 and 3). This corresponds approximately to the upper half of the Agua Negra Fm which is a succession of some 800 m in thickness and has been identified between (Heredia et al., 2002) the Quebrada de las Animas and the Quebrada de las Ñipas (Fig. 4).

Two successions have been distinguished within the Agua Negra Fm (Rodríguez Fernández et al., 1997; Heredia et al., 2002) in the Castaño Viejo sector (Figs. 2 and 4). The first of these is considered to be earlier than the Upper Palaeozoic. It is predominantly siliciclastic and is made up of lutites, sandstones, conglomerates and microconglomerates containing clasts such as sedimentary materials and high grade metamorphic rocks. The sediments were originated from the erosion of previous deposits which accumulated in a shallow marine setting and sporadically affected by storm events (Fig. 4). The second succession, with a thickness of approximately 400 m has been dated as Lower Permian (Heredia et al., 2002). This succession is separated from the underlying rocks by an unconformity above which polymictic orthoconglomerates (Fig. 4) with abundant olistoliths of metric scale are exposed. This is followed by a section characterised by sandstones, lutites, very thin ignimbrites and para-conglomerates with sedimentary and volcanic clasts. The succession is capped

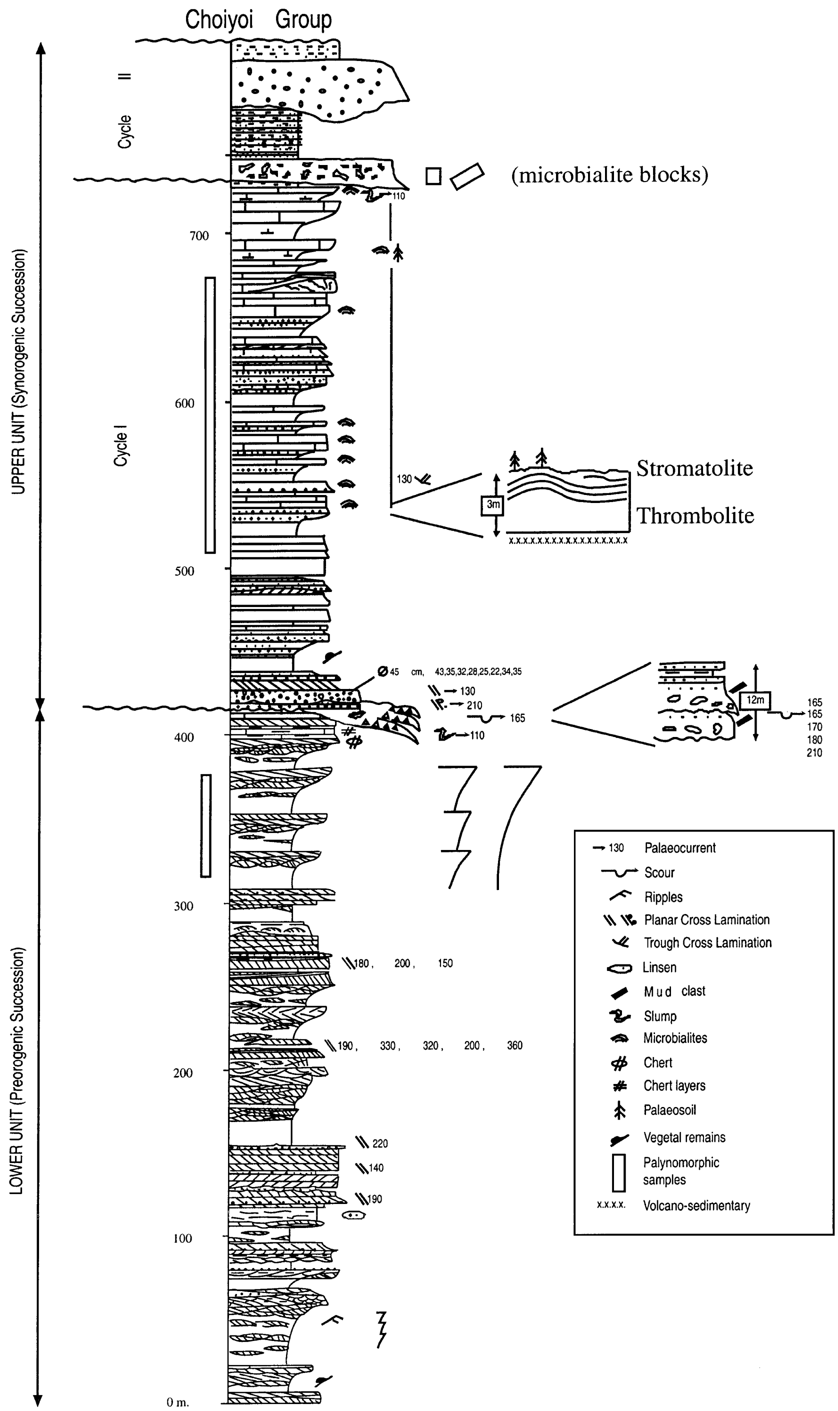

Fig. 4. Stratigraphic column of the Agua Negra Fm outcropping in the Quebrada de las Ñipas y and the Quebrada de las Animas (Castaño Viejo area). See Fig. 2 for location (Heredia et al., 2002, modified).

by microbialite limestones intercalated with fine volcanoclastic sediments.

4. Sedimentological analysis

The Agua Negra Fm in the Castaño Viejo area, as indicated above, has been subdivided into two successions (Fig. 4). The lower succession presents a dominant organization of stacks of sequences ranging from 8 to 10 m up 150 m in thickness. These are thickening and coarsening upward sequences with primary tractive sedimentary structures. The series presents a vertical organization of shallowing-upwards sequences.

The sedimentary setting would correspond to a shallow shelf exposed to repeated prograding–aggrading processes, which gave rise to various negative macro-sequences indicating important surges in activity. The series begins with a swift deepening represented by thick sections of lutites which, moving up the sequence, are gradually intercalated with sandy sections (Fig. 4). These sandy sections begin with linsen-type structures and end at the top of the sequence with megaripples and hydraulic dunes (Fig. 5). The sequences located in the lower part of the succession also contain abundant fragments of sub-aerial plant remains, which suggest episodes of shallowing. The upper third of the preorogenic succession, also contains thick intervals of lutites, suggesting strong deepening surges.

The top of the lower succession is marked by an important erosive surface above which appears a totally different succession. The contact between the two successions can be observed at the head of the Quebrada de las Ñipas (Fig. 5) where the rest of the succession is clearly displayed. Prior to this study this succession had been dated as Carboniferous–Permian and interpreted as a large Gondwanic synorogenic sequence (Rodríguez Fernández et al., 1997; Heredia et al., 2002).

The sediments corresponding to the upper synorogenic succession have an estimated total thickness of about 400 m, and are unconformably separated from the lower preorogenic succession of the Agua Negra Fm below and the Choiyoi Group, above.

The base of the upper succession is formed of various metric levels of coarse terrigenous material marked by sharp bases and tops with positive granulometric gradation (Fig. 4). These levels are made up of conglomerates with clasts floating in a poorly sorted sandy matrix. This suggests that the clasts were already situated within the matrix when all the clastic materials were transported by the active sedimentary flows at the time of deposition. The sharp bases are, in some cases, more or less flat, whereas in other cases, gutter casts of various orders and magnitudes appear, mainly aligned in a roughly N–S direction (Fig. 5). This suggests that the dominant palaeocurrents, responsible for producing basal marks of this type also followed a mainly N–S direction. The middle part of the conglomerates, despite its fairly massive appearance, exhibits a certain granulometric gradation with positive tendencies. Towards the upper part of the conglomerate levels, there is a markedly positive granulometric gradation.

This sequential ordering is repeated several times, with unit thicknesses of the order of 2 to 2.5 m. In this way a 12-m-thick compound sequence is made up of five lesser order sequences (simplified in Fig. 4).

The various lower-order sedimentary events must have been turbulent in nature. This can be inferred from the generation of erosive bases marked by the presence of gutter-type sedimentary structures of varying order and magnitude. The vertical facies variations suggest the existence of very dense sediment gravity flows. These flowed down the topographic slopes which formed as a consequence of the tectonic activity, as evidenced by the unconformity which separates the lower and upper successions described for the Agua Negra Fm. The sedimentary setting was sub-aquatic, as suggested by both the erosive bases and above all by the complete, though very gradual, transition from the lower to middle part of the levels. These are characterised by poor sorting in the basal parts, and a better granulometric sorting in the upper part. These flows were progressively reduced by dynamic dilatation processes as they entered the static waters of the basin. The final result would be the accumulation of sediments transported by flows that were initially of high density, but became progressively more diluted as they advanced, and were gradually transformed into lower density turbulent flows.

