

# Tertiary tectonics of the sub-Andean region of the North Patagonian Andes, southern central Andes of Argentina (41–42°30'S)

Raúl E. Giacosa<sup>a,b,\*</sup>, Juan C. Afonso<sup>c</sup>, Nemesio Heredia C.<sup>d</sup>, José Paredes<sup>b</sup>

<sup>a</sup> Servicio Geológico y Minero Argentino, Instituto de Geología y Recursos Minerales, CC 38 B, Km 8, (9003) Comodoro Rivadavia, Chubut, Argentina

<sup>b</sup> Departamento de Geología, Universidad Nacional de la Patagonia, Ciudad Universitaria, Km 4, (9000) Comodoro Rivadavia, Chubut, Argentina

<sup>c</sup> Department of Earth Sciences and Ottawa-Carleton Geoscience Centre, Carleton University, Ottawa, K1S 5B6, Ontario, Canada

<sup>d</sup> Instituto Geológico y Minero de España, Parque Científico de León, Avda. Real, 1, E24006 León, Spain

Received 1 November 2003; accepted 1 May 2005

## Abstract

The sub-Andean region of the North Patagonian Andes is located between the north Patagonian foreland and the highest elevations of the Andean Cordillera. Its Tertiary contractional structure, active since the upper Late Oligocene and through the upper Late Miocene, corresponds to the external sector of the North Patagonian Andes fold-and-thrust belt, which is characterized by east-vergent thrusts that affect stratified Cenozoic rocks. The units involved in the deformation correspond to El Maitén Oligocene volcanic belt, deformed between east-vergent thrusts and backthrusts, and Oligocene–Miocene sedimentary rocks of the Ñirihuau–Collón Curá Basin. The northern sector of the basin was structured as a thin-skinned fold belt that comprises the Ñirihuau fold belt and a frontal sedimentary wedge. To the south, sedimentary depocenters are confined between medium- to high-angle reverse faults with evidence of basement structural control. In both cases, the general tectonosedimentary framework shows the youngest units toward the east, in agreement with the advance of the orogenic wedge. Most of the Ñirihuau–Collón Curá Basin infill fits a foreland basin system model. Some sectors of the basin show evidence of structural control by normal faults in the initial sedimentation stages. This early extensional regime might be associated with late phases of Oligocene volcanism. Extensional structures probably were partially reactivated during the upper Late Oligocene, as suggested by seismic data.

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**Keywords:** North Patagonian Andes; Andean tectonics; sub-Andean region; fold-and-thrust belt; Tertiary basins

## Resumen

La región subandina de los Andes Nordpatagónicos está situada entre el antepaís nordpatagónico y la región andina principal. Su estructura contraccional terciaria desarrollada a partir del Oligoceno superior tardío y durante el Mioceno superior tardío, corresponde al sector externo de la faja plegada y corrida de los Andes Nordpatagónicos, que se caracteriza por corrimientos de vergencia este en rocas estratificadas cenozoicas. Las rocas estratificadas cenozoicas involucradas en la deformación pertenecen al cinturón volcánico oligoceno de El Maitén, estructurado entre corrimientos de vergencia este y retrocorrimientos y, a las sedimentitas oligoceno–miocenas de la cuenca de Ñirihuau–Collón Curá. El sector norte de la cuenca fue estructurado como una faja plegada y corrida epidérmica y una cuña sedimentaria con poca deformación en el subsuelo, en tanto que al sur, los depocentros sedimentarios se encuentran confinados entre fallas de vergencia opuesta de mediano a alto ángulo, lo que evidencia el control estructural del basamento de la cuenca. En ambos casos, el patrón tectosedimentario general muestra a las unidades más jóvenes hacia el este, en concordancia con el avance en secuencia hacia el antepaís de la cuña orogénica. Si bien, desde el punto de vista tectosedimentario, la mayor parte del relleno ajusta con un modelo de cuenca de antepaís, en algunos sectores de la cuenca, el inicio de la sedimentación habría sido controlado por fallas normales, las que muestran algunas evidencias en el subsuelo de inversión tectónica parcial. Este fallamiento normal estaría relacionado con los estadios finales del régimen extensional asociado al volcanismo Oligoceno.

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**Palabras clave:** Andes nordpatagónicos; Tectónica Andina; región subandina; faja plegada y corrida; cuencas terciarias

\* Corresponding author. Address: Servicio Geológico y Minero Argentino, Instituto de Geología y Recursos Minerales, CC 38 B, Km 8, (9003) Comodoro Rivadavia, Chubut, Argentina. Tel.: +54 297 4559342; fax: +54 297 4535115.

E-mail address: giacosaraul@yahoo.com.ar (R.E. Giacosa).

## 1. Introduction

The central Andes traditionally have been subdivided into different geologic provinces with distinct stratigraphies and structural features. The North Patagonian Andes, one of these morphostructural domains, is located between 40° and 45°S latitude and comprises more than 500 km of the Andean Cordillera (Fig. 1). The morphology of the region has been highly influenced by aggradational and erosional processes during Plio–Pleistocene glaciations. The highest sector (41–43°S) is characterized by average elevations of 2000–2300 m; Monte Tronador is the main topographic feature (3478 m).

The sub-Andean region (east of 71°W) consists of a 25 km wide N–S to NNW mountain belt with maximum elevations of approximately 2000 m and a 30 km wide area of fluvial plains. Tertiary volcanic and sedimentary rocks represent the predominant stratigraphic units. To the east (Fig. 1(b)), the foreland region encompasses the northern part of the Patagonian Precordillera (part of the Northpatagonian Massif affected by Andean tectonics).

The geodynamic evolution of the North Patagonian Andes remains obscure because of the scarcity of comprehensive studies on the origin and evolution of its igneous–metamorphic basement and Mesozoic basins. Some recent works have attempted to provide insights (e.g. Jordan et al., 2001; Folguera and Ramos, 2002; Folguera and Iannizzotto, 2004); however,

several topics must still be clarified. Foremost among these include the geometry of the regional structure, which has been attributed to wrench tectonics (Dalla Salda and Franzese, 1987) or a fold-and-thrust belt model (Ramos and Cortés, 1984; Giacosa and Heredia, 2000), and the relative influence of strike-slip (Diraison et al., 1998) and dip-slip components on the main structures (Giacosa and Heredia, 2000). In any case, cartographic evidence is needed to support the strain partitioning indicated by fault slip data (Diraison et al., 1998).

The origin and evolution of the tertiary basins are also controversial. They have been described in terms of a pull-apart model (Spalletti and Dalla Salda, 1996), pure crustal extension in the backarc (Mancini and Serna, 1989; Cazau et al., 1989), or synorogenic deposition in a foreland basin related to different eastward migration episodes of the orogenic front (Ramos and Cortés, 1984; Giacosa and Heredia, 1999, 2000). In this context and without suggesting a specific origin, Diraison et al. (1998) highlight the lack of synextensional seismic fabrics in the basin. However, some evidence suggests that the Ñirihuau–Collón Curá Basin, similar to most retroarc basins, has a complex tectonic evolution and should be regarded as a polyphase basin (Afonso, 2002).

Giacosa and Heredia (1999) identify two different tertiary basins (Fig. 1(c)) that are geographically and temporally separated by the Oligocene El Maitén volcanic belt (Rapela et al., 1988). The western depocenter corresponds to El Bolsón

