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The Mercedario rift system in the principal Cordillera of Argentina and Chile (32° SL)

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Abstract

Recent studies carried out in the High Andes of central-western Argentina in the provinces of San Juan and Mendoza have established its stratigraphic and structural evolution. This paper presents new data on the Triassic–Early Jurassic rift system, the depositional sequences, and a synthesis of the tectonic evolution of the region, along with a correlation with the Chilean continental margin.

The paleogeographic evolution of the Cordillera Principal at these latitudes is controlled by the development of the Mercedario rift system. This rift began with the sedimentation of synrift deposits of the Rancho de Lata Formation, during the Rhetian (about 190 Ma). Subsidence was driven by normal faults, locally preserved in spite of the severe tectonic inversion of the Andes during the Cenozoic. Different authors have emphasized that an important extension dominated the transition between the Triassic and Jurassic periods along the magmatic arc in the Coastal Cordillera of Chile on the western side of the Andes. Extension was related to the bimodal magmatism that characterized the evolution of this segment (30°–33° SL). The granitic plutonism and the associated mafic volcanism indicate that they were controlled by extension during 220–200 Ma. The first subduction related granitoids at these latitudes are 170 Ma old (Bathonian).

The geometry of the Mercedario rift system may be reconstructed by the pattern of the normal faults. Rifting was followed by a thermal subsidence that expanded the original area of sedimentation and controlled the paleogeography of the Los Patillos Formation during Pliensbachian to early Callovian times. This period of cooling and thermal subsidence is correlated with magmatic quiescence in the continental margin. The evolution of the basin closely matches the magmatic history of the Chilean continental margin. Subduction at the continental margin began in the Bathonian, together with deposition of the upper section of Los Patillos Formation.

Arc magmatism shifted to the Cordillera Principal during the Kimmeridgian, where it is represented by the volcanic and volcaniclastic deposits of Tordillo Formation.

Early Mesozoic evolution of the Andean system at these latitudes is, thus, reconstructed by a comparative analysis of these two adjacent regions, driven by a common tectonic regime, but through different geological processes.

Resumen

Estudios recientes llevados a cabo en los Andes Principales del centro-oeste de Argentina, en las provincias de San Juan y Mendoza han establecido la evolución estratigráfica y tectónica de esta área. En este trabajo se presentan nuevos datos sobre el sistema de rift del Triásico–Jurásico Temprano, las secuencias deposicionales y una síntesis de la evolución tectónica de la región.

La evolución paleogeográfica de la Cordillera Principal a estas latitudes estuvo controlada por el desarrollo del sistema de rift Mercedario. Este rift comenzó con la sedimentación de depósitos de sinrift de la Formación Rancho de Lata, durante el Rético (aproximadamente 190 Ma). La subsidencia fue conducida por fallas normales, las cuales se encuentran localmente preservadas

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a causa de la fuerte inversión tectónica ocurrida en los Andes durante el Cenozoico. Diferentes autores han enfatizado que una extensión importante dominó la transición entre el Triásico y el Jurásico a lo largo del arco magmático en la Cordillera de la Costa de Chile, en el sector occidental de los Andes. El magmatismo bimodal es asociado a un período de extensión que caracteriza la evolución de este segmento (30°–33° SL). El plutonismo granítico y el volcanismo máfico asociado indica que ellos fueron controlados por extensión durante los 220–200 Ma. Los primeros granitoides asociados a subducción a estas latitudes datan de aproximadamente 170 Ma (Bathoniano).

La geometría del sistema de rift Mercedario pudo ser reconstruida por los patrones de fallas normales. El período de rifting fue seguido por subsidencia térmica que produjo la expansión del área original de sedimentación y controló la paleogeografía de la Formación Los Patillos durante el intervalo Pliensbachiano–Caloviano. Este período de enfriamiento y subsidencia termal es correlacionado con un episodio de quietud magmática en el margen continental chileno. La subducción en el margen continental comenzó en el Bathoniano, junto con la sedimentación de la parte superior de la Formación Los Patillos.

El arco magmático migró en los Andes Principales durante el Kimmeridgiano, donde está representado por depósitos volcánicos y volcaniclásticos de la Formación Tordillo.

La evolución del sistema andino durante el Mesozoico temprano a estas latitudes es así reconstruida mediante el análisis comparativo de estas dos regiones adyacentes, pero con diferentes procesos geológicos, en un régimen tectónico común.

1. Introduction

The Triassic continental basins of central Argentina present a northwest trend, oblique to the main structure of the Andes. Most of the present knowledge from these basins was derived from the eastern foothills, where the Cuyo basin is one of the main oil producers of the Mendoza region. Due to the extreme tectonic inversion of the basins developed along the axis of the Andean fold and thrust belt, their characteristics and tectonic settings were poorly understood.

La Ramada basin is developed between 31° and 32° South latitude, close to the international border of Argentina and Chile. It is composed of a synrift sequence of conglomerates, sandstones and shales associated with tuffs, pyroclastic breccias, and bimodal volcanic rocks. Calcareous sandstones, mudstones, wackestones and black shales characterize the sag sequences. The basin fill is covered by a thick series of gypsum, red beds and marine deposits of late Jurassic–early Cretaceous age and a Cenozoic volcanic cover.

The Mesozoic half graben system together with different mechanisms of tectonic inversion that took place during the Andean orogeny may be unraveled through a structural analysis. Its oblique orientation in relation to the main Andean stresses produced a complex en echelon structure, carried by the different thrust sheets.

The Mesozoic deposits in the High Andes of San Juan have been widely known since the last century due to the exploration accomplished by Stelzner (1873), Schiller (1907, 1912) and Lambert (1943), among others. However, the tectonic setting and the paleogeography of Early Mesozoic sequences were unknown. Recent studies performed in the last years shed some light on the understanding of the structure, biostratigraphy, and tectonic evolution of the region (Alvarez, 1996a; Ramos et al., 1996a, b). This paper reviews the present knowledge of the tectonic evolution and paleogeographic development of the Triassic and Jurassic deposits of the northernmost sector of the Cordillera Principal at the latitude of San Juan (Fig. 1). At the same time, we aim to link the sedimentary history of the basin to the evolution of the continental margin through the tectonomagmatic events recorded in Chile and Argentina.

2. Tectonic setting

The Triassic paleogeography of Argentina and Chile at these latitudes presents some important links on both sides of the Andes, as shown by the early reconstruction of Charrier (1979) and the most recent of Uliana and Biddle (1988), Ramos and Kay (1991) and Ramos (1992). It is evident that Pangea was affected by an important extensional regime related to the almost complete cessation of subduction along the peripheral continental margin of the supercontinent (Kay, 1993). The high temperature thermal anomalies produced by blanketing of the mantle by supercontinents as proposed by Anderson (1982), later modelled by Gurnis (1988), controlled the Pangea break-up, and the consequent dispersal of the different blocks. This process led to the inception of important rift systems along weakness zones of the supercontinent, such as hanging-wall sutures of several collisional orogens around the world. The peripheral development of rift systems in southern South America was controlled by ancient major crustal boundaries among previously amalgamated terranes (Ramos and Kay, 1991; Ramos et al., 1996b) (Fig. 2). Soon after a major period of shortening during the middle Permian, known as the Sanrafaelic orogenic phase, an important interval of quiescence and mild extension originated the Choiyoi acidic magmatism. This extensive rhyolitic plateau,