In the Quebrada de las Ñipas, these sediments occasionally form progressive unconformities (Fig. 5). The sedimentary succession located immediately

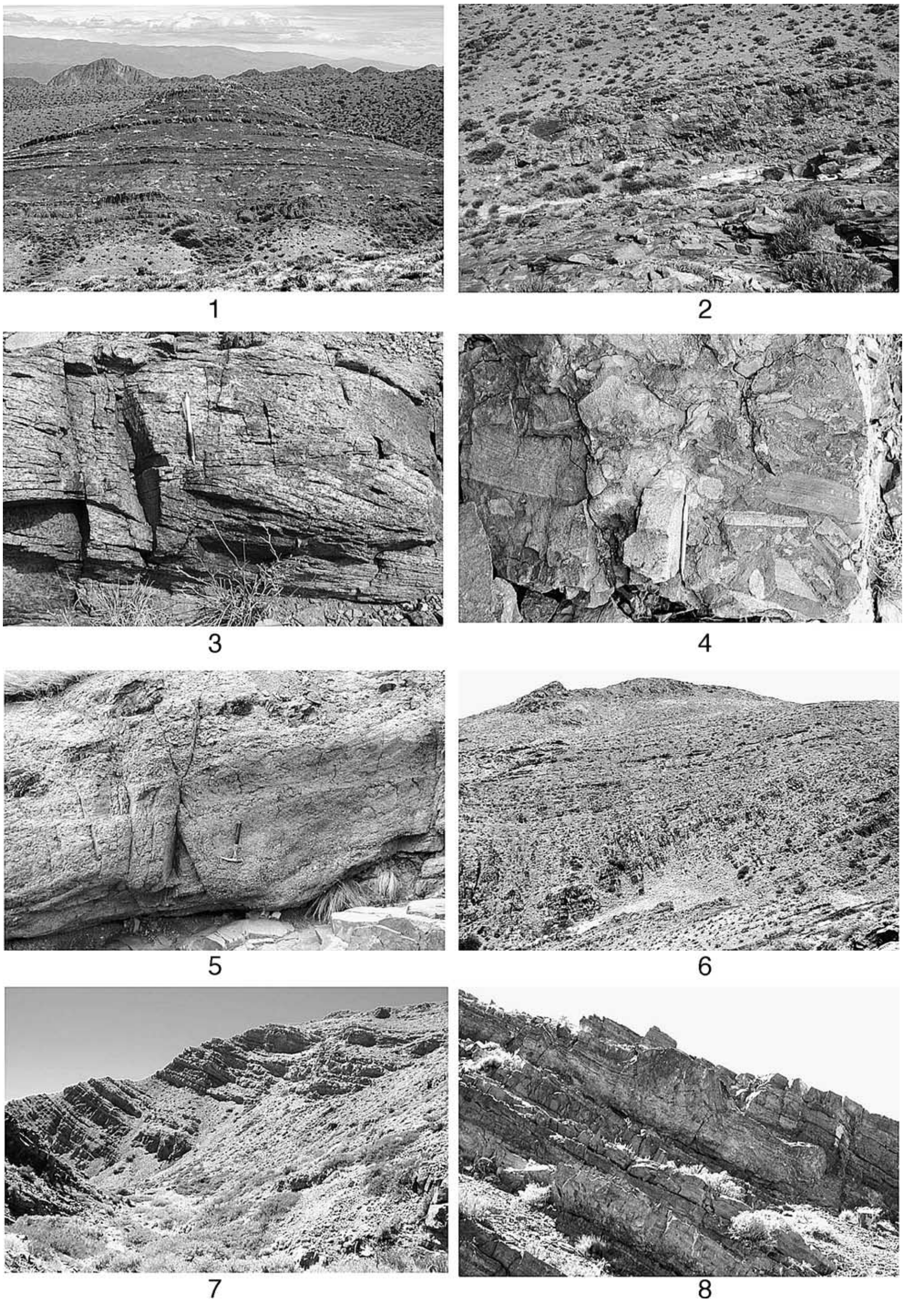

Fig. 5. Field photographs of the Agua Negra Fm: (1) view of the lower unit which contains Upper Carboniferous palynomorphs; (2) outcrop of cross-bedding interpreted as hydraulic dunes in the lower unit; (3) cross-stratification within the hydraulic dunes; (4) breccia at the base of the upper unit including lower unit clasts; (5) gutter cast at the base of conglomerates with cross-lamination of the base of the upper unit; (6) progressive unconformities in the upper unit in the Quebrada de las Ñipas; (7) microbialite limestones of the upper unit at the Quebrada de las Ñipas; (8) close up view of microbialite limestones with thrombolite constructions.

above represents periods of certain stability in these areas of the basin which were affected by supplies of volcanic or volcanoclastic material.