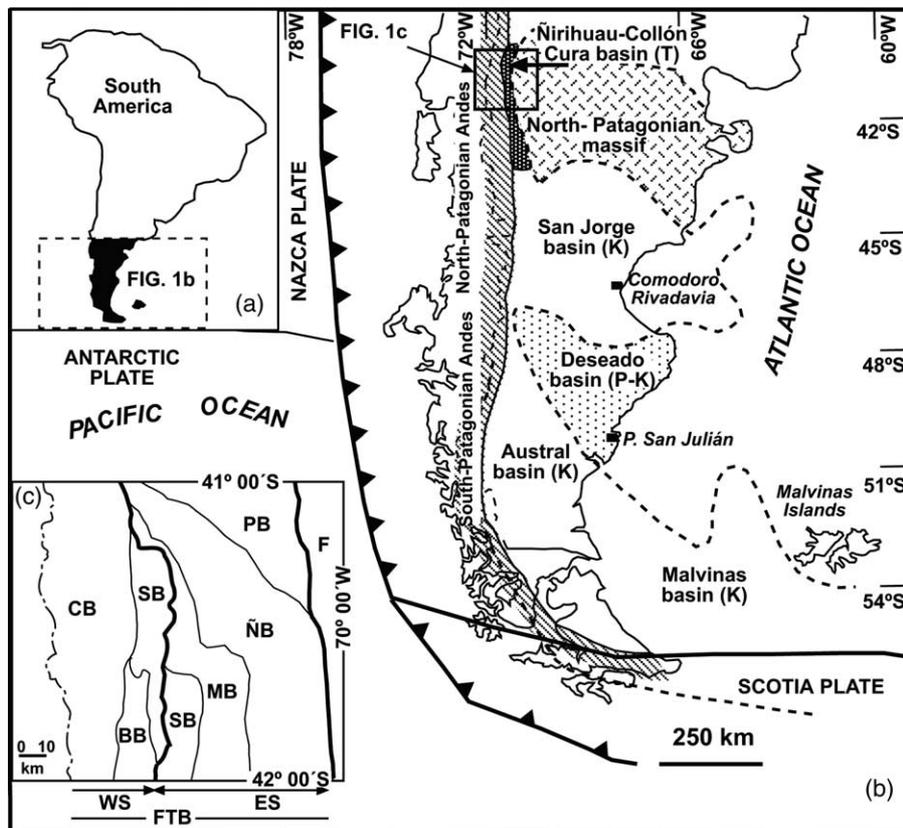


Fig. 1. (a, b) Location of the study area. (c) Map showing the main tectonomagmatic and tectosedimentary division of northwestern Patagonia. Key: CB, Cordilleran Batholith; SB, subcordilleran Batholith; PB, Pilcaniyeu belt; MB, Maitén belt; BB, Bolsón Basin; ÑB, Ñirihuau Basin; F, foreland; FTB, fold-and-thrust belt; WS, western sector; ES, eastern sector.

Basin, a Middle Eocene–Lower Oligocene marine and continental sedimentary sequence (Giacosa and Heredia, 2004a). The eastern depocenter coincides with the Upper Oligocene–Miocene Ñirihuau–Collón Curá Basin, in which the most extensive tertiary sediments are deposited.

In this article, we characterize the structure and tectonosedimentary evolution of the sub-Andean region of the North Patagonian Andes on the basis of an integrated analysis, including new 1:250,000 scale geological mapping, 28 seismic lines, and results from three exploration wells drilled by Exxon company. Because only hard copies are available, seismic lines are not reproduced in this article.

## 2. Regional stratigraphy

The stratigraphic record of the North Patagonian Andes between latitudes 41 and 42°30'S is characterized by three major lithological associations (Fig. 2): the pre-Mesozoic basement, Mesozoic igneous and sedimentary rocks, and Tertiary volcanic and sedimentary rocks.

The pre-Mesozoic basement consists of igneous and metamorphic rocks of medium to medium-high metamorphic grade, produced as a result of a Late Paleozoic remobilization of the Precambrian or Early Paleozoic basement during the Gondwanic orogeny (Ramos, 2000). In the Andean region, these rocks are assigned to the Colohuincul Complex (Turner, 1965), composed of micaceous schists and gneisses, granitic and dioritic orthogneisses, and granodioritic–tonalitic intrusives. The U–Pb and K–Ar ages indicate that magmatism, metamorphism, and deformation occurred during the Late Paleozoic ( $345 \pm 4.4$  Ma), predating a Middle–Late Triassic regional uplift ( $230 \pm 5$ ,  $205 \pm 6$  Ma; Basei et al., 1999). In the foreland region, the Cushamen Formation (Volkheimer, 1964) consists of garnet-micaceous schists and gneisses, granitic and tonalitic orthogneisses, granitic pegmatites, and metavolcanic rocks (Giacosa et al., 2001). U/Pb data point to a possible Gondwanian crystallization age ( $334 \pm 28$ ,  $269 \pm 13$  Ma, Lower Carboniferous–Lower Permian) for the plutonic rocks. K/Ar analysis suggests a late ductile deformation episode between  $262 \pm 7$  and  $235 \pm 8$  Ma, followed by a cooling event, probably associated with regional uplift (Varela et al., 1999).

Mesozoic igneous rocks are well exposed along a 40 km wide N–S belt, west of 71°15'W, as part of the subcordilleran Patagonian Batholith (Gordon and Ort, 1993). In simple terms, the latter is composed predominantly of Lower Jurassic tonalites, granodiorites, and microgranites. A large volume of Cretaceous calc-alkaline plutonic rocks comprises the main sector of the Cordilleran Batholith (Fig. 1(c)), which consists of hornblende–biotite tonalites, granodiorites, and andesitic–tonalitic dikes. In the highest sector of the mountain range, on top of the Cretaceous plutonites, large roof pendants of Lower Jurassic rocks are preserved. These rocks, assigned to different units (see Giacosa et al., 2001), are andesitic–rhyodacitic lavas and pyroclastic rocks interbedded with conglomerates, mudstones, and some limestones containing Liassic marine fossils.

Tertiary rocks constitute the most extensive units in the sub-Andean region and consist predominantly of volcanic and sedimentary rocks related to subduction processes along the western margin of the South American plate (Dalla Salda et al., 1981). The main volcanic unit has been subdivided into two different belts, each with a distinct age and composition (Rapela et al., 1988). East of the foreland border (Fig. 1(c) and 2(b)), the Upper Paleocene–Middle Eocene Pilcaniyeu belt consists of a bimodal volcanic succession in which acid-member rocks predominate. In the sub-Andean region, rocks of the Ventana Formation, a polymodal association in which andesitic and basaltic rocks dominate, characterize the Oligocene El Maitén belt. These rocks also have a more tholeiitic affinity than those from the Pilcaniyeu belt, which may suggest a similarity with the magmatic evolution of seafloor (Rapela et al., 1988). Marine and continental sediments are commonly interbedded within the unit, mostly in the lower section. Large post-Miocene basaltic flows are common in the transition area toward the foreland.

Tertiary sedimentary units are distributed in two different basins (Giacosa and Heredia, 1999). The Mallín Ahogado Formation (Diez and Zubía, 1981) and equivalent units dominate the stratigraphy of El Bolsón Basin, located at approximately 71°30'W (Figs. 1(c) and 2), with primarily continental rocks of Middle Eocene–Early Oligocene age and evidence of transient marine incursions. The Ñirihuau–Collón Curá Basin fill (Fig. 3) consists of a thick sequence of continental fluvial to lacustrine sediments of Late Oligocene–Late Miocene age (Ñirihuau and Collón Curá formations; Cazau et al., 1989). The Martín Formation, deposited close to the Pliocene–Pleistocene boundary (Fig. 3), is a coarse unit that includes a conspicuous proximal facies containing meter-sized angular clasts to the east of the Pantanos thrust.

## 3. Regional structure

### 3.1. Preorogenic Andean stage

Structures developed during the Mesozoic correspond to the extensional preorogenic stage of the Andean cycle (Giacosa and Heredia, 2000). The distribution of Jurassic volcanic rocks to the west of the Ventana–Catedral thrust and backthrust systems (Fig. 2) suggests the presence of an important system of Mesozoic normal faults inverted during the Tertiary compressive stage (Giacosa and Heredia, 2004b). These faults created a graben and half-graben system on the western blocks, which controlled the development of associated extensional basins. In contrast, the eastern sector remained a high-standing basement block in which plutons have intruded preferentially.

Some evidence provided by kinematic fault analysis is consistent with a N–S shortening and W–E extension in Jurassic rocks (data presented in Locality 6, Fig. 4; Diraison et al., 1998). If these data are suitable for Mesozoic faults, they might indicate transtensional components during the extensional stage.

