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New age constraints for the Cenozoic marine transgressions of northwestern Patagonia, Argentina (41°–43° S): Paleogeographic and tectonic implications

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ABSTRACT

In this contribution we address the current controversial issues related to the age, correlation, tectonic setting and paleogeographic links of the Cenozoic fossiliferous marine strata that crop out in the eastern sector of the North Patagonian Andes between 41° and 43°S based on new field (detailed geologic and structural mapping), geochronological (U–Pb LA-ICPMS analyses in zircons) and biostratigraphic (calcareous nannofossils studies) data. The marine strata form part of the volcano-sedimentary infill of several depocenters included in the Ñirihuau basin. We constrained the age of the main Cenozoic fossiliferous marine successions within the Early Miocene (23–16 Ma). In addition, strata previously interpreted as deposited in marginal-marine environments suggest that the marine influence in the area could have lasted until the Middle Miocene. Our results indicate that the main depocenters of the basin evolved simultaneously during the Late Oligocene? to Miocene, and also give some clues about possible connections between them during distinctive stages of their evolution. We interpret that the marine transgressions registered in the Ñirihuau basin were related to a regional extensional tectonic stage that took place during the Oligocene to Early Miocene. The ingression of the sea occurred before the main contractional phase that gave place to the uplift of the North Patagonian Andes between the Early-Middle Miocene and the Pliocene, and the marine influence probably lasted until the early stages of the fold and thrust belt development. The marine strata can be correlated with one or more pulses of a major transgression that flooded a wide area of Patagonia between the Late Oligocene and the Middle Miocene. Considering the currently available data, a direct link of the Ñirihuau basin with the Atlantic Ocean on its northern, eastern or southern sides is unlikely. Marine connections would have taken place most likely with Pacific marine basins located to the west.

1. Introduction

The occurrence of Cenozoic strata containing marine invertebrate fossils in the eastern slope of the North Patagonian Andes is known since the pioneer discoveries of Roth (1922). Although numerous stratigraphic and paleontological contributions have referred to these marine beds, there is still no general agreement about their age, possible connections with rather the Pacific or Atlantic Oceans, and the tectonic framework during the ingression of the sea into this continental area (Camacho, 1967; Ramos, 1982a; Spalletti, 1983; Malumián et al., 2008; Cazau et al., 2005; Asensio et al., 2010; Ramos and Bechis, 2010; Encinas et al., 2012a).

The marine strata were deposited in several depocenters included in the Ñirihuau basin, which developed in the eastern sector of the North Patagonian Andes between 41° and 43°S (Fig. 1; Cazau, 1972, 1980; Cazau et al., 1989, 2005; Giacosa and Heredia, 2004a). Its infill is constituted by a thick succession of volcanic and sedimentary rocks related with either continental or marine fossil assemblages, and the main depocenters of the basin correspond to the Ñirihuau, Ñorquinco and El Bolsón depocenters (Fig. 2). The Ñirihuau and Ñorquinco

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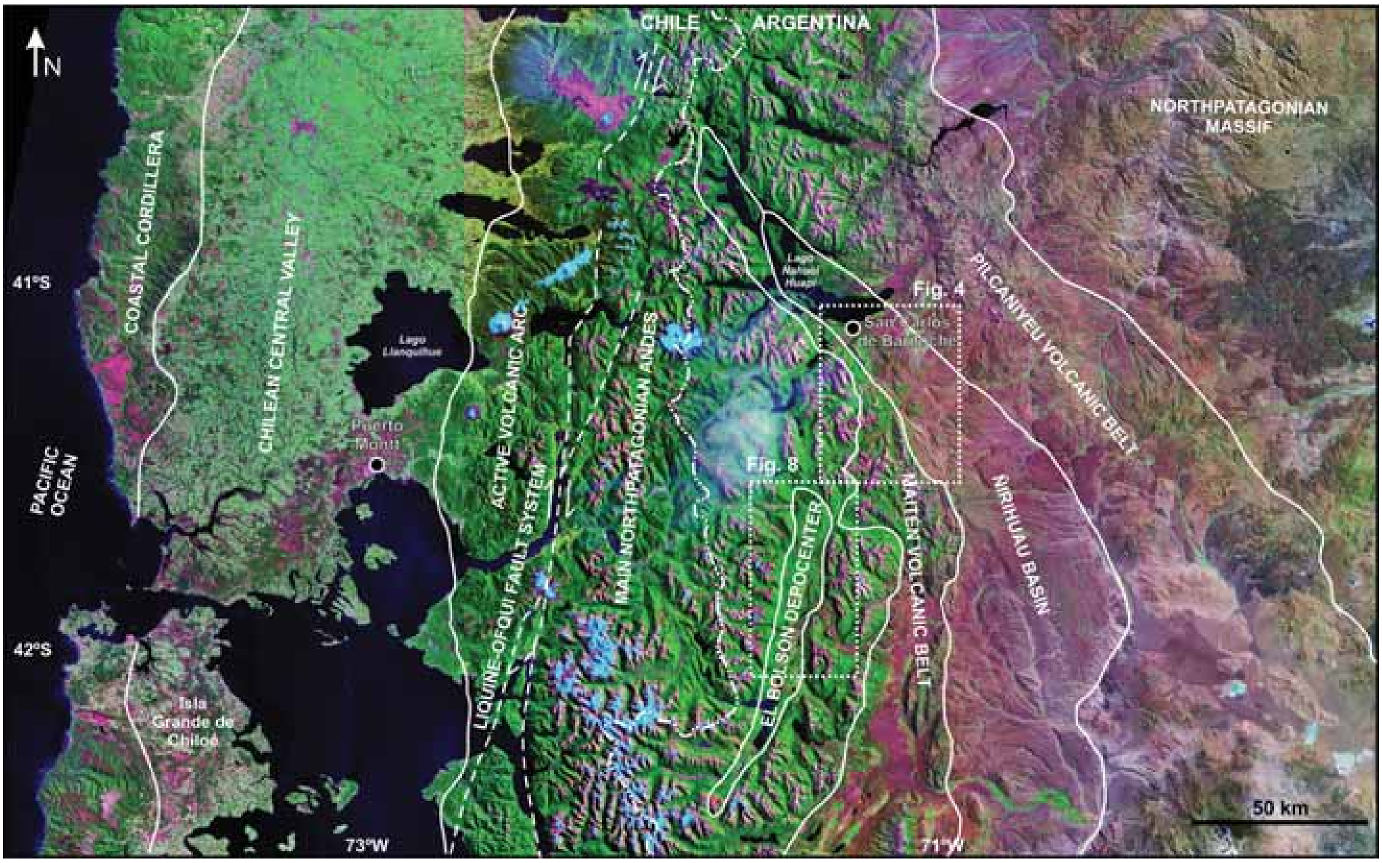

Fig. 1. Mosaic of Landsat TM satellite images showing the distribution of the main morphostructural units of the Andean margin between 39° and 43°S.

depocenters are located in the eastern border of the North Patagonian Andes, and the lateral continuity of their deposits can be traced by superficial and subsurface data (Cazau et al., 1989; Mancini and Serna, 1989). Their infill shows similar characteristics and evolution, and it is represented by the Nahuel Huapi Group (Fig. 3; González Bonorino and González Bonorino, 1978). On the other hand, the El Bolsón depocenter is now disconnected from the other depocenters, as it is confined within an intramontane valley (Fig. 1). Its infill is included in the El Foyel Group, which registers a more important marine influence during sedimentation (Fig. 3; Asensio et al., 2005). Most studies have proposed that the El Bolsón depocenter originally formed part of the Ñirihuau basin and that it was later disconnected due to the uplift of basement blocks during the main Andean contractional deformation in the Neogene (Ramos, 1982a; Spalletti, 1983; Giacosa and Heredia, 2004a; Cazau et al., 2005; Paredes et al., 2009; Asensio et al., 2010). However, previous stratigraphic proposals based on scarce geochronological and paleontological data have interpreted an Eocene to Early Oligocene age for the El Bolsón depocenter infill (Fig. 3; Giacosa et al., 2001; Asensio et al., 2005, 2010), while the infill of the Ñirihuau and Ñorquinco depocenters was dated as Oligocene to Late Miocene (Rapela et al., 1988; Cazau et al., 1989). Some disperse geochronological and biostratigraphic data have recently suggested a much younger age for the marine beds of the El Bolsón depocenter, that could even reach the Middle Miocene (Barreda et al., 2003; Malumián et al., 2008; Encinas et al., 2011, 2012a; Malumián and Náñez, 2011; Bechis et al., 2012). These data pointed out the need for an integrated and detailed review of the age, correlation and evolution of the infilling of the distinct depocenters of the Ñirihuau basin, and particularly of the marine sedimentation registered in each sector.

The tectonic setting during the evolution of the Ñirihuau basin, and consequently during the marine sedimentation registered in its infill, is also a controversial topic. Extensional, contractional and strike-slip tectonics were alternatively proposed for the evolution of the basin (Ramos and Cortés, 1984; Dalla Salda and Franzese, 1987; Cazau et al., 1989; Mancini and Serna, 1989; Spalletti and Dalla Salda, 1996; Giacosa and Heredia, 2004a). Most recent proposals agree that the region was subjected to extension during the Oligocene, and that tectonic conditions changed to compression during the Miocene. However, the precise dating of the transition between both contrasting tectonic regimes is still under discussion, as some works have suggested that contraction in the area started during the Late Oligocene or the Early Miocene (Giacosa et al., 2005; Paredes et al., 2009; Ramos et al., 2011; Orts et al., 2012), while others propose that contraction started later, during the Middle or Late Miocene (Cazau et al., 1989; Mancini and Serna, 1989; Bechis, 2004; Bechis and Cristallini, 2005, 2006).

Regarding the origin of the marine transgressions registered in the study area, several proposals have suggested marine connections with the Atlantic Ocean (Camacho, 1967; Bertels, 1980; Griffin et al., 2002; Barreda et al., 2003), while others favor a Pacific origin (Ramos, 1982a; Spalletti, 1983; Malumián et al., 2008). Recently, Asensio et al. (2010) have suggested that two events of different provenance are registered in the marine deposits.

In this contribution we address the described controversial issues related to the age, correlation, tectonic setting and paleogeographic links of the Cenozoic fossiliferous marine strata of the Ñirihuau basin based on new field, geochronological and biostratigraphic data. We reviewed classic and new localities in the Ñirihuau and El Bolsón depocenters, where most of the stratigraphic units were defined and where the best outcrops of the marine successions are found. Here we present the results of our geological and structural mapping, together with new

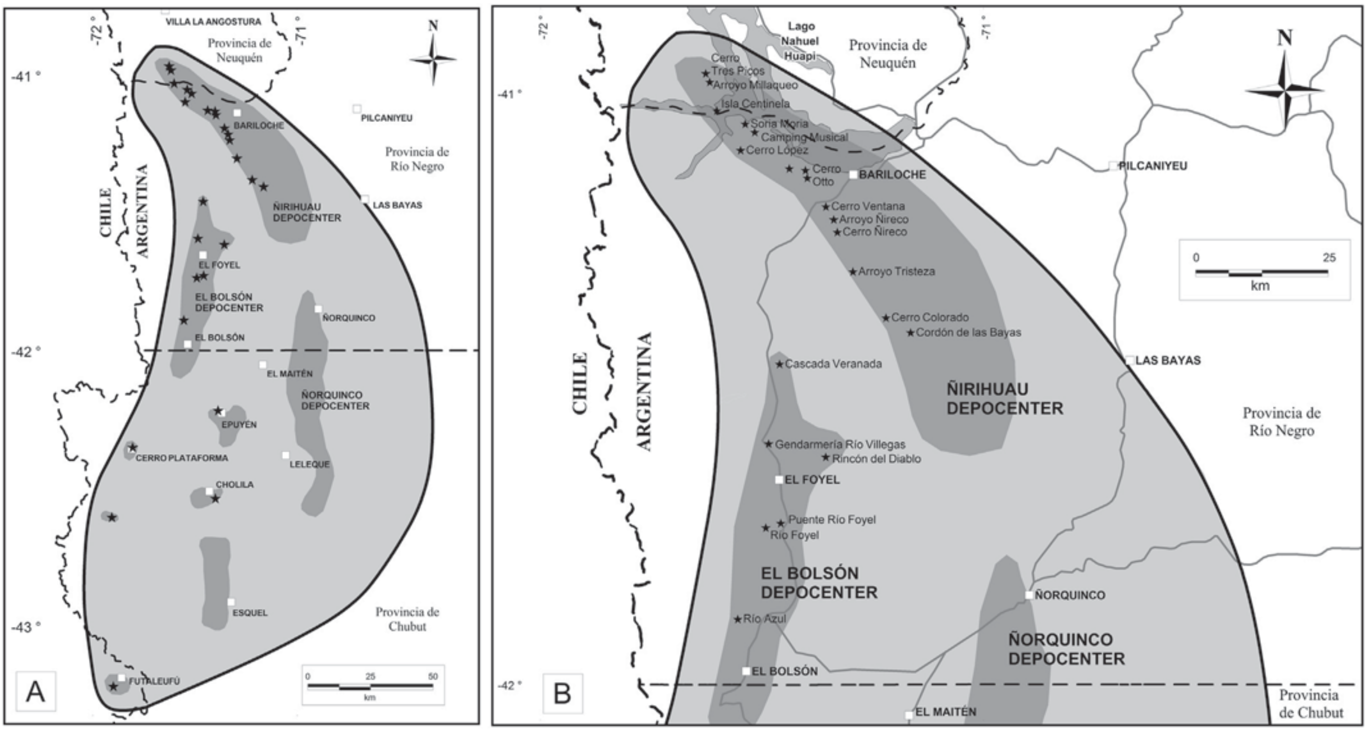

Fig. 2. A) Regional map showing the approximate areal extent of the Ñirihuau basin and its main depocenters. The dark-colored gray areas correspond to the outcrops of the basin infill units, and the black stars correspond to the localities with fossiliferous marine strata. B) Detail of the northern sector of the basin, where this study was carried out.

geochronologic data from U–Pb LA-ICPMS analyses in zircons, and new biostratigraphic data from calcareous nannofossils studies. With these data we have constrained the age of the main Cenozoic marine successions of the eastern side of the North Patagonian Andes within the Early Miocene. Our results indicate that the Ñirihuau basin depocenters evolved simultaneously during the Late Oligocene? to Miocene, and also give some clues about possible connections between them during distinctive stages of their evolution. We also integrate our new data with previous local and regional evidences in order to evaluate the tectonic setting during the marine transgression, and the possible paleogeographic connections with other areas of Patagonia that register marine sedimentation during the same period.