5. The microbialites of the upper succession

The upper part of the succession consists of 200 m (Fig. 4) of carbonate microbialites (as defined by Burne and Moore, 1987) intercalated with thin detritic horizons, often volcanoclastic in nature.

The carbonate microbialites form sequences, from 1 to 6 m thick of large, and in some cases interconnected, domes with a diameter of around 2.5 m (Fig. 5). These are formed of non-laminated facies (thrombolites in the sense of Aitken, 1967) in the lower parts, and laminated facies (stromatolites as defined by Kalkowski, 1908, and Aitken, 1967) in the upper parts (Fig. 6). These sequences are capped by palaeosoil facies (Fig. 6).

The thrombolitic facies, which represent 2/3 of the sequence thickness, include ooids, peloids and fenestral cavities filled with spar calcite (Fig. 6). The stromatolite facies are made up of microlaminae of micrite and microsparcalcite, which are brecciated (Fig. 6) in the uppermost part of the sequence. The succession was interpreted as shallowing upwards sequences and these can be observed throughout the succession.

Silt size quartz grains found in the limestones are considered to be aeolian because of their granulometric characteristics, and their mottled and polished morphology. There are also silicifications partially filling the fenestral cavities.

The palaeosoils show abundant silicified plant remains including, in some cases, tree stumps in life position (Fig. 6).

The best palynological results of this study have been obtained from the clastic and volcanoclastic horizons.

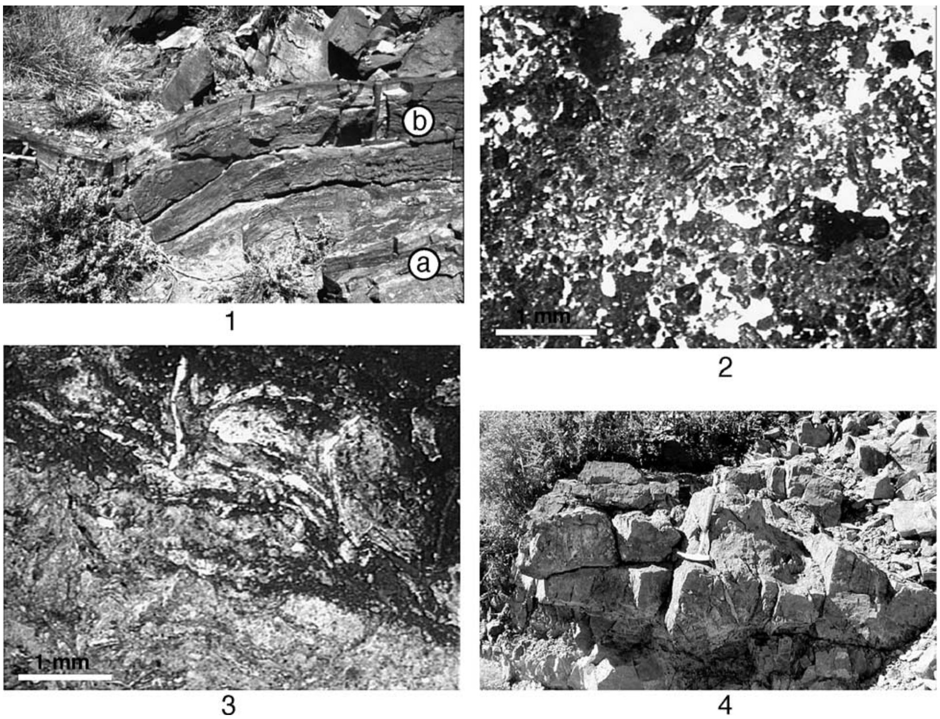

Fig. 6. (1) Stromatolite domes in the Quebrada de las Ñipas showing the thrombolites (a) and stromatolite (b). (2) Non-laminated microfacies within the thrombolite. (3) Brecciated stromatolite microfacies within the stromatolite. (4) Palaeosoil at the top of the stromatolite dome with remains of tree stumps.