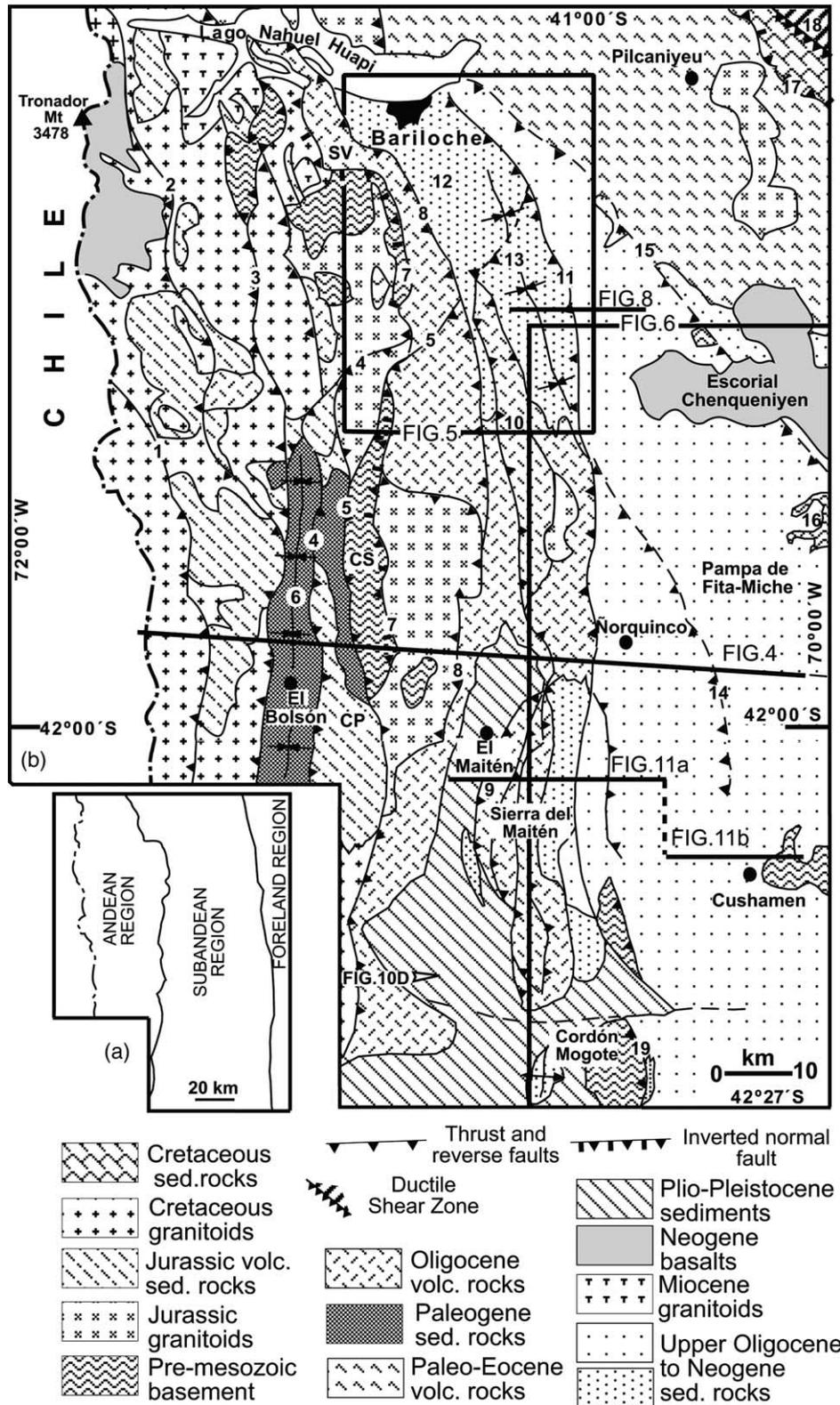


Fig. 2. (a) Location of the sub-Andean region. (b) Geological and structural map based on 1:250,000 scale Hoja Geológica San Carlos de Bariloche (Giacosa et al., 2001). Key: (1) Hielo Azul thrust, (2) Bolsón–Tronador thrust, (3) López thrust, (4) Piltriquitrón backthrusts, (5) Serrucho backthrusts, (6) Bolsón syncline, (7) Ventana–Catedral thrust, (8) Otto thrust, (9) El Maitén backthrusts, (10) Las Bayas pop-up, (11) Pantanos thrust, (12) Ñirihuau fold belt, (13) David syncline, (14) Fita Miche thrust, (15) Río Chico thrust or reverse fault, (16) Río Chico antiform, (17) Pilcaniyeu fault, (18) Carhué ductile shear zone; CS, Cordon Serrucho; CP, Cordon Piltriquitrón; SV, Sierra de la Ventana.

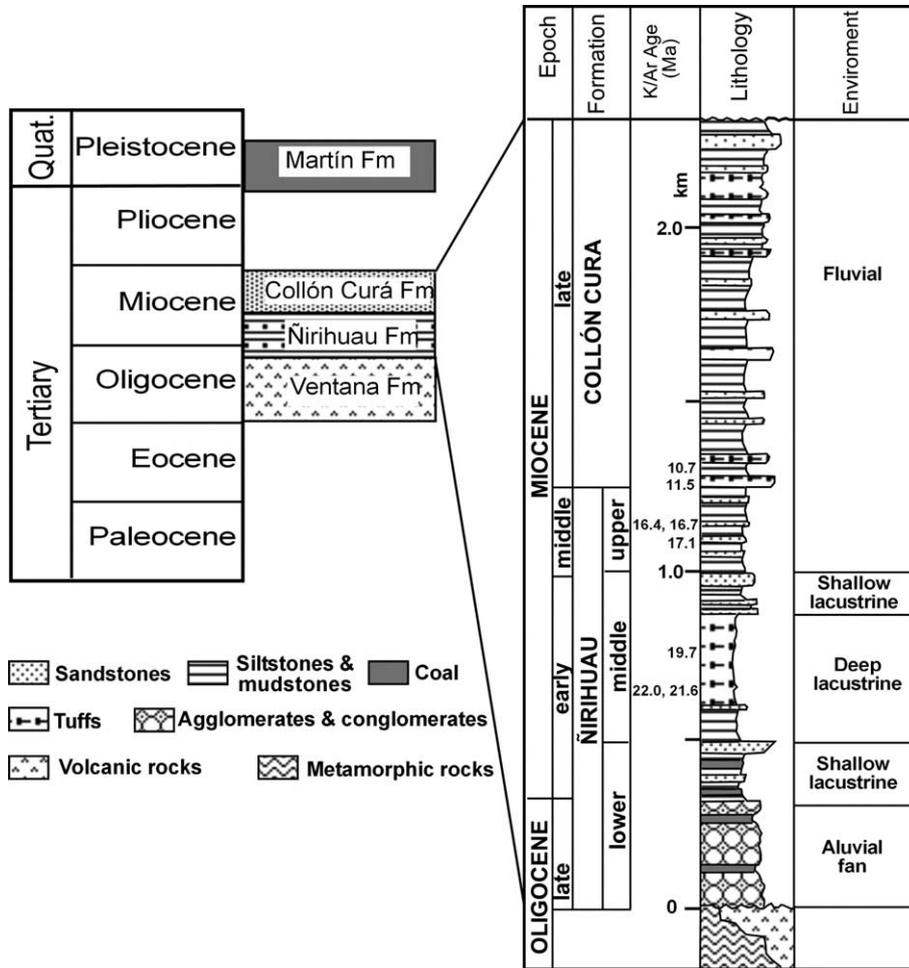


Fig. 3. Summary of the lithostratigraphy of the sub-Andean region and schematic stratigraphic column for the Ñirihuau-Collón Curá Basin (modified from Mancini and Serna, 1989; Cazau et al., 1989).

The expansion of the Cretaceous plutonic arc to the east was also restricted by these extensional paleostructures.

In the foreland region (Fig. 2), extensional structures have a dominant NW-strike that controls the geometry of Upper Triassic and Upper Cretaceous continental basins (Pilcaniyeu fault), as well as the intrusion of the Lower Jurassic Pilcaniyeu pluton in transtensional areas (Giacosa et al., 2001).

### 3.2. Synorogenic Andean stage

Structures developed during the synorogenic stage of the Andean cycle are associated with a fold-and-thrust belt, which was controlled geometrically by pre-Cenozoic basement structures. The belt trends N–S to NNW–SSE, with a syntaxis in the Nahuel Huapi Lake area (Fig. 2). It is characterized by an east-vergent imbricate thrust system associated with several west-vergent backthrusts (Figs. 2 and 4). The structures and rocks involved in the deformation distinguish western and eastern sectors separated by the Ventana–Catedral thrust (Giacosa and Heredia, 2000). The western sector is characterized by the deformation of both Mesozoic rocks (mostly plutonic) and the Neopaleozoic basement.

The scarcity of stratified rocks makes folded structures uncommon. The most important structures are (from west to east; Figs. 2 and 4) the Hielo Azul, Bolsón–Tronador, López, and Ventana–Catedral thrusts; the Piltriquitrón and Serrucho backthrusts; and El Bolsón syncline. Microstructural observations from various locations in the Piltriquitrón backthrust system indicate fault planes with typical dip angles of approximately 40° and slip almost parallel to the dip of the planes (pitch ~80°).

The eastern sector more clearly shows the curved pattern of the fold-and-thrust belt (Fig. 2). The deformation also affects the Cenozoic sedimentary and volcanic units, favoring the generation of large-scale folds. The main structures recognized in this sector are the Otto, Pantanoso, and Río Chico thrusts; El Maitén backthrust; the Ñirihuau fold belt (Fig. 5); and, in the subsurface, Ñorquinco sedimentary wedge (Fig. 6(a)). We consider the NNW Río Chico thrust, which deforms Paleozoic metamorphic rocks into a gentle antiform, the frontal Andean structure. The trend of this thrust is suggested by the distribution of metamorphic rocks, Jurassic granitoids, and western border of the Paleocene volcanic rocks (Figs. 2 and 5).