2. Regional geology

Main morphostructural units of the Andean margin at these latitudes are, from west to east, the Coastal Cordillera, the Central Valley, the North Patagonian Andes, and the North Patagonian Massif (Fig. 1).

The Coastal Cordillera is constituted by an accretion complex of late Paleozoic to Triassic age, represented by the Bahía Mansa Metamorphic Complex (Duhart et al., 2001). This metamorphic basement is covered by Oligocene to Lower Miocene volcanic rocks grouped in the Coastal Magmatic Belt (Muñoz et al., 2000), and continental and marine deposits of Late Oligocene to Pliocene age (McDonough et al., 1997; Encinas et al., 2012b).

The Central Valley of Chile is a linear depression more than 1000 km long and 75 km wide located between the Coastal Cordillera and the North Patagonian Andes. An infill represented by continental and marine deposits of Late Oligocene to Miocene age is inferred based on some scarce outcrops and subsurface data (McDonough et al., 1997; Encinas et al., 2012b; Elgueta and Mpodozis, 2012). On its eastern border, the valley merges with the products of the stratovolcanoes of the Southern Volcanic Zone (Stern, 2004). The active volcanoes are aligned along the Liquiñe-Ofqui fault zone, characterized by lineaments, faults and ductile shear zones with general NNE trend and dextral strike-slip kinematics from the Pliocene to Recent (Lavenu and Cembrano, 1999).

The North Patagonian Andes consists of an upper Paleozoic metamorphic basement and deformed igneous rocks, known as the Colohuincul Complex (Dalla Salda et al., 1991; Varela et al., 2005). A poorly known Early Jurassic volcano-sedimentary complex crops out mainly as roof-pendants at the top of the mountains (González Díaz and Lizuaín, 1984). Early Cretaceous volcanic rocks assigned to the Divisadero Group were also identified in some high areas of the cordillera (Orts et al., 2012). These Paleozoic to Mesozoic units were intruded by an extended suite of calc-alkaline subduction-related plutonic rocks, included in the Early Jurassic Subcordilleran plutonic belt (Gordon and Ort, 1993; Rapela et al., 2005) and the Middle Jurassic to Miocene North Patagonian Batolith (Toubes and Spikerman, 1973; González Díaz, 1982; Munizaga et al., 1988; Castro et al., 2011). Spaced stratovolcanoes of Pliocene to Pleistocene age unconformably cover all the previous units (Lara et al., 2001).

Thick successions of Cenozoic volcanic and sedimentary rocks crop out in the eastern sector of the North Patagonian Andes from 39° to 43°S (Fig. 1). Paleogene volcanic rocks were divided according to their age and facies distribution into the extra-Andean or Pilcaniyeu belt to the east, of Eocene age, and the Andean or Maitén belt to the west, of Oligocene to Early Miocene age (Feruglio, 1941; Ramos, 1982a; Rapela et al., 1983, 1988). Geochemical characteristics of both belts show similarities with the typical Andean calc-alkaline magmatic series (Dalla Salda et al., 1981; Rapela et al., 1988), but they have been interpreted to be derived from an asthenospheric source with intermediate characteristics between the modern subduction-related volcanic arc and the back-arc plateau basaltic series (Kay and Rapela, 1987; Kay et al., 2006; Aragón et al., 2011). The volcanic rocks of the Pilcaniyeu and Maitén belts are grouped in the Huitrera and Ventana Formations, respectively (Ravazzoli and Sesana, 1977; González Bonorino and González Bonorino, 1978).

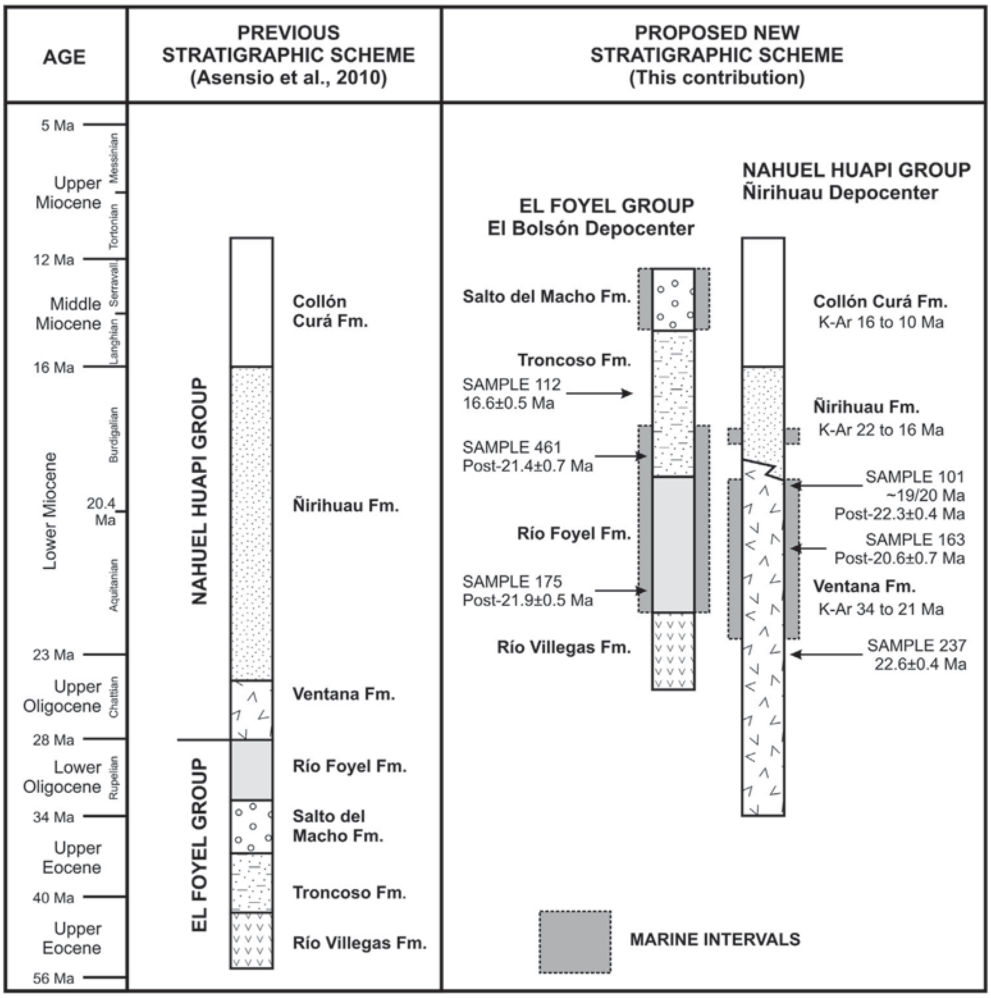

Fig. 3. Correlation chart with the previously accepted stratigraphic setting and the new scheme proposed in this contribution based on new field, geochronologic and biostratigraphic data. The stratigraphic position of the new U–Pb dating and the marine intervals are shown in the chart.

The Ventana Formation constitutes the basal unit of the Nahuel Huapi Group and forms part of the initial infill of the Ñirihuau basin. Also, thick sedimentary and pyroclastic successions that crop out to the east and west of the Maitén volcanic belt were deposited in several depocenters included in the Ñirihuau basin (Fig. 1). Their main characteristics and stratigraphic setting will be described and discussed in detail in the following chapters.

The North Patagonian Massif extends from the North Patagonian Andes to the west, to the Atlantic coast to the east. The stratigraphy of its western sector is constituted by upper Paleozoic igneous and metamorphic rocks grouped in the Río Chico Complex (Dalla Salda et al., 1994), volcanic and clastic rocks assigned to the Late Triassic to Jurassic, Cretaceous continental deposits, and Cenozoic volcanic and sedimentary rocks (González, 1998).

3. The Ñirihuau Basin and its related marine intercalations

3.1. Ñirihuau and Ñorquinco depocenters

The Ñirihuau and Ñorquinco depocenters are located in the eastern border of the North Patagonian Andes between 41° and 43°S (Figs. 1 and 2; Cazau, 1972, 1980; Cazau et al., 1989, 2005). Their infill shows similar characteristics and evolution, and it is represented by the Nahuel Huapi Group, constituted, from base to top, by the Ventana, Ñirihuau and Collón Curá Formations (Fig. 3; González Bonorino and González Bonorino, 1978; Cazau et al., 1989). The basin in this sector has a strongly asymmetric profile, showing the most important depocenters on its western area, where their infill was deformed during the Andean contraction (Cazau et al., 1989; Mancini and Serna, 1989; Bechis, 2004; Bechis and Cristallini, 2006; Giacosa et al., 2005; Ramos et al., 2011). On the contrary, the eastern border shows little or no deformation, and the infill thickness diminishes progressively showing onlap relationships with the basement, constituted by the Paleogene volcanic rocks of the Huitrera Formation and by upper Paleozoic igneous and metamorphic rocks assigned to the Río Chico Complex.

The basin infill in this sector starts with the volcanic and sedimentary rocks of the Ventana Formation. This unit was first interpreted as part of the structural basement of the basin (Cazau et al., 1989), but it has been recently reinterpreted as part of its initial infill (Cazau et al., 2005). It is dominated by volcanic rocks of andesitic to dacitic composition, with subordinated rhyolites and basalts (Rapela et al., 1988). The Ventana Formation contains the main Cenozoic marine strata of these depocenters, which crop out in the northern sector of the Maitén belt (Fig. 1). One of the thickest and more continuous successions of this unit is located in the northeastern slope of Cerro Ventana and Cerro Ñireco, where more than 3000 m of interbedded volcanic and sedimentary rocks crop out (Fig. 4; González Bonorino and González Bonorino, 1978). In this section, the unit is folded by NW-trending asymmetric folds with NE vergence, and the contact with the Ñirihuau Formation is structural and related to the SW-dipping Otto thrust (Figs. 5A and

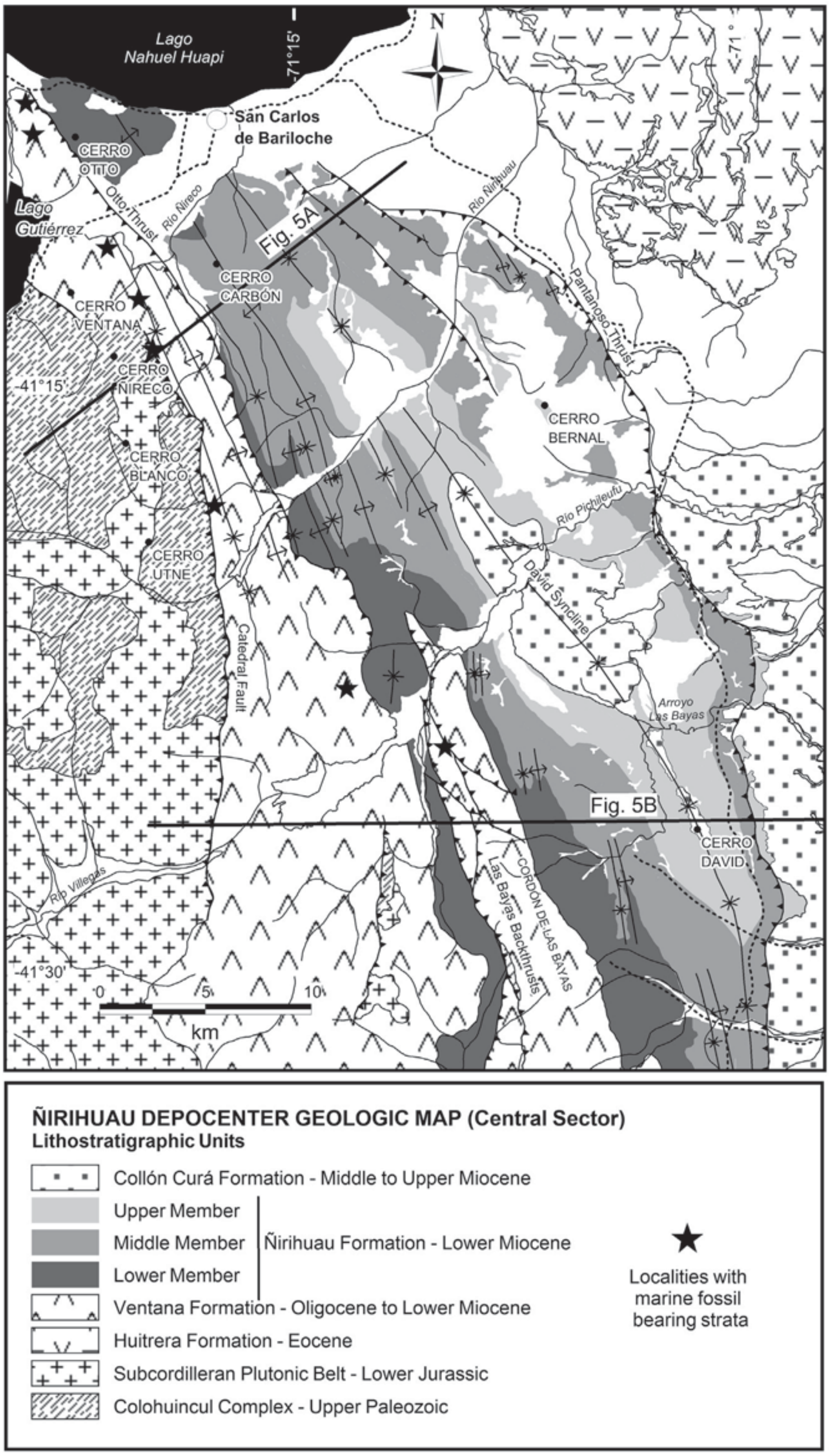

Fig. 4. Geologic and structural map of the Ñirihuau depocenter (modified from Bechis, 2004). Areas mapped in white correspond to Quaternary deposits. See location of the map on Fig. 1.