The conglomerates and breccias at the bottom of the succession, the angular unconformities located in the middle part of the succession and even some small scale slumps in the limestone of the upper part suggest clearly the synorogenic nature of the succession. This succession lies on top of a preorogenic succession, from which it is separated by a clear and sharp erosive surface.

6. Palynomorphic record and stratigraphic age considerations

In the lower part of the Quebrada de las Animas (Figs. 2 and 4), between the limestones of the San Ignacio Fm (Heredia et al., 1996) three samples provided the following palynomorphs: *Ancistrospora verrucosa* Menéndez and Azcuy 1972; *Apiculiretu-*

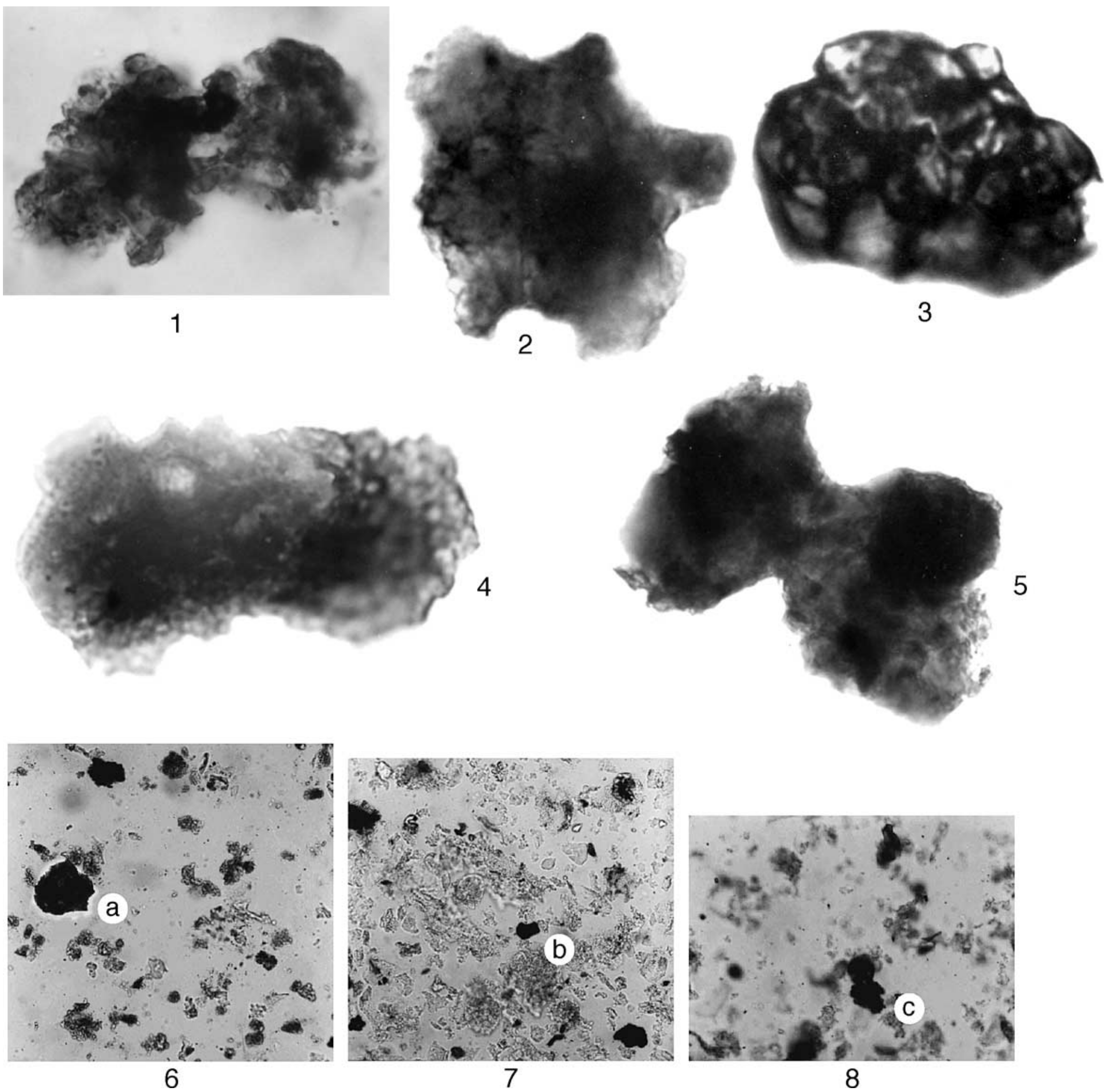

Fig. 7. 1—*P. papilionis* ×500. 2—*R. paganciana* ×800. 3—*A. verrucosa* ×1000. 4—*Limitisporites* sp. ×800. 5—*Lunatisporites* sp. ×400. 6–8—Palynofacies from different samples with very poorly preserved palynomorphs ×100. 6—*Convolutispora*. 7—Black chitinozoa. 8—*Platysaccus*.

sispora tuberculata Azcuy 1975; *Cristatisporites* sp.; *Lundbladispora* cf. *braziliensis* (Pant and Srivastava) Marques-Toigo and Pons 1974; *Raistrickia paganciana* Azcuy 1975; *Raistrickia* cf. *rotunda* Azcuy 1976, cf. *Reticulatisporites pseudopalliatus* Staplin 1960, *Colpisaccites granulosus* Archangelsky & Gomerro 1979; *Limitisporites* sp.; *Platysaccus papilionis* Potonie and Klaus 1954; *Lunatisporites* sp. and *Bisaccate* spp. (Fig. 7).

The bottom part of the section in the Quebrada de las Animas (Figs. 2 and 4) contains *R. paganciana* Azcuy 1975 and some undetermined bialate remains.

A sample taken from the limestones in the Quebrada de las Ñipas contains *Ancistrospora* sp. *A* Azcuy 1975; *Convolutispora muriornata* Menéndez 1965 and *Platysaccus* sp.

In all the samples from Castaño Viejo, the trilete spores are accompanied by some bialate forms, while only one striated form (*Lunatisporites*) was found. The lack of striated forms that are characteristic of the Permian is noticeable. The samples that contain the better-preserved associations of palynomorphs include spores and bialates that would correspond to an Upper Carboniferous age environment. The remains of highly metamorphosed large, black spores are evidence of coarse processes and chitinozoa indicative of a possible Devonian age, and are considered to have been reworked and resedimented in the Upper Carboniferous basin.