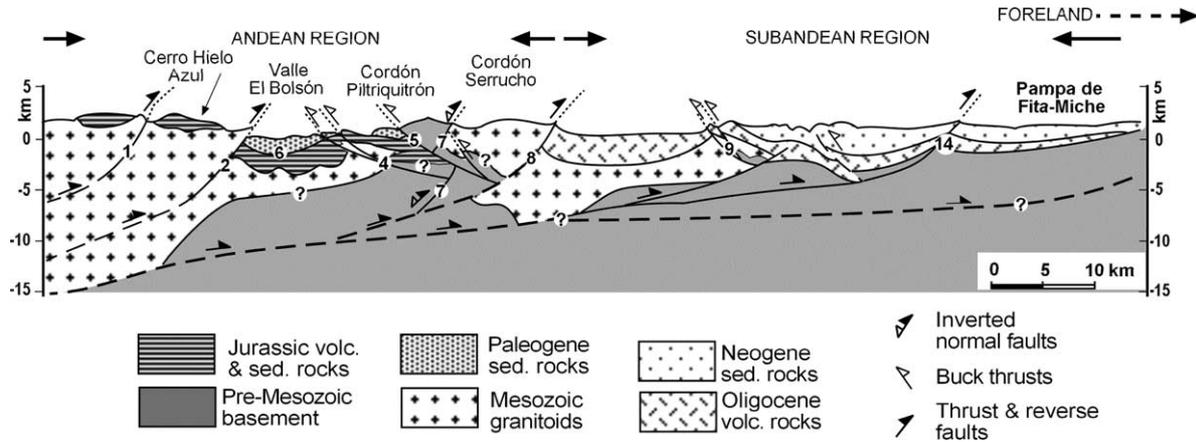


Fig. 4. Regional structural cross-section (not balanced) of the North Patagonian Andes of Argentina (Giacosa and Heredia, 2000; Giacosa et al., 2001). There is no vertical exaggeration. The section was constructed on the basis of surface geology; seismic control is also available east of Cerro David. In the western sector, a basal thrust surface is considered to lay at a depth of 15 km (Ramos and Cortés, 1984; Zapata et al., 1999). The trace of the cross-section as indicated in Fig. 2(a).

4. The Ñirihuau–Collón Curá Basin

4.1. Basin morphology

The Ñirihuau–Collón Curá Basin is a relatively small, N–S trench that covers an area of roughly 200 km by 50 km. Its

geometry is strongly asymmetric in a W–E cross-section and displays an active deep margin to the west and an unaffected eastern margin, where Tertiary units show a characteristic onlap pattern (Fig. 6(b)).

The analysis of more than 580 km of high-quality seismic reflection profiles, surface geology, and data from three

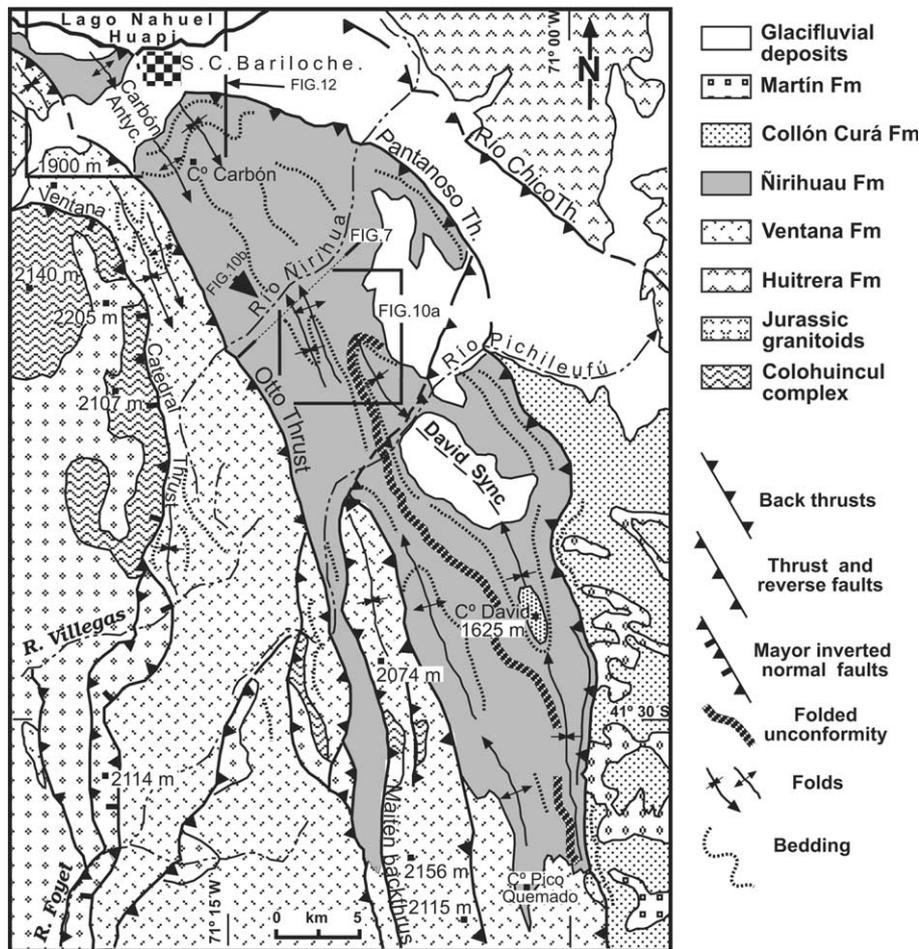


Fig. 5. Geological and structural map of the Ñirihuau fold belt (Feruglio, 1947; González Bonorino and González Bonorino, 1978; Ramos, 1981; Giacosa et al., 2001). Location as indicated in Fig. 2(a).

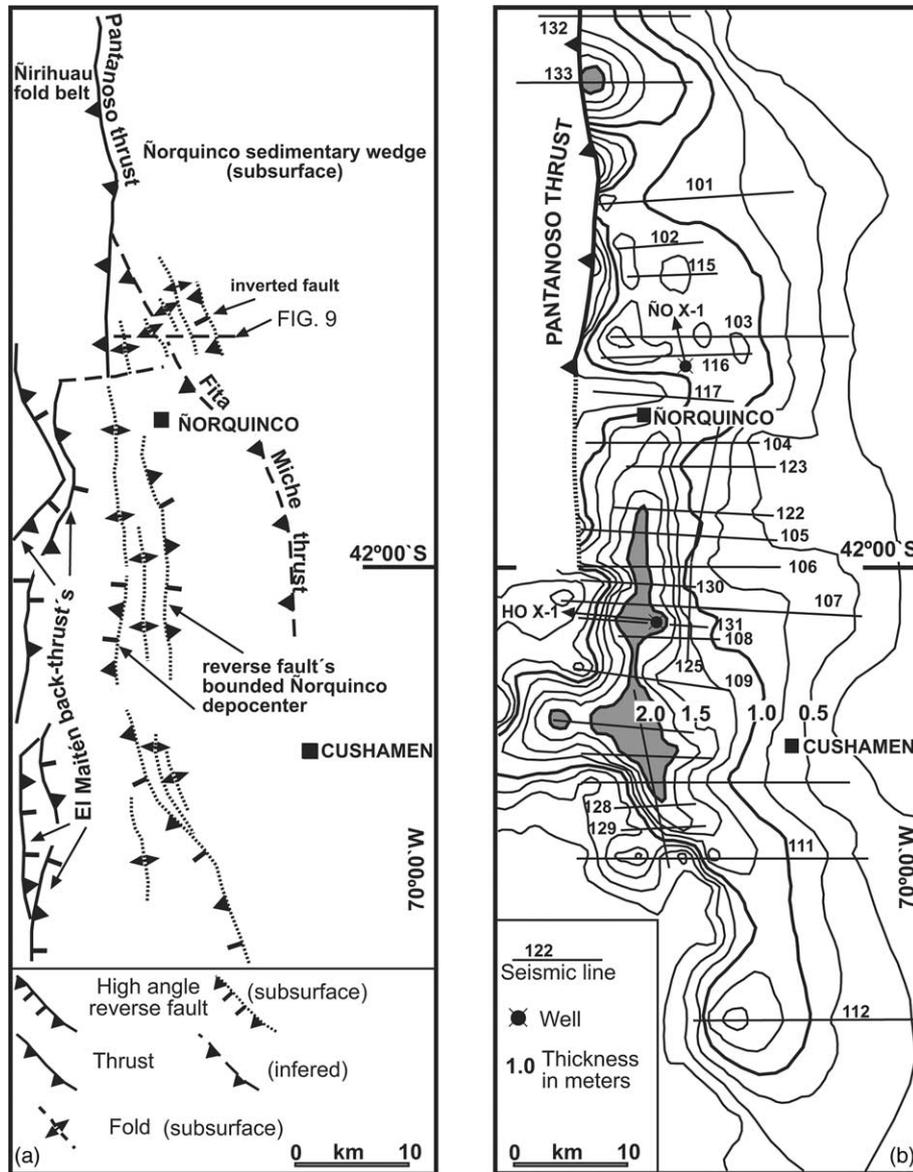


Fig. 6. (a) Structural map of the sub-Andean region and transitional zone. Note the scarcity of structures in the Ñorquinco sedimentary wedge and contrast with the numerous inverse faults and folds in the subsurface of the southern sector. (b) Isopach map of the Ñirihuau-Collón Curá Basin using seismic lines and exploration wells. Location as indicated in Fig. 2a.

exploration wells provides good controls on the geometry and structure of the basin and its basement. Most of the seismic data coincide with the less-deformed part of the basin and therefore provide a good opportunity to characterize the geometry of the sedimentary sequences.