6A). The succession is formed by a basal section of dacitic, andesitic and basaltic lavas and subvolcanic bodies, a middle section of volcanic breccias, lapilli tuffs, tuffs, sandstones and conglomerates, and subordinated andesitic and basaltic lavas, and an upper section constituted by lapilli tuffs, tuffs and tuffaceous siltstones intercalated with thick basaltic bodies (Fig. 7A). Sedimentary beds bearing fossil marine invertebrates are intermittently but repeatedly interbedded in the upper section, which is nearly 500 m thick, recording a period of concomitant sedimentation and volcanism within a marine environment. The upper contact of with the Ñirihuau Formation is eroded and does not crop out in this section (Fig. 5A). Previous K–Ar and U–Pb ages of the Ventana Formation along the Maitén belt indicate an Early Oligocene to Early Miocene age, with most data ranging between 34 and 21 Ma (Table 1).

The Ñirihuau Formation (González Bonorino and González Bonorino, 1978) is here considered to be equivalent to the Ñorquinco Formation, which was originally defined in the Ñorquinco depocenter (Cazau, 1972). The unit shows strong variable thickness

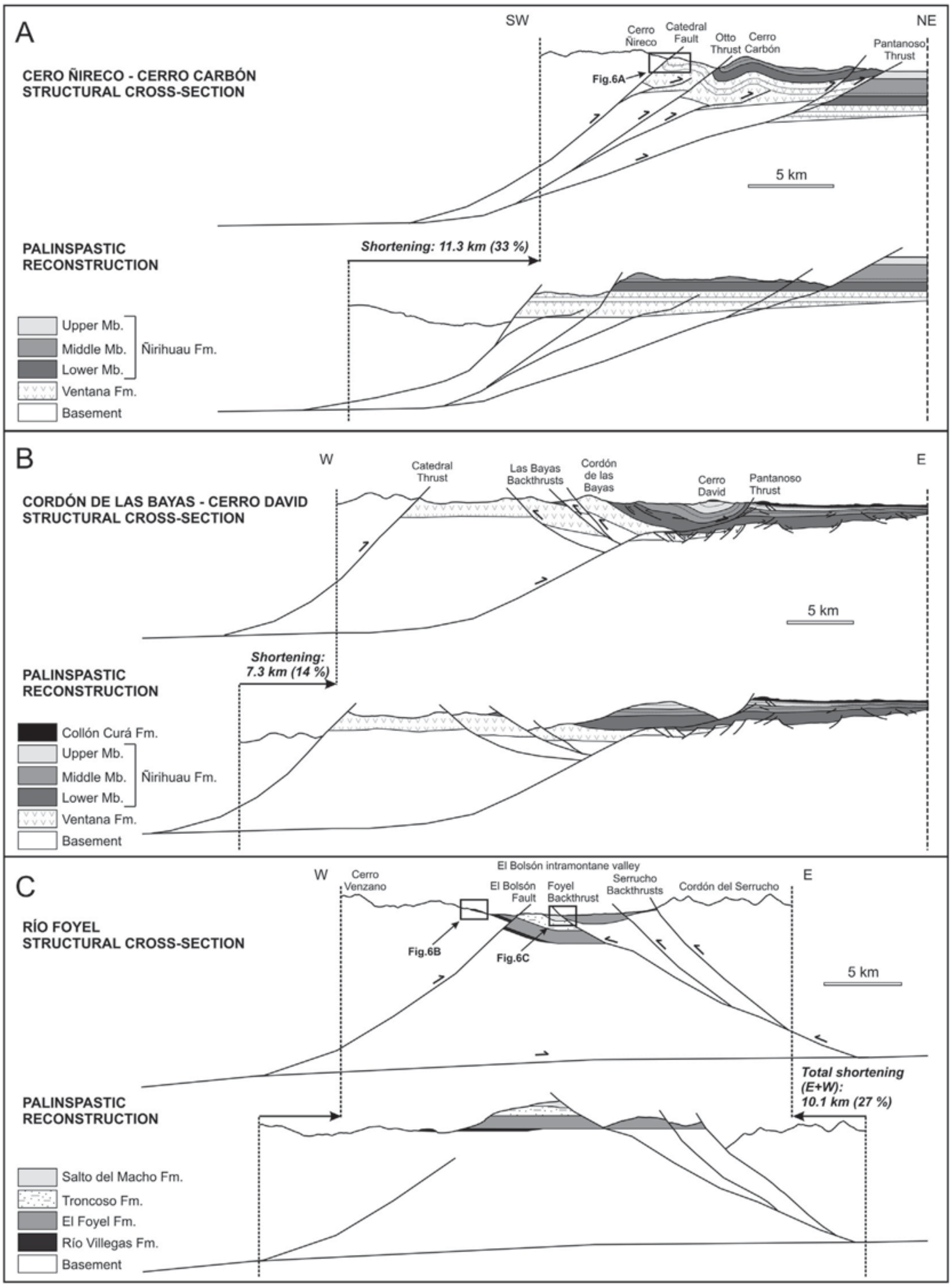

Fig. 5. Balanced structural cross-sections including the best exposed and studied stratigraphic sections. A) Cerro Ñireco – Cerro Carbón cross-section, see location on Fig. 4. B) Cordón de las Bayas – Cerro David cross-section, see location on Fig. 4. C) Río Foyel cross-section, see location on Fig. 8.

and facies distribution, reaching nearly 3500 m in its thickest section to the east of the Cordón de las Bayas (Bechis, 2004). The Ñirihuau Formation comprises clastic and pyroclastic deposits and subordinated carbonates interpreted as deposited in alluvial, lacustrine, deltaic and fluvial environments (Cazau, 1972, 1980; Spalletti, 1981; Cazau et al., 1989; Mancini and Serna, 1989; Bechis, 2004; Giacosa et al., 2005; Paredes et al., 2009). The lower and middle members have been interpreted as deposited mainly in alluvial and lacustrine environments, while from the top of the middle member upwards, deltaic and fluvial deposits prograded over the lacustrine beds. Although the Ñirihuau Formation is predominantly continental, a transient connection with the sea during deposition of its middle member was interpreted after the observation of sedimentary structures indicating tidal influence in the northern sector of the Ñirihuau depocenter (Spalletti, 1981, 1983; Asensio et al., 2004), the finding of microfossils (dinoflagellates and acritarchs) of marine affinity in samples from exploratory wells (Cazau et al., 1989), and the discovery of marine molluscs in the

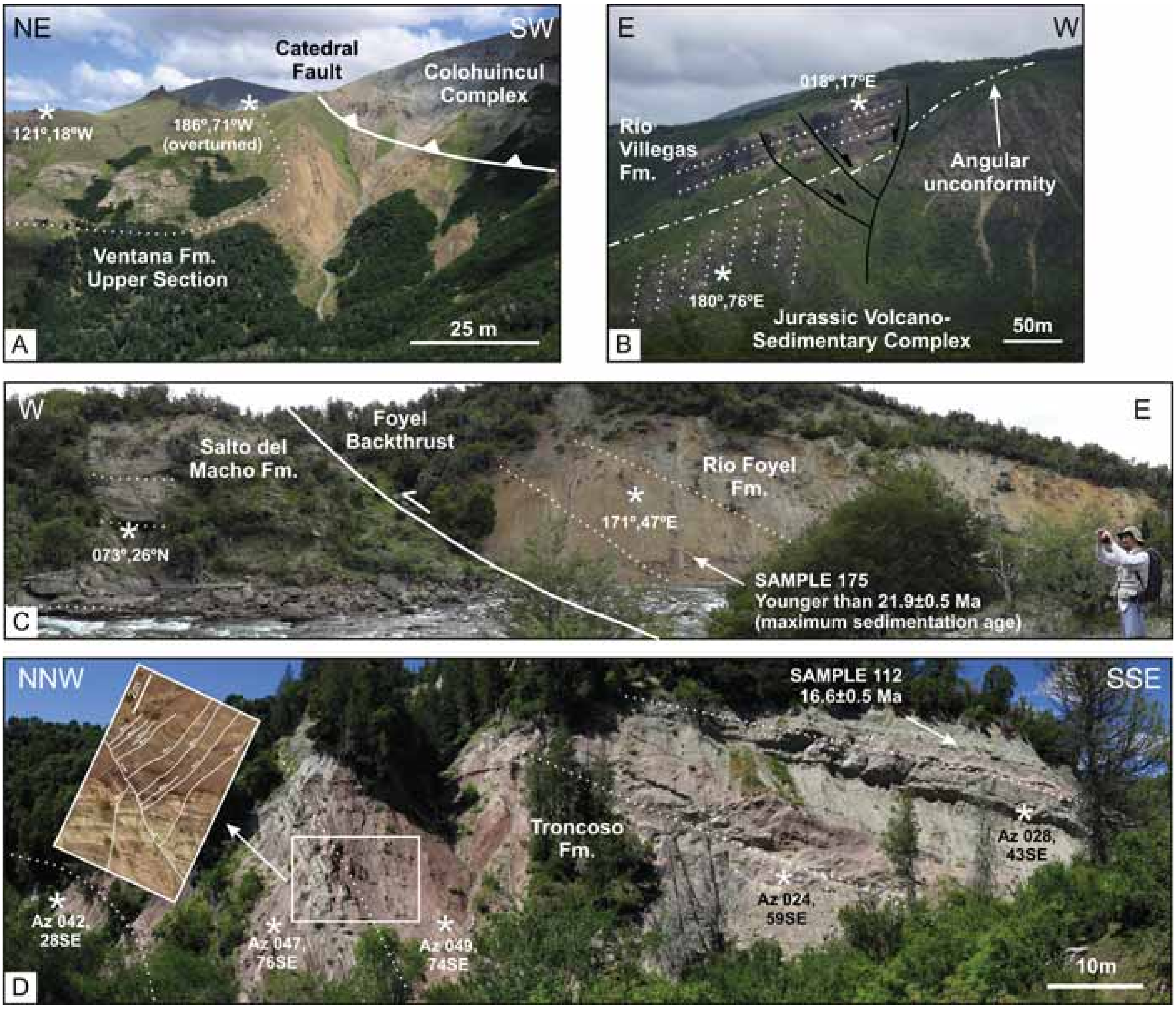

Fig. 6. A) Field photograph showing an east-vergent syncline deforming the volcanic and marine sedimentary beds of the upper section of the Ventana Formation in the northeastern slope of Cerro Ñireco. See location on Fig. 5A. B) Field photograph of Cerro Buitrera, where andesitic agglomerates and conglomerates assigned to the Río Villegas Fm. unconformably overlie Lower Jurassic volcanic and sedimentary rocks. The Río Villegas Fm. is also affected by normal faults probably related to the early stages of the El Bolsón depocenter evolution. See location on Figs. 8 and 5C. C) Field photograph of the Río Foyel margin showing the west-vergent Foyel backthrust that puts the older fine-grained strata of the Río Foyel Formation on top of the younger conglomerates of the Salto del Macho Formation. See location on Fig. 5C. D) Field photograph of the middle section of the Troncoso Formation in the Arroyo Palenque margin, showing progressive unconformities associated to small-scale normal faults. See location of Arroyo Palenque on Fig. 8.

Ñorquinco depocenter (Ramos, 1982a). Fossil fishes recovered from the Ñirihuau Formation were first assigned to several families of both freshwater and marine affinities (Bocchino, 1964, 1971; Cazau, 1980). However, the materials have been reviewed later and all of them were reassigned to freshwater fish families (Cione and Báez, 2007). Intercalated tuffs and volcanic breccias point out that volcanism was still active during deposition of the Ñirihuau Formation, and the middle and upper members of the unit register a progressive increment of pyroclastic products input into the basin. Previous K–Ar dating on intercalated tuffs yielded radiometric ages from 22 to 16.4 Ma, indicating an Early Miocene age (Table 1).