The association of palynomorphs found in all the samples would appear to correspond to the Ancistrospora palynological zone identified by Azcuy (1986) in the Paganzo Basin. The characteristic forms in this zone such as *A. verrucosa* and *C. muriornata*, both indicative of an Upper Carboniferous age, are found in the samples from Castaño Viejo analysed in this study. The association of palynomorphs found in the samples from Castaño Viejo could correspond to the *R. densa*–*C. muriornata* Biozone (Césari and Gutiérrez, 2000) of an Upper Carboniferous age.

7. The palynomorph environment

The abundance of Pteridophyta type spores such as Lycopsida, Philicopsida and Sphenopsida, are indicative of a flat swampy humid area (Azcuy, 1978), in which microbioliths grow. These spores are associated with bisaccate forms, some of which may belong to the Coniferae. They may have been transported from higher topographic areas with more arid climatic conditions.

8. Discussion

Pöthe de Baldis et al. (1987) processed 8 samples from the same series, and found only Acritarchs and Chitinozoa of Silurian–Lower Devonian age. However, our study of a larger number of samples (40) provided associations characteristic of Upper Carboniferous age. This is indicated by the coincidence of reworked Devonian black spores and Chitinozoa with palynomorphs of the Upper Carboniferous age.

In this way, the upper part of the upper succession of the Agua Negra Fm, of Upper Carboniferous age, can be correlated with the old San Ignacio Fm (Heredia et al., 1996) with which it shares many characteristics.

Gutiérrez (1992) found in Cerro Agua Negra some palynomorphs such as *Granulatisporites*, *Apiculiretusispora* and *Cristatisporites* and interpreted these as corresponding to the Lower Permian–Upper Carboniferous. In addition, Ottone and Rosello (1996) found in the La Puerta Fm palynomorphs such as *Limitisporites*, *Lueckisporites*, *Lunatisporites* and *Vittatina*, which are considered to be characteristic of the Permian.

The reclassification of the age of the limestones in the basement of the Andean Frontal Cordillera implies that there may not be great differences between the sedimentary sequences in this morphostructural unit and those of similar age that outcrop in the Precordillera.