The basement of the basin typically comprises two main units: the metamorphic Cushamen Formation and the volcanic Ventana Formation. Both units have been identified in the sub-surface; metamorphic rocks have been located at 2300 m in the Horqueta X-1 wellbore, and volcanic rocks appear at 1264 m in the Ñorquinco X-1 wellbore.

We recognize two major depocenters within the basin: the Ñirihuau depocenter, deformed during the formation of the Ñirihuau fold belt in the northern part of the basin (Fig. 6(b)), and the Ñorquinco depocenter, a 2000 m thick sedimentary succession affected by medium- to high-angle reverse faults of

opposite vergence. Toward the foreland, both depocenters gradually become more shallow and adopt a sedimentary wedge morphology.

#### 4.2. Stratigraphy and paleoenvironments

Two major lithological units are recognized in the Ñirihuau-Collón Curá Basin: the Ñirihuau Formation (or Ñorquinco Formation *sensu* Cazau, 1972) and the Collón Curá Formation (Fig. 3). Facies analysis on the Ñirihuau Formation suggests three members (lower, middle, and upper), each with characteristic depositional and seismic facies (Mancini and Serna, 1989; Cazau et al., 1989).

The type section of the Ñirihuau Formation, located at the southern margin of the Ñirihuau River, is mainly composed of volcanoclastic and epiclastic deposits. The unit is 1300 m

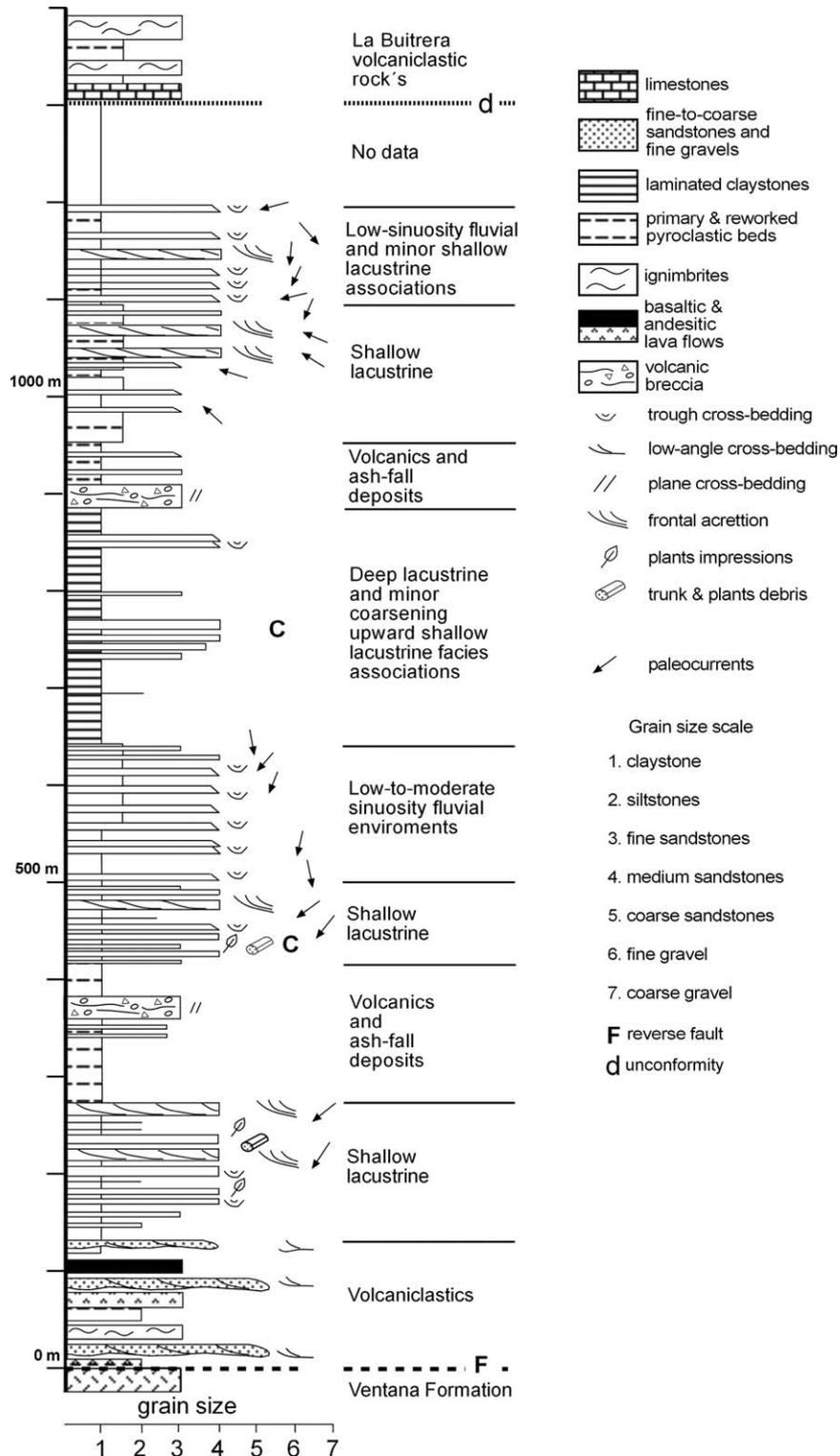


Fig. 7. Stratigraphic column and paleosedimentary environments of the Ñirihuau Formation at the type locality near Ñirihuau River. Location as indicated in Fig. 5.

thick in this area (Fig. 7). Its major stratigraphic feature is the occurrence of an entirely continental record, characterized by lacustrine and alluvial sediments, which are interbedded with tens of meters thick deposits of volcanic breccias, tuffs, and pyroclastic flows (Fig. 7).

The basal section is 150 m thick and primarily composed of ignimbrites, volcanic breccias, and thin andesitic and basaltic

flows. Sandy bodies representing channel-fill deposits in a low-sinuosity environment are commonly included. The Ventana Formation has been overthrust (Otto thrust) onto this basal section (Fig. 5), and therefore, part of it might be absent. Facies analysis of the whole stratigraphic section indicates the development of a shallow deltaic-lacustrine system that evolved into a low- to moderate-sinuosity fluvial system in

the first 500 m. This fluvial association grades to shallow and deep lacustrine facies, including minor shallowing cycles and thick breccia deposits. Toward the top of the section, deep lacustrine facies evolve into a shallow deltaic-lacustrine system that contains sandy and pyroclastic bodies that constitute lobes and banks with preferential W–NW and W–SW prograding directions. The last 400 m are characterized by a low-sinuosity fluvial system with important pyroclastic material contents. An angular unconformity, visible in the lower section of Cerro La Buitrera (Fig. 5), separates the previous lithologies from limestones and lesser carbonate breccias covered by thick beds of ignimbrites (Fig. 7). Some ambiguities remain regarding the formal units to which these strata belong. Feruglio (1947) and Dessanti (1972) assign them to the Collán Curá Formation, whereas González Bonorino and González Bonorino (1978) suggest a stratigraphic position within the Nirihuau Formation. These interpretations, which are based on the structural relationship between the ignimbrite rocks in Cerro La Buitrera and the fluvial facies of the upper part of the Nirihuau Formation, are important for the general structural understanding of the area (see Section 6).

Farther east, Tertiary sediments overlap the igneous-metamorphic basement exposed near Cushamen (Fig. 11(b)). The numerous clasts of basement lithologies incorporated into the sediments suggest that during the early to late Miocene the basement rocks of Northpatagonian Massif were already exposed.