The lower and upper contacts of the Ventana Formation with the crystalline basement and the Ñirihuau Formation, respectively, are exposed in the Cordón de las Bayas, which is a key section for the observation of the stratigraphic relationships between the units of the Nahuel Huapi Group (Fig. 4). Two main interpretations have been proposed for the structure in the Cordón de las Bayas, the first supports a west-vergent thrust system (Ramos and Cortés, 1984; Bechis, 2004; Bechis and Cristallini, 2006), and the second a pop up limited by reverse faults of opposite vergence (Giacosa and Heredia, 2004a; Giacosa et al., 2001, 2005). Near the headwaters of Arroyo Las Bayas, the complete Cenozoic succession is exposed in a tectonic block tilted to the east by a west-vergent backthrust, which crops out in the western slope of the range (Figs. 4 and 5B). Thus, our field data clearly support the first group of interpretations. From base to top (west to east), the Cordón de las Bayas section starts with gneisses of the Colohuincul Complex, followed by a 2000 m thick predominantly volcanic succession assigned to the Ventana Formation. The basal section of the Ventana Formation has dark-colored andesitic lavas, volcanic breccias

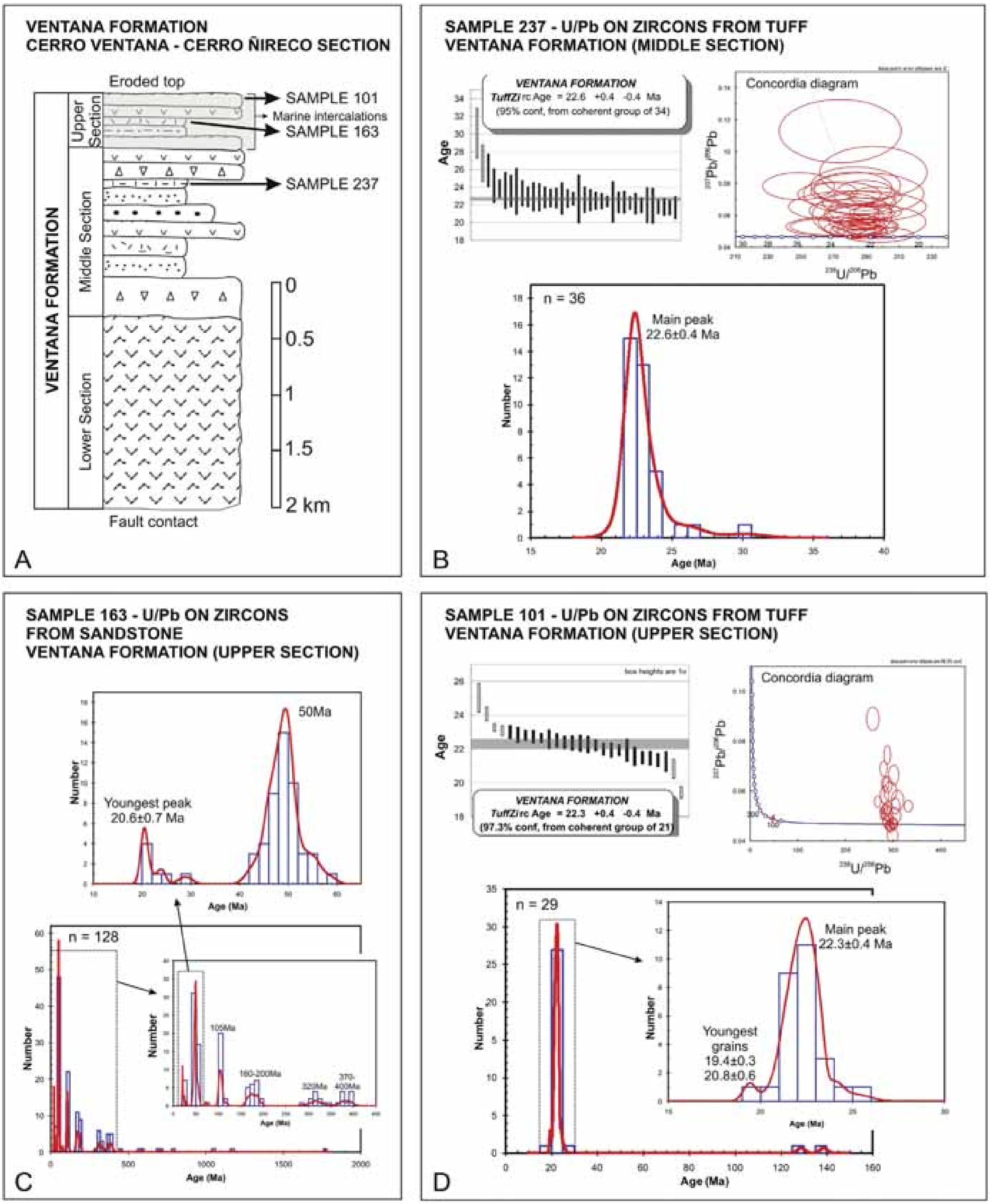

Fig. 7. Results of new geochronologic dating of the Ventana Formation (Nahuel Huapi Group) by U–Pb LA-ICPMS analysis. A) Stratigraphic location of the samples in the Cerro Ventana – Cerro Ñireco section is indicated on a schematic profile (modified from González Bonorino and González Bonorino, 1978; Giacosa et al., 2001). B) Results of sample 237 (41°11′29.03″S, 71°21′54.39″W, WGS84). C) Results of sample 163 (41°12′52.50″S, 71°20′19.84″W, WGS84). D) Results of sample 101 (41°13′17.65″S, 71°19′48.76″W, WGS84).

Table 1

Compilation of previous and new geochronologic data of the Nahuel Huapi and El Foyel Groups. Note that the symbol "?" was used in cases where the geochronologic method and/or the error were not informed in the original report. References: a) this contribution, b) González Díaz (1979), c) Rapela et al. (1983), d) Rapela et al. (1988), e) Cazau et al. (1989), f) Aragón et al. (2011), g) Rabassa (1978), h) Mazzoni and Benvenuto (1990), i) Marshall et al. (1977), j) Lizuaín (1983), k) Orts et al. (2012), l) Giacosa and Heredia (2004a), m) Griffin et al. (2004), m.s.a.: maximum sedimentation age.

Unit		Location	Lithology	Method	Age (Ma)		Reference
					Value	Error	
Nahuel Huapi Group	Ventana Formation (Maitén Volcanic Belt)	Lago Espejo	dacite	K/Ar	21	2	b
		West coast of Lago Nahuel Huapi	dacite	K/Ar	21	2	b
			dacite	K/Ar	14	2	b
		West coast of Lago Gutiérrez	andesite	K/Ar	11	2	c
		Cerro Ventana	dacitic ignimbrite	K/Ar	28.3	1.8	d
		Cerro Ventana	ryolitic ignimbrite	K/Ar	16.3	0.8	d
		East of El Maitén	dacite	K/Ar	24.9	1.3	d
		East of El Maitén	dacite	K/Ar	32.3	1.6	d
		West ofEl Maitén	andesite	K/Ar	31.2	1.8	d
		Cholila	andesite	K/Ar	31.9	1.6	d
		Ñorquinco X-1 Well	basalto	?	34	?	e
		Mina María	dacite	?	33	?	e
		Portezuelo Apichig	dacite	?	32	?	e
		Cordón Leleque	andesite	?	31	?	e
		Mina Indio	andesite	?	30	?	e
		Cerro Horqueta	andesite	?	29	?	e
		South of El Maitén	andesite	?	29	?	e
		Arroyo Las Bayas	andesite	?	27	?	e
		Alto Río Chubut	dacite	?	25	?	e
		Portezuelo Apichig	ryolitic ignimbrite	?	25	?	e
		Portezuelo Apichig	andesite	?	24	?	e
		Mina Indio	dacite	?	24	?	e
		Alto Río Chubut	ryolitic ignimbrite	?	24	?	e
		South of El Maitén	andesite	?	21	?	e
		Paso Puyehue	basaltic trachy-andesite	U/Pb SHRIMP	22	2	f
		Cerro Ventana (sample 237)	tuff	U/Pb LA-ICPMS	22.6	0.4	a
		Cerro Ñireco (sample 163)	detrital Zr from sandstone (m.s.a.)	U/Pb LA-ICPMS	20.6	0.7	a
		Cerro Ñireco (sample 101)	tuff (probable age)	U/Pb LA-ICPMS	19/20?	-	a
			tuff (maximum deposition age)	U/Pb LA-ICPMS	22.3	0.4	a
	Ñirihuau Formation	Cerro Horqueta – Middle Member	tuff	?	22	?	e
		Arroyo Cushamen - Middle Member	tuff	?	21.6	?	e
		Cerro Horqueta – Middle Member	tuff	?	19.7	?	e
		Arroyo Las Bayas – Upper Member	tuff	?	17.1	?	e
		Río Ñirihuau - Upper Member	tuff	?	16.7	?	e
		Quebrada Aguilucho - Upper Member	tuff	?	16.4	?	e
	Collón Curá Formation	Pilcaniyeu	ignimbrite	?	15	?	g
		Quebrada Aguilucho	tuff	?	11.5	?	e
		Quebrada Aguilucho	tuff	?	10.7	?	e
		Paso Flores	tuff	K/Ar	16.1	2.6	h
		Estancia Thorp	?	K/Ar	15.9	3.1	h
		B. Saavedra	ignimbrite	K/Ar	13.8	0.9	h
		Río Collón Curá	biotite from ignimbrite	K/Ar	14	0.3	i
		Río Collón Curá	biotite from ignimbrite	K/Ar	14.1	0.3	i
		Río Collón Curá	plagioclase concentrate from ignimbrite	K/Ar	14.4	0.3	i
		Río Collón Curá	plagioclase concentrate from ignimbrite	K/Ar	15.4	0.3	i
El Foyel Group	Troncoso Formation	Gendarmería Río Villegas (sample 461)	detrital Zr from sandstone (m.s.a.)	U/Pb LA-ICPMS	21.4	0.7	a
		Arroyo Palenque (sample 112)	tuff	U/Pb LA-ICPMS	16.6	0.5	a
	Troncoso Formation?	Cerro Plataforma	volcanic rock	K/Ar	15	?	j
	Río Foyel Formation?	Cerro Plataforma	detrital Zr from sandstone (m.s.a.)	U/Pb LA-ICPMS	18.3	0.6	k
	Río Foyel Formation	Cascada Nahuel Pan	intruded sill (minimum age)	K/Ar	31	1	l
		Puente Río Foyel	bivalve shelf	Sr/Sr	30.65	?	m
		Río Foyel (sample 175)	detrital Zr from sandstone (m.s.a.)	U/Pb LA-ICPMS	21.9	0.5	a

and tuffs, followed by an intermediate section of light-colored volcanic breccias, lapilli tuffs and tuffs and some intercalated conglomerates and sandstones, and ends with an upper section of tabular grayish andesitic to dacitic lavas. We did not observe interbedded fossiliferous marine strata in this section, but they were described by Bechis (2004) in a nearby locality in the northern sector of the Cordón de las Bayas (Fig. 4). On the eastern foot of the range, the Ventana Formation is overlain by the basal strata of the Ñirihuau Formation, here represented by a 400 m thick succession of coarse and poorly selected polymictic conglomerates, showing a general thinning upward tendency. The clasts, that can reach sizes up to 50 cm, are subrounded, showing a varied composition of porphyritic volcanic rocks of the Ventana Formation (including clasts from the underlying lavas), metamorphic rocks of the Colohuincul Complex and granites of the Subcordilleran plutonic belt. Interbedded tuffaceous sands and siltstones containing fossil leaves were also found within the conglomeratic succession (Passalia and Bechis, 2012). Scattered tuffs, basalts and volcanic agglomerates intercalated in the lower section of the conglomerates indicate a contemporaneous and diminishing volcanic activity. The conglomerates are abruptly overlain by a 500 m thick lacustrine succession of interbedded fine sandstones, carbonates and pelites, that contain fossil freshwater bivalves and decapods (Aguirre Urreta, 1992), corresponding to the lacustrine succession assigned to the lower member of the Ñirihuau Formation (Cazau et al., 1989; Mancini and Serna, 1989; Bechis, 2004). The section continues with a 2500 m thick succession of lacustrine, deltaic, and fluvial deposits assigned to the middle and upper members of the

Ñirihuau Formation. In this sector, the unit is folded forming part of the wide David syncline, limited to the east by the west-dipping Pantanoso thrust (Figs. 4 and 5B).

The upper unit of the Nahuel Huapi Group is represented by the Collón Curá Formation (Yrigoyen, 1969), constituted by tuffs and tuffaceous conglomerates and sandstones interpreted as deposited in a fluvial environment (Rabassa, 1978). The contact between the Ñirihuau and Collón Curá Formations is marked by an angular unconformity in the Ñirihuau depocenter (Bechis, 2004; Bechis and Cristallini, 2005) and by a lithological transition and progressive unconformities in the Ñorquinco depocenter (Ramos et al., 2011). Previous K–Ar ages of tuffs assigned to this unit range between 16 and 10 Ma, indicating a Middle to Late Miocene age (Table 1).

3.2. El Bolsón depocenter

The El Bolsón depocenter comprises the disconnected outcrops of predominantly marine and subordinated continental strata described in the El Bolsón intramontane valley and some isolated outcrops further south (Figs. 1 and 2; Giacosa and Heredia, 2004a). Structural and stratigraphic studies in this area are particularly complex because of a widespread forest cover and the effects of erosional and depositional processes related to the Quaternary glaciations. The El Bolsón intramontane valley is limited to the E and W by basement blocks uplifted by reverse faults of opposing vergence that delimit a thick-skinned triangular zone (Giacosa and Heredia, 2004b). Within the valley, the Cenozoic succession is also affected by thrusts of opposing vergence, which complicate the observation of the geological contacts among the different units (Figs. 8 and 5C). These characteristics make it difficult to determine the original extension and limits of this depocenter.

The more continuous and best exposed succession of the El Bolsón depocenter infill is found along the Río Foyel margins, where Asensio et al. (2005) defined the El Foyel Group, constituted by the Río Villegas, Río Foyel, Troncoso and Salto del Macho Formations (Fig. 3). We follow the original stratigraphic division, but we propose changes in the age and ordering of the units based on our field, geochronological and biostratigraphic data (Figs. 3 and 9A). The group is partially equivalent to other proposed lithostratigraphic names as the Rincón de Cholila and Mallín Ahogado Formations (Cazau, 1972; Giacosa et al., 2001).

The Río Villegas Formation is constituted by 150 m of andesitic agglomerates and conglomerates that are apparently restricted to the northernmost sector of the El Bolsón depocenter, where they are separated of the underlying Early Jurassic volcano-sedimentary complex by a very well exposed angular unconformity (Fig. 6B; Bechis et al., 2011).

The Río Foyel Formation comprises more than 600 m of black shales, fine sandstones and carbonates, which contain a rich marine fauna that has been object of numerous paleontological studies (Roth, 1922; Bertels, 1980, 1994; Malumián et al., 2008; Pöthe de Baldis, 1984; Rossi de García and Levi, 1984; Chiesa and Camacho, 2001; Barreda et al., 2003; Casadío et al., 2004; Asensio et al., 2010). In the original proposal of Asensio et al. (2005) the Río Foyel Formation was interpreted to be the youngest unit of the El Foyel Group. These authors describe a sharp basal contact of this unit with the Salto del Macho Formation in the Río Foyel section, which they interpret as a flooding surface. However, we have revisited the contact between these units along the river banks, and it corresponds to a west-vergent backthrust that puts the older fine sediments of the Río Foyel Formation on top of the younger coarse conglomerates of the Salto del Macho Formation (Figs. 5C, 6C and 8). This structural relationship implies that the marine beds must be placed near the base of the Cenozoic succession in this section.