The preorogenic succession of the Agua Negra Fm is similar to the deposits of the same age that crop out in the Precordillera (Paganzo Basin), though more distal in origin and more clearly marine. This succession would have its source area to the E, in the Sierras Pampeanas, which are formed of high grade metamorphic rocks. Fragments of highly metamorphosed rocks have indeed been found in the preorogenic succession (Heredia et al., 2002). The preorogenic succession would then have been deposited in a retroarc basin, as proposed by Ramos (1988).

At that time the volcanic arc proposed by Ramos (1988) was situated further to the west.

In such a scenario it is not necessary to postulate a great separation between Cuyania and Chilenia prior to their amalgamation, nor would there be any large ocean consumed in this process. Had such a process taken place, it would also have involved an important subduction at the limit of one or other of the two land masses and an important level of volcanic activity to the east, amongst other characteristics. On the western margin of Chilenia, subduction did take place, forming an accretionary prism, according to Rebolledo and Charrier (1994). Yet no evidence of this exists either in the Precordillera or in the outcrops recently described by Heredia et al. (2002) in the Frontal Cordillera.

Our data also suggest the existence, during the synorogenic succession, of a well developed Upper Carboniferous retroarc foreland basin in the Castaño Viejo area related to the Gondwanic Orogeny. This synorogenic succession, previously considered to be exclusively Permian in origin (Heredia et al., 2002), contains carbonate and siliciclastic platforms with some volcanic supply. The source area for the greater part of the sediments would have been situated to the W, where the volcanic arc was located. During the orogenic process, this arc would have been elevated and eroded together with other Gondwanic reliefs made up of Silurian–Devonian sedimentary rocks.

The presence of N–S palaeocurrents, running parallel to the shore of the foreland basin, is common in this type of basin. Typically, palaeocurrents are only orthogonal, indicating the position of the source area, in the area immediately around the source (near the elevated area).

The carbonate platforms developed in the passive margin between areas filled with siliciclastic supplies and were progressively destabilised and eroded as deformation advanced eastwards.

9. Conclusions

The Upper Carboniferous series in the Castaño Viejo area of the Frontal Cordillera are part of a Retroarc Foreland Basin (following Dickinson, 1974) infilled during the Gondwanic deformation. Palynomorph dating demonstrates that the ages derived from the studied succession point to the Upper Carboniferous, given the absence of records attributable to the Permian. The palynomorph association probably corresponds to the *R. densa–C. muriornata* Biozone (Césari and Gutiérrez, 2000), indicating flat swampy and humid environments (Azcuy, 1978). The lack of striated forms that are characteristic of the Permian is noteworthy. The combination of Upper Carboniferous palynomorphs with chitinozoa and some spores of Devonian age is the result of reworking and erosion of nearby uplifting reliefs.

Stratigraphic and sedimentological considerations, together with the faunal content, indicate that the Upper Carboniferous series include two separate successions that represent different environments within the retroarc foreland basin. The lower succession is characterised by coastal siliciclastic sediments, associated with beaches and barrier islands. These are organised in shallowing, thickening and coarsening upwards sequences. This lower succession may represent the passive marginal facies of the foreland basin. The upper succession includes detritic components which clearly originated in the underlying passive margin succession and in the metamorphic substratum beneath. Also, the presence in some areas of progressive unconformities indicates that the upper succession was deposited during the uplift and erosion of nearby reliefs that is, the upper succession is synorogenic. The presence of series of relatively thin microbialite limestones in the upper part indicates the occurrence of periods associated with a certain degree of stability during the final stages of the infilling of the syntectonic basin.

The source area of lower passive marginal facies may have been located towards the E (Sierras Pampeanas), and would correspond to the proximal facies in the Precordillera. The source area of the upper syntectonic facies have been located towards the W, in the area in which a volcanic arc developed, and where active deformation processes led to an amalgamation with Silurian–Devonian rocks which may also have originated to the west. The superposition of both facies indicates an eastward migration of the deformation associated with the progressive cannibalisation of foreland basin sediments.

Our study indicates that no Silurian–Lower Devonian limestones appear in the basement of the

Cordillera Frontal. This finding, together with the new data on the Upper Carboniferous series, implies that earlier interpretations based on a large separation between the Precordillera (Cuyania terrane) and the Cordillera Frontal (Chilenia terrane) at 31° latitude in the Andes should be reviewed.

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