Initial facies of the Nirihuau Formation were deposited during the Late Oligocene; isotopic ages (Fig. 3) in pyroclastic-rich levels of the middle and upper members indicate Early Miocene (~21–22 Ma) and Early–Middle Miocene (16–17 Ma) ages for the middle and upper members, respectively (Cazau et al., 1989). Combining paleontological and isotopic data, Giacosa et al. (2001) assign the Collán Curá Formation an early Middle–early Late Miocene (Langhiane–Tortoniane) age.

## 5. Structure of the sub-Andean region

Based on its distinctive structural evolution during the Tertiary, the sub-Andean region can be subdivided into two segments (approximately north and south of 42°S). The boundary between them (Fig. 6(a)) is a complex area of transfer zones in which faults of opposite vergence interact to accommodate displacements. Some faults might be the result of reactivation of normal faults developed during the early history of the basin.

### 5.1. Northern sector

A west–east structural section at 41°30'S shows a thin-skinned fold belt, comprising the Nirihuau fold belt and a frontal sedimentary wedge (Fig. 6(a)). The Nirihuau fold belt consists of two thrust sheets and a strongly folded belt. The western sheet is composed of Tertiary volcanic rocks and bounded to the west and east by the Ventana–Catedral and Otto thrusts, respectively. Internally, it contains smaller thrusts and

horses that affect mainly Mesozoic granitoids. In the northern area (Sierra Ventana, Fig. 5), sediments of the Ventana Formation are folded on several scales. The eastern folded sheet is the hangingwall block of the Pantanoso thrust (Fig. 8), composed of Tertiary sedimentary rocks. It is a NNW-trending fold-and-thrust belt characterized by (1) overturned folds near the Otto thrust that grade eastward into asymmetric folds with maximum flank dips of approximately 80° and (2) a symmetric, 50 km long, fault-bend syncline exhibiting slightly dipping flanks with kink geometry (Fig. 10(a) and (b)), with an axis that trends parallel to the Pantanoso thrusts (Fig. 5).

In the northernmost part of the fold belt, the frontal ramp of the Pantanoso thrust changes gradually into an oblique ramp dipping southwest, which makes the northern closure of the Nirihuau fold belt a small area with steeply plunging oblique folds, similar to those that characterize the Cerro Carbón and Cerro Otto areas (Figs. 10(c) and 12). At its southern end, the Pantanoso thrust dies out along-strike and transfers the displacement to a subsurface fault propagation fold. This pattern is evidenced in several seismic profiles in the near west of Ñorquinco (Fig. 6(a)).

To the east of the Pantanoso thrust, the sedimentary cover overlies a tilted basement dipping approximately 5°W and affected by small faults that seem to reach the lower part of the Nirihuau Formation (Fig. 8). The sediments display a general subhorizontal bedding, which conforms a sedimentary wedge toward the foreland with a typical onlap seismic pattern. At 41°45'S, the structure is a transitional area of subsurface thrusts and medium- to high-angle reverse faults (Fig. 6), as well as minor folds and partially reactivated normal faults. The zone coincides with the bifurcation of the Pantanoso thrust into two main traces. The western trace gradually dies out to the south and transfers the displacement to a fault propagation fold. The eastern trace becomes a low-angle thrust (Fita Miche thrust) with a hangingwall syncline to the east. This thrust might be responsible for the deformation of the youngest Tertiary sediments in the basin (Fig. 9).

### 5.2. Southern section

This sector extends from Ñorquinco to the southernmost border of the Nirihuau–Collán Curá Basin (Fig. 2). A structural section based on seismic lines, surface geology, and borehole data was constructed at 42°05'S (Fig. 11(a)); it shows a more important control of the pre-Cenozoic basement than in the northern sector, with a geometry that fits well the kinematic models of structures developed in basement-involved foreland basins (e.g. Mitra and Mount, 1998).

The most important structural elements are El Maitén backthrust system and a medium- to high-angle reverse fault to the east, which defines the eastern limit of the Ñorquinco depocenter (Fig. 11(a)). The 20 km long Sierra del Maitén is the main topographic feature of the sector and consists of east-dipping Oligocene volcanic rocks of the Ventana Formation, which overlies the pre-Mesozoic basement. An imbricate backthrust system composed of three east-dipping medium-angle reverse faults characterizes this isolated range.

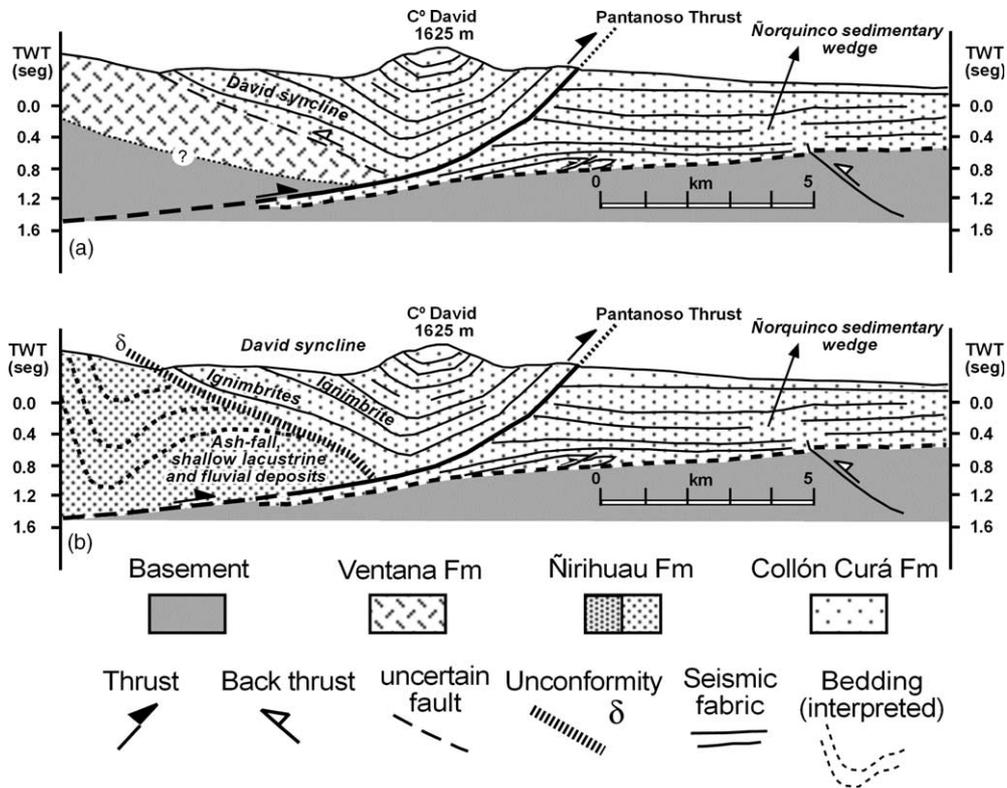


Fig. 8. Structural and geological interpretation of the Cerro David area (see location in Fig. 2(a)). (a) After Afonso (2002) and Giacosa and Heredia (2004b); the seismic triangular sector in the western flank of the David syncline is interpreted as a frontal tectonic wedge. (b) Based on new field data, we interpret a folded unconformity in the boundary between the strongly folded sediments (mostly clastic and ash-fall sediments) and the ignimbrites of the David syncline.

The cartographic pattern of these faults and evidence from seismic profiles suggest that they join (Fig. 10(d)) or turn into the 100 km long westernmost backthrust at depth (Fig. 2). On the basis of stratigraphic and structural evidence, we interpret El Maitén backthrust system as the result of an inversion of normal faults that were active during Oligocene volcanism.