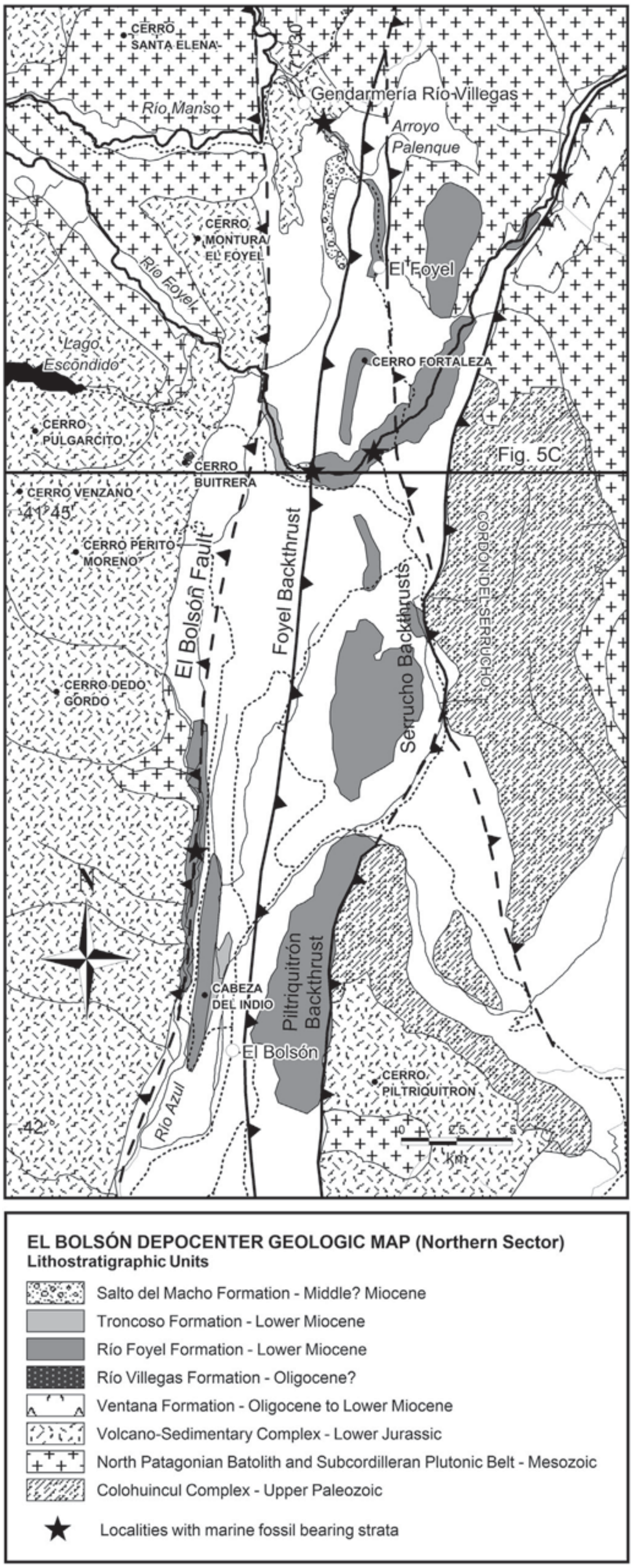

Fig. 8. Geologic and structural map of the northern sector of the El Bolsón depocenter based on new data and compiled previous works (González Bonorino, 1944; Diez and Zubia, 1981; Giacosa and Heredia, 2004a, 2004b). Areas mapped in white correspond to Quaternary deposits. See location on Fig. 1.

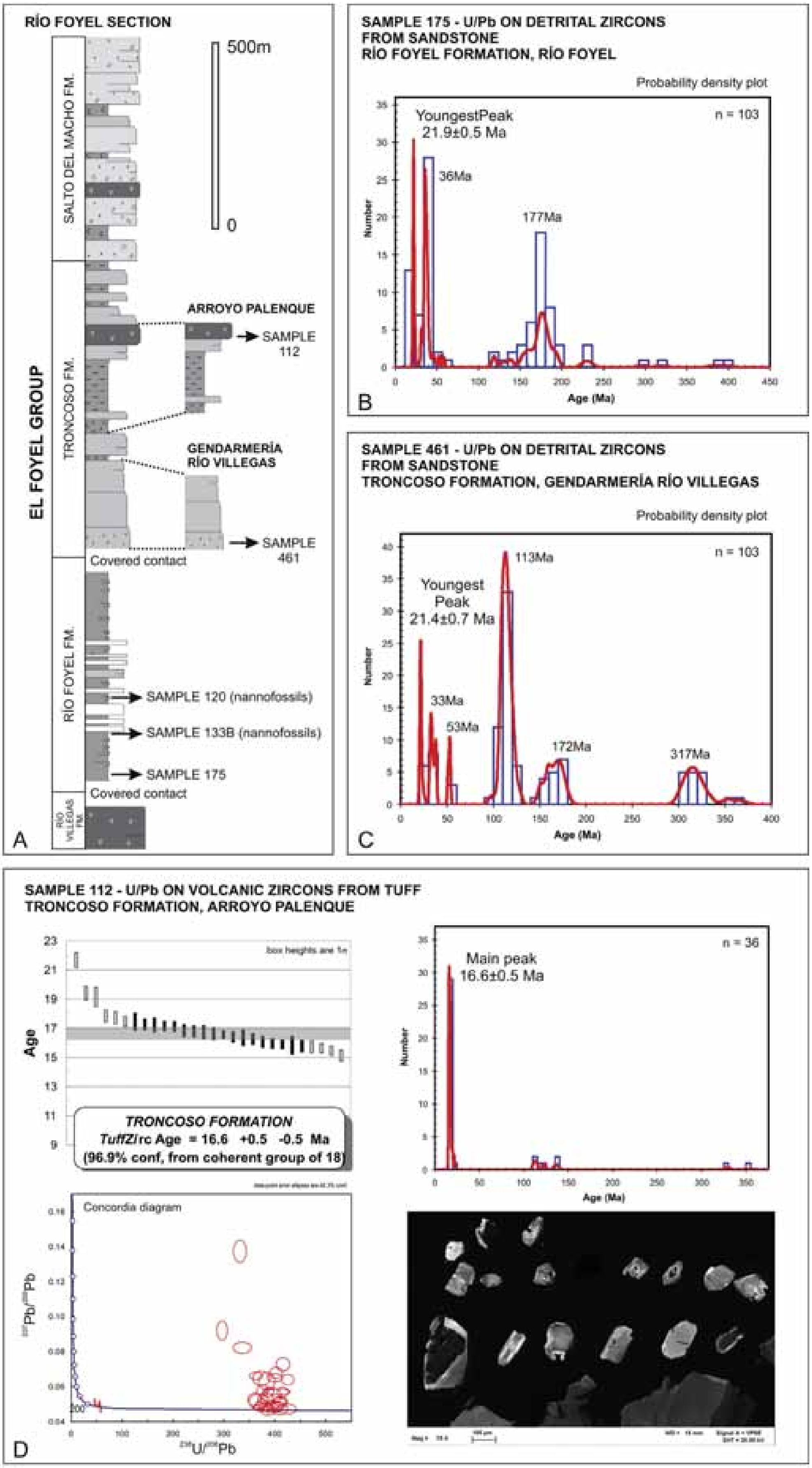

Fig. 9. Results of new geochronologic dating of the Río Foyel and Troncoso Formations (El Foyel Group) by U–Pb LA-ICPMS analysis. A) Stratigraphic location of the samples in the Río Foyel and correlated sections is indicated on a schematic profile (modified from Asensio et al., 2005; Cornou et al., 2012). B) Results of sample 175 (41°44′01.93″S, 71°29′29.33″W, WGS84). C) Results of sample 461 (41°35′31.27″S, 71°29′06.97″W, WGS84). D) Results of sample 112 (41°36′04.82″S, 71°28′30.83″W, WGS84).

The Río Foyel Formation was interpreted as deposited in a restricted littoral marine environment with lower than normal marine salinity and warm-temperate to warm waters, rich in nutrients (Bertels, 1980, 1994; Barreda et al., 2003; Quattrocchio et al., 2012). Palynologic assemblages suggest estuarine and inner neritic environments (Barreda et al., 2003; Quattrocchio et al., 2012), while foraminifera assigned to the genus *Transversigerina*, which has an upper to middle bathyal preference, were also reported in the unit (Malumián et al., 1984; Asensio et al., 2010). The unit shows an upward shallowing trend (Asensio et al., 2010; Quattrocchio et al., 2012), and the upper contact with the Troncoso Formation is commonly covered and seems to be transitional.

The age of the Río Foyel Formation was first interpreted as Eocene to Oligocene (Bertels, 1980, 1994; Pöthe de Baldis, 1984; Rossi de García and Levi, 1984; Chiesa and Camacho, 2001), while some recent contributions have postulated that it could reach the Lower or Middle Miocene (Barreda et al., 2003; Malumián et al., 2008). Sr–Sr dating of a bivalve shell gave an Early Oligocene age (30.65 Ma; Griffin et al., 2004), and a sill intruded in the sedimentary succession near El Bolsón was dated by the K–Ar method in 31 ± 1 Ma (Giacosa and Heredia, 2004a). These previous data are contradictory and not conclusive for determining the precise age of the Río Foyel Formation. Furthermore, no age constraints were known for the rest of the units that constitute the El Foyel Group before this contribution (Table 1).

The Troncoso Formation is a 750 m thick succession of green sandstones bearing marine fossil invertebrates, tuffs and tuffaceous pelites, sandstones and conglomerates (Asensio et al., 2005). It can be divided in two sections, a basal marine section and an upper continental one. The basal section crops out in the Río Foyel margins and near the Gendarmería Río Villegas, where it is represented by green sandstones bearing a fossil marine fauna of bivalves and bryozoans (González Bonorino, 1944; Asensio et al., 2005). The upper section registers an increment of pyroclastic input into the basin, and its palynologic content indicates a continental environment with temperate and humid conditions (Quattrocchio et al., 2012). An erosional and low-angle unconformable contact that crops out in the Río Foyel section separates the Troncoso Formation from the overlying coarse conglomerates of the Salto del Macho Formation (Asensio et al., 2005).

The Salto del Macho Formation is represented by 500 m of polymictic conglomerates with scarce intercalations of sandstones, tuffs and pelitic intervals, which have been interpreted as deposited in a marginal-marine fan-deltaic environment (Asensio et al., 2005; Cornou et al., 2012; Quattrocchio et al., 2012). The clasts show a varied composition of porphyritic volcanic rocks, metamorphites and granites (Asensio et al., 2005), reflecting a mixed provenance from the Ventana Formation and/or the Early Jurassic volcano-sedimentary complex, the Colohuincul Complex, and the Subcordilleran plutonic belt and/or the North Patagonian Batolith, respectively. This unit is apparently restricted to the northern sector of the El Bolsón depocenter.

4. New geochronological data

We collected tuffs and sandstones samples intercalated with the main marine strata of the Ñirihuau and El Bolsón depocenters in order to date these units. LA-ICP-MS U–Pb analyses in zircons were conducted at the Washington State University, both in igneous zircons from tuffs and in detrital zircons from sandstones.

A new U–Pb LA-ICPMS zircon age of 22.6 ± 0.4 Ma was obtained for a tuff from the middle section of the Ventana Formation, located below the first marine fossil record in the Cerro Ventana – Cerro Ñireco section (sample 237; Fig. 7). Analysis undertaken on detrital zircons gave a maximum age of 20.6 ± 0.7 Ma for a sandstone intercalated in the marine succession of the upper section of the unit (sample 163; Fig. 7). Zircons recovered from a tuff intercalated at the top of the fossiliferous upper section were also analyzed with this method (sample 101; Fig. 7). For sample 101 the most prominent age peak comprising 21 analyses gave a weighted mean age of 22.3 ± 0.4 Ma, and younger ages of 19.4 ± 0.3 Ma and 20.8 ± 0.6 Ma were obtained for two zircon grains (sample 101; Fig. 7). Although the 22 Ma age obtained for the main peak seems a robust age for the tuff deposition, the maximum sedimentation age obtained for the sandstone of sample 163 located in a lower stratigraphic level suggest that the tuff should be younger than 20.6 ± 0.7 Ma. Thus the ages ranging between 19 and 21 Ma obtained for the two youngest zircons could be closer to the age of the tuff of sample 101, and the older peak could be related to reworking of previous volcanic deposits. Considering these assumptions, we interpret 22.3 ± 0.4 Ma as a maximum age, and between 19 and 20 Ma as a probable age for the tuff of sample 101. This data allow us to constrain the age of the upper section of the Ventana Formation and its related marine transgression within the Early Miocene, between 23 and 19 Ma (Aquitanian – Burdigalian).

New U–Pb LA-ICPMS geochronology undertaken on detrital zircons gave a maximum age of 21.9 ± 0.5 Ma for a sandstone intercalated at the base of the Río Foyel Formation in the Río Foyel section (sample 175; Fig. 9). This U–Pb data disregards previous non confident geochronological ages and poses a maximum age for deposition of the unit in the Early Miocene (Aquitanian). This result is strongly consistent with our stratigraphic and structural observations and with the results of our biostratigraphic studies (next section), constraining the age of the Río Foyel Formation to the Early Miocene (Aquitanian – Burdigalian).

New U–Pb LA-ICPMS geochronology undertaken on detrital zircons gave a maximum age of 21.4 ± 0.7 Ma for the fossil-bearing marine sandstone of the basal section of the Troncoso Formation at the Gendarmería Río Villegas (sample 461; Fig. 9). In addition, a crystalline tuff intercalated in continental strata from the upper section of this unit in the nearby Arroyo Palenque gave a U–Pb LA-ICPMS zircon age of 16.6 ± 0.5 Ma (sample 112; Fig. 9). These data represent the first geochronological constraints for these marine beds, which are then constrained within the Lower Miocene (Aquitanian – Burdigalian).