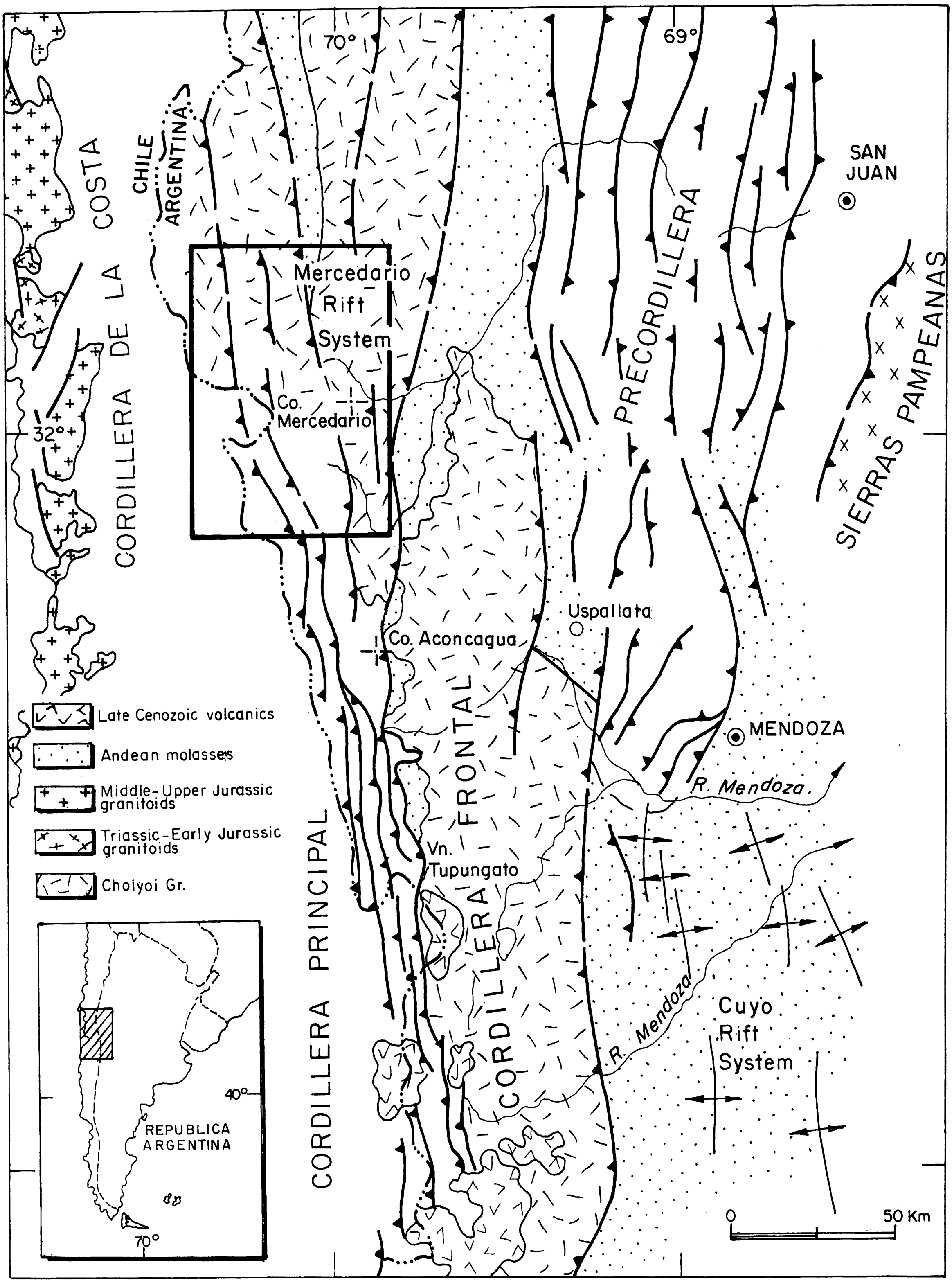

Fig. 1. Location map of the study area with the main tectonic units (based on Ramos and Alvarez, 1996) and location of late Triassic–Jurassic granitoids in the Coastal Range in Chile (based on Gana, 1991 and Parada et al., 1991).

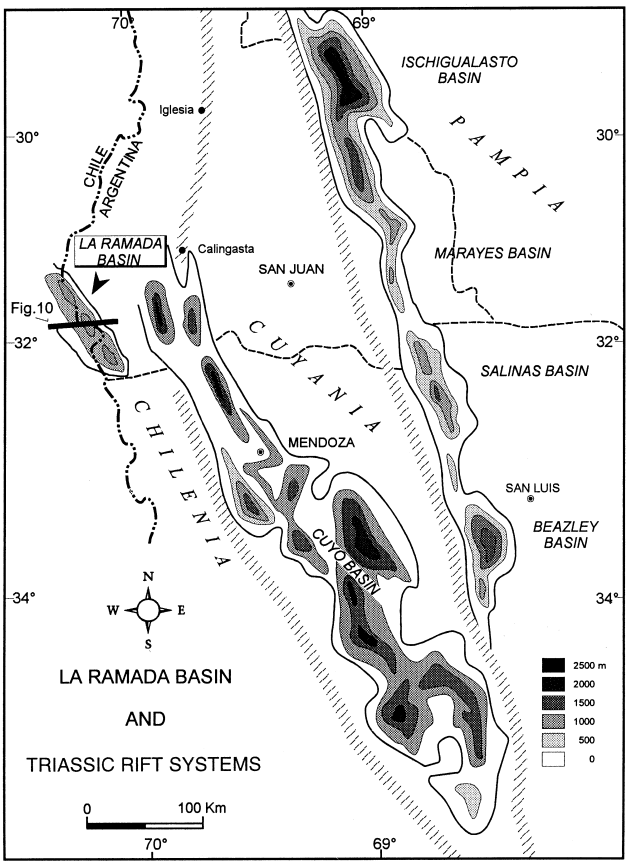

Fig. 2. Inception of the La Ramada basin in the Triassic Rift System of Argentina (modified from Ramos, 1994).

developed along hundreds of kilometers from northern Chile to southern Argentina (Kay et al., 1989), with volcanic piles from 2–4 km thick, is only locally connected with rifting and active extension.

The Mercedario rift system was severely inverted during the Andean compression in Cenozoic times, however, a detailed study of Andean structures permitted a palinspastic restoration of the previous extensional units (see Cristallini, 1996, for details).

The major rift systems were developed during late Triassic times between 235 and 230 Ma. This rifting episode is recorded in several basins, such as the Cuyo, Marayes, Ischigualasto and Puesto Viejo basins by the age of the synrift deposits and associated mafic alkaline magmatism.

The available paleogeographic reconstructions of these rift systems, as described by Uliana and Biddle (1988), Ramos and Kay (1991) and Ramos et al. (1993) have not identified any rifting episode along the High Andes of San Juan and Mendoza. In the Mendoza region (Fig. 2) Yrigoyen (1979) and Ramos (1985 a, b), as well as Cegarra et al. (1993), point out the absence of an Early Jurassic rift. The middle to upper Jurassic marine La Manga Formation was here deposited on an unbroken peneplain developed on the Choiyoi Group volcanics. The studies of Alvarez and Pérez (1993), Alvarez et al. (1995), Cristallini et al. (1995) and Cristallini (1997) demonstrated a different tectonic setting in La Ramada basin developed along the High Andes of San Juan.

3. La Ramada basin

La Ramada basin is a composite basin that began in the late Triassic to early Jurassic as a rift depocenter isolated from the main Andes basins of Argentina and Chile and continued during early Cretaceous time as a retroarc basin. An important topographic high, which was present from the Triassic to the mid Jurassic, separated the La Ramada basin from the Neuquén basin to the south. The high, known since the early studies of Groeber (1918), was located between the Las Vacas and Diamante rivers, in the northern part of the Mendoza province (Fig. 3) and separated two different depocenters with similar geologic history (Alvarez, 1996a).

These basins began as rift systems in a period of null or very slow convergence in the Pacific margin. The beginning of the subduction in the early Bathonian (approx. 170 Ma), as inferred from the magmatic arc activity at these latitudes, marked the inception of thermal subsidence in a retroarc setting. The retroarc basin recorded several depositional sequences, mainly related to eustatic sea-level changes, locally modified by tectonism. Fig. 4 illustrates the stratigraphy of the region.

The early Jurassic outcrops are distributed in three belts: the eastern, central, and western belts, as a result of the Andean tectonics. Each belt presents distinctive stratigraphic and magmatic histories.

4. The Rancho de Lata synrift sequence

The detailed surveys performed along the eastern slope of the Cordón del Espinacito by Alvarez (1991) and Benoit (1992), showed that a sequence of continental deposits developed between the rhyolites and associated pyroclastics of the Choiyoi Group (Permian–upper Triassic), and the marine Los Patillos Formation (early and middle Jurassic) (Alvarez, 1996c). These continental deposits consist of conglomerates, red beds, and tuffs associated with bimodal magmatism that are included in the Rancho de Lata Formation (uppermost Triassic–early Jurassic) (Fig. 4) by Alvarez (1991) and Alvarez et al. (1995). This unit is locally separated by normal faults from the volcanic rocks of the Choiyoi Group.

