A Toarcian retro-arc basin of Central Patagonia (Chubut), Argentina: Middle Jurassic closure, arc migration and tectonic setting

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ABSTRACT

The Chubut Basin (new name for the 'Liassic Western Chubut Basin' of other authors), developed during the Early Jurassic in the western part of central extra-Andean Patagonia in Argentina (42º30'S and 44º30'S), accumulated shallow marine and continental sedimentary beds, with pyroclastic input, of the Osta Arena Formation and equivalent units. To the west it was bounded by a coeval subduction-related magmatic arc (Subcordilleran Plutonic Belt) and a subduction complex of Late Triassic-Early Jurassic age (Chonos Metamorphic Complex). In turn, the eastern basin floor developed over the remnants of a previous Late Triassic-earliest Jurassic magmatic arc (Batholith of Central Patagonia) and over neopaleozoic sedimentary rocks of an accretionary prism. To the east, the basin was limited by a Toarcian volcanic system associated to the Karroo plume. The western magmatic arc continued to the north, where it is represented by the Icalma Member of the Nacientes del Biobío Formation, bounding this time the Neuquén Basin developed to the east. The closure of the Toarcian basin in the Middle Jurassic coincides in time with a migration to the southwest of the Toarcian magmatic arc, from a position in central extra-Andean Patagonia and a NNW orientation, to a location in the Patagonian Cordillera and a north-south orientation. Synchronously, rift-related anatectic silicic volcanism developed east of the basin. Hence, a major change in tectonic setting took place during the Middle Jurassic. It is here proposed that the migration of the arc was related to the growth of a plume under north-eastern Patagonia.

Key words: Retro-arc basin, Subduction, Plume, Patagonia, Argentina.

RESUMEN

Cuenca de retroarco toarciana en Patagonia central (Chubut), Argentina: cierre, migración del arco y ambiente tectónico durante el Jurásico Medio. La Cuenca de Chubut (nuevo nombre para la 'Cuenca Liásica de Chubut Occidental' de otros autores), desarrollada durante el Jurásico Inferior en la parte occidental de la región extra-Andina de la Patagonia central, en Argentina (42º30'S y 44º30'S), acumuló sedimentos continentales y de mar somero, con aporte piroclástico, de la Formación Osta Arena y unidades equivalentes. Esta cuenca estuvo limitada al oeste por un arco magmático (Faja Plutónica Subcordillerana) y un complejo de subducción del Triásico tardío-Jurásico temprano (Complejo Metamórfico Los Chonos). A su vez, la parte oriental del fondo de la cuenca se desarrolló sobre un arco remanente de edad triásica superior-jurásica inferior (Batolito de Patagonia Central) y sobre las sedimentitas neopaleozoicas de un prisma de acreción. Hacia el este, la cuenca estaba limitada por un sistema volcánico toarciano asociado a la pluma de Karroo (Formación Marifil). El arco continuaba hacia el norte, donde está representado por el Miembro Icalma de la Formación Nacientes del Biobío, que bordeaba por el oeste a la Cuenca de Neuquén. El cierre de la Cuenca de Chubut ocurrió durante el Jurásico Medio y coincide en el tiempo con una brusca migración al suroeste del arco magmático toarciano, desde una posición en la Patagonia central extra-Andina, con una orientación NNW, a una ubicación en la Cordillera Patagónica con una orientación norte-sur. Sincrónicamente, se desarrolló volcanismo silícico anatéctico asociado a tectonismo extensional al este del arco. En consecuencia, durante el Jurásico Medio hubo un cambio tectónico mayor en la región patagónica. Se propone que la migración del arco estuvo relacionada con el crecimiento de una 'pluma' bajo Patagonia nororiental.

Palabras claves: Cuenca de retroarco, Subducción, 'Pluma', Patagonia, Argentina.

INTRODUCTION

This article aims to provide a paleogeographic and tectonic framework of central and northern Patagonia during the Early-Middle Jurassic. It is a review paper with local observations of the authors. One of the main elements in this work is the Early Jurassic evolution of a major basin (the 'Liassic Western Chubut Basin') during the early development of a subduction-related magmatic arc. Evidence for the presence of a previously little known Middle Jurassic tectonic phase in the region is given, mainly based on new field observations of the Early Jurassic Osta Arena Formation of Loncopán, Aldea Apeleg and Cerro Ferrarroti, in western Chubut Province, Argentina (Fig. 1).

Lower Jurassic marine sedimentary rocks in Patagonia are mainly restricted to the early deposits of the Neuquén Basin, a Meso-Cenozoic rift to back-arc basin developed in Chile and Argentina, extending from approximately 40º-41ºS to 31ºS. Between 34º and 37ºS the Neuquén Basin is restricted to the Andean Cordillera as a narrow north-south elongated belt, whereas to the south it broadens eastwards into extra-Andean domains, forming the Neuquén Embayment (Fig. 1; Gulisano and Gutiérrez-Pleimling, 1994; Franzese and Spalletti, 2001).

Although the southern boundary of the Neuquén Basin is generally accepted to be at about latitude 40º (Digregorio *et al.* 1984; Legarreta and Gulisano, 1989) or 41ºS (see Gulisano and Gutiérrez-Pleimling, 1994), fossiliferous marine beds of Early Jurassic age are known to occur further south (from 41º00' to 46º30'S, and from 68º to 71ºW) where they accumulated in the informally named 'Liassic Western Chubut Basin' by Franchi *et al.* (1989) (Fig. 1), that herein we propose to be named the Chubut Basin.

GEOLOGICAL SETTING

Early Jurassic marine beds in the Chubut Province, Argentina, were first mentioned by Roth (*in* Feruglio, 1949). Later, in 1917 Keidel described beds of this succession but assigning them to the Late Triassic (*in* Feruglio, 1949). The latter author also mentioned the work of Piatnitzky (1933, 1936) and Wahnish de Tolosa Carral (1942 *in* Feruglio, 1949), indicating that some of the paleontologic determinations of the latter author were rectified by Leanza (1942 *in* Feruglio, 1949). Feruglio (1949, p. 78) described the Sierra de Olte Complex, exposed in the Chubut River, *ca.* 30 km northwest of Paso de Indios (43º30'S, 69º30'W), as formed by volcanic rocks, mainly at the base, overlain by sedimentary beds with basaltic intercalations, and underlying with an angular unconformity subhorizontal beds of his 'Chubutense'. In Sierra del Cerro Negro (44ºS, 69º39'W) he described an Early Jurassic succession composed of clastic sedimentary beds, with limestone intercalations, and tuffs, of marine and continental facies. Massive volcanic rocks (lavas) overlie the above succession which, in turn, underlie with an erosional unconformity the 'Chubutense' (Feruglio, 1949, p. 104). Part of the latter was defined as Chubut Group by Lesta (1968).

Groeber (1942) described a comparable succession of marine sedimentary rocks overlain by continental sedimentary and volcanic rocks. Suero (1953) also described marine Lower Jurassic sedimentary beds in this region. Subsequent studies resulted in a number of stratigraphic names for the Jurassic rocks exposed in the Chubut Province, with differences in the ages and stratigraphic position of the same units, which have not facilitated the comprehension of the Jurassic geologic history of the area (Page *et al.*, 1999).

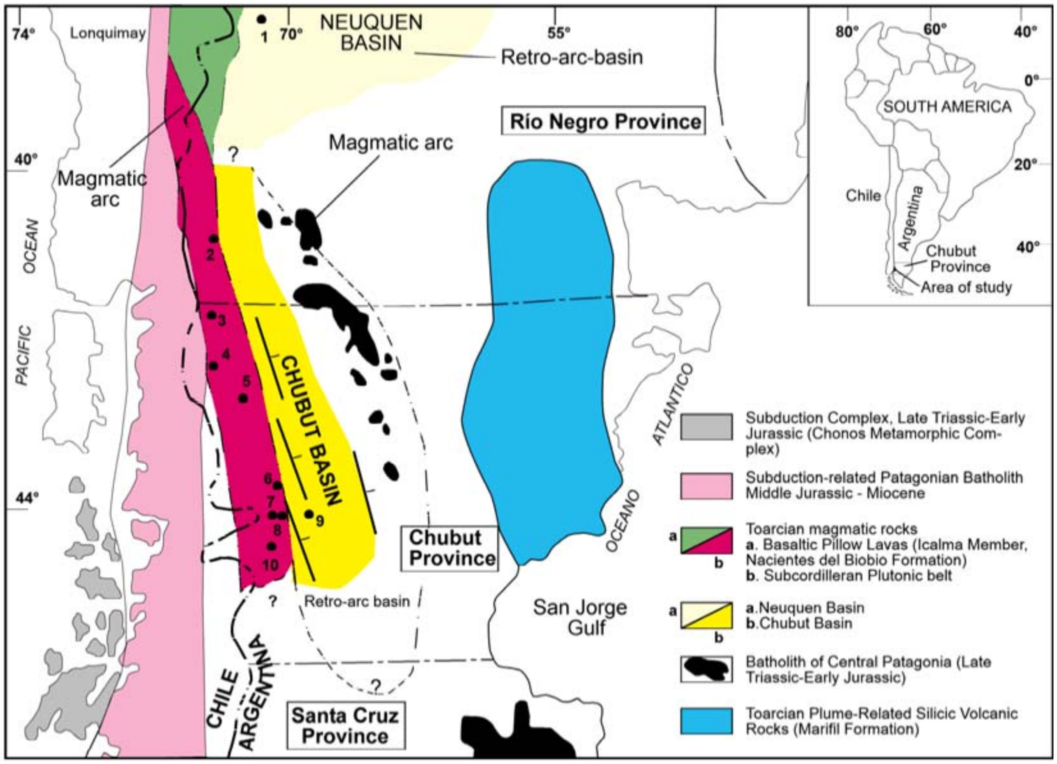

FIG. 1. Sketch geologic map of Patagonia modified after Rapela (1999), showing the southern border of the Neuquén Basin according to Gulisano, Gutiérrez Pleimling and Digregorio (1984), the known extent of the marine 'Liassic Western Chubut Basin' according to Franchi *et al.* (1989), Lizuaín (1999) and Uliana and Legarreta (1999). The outcrops of the Lower Jurassic Marifil Formation and of the Triassic-Lower Jurassic plutonic rocks are after Gust *et al.* (1985), Pankhurst *et al.* (1998) and Rapela (1999). The Subcordilleran Plutonic Belt is after Rapela (1999) and Rapela *et al.* (2003). The Chonos Metamorphic Complex, interpreted as an Upper Triassic-Lower Jurassic subduction complex, after Hervé *et al.* (1998, 2000) and Fang *et al.* (1998). Numbers indicate localities in Argentina: **1.** Cordillera del Viento, **2.** San Carlos de Bariloche, **3.** El Bolsón, **4.** Esquel, **5.** Tecka, **6.** San José de San Martín, **7.** Aldea Apeleg, **8.** Puesto Loncopán, **9.** Cerro Ferrarotti, **10.** Alto Río Senguerr.

Part of the Early Jurassic beds were included in the Osta Arena Formation (Herbst, 1966). Herbst (1966) indicates that this formation was first recognized by Piatnitzky (1933, 1936) and Feruglio (1949), and stratigraphic sections published by these authors were used in its definition (*in* Nullo, 1983). This unit unconformably overlies Carboniferous-Permian rocks (Río Genoa and Tepuel groups; Lesta and Ferello, 1972) in the northern Precordillera of Chubut Province, Argentina, whereas, in other localities overlies and interdigitates with the El Córdoba Formation (Robbiano, 1971), an association of Lower Jurassic clastic sedimentary and volcanic rocks (Nullo, 1983). The Osta Arena Formation is composed of conglomerates, tuffaceous sandstones, subordinate limestones (Ploszkiewicz, 1987), and tuffs, with marine fossils assigned to the Toarcian (Mussachio and Riccardi, 1971; Blasco *et al.,* 1979)(Fig. 2).

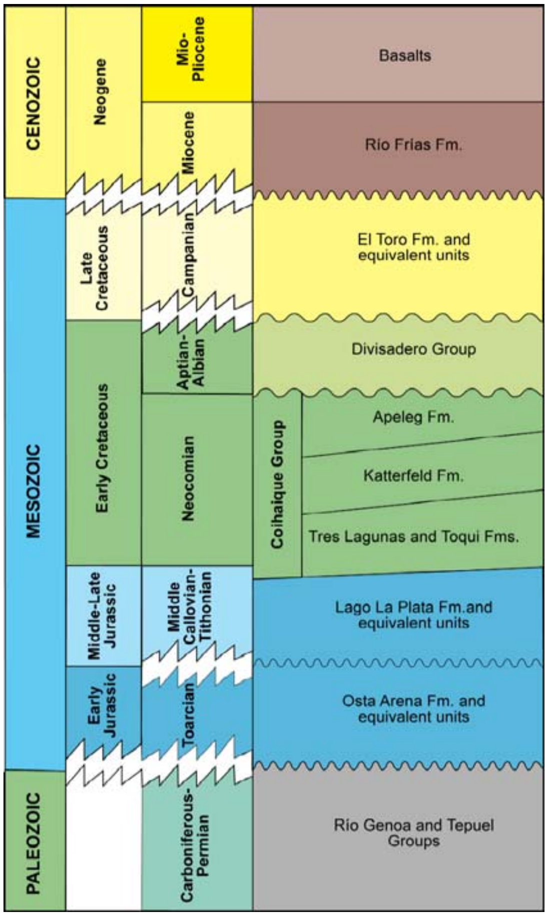

FIG. 2. Stratigraphic scheme of Meso-Cenozoic units of the central Patagonian Cordillera.

It was preceded by Upper Triassic-early Lower Jurassic plutonic rocks ('Batholith of Central Patagonia', Rapela and Pankhurst, 1992, 1996) that form a narrow northwest-southeast belt obliquely crossing northern and central Patagonia from latitude 40ºS to almost latitude 44ºS, and probably reaching close to the Atlantic coast at *ca*. 46ºS.

Volcanism continued with the Early to Late Jurassic Chon Aike Province, that covers a wide area of Patagonia, from approximately 40ºS to 55ºS, and constitutes one of the world's most voluminous volcanic silicic provinces (Kay *et al*., 1989; Pankhurst *et al.* 1998, 2000; Riley and Leat, 1999; Riley *et al.,* 2001). Volcanism spanned more than 30 Ma, but based on SHRIMP U-Pb zircon, Rb-Sr whole-rock and $^{40}Ar/^{39}Ar$ data, three episodes of peak activity have been recognized (Feraud *et al.,* 1999; Pankhurst *et al.,* 2000): a Toarcian-Aalenian episode, between 188-178 Ma, a Bajocian-Bathonian episode, between 172 and 162 Ma and an Oxfordian-Kimmeridgian episode, between 157 and 153 Ma. This information agrees with data by other authors working both in Argentina and Chile. However, in Chile, the final stages of this volcanism, represented by the Ibáñez Formation, have proven to be diachronous from Tithonian up to the Berriasian, based on ammonite-bearing strata (Covacevich *et al.,* 1994; De la Cruz *et al.,* 1996; Suárez *et al.,* 1996), Berriasian biotite K-Ar dates (Suárez and De la Cruz, 1997a, b), Valanginian U-Pb SHRIMP ages (Pankhurst *et al.*, 2003), and recently by Hauterivian SHRIMP U-Pb dates (M. Suárez, M. Fanning, R. De la Cruz, unpublished data).

To the north of latitude 40º-41ºS, a mayor basin, known as the Neuquén Basin, started to develop in late Triassic-earliest Jurassic times, with a series of fault bounded depressions (Howell *et al.*, 2005). These depocenters became progressively interconnected, and were integrated into an extensive area of marine sedimentation in Pliensbachian times (Digregorio *et al.,* 1984; Legarreta *et al.,* 1993; Gulisano and Gutiérrez-Pleimling, 1994). During Late Triassic and Early Jurassic deposition in the Neuquén Basin was characterized by sandstones and conglomerates, and also by pyroclastic deposits and lavas. These deposits accumulated both as subaerial tuffs and alluvial, fluvial and lacustrine sediments (Lapa and Chacaico Formation and equivalent units; Gulisano *et al.,* 1984; Kokogian *et al.* 1999), and as shallow marine sandstones, shales, tuffites and tuffs ('Unnamed Unit' of Gulisano and Gutiérrez-Pleimling, 1994; 'Cerro La Primavera unit', Suárez and De la Cruz, 1997c), deposited above silicic ignimbrites and domes of the Choiyoi Group in the area of Cordillera del Viento, in the Argentina (*ca*. 37º15'S). In this latter area, bimodal magmatism took place during the Toarcian. Here marine deposits include rhyolitic tuffs and basaltic peperites, which have been interpreted as littoral calderas developed in an extensional tectonic setting (Suárez and De la Cruz, 1997c).

In southernmost South America (southern Chile and Argentina) and at a younger period, another basin, known as the Austral Basin, developed throughout a wide area of present day Patagonia. The transgressive facies diachronically covered during the Tithonian to Valanginian previously formed volcanic successions (Ibáñez Formation and equivalent units) (Natland *et al.,* 1974; Riccardi and Rolleri, 1980; Riccardi, 1987;

Riccardi, 1988; Niemeyer *et al.* 1984; Biddle *et al.,* 1986; Ploszkiewcz, 1987; De la Cruz *et al.* 1996, 2003; Suárez *et al.,* 1996, 2005). In the area of this study, in central Patagonia, the sedimentary rocks accumulated during the initial stages of the Austral Basin constitute the Coihaique Group, which is formed, from base to top, by the Tres Lagunas, Katterfeld and Apeleg formations (Fig. 2; *e.g*., Ramos, 1981; Ploszkiewicz, 1987). In Chile, the lowermost unit has been referred to as the Toqui Formation (De la Cruz *et al.,* 1996, 2003; Suárez *et al.,* 1996). No major unconformity exists within the Coihaique Group and between the Ibáñez and Toqui formations.

The Coihaique Group, in turn, is overlain by the Divisadero Group, a thick succession of subaerial volcanic rocks of Aptian-Albian age, in turn overlain by Upper Cretaceous volcanic rocks (Niemeyer *et al.,* 1984; Suárez *et al.,* 1996; De la Cruz *et al.,* 2003; Pankhurst *et al.*, 2003; Demant *et al.*, 2007). The Cenozoic record in the area of this study includes basalts of Late Paleocene-Eocene, Miocene, Pliocene and Quaternary ages, and tuffaceous beds of the Miocene Río Frías Formation (Ramos, 1981; Ploszkiewicz, 1987; Marshall and Salinas, 1990; Prieto and Cortés[1]).

GEOTECTONIC SETTING DURING THE LIAS

A complete Andean-type arc trench system can be identified in central Patagonian Cordillera during the Late Triassic-Early Jurassic. Although in the geological record this is unusual, the following tectonic elements identified from west to east, for this period, supports the latter (Fig. 1):

CHONOS METAMORPHIC COMPLEX: AN UPPER TRIASSIC-LOWER JURASSIC SUBDUCTION COMPLEX

Along the westernmost part of Patagonia, between latitudes 44º and 47ºS, the Upper Triassic-Lower Jurassic Chonos Metamorphic Complex (Fig. 1), has been interpreted as a subduction complex (Hervé, 1993; Hervé *et al.,* 1998; Fang *et al.,* 1998; Hervé *et al*., 2000), implying the existence of a coeval and related magmatic arc to the east. Therefore, a subduction system was already active along western northern and central Patagonia during the latest Triassic-earliest Jurassic and probably continued in the Lias.

THE ICALMA PILLOW BASALTS AND SUBCORDILLERAN PLUTONIC BELT: TOARCIAN SUBDUCTION-RELATED MAGMATISM

An Early Jurassic magmatic arc is represented by the 'Subcordilleran Plutonic Belt' (Rapela *et al.,* 2003)('Subcordilleran Plutonism of Río Negro and Chubut' or 'Subcordilleran Patagonian Batholith', Rapela, 1999; Giacosa and Márquez, 1999) (Fig.1). The 'Subcordilleran Plutonic Belt' includes Upper Triassic-Lower Jurassic calcalkaline granitoids exposed in the area of San José de San Martín, in Chubut (*ca*. 44º20'S; Busteros *et al.,* 1996), and Lower and Middle Jurassic plutonic rocks, exposed in the southwestern part of the Río Negro Province and northeastern part of the Chubut province (between latitudes 41º-42º30'S; Gordon and Ort, 1996; Giacosa and Márquez, 1999; Rapela, 1999). Recently, U-Pb zircon ages of *ca*. 185 Ma have been obtained from rocks of this belt, thus confirming its mainly Toarcian age (Rapela *et al.,* 2003). These authors also indicate that the petrology and geochemistry of rocks of this belt clearly identifies them as subduction-related volcanic arc granites. It is not clear whether this plutonic belt terminates to the south at *ca.* 45ºS or continues along a south-southeast belt in subsurface.

Northwards, the Neuquén Basin was flanked to the west, in the Lonquimay area of Chile (*ca*. 38º30'S; Fig. 1), by pillow basalts (Icalma Member of the Nacientes del Biobío Formation; Suárez and Emparán, 1997) intercalated with Toarcian ammonite-bearing turbidites (Lolén-Pacunto Member of the Nacientes del Biobío Formation; De la Cruz and Suárez, 1997). The pillow lavas are tholeiitic and have an island arc geochemical signature that implies a causal relationship with an east-dipping subduction zone (REE unpublished data, S. Kay, M. Suárez, C. Emparan, R. De la Cruz). These pillow lavas can be interpreted as the relicts of a Lower Jurassic magmatic arc located along the present-day southern Andes (Fig. 1).

[1] 1995. Geología del sector oriental de la Hoja Río Cisnes (71º a 72º20'LW y 44º a 45ºLS), Región de Aisén. Informe de Avance (Inédito), *Servicio Nacional de Geología y Minería,* 50 p., 3 mapas escala 1:100.000. Santiago.

THE CHUBUT BASIN: A RETRO OR INTRA-ARC BASIN

The 'Liassic Western Chubut Basin' (Franchi *et al.,* 1989), here proposed to be named the Chubut Basin (to be discussed later), developed behind a calcalkaline magmatic arc located to the west, hence a retroarc setting may be inferred to it. However, Ramos (1983), based on the presence of volcanic intercalations in the eastern sedimentary infill of this basin, indicative of volcanic centers to the east, indicated an intra-arc setting for this basin . We favour that the magmatic arc of the Chubut Basin, represented by the 'Subcordilleran Plutonic Belt', was connected with that of the Neuquén Basin to the north, represented by the basalts of the Icalma Member, during at least the Toarcian (see below). It has been indicated that during the Early Jurassic there was no evidence of a subducted slab beneath the Neuquén Basin and that development of the Andean magmatic arc began in the Middle Jurassic (Franzese *et al.,* 2003). However, the presence of pillow lavas with an island arc geochemical signature, as indicated above, west of the Neuquén Basin, would suggest a retro-arc setting for the latter as early as the Toarcian (De la Cruz and Suárez, 1997).

BATHOLITH OF CENTRAL PATAGONIA: LATE TRIASSIC-EARLIEST JURASSIC MAGMATIC ARC; A REMNANT ARC DURING THE TOARCIAN

A belt of I-type granitoids with late Triassic-earliest Jurassic radiometric dates (*ca.* 202-220 Ma, Norian-Hettangian/Sinemurian; Rapela and Pankhurst, 1992), the Batholith of Central Patagonia, forms an oblique northwest-southeast narrow belt crossing northern Patagonia from latitude 40ºS to almost latitude 44ºS (Fig. 1; Rapela *et al.,* 1992; Rapela and Pankhurst, 1992, 1996; Franzese *et al.,* 2003). These granitoids (and rhyolites) are of calcalkaline I-type, and are inferred to have been generated in a continental magmatic arc setting, representing the roots of a volcanic arc, emplaced along the inferred northwest-southeast strike-slip Gastre Fault, and adjacent to the convergent margin of the time (Gastre Fault Zone; see Rapela and Pankhurst, 1992; Franzese *et al.,* 2003). This magmatic arc was probably extint and had migrated southeastwards along a dextral movement of the Gastre Fault by the Toarcian (see Franzese *et al.,* 2003), therefore forming, the basement to parts of the Chubut Basin.

MARIFIL FORMATION OF THE CHON AIKE PROVINCE: EARLY JURASSIC MANTLE-PLUME SILICIC VOLCANISM

During the Toarcian-Aalenian (178-188 Ma; Pankhurst *et al.,* 1998, 2000; Feraud *et al.,* 1999), the Marifil Formation, a large volume of silicic volcanic rocks forming the earliest volcanic rocks of the Chon Aike Province (Pankhurst *et al.,* 1998), developed in northeastern Patagonia (*ca.* 40º-44ºS), mainly to the east of the Chubut Basin (Fig. 1). These rocks were thus emplaced 'behind' the subduction-related arc of that time. The Marifil Formation represents the eruption of a vast volume of predominantly rhyolitic ignimbrites, and minor lavas, with within-plate affinities. They represent lower-crustal melts that have incorporated upper-crustal material (Pankhurst *et al.,* 2000). The close relationship in time and space among the Marifil Formation, volcanic rocks of the Antarctic Peninsula and the Karoo province led Pankhurst *et al.* (2000) to infer a single plume related origin for all these rocks, as was originally proposed for the Karoo volcanism by Brewer *et al.* (1992) and Cox (1992).

THE CHUBUT BASIN, AN ARC-RELATED BASIN

THE BASIN

Marine and continental sedimentary deposits of Early Jurassic age, mainly exposed in the western region of the Chubut Province and center-north Santa Cruz Province, and extending northwards into the Río Negro Province, of Argentina (from 41º00' to 46º30'S, and from 68º to 71ºW) have been informally included in the 'Liassic Western Chubut Basin', a narrow NNW-SSE elongated depocenter, by Franchi *et al.* (1989; Fig. 1), herein referred to as the Chubut Basin. Between latitudes 44º40' and 45º30' S, Early Jurassic deposits have been locally inferred in the subsurface from wells (Lesta *et al.,* 1980).

The marine basin extended as far south as *ca.* 46º30'S, south of which the marine sedimentation gives way to continental deposits (Uliana and Legarreta, 1999), with exposures of a continental succession of Early Jurassic beds approximately at latitude 49ºS (Herbst, 1960).

Previously, Ugarte (1966), using in part the work of Suero (1962), postulated a marine basin, which he referred to as 'Cuenca Compuesta Carbonífero Jurásica' ('Carboniferous Jurassic Composite Basin'), that coincides with the central and southern part of the Chubut Basin, as it ended to the north approximately at latitude 42ºS, but without proposing a connection with the Neuquén Basin. Previously, Suero (1962) named as 'Geosinclinal Central Patagónico' ('Central Patagonian Geosyncline') the depocenter for neopaleozoic/liassic sedimentary deposits. The sedimentary succession of the Chubut Basin accumulated under an extensional tectonic regime (Lizuaín, 1999; Uliana and Legarreta, 1999), starting with sedimentary and volcanic continental deposits (Puntudo Alto and El Córdoba formations) overlain by shallow marine and continental sedimentary and pyroclastic successions (Osta Arena Formation, Herbst, 1966; Malumián and Ploszkiewicz, 1976; Ploszkiewicz, 1987; Lepá Formation, Turner, 1982; Mulanguiñeo Formation, Fernández Garrasino, 1977; Velázquez Formation, Turner, 1983; and equivalent units, Franchi *et al.,* 1989; Giacosa and Márquez, 1999). These marine beds interfinger with continental facies, mainly pyroclastic, to the east (Franchi *et al.,* 1989). Most parts of this basin comprise deposits that belong to the fossiliferous Toarcian Osta Arena Formation, exposed at latitude 44º40'S (the limestones of Puesto Loncopán; Malumián and Ploszkiewicz, 1976) and 44º30'S and 69º50´W (Herbst, 1966; Ploszkiewicz, 1987).

OSTA ARENA FORMATION: EARLY JURASSIC VOLCANO-SEDIMENTARY RETRO–ARC OR INTRA-ARC ASSEMBLAGES

Early Jurassic volcano-sedimentary deposits in the Chubut Basin include different formations with variable percentages of volcanic and sedimentary components. The predominantly sedimentary assemblages, with interbedded pyroclastic layers, are represented by the Osta Arena Formation (Ploszkiewicz, 1987), whereas the units mainly composed of pyroclastic beds, with subordinate lava flows and sedimentary strata, correspond to the Piltriquitrón Formation (*e.g.*, Lizuaín, 1980, 1999), exposed in the area of El Bolsón and Esquel at *ca.* 42ºS, to the Lepá Formation, exposed in the area of Tecka (*ca.* 43ºS; Turner, 1982), and to the Mulanguiñeu Formation, that crops out to the east and northeast of the study area (Fernández Garrasino, 1977).

The Osta Arena Formation comprises marine facies rich in invertebrate fossils with ammonites, bivalves and arthropods (Malumián and Ploszkiewicz, 1976)(Lomas Chatas Member), and continental facies (Cerro Ferrarotti Member) (Ploszkiewicz, 1987). The formation unconformably overlies Paleozoic beds of the Río Genoa Group.

The Osta Arena Formation is mainly formed by conglomerates, sandstones, many of them tuffaceous, shales, tuffs and subordinate limestones. Ploszkiewicz (1987) includes in this formation limestones exposed in a small and isolated low-altitude outcrop (200 m long by 50 m wide), surrounded by Holocene fluvioglacial deposits, and adjacent to the currently abandoned Puesto Loncopán, approximately 2 km to the northeast of the Aldea Apeleg (Figs. 3, 4).

The fossiliferous content of the Osta Arena Formation indicates a Toarcian age (Musacchio and Riccardi, 1971; Blasco *et al.,* 1979; Ploszkiewicz, 1987). Malumián and Ploszkiewicz (1976) described the presence of fine-grained sandstones with pelitic intercalations bearing ammonites and bivalves, some of which are indicative of a Toarcian age (*Peronoceras* sp. and *Myophorigonia* sp.), and the presence of *Gryphaea* sp. in some limestone beds.

The Osta Arena Formation at Loncopán includes recrystallised bioclastic limestones, some silicified, deformed oolitic limestones, silicified vitric tuffs, red chert, marls with pyro- and/or epiclastic detritus and a 20 cm thick stromatolite bed. This succession is inferred to represent shallow marine sedimentation synchronous with explosive volcanism. To the west and south, these rocks are surrounded by structureless andesitic breccias and tuffs (Fig. 4).

The Osta Arena Formation at Loncopán is tightly folded (Figs. 4, 5), locally with isoclinal folds, and faulted. The bedding has a general north-northwest to south-southeast trend. The anticlines and synclines have a metric wavelength and represent S and Z folds located in the limbs of bigger folds that are not exposed. Considering the geographic distribution and attitude of the secondary folds, the larger folds probably

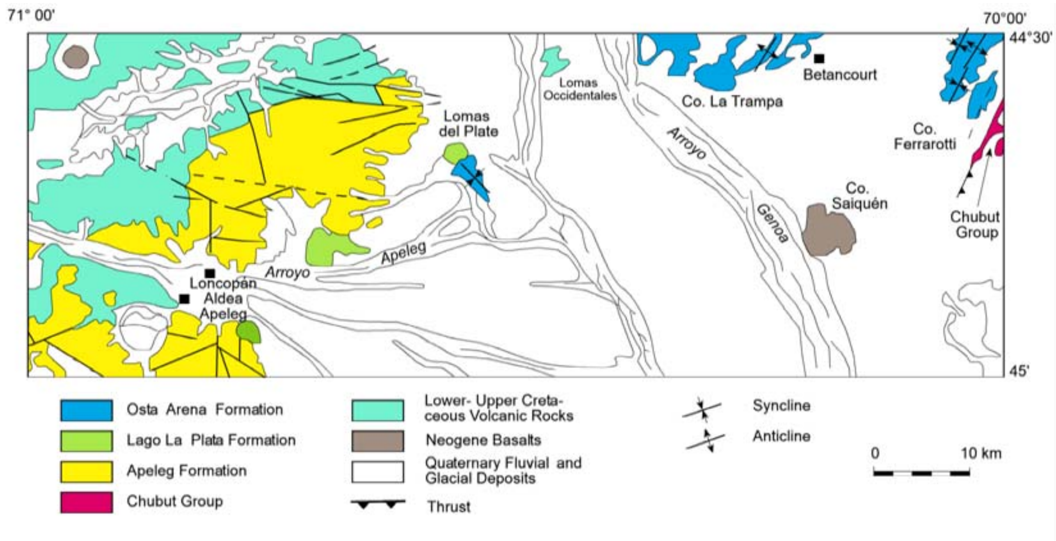

FIG. 3. Sketch map showing the distribution of the Osta Arena Formation in the area of this study, after Ploszkiewicz (1987).

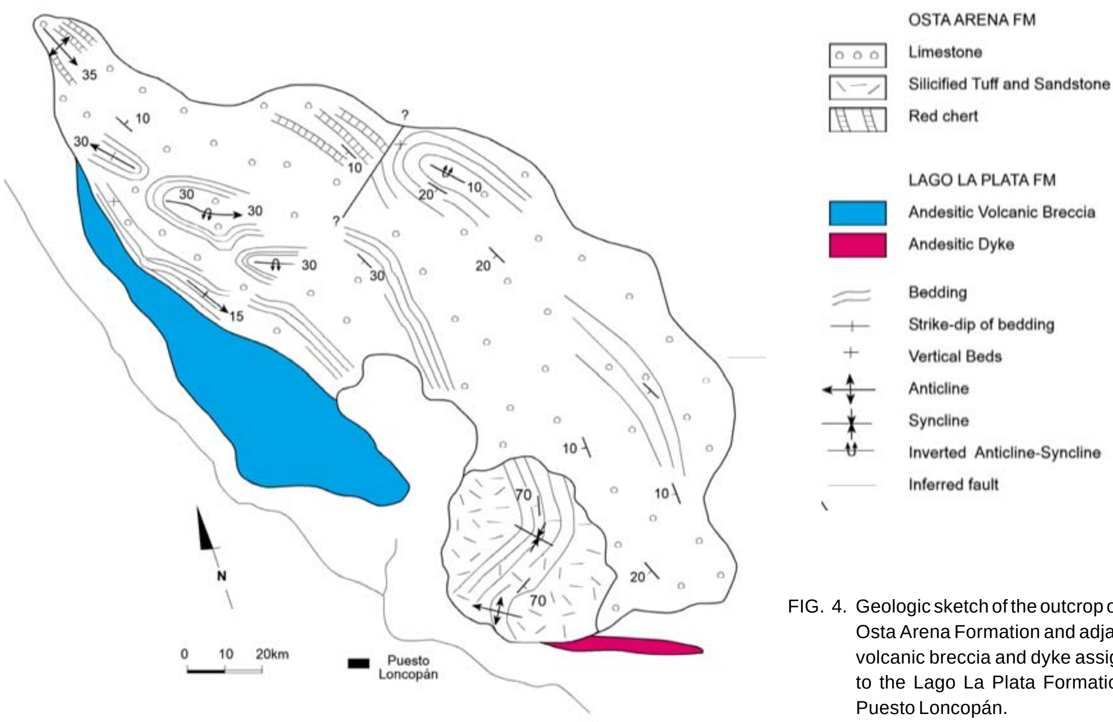

FIG. 4. Geologic sketch of the outcrop of the Osta Arena Formation and adjacent volcanic breccia and dyke assigned to the Lago La Plata Formation in Puesto Loncopán.

correspond to tight folds of tens of meters in wavelength and with subhorizontal axial planes. This folding and faulting is interpreted as of contractional tectonic origin instead of generated as a slump, based on the combination of a series of observations, which, however are not conclusive taken independently: the subparallel NNW-trend of most of the fold axes, the fact that all the exposed rocks are folded and faulted, irrerspective of lithology, and the observation that coeval beds of the Cerro Ferrarotti Member, approximately 50 km to the east, also exhibit tight folding with

FIG. 5. Folded limestone of the Osta Arena Formation, Puesto Loncopán exposure.

approximately north-south axes.

The adjacent volcanic rocks show no internal structures, and comprise andesitic volcanic breccias, and coherent pyroxene andesites that either represent lava flows or dykes. Andesitic and doleritic dykes, the former petrographically comparable to the andesitic breccias and hence, probably consanguineous, cut the folded beds. On the southwestern outcrops of the Osta Arena Formation, a north-south trending swarm of three narrow (2-10 cm wide) vertical dolerite dikes cross cut limestones generating contact metamorphism with the growth of garnet.

These volcanic rocks do not show the tight folding and faulting of the Osta Arena Formation and, hence, an unconformity must separate them, as suggested previously (*e.g.* Ploszkiewicz, 1987; Barcat *et al.,* 1989; Scasso, 1989). The geographic distribution of the volcanic rocks suggest that they were deposited above a paleotopographic high of Osta Arena Formation. The volcanic beds have been tentatively assigned to the La Plata Formation (Malumián and Ploszkiewicz, 1976), an assumption that may be correct, although no conclusive data has been obtained to support this inference.

To the north (1 km) and south (3 km) of the Osta Arena Formation at Loncopán, gently-dipping beds of the Lower Cretaceous Apeleg Formation crop out, without exhibiting the tight folding of the Osta Arena Formation (Fig. 6). The structural style of the Apeleg Formation is the same as that of the underlying Upper Jurassic to Lower Cretaceous units (Katterfeld, Tres Lagunas and Toqui formations, and Lago La Plata and Ibáñez formations). This corroborates other studies (Ramos, 1981; Ploszkiewicz, 1987; Bell and Suárez, 1997; De la Cruz *et al.*, 2003) that indicate that no major contractional tectonic phase took place during the time of the deposition of the Lago La Plata or Ibáñez Formation and Coihaique Group. Hence, the tight folding and faulting of the beds of Puesto Loncopán occurred prior to the deposition of the Middle-Upper Jurassic Lago La Plata Formation.

A continental facies association of the Osta Arena Formation is represented by the Cerro Ferrarotti Member exposed on the eastern part of figure 2 (Ploszkiewicz, 1987). It is composed of sandstones, many showing cross bedding, tuffaceous sandstones, tuffs and minor intercalations of thinly-bedded (20 cm thick) limestones. These rocks are tightly folded with disharmonic folds with south-southwesterly plunging axes (see Ploszkiewicz, 1987). This deformation ends abruptly to the east where this author describes a tectonic contact with a homoclinal succession of the Cretaceous Chubut Group that do not show the same intense folding. This is a reverse fault system over 100 km in length, that puts the Cretaceous rocks over Cenozoic rocks and is one of the main structures related with Miocene tectonism. Therefore, the tight folding and thrusting present in the Cerro Ferrarotti member stands out as apparently being peculiar to the Toarcian beds.

Tight anticlines and synclines with an approximate north-south trend and occasional plunging axes, in the Early Jurassic sedimentary and tuffaceous rocks exposed in the area between Puesto Loncopán and Cerro Ferrarotti have been indicated by several authors (Keidel,1920; Feruglio, 1949; Ugarte, 1966). This tight folding has also been identified in the area of Lomas de Altamirano (44º16'S-70º25'W), Cerro Salazar (44º12'S-70º17'W), Lomas Chatas (44º16'S-70º16'W) and Piedra Shotle (44º23'S-70º24'W) (Ugarte, 1966). In the eastern flank of Cordón Esquel (42º49'S-71º12'W), the Liassic succession is folded and faulted and unconformably underlies mesosilicic volcanic rocks of Jurassic and/or Cretaceous age (Márquez, 2003; Márquez *et al.,* in press).

Further north, Early Jurassic volcanosedimentary rocks in the area of El Bolsón (Provincia de Río Negro) and El Hoyo (42º10'S-71º24'W, Provincia de Chubut) are strongly deformed with disharmonic folds, with north-south oriented larger folds and secondary folds trending to the north-west (M. Tabacchi[2]; Márquez *et al.,* in press). In the latter case, the folded Liassic beds experienced a post-tectonic thermal metamorphism related to the emplacement of Jurassic and/or Cretaceous plutons, that supports the existence of a previous compressive deformation.

However, the Early Jurassic beds exposed in the region exhibit a heterogeneous deformation style, with outcrops such as those exposed in the area of Genoa, Tepuel and Tecka showing only open folding. Therefore, intense tectonism represents localized shear zones.

The Toarcian shallow marine beds of the Osta Arena Formation, accumulated in the Chubut Basin, include pyroclastic deposits indicative of synmagmatic accumulation. They crop out to the east of a belt of mainly Toarcian calcalkaline plutonic rocks of the Subcordilleran Plutonic Belt (Busteros *et al.*, 1996; Giacosa and Márquez, 1999; Rapela *et al.,* 2003). In turn, they interfingerr with volcanic rocks to the east, thus indicating an intra-arc setting for it (Ramos, 1983).

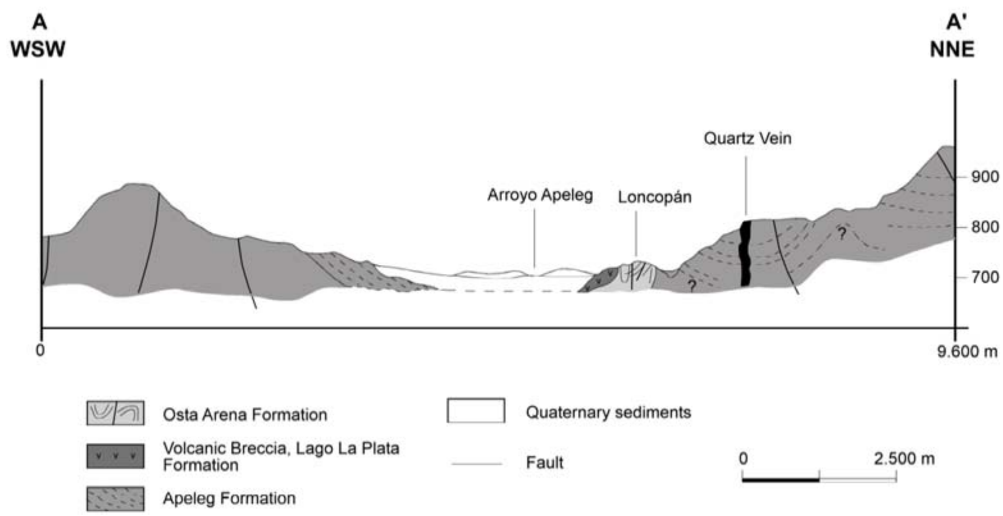

FIG. 6. Cross-section from the Puesto Loncopán area.

LATE BAJOCIAN-CALLOVIAN CONTRACTIONAL TECTONISM IN WESTERN CHUBUT

The structural style exhibited by the Osta Arena Formation exposed in Puesto Loncopán and in Cerro Ferrarotti, with tight folding (Figs. 4, 5) and faulting, contrasts with the 'mid-Cretaceous' and Cenozoic weak folding shown by the Middle-Late Jurassic and Cretaceous formations exposed in the same area. Previous authors have given

[2]1953. Estudio geológico-minero del yacimiento cuprífero Condorcanqui . Departamento Cushamen, Chubut (Inpublished). *Dirección General de Fabricaciones Militares.* Buenos Aires, Argentina.

information on this tectonic event. Keidel (1920) indicated the complexity and intensity of the deformation of the Paleozoic and Mesozoic rocks that underlie the 'beds with dinosaurs' (Chubut Group of Late Cretaceous age) in the extra-Andean region of the Chubut Province. By doing this, Keidel (1920) was the first to identify a compressive tectonic phase prior to the deposition of the Chubut Group. Feruglio (1949) indicates for the area of Cerro Ferrarotti an erosional unconformity separating the intensely folded Paleozoic and Early Jurassic rocks from Middle Jurassic volcanic rocks later to be assigned to the Lago La Plata Formation. This unconformity was later reported by Fernández Garrasino (1977) from an area few kilometres north of Cerro Ferrarotti. Ugarte (1966) indicates that the Chubut Group unconformably overlies Jurassic beds. This author recognized the existence of an inter-Malm tectonism generating an important uplift west of the Chubut Basin.

The presence of a well marked angular unconformity between the Toarcian limestones of the Osta Arena Formation and the Middle-Upper Jurassic volcanic rocks of the Lago La Plata Formation, represents an important contractional (or transpressional?) tectonic phase sometime during the intervening period. Also during the Middle Jurassic the Toarcian magmatic arc, that had a NNW orientation, ceased and the subsequent magmatic arc was emplaced further to the southwest (Rapela *et al.*, 2003) and is identified in the Patagonian Cordillera, forming part of the Patagonian Batholith, with a north-south orientation, during the Late Jurassic (Suárez and De la Cruz, 2001). Hence, a major tectonism occurred during the Middle Jurassic with the closure of the Chubut Basin and the abrupt migration of the magmatic arc from a northeastern position to a southwestern location.

CONCLUSIONS

When the central part of Patagonia is considered (42-46ºS), a magmatic arc (Central Patagonian Batholith)-subduction complex (Chonos Metamorphic Complex) system existed during the late Triassic-earliest Jurassic. Consequently, the Toarcian Chubut Basin developed in the former forearc region of the Upper Triassic-early Lower Jurassic magmatic arc. Hence, the Central Patagonian Batholith represents a remnant arc during the development of the Chubut Basin.

Toarcian shallow marine debs of the Osta Arena Formation, deposited in the Chubut Basin (42º30´and 44º30´S; Franchi *et al.,* 1989), include interbedded pyroclastic deposits indicative of volcanic activity. They crop out to the east of a belt of mainly Toarcian calcalkaline plutonic rocks of the Subcordilleran Plutonic Belt (Busteros *et al.,* 1996; Giacosa and Márquez, 1999; Rapela *et al.,* 2003). This magmatic arc continues to the north along the Toarcian arc-related basalts of the Icalma Formation of the Nacientes del Biobío Group, that represents the magmatic arc west of the Neuquén Basin (De la Cruz and Suárez, 1997; Suárez and Emparan, 1997). In turn, to the west of this Early Jurassic magmatic arc, a subduction complex, the continuation in time of the Upper Triassic-Lower Jurassic Chonos accretionary complex (Fang *et al.,* 1998), is inferred to have existed. Therefore, the Early Jurassic magmatic arc was genetically associated to an easterly dipping subduction zone developed to the west (Fig. 7). The sedimentary deposits accumulated in the Chubut Basin interfingered with volcanic rocks to the east allowing the interpretation of an intra-arc setting for it (Ramos, 1983). However, further east, this basin was bounded by coeval subaerial silicic volcanic rocks of the Marifil Formation, interpreted as originated by cortical fusion related to the existence of a mantle plume (*e.g.,* Pankhurst *et al.,* 2000). Therefore, in the absence of geochemical work, it is not clear whether the interfingering volcanic rocks to the east of the Osta Arena Formation represent subduction-related rocks, in which case the Chubut Basin was an intra-arc basin, or are part of the plume-related volcanic rocks, in which case it represents a retro-arc basin.

Intense folding and faulting of Early Jurassic sedimentary and volcaniclastic beds is a common feature in the Patagonian Precordillera and Bernardides (*e.g*., Keidel, 1920; Feruglio, 1949), that, although identified by several authors has not been stressed before in the literature. It represents an important contractional tectonic episode that, according to the exposed evidences would have taken place during the Middle Jurassic. Intense deformation has been observed in the Toarcian beds of the Osta Arena Formation, deposited in the Chubut Basin and

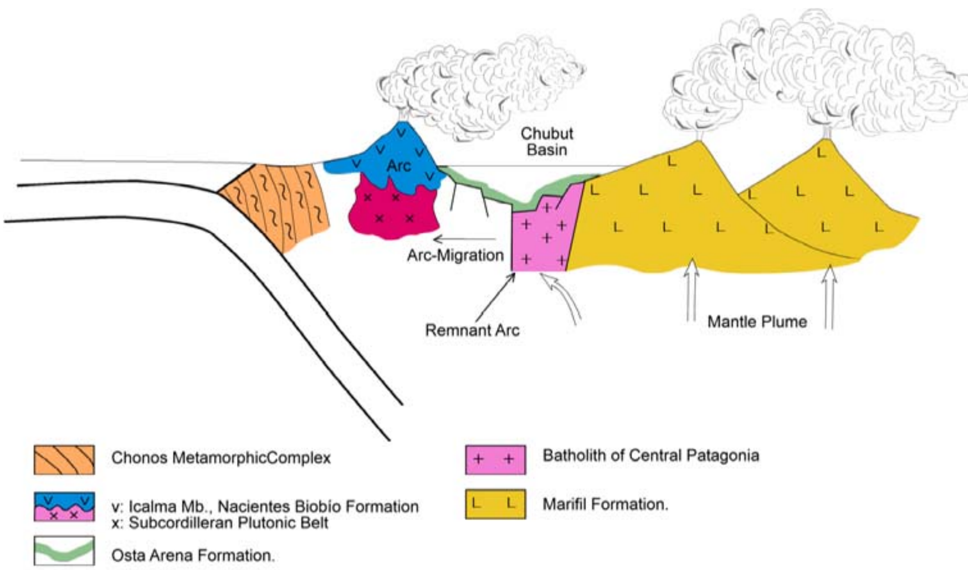

FIG. 7. Schematic interpretative tectonic setting of central Patagonia during the Toarcian.

exposed in the area of Puesto Loncopán, Chubut Province, Argentinian Patagonia. The overlying andesitic breccias assigned to the La Plata Formation and the overlying successions of the Katterfeld and Apeleg formations were not affected by this tectonism, indicating that this tectonic phase took place during the Middle Jurassic. Approximately 50 km to the east, in the area of Cerro Ferrarotti, Early Jurassic beds exhibit a comparable tight folding, probably of the same age, contrasting with the homoclinal attitude of the Cretaceous Chubut Group with which they are in fault-contact.

Recently, Rapela *et al.* (2003) have indicated a southwestward migration of the magmatic arc from the Upper Triassic-early Lower Jurassic Central Patagonian Batholith to the Late Jurassic plutons located along the eastern side of the Patagonian Batholith (Suárez and De la Cruz, 2001).

It is important to emphasize that there is a coincidence in time between the Middle Jurassic cessation of activity of the Toarcian arc, the migration of the arc to the SSW, the closure of the Toarcian back-arc basin and the initiation of anatectic silicic volcanism associated to rifting covering a larger area than that of Marifil volcanism, which may have been causally related. The emplacement, during the Toarcian, of the Karroo mantle plume to the east of the area, as proposed by Pankhurst *et al.* (2000) and Rapela *et al.* (2003, 2005), may have been responsible for the arc-migration. Therefore, one main result of the existence of a mantle plume adjacent to a subduction zone, may be the migration of the subducting slab away from it and, consequently, the migration of the related magmatic arc system. An alternative interpretation has been succintly exposed by Hervé and Mpodozis (2005), who suggests that the latter was due to the collision of a late Paleozoic allocthonous terrane ('Fitzroy Terrane' formed by the Eastern Andean Metamorphic Complex) during the Jurassic. However, the northern exposures of this alleged exotic terrane (*ca.* 46ºS) crops out between the Late Triassic-Early Jurassic accretionary complex (Chonos Metamorphic Complex) and the coeval and related magmatic arc (Central Patagonian Batholith; see Sernageomin, 2002). This indicates that the Eastern Andean Metamorphic Complex was already part of the continent during this time and that no terrane accretion occurred in the intervening region during the Early Jurassic.

The Chubut Basin and the Neuquén Basin developed behind the same Early Jurassic magmatic arc. Although both basins had several geologic similarities it is not yet clear whether they were connected during the Early Jurassic, particularly during the Toarcian (see Lesta *et al.,* 1980; Gabaldón and Lizuain, 1982). There is not sufficient geologic data from the cordilleran area between latitudes 40º and 41ºS, mainly due to difficulty in access and to Cenozoic tectonism that have modified the original setting. Current knowledge indicates that the Neuquén Basin tends to close against a basement high south of río Limay, in the area of Paso Flores (40º30'S). In the cordillera, 60 km to the west of this area (71º45'W), Jurassic volcanic rocks are exposed (Montes de Oca Formattion), which continues southwards along both margins of lago Nahuel Huapi and with a thickness of several hundreds of meters at El Bolsón. In this last region the volcanic succession, known as Piltriquitron Formation, has sedimentary intercalations with marine fossils of Toarcian age. However, the existence of marine sedimentary intercalations has not been demonstrated for the older, Early Jurassic part of these volcanic rocks, nor the intense folding present in the rocks at Piltriquitron. Consequently, one possibility is that there were two subparallel unconnected basins at latitude 41ºS, with the Chubut Basin being mainly volcanic and continuing into Chile, and the Neuquén Basin, mainly sedimentary and closing to the south. Another possibility connects both basins as suggested previously by Feruglio (1949), Lizuain and Gabaldón (1982), and strongly advocated by Vicente (2005). The last author proposed a retroarc setting for Jurassic Andean basins and a northern transgression, from the Neuquén Basin to the Chubut Basin as named herein, which was flanked by positive elements.

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