5. New biostratigraphic constraints

Micropaleontological studies were carried out to find an answer for the long-standing question about the age of the fossiliferous black-shales of the Río Foyel Formation. Data presented here constitute the first mentions of calcareous nannofossils found within this unit.

Calcareous nannofossils were recovered from the Río Foyel Formation in the Río Foyel section (samples 120 and 133B; Figs. 10 and 11). The association is scarce to frequent in some stratigraphic levels, poses a moderate preservation showing some traces of dissolution, and contains *Cyclicargolithus floridanus* (Roth and Hay) Bukry, *Coccolithus pelagicus* (Wallich) Schiller, *Discoaster deflandrei* Bramlette and Riedel, *Helicosphaera euphratis* Haq, *Reticulofenestra haqii* Backman, *Reticulofenestra minuta* Roth and *Thoracosphaera heimii* (Lohmann) Kamptner. The recognized nannoflora is generally composed by Cenozoic long ranging taxa. However, *Discoaster deflandrei*, is a warm water taxon with a broad distribution, extending its biochron from the Paleogene to NN7, Middle Miocene (Martini, 1971; Perch-Nielsen, 1985; Young, 1998). *Cyclicargolithus floridanus* (Roth and Hay) Bukry, is present between the Paleogene and the NN7, being considered its last occurrence as a reliable marker (Raffi et al., 2006), *Reticulofenestra haqii* indicates NN2 to NN15, Early Miocene to Late Pliocene

(Young, 1998) and *Helicosphaera euphratis*, poses a stratigraphical distribution ranging from the Paleogene to NN4, Early-Middle Miocene, Burdigalian to the base of Langhian (Young, 1998; Raffi et al., 2006). *Pyrocyclus orangensis* (Bukry) Backman is here detected, and is considered as relict reticulofenestrid cores or some proto-coccolith rings as well as some undetermined coccosphere, that can indicate some quiet water conditions, at least in some levels (Young, 1998).

Considering the joint presence of the *Reticulofenestra haqii* and *Helicosphaera euphratis*, the Río Foyel Formation can be assigned to NN2-NN4 (Martini, 1971), Early to Middle Miocene (Aquitanian – Langhian; Fig. 11).

6. Stratigraphic setting, age and correlation of the infill of the Ñirihuau and El Bolsón depocenters

Our field, geochronological and biostratigraphic data point out an Early Miocene age for the Río Foyel and Troncoso Formations, where the main marine strata of the El Foyel Group are found (Fig. 3). The Río Foyel Formation is constrained between the Aquitanian and Langhian by calcareous nannofossils studies (NN2-NN4), and between the Aquitanian and Burdigalian by U–Pb dating (younger than 21.9 ± 0.5 Ma and older than 16.6 ± 0.5 Ma), considering that our structural observations indicate that it must be older than the Troncoso Formation. Previous studies reported

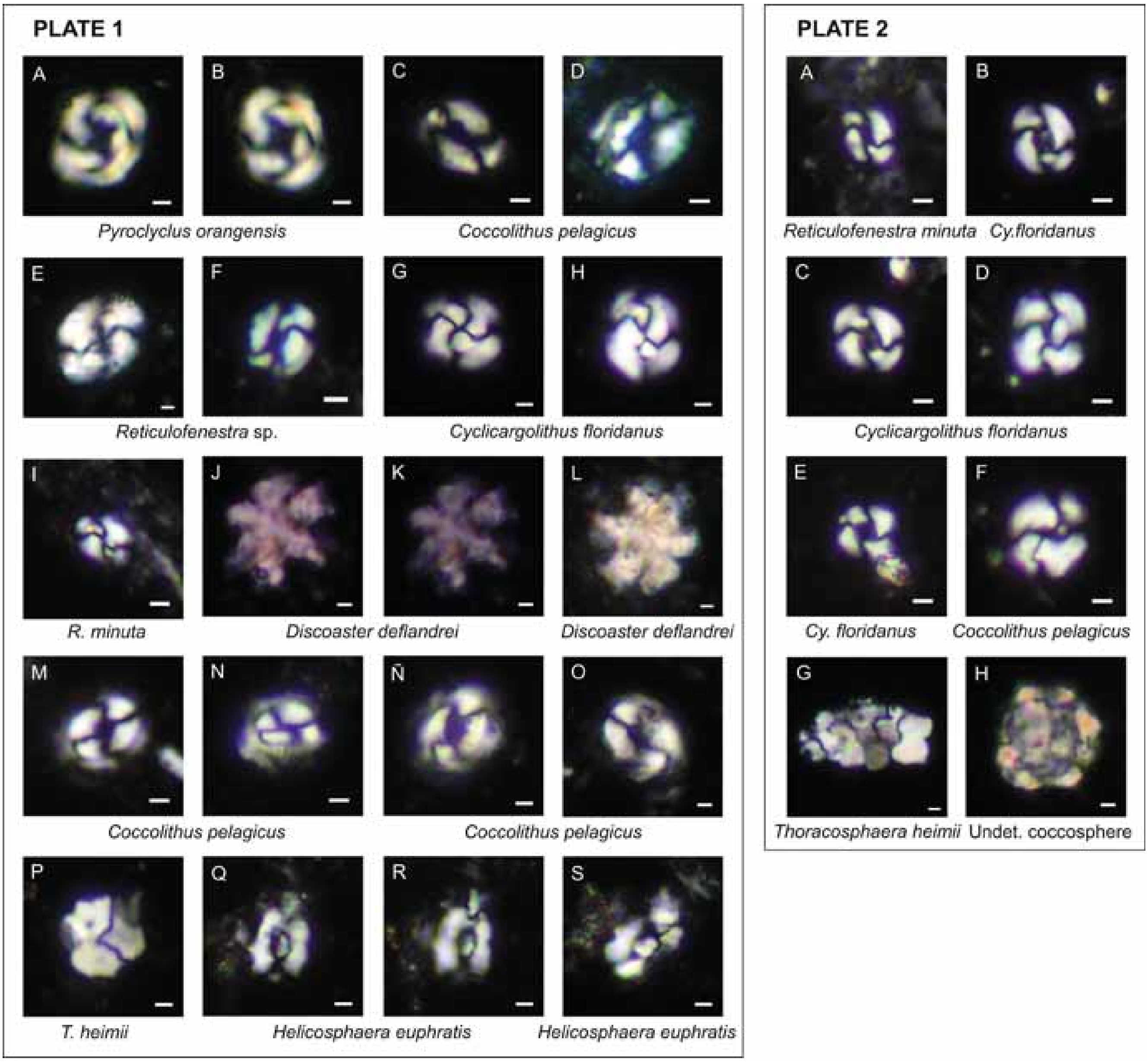

Fig. 10. Plate 1) Calcareous nannofossils from sample 120, Río Foyel Formation (41°44′0.56″S, 71°29′15.07″W, WGS84). A, B: *Pyrocyclus orangensis* (Bukry) Backman, 1980. C, D: *Coccolithus pelagicus* (Wallich) Schiller, 1930. E, F: *Reticulofenestra* sp. G, H: *Cyclicargolithus floridanus* (Roth and Hay) Bukry, 1971. I: *Reticulofenestra minuta* Roth, 1970. J, K, L: *Discoaster deflandrei* Bramlette and Riedel, 1954. M, N, Ñ, O: *Coccolithus pelagicus* (Wallich) Schiller, 1930. P: *Thoracosphaera heimii*, (Lohmann) Kamptner, 1941. Q, R, S: *Helicosphaera euphratis* Haq, 1966. Plate 2) Calcareous nannofossils from sample 133B, Río Foyel Formation (41°44′1.21″S, 71°29′17.41″W, WGS84). A: *Reticulofenestra minuta* Roth, 1970. B, C, D, E: *Cyclicargolithus floridanus* (Roth and Hay) Bukry, 1971. F: *Coccolithus pelagicus* (Wallich) Schiller, 1930. G: *Thoracosphaera heimii* (Lohmann) Kamptner, 1941. H: Undetermined coccosphere. In all cases the bar indicates 1 μm. All photographs were taken under crossed nicols. See stratigraphic position of the samples on Fig. 9.

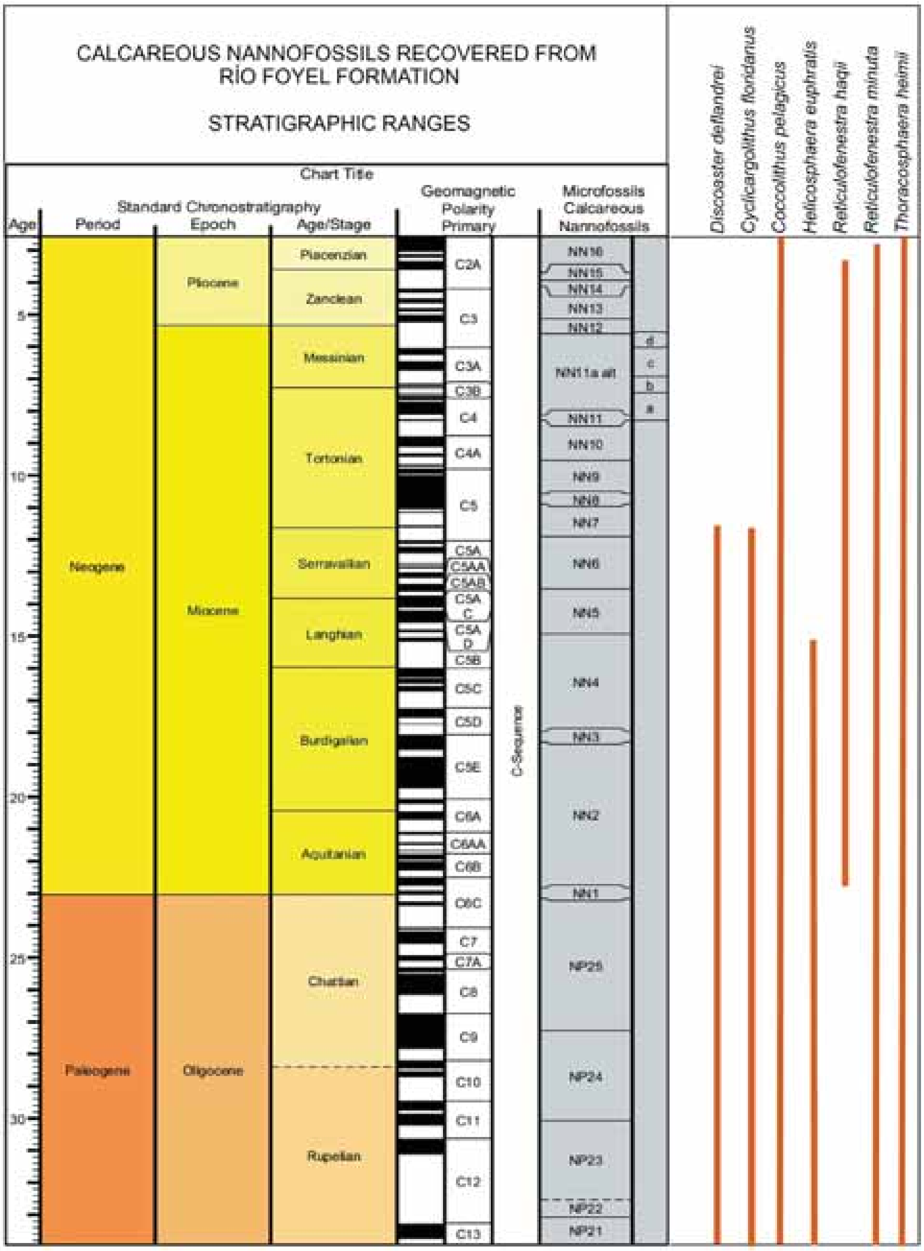

Fig. 11. Chart showing the stratigraphic ranges of the calcareous nannofossils recovered from the Río Foyel Formation.

internal gypsum casts of the foraminifera *Transversigerina cf. transversa* for the Río Foyel Formation in the Río Foyel section (Malumián et al., 2008). This genus appears in the uppermost Oligocene and the compared species is distributed along the Lower Miocene (Malumián et al., 2008). This report reinforces our data indicating an Early Miocene age for the unit. All these constraints were obtained in the Río Foyel section, where the base of the unit is tectonically suppressed by the west-vergent Foyel backthrust (Figs. 5C and 6C). Thus, a slightly older age for the basal section of the Río Foyel Formation cannot be discarded. The marine beds at the lower section of the overlying Troncoso Formation are also constrained between the Aquitanian and Burdigalian by U–Pb dating (younger than 21.4 ± 0.7 Ma and older than 16.6 ± 0.5 Ma). The lowermost unit of the El Foyel Group, the Río Villegas Formation, is older than the Early Miocene age obtained for the Río Foyel Formation. The Salto del Macho Formation overlies the Troncoso Formation and therefore must be younger than 16.6 ± 0.5 Ma. Our data indicate that the main marine beds in the Río Foyel section must be placed near the base of the Cenozoic succession in the El Bolsón depocenter. In accordance, marine strata that correlate with the Río Foyel and Troncoso Formations overlie Mesozoic granitic rocks in Río Azul and Cerro Plataforma, and the Ventana Formation at Cholila (Table 2, Fig. 3; Miró, 1967; Cazau, 1972, 1980; Lizuaín, 1979, 1983; Diez and Zubia, 1981; Ramos, 1982a; Griffin et al., 2002; Orts et al., 2012). In all these localities, the marine deposits are dominated by sandstone facies, probably corresponding to lateral equivalents deposited in shallower marine environments than the Río Foyel Formation (Spalletti, 1983). Also, in most cases they are followed by continental beds with an increasing volcanic and pyroclastic input into the sedimentation, in a similar way as the general tendency registered in the upper section of the Troncoso Formation. In the Cerro Plataforma section, U–Pb dating of detrital

Table 2
Schematic chart showing the correlation of the El Foyel Group with equivalent units that crop out in distinct localities of the El Bolsón depocenter and some isolated outcrops further south. See location on Fig. 2.