Chaotic conglomerates at the base; fining-upward sandstones and conglomerates with cross-bedding and fine epiclastic beds bearing abundant microflora and

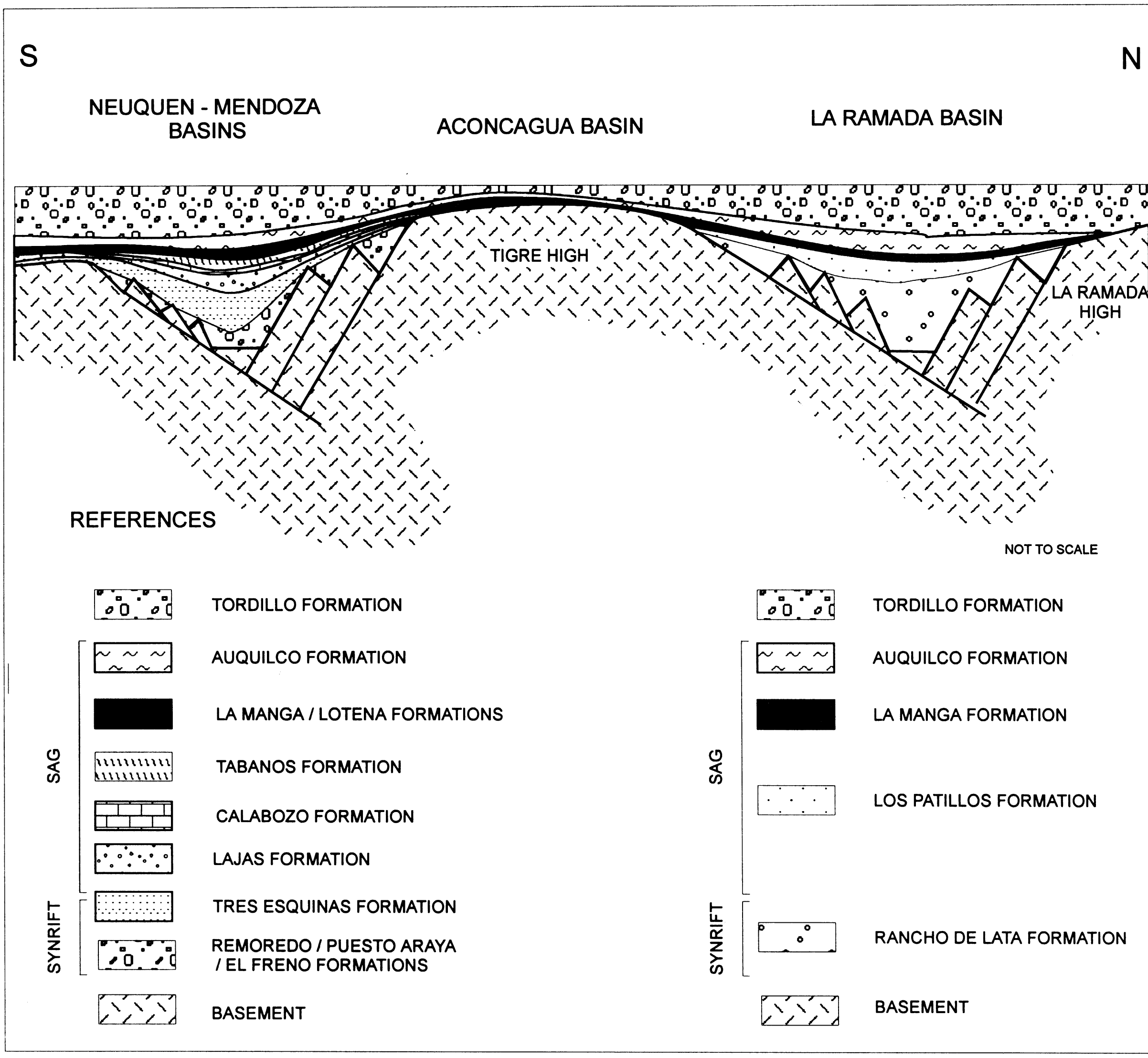

Fig. 3. Schematic section showing the relationship between La Ramada basin and Neuquén–Mendoza basin.

fossil plants, which corroborate its continental origin, characterize the Rancho de Lata Formation. The facies corresponds to fluvial deposits at the base which grade to lacustrine facies towards the top. Locally, some calcareous black shales and thin stromatolites characterize lacustrine facies. The sedimentary sequence is interbedded with pyroclastic products related to explosive volcanism.

The pyroclastic facies consist of ignimbritic breccias, flow tuffs, and Plinian fall tuffs. Surge deposits have been identified at the base. Rhyolitic domes and fissural volcanism are controlled by north-south fractures. Olivine basalts in dikes and sills are widespread within this unit.

The thickness of the Rancho de Lata Formation measured in the eastern belt of outcrops ranges from 100 meters at Río Colorado (Fig. 6), to 150 meters at Espinacito and more than 500 meters in Arroyo Rancho de Lata. In the Central belt, thicknesses of this unit are 150 meters in Arroyo de las Garzas, 140 meters in Ciénaga del Gaucho, and more than 300 meters with unexposed base in Arroyo Las Flores. The Rancho de Lata Formation is 15 meters thick at El Pachón, in the western belt (Fig. 5). These thicknesses denote a pattern of thickening towards the south and the east.

4.1. Lithofacies and depositional system

This sequence corresponds to an early fill of the basin that is associated with acidic volcanism, developed in an extensional regime and controlled by normal faulting. Based on sedimentological characteristics, these synrift deposits are interpreted as continental deposits, as confirmed by terrestrial flora and pollen studies (Ottone et al., 1992).

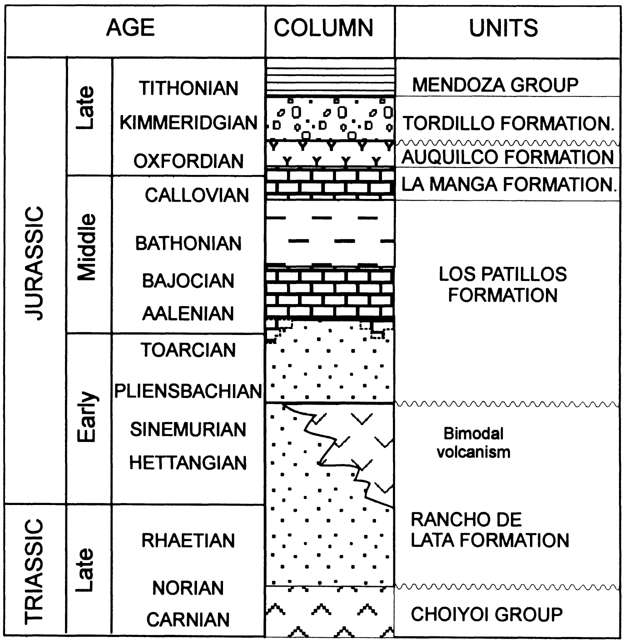

Fig. 4. Stratigraphic chart of the Triassic and Jurassic deposits of La Ramada basin.

The epiclastic facies were deposited in proximal alluvial fans, fluvial, and lacustrine environments, while the pyroclastic rocks are associated with an acidic explosive volcanic event. These pyroclastic facies represent ignimbritic breccias, flow-tuffs, and ash-fall tuffs. They are lithic in composition with the dominant rhyolitic clasts being derived from the Triassic Choiyoi Group. These sequences are locally chloritized, mainly due to the thermal overprint of basaltic dikes. The coarse facies at the base may represent surge deposits, where pyroclastics with contorted lamination are associated with a distinctive preserved breccia.

The upper half of the section belongs to another ignimbritic episode, where several facies have been recognized. It starts with welded tuffs characterized by abundant vitric fiamme. A large volume of crystals and lithics denote the explosive nature of the deposit. Toward the top, flattening of the fiamme decreases and the rock is poorly sorted. The upper part of the deposit includes vitric shards and vesicules, filled with zeolites, clays and glass, indicative of fumarolic activity. At this level lithics and crystals are scarce.

Within the epiclastic facies, chaotic, finning upward conglomerates grade to cross laminated sandy tuffs. Clast composition is mainly volcanic, with a dominance of rhyolites and tuffs. This facies is interpreted as having formed in a braided fluvial environment.

Siltstones and light coloured clays are interbedded with dark levels of calcareous shales, some organic rich, bearing abundant microflora. Within this sequence, stromatolitic levels are locally observed. They have a fine fenestral fabric, characteristic of an unstable intertidal substratum that is cemented by calcareous and fragmentary crusts. This facies indicates rapid sedimentation in an environment characterized by blue and green algae build-ups in warm water, located at the shoreline of a lake in maximum flooding.

A fine-grained conglomerate made up of stromatolite clasts covers the previously described sequence. This may be interpreted as a contraction of the lake shore and subsequent erosion of the inter and supratidal deposits. Fining-upwards cycles of braided fluvial facies are unconformably developed on top of the lacustrine deposits.

A new level of dark gray organic rich shales, with abundant carbonaceous plant remains, was deposited in a lacustrine anoxic environment. This sequence bears abundant palynomorphs and fossil plants, such as *Dicroidium* and *Cordaicarpus* (Alvarez et al., 1995).

An ash-fall tuff in the upper section was deposited in a subaqueous environment. This is inferred by the presence of fresh glass shards, finely oriented parallel to the bed lamination. Ostracods were found in these levels, associated with plant debris and microflora similar to the previous level. The fact that the ashes have not been transported and the occurrence of ripple marks in the sequence shows that deposition took place near a shore lake.

Siltstones with wavy bases are frequent towards the top of the section and are inferred to represent erosion intervals associated with deposition of distal turbidites in a lacustrine environment. These turbidites may be related to water level falls, as deduced from synextensional minor normal faults.

5. The Los Patillos sag phase sequence

The continental synrift deposits are covered by the marine Los Patillos Formation (Fig. 4). This unit consists of calcareous sandstones, packstones, nodular mudstones and tuffs. The sequence starts with a residual conglomerate immediately overlain by fossiliferous limestones. These bioclastic limestones interfinger with characteristic near-shore facies of cross-bedded coarse sandstones. The sequence grades upward to fine sandstones with parallel stratification and massive sandy bioclastic limestones, the latter with densely packed fossil invertebrates. The presence of large logs is indicative of a near-shore, high-energy environment. High energy levels related to storm events are present along this marine sequence up to the Late Aalenian. The deepening of the basin during Bajocian times persists up to the Early Callovian with a minor regression during the Early Bathonian.

The thickness of the Los Patillos Formation in the eastern belt varies from 250 meters in Arroyo Las

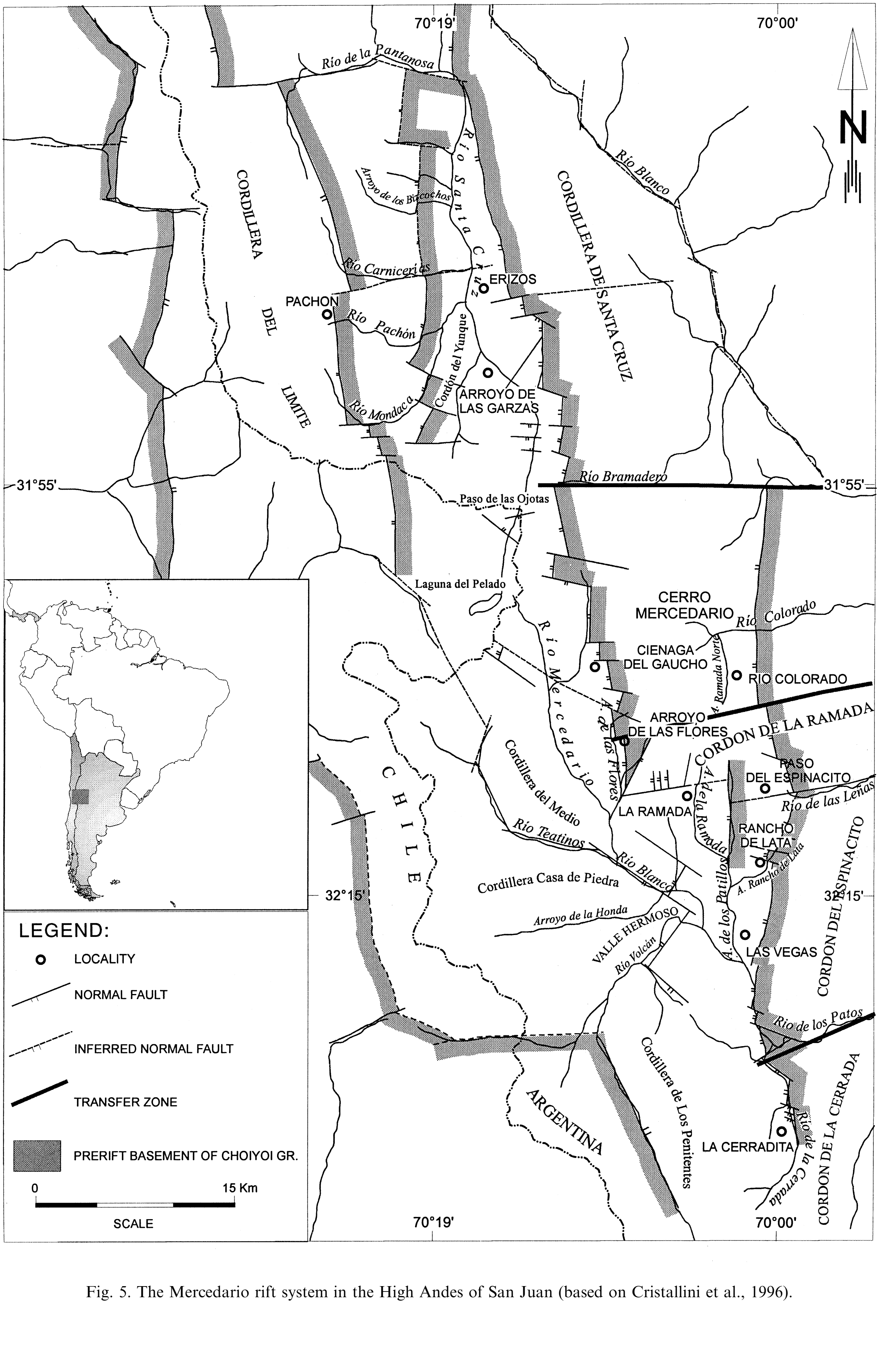

Fig. 5. The Mercedario rift system in the High Andes of San Juan (based on Cristallini et al., 1996).

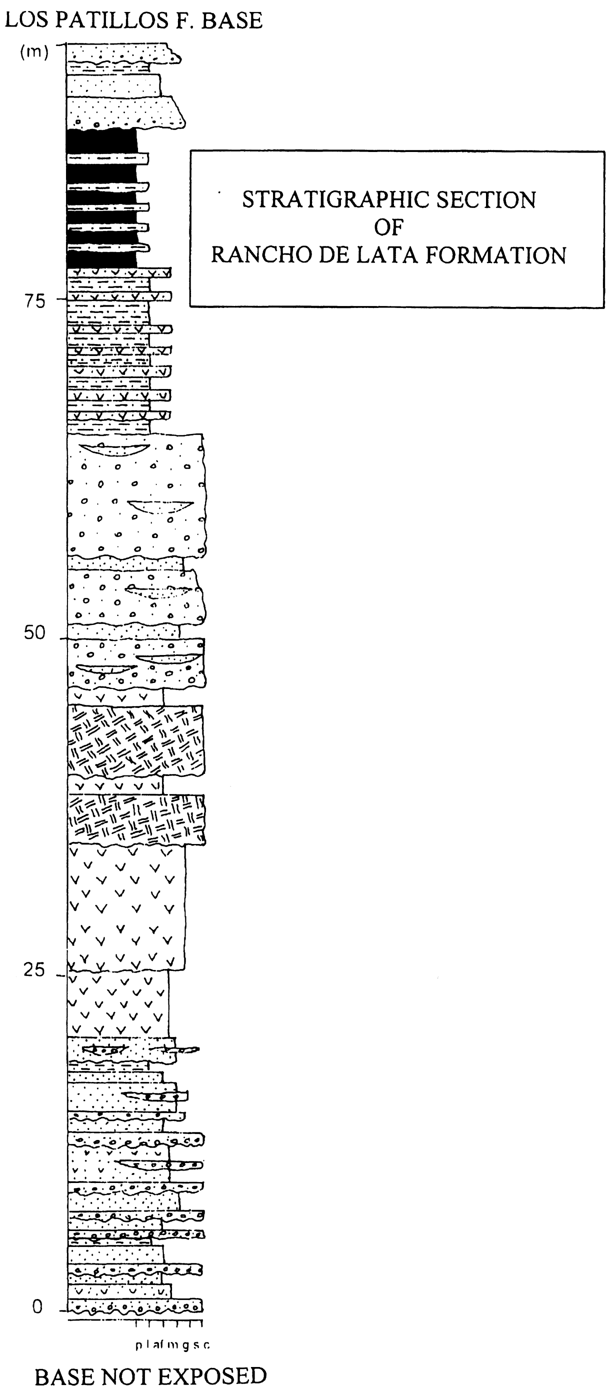

Fig. 6. Stratigraphic section of Rancho de Lata Formation at Río Colorado locality (Late Triassic–Early Jurassic), based on Alvarez (1996a).

Vegas, to 120 meters in Paso del Espinacito to 200 meters in La Ramada (Fig. 7). In the central belt of outcrops, thicknesses are 220 meters at Ciénaga del Gaucho, 115 meters in Arroyo de las Flores (top unexposed), and 150 meters in Arroyo de las Garzas. In the western outcrops, the thickness is 100 meters at Pachón. These thicknesses are indicative of a more homogenous fill than that of the Rancho de Lata Formation and of northwest depocenter trend. The lower Jurassic deposits are only developed in the southern end of the central and eastern belts, whereas the Middle Jurassic is extensive throughout most of the area (see Alvarez, 1996b).

5.1. Lithofacies and depositional system

The lithology and sedimentary structures, as well as the fossil content of the Los Patillos Formation, indicate a typical marine sedimentation. The great abundance of fossils in most of the section suggests that living conditions were extremely favorable. The marine sequence has a sharp contact with the residual conglomerates and consists of fine to medium grained calcareous sandstones, with sedimentary structures indicative of a high flux regime. They are followed by lithoclastic wackestones with shales and siltstones in tabular beds with sharp contacts. These deposits have bivalve and ammonite bioclasts, associated with aligned silicified logs. The sequence is interpreted as a storm dominated marine environment, indicative of a low to transitional shore-face, as evidenced by fine grained sandstones and shales with parallel lamination, and *paschinia* bioturbation on the bed tops. These fine levels alternate with storm beds, characterized by an erosive base covered by shell deposits, that grade upwards to medium to fine sands derived from near shore sectors. During these intervals of high energy, the benthic fauna is remobilized from the substratum and chaotically redeposited. Based on the preservation of the different kinds of shells, a minimum transport is assumed, with the fauna being partially autochthonous, as indicated by the common occurrence of articulated bivalves. These facies of sandstones and wackestones correspond to proximal silicoclastic tempestites, typical of middle shorefaces. The thick, fine- to medium-grained sandstones are interpreted as amalgamate surfaces formed by storm events, characteristic of middle to low shoreface environments. The shales and siltstones are interbedded with fine-grained sandstones and are interpreted as distal tempestites in inner-shelf environments.

Based on the distribution of these sedimentologic features, a deepening of the basin is assumed from Pliensbachian to Toarcian times, as the younger sequences were deposited in deeper environments, dominated by distal tempestites. High energy levels are frequent along the basin border until the Aalenian–Bajocian boundary.

The Bajocian deposits at these latitudes vary from approximately 30 to 60 m thick, depending on their position within the basin. Localities in the central part of the basin, such as Arroyo de las Vegas, Arroyo de la Cerrada and in the Cordón de la Ramada, are

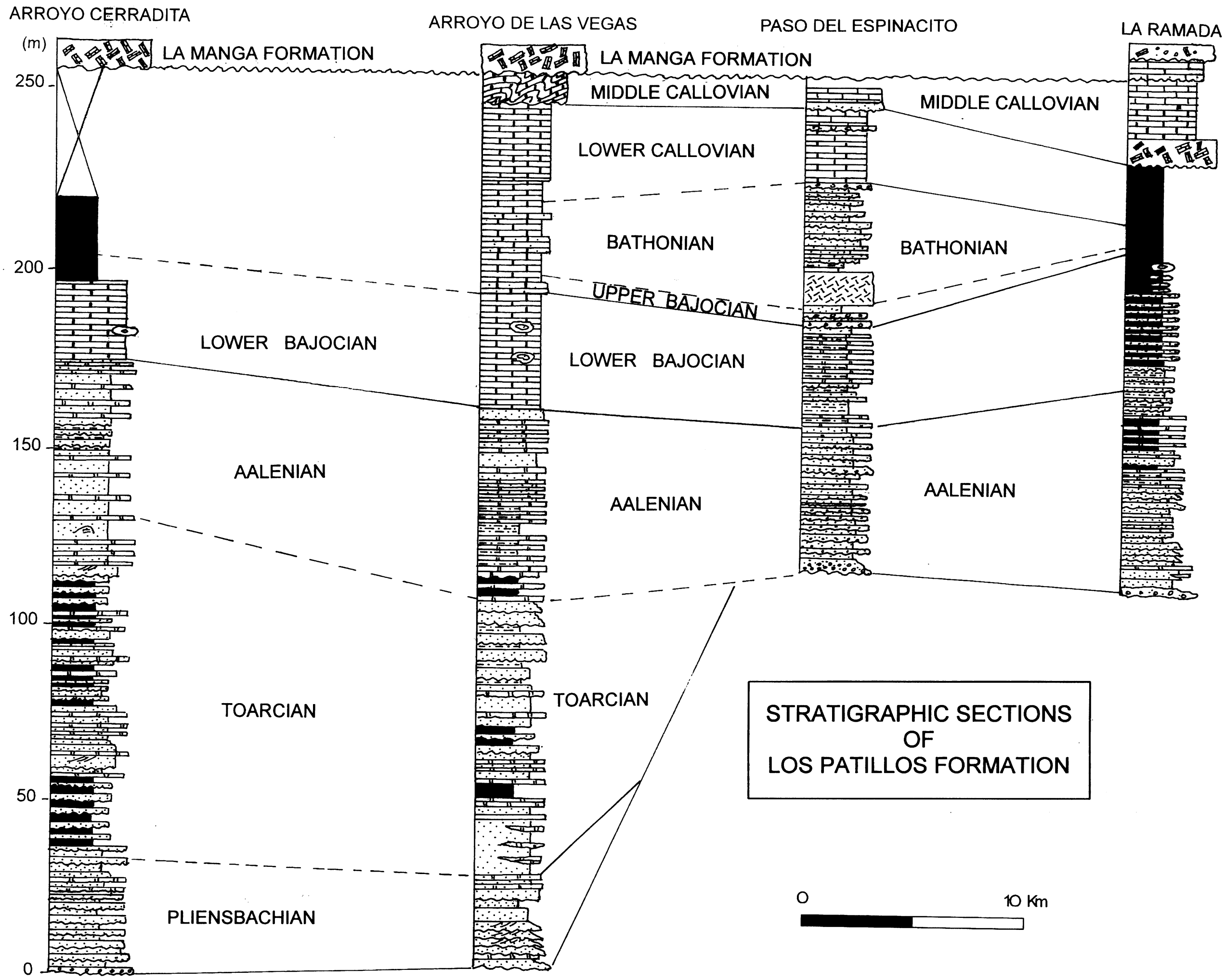

Fig. 7. Stratigraphic sections of Los Patillos Formation (Early–Middle Jurassic) based on Alvarez (1996a).

characterized by offshore sedimentation, composed of black mudstones and shales with high organic content. Levels with carbonate nodules are widely distributed in this sequence in the eastern belt of exposures, showing a generalized episode of chemical precipitation. In most of these localities, condensed sections represent high sea level stands. Coeval deposits at the basin margin consist of medium to fine grained sandstones with low angle cross-bedding, hummocky, and parallel laminations. These facies are interpreted as middle to high shoreface deposits dominated by storm events.

A generalized shallowing of the basin is observed in the late early and late Bajocian, represented by a lowstand system tract, which persisted until the Bathonian. The corresponding sequences are characterized by the alternating of carbonatic fine-grained sandstones and tuffaceous sandstones, which have tabular bedding with parallel lamination, interfingered with lenssoid beds of fine to middle conglomerates. This set of lithofacies is developed in a marginal marine nearshore environment. Shales and mudstones in the interior of the basin represent the basinal facies.

The basal lower Callovian sequences are characterized by conglomerates, which show evidence of remobilization and resedimentation of the older facies. These conglomerates are followed by a flooding episode represented by mudstones and wackestones associated with ooidal packstones levels. These levels are interpreted as a middle to distal carbonate ramp environment.

The uppermost section of Los Patillos Formation, in the eastern belt of exposures, is characterized by red packstones of oysters, no thicker than 10 m thick, associated with an open carbonatic ramp environment.

A carbonatic assemblage of lithofacies was recognized at the central belt of exposures for the early to middle? Callovian. Packstones, oolithic-skeletal grainstones and equinoid and oysters wackestones characterize these facies.

The systematics, along with an analysis of equinoid

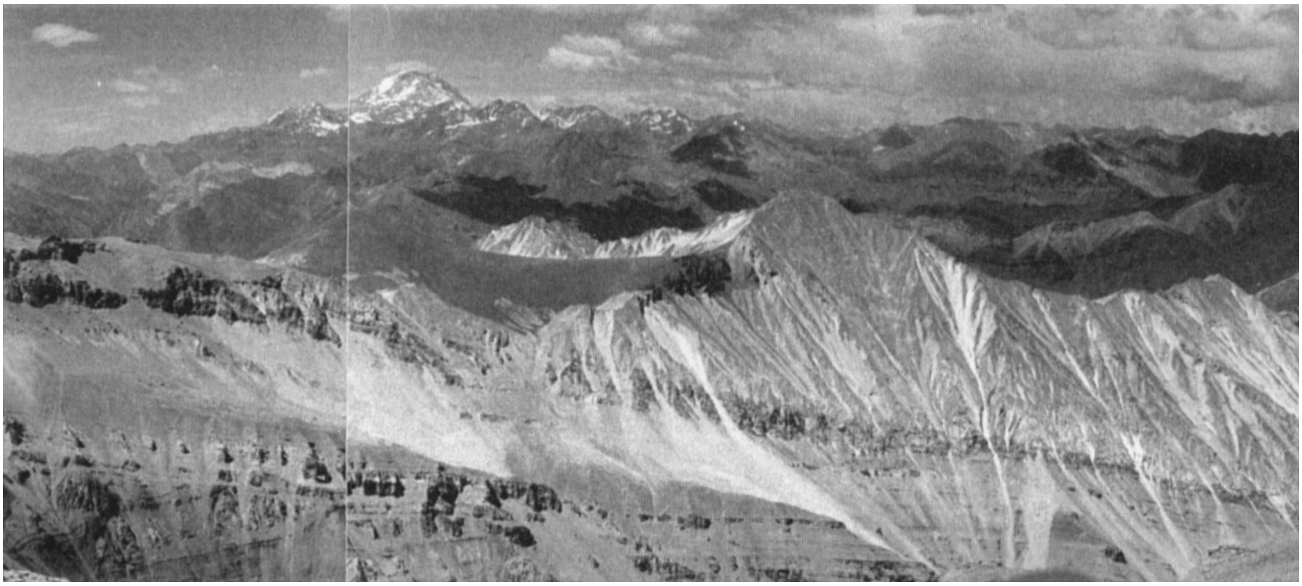

Fig. 8. The synrift deposits and the sag fill along the arroyo Flores. View from the Ramada massif to the south (Ramos and Alvarez, 1996).

morphology of the lithofacies and associated fauna, indicate warm shallow waters in a high energy platform environment associated with frequent storm events. This interpretation is supported by the presence of wackestones and oolithic packstones.

6. Tectosedimentary history

The contact between Los Patillos and Rancho de Lata Formations in most of the sections is conformable, but in some areas such as the Brazo Sur of Arroyo de las Flores and the Cerrada sections, a clear angular unconformity between these units is seen (Figs. 8 and 9). The Arroyo de las Flores area previously studied by Kühn (1914) and Stipanicic (1966), is a well exposed section that characterizes the tectonic setting of the Jurassic sequences. The initial fill is exposed in a series of half-grabens, controlled by west-dipping normal faults, filled with the Rancho de Lata Formation deposits. The highly variable thickness of this unit indicates synrift facies that were deposited during the active faulting of the basin. Above this break-up unconformity, a sequence of shales and sandstones with tabular development overstep the different grabens, without being affected by the normal faulting.

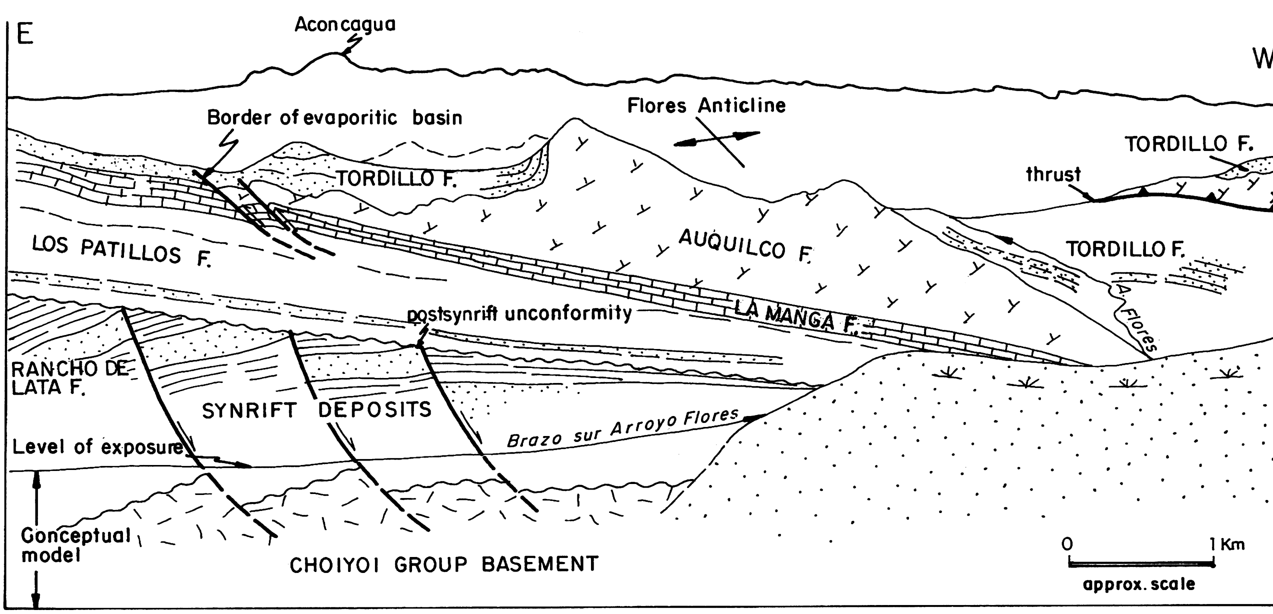

Fig. 9. Structural cross-section of Figure 8, with conceptual interpretation beneath the level of exposures.

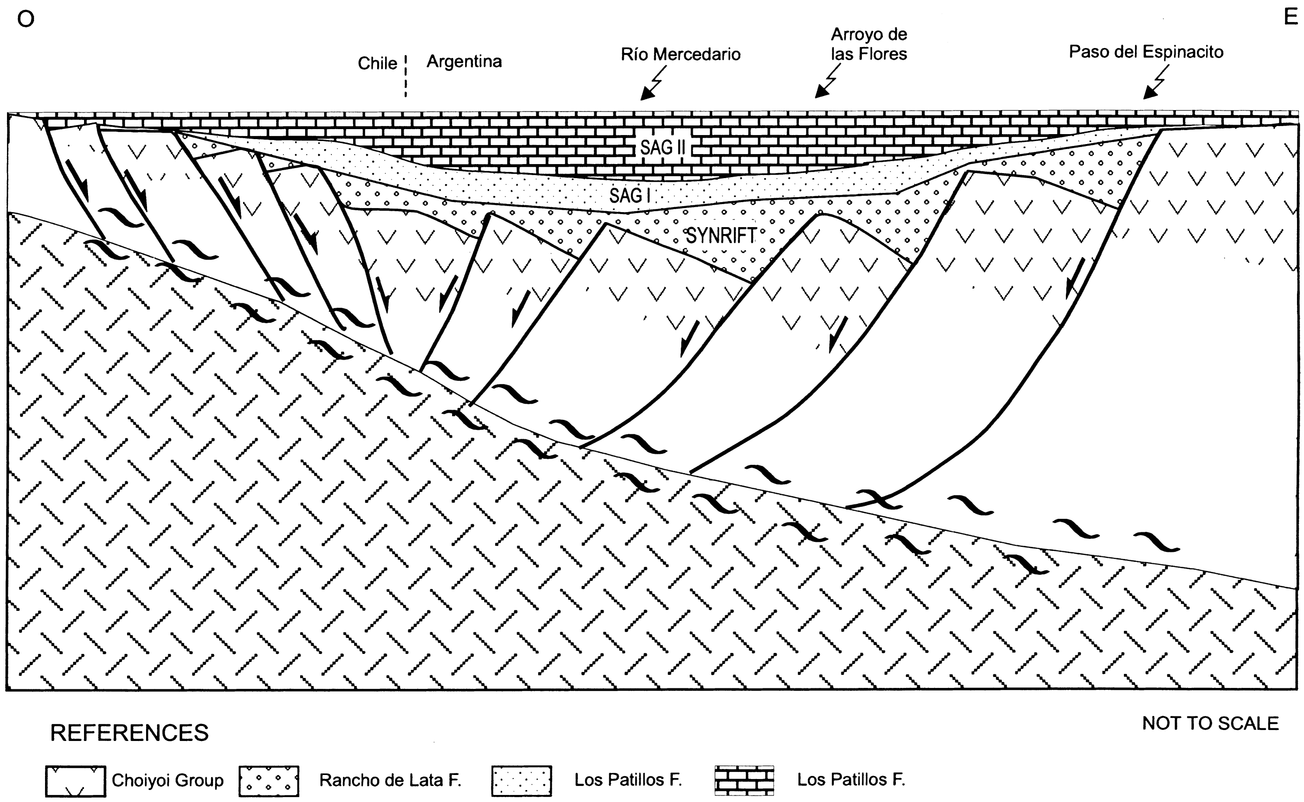

Fig. 10. Schematic cross-section of the Mercedario rift system (see Fig. 2 for location).

Fossil content of this sequence permits correlation of the Arroyo de las Flores section with the type locality of Los Patillos Formation (see Alvarez et al., 1995). The La Manga Formation limestones cover this sequence.

Two cycles have been identified within the thermal sag phase sequences. The lower one corresponds to the early sag, where the marine sequences of Los Patillos Formation developed within the initial early Jurassic depocenters. The upper one corresponds to a late sag and is represented by the middle Jurassic sequences, which have a more generalized subsidence and cover the entire basin. The relationship between both sag sequences is characterized by a coastal onlap. Both units are interpreted as sag facies related to the thermal subsidence of the rift system. They have a wide extent and overlap not only the synrift sequences, but also the prerift sequences of Choiyoi Group in some areas. Locally, as in Arroyo de las Flores, the Jurassic sequence ends with gypsum deposits of the Auquilco Formation (late Oxfordian–Kimmeridgian) and continental red beds of Tordillo Formation. These continental deposits are related to a new sedimentary cycle of Tithonian–early Neocomian age.

Based on the above description, there is no doubt that the Rancho de Lata Formation coincides with the period of active normal faulting while the Los Patillos and La Manga Formations are associated with the thermal postrift subsidence of the Triassic–Early Jurassic basin.

7. The Mercedario rift system

The Mercedario rift system is the first to be identified in the Cordillera Principal of the High Andes of San Juan and Mendoza. The rift consists of an elongated northwesterly trending trough, with an approximate width of 30 km, and an en echelon eastern border (Fig. 5).

A weakness zone within the basement of the Chilenia terrane is assumed, as in most other cases, to control the rift geometry. This zone may correspond to a suture, if Chilenia is interpreted as a composite terrane (Ramos et al., 1996c). Another feasible alternative is to assume a first order synthetic fault zone related to an intense deformation within Chilenia, developed during collision with the Precordillera terrane (Fig. 2). This fault zone should dip to the east and be synthetic to the suture zone between the Chilenia and Precordillera terranes.

A conceptual model for the Mercedario rift is presented in Fig. 10. It corresponds to an asymmetric simple shear rift as proposed by Wernicke (1985) and Wernicke and Tilke (1990), among others. This system began to develop during the early Triassic (Rodríguez

Fernández et al., 1995; Ramos, 1996; Cristallini, 1996), but maximum extension was obtained during the late Triassic and continued up to the early Jurassic, when active faulting ceased.

The rift axis has a northwesterly trend, reconstructed on the basis of the early Jurassic depocenters. These centers are partially isolated by intrabasinal highs. The eastern border of the basin is bounded by two sets of normal faults: north–northwesterly trending faults dipping to the west and east–west faults. This last set, which coincides with the east–west regional lineaments that segmented the Cordilleras of Santa Cruz, La Ramada–Mercedario, Espinacito, and La Cerrada, has been interpreted as an en echelon transfer system (Cristallini et al., 1995).

The western margin of the basin is on the Chilean side of the Cordillera Principal and was not examined in the field. The boundaries have been identified from the geologic map of Illapel (Rivano and Sepúlveda, 1991). The Estero del Cenizo graben is interpreted as the boundary of the west-dipping faults. West of this graben, the normal faults dip to the east, as seen in the Pocuro, Llimpo, and Maquegua faults recognized by Rivano and Sepúlveda (1991).

Based on the Thematic Mapper images, several regional lineaments have also been recognized, complementing the outline of the rift geometry.

Therefore, different direct and indirect criteria were used to identify the rift system developed north and south of Cerro Mercedario, at the southern sector of Cordillera Principal of San Juan. The structural framework was built based on the following evidence:

1. Direct observation of normal faulting and synrift deposits, such as in the Espinacito Pass (Alvarez et al., 1995), Arroyo Flores (Ramos et al., 1993) and Ciénaga del Gaucho (Ragona, 1993; Blengino, 1994).
2. Indirect interpretation of basement control of the Andean structures. For example, at Río Volcán and Los Teatinos, younger deposits cover the early Mesozoic structures. However, the structural interpretation indicates that the thrust plate geometry was modified by a series of lateral and oblique ramps that produced a series of interferences between the eastward transport and the basement geometry (see for discussion Cristallini et al., 1995).

Based on this evidence, a set of northwesterly trending half-grabens can be identified. This system is similar to the one proposed by Charrier (1979), and explains the en echelon pattern of the early to middle Jurassic exposures, oblique to the main north-south Andean trend (Ramos et al., 1993).

8. Rift architecture

The complexity of continental rift systems is strongly influenced by the preexisting fabric. A set of isolated segments is developed at an early stage, connected by oblique or transverse jumps that transfer the fault displacements among segments. These conspicuous jumps have been identified in the Mercedario rift system as orthogonal structures, parallel to the extension direction. The strain concentrates at the surface along the orthogonal structures, outlining the transfer fault traces with an en echelon pattern, similar to that described by Morley (1995). The transfer zones identified in the region are synthetic (*sensu* Morley, 1995), as they separate faults of similar dips. Fig. 5 illustrates east–west transfer zones, which join the different rift segments. The surface pattern of the different blocks is complemented by zigzag faults, transverse strike-slip faults and transfer zones (Alvarez, 1997), although the tectonic inversion may have affected the original structures.

8.1. Rift polarity

The polarity of the master detachment in the Mercedario rift system is based on stratigraphic and structural surface observations. The maximum extensional throws are found in the eastern margin of the rift, where the largest synrift thicknesses have been measured, corresponding to the *c zone* of Wernicke (1985).

The isopachs of the sag-phase deposits of the Los Patillos Formation follow a similar trend, with a gentle pinch-out toward the west. The thermal subsidence has been larger in the eastern sector, indicating an east-dipping master detachment. This implies a larger subcrustal attenuation in this sector with a higher heat flux. As partial evidence of this assumption, a bimodal volcanic activity associated with the initial stages has been identified only in the eastern sector (Alvarez, 1997). The volcanic activity is concentrated in the *c* and *d zones* of the upper plate, according to Wernicke's model, where the maximum heat flux occurs.

All the observations indicate an east-dipping polarity of the master detachment, similar to other Triassic rifts found in Central Argentina (Uliana and Biddle, 1988; Ramos, 1992).

9. The magmatism at the continental margin

Different authors have emphasized that an important extension dominated the transition between the Triassic and Jurassic periods along the magmatic arc

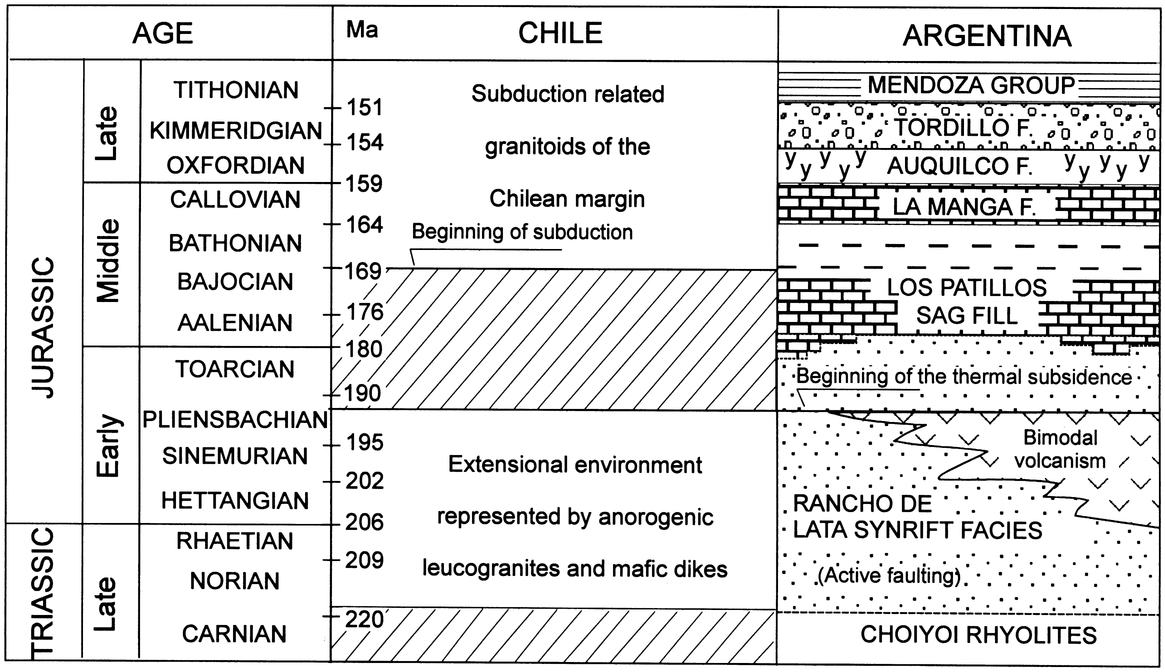

Fig. 11. Main geologic events along both sides of the Andes (30°–33° S).

in the 30°–33° segment of the Coastal Cordillera of Chile.

According to Parada et al. (1991) and Gana (1991), who studied the geochemistry and the petrology of the granitic plutonism and the associated mafic volcanism, the plutonic history of Central Chile between 30° and 33° S shows two distinctive stages for the Mesozoic (Fig. 1).

Leucogranites and mafic dikes that result from partial melting of a quartz-feldspathic source characterize the first stage, probably Upper Paleozoic plutonic rocks (see Parada et al. 1991). This upper Triassic–lower Jurassic bimodal plutonic suite occurs along the Cordillera de la Costa in northern Chile. It consists of leucogranites of the Tranquilla–Millahue Unit, and monzodiorites to gabbros of the Talinay Unit (Gana, 1991). The $Sr^{87/86}$ ratio is high, between 0.7048–0.7134 (Parada 1990). The age of these rocks can be constrained between 220 and 191 Ma (Parada et al., 1991).

Gabbros, diorites, tonalites and minor granites of middle to upper Jurassic age, represent the second stage. This hornblende-bearing suite has lower $Sr^{87/86}$ ratios (0.7033–0.7056) and geochemical affinities of typical subduction related magmatism. The beginning of this second stage can be placed at up to 171 Ma (late Bajocian) (Parada et al., 1991).

Magmatism in the Coastal Cordillera was therefore controlled by extension during 220–200 Ma (Parada et al. 1997) while the first orogenic calcalkaline granitoids and associated subduction are only 170 Ma old (Bathonian).

The paleogeographic evolution of the Principal Cordillera closely matches the magmatic history of the Chilean continental margin. Therefore, the beginning of subsidence on the taphrogenic basin of Rancho de Lata Formation was approximately dated as Rhetian (about 190 Ma). The subsidence of this tectonic basin was driven by normal faults, which are still preserved in spite of the severe tectonic inversion of the Andes during the Cenozoic, along the international border of Argentina and Chile.

10. Concluding remarks

The analysis of the tectonic history along the continental margin of Chile, when combined with the main tectonic events recorded in the High Andes of San Juan shows a striking correlation.

Important extension is recorded in Triassic times along the Coastal Cordillera and in the Principal Cordillera after the amalgamation of Pangea. The bimodal sequence of granitoids and mafic dikes along the continental margin is coeval with active faulting in the Mercedario rift system (Fig. 11). The synrift sequences of Rancho de Lata Formation were deposited at the same time as the emplacement of the Chilean Talinay and Tranquilla–Millahue synextensional magmatic units. The bimodal volcanism at the top of Rancho de Lata coincides with the end of active faulting and the emplacement of the extensional magmatic suites in Chile (Ramos and Alvarez, 1996). The basement fabric controlled the rift architecture. As result of that polarity, the master detachment produced maximum throws in the eastern sector, indicating a regional east dipping detachment.

There is a time interval when no magmatism is registered on the Chilean side at these latitudes. The main tectonic activity is the thermal subsidence of Los Patillos Formation, driven by the lithospheric cooling of the Mercedario rift system. The thermal sag subsidence started along the axis of the rift during Pliensbachian times, continued along the Toarcian in the depocenter of the rift, to finally cover nearly the whole area during Aalenian and Early Bajocian times. Onlap relationships are evident between the depositional center and the peripheral parts of the basin, showing maximum regional subsidence during this period. The age of the marine transgression was constrained by the different ammonite assemblages.

Based on the available ages of subduction-related magmatism along the Chilean border, active subduction started 170 my ago, at the beginning of the Bathonian and has continued since then. This stage is characterized by different sedimentary cycles, probably related to eustatic sea-level changes, partially controlled by the local tectonics of the Cordillera Principal. The Middle Jurassic carbonate platform of La Manga Formation was replaced by the low-stand facies of Auquilco gypsum and by coarse clastic continental sequences by the end of the Jurassic. This fact clearly indicates the progression of the volcanic front to the foreland, as shown by the volcaniclastic provenance of the Tordillo red beds.

A comprehensive tectonic evolution of the continental margin was reconstructed based on two different data sets representing the sedimentary history of the Mercedario rift system in Argentina and the coeval magmatic episodes at the Chilean continental margin.

Based on the data presented here, the previously unknown Mercedario rift system is now incorporated into the tectonic framework and paleogeography of the Late Triassic–Early Jurassic of the High Andes of San Juan.

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