In the eastern foothills of Sierra del Maitén, approximately 45° west-dipping antithetic reverse faults deform the sedimentary rocks of both the Ñirihuau and Collón Curá formations. Estimations from seismic and surface data suggest these faults have maximum vertical motion components of approximately 1000 m, as shown in Fig. 11(a). To the east, seismic profiles reveal an important

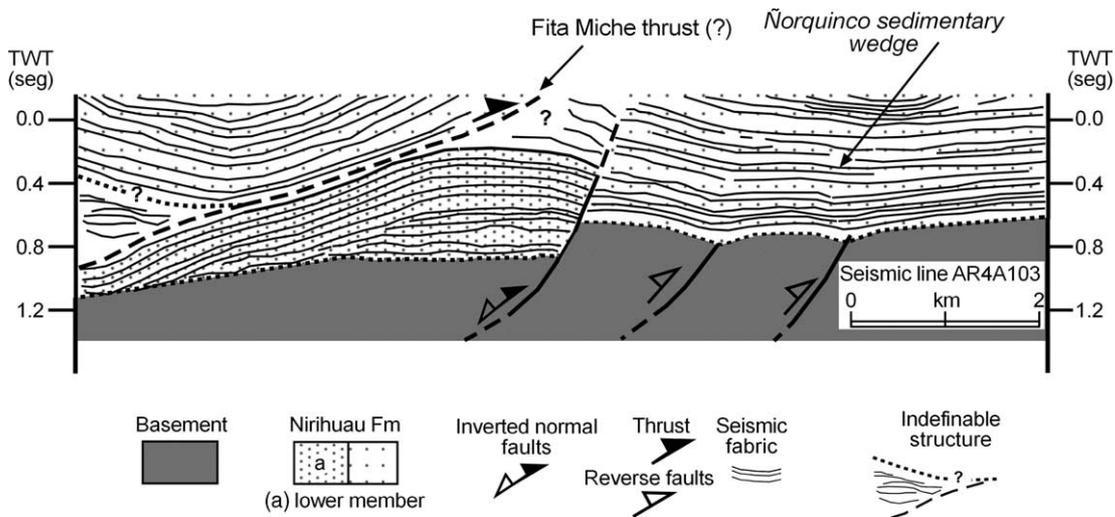


Fig. 9. Structural interpretation of seismic line AR4A103 (see location in Fig. 6). The sedimentation of the lower section of the Ñirihuau Formation seems controlled by a preexistent high–medium-angle basement fault dipping to the west. Note that the upper parts of the sedimentary sequence are not affected by basement-involved faults and that it exhibits a seismic fabric similar to that in the Ñorquingo sedimentary wedge (cf. Fig. 8).

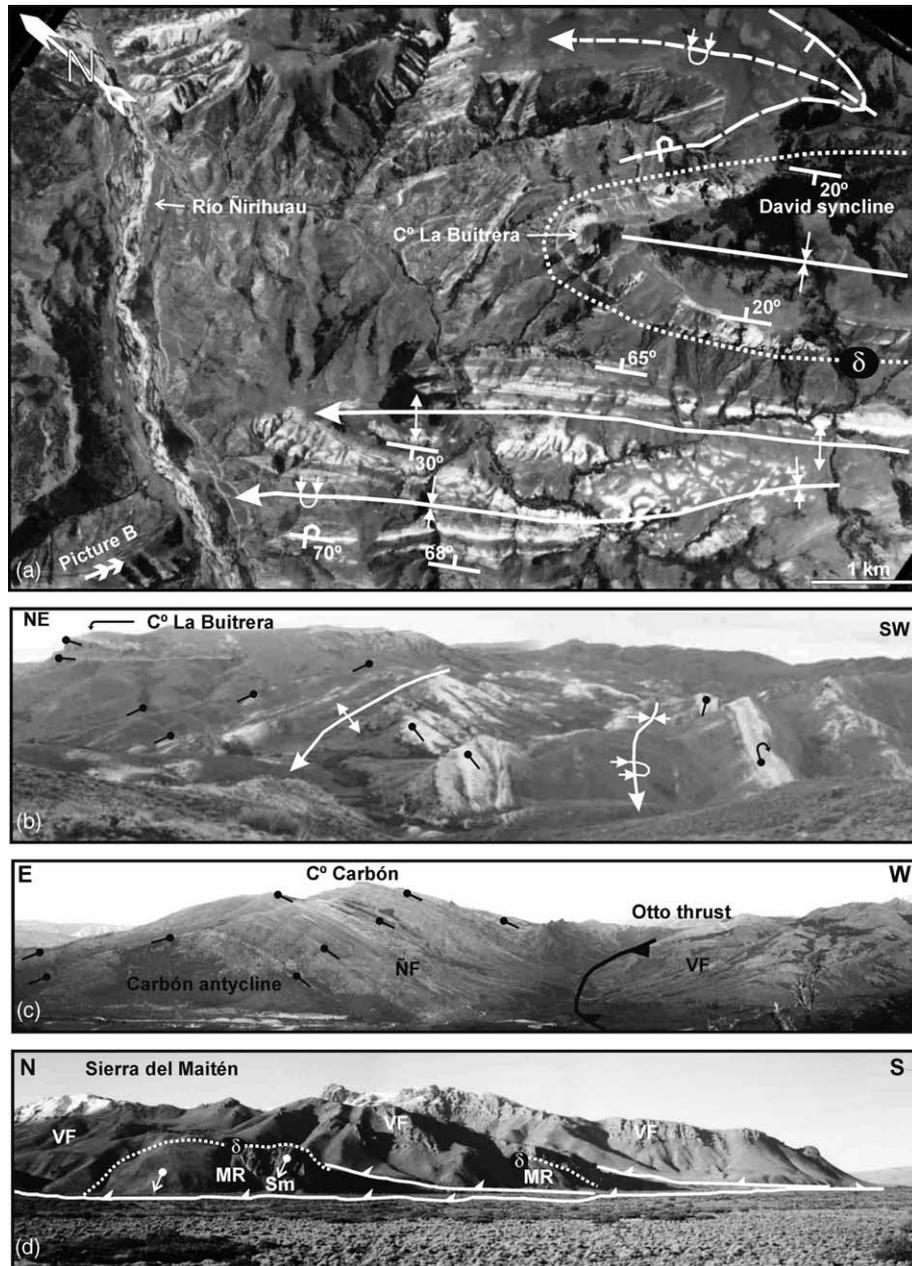


Fig. 10. (a) Aerial view of the southern margin of the Ñirihuau River. Note the tight, overturned folds in strata of the Ñirihuau Formation on both sides of the David syncline. Its northern end is located in the region of Cerro La Buitrera. A possible folded unconformity ( $\delta$ ) is indicated at the base of the David syncline. Location as in Fig. 5. (b) Panoramic view of the same sector. Note the change of attitude along-strike of the white bed in the right part of the picture. Location as in Figs. 5 and 10(a). (c) View of the northern sector of the Ñirihuau fold-and-thrust belt in the area of Cerro Carbón. Location as in Fig. 12. (d) El Maitén backthrust system in the southern sector of Sierra del Maitén. This isolated hill is mainly composed of volcanic rocks of the Ventana Formation (VF) that cover a Paleozoic metamorphic basement (MR). The metamorphic foliation (Sm) and a nonconformity ( $\delta$ ) separating these units are indicated. Location as in Fig. 2(a).

medium–high-angle basement-involved fault and associated drag folds, which clearly postdate the deposition of the Ñirihuau Formation and at least part of the Collón Curá Formation. There is no evidence of significant variations in the thickness of the Ñirihuau Formation on either side of the fault. The cross-cutting relationship between the fault and the upper members of the Collón Curá Formation remains uncertain, primarily due to the lack of good stratigraphic markers from the upper part of the unit. Although vertical

components on the order of 900 m can be inferred from seismic data, glaciofluvial sediments cover the trace of the fault and preclude a direct assessment.

Southeast of Sierra del Maitén ( $42^{\circ}15'S$ ), there are only sub-surface, W-dipping, medium–high-angle reverse faults that frequently transfer their displacements to smaller faults or folds (Fig. 6(a)). The easternmost fault exhumed large basement blocks at both sides of the Río Chubut (e.g. Cordón Mogote, Fig. 2).

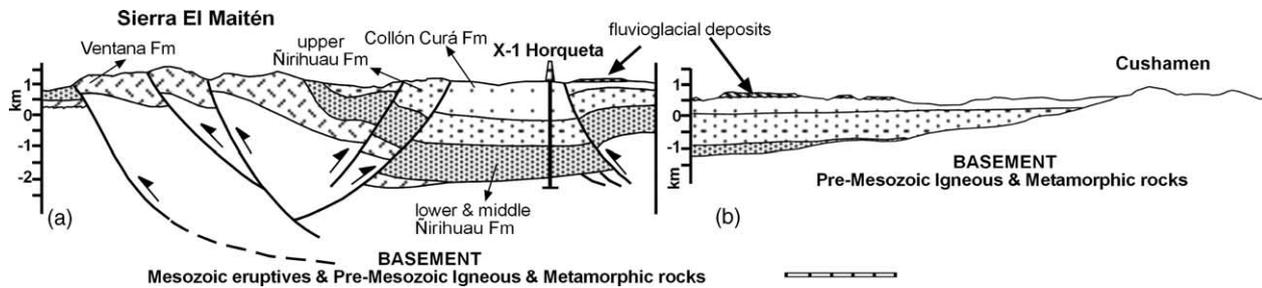


Fig. 11. Structural and geological interpretation in the southern sector of the basin. The interpretation is constrained by surface geology, seismic, and borehole data (Afonso, 2002). (a) Note characteristic medium- to high-angle basement-involved faults and associated drag folds. Compare with structures of the northern part of the basin (Fig. 8). (b) Cross-section showing major stratigraphic relations between Tertiary rocks and igneous-metamorphic basement exposed near Cushamen. The trace of the cross-section is indicated in Fig. 2(a).

## 6. Discussion

One of the main structural features of the sub-Andean region in the North Patagonian Andes of Argentina is the presence of a fold-and-thrust belt associated with inverted blocks, which are bound by medium- to high-angle reverse faults. Many of these faults represent reactivations of pre-existent basement structures.

In the Nirihuau fold belt area, the tectonostratigraphic relations between the David syncline and surrounding tight folds are essential to understand its evolution. González Bonorino and González Bonorino (1978), (sections GG' and HH') propose that the thick ignimbritic deposits of the David syncline are structurally concordant with the underlying Nirihuau Formation. Alternatively, Afonso (2002) and Giacosa and Heredia (2004b) suggest that the David syncline and the seismic triangular fabric in its western flank developed in response to the emplacement of a frontal tectonic wedge moving toward the foredeep. However, new evidence from recent field observations seems to disagree with these previous interpretations. We emphasize, for example, the remarkable structural disharmony between the David syncline and surrounding structures (Fig. 10(a) and (b)), as well as the noticeable continuity of the tight and overturned folds east of the David syncline. Any attempt to propose an alternative interpretation must be consistent with these new observations. We suggest that the triangular zone with no reflections in seismic line AR4A132 corresponds to strongly folded strata of the Nirihuau Formation (Fig. 8(b)), partially visible on the surface (Fig. 10(a)). This interpretation implies that the base of the David syncline is a folded unconformity and thereby indicates compressive deformations during the sedimentation of the uppermost members of the unit.

The analysis of seismic lines across major faults enables some interesting observations. First, seismic profile AR4A132 shows no evidence of thickness variation in the Nirihuau Formation across the faults. However, a progressive thickening of the sediments from east to west can be seen along the profile (Fig. 8). Second, seismic profile AR4A103 (Fig. 9; cf. Mancini and Serna, 1989, Fig. 6) shows a lower member of the Nirihuau Formation that seems thicker on the hangingwall of the thrust than on the footwall block. Third, seismic section AR4A107

(Fig. 11(a)) again shows no evidence of thickness variations on either side of the medium- to high-angle reverse fault.

The second item constitutes the only seismic evidence of sedimentation associated with normal faulting (growth faults) and only for the lower member of the Nirihuau Formation. This finding was also pointed out by Diraison et al. (1998), who conclude that there is no other seismic or field evidence of synextensional sedimentation during the Tertiary. In addition, field observations and seismic data suggest that the sedimentation of the upper members of the Nirihuau, Collón Curá, and possibly Martín formations constitute the fill of a foreland basin (sensu De Celles and Giles, 1996) associated with the evolution of the Andean orogenic front. We highlight, as significant evidence, the following: (1) there are no significant changes in thickness on either side of the faults; (2) the thickness of Tertiary units decreases gradually toward the foreland to constitute a sedimentary wedge; (3) the basin geometry is clearly asymmetric in a west–east cross-section, exhibiting a deformed active western flank and an undeformed passive eastern flank; (4) sediments become progressively younger toward the foreland, in agreement with the propagation of the orogenic front; and (5) the upper members of the Nirihuau Formation are pervasively deformed under a compressive regime.

In the western valley of the Sierra del Maitén, the volcanoclastic sequences of the Ventana Formation overthrust the lower member of the Nirihuau Formation (Figs. 2 and 11(a)). However, the middle and upper members, as well as the Collón Curá Formation, are not present in the valley. Therefore, the area to the west of Sierra del Maitén might not have been part of the depositional area of these units, which appear only to the east of the range.

An alternative explanation is to consider a more recent uplift of the Sierra del Maitén and a subsequent erosion of the youngest members of the Nirihuau and Collón Curá formations. In addition to such selective erosion being improbable, this alternative seems incompatible with the actual distribution of outcrops along the western margin on the basin.

The Pliocene (3 Ma) Chenqueniye Basalt is the youngest undeformed unit that overlies Andean compressive structures in the sub-Andean foreland region. Farther west, in the Andean region, basalts of the Tronador Formation (3.2 Ma) were deposited over the Bolsón–Tronador thrust, which provides an

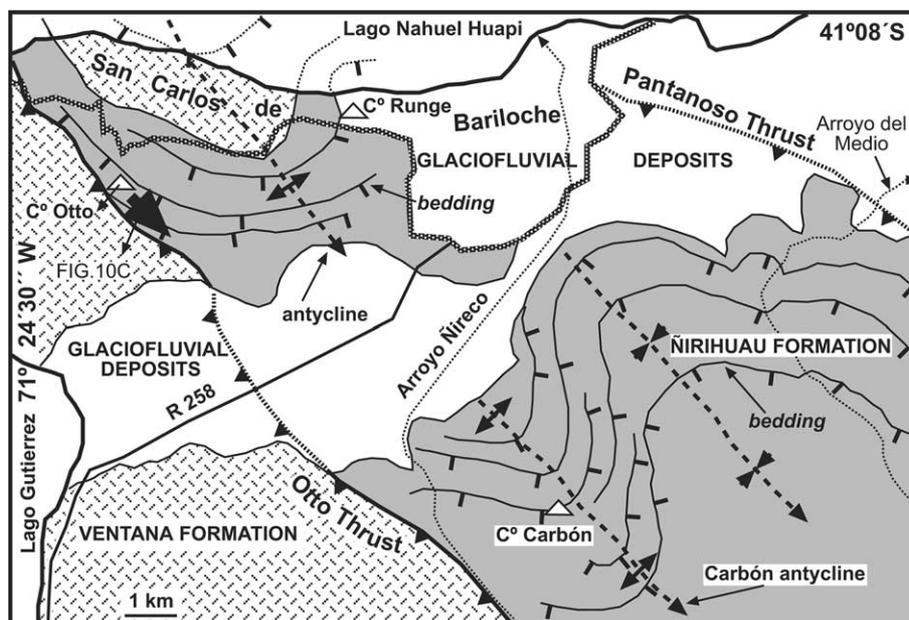


Fig. 12. Structural map of the northern sector of the Ñirihuau fold belt. The Carbón anticline continues to the north to Cerro Otto, where volcanic rocks of the Ventana Formation are exposed. Location as indicated in Fig. 5.

upper constraint on its age (Fig. 2). The western sector of the fold-and-thrust belt thus was uplifted before the Late Pliocene.

Finally, we suggest that the Plio–Pleistocene coarse deposits of the Martín Formation might be associated with the last Pliocene tectonic pulse in the sub-Andean region. This unit exhibits a clear gradational pattern from proximal facies (large-scale clasts west of the Pantanosos thrust) (Fig. 5) to intermediate–distal facies toward the foreland. Additional stratigraphic and biostratigraphic data are necessary to better constrain the relationship between the position of the orogenic front and synorogenic sedimentation.

## 7. Conclusions

The structure of the sub-Andean region in the North Patagonian Andes of Argentina can be subdivided in two main sectors. The northern part is a thin-skinned fold-and-thrust belt with a poorly deformed sedimentary wedge at its front. The southern part is characterized by medium–high-angle basement-involved reverse faults, which reflect reactivation of preexisting fault zones. The boundary between the two sectors is a complex area of transfer zones in which thrusts and folds interact with faults of opposite vergence to accommodate their displacements.

The evidence presented by this work suggests that a major part of the Ñirihuau–Collón Curá Basin fill, which consists of the upper members of the Ñirihuau and Collón Curá formations, fits a foreland basin system model, in which tectonosedimentary evolution is controlled mainly by the propagation of an adjacent orogenic front. In the Ñirihuau fold belt area, we suggest the presence of a folded unconformity in the lower section of the David syncline. It is positioned in the upper part of the Ñirihuau Formation, which implies an active compressive stage during, or shortly after, the deposition of the

uppermost members. However, in some sectors of the basin, the deposition of the lower member of the Ñirihuau Formation might have been influenced by late stages of the extensional regime associated with the Oligocene volcanism.

## Acknowledgements

This article presents part of the results obtained during the cartography at 1:250,000 scale of the Hoja Geológica San Carlos de Bariloche, as an agreement between the Gobierno Provincial de Río Negro and the Servicio Geológico y Minero Argentino. Collaboration with the Instituto Geológico y Minero of Spain was supported by the Institute of Ibero-American Cooperation. This article also contains some of the results obtained in the DGICYT Project BTE 2002-04316-C03-01 (Spanish Science and Technology Agency). The authors thank F. Devine, who provided helpful comments on a preliminary version. JCA thanks Universidad Nacional de la Patagonia, Carleton University, and OGS (Ontario Graduate Scholarship) for their support.

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