Age	Futaleufú (Castillo, 1983)	Cholila (Miró, 1967; Cazau, 1972)	Cerro Plataforma (Lizuaín, 1983; Orts et al., 2012)	Río Azul and El Bolsón (Diez and Zubia, 1981)	Río Foyel and Ruta 40 (Asensio et al., 2005; this contribution)	Depositional environment
Middle Miocene		-	-	-	Salto del Macho Fm.	**Transitional?**
Lower Miocene		Ñorquinco/Ñirihuau Fm.	Volcanic and clastic (upper section)	Clastic and volcanic (upper section)	Troncoso Fm. (upper section)	**Continental**
	La Cascada Fm.	Las Minas/Rincón de Cholila Fm.	Marine clastic (lower section)	Marine clastic (lower section)	Troncoso Fm. (lower section) and Río Foyel Fm.	**Marine**
Oligocene to Lower Miocene		Ventana Fm. (Maitén Volcanic Belt)	-	-	Río Villegas Fm.	**?**
Mesozoic		Jurassic Volcano-Sedimentary Complex	North Patagonian Batolith	North Patagonian Batolith	Jurassic Volcano-Sedimentary Complex	**Basement**

zircons from a sample obtained from the top of the 300 m thick marine succession gave a maximum sedimentation age of 18.3 ± 0.6 Ma, while K–Ar dating of a volcanic rock that overlies the marine beds gave a 15 Ma age (Lizuaín, 1983; Orts et al., 2012). These data indicate an Early Miocene age for the marine beds of the Cerro Plataforma section, which can be correlated with the marine strata of the Río Foyel and Troncoso Formations (Table 2).

In the case of the Nahuel Huapi Group, the marine beds intercalated in the upper section of the Ventana Formation are also constrained within the Early Miocene (Aquitanian – Burdigalian) by our U–Pb dating of intercalated tuffs and sandstones (22.6 ± 0.4 Ma to 19.5 ± 0.3 Ma). Since the top of the Ventana Formation is eroded and does not crop out in the Cerro Ventana – Cerro Ñireco section (Fig. 5A), a younger age for the end of the marine sedimentation cannot be discarded. Although the evidence supporting transient marine connections during deposition of the middle member of the Ñirihuau Formation is scarce (Spalletti, 1981, 1983; Ramos, 1982a; Cazau et al., 1989; Asensio et al., 2004), it cannot be dismissed with the currently available information. According to available K–Ar dating of the unit, the Ñirihuau Formation is approximately constrained between 22 and 16.4 Ma (Table 1).

Considering the currently available geochronologic data (Table 1), the Río Foyel Formation can be correlated with the upper section of the Ventana Formation, and the Troncoso Formation with the Ñirihuau Formation (Fig. 3). However, as the ages obtained by U–Pb dating of detrital zircons from the Río Foyel and Troncoso Formations correspond to maximum deposition ages of 22 and 21 Ma and their marine beds show no signs of volcanic or pyroclastic intercalations, the marine beds of the Ventana Formation dated between 23 and 19 Ma could be slightly older than those of the El Foyel Group. The marine beds at the lower section of the Troncoso Formation could be tentatively correlated with the transient marine connections suggested for the middle member of the Ñirihuau Formation. Also, both units register a progressive increment of pyroclastic products input in the sedimentation towards the top. We also correlate the Salto del Macho and Collón Curá Formations based on their lithological characteristics, the available age constrains, and their similar stratigraphic position (Fig. 3).

The El Foyel Group was previously associated with an Eocene to Early Oligocene tectono-sedimentary cycle previous to the deposition of the Nahuel Huapi Group during the Oligocene to Miocene (Giacosa et al., 2001; Asensio et al., 2010). Our new age constraints indicate that the El Foyel Group is coeval with the Nahuel Huapi Group, and therefore the Ñirihuau and El Bolsón depocenters evolved simultaneously. Our field observations in the completely exposed succession of the Nahuel Huapi Group in the Cordón de las Bayas section indicate that there is no way to place the complete or partial succession of the El Foyel Group below the Nahuel Huapi Group, like some previous works have suggested (Asensio et al., 2010; Bernardo et al., 2009), because the volcanic rocks of the Ventana Formation were observed lying on top of the metamorphic basement.

7. Discussion

7.1. Tectonic setting and local paleogeography during the marine transgression

The integration of our new data with previous observations allows us to make some inferences about the tectonic setting and the local paleogeographic configuration of the Ñirihuau basin during the marine transgression into this continental area (Fig. 12). The main marine deposits recognized in the study area correspond to the Río Foyel Formation and the lower section of the Troncoso Formation in the El Bolsón depocenter, and the upper section of the

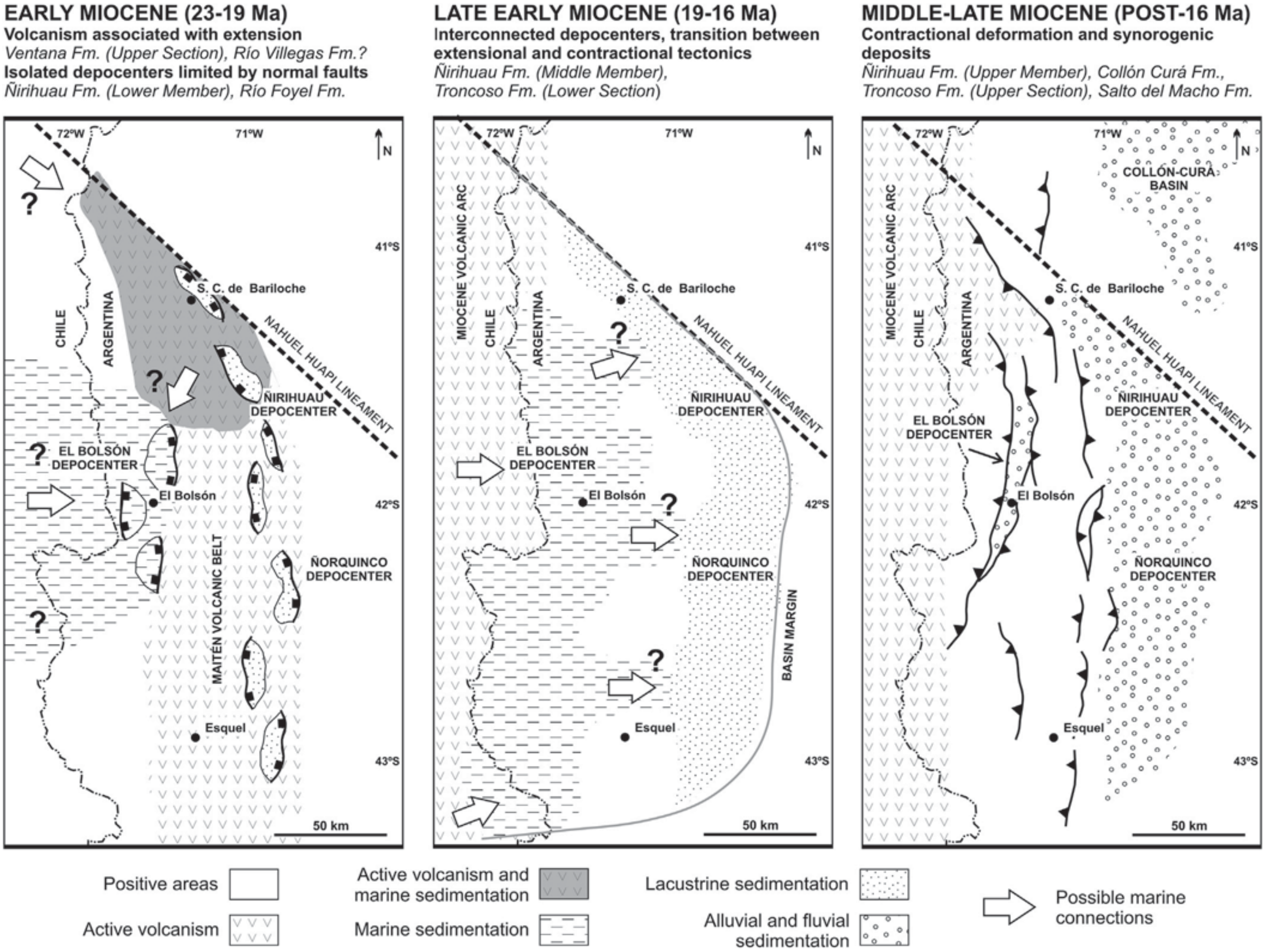

Fig. 12. Simplified maps showing the proposed tectonostratigraphic and paleogeographic evolution of the Ñirihuau basin during the Miocene. White arrows indicate possible marine connection areas with the basins of the Pacific side and between the distinct depocenters of the Ñirihuau basin. The trace of the Chile–Argentina international border and the main cities are shown for location purposes.

Ventana Formation in the Ñirihuau depocenter. Our new age constraints for these units indicate that most of the marine sedimentation took place during the Early Miocene interval (23–16 Ma) and that it was probably synchronous in both depocenters, suggesting that they were connected during the marine transgression. The marine strata could have been deposited during one or more pulses of a unique transgression, and the lithological and paleoenvironmental differences observed could be associated with local factors that controlled the particular evolution of the infilling of each depocenter.

The strong angular unconformity that separates the Río Villegas Formation from the underlying and more deformed Jurassic rocks in the northern sector of the El Bolsón depocenter was interpreted as related to the early stages of Andean contraction during the Cretaceous to Early Paleogene (Fig. 6B; Bechis et al., 2011). This stage is well documented further north between 36° and 39°S (Cobbold and Rosello, 2003; Zamora Valcarce et al., 2006) and recently identified in the high Patagonian Andes south of the study area (Orts et al., 2012; Tobal et al., 2012). The first and greatest Atlantic transgression that covered most of Patagonia occurred during the Maastrichtian to Danian (Windhausen, 1926; Malumián and Náñez, 2011). Marine deposition was also registered during this period in the forearc of south-central Chile (Biró-Bagóczky, 1982; Radic et al., 2009). However, the North Patagonian Andes remained emerged as a positive area during this period, probably because of its relatively thick crust, related to the early stages of contraction in this Andean segment.

The opening and early evolution of several volcano-sedimentary basins developed in the western border of South America between 26° and 45°S was associated with extensional tectonics during the Oligocene to Early Miocene (Jordan et al., 2001; Charrier et al., 2007; Godoy, 2011; references therein). A progressive crustal thinning related to extensional tectonics was also interpreted for the Oligocene to Lower Miocene volcanic rocks of the Ventana Formation in the Maitén volcanic belt (Rapela et al., 1983; Kay and Rapela, 1987; Kay et al., 2006). We interpret that the crustal thinning related to this regional extensional stage was the main factor that favored the marine transgression into the eastern border of the North Patagonian Andes during the earliest Miocene. In the Ñirihuau and Ñorquinco depocenters, extensional conditions were interpreted to have continued during deposition of the alluvial and lacustrine beds of the lower member of the Ñirihuau Formation, restricted to isolated depocenters limited by normal faults (Mancini and Serna, 1989; Bechis, 2004; Bechis and Cristallini, 2005, 2006). The northern limit of the extensional basin is marked by the Nahuel Huapi lineament (Fig. 12), which is a long-lived structure probably related to the collision of allochthonous terranes in the southwestern margin of Gondwana during the late Paleozoic (Ramos, 1984, 2008; Pankhurst et al., 2006). The upper member of the Ñirihuau Formation and the Collón Curá Formation were interpreted as synorogenic deposits associated to contractional deformation in the eastern side of the North Patagonian Andes during the Middle Miocene to Pliocene (Bechis, 2004; Bechis and Cristallini, 2005, 2006). Other contributions interpreted that most or the total thickness of the Ñirihuau Formation was deposited in a foreland basin related to contraction from the Early Miocene onwards (Giacosa and Heredia, 2004a; Giacosa et al., 2005; Paredes et al., 2009; Ramos et al., 2011). However, the most important evidences of contractional deformation within the basin correspond to growth strata and angular unconformities that are registered from the middle member of the Ñirihuau Formation upwards in both the Ñirihuau and Ñorquinco depocenters (Bechis, 2004; Bechis and Cristallini, 2005, 2006; Giacosa and Heredia, 2004a; Giacosa et al., 2005; Paredes et al., 2009; Ramos et al., 2011).

Normal faults were observed affecting the Río Villegas Formation in the northern sector of the El Bolsón depocenter (Fig. 6B; Bechis et al., 2011). The Río Foyel Formation was interpreted as deposited in a relatively deep marine environment, but with restricted oceanic circulation and an important coastal influence (Bertels, 1980, 1994; Barreda et al., 2003; Quattrocchio et al., 2012; Spalletti, 1983). This particular depositional environment could be preliminary related to a marine transgression that inundated normal-fault limited depocenters, as was also previously suggested by Asensio et al. (2010). The Troncoso Formation shows marked lateral thickness variations and progressive unconformities indicating concomitant deformation and sedimentation, and small-scale normal faults related to these syntectonic strata suggest an extensional tectonic setting during deposition of the unit (Bechis et al., 2011). These data suggest that extensional conditions could have lasted until the end of the Early Miocene, as the growth strata and related normal faults were observed affecting the Troncoso Formation below the tuff dated by U–Pb in 16.6 ± 0.5 Ma (Fig. 6D). On the other hand, Orts et al. (2012) interpreted that deposition of the marine strata that crop out in Cerro Plataforma was concomitant with a contractional deformation stage constrained between 18 and 15 Ma. The coarse-grained succession of the Salto del Macho Formation was previously interpreted as deposited in a fan deltaic environment during an extensional tectonic stage (Asensio et al., 2008). Our new age constrains and the new stratigraphic position we propose for the unit allow us to correlate it with the Collón Curá Formation (Fig. 3), which shows unequivocal evidence of contractional deformation in the eastern sector of the Ñirihuau basin (angular and progressive unconformities related to thrusts and folds; Giacosa and Heredia, 2004a; Giacosa et al., 2005; Bechis and Cristallini, 2005; Paredes et al., 2009; Ramos et al., 2011). Therefore, the tectonic context was without doubt compressive by the time of deposition of the Salto del Macho Formation, and then we interpret that the angular unconformity observed at its basal contact was related to contractional deformation within the El Bolsón depocenter during the Middle Miocene, and that the polymictic composition of its clasts including plutonic and metamorphic rocks could indicate an exhumation of the basin basement due to tectonic uplift.

Summarizing, we interpret that the marine transgressions in the North Patagonian Andes between 41° and 43°S are related to a regional extensional tectonic stage that took place along the western margin of the South America during the Oligocene to Early Miocene (Fig. 12). The oldest marine strata we detected are earliest Miocene in age, and are intercalated with the volcanic rocks of the Ventana Formation, evidencing a strong connection between subsidence and a thinned crust below the Maitén belt. At the same time or slightly later, disconnected normal fault-bounded depocenters developed near the margins of this volcanic belt. This disconnection explains why some areas were inundated by the sea, as the El Bolsón depocenter (Río Foyel Formation), while in other sectors deep lacustrine environments developed, like in the Ñirihuau depocenter (lower member of the Ñirihuau Formation). Progressive extension and later thermal cooling effects produced a generalized subsidence with eventual interconnection of the Ñirihuau basin depocenters, allowing the sea waters to invade lacustrine environments to the east (Troncoso Formation and middle member of the Ñirihuau Formation). Although the currently available data seem contradictory and could be related to a diachronic evolution of the different sectors or depocenters of the basin, the transition between extensional and contractional tectonics took place between the late Early Miocene and the early Middle Miocene. This contraction was concomitant with a progressive increment of pyroclastic input into the basin, and is registered by progressive and angular unconformities observed in the synorogenic deposits (upper section of the Troncoso Formation, upper member of the Ñirihuau Formation, Salto del Macho and Collón Curá Formations). The marginal-marine fan-deltaic environment previously interpreted for the coarse conglomerates of the Salto del Macho Formation may represent the last marine influence in the eastern slope of the North Patagonian Andes during the foreland basin stage, probably related to a strong load subsidence due to the emplacement of basement thrust sheets.

7.2. *Regional paleogeography of the marine transgressions: Pacific vs. Atlantic links*

According to recent paleogeographic reconstructions, the marine strata recorded in the Ñirihuau basin could be part of a major transgression that flooded a wide area of Patagonia between the Late Oligocene and the Middle Miocene (Fig. 13; Malumián and Náñez, 2011). As Ramos (1982a) and later others clearly pointed out, the well-documented existence of Oligocene to Middle Miocene continental deposits to the north, east and south of the Ñirihuau basin reject a direct connection with the Atlantic Ocean through this area during mid-Cenozoic times. These continental deposits correspond to the Rancahue, Chimehuín and Collón Curá Formations to the north (Franzese et al., 2011; García Morabito et al., 2011), La Pava and Collón Curá Formations to the east (Rabassa, 1978; Nullo, 1979; González, 1998), and Sarmiento, Carinao and Mimosa Formations to the south (Franchi and Page, 1980; Turner, 1982; Cabaleri and Ubaldón, 2008). In contrast, most of the localities with Cenozoic marine deposits in northwestern Patagonia are now placed in the forearc area, to the west of the main Andes (Fig. 13). These deposits form part of the infill of the Temuco, Valdivia, Osorno-Llanquihue, Chiloé and other coeval basins south of 38°S (Cisternas and Frutos, 1994; Rojas et al., 1994; Hervé et al., 1995; McDonough et al., 1997; Le Roux and Elgueta, 2000; Bernabé et al., 2009; Encinas et al., 2008, 2012b). The age of these marine beds has been a controversial topic, and it was interpreted as Middle Miocene to Early Pliocene, mainly from its foraminiferal content (Finger et al., 2007; Encinas et al., 2008, 2012b). However, more recent contributions have concluded that most of the marine sedimentation took place between the Early and Middle Miocene (Gutiérrez et al., 2013; Finger et al., 2013; Le Roux et al., 2013). As the Ñirihuau basin was surrounded by emerged areas on its eastern side, it evolved as a restricted marine embayment that must have had connection with the Pacific Ocean on its western side during the Early Miocene.

The nature and location of the necessary marine connections on the western side of the Ñirihuau basin are difficult to constrain because of the tectonic uplift of basement blocks and the erosion of

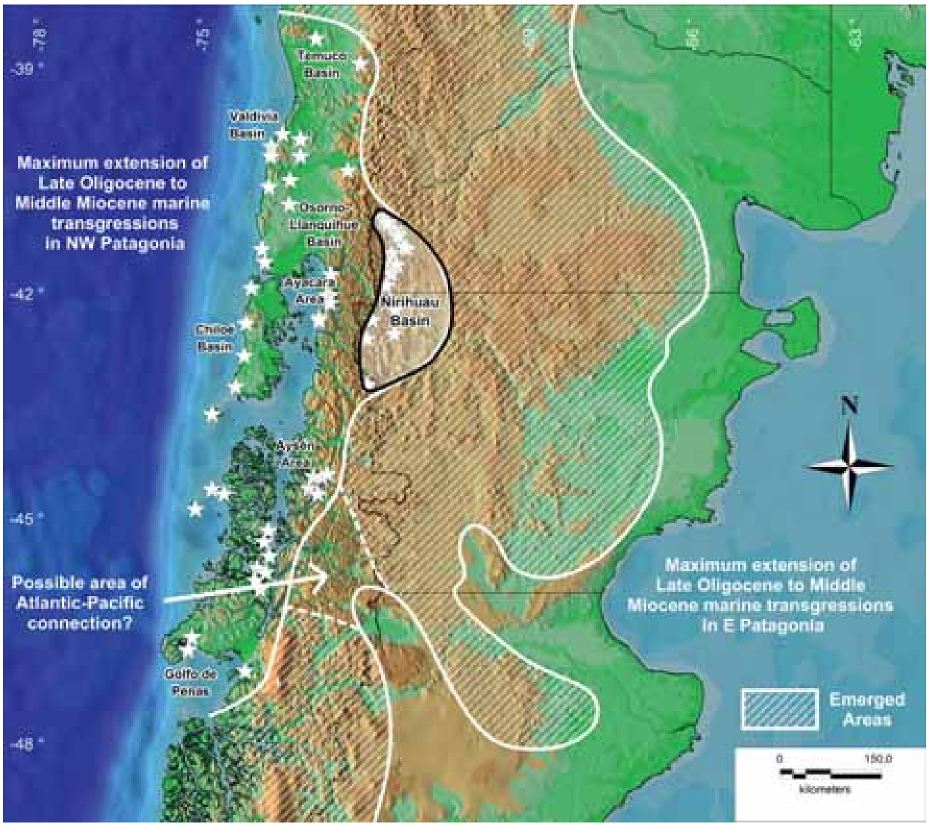

Fig. 13. Paleogeographic map showing the areal extension of the Late Oligocene to Middle Miocene marine transgressions of central and northern Patagonia (modified from Uliana and Biddle, 1988; Malumián and Náñez, 2011; Le Roux, 2012). White stars mark the location of outcrops with Lower to Middle Miocene marine beds in northwestern Patagonia, after an up-to-date compilation of previous works. A possible marine connection during the Late Oligocene? to Early Miocene between the Atlantic and Pacific Oceans in the Lago Buenos Aires – General Carreras area is proposed.

the Meso-Cenozoic cover units that took place during the Middle Miocene to Pliocene in the main North Patagonian Andes, which gave way to the exhumation of the North Patagonian Batholith (Adriasola et al., 2005; Thomson, 2002; Thomson et al., 2001, 2010). As we settled in the previous section, the marine strata intercalated in the Ventana Formation constrained as earliest Miocene in age probably register the first marine transgressions in the area, favored by a thinned crust below the Maitén belt. The areal distribution of these marine strata follows the marked NW trend of the volcanic belt in its northern sector, and the westernmost marine localities were found in the western border of Lago Nahuel Huapi (Figs. 1 and 2; González Díaz, 1979). These characteristics suggest a possible connection with the Osorno-Llanquihue basin between 40°30′ and 41°S, near the Oligocene-Miocene boundary (Figs. 12 and 13). Further south, Cenozoic marine deposits in the western border of the cordillera assigned to the Ayacara Formation crop out at 42°S facing the El Bolsón depocenter on its western side. This unit gave maximum sedimentation ages between 21 and 17.5 Ma by U–Pb dating of detrital zircons from intercalated sandstones (Encinas et al., 2012a), and an Ar–Ar age of 16.5 ± 0.5 Ma obtained for a tuff intercalated near the top of the Caleta Ayacara section (Rojas et al., 1994). These data indicate an Early Miocene age for the unit, being strongly consistent with the present constraints of the Río Foyel and Troncoso Formations, suggesting a probable connection with the El Bolsón depocenter (Fig. 12).

On the other hand, paleontologists persistently remark the great affinity of the mega- and microfossils identified in the Ñirihuau and other coeval basins of northwestern Patagonia with the forms described for the marine beds near the Atlantic coast of Patagonia in the Austral and Golfo San Jorge basins, so an inter-oceanic connection cannot be discarded (Camacho, 1967; Bertels, 1980; Griffin et al., 2002; Barreda et al., 2003; Casadío et al., 2004; Nielsen, 2005). The currently available data indicate that the Ñirihuau basin was surrounded by emerged areas to the north, east and south, and that marine connections would have taken place most likely with marine basins located in the Pacific side. Therefore, an inter-oceanic connection, if existed, was probably located in other sector of Patagonia. Marine strata assigned to the Traiguén Formation constrained by U–Pb analysis on detrital zircons as younger than 26 to 23 Ma were reported between 44°30′S and 46°S in the Pacific side of the Patagonian Andes (Hervé et al., 1995, 2001; Riffo et al., 2013). These forearc localities are the closest to the marine embayment of Atlantic origin, which reached the innermost sectors of Patagonia during the Early Miocene (Fig. 13; Malumián and Náñez, 2011). In the eastern side of the Patagonian Andes, Upper Oligocene to Lower Miocene marine beds of the Centinela and Guadal Formations crop out near Lago Buenos Aires – General Carreras at 46°S (Fig. 13; Ramos, 1982b; Frassinetti and Covacevich, 1999; Escosteguy et al., 2002). A possible connection between the Atlantic and Pacific Oceans near this latitude was proposed by several authors (Uliana and Biddle, 1988; Le Roux, 2012), and implies that the main phase of mountain uplift in the eastern sector of the Andes at this latitude should have occurred after the inter-oceanic marine connection. Fission-track data indicate that the maximum denudation and uplift in the Main Patagonian Andes north of the Chile Triple Junction and near the present-day main topographic divide occurred between 12 and 8 Ma (Thomson et al., 2001). This is in agreement with stable isotope analysis that indicate that more than 1 km of surface uplift occurred between ca. 17 and 14 Ma (Blisniuk et al., 2005), and with structural data indicating a major contractional phase leading to the development of the main thrust front in the area between 15 and 10–9 Ma (Lagabrielle et al., 2004). Thus, the marine connection near 46°S, if existed, must have occurred during the latest Oligocene to Early Miocene.

8. Conclusions

We have analyzed and discussed the current controversial issues related to the age, correlation, tectonic setting and paleogeographic links of the Cenozoic fossiliferous marine strata that crop out in the eastern sector of the North Patagonian Andes between 41° and 43°S based on new field (detailed geologic and structural mapping), geochronological (U–Pb LA-ICPMS analyses in zircons) and biostratigraphic (calcareous nannofossils studies) data.

The marine strata form part of the volcano-sedimentary infill of several depocenters included in the Ñirihuau basin. We reviewed classic and new localities in the Ñirihuau and El Bolsón depocenters, where most of the stratigraphic units were defined and where the best outcrops of the marine successions are found. The basin infill is represented by the Nahuel Huapi and El Foyel Groups, defined in the Ñirihuau and El Bolsón depocenters, respectively. Our new constrains point out a Miocene age for most of the El Foyel Group, being much younger than previously thought. Based on these data, there is no doubt that deposition of the El Foyel Group was coeval with the upper section of the Nahuel Huapi Group during the Miocene, and it does not represent a previous tectono-sedimentary cycle, as previously considered.

The main marine deposits recognized in the area correspond to the upper section of the Ventana Formation in the Ñirihuau depocenter, and the Río Foyel Formation and the lower section of the Troncoso Formation in the El Bolsón depocenter. We constrained the age of the marine beds between 23 and 19 Ma in the case of the Ventana Formation, and between 22 and 16 Ma in the case of the Foyel and Troncoso Formations. These data indicate that most of the marine sedimentation took place during the Early Miocene interval (23–16 Ma, Aquitanian to Burdigalian) and that it was probably synchronous in both depocenters, suggesting that they were connected during the marine transgression. In addition, strata of the middle member of the Ñirihuau Formation and the Salto del Macho Formation have been interpreted by previous workers as deposited in marginal-marine environments. As the age of the last unit is younger than 16 Ma, the marine influence in the area could have lasted until the Middle Miocene.

Based on an integration of our new data with previous works, we interpret that the marine transgressions registered in the Ñirihuau basin were related to a regional extensional tectonic stage that took place during the Oligocene to Early Miocene. The ingression of the sea occurred before the main contractional phase that gave place to the uplift of this Andean segment, which started most likely by the end of the Early Miocene. The marine influence probably lasted until the early stages of the fold and thrust belt development.

According to recent paleogeographic reconstructions, the marine strata identified in the Ñirihuau basin can be correlated with one or more pulses of a major transgression that inundated a wide area of Patagonia between the Late Oligocene and the Middle Miocene. Considering the currently available data, a direct link of the Ñirihuau basin with the Atlantic Ocean on its northern, eastern or southern sides is unlikely. Marine connections would have taken place most likely with marine basins located in the Pacific side, in particular with the Osorno-Llanquihue basin and its probable extension to the south, in the Ayacara area.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jsames.2014.02.003.

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