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Abstract: The northern Austral basin from Patagonia is characterized by an Early Cretaceous (Barremian-Albian) coarse-grained regressive sequence. These littoral to continental deposits conform a 150 km long basin cropping out along the Southern Patagonian Andes between 47- 48ºS. In this study we analyze the tectonic setting and provenance during deposition of the coarse-grained sequence using sedimentary petrography in four stratigraphic profiles covering the northern basin. Our dataset indicates mainly a recycled orogenic sandstones provenance, in agreement with potential surrounding basement sources.

Highlights

- ☐ Presentation of four stratigraphic profiles of the first coarse-grained regressive sequence along the northern Austral basin from Patagonia.
- ☐ Sedimentary petrography as tool to study the tectonic setting during the Lower Cretaceous.
- ☐ Provenance analysis shows mainly orogen recycled source and subordinated magmatic arc.
- ☐ Potential surrounding basement sources in agreement with proposed Aptian uplift and exhumation of Patagonia.

Lower Cretaceous provenance in the northern Austral basin of Patagonia from sedimentary petrography

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ABSTRACT

The northern Austral basin from Patagonia is characterized by an Early Cretaceous (Barremian-Albian) coarse-grained regressive sequence. These littoral to continental deposits conform a 150 km long basin cropping out along the Southern Patagonian Andes between 47- 48ºS. The basin fill consist of basal deltaic sandstones with interbedded shales and limestones from the Río Belgrano Formation, topped by up to 350 m of fluvial conglomerates and reworked tuffs of the Río Tarde and Kachaike formations. This continental depocenter represent a major geodynamic and paleoenviromental change from the underling marine Río Mayer Formation. In this study we analyze the tectonic setting and provenance during deposition of the coarse-grained sequence using sedimentary petrography of 37 thin sections in four stratigraphic profiles covering the northern basin. Our dataset indicates mainly a recycled orogenic sandstones provenance, in agreement with potential surrounding basement sources.

Keywords: *Austral basin, Southern Patagonian Andes, Early Cretaceous, sandstone provenance, sedimentary petrography.*

1. Introduction

In the northern Austral basin located between 46,5º and 48,5ºSL in the southern extreme of South America, an isolated Barremian-Albian coarse-grained depocenter developed on top of the previous deep marine sag sequence. This littoral to continental depocenter is recognized along the Southern Patagonian Andes with outcