PERGAMON

Journal of South American Earth Sciences 14 (2001) 257–270

Journal of
South American
Earth Sciences

www.elsevier.com/locate/jsames

Late Triassic–early Jurassic continental extension in southwestern Gondwana: tectonic segmentation and pre-break-up rifting

Juan R. Franzese*, Luis A. Spalletti

Centro de Investigaciones Geológicas, Universidad Nacional de La Plata/CONICET, Calle 1 No. 644, La Plata 1900, Argentina

Received 1 April 2000; revised 1 January 2001; accepted 1 January 2001

Abstract

From the earliest Jurassic to the Cenozoic, the Neuquén Basin (central Argentina and Chile) evolved as an intra-arc and transarc–retroarc depression through the gradual development of the Andean magmatic arc. However, the region adjacent to the proto-Pacific margin of Gondwana between 30 and 40°S was subject to pre-Andean continental extension that began in the Late Triassic and lasted about 30 million years until the Early Jurassic. This extension resulted in the generation of a series of rifts oriented parallel to the margins of the extended area and characterized by continental volcaniclastic and pyroclastic deposits associated with lava flows and bimodal plutonic intrusions. The inception of the Neuquén Basin as a single depocenter occurred in the Early Pliensbachian, when post-rift thermal subsidence led to a general marine transgression. The T–J extension is closely linked to structures created by previous tectonothermal episodes such as the development of a Carboniferous–Permian orogenic belt (330–280 Ma), and to events along the proto-Pacific margin of Gondwana. Lithospheric thickening related to Late Paleozoic convergence caused strong gravitational instability in the orogenic belt between 30 and 40°S. Subsequent cessation of subduction, coeval with establishment of dextral strike-slip tectonics parallel to the continental margin, caused detachment of the subducting slab and generation of an asthenospheric window. Anomalous heating of the upper mantle resulted in bimodal magmatism, uplift, thermal weakening, and gravitational collapse of the upper crust. South of this extended area, proto-Pacific subduction was active during the same Late Triassic–Early Jurassic interval. Thus, the contrasting tectonic behaviour of the Gondwana margin north and south of 40°S suggests significant pre-Andean tectonic segmentation that coincides with the southern boundary of the area extended in the Late Triassic–Early Jurassic. Previous intepretations assumed a common massive extension in the Andean and Patagonian regions of southern South America. Our results demonstrate that T–J extensional rifting and magmatism between 30 and 40°S were the result of mechanical interaction between different lithospheric plates at the pre-Andean (proto-Pacific) continental margin. On the other hand, the mechanical and thermal processes that affected much of Patagonia during the Middle and Late Jurassic were a response to the tectonic and magmatic processes that caused the initial break-up of Gondwana with the opening of the Weddell Sea after 180 Ma.

Keywords: Extension; Rifting; Gondwana; Late Triassic; Early Jurassic; Neuquén basin; South America; Argentina

1. Introduction

The Jurassic tectonostratigraphic evolution of the southern Andes was characterized by gradual development of the Andean magmatic arc under continuous extensional conditions (Dalziel et al., 1987; Mpodozis and Ramos, 1989; Parada et al., 1991). This tectonic situation contributed to the location of marginal basins separated by ridges or arcs oblique to the Andean chain and the continental margin (Dalziel and Forsythe, 1985). These basins developed in response to different diachronous extensional phenomena documented from Chile and Peru (Sempere, 1995) to the Antarctic Peninsula (Storey et al., 1996). However, some of these basins were created before the development of the Andean magmatic arc — for example, in the area of the proto-Pacific continental margin between 30 and 40°S, extensional processes began in Late Triassic times and created a series of pre-Andean rift basins (Charrier, 1979).

One of the most important marginal basins is the Neuquén Basin (and its extension to the north, the so-called Aconcagua Platform; Mpodozis and Ramos, 1989), which developed in Jurassic and Cretaceous times; it occupies an area of 120,000 km^2 located between 30 and 40°S (Yrigoyen, 1991). The Neuquén Basin has been recognized as an ensialic depression located in intra-arc and back-arc positions since the latest Early Jurassic, although its origin goes back to pre-Andean extensional processes in the latest Triassic and the earliest Jurassic (Legarreta and Uliana,

* Corresponding author. Tel.: +54-221-421-5677; fax: +54-221-421-5677.

E-mail address: franzese@cig.museo.unlp.edu.ar (J.R. Franzese).

0895-9811/01/$ - see front matter
PII: S0895-9811(01)00029-3

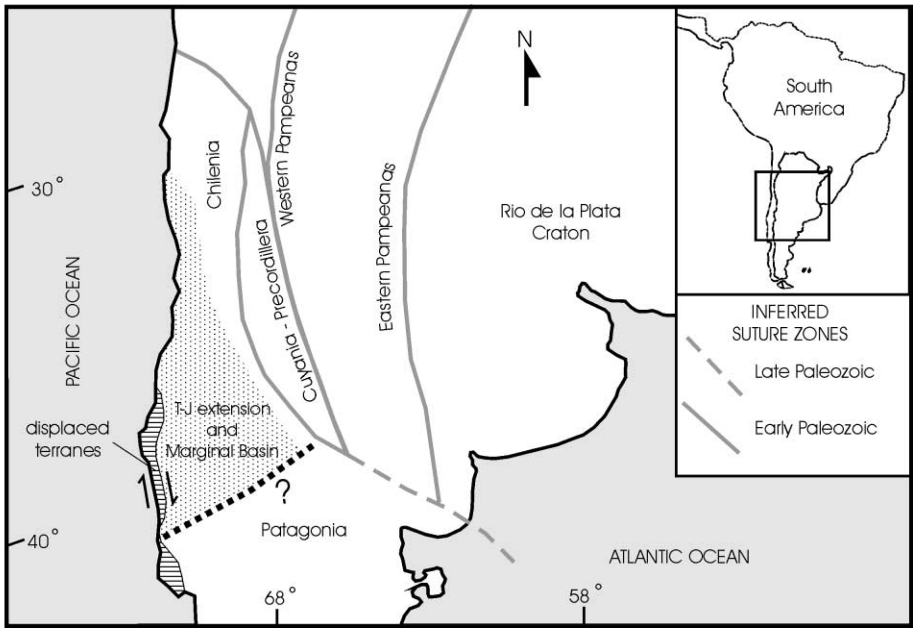

Fig. 1. Location of T–J continental extension and marginal basin formation within the framework of accreted Paleozoic southwestern Gondwana terranes (derived from Ramos et al., 1986; Kay, 1993; Bahlburg and Hervé, 1997).

1996). Uliana et al. (1989) related this extensional event to the first stages of the Gondwana break-up. Here, we focus on stratigraphic, magmatic, and structural aspects of the Late Triassic–Early Jurassic (T–J) extension and marginal basin formation along the proto-Pacific continental margin between 30 and 40°S. This contribution is part of a series of projects carried out at the Neuquén Basin by the Centro de Investigaciones Geológicas at the Universidad Nacional de La Plata (UNLP/CONICET); it arose from the compilation of a bibliography on structural, magmatic, and stratigraphic aspects of the basin and mapping as well as personal work in the central and southern areas of the basin.

2. Tectonic framework

The region between 30 and 40°S that was subjected to T–J extension is roughly triangular (Figs. 1 and 2). Its margins to the east and south seem to be inherited from the pre-Mesozoic western margin of Gondwana (Fig. 1). During the Paleozoic, the tectonic evolution of this region was characterized by the accretion of different exotic terranes: Cuyania-Precordillera, Chilenia, and Patagonia (Ramos et al., 1986; Kay, 1993; Bahlburg and Hervé, 1997). The studied area is located mainly between the Chilenia and Patagonia terranes. The connections between both terranes are not clearly defined (see: Fig. 1 in Ramos et al., 1986; Fig. 4 in Ramos, 1989; Fig. 1 in Kay, 1993; Fig. 12 in Bahlburg and Hervé, 1997). Chilenia was defined by Ramos et al. (1986) as an allochthonous terrane added to the Gondwana margin in Devonian to Early Carboniferous times. Patagonia probably represents an exotic block that collided with the rest of Gondwana in the Late Paleozoic (Ramos, 1984), although several authors have presented evidence that casts some doubt on its allochthonous nature (Cingolani et al., 1991; Rapalini 1998).

The western border of the studied area is formed by the proto-Pacific margin of Gondwana, where there is evidence of Late Permian to Late Triassic–Jurassic terrane movement parallel to the continental margin (Kato et al., 1997; Martin et al., 1999b) (Fig. 1). The large mobile terrane (Pichidangui Terrane) on the Chilean coast that was proposed by Forsythe et al. (1987) is not recognized in more recent analyses (Beck et al., 1991; Bahlburg and Hervé, 1997), at least not at the scale originally suggested.

The main geologic and tectonic units that shaped the subsequent T–J extension are shown in Fig. 2. The area occupied by the Neuquén marginal basin is floored by igneous and metamorphic basement units (Precambrian–Early Paleozoic), an Upper Paleozoic orogenic belt, and an assembly of Permian–Triassic igneous rocks, especially volcanics and volcaniclastics (Choiyoi Group; Stipanicic, 1967), that are widely distributed on the eastern edge of the extended region (Fig. 2).

The igneous-metamorphic basement crops out only in some areas in the south. The main units are the Colohuincul Complex, exposed in the Andean area between Aluminé and Bariloche, and the Río Chico Complex towards the south-east (Dalla Salda et al., 1990). Traditionally, both complexes have been assigned to the Late Precambrian–Early Paleozoic, although recent studies clearly show the activity of younger (Late Paleozoic and Triassic) processes (Basei et al., 1999; Varela et al., 1999).

During Carboniferous and Permian times, development

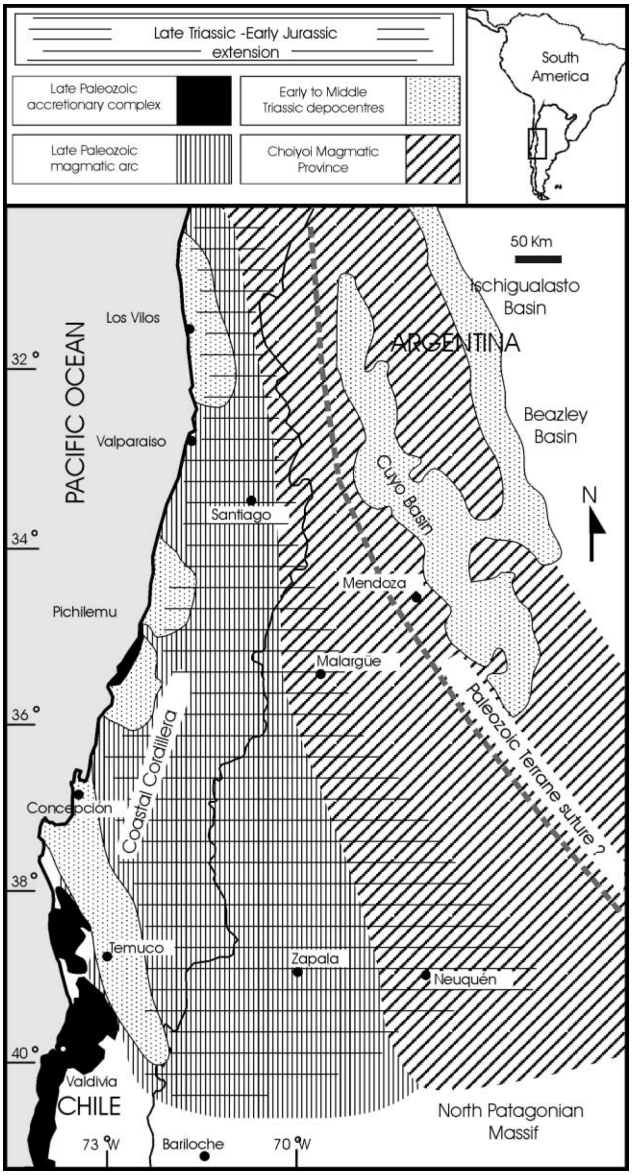

Fig. 2. Distribution of the main pre-Upper Triassic units of the southern Andes between 30 and 40°S.

of an accretionary complex and magmatic arc on the western margin of Gondwana resulted in an assembly of metamorphic and calc-alkaline plutonic rocks, grouped into the so-called Gondwana Orogenic Cycle (Llambías et al., 1984). The distribution of the Upper Paleozoic igneous and metamorphic rocks is shown in Fig. 2. The most important record of plutonic rocks of the Upper Paleozoic arc is in the Coastal Cordillera (Chile) and, less well exposed, in the area of Lakes Riñihué and Ranco (Chile). These plutonic rocks also appear in the Neuquén Province of Argentina, in the areas of Cerro Chachil, Cordón de la Piedra Santa, Collón Curá River, and Cerro Granito, and also in several wells drilled in the Neuquén Basin. Other outcrops assigned to this Upper Paleozoic arc are located in the northwestern portion of the North Patagonian Massif (Fig. 2). The ages stated for igneous activity are in the range 330–280 Ma. The metamorphic rocks of the orogenic belt are broadly distributed in the Coastal Cordillera of Chile. Traditionally, they have been divided into two series. The Eastern Series is closely associated with the plutonic arc, with greenschist facies metamorphism (low to medium P/T). The Western Series represents the accretionary prism of the subduction complex, with high P/T metamorphism (Kato, 1985; Hervé, 1988; Martin et al., 1999b). In Argentina, the Piedra Santa Formation (Franzese, 1995) is an assemblage of metasediments correlated with the low P/T Eastern Series; more to the south, metamorphosed plutonic rocks appear in the northwestern sector of the North Patagonian Massif (Basei et al., 1999; Varela et al., 1999). Metamorphism has been dated in the range 370–235 Ma.

One of the features of the Upper Paleozoic orogenic belt is its widening between 39 and 41°S (Fig. 2). Hervé (1988), Cingolani et al. (1991), Franzese (1995), and Martin et al. (1999b) have shown that there is an oblique contact between the metamorphic and magmatic rocks and the accretionary prism in that area. To the south, in the North Patagonian Massif, there is only a scattered record of Upper Paleozoic calc-alkaline rocks (Cingolani et al., 1991). Geochronological, petrological, and structural evidence suggests that the tectonic regime of the Upper Paleozoic belt evolved from crustal thickening and deformation during the Carboniferous and Early Permian to Middle–Late Triassic uplift and erosion (Hervé, 1988; Basei et al., 1999; Martin et al., 1999b; Varela et al., 1999).

After batholith emplacements and metamorphism of the Paleozoic orogenic belt, and immediately before the T–J extension, the plutonic-volcanic Choiyoi magmatic event (Llambías and Sato, 1990, 1995; Llambías et al., 1993) occurred along the eastern and northeastern edges of the Neuquén Basin between the Late Permian and the Early Triassic (280–240 Ma). The Choiyoi has been subdivided into two phases: an older phase that represents the Upper Paleozoic magmatic arc, and a younger phase, essentially Early Triassic, that is the result of intracontinental extensional tectonism. This extensional event is situated on Lower Paleozoic siliciclastic and carbonatic sequences; according to Ramos (1993), see his Fig. 2, it is closely related to the suture between the Cuyania-Precordillera and Chilenia terranes. The event can be linked to a period of no subduction on the proto-Pacific Gondwana margin in Late Permian–Triassic times (Ramos and Kay, 1991; Mpodozis and Kay, 1992; Llambías et al., 1993). The main expression of this magmatism is an extensive rhyolitic–ignimbritic plateau along the eastern margin of the Neuquén Basin (Fig. 2). Accompanying the volcanism, a system of Lower to Middle Triassic extensional basins developed. The plateau area is characterized by narrow, short-lived depocenters. Towards the east, an important system of rift basins with continental clastic fill (Cuyo, Beazley, and Ischigualasto Basins) was active throughout the Triassic, linked in its initial phases to the

Choiyoi volcanism (Fig. 2). The basins are located in the hanging-wall block of the Paleozoic suture between Chilenia and Precordillera (Ramos, 1993). Subsequently, during the Middle–Late Triassic, this eastern basin system entered a thermal sag stage phase, accompanied by basaltic lava flows. Towards the oceanic margin, small rift basins formed oblique to the continental margin (Fig. 2) and floored by Upper Paleozoic rocks. Charrier (1979) suggested that these narrow and short-lived troughs were generated under a strike-slip tectonic regime.

In the North Patagonian Massif, away from the area affected by T–J extension, the Choiyoi magmatism is represented by the Somuncura Batholith, where two complexes are recognized (Pankhurst et al., 1992): the latest Lower Permian La Esperanza Complex (258–259 Ma) and the lower Middle Triassic Dos Lomas Complex (239 Ma) —the latter with alkaline affinity (Pankhurst et al., 1992; Rapela et al., 1996). The Somuncura granitoids represent the maximum southwestward extent of Choiyoi magmatism.

3. T–J extension and rifting

The most important expression of the T–J extension was the development of a system of rift clusters (Sengör, 1995) subparallel to the borders of adjacent terranes (Fig. 3). Subsurface studies based on seismic records and well logs (Legarreta and Gulisano, 1989; Manceda and Figueroa 1995; Vergani et al., 1995) demonstrated that the rifts are elongate troughs 150 km long and 50 km wide, filled by more than 2000 m of sedimentary and volcanic rocks. The depocenters are bounded by listric or planar normal faults and commonly have a half-graben geometry. A series of subparallel half-grabens with alternating polarity has been recognized along the northeastern edge of the area extended during the T–J (Vergani et al., 1995). In the western part of this area, inversion caused by Andean tectonics carried a great part of the syn-rift record up to the surface, making it difficult to state precisely the limits of each depocenter. In the central Neuquén Basin, where syn-rift rocks crop out close to Cerro Chachil and Aluminé (Fig. 3), it is possible to define areas of ramp development with a condensed infill pattern and even identify areas devoid of early syn-rift deposits (Franzese et al., 1998). This has demonstrated an important asymmetry in the facies distribution of sedimentary sequences.

The presence of discontinuities and unconformities in the stratigraphic record has been mentioned by many authors (Legarreta and Gulisano, 1989; Gulisano and Gutiérrez Pleimling, 1994; Spalletti, 1997; Franzese et al. 1998; Uliana et al., 1999). Gómez Pérez and Franzese (1999) demonstrated the generation and reactivation of normal faults during the opening of new depocenters. All these features allow us to define various periods of tectonic reactivation of the half-grabens which, in turn, controlled the characteristics and distribution of syn-rift facies.

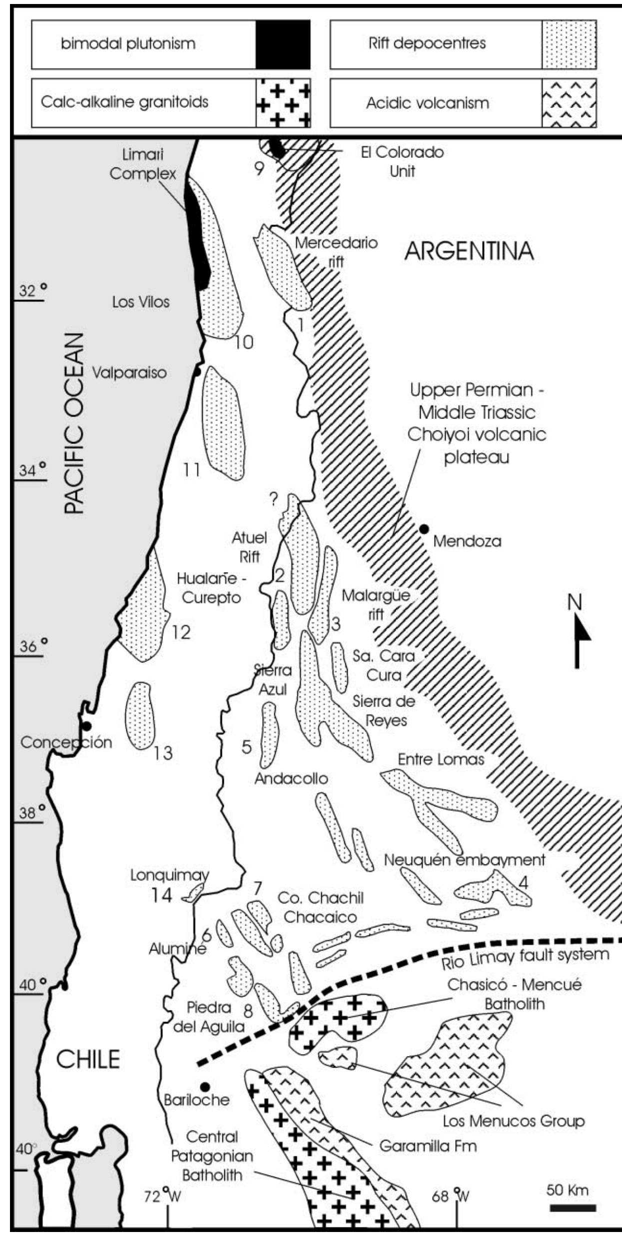

Fig. 3. Sketch map showing depocenters and magmatic complexes generated during T–J extension (distribution of rift basins from Uliana et al., 1999). Calc-alkaline magmatism is recorded only south of the Limay fault system. See text for discussion. Numbers refer to depocenters cited in Fig. 4.

Most depocenters caused by T–J extension show a depositional history linked to contemporaneous volcanic activity. The initial infill of these basins consists of syn-rift volcanic, volcaniclastic, and continental epiclastic rocks showing diachronous transitions to marine facies in Chile and adjacent areas of Argentina (Riccardi et al., 1997). The main sources of siliciclastic material for extensional basin infill were uplifted areas of the Upper Paleozoic orogenic belt, marginal Choiyoi

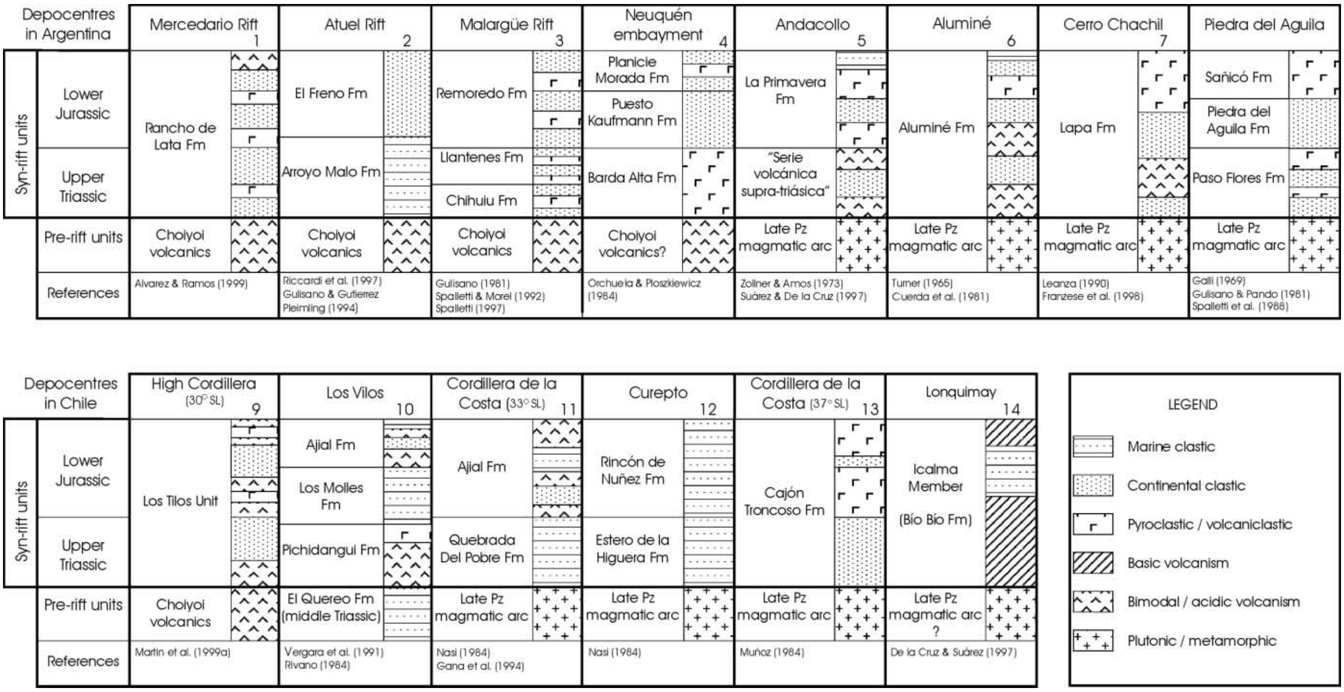

Fig. 4. Main stratigraphic units generated during the syn-rift stage of the T–J continental extension event. Numbers refer to depocenters cited in Fig. 3.

rhyolite plateau, and coeval volcanic and pyroclastic contributions. The distribution and stratigraphic characteristics of the main syn-rift units of the marginal basin are summarized in Fig. 4.

It is difficult to determine the precise age of initial sedimentation due to the lack of biostratigraphic control in many of the volcaniclastic continental sequences. Different authors suggest that deposition began in the Late Triassic (Legarreta and Gulisano, 1989; Legarreta et al., 1993; Uliana et al., 1999), during the Florian Stage (Spalletti, 1999; Spalletti et al., 1999). The marine sediments found in Chile and, more restricted, in Argentina are characterized by an Upper Triassic invertebrate fauna (Cecioni and Westermann, 1968; Escobar 1980; Corvalán, 1982; Riccardi et al., 1997). Fossil plants (*Dicroidium* flora) have allowed dating of various earliest syn-rift continental units in Chile and Argentina as Late Triassic (Charrier, 1979; Spalletti et al., 1988; Arrondo et al., 1991). In some depocenters (e.g. Piedra del Aguila, Figs. 3 and 4), however, initial syn-rift deposition started in the Early Jurassic (Stipanicic et al., 1968). The diachroneity of the initial sedimentary record suggests that rifting was active throughout the Late Triassic–Early Jurassic interval. The end of the active rifting stage and the transition to the post-rift stage is clearly determined by the first generalized marine transgression during the early Pliensbachian, documented by fossils throughout the entire Neuquén Basin. In Argentina, the syn-rift continental deposits were grouped by Gulisano et al. (1984)in the so-called Precuyano, although some of the Upper Triassic units were not included.

4. Stratigraphic record

The initial volcanic and volcaniclastic syn-rift deposits of the central area of the Neuquén Basin have been assigned, based on lithologic similarity, to the Choiyoi magmatic province (Leanza, 1990; Gulisano and Gutiérrez Pleimling, 1994). These volcanic–volcaniclastic–epiclastic sequences are, in fact, younger than the Choiyoi volcanism. Groeber (1918) named them "Serie Porfirítica Supratriásica" and later "Choiyoilitense" (Groeber, 1946). This is the reason for the confusion, since at present 'Choiyoi' solely designates the oldest event, with rocks mainly located in the eastern margin of the T–J extension.

The field relations between volcaniclastic facies and regional structures clearly show the link between the 'Supratriassic Series' and the initial extensional activity of the marginal basin. This is observed in the central southern part of the study area, near Zapala. In the Cerro Chachil and Chacaico depocenters (Figs. 2 and 3), a syn-rift succession has been identified that was previously assigned to the Choiyoi Formation (Leanza, 1990). As shown in Fig. 4, this succession starts with bimodal volcanic rocks associated with thick alluvial sediments and subordinate lacustrine carbonates followed by a pyroclastic unit (Lapa Formation; Leanza, 1990) composed of tuffs, ignimbrites, and reworked volcaniclastic deposits. The change to the post-rift stage was marked by a rapid Pliensbachian marine transgression (Chachil Formation–Sierra de Chacaico Formation; Leanza, 1990) with volcaniclastic and carbonate facies (Franzese et al., 1998; Fig. 4).

Along the eastern foothills of the Andes, west of the previously mentioned area, the Aluminé Formation (Turner, 1965) consists of andesitic and rhyolitic lavas, breccias, and tuffs (Fig. 4). Though Turner (1965) dated it as Late Triassic, Cuerda et al. (1981) have linked the transition from volcaniclastics and volcanics to interstratified lavas and marine sediments with a Lower Jurassic fauna. In addition, a K–Ar age of 201 ± 10 Ma for andesite lavas intercalated in this unit has been reported by Rapela et al. (1983).

In Andacollo (Figs. 3 and 4), the base of the syn-rift section consists of a thick succession of bimodal volcanic rocks and associated sediments. It was referred to as the Choiyoi Formation, even though it was assigned to the Late Triassic ("Serie Volcánica Supratriásica") by Zöllner and Amos (1973). This unit is followed by an assemblage of Lower Jurassic pyroclastic deposits and shallow marine sediments (La Primavera Formation; Suárez and De la Cruz, 1997; cf. Zöllner and Amos, 1973). All of the T–J succession lies on Carboniferous sediments and Lower Permian granitoids. Similar lithologic associations and stratigraphic relations for the syn-rift record have been described in the Sierra de Reyes, Sierra de Cara Cura, and Sierra Azul (south of Mendoza, Fig. 3). In this area, Freytes (cited in Digregorio, 1972) defined the Cara Cura and Aguada del Charqui Formations as tuff and tuffite deposits with intercalation of breccias, tuffaceous sandstones, andesite and rhyolite sheets. These deposits were assigned to a Late Triassic syn-rift stage by Vergani et al. (1995).

In the southern and southeastern regions of the area extended in the T–J (Piedra del Aguila, Fig. 3) the syn-rift deposits lie on Upper Paleozoic magmatic arc rocks. They consist of a continental volcaniclastic succession (Fig. 4) of Late Triassic age (Paso Flores Formation), followed by Lower Jurassic clastic units (Nestares and Piedra del Aguila Formations). The most voluminous acidic volcaniclastic–pyroclastic episode was recorded in the Early Jurassic (pre-Pliensbachian) with deposition of the Sañicó Formation (>1000 m thick; Galli, 1969; Gulisano and Pando, 1981). In this area, the transition from syn-rift to post-rift stages is again represented by Pliensbachian marine deposits (Damborenea et al., 1975).

To the east and north of the zone described above, the syn-rift sequences are preserved in the subsurface and lie on rocks of the Choiyoi magmatic province. In the Neuquén Embayment (Figs. 3 and 4), basement consisting of volcanic and pyroclastic rocks assigned to Choiyoi magmatism has been recognized (Vulcanitas Medanito, Barda Alta Formation; Orchuela and Ploszkiewicz, 1984). A thick succession of lacustrine sediments lies on these rocks (Puesto Kaufmann Formation). These deposits constitute a high-quality oil source rock (Legarreta et al., 1999). They are covered by the Planicie Morada Formation, which is composed of volcaniclastic deposits with volcanic intercalations. This unit was correlated with the Precuyano Cycle by Orchuela and Ploszkiewicz (1984).

It must be reiterated that the volcanic and volcaniclastic basement recognized in oil wells in various depocenters in the subsurface has been asigned to the Choiyoi Formation, even though there is no clear control on the age. In addition, in some sections, volcanic sequences attributed to the Choiyoi Formation have been assigned Late Triassic ages (e.g. Barda Alta Formation), and they seem to be specifically related to elements of the T–J syn-rift (Fig. 4).

In the High Cordillera, the Mercedario Rift (Fig. 3) has been described by Alvarez and Ramos (1999) as a Jurassic half-graben structure filled, in its syn-rift stage, by a thick acidic volcano-sedimentary sequence called the Rancho de Lata Formation (Fig. 4). The initial post-rift stage is represented by the Los Patillos Formation, which records the Pliensbachian marine transgression (Alvarez and Ramos, 1999). The Atuel–Malargüe depocenter (Fig. 3) lies in the cordilleran area, but more to the south. It is developed on a pre-rift substrate formed by rocks of the Choiyoi magmatic province. The early syn-rift deposits (Late Triassic) are represented by the Chihuíu and Llantenes formations (Fig. 4) that consist of fluvial and lacustrine clastic continental deposits, with volcaniclastic and pyroclastic contributions (Spalletti and Morel, 1992; Spalletti 1997). Late syn-rift (Early Jurassic) acidic volcaniclastic deposits (Remoredo Formation) were first assigned by Gulisano (1981) to the initial sedimentary cycle of the Neuquén Basin ('sedimentitas precuyanas') although, as mentioned above, here it is considered that the Upper Triassic underlying units should also be integrated into the history of the T–J extension. To the west and northwest of the Atuel–Malargüe depocenter, the syn-rift record (Fig. 4) is composed of clastic marine sediments described as the Arroyo Malo Formation (Riccardi et al., 1997). Reactivation of the rift systems in the earliest Jurassic caused the development of thick fluvial deposits (El Freno Formation), followed by the initial, mostly Pliensbachian post-rift marine facies (Puesto Araya Formation) (Volkheimer, 1978; Riccardi et al., 1991; Gulisano and Gutiérrez Pleimling, 1994).

In Chile, the syn-rift successions are also related to volcanic environments. To the north, in the High Cordillera (Figs. 3 and 4), the Los Tilos unit (Martin et al., 1999a) consists of ignimbrites and rhyolitic lava flows, associated with clastic sediments, lying on Upper Triassic volcaniclastic and granitoid units equivalent to the Choiyoi Formation (Guanaco Sonso Formation). Towards the west the volcanism is minimal, as in the case of the Las Breas and Tres Cruces formations (Cornejo et al., 1984) although plutonism of Late Triassic–Early Jurassic age is recorded locally (Parada, 1988).

In the coastal region at 32°S (Fig. 3), the Chilean depocenters become progressively broader and show a drastic change in facies arrangement, with deep marine deposits (Pichidangui Formation). This has been defined as a quasi-oceanic volcanic unit (Vergara et al., 1991) that lies on Lower Triassic clastic rocks and shows a thick association of lavas, ignimbrites, breccias, and tuffs (Fig. 4). It is followed by the turbidites of Los Molles Formation, with an Upper Triassic to Hettangian fauna.

In the central portion of the Coastal Cordillera (33°S), the sequences related to the T–J extension lie on rocks of the Upper Paleozoic magmatic arc. They are represented by the Quebrada del Pobre Formation and the diachronous Ajial Formation (Fig. 4). The former is composed of marine siliciclastic rocks, the latter consists of a thick succession of sediments and acidic volcanics (Nasi, 1984; Rivano, 1984). The sediments contain a Sinemurian–Pliensbachian fauna, and it is possible volcanism began earlier, in the Early Jurassic or even in the Late Triassic, as pointed out by Gana et al. (1994). At 35°S, in the coastal region of Chile (Figs. 3 and 4), the Hualañe–Curepto sub-basin (Nasi, 1984) developed from Late Triassic to Early Jurassic times, with a marine siliciclastic infill (Estero de la Higuera and Rincón de Núñez formations), coeval with the volcaniclastic sequences located in the axis of the Coastal Cordillera (Nasi, 1984). More to the south in the Coastal Cordillera, at 37°S, the Cajón Troncoso Formation, which has been described by Muñoz (1984), represents the syn-rift record with acidic volcanic deposits (Figs. 3 and 4). In the Andean region around Lonquimay (39°S, Fig. 3). De la Cruz and Suárez (1997) described a sequence comparable in age to the Ajial Formation but with a very different lava composition (Nacientes del Bío Bío Formation). The lower member of this formation (Icalma Member) consists of a lower Pliensbachian turbiditic sequence over a thick succession of pillow basalts, possibly dating from the end of the Triassic or beginning of the Jurassic (Fig. 4).

5. T–J extension and magmatism

An important episode of Upper Triassic to Lower Jurassic plutonism, closely associated with graben formation and filling, accompanied extension. Contemporaneous plutonism (dated between 220 and 200 Ma) has already been described from Chile; it is represented by the Limarí Complex, Tranquilla and Millahue units (Parada, 1988; Parada et al., 1991, 1994), and the gneissic Cartagena Diorites (Gana et al., 1994) of the central Coastal Cordillera (30–34°S, Fig. 3). The El Colorado Unit (221–219 Ma) crops out in the High Cordillera (Martin et al., 1999a).

This magmatism shows a strong bimodal signature. The plutonic rocks consist of calc-alkaline leucogranites (with high silica), diorites, and gabbros. A similar signature is seen in the volcanic rocks of the Los Tilos Unit (Martin et al., 1999a) and for the Pichidangui Formation (Vergara et al., 1991). In Argentina, abrupt changes in the composition of lava flows (basalts and rhyolites) in the Cerro Chachil, Aluminé, and Andacollo areas (Fig. 3) confirms the bimodal tendency.

The magmatic processes related to the T–J extension have been linked to abnormally hot mantle that caused crustal anatexis by the underplating of basaltic magmas. Widespread partial melting is attributed to the decompression of the upper mantle, which could be linked to a slow subduction or lack of a subducted slab beneath the western margin of Gondwana (Gana, 1991; Parada et al., 1997).

Studies of magmatism have also allowed identification of another tectonic environment to the south of the area extended in the T–J (Fig. 3). Calc-alkaline magmatism of very different characteristics, represented by the batholiths of Chasicó–Mencué and Central Patagonia, is recognized south of 41°S (Cingolani et al., 1991; Dalla Salda et al., 1991; Rapela and Alonso 1991; Rapela et al., 1991; Rapela and Pankhurst, 1992). It is represented by an assemblage of granitic and granodioritic plutons with magmatic arc affinity, which would represent active subduction contemporary with extension in the marginal basin area to the north. The presence of an Upper Triassic accretionary prism at 45°S (Fang et al., 1998) favours this interpretation.

In northern Patagonia, acidic lavas and associated volcaniclastic sediments crop out east of the subduction-related granitoids (Fig. 3). These rocks, dated as Late Triassic–Early Jurassic, are known as the Los Menucos Group and the Garamilla Formation (Coira 1979; Labudía et al., 1995; Rapela et al., 1996). Spalletti (1999) has suggested that these volcanics may be related to trans-arc extensional phenomena.

There is no evidence of subduction-related processes north of 40°S in the area occupied by the marginal basin. This particular contrast in the geotectonic environments of the western margin of Gondwana allows us to suggest Late Triassic–Early Jurassic pre-Andean segmentation. This segmentation is significant since it marks the southern border of the marginal basin and, therefore, of the area subjected to continental extension during the T–J.

6. Discussion

6.1. Boundaries of T–J extension

As is seen in the Chilean Coastal Cordillera, Andacollo, Cerro Chachil, Chacaico, Aluminé, and Piedra del Aguila (Figs. 3 and 4), the sedimentary and volcanic rocks associated with early extension of the Neuquén Basin are located on metamorphic and granitoid rocks of the Carboniferous–Lower Permian orogenic belt. Laterally, both to the eastern side of the extended area (subsurface of the Neuquén Embayment) and to the northwest (High Cordillera, Mercedario Rift, Atuel–Malargüe; Fig. 3), the T–J depocenters developed on rocks of the Upper Permian–Lower Triassic Choiyoi magmatic province, probably seated on the same Upper Paleozoic arc rocks (Figs. 3 and 4). In areas such as Los Vilos and Andacollo, the syn-rift units lie on strongly uplifted and eroded Upper Paleozoic sedimentary sequences, possibly related to intra-arc basins (Los Vilos Formation, Andacollo Group).

The northeastern and southern limits of the extended area

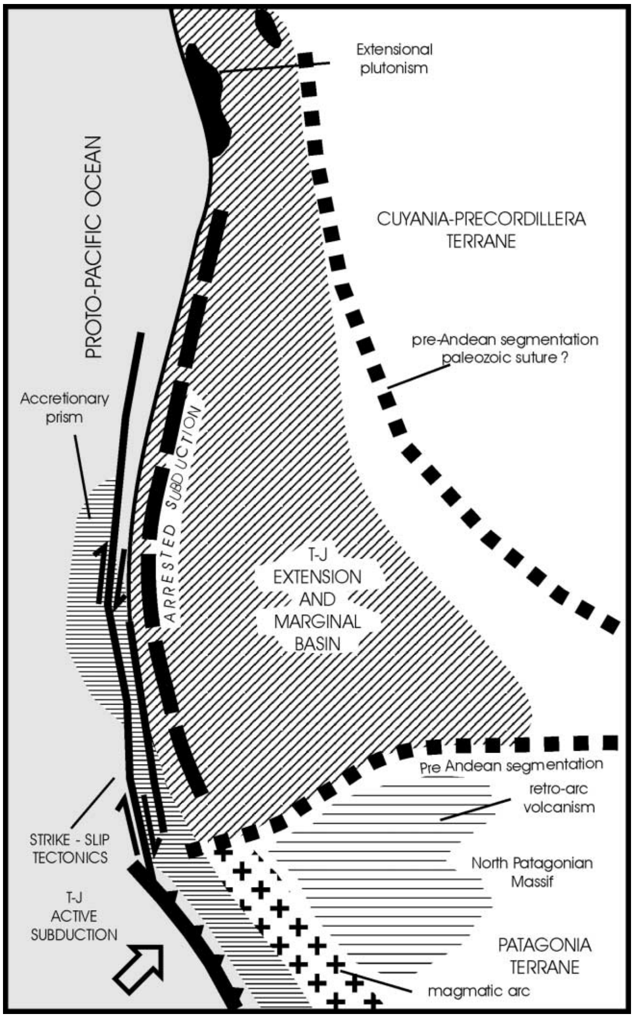

Fig. 5. Sketch map showing the pre-Andean tectonic scenario during the T–J extension. Development of the Neuquén marginal basin is controlled by the pre-Triassic tectonic segmentation of southwestern Gondwana.

are closely related to the boundaries of the Upper Paleozoic batholiths. The marginal basin is flanked to the east by the volcanic plateau of the Choiyoi province, controlled by the suture between exotic terranes accreted during the Paleozoic (Figs. 2, 3, and 5). To the south and southeast, the extended area is bounded by the so called North Patagonian Massif (Fig. 5) where cordilleran calc-alkaline plutonism synchronous with the extension of the Neuquén marginal basin was developed (Cingolani et al., 1991; Dalla Salda et al., 1991; Rapela and Alonso 1991; Rapela et al., 1991; Rapela and Pankhurst, 1992). As previously indicated, these Upper Triassic–Lower Jurassic batholiths are related to protracted subduction to the south of the region occupied by the area extended in the T–J (Fig. 5). The North Patagonian region lacks evidence of T–J extension, and rift basins are not observed. Only volcanic and clastic deposits of limited regional extent and thickness are recognized as perivolcanic retroarc accumulations (Fig. 5).

The boundary between the marginal basin and the North Patagonian Massif represents the contact between two different Upper Triassic-Lower Jurassic pre-Andean tectonic segments (Figs. 3 and 5). It runs northeast–southwest, associated with the current course of the Limay River, which has been shown to be an important area of fracturing (Ramos, 1978; Gulisano and Pando, 1981). This structure constitutes a first-order boundary in the tectonostratigraphic organization of northern Patagonia. Its position is linked to the maximum expansion to the east of the Upper Paleozoic orogenic belt and acts as a limit in the distribution of the Choiyoi magmatic province to the south, as well as in that of the Late Triassic–Early Jurassic arc plutonism to the north (Figs. 2, 3, and 5).

The causes of the tectonic segmentation of the T–J extension lie in the different composition and geologic evolution of the pre-Andean active margin and seem also to have controlled younger processes. In the studied area, this segmentation influenced not only the evolution of the Neuquén Basin but also the establishment of the Meso-Cenozoic Andean magmatic arc which, unlike adjacent areas to the north and south, behaved as a stationary arc between 33 and 40°S (Mpodozis and Ramos, 1989; Sanguinetti and Ramos, 1993).

6.2. Distribution of T–J rifts

Fig. 3 shows the distribution of depocenters generated during T–J extension. One striking feature is the concentration and continuity of depocenters close to the margins. The orientation of the main structures is parallel to the margins of the extended area, particularly in the northeast where a parallel chain of depocenters can be observed. In the south, several depocenters are aligned in a quasi-orthogonal arrangement to the first ones, along the sharp limit with the North Patagonian Massif (Fig. 3). Most of the structures of the central and western areas follow a northwest–southeast trend which could reflect inheritance of Paleozoic structures that are oblique to the Andes, possibly perpendicular to the convergence of the Carboniferous and Permian active Gondwana margin (Kato, 1985; Hervé, 1988; Franzese 1995; Kato et al., 1997; Martin et al., 1999b).

The diverse orientation of the narrow troughs is typical of a wide rifting system in which fracturing and extension responded to distribution of stress in previously weakened lithosphere (Kusznir and Ziegler, 1992). This structural style is strongly influenced by crustal homogeneity imposed by widely distributed Upper Paleozoic batholiths and associated metamorphic rocks. The varied and contrasting directions in the arrangement of extensional structures related to the same episode shows that they have not responded to a unidirectional stress field but rather to a multiple extensional field (Nieto-Samaniego et al., 1999). This interpretation differs from that of Vergani et al. (1995), who assumed that the initial rifting of the Neuquén Basin and later Jurassic and Cretaceous reactivations, were caused by a stress field with a northeast–southwest direction.

6.3. Extension mechanisms

The abundance of volcanic and pyroclastic material in the depocenters generated during T–J extension and the location of contemporaneous plutons show that magmatism played an essential tectonic role in lithospheric extension. The strongly bimodal nature of the plutonic and volcanic rocks is consistent with fusion of the upper mantle, underplating of basaltic magma, and crustal anatexis producing abundant granitic and rhyolitic rocks. This important thermal anomaly of the lithospheric mantle in the extended area is also evident from the strong tectonic uplift of the Upper Paleozoic magmatic arc (Hervé, 1988; Martin et al., 1999b).

The development of thickened and elevated lithosphere prior to T–J extension must have caused gravitational instability and a potential field of extension. The gravitational collapse and the lateral expansion of that unstable lithosphere has been considered as the main cause of major continental rifting phenomena (Wernicke et al., 1987; Dewey, 1988), and it has also been considered as the cause of the large-scale Triassic and Jurassic extension in southern South America (Gust et al., 1985; Uliana et al., 1989; Tankard et al., 1995). However, in the case of the large T–J extension, gravitational collapse must be related to previous thermal weakening of the lithosphere (Liu and Shen, 1998).

Lithospheric uplift caused by the thermal anomaly and fusion of the upper mantle as well as the subsequent thermomechanical weakening would have lasted at least 60 million years after the intrusion of the youngest plutons of the Upper Paleozoic orogenic belt (280 Ma) and the beginning of T–J — rifting and magmatism (ca. 220 Ma). This time lag between the end of activity in the orogenic belt and the peak of extension, when thickened lithosphere reached its minimum strength, corresponds to the interval predicted in models proposed by Glazner and Bartley (1985) and Sonder et al. (1987).

The characteristics of the T–J pre-Andean extension are closely related to the history of the adjacent active margin; they are the result of the mechanical interaction between different lithospheric plates (Kusznir and Ziegler, 1992; Axen et al., 1993; Bohannon and Parsons, 1995). In this case, the main causes of continental extension are either: (a) generation of an asthenospheric window due to the collapse of the subducted plate, or (b) partitioning of convergence displacement due to oblique subduction (Dickinson and Snyder, 1979; Stock and Hodges, 1989; Bohannon and Parsons, 1995). Both processes have been suggested for the pre-Andean margin of the central southern Andes. Based on petrologic and paleomagnetic data, Mpodozis and Ramos (1989) and Mpodozis and Kay (1992) have suggested that there was no subducted plate from Late Permian to Early Jurassic times. Parada et al. (1997) concluded that Late Triassic to Early Jurassic magmatism in Chile between 30 and 34°S could be related to lithospheric delamination caused by drowning of subduction. Structural and petrologic information (Kato et al., 1997; Martin et al., 1999b) also provide evidence of subduction recession and onset of transcurrent tectonics in the Upper Paleozoic accretionary prism between 35 and 40°S. To the south, the arc-related magmatic rocks of the Central Patagonian Batholith suggest the development of a convergent margin in which subduction was combined with transcurrent movements (Pankhurst et al., 1992; Rapela and Pankhurst, 1992).

6.4. Summary of the tectonic evolution of the marginal basin

The Late Paleozoic–Early Jurassic tectonic evolution of the area that extended in the T–J (marginal Neuquén Basin) can be described in four stages (Fig. 6).

STAGE 1:

- Accretion of exotic terranes during the Paleozoic.
- Amalgamation of Cuyania–Precordillera, Chilenia, and Patagonia (?).
- Establishment of a compressional magmatic arc on the western margin of Gondwana from the Carboniferous to the Early Permian (Fig. 6a).

STAGE 2:

- Slow subduction and collapse of the subducted slab after the Late Permian and development of strike-slip tectonics subparallel to the continental margin.
- Tectonic uplift and weakening of lithosphere thickened during Late Paleozoic subduction.
- Extension, with generation of volumetrically important magmatism (Choiyoi) controlled by the distribution of Paleozoic accreted terranes. Opening of Lower to Middle Triassic narrow rift basins — e.g. Cuyo Basin in the footwall block of the Paleozoic suture (Fig. 6b).

STAGE 3:

- Generalized extension located on the previous Upper Paleozoic orogenic belt.
- Rifting parallel to the margins of the extended area, with generation of a system of narrow, elongate troughs and bimodal magmatic activity.
- Thermal subsidence followed by closure of the pre-existing Triassic basins and tectonic uplift of the Choiyoi volcanic plateau, to the east of the Neuquén Basin. Protracted strike-slip tectonics in the accretionary prism of the western margin of Gondwana (Figs. 5 and 6c).

STAGE 4:

- Establishment of the Andean magmatic arc late in Early Jurassic time.
- Post-rift thermal subsidence leads to integration of individual rifts into a single marginal basin in intra-arc

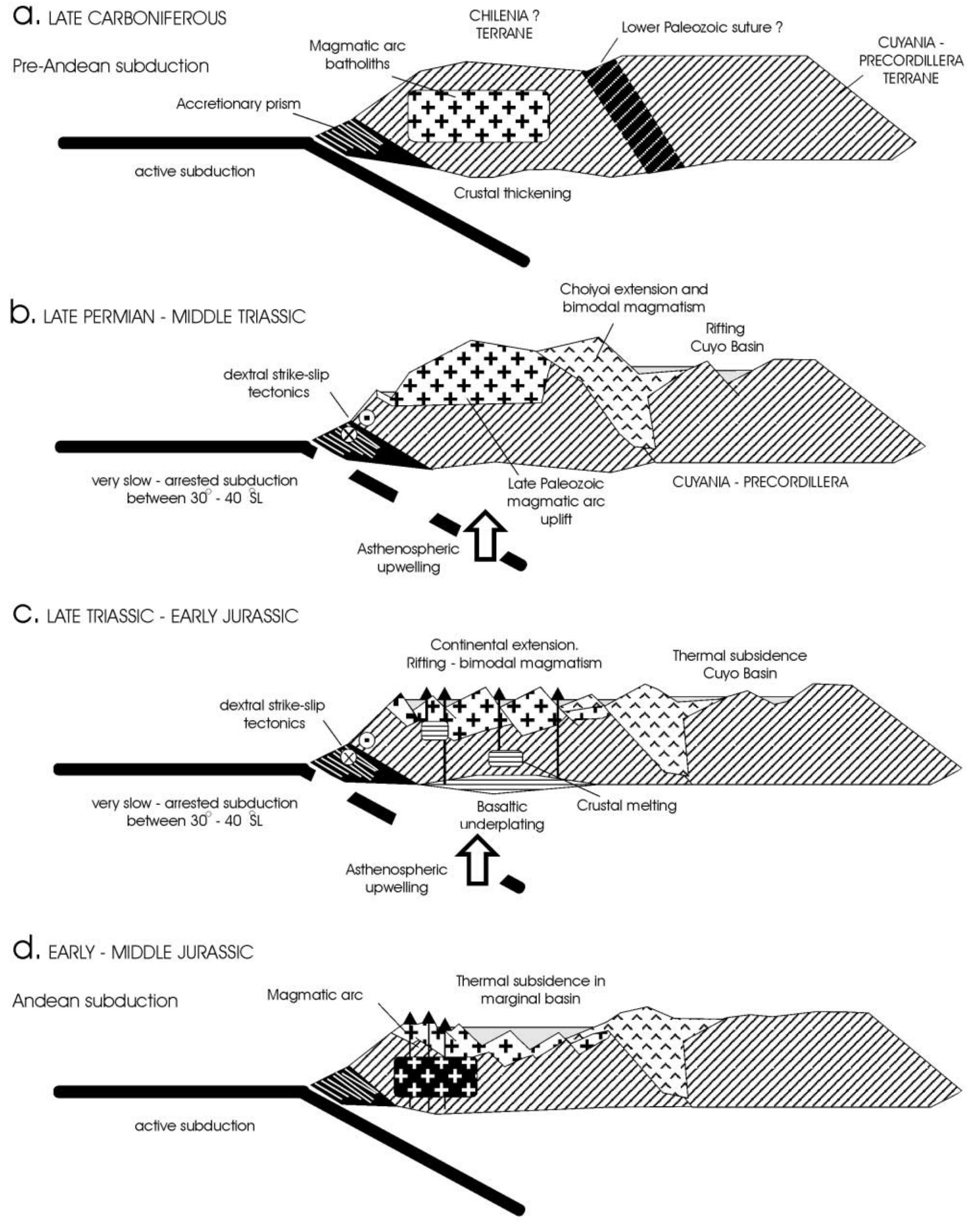

Fig. 6. Schematic cross-section of the study area around 37°S showing the Late Paleozoic to Middle Jurassic tectonic evolution of the Andean region and northwestern Patagonia. See text for discussion.

(Chile) and back-arc (Argentina) positions (Fig. 6d).
- Generalized transgression across the entire extended area.

6.5. Relation of T–J extension to early triassic extension and jurassic breakup of gondwana

T–J extensional processes were closely linked to geodynamic evolution of the Upper Paleozoic–Lower Mesozoic pre-Andean continental margin between 30 and 40°S. Extension was localized entirely within the Upper Paleozoic orogenic belt and limited by tectonic segmentation inherited from the Paleozoic accretionary framework of Gondwana. Therefore, T–J extension should be isolated from the rest of the extensional episodes that dominated the tectonic evolution of southern South America, both previously and following during the Jurassic.

The Lower Triassic basins (which are beyond the scope of this paper) were short-lived and did not evolve as marginal basins. For example, one of the most important basins of those times, the Cuyo Rift Basin (Fig. 2) developed contemporaneously with Choiyoi magmatic activity and completed its mechanical subsidence stage (passing to a sag phase; Ramos and Kay, 1991) by the beginning of T–J extension.

The Upper Jurassic extensional basins in Patagonia (e.g. Cañadón Asfalto, San Jorge, and Magallanes basins), are separated both spatially and temporally from the T–J

Neuquén marginal basin (Spalletti and Franzese, 1996a, 1997b). Although all these basins were formed under extensional regimes, they cannot be placed in a single tectonic framework. This conclusion differs from previous schemes that assumed common massive extension during the Triassic and Jurassic in both the Andean and the Patagonian regions of southern South America (Gust et al., 1985; Uliana and Biddle, 1988; Uliana et al., 1989; Tankard et al., 1995). During the Middle and Late Jurassic, the mechanical and thermal processes that greatly affected Patagonia were a response to a mantle plume impact that caused the initial break-up of Gondwana with the opening of the Weddell Sea after 180 Ma (King et al., 1996; Storey et al., 1996; Pankhurst et al., 2000). On the other hand, Late Triassic to Early Jurassic extensional rifting and magmatism were the result of mechanical interaction between different lithospheric plates at the pre-Andean (Pacific) continental margin. In such a setting, slab detachment that represents the terminal stage of a long-lived subduction zone (Pysklywec et al., 2000; Wortel and Spakman, 2000) played an essential role in T–J extension.

7. Conclusions

The region adjacent to the proto-Pacific margin of Gondwana between 30 and 40°S was subject to continental extension which began in the Late Triassic and lasted about 30 million until the Early Jurassic. This extension resulted in the generation of an extensive complex marginal basin (Neuquén) in which Jurassic and Cretaceous times, was closely linked to the evolution of the Andean magmatic arc.

The location of the extended region was strongly controlled by the previous tectonothermal history, characterized by the development of the Carboniferous–Permian orogenic belt (330–280 Ma). The boundaries of the T–J extension are related to tectonic segmentation that was partly inherited from the accretionary tectonics of the Paleozoic pre-Andean margin.

The main tectonic expression of the T–J continental extension is a rift system oriented parallel to the margins of the extended area. Rifts are elongate, narrow depressions, infilled by continental volcaniclastic and pyroclastic deposits associated with lava flows and plutonic intrusions. Coeval magmatism has a bimodal signature consistent with the interpretation of an extensional tectonic regime. A transition to marine and oceanic environments is observed on the proto-Pacific margin. Post-rift thermal subsidence generated a strong marine transgression during the Early Pliensbachian; from this time, the basin behaved as a homogeneous geodynamic entity.

The causes of extension are linked to the activity of the proto-Pacific margin of Gondwana and are not related to the tectonics that caused the later break-up of Gondwana. Lithospheric thickening related to Upper Paleozoic convergence caused a strong gravitational instability in the orogenic belt between 30 and 40°S. Subsequent cessation of subduction during the Late Permian–Early Jurassic, coeval with the establishment of dextral strike-slip parallel to the continental margin, caused the collapse of the subducted slab and the generation of an asthenosphere window. As a result, anomalous heating of the upper mantle produced bimodal magmatism, uplift, thermal weakening, and gravitational collapse of the upper crust.

Subduction was active to the south of the marginal basin during the Late Triassic and Early Jurassic. The contrasting tectonic behavior of the Gondwana margin north and south of 40°S suggests significant pre-Andean tectonic segmentation that coincides with the southern boundary of the T–J extension area.

Acknowledgements

We are grateful for the helpful reviews of Carlos Rapela, David Macdonald, and Irene Gómez Pérez. The paper also benefited from reading and comment by Alan Vaughan and Terence Kato. This research was supported by grants PIP 4352 and PIP N 0912 from the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina (CONICET). This is a contribution to IGCP Project 436: Pacific Gondwana Margin.

References

Alvarez, P.P., Ramos, V.A., 1999. The Mercedario rift system in the principal Cordillera of Argentina and Chile (32°SL). Journal of South American Earth Sciences 12, 17–31.

Arrondo, O., Spalletti, L., Morel, E., Ganuza, D., 1991. The sedimentological and paleobotanical characteristics of an Upper Triassic–Lower Liassic basin in northwestern Patagonia (Argentina). In: VII International Gondwana Symposium (Instituto Geociencias, Universidade de Sao Paulo). vol. 714, pp. 517–532.

Axen, G.J., Taylor, W.J., Bartley, J.M., 1993. Space-time patterns and tectonic controls of Tertiary extension and magmatism in the Great Basin of the western United States. Geological Society of America, Bulletin 105, 56–76.

Bahlburg, H., Hervé, F., 1997. Geodynamic evolution and tectonostratigraphic terranes of northwestern Argentina and northern Chile. Geological Society of America, Bulletin 109, 869–884.

Basei, M.A.S., Brito Neves, B.B., Varela, R., Teixeira, W., Siga, jr., O., Sato, A.M., Cingolani, C.A., 1999. Isotopic dating on the crystalline basement rocks of the Bariloche region, Río Negro, Argentina. II South American Symposium on Isotope Geology, Actas, pp. 15–18.

Beck Jr., M.E., García, A., Burmester, R.F., Munizaga, F., Hervé, F., Drake, R.E., 1991. Paleomagnetism and geochronology of Late Paleozoic granitic rocks of Lake District of southern Chile: implications for accretionary tectonics. Geology 19, 332–335.

Bohannon, R.G., Parsons, T., 1995. Tectonic implications of post-30 Ma Pacific and North American relative plate motions. Geological Society of America, Bulletin 107, 937–959.

Cecioni, G., Westermann, G.E.G., 1968. The Triassic/Jurassic marine transition of coastal central Chile. Pacific Geology (Tokyo) 1, 41–75.

Charrier, R., 1979. El Triásico de Chile y regiones adyacentes de Argentina: Una reconstrucción paleogeográfica y paleoclimática. Comunicación (Departamento de Geología, Universidad de Chile) 26, 1–37.

Cingolani, C., Dalla Salda, L., Hervé, F., Munizaga, F., Pankhurst, R.J., Parada, M.A., Rapela, C.W., 1991. The magmatic evolution of northern Patagonia: new impressions of pre-Andean and Andean tectonics. Andean Magmatism and its Tectonic Setting, Harmon, R.S., Rapela, C.W. (Eds.). Geological Society of America, Special Paper 265, 29–44.

Coira, B., 1979. Descripción Geológica de la Hoja 40d, Ingeniero Jacobacci. Servicio Geológico Nacional (Buenos Aires), Boletín 168, 94.

Cornejo, P., Nasi, C., Mpodozis, C., 1984. La alta cordillera entre Copiapó y Ovalle. In: Seminario Actualización de la Geología de Chile. Servicio Nacional de Geología y Minería (Santiago de Chile), Miscelánea, vol. 4, pp. H1–H45.

Corvalán, J., 1982. El límite Triásico–Jurásico en la Cordillera de la Costa en las provincias de Curicó y Talca. In: III Congreso Geológico Chileno (Concepción), Actas. vol. 3, pp. F63–F85.

Cuerda, A.J., Schauer, O.C., Sunesen, A., 1981. Afloramientos fosilíferos de la Formación Aluminé, en el sector de Rahue, provincia del Neuquén. Revista de la Asociación Geológica Argentina 36, 329–332.

Dalla Salda, L., Cingolani, C.A., Varela, R., 1990. El basamento de la región occidental del Macizo Norpatagónico, Argentina. In: XI Congreso Geológico Argentino, Actas. vol. 2, pp. 11–14.

Dalla Salda, L., Varela, R., Cingolani, C.A., 1991. Los granitoides de Chasicó–Mencué, Macizo Norpatagónico, Río Negro: Su implicancia geotectónica. Revista de la Asociación Geológica Argentina 46, 189–200.

Dalziel, I.W.D., Forsythe, R.D., 1985. Andean evolution and the terrane concept. In: Howell, D.G. et al. (Eds.), Circum-Pacific Terranes Conference, American Association of Petroleum Geologists, Earth Science Series, vol. 1, 565–581.

Dalziel, I.W.D., Storey, B.C., Garret, S.W., Grunow, A.M., Herod, L.D.B., Pankhurst, R.J., 1987. Extensional tectonics and the fragmentation of Gondwanaland. In: Coward, M.P., Dewey, J.F., Hancock, P.L. (Eds.). Continental Extensional Tectonics, vol. 28. Geological Society of London, Special Publication, pp. 433–441.

Damborenea, S., Manceñido, M., Riccardi, A.C., 1975. Biofacies y estratigrafía del Liásico de Piedra Pintada, Neuquén, R. Argentina. In: I Congreso Argentino de Paleontología y Bioestratigrafía (Tucumán), Actas. vol. 2, pp. 173–228.

De la Cruz, R., Suárez, M., 1997. El Jurásico de la Cuenca de Neuquén en Lonquimay Chile: formación Nacientes del Biobío (38–39°S). Revista Geológica de Chile 24, 3–24.

Dewey, J., 1988. Extensional collapse of orogens. Tectonics 7, 1123–1140.

Dickinson, W.R., Snyder, W.S., 1979. Geometry of triple junction related to San Andreas transform. Journal of Geophysical Research 84 (B2), 561–572.

Digregorio, J.H., 1972. Neuquén. In: Leanza, A.F. (Ed.). Geología Regional Argentina. Academia Nacional de Ciencias, Córdoba, Argentina, pp. 439–506.

Escobar, T.F., 1980. Paleontología y bioestratigrafía del Triásico superior y Jurásico inferior en el área de Curepto, Provincia de Talca. Instituto Investigaciones Geológicas (Chile), Boletín 35, 1–78.

Fang, Z., Boucot, A., Covacevich, V., Hervé, F., 1998. Discovery of Late Triassic fossils in the Chonos Metamorphic Complex, southern Chile. Revista Geológica de Chile 25, 165–173.

Forsythe, R., Kent, D., Mpodozis, C., Davidson, J., 1987. Paleomagnetism of Permian and Triassic rocks, central Chilean Andes. Structure, Tectonics and Geophysics, McKenzie, G. (Ed.). American Geophysical Union, Geophysical Monograph 40, 241–251.

Franzese, J.R., 1995. El Complejo Piedra Santa (Neuquén, Argentina): Parte de un cinturón metamórfico de edad neopaleozoica del Gondwana suroccidental. Revista Geológica de Chile 22, 193–202.

Franzese, J.R., Gómez Pérez, I., Veiga, G., 1998. Estratigrafía sin-rift de la Cuenca Neuquina en el area de los ríos Ñireco y Catán Lil, Neuquén, Argentina. In: X Congreso Latinoamericano de Geología (Buenos Aires), Actas. vol. 1, p. 32.

Galli, C.A., 1969. Descripción Geológica de la Hoja 38c, Piedra del Aguila, Provincias del Neuquén y de Río Negro. Dirección Nacional de Geología y Minería (Buenos Aires), Boletín 111, 1–67.

Gana, P., 1991. Magmatismo bimodal del Triásico superior–Jurásico inferior en la Cordillera de la Costa, provincias de Elqui y Limarí. Revista Geológica de Chile 18, 55–68.

Gana, P., Wall, R., Gutiérrez, A., Yáñez, G., 1994. Geología de la Cordillera de la Costa, regiones de Valparaiso y Metropolitana, al oeste de los 71°00′W. In: VII Congreso Geológico Chileno, Actas. vol. 1, pp. 43–46.

Glazner, A.F., Bartley, J.M., 1985. Evolution of lithospheric strength after thrusting. Geology 13, 42–45.

Gómez Pérez, I., Franzese, J., 1999. Early evolution of the Neuquén Basin (cerro Chachil area, Argentina): relevance for syn-rift hydrocarbon plays. In: Macdonald, D., Flecker, R., (Eds.), The Role of Geological Fieldwork in Hydrocarbon Exploration and Production: Abstracts. Geological Society of London, Petroleum Group and Cambridge Arctic Shelf Programme, Cambridge UK, pp. 43–44 (76 pages).

Groeber, P., 1918. Edad y extensión de las estructuras de la Cordillera entre San Juan y Nahuel Huapi. Physis 4, 208–240.

Groeber, P., 1946. Observaciones geológicas a lo largo del meridiano 70°, I: Hoja Chos Malal. Revista de la Sociedad Geológica Argentina 1, 177–208.

Gulisano, C.A., 1981. El Ciclo Cuyano en el norte de Neuquén y sur de Mendoza. In: VIII Congreso Geológico Argentino, Actas. vol. 3, pp. 579–592.

Gulisano, C.A., Gutiérrez Pleimling, A.R., Digregorio, R.E., 1984. Esquema estratigráfico de la secuencia jurásica del oeste de la provincia del Neuquén. In: IX Congreso Geológico Argentino, Actas. vol. 1, pp. 236–259.

Gulisano, C.A., Gutiérrez Pleimling, A.R., 1994. The Jurassic of the Neuquén Basin, Part (a) Neuquén Province. Asociación Geológica Argentina (Buenos Aires), Serie, E- 2, 111.

Gulisano, C., Pando, G.A., 1981. Estratigrafía y facies de los depósitos jurásicos entre Piedra del Aguila y Sañicó. Departamento Collón Cura, provincia del Neuquén. In: VIII Congreso Geológico Argentino, Actas. vol. 3, pp. 553–577.

Gust, D., Biddle, K., Phelps, D., Uliana, M., 1985. Associated Middle to Late Jurassic volcanism and extension in southern South America. Tectonophysics 116, 223–253.

Hervé, F., 1988. Late Paleozoic subduction and accretion in southern Chile. Episodes 11, 183–188.

Kato, T., 1985. Pre-Andean orogenesis in the Coast Ranges of central Chile. Geological Society of America, Bulletin 96, 918–924.

Kato, T., Godoy, E., McDonough, M., Duhart, P., Martin, M., Sharp, W., 1997. Un modelo preliminar de deformación transpresional mesozoica y gran desplazamiento hacia el norte de parte de la Serie Occidental. Complejo Acrecionario (38°S a 43°S), Cordillera de la Costa, Chile. In: VIII Congreso Geológico Chileno (Antofagasta), Actas. vol. 2, 98–102.

Kay, S.M., 1993. Late Paleozoic tectonics in southern South America. In: XII Congrès International de la Stratigraphie et Géologie du Carbonifère et Permien, Comptes Rendus. vol. 1, pp. 109–122.

King, E.C., Livermore, R.A., Storey, B.C., 1996. Weddell sea tectonics and Gondwana break-up: an introduction. Weddell Sea Tectonics and Gondwana Break-Up, Storey, B.C., King, E.C. (Eds.). Geological Society of London, Special Publication vol. 108, 1–10.

Kusznir, N.J., Ziegler, P.A., 1992. The mechanics of continental extension and sedimentary basin formation: a simple-shear/pure shear flexural cantilever model. Tectonophysics 215, 117–131.

Labudía, C.H., Llambías, E.J., Rapela, C.W., Artabe, A.E., 1995. El Triásico de Los Menucos: Procesos volcánicos y sedimentarios. In: II Reunión Triásico del Cono Sur (Universidad Nacional del Sur, Bahía Blanca), Actas. pp. 17–21.

Leanza, H.A., 1990. Estratigrafía del Paleozoico y Mesozoico anterior a los movimientos intermálmicos en la comarca del cerro Chachil, provincia del Neuquén. Revista de la Asociación Geológica Argentina 45, 272–299.

Legarreta, L., Gulisano, C.A., 1989. Análisis estratigráfico secuencial de la Cuenca Neuquina (Triásico superior–Terciario inferior, Argentina). In: Chebli, G., Spalletti, L. (Eds.), Cuencas Sedimentarias Argentinas.

Universidad Nacional de Tucumán, Serie Correlación Geológica, vol. 6, 221–243.

Legarreta, L., Uliana, M.A., 1996. The Jurassic succession in west-central Argentina: Stratal pattern, sequences and paleogeographic evolution. Palaeogeography, Palaeoclimatology, Palaeoecology 120, 303–330.

Legarreta, L., Gulisano, C.A., Uliana, M.A., (1993). Las secuencias sedimentarias jurásico–cretácicas. In: Ramos, V.A. (Ed.), Geología y Recursos Naturales de Mendoza. In: XII Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos (Mendoza), Relatorio, 1(9), 87–114.

Legarreta, L., Laffitte, G.A., Minniti, S.A., 1999. Cuenca Neuquina: Múltiples posibilidades en las series jurásico–cretácicas del depocentro periandino. In: IV Congreso de Exploración y Desarrollo de Hidrocarburos (Mar del Plata), Actas. vol. 1, pp. 145–176.

Liu, M., Shen, Y., 1998. Crustal collapse, mantle upwelling, and Cenozoic extension in the North American Cordillera. Tectonics 17, 311–321.

Llambías, E., Sato, A., 1990. El Batolito de Colanguil (29–31°S) Cordillera Frontal de Argentina: Estructura y marco tectónico. Revista Geológica de Chile 17, 89–108.

Llambías, E., Sato, A., 1995. Tectónica y magmatismo en el límite Pérmico–Triásico de la Cordillera Frontal. In: II Reunión Triásico del Cono Sur (Universidad Nacional del Sur, Bahía Blanca), Actas, pp. 22–26.

Llambías, E., Caminos, R., Rapela, C., 1984. Las plutonitas y vulcanitas del Ciclo Eruptivo Gondwánico. In: Ramos, V. (Ed.), Geología y Recursos Naturales de la Provincia de Río Negro. IX Congreso Geológico Argentino, Relatorio, 1 (4), 85–117.

Llambías, E., Kleiman, L., Salvarredi, J., 1993. El magmatismo gondwánico. In: Ramos, V.A. (Ed.), Geología y Recursos Naturales de Mendoza. In: XII Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos, Relatorio, 1(7), pp. 53–64.

Manceda, R., Figueroa, D., 1995. Inversion of the Mesozoic Neuquén Rift in the Malargüe Fold and Thrust Belt, Mendoza, Argentina. Petroleum Basins of South America, Takard, A.J., Suárez Soruco, R., Welsink, H.J. (Eds.). American Association of Petroleum Geologists, Memoir 62, 369–382.

Martin, M.W., Clavero, J., Mpodozis, C., 1999a. Late Paleozoic to Early Jurassic tectonic development of the high Andean Principal Cordillera, El Indio Region, Chile (29–30°S). Journal of South American Earth Sciences 12, 33–49.

Martin, M.W., Kato, T.T., Rodríguez, C., Godoy, E., Duhart, P., McDonough, M., Campos, A., 1999b. Evolution of the Late Paleozoic accretionary complex and overlying forearc-magmatic arc, south central Chile (38°–41°S): Constraints for the tectonic setting along the southwestern margin of Gondwana. Tectonics 18, 582–605.

Mpodozis, C., Kay, S.M., 1992. Late Paleozoic to Triassic evolution of the Gondwana margin: evidence from Chilean Frontal cordilleran batholiths. (28°S to 31°S). Geological Society of America, Bulletin 104, 999–1014.

Mpodozis, C., Ramos, V., 1989. The Andes of Chile and Argentina. Geology of the Andes and its Relation to Hydrocarbon and Mineral Resources, Ericksen, G.E., Cañas Pinochet, M.T., Reinemund, J.A. (Eds.). Circum-Pacific Council for Energy and Mineral Resources (Houston TX USA), Earth Science Series 11, 59–90.

Muñoz, B.J., 1984. Cordillera Principal de los Andes de Chile entre Talca (35°L.S.) y Temuco (39°L.S.). In: Seminario Actualización de la Geología de Chile. Servicio Nacional de Geología y Minería (Santiago de Chile), Miscelánea, vol. 4, pp. N1–N15.

Nasi, P.C., 1984. Geología de la Cordillera de la Costa de Chile Central. In: Seminario Actualización de la Geología de Chile. Servicio Nacional de Geología y Minería (Santiago de Chile), Miscelánea, vol. 4, pp. L1–L17.

Nieto-Samaniego, A.F., Ferrari, L., Alaniz-Alvarez, S.A., Labarthe-Hernández, G., Rosas Elguera, J., 1999. Variation of Cenozoic extension and volcanism across the southern Sierra Madre Occidental volcanic province, Mexico. Geological Society of America, Bulletin 11, 347–363.

Orchuela, I.A., Ploszkiewicz, J.V., 1984. La Cuenca Neuquina. In: Ramos, V. (Ed.), Geología y Recursos Naturales de la Provincia de Río Negro. In: IX Congreso Geológico Argentino, Relatorio, 1(4), pp. 163–188.

Pankhurst, R.J., Rapela, C.W., Caminos, R., Llambías, E., Párica, C., 1992. A revised age for the granites of the central Somuncura Batholith, North Patagonian Massif. Journal of South American Earth Sciences 5, 321–326.

Pankhurst, R.J., Riley, T.R., Fanning, C.M., Kelley, S.P., 2000. Episodic silicic volcanism in Patagonia and the Antarctic Peninsula: Chronology of magmatism associated with the break-up of Gondwana. Journal of Petrology 41, 605–625.

Parada, M.A., 1988. Pre-Andean peraluminous and metaluminous leucogranitoid suites in the high Andes of central Chile. Journal of South American Earth Sciences 1, 211–221.

Parada, M.A., Levi, B., Nyström, J.O., 1991. Geochemistry of the Triassic to Jurassic plutonism of central Chile (30° to 33°S): petrogenetic implications and a tectonic discussion. Andean Magmatism and its Tectonic Setting, Harmon, R.S., Rapela, C.W. (Eds.). Geological Society of America, Special Paper 265, 99–112.

Parada, M.A., Nyström, J.O., Levi, B., 1994. The coastal batholith of central Chile (31–34°S): Arc magmatism progressively more inmature with time. In: VII Congreso Geológico Chileno (Concepción), Actas. vol. 2, pp. 1419–1423.

Parada, M.A., Nyström, J.O., Levi, B., 1997. The role of lithospheric delamination during the evolution of the coastal batholith of central Chile (31 to 34°S). In: VIII Congreso Geológico Chileno (Antofagasta), Actas. vol. 3, pp. 1699–1703.

Pysklywec, R.N., Beaumont, C., Fullsack, P., 2000. Modeling the behavior of the continental mantle lithosphere during plate convergence. Geology 28, 655–658.

Ramos, V.A., 1978. Estructura. In: Geología y Recursos Naturales del Neuquén. In: VII Congreso Geológico Argentino (Neuquén), Relatorio, pp. 99–125.

Ramos, V.A., 1984. Patagonia: ¢Un continente paleozoico a la deriva? In: IX Congreso Geológico Argentino, Actas. vol. 2, pp. 311–325.

Ramos, V.A., 1989. The birth of southern South America. American Scientist 77, 444–450.

Ramos, V.A., 1993. Interpretación tectónica. In: Ramos, V.A. (Ed.), Geología y Recursos Naturales de Mendoza. XII Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos, Relatorio, 2(I-19), pp. 257–266.

Ramos, V.A., Kay, S.M., 1991. Triassic rifting and associated basalts in the Cuyo basin, central Argentina. Andean Magmatism and its Tectonic Setting, Harmon, R.S., Rapela, C.W. (Eds.). Geological Society of America, Special Paper 265, 79–91.

Ramos, V.A., Jordan, T.E., Allmendinger, R.W., Mpodozis, C., Kay, S.M., Cortés, J.M., Palma, M., 1986. Paleozoic terranes of the central Argentine–Chilean Andes. Tectonics 5, 855–880.

Rapalini, A.E., 1998. Syntectonic magnetization of the mid-Palaeozoic Sierra Grande formation: further constraints on the tectonic evolution of Patagonia. Journal of the Geological Society of London 155, 105–114.

Rapela, C.W., Alonso, G., 1991. Composición litológica y geoquímica del Batolito de la Patagonia Central. In: VI Congreso Geológico Chileno, Actas. vol. 1, pp. 236–240.

Rapela, C.W., Pankhurst, R.J., 1992. The granites of northern Patagonia and the Gastre fault system in relation to the break-up of Gondwana. Magmatism and the Causes of Continental Break-Up, Alabaster, B., Pankhurst, R. (Eds.). Geological Society of London, Special Publication 68, 209–220.

Rapela, C.W., Spalletti, L.A., Merodio, J.C., 1983. Evolución magmática y geotectónica de la Serie Andesítica andina (Paleoceno–Eoceno) en la cordillera Nordpatagónica. Revista de la Asociación Geológica Argentina 38, 469–484.

Rapela, C.W., Dias, G., Franzese, J., Alonso, G., Benvenuto, A., 1991. El Batolito de la Patagonia Central: Evidencias de un magmatismo triásico–jurásico asociado a fallas transcurrentes. Revista Geológica de Chile 18, 121–138.

Rapela, C.W., Pankhurst, R.J., Llambías, E.J., Labudía, C.H., Artabe, A.E., 1996. Gondwana magmatism of Patagonia: inner cordilleran calc-alkaline batholiths and bimodal volcanic provinces. In: III International Symposium on Andean Geodynamics (Saint Malo), Extended Abstracts, pp. 791–794.

Riccardi, A.C., Damborenea, S.E., Manceñido, M.O., Ballent, S.C., 1991. Hettangian and Sinemurian (Lower Jurassic) biostratigraphy of Argentina. Journal of South American Earth Sciences 4, 159–170.

Riccardi, A.C., Damborenea, S., Manceñido, M., Scasso, R., Lanés, S., Iglesia Llanos, M., 1997. Primer registro de Triásico marino fosilífero de la Argentina. Revista de la Asociación Geológica Argentina 52, 228–234.

Rivano G.S., 1984. Geología del Meso-Cenozoico entre los 31° y 33° Lat. Sur. In: Seminario Actualización de la Geología de Chile. Servicio Nacional de Geología y Minería (Santiago de Chile), Miscelánea, vol. 4, pp. K1–K17.

Sanguinetti, A.S., Ramos, V.A., 1993. El volcanismo de arco mesozoico. In: Ramos, V.A. (Ed.), Geología y Recursos Naturales de Mendoza. XII Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos, Relatorio, pp. 115–122.

Sempere, T., 1995. Phanerozoic evolution of Bolivia and adjacent regions. Petroleum Basins of South America, Tankard, A.J., Suárez Soruco, R., Welsink, H.J. (Eds.). American Association of Petroleum Geologists, Memoir 62, 207–230.

Sengör, A.M.C., 1995. Sedimentation and tectonics of fossil rifts. In: Busby, C.J., Ingersoll, R.V. (Eds.). Tectonics of Sedimentary Basins, vol. 579. Blackwell Science, Oxford UK, pp. 53–118.

Sonder, L.J., England, P.C., Wernicke, B., Christiansen, R.L., 1987. A physical model for Cenozoic extension of western North America. Continental Extensional Tectonics, Coward, M.P., Dewey, J.F., Hancock, P.L. (Eds.). Geological Society of London, Special Publication 28, 187–201.

Spalletti, L.A., 1997. Los sistemas deposicionales fluvio-lacustres en el rift triásico de Malargüe (sur de Mendoza, República Argentina). Academia Nacional de Ciencias Exactas, Físicas y Naturales (Argentina), Anales 49, 109–124.

Spalletti, L.A., 1999. Cuencas triásicas del oeste argentino: Origen y evolución. Acta Geológica Hispánica 32, 29–50.

Spalletti, L.A., Morel, E.M., 1992. La sedimentación fluvial en la etapa inicial de evolución de una cuenca vinculada con fallas activas y vulcanismo explosivo: La Formación Chihuíu (Triásico), sur de Mendoza, Argentina. In: IV Reunión Argentina de Sedimentología (La Plata), Actas. vol. 1, pp. 159–166.

Spalletti, L., Franzese, J., 1996. Evolution of southern South American basins during the Mesozoic. SAMC News (IGCP Project 381: South Atlantic Mesozoic Correlations), vol. 5, pp. 60–62.

Spalletti, L., Franzese, J., 1996. Mesozoic palaeogeography of southern South America. In: III International Symposium on Andean Geodynamics (Saint Malo), Extended Abstracts, pp. 497–500.

Spalletti, L., Arrondo, O., Morel, E., Ganuza, D., 1998. Estudio sedimentológico y paleoflorístico de la Formación Paso Flores (Triásico superior) en el sector occidental del Macizo Norpatagónico. Argentina. In: V Congreso Geológico Chileno, Actas. vol. 2, pp. c395–c413.

Spalletti, L., Artabe, A., Morel, E., Brea, M., 1999. Biozonación paleoflorística y cronoestratigrafía del Triásico argentino. Ameghiniana 36, 419–451.

Stipanicic, P.N., 1967. Consideraciones sobre las edades de algunas fases magmáticas del Neopaleozoico y Mesozoico. Revista de la Asociación Geológica Argentina 22, 101–133.

Stipanicic, P.N., Rodrigo, F., Baulies, O.L., Martínez, C.G., 1968. Las formaciones pre-senonianas en el denomibado Macizo Nordpatagónico y regiones adyacentes. Revista de la Asociación Geológica Argentina 23, 67–98.

Stock, J.M., Hodges, K.V., 1989. Pre-Pliocene extension around the Gulf of California and the transfer of Baja California to the Pacific Plate. Tectonics 8, 99–115.

Storey, B.C., Vaughan, A.P.M., Millar, I.L., 1996. Geodynamic evolution of the Antarctic Peninsula during Mesozoic times and its bearing on Weddell Sea history. Weddell Sea Tectonics and Gondwana Break-Up, Storey, B.C., King, E.C., Livermore, R.A. (Eds.). Geological Society of London, Special Publication 108, 87–103.

Suárez, M., De la Cruz, R., 1997. Volcanismo pliniano del Lias durante los inicios de la Cuenca de Neuquén. Cordillera del Viento, Neuquén, Argentina. In: VIII Congreso Geológico Chileno, Actas. vol. 1, pp. 266–270.

Tankard, A., Uliana, M., Welsink, H., Ramos, V., Turic, M., Franca, A., Milani, E., Brito Neves, B., Eyles, N., Skarmeta, J., Santa Ana, H., Wiens, F., Cirbián, M., López Paulsen, O., Germs, G., De Wit, M., Machacha, T., McG. Miller, R., 1995. Structural and tectonic controls of basin evolution in southwestern Gondwana during the Phanerozoic. Petroleum Basins of South America, Tankard, A.J., Suárez Soruco, R., Welsink, H.J. (Eds.). American Association of Petroleum Geologists, Memoir 62, 5–52.

Turner, J.C.M., 1965. Estratigrafía de Aluminé y adyacencias (provincia del Neuquén). Revista de la Asociación Geológica Argentina 20, 153–184.

Uliana, M.A., Biddle, K.T., 1988. Mesozoic–Cenozoic paleogeographic and geodynamic evolution of southern South America. Revista Brasileira de Geociencias 18, 172–190.

Uliana, M.A., Biddle, K.T., Cerdán, J., 1989. Mesozoic extension and the formation of Argentina sedimentary basins. Extensional Tectonics and Stratigraphy of the North Atlantic Margin, American Association of Petroleum Geologists, Memoir 46, 599–613.

Uliana, M.A., Legarreta, L., Laffitte, G., Villar, H., 1999. Estratigrafía y geoquímica de las facies generadoras de hidrocarburos en las cuencas petrolíferas de Argentina. In: IV Congreso de Exploración y Desarrollo de Hidrocarburos (Mar del Plata), Actas. vol. 1, 1–63.

Varela, R., Basei, M.A.S., Brito Neves, B.B., Sato, A.M., Teixeira, W., Cingolani, C.A., Siga Jr, O., 1999. Isotopic study of igneous and metamorphic rocks of Comallo-Paso Flores, Rio Negro, Argentina. In: II Simposio Sudamericano de Geología Isotópica (Córdoba), Actas, pp. 148–151.

Vergani, G.D., Tankard, A.J., Belotti, H.J., Welsink, H.J., 1995. Tectonic evolution and paleogeography of the Neuquén Basin, Argentina. In: Tankard, A.J., Suárez Soruco, R., Welsink, H.J. (Eds.). Petroleum Basins of South America. American Association of Petroleum Geologists, Memoir, 62. , pp. 383–402.

Vergara, M., López Escobar, L., Cancino, A., Levi, B., 1991. The Pichidangui formation: some geochemical characteristics and tectonic implications of the Triassic marine volcanism in central Chile (31°55′ to 32°20′S). Andean Magmatism and its Tectonic Setting, Harmon, R.S., Rapela, C.W. (Eds.). Geological Society of America, Special Paper 265, 93–98.

Volkheimer, W., 1978. Descripción Geológica de la Hoja 27b, Cerro Sosneado, Provincia de Mendoza. Servicio Geológico Nacional (Buenos Aires), Boletín 151, 1–85.

Wernicke, B., Christiansen, R.L., England, P.C., Sonder, L.J., 1987. Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera. Continental Extensional Tectonics, Coward, M.P., Dewey, J.F., Hancock, P.L. (Eds.). Geological Society of London, Special Publication 28, 203–221.

Wortel, M.J.R., Spakman, W., 2000. Subduction and slab detachment in the Mediterranean–Carpathian region. Science 290, 1910–1917.

Yrigoyen, M.R., 1991. Hydrocarbon resources of Argentina. Petrotecnia, Special Issue (13th. World Petroleum Congress, Buenos Aires), pp. 38–54.

Zöllner, W., Amos, A., 1973. Descripción Geológica de la Hoja 32b Chos Malal, Provincia del Neuquén. Servicio Nacional de Minería y Geología (Buenos Aires), Boletín 143, 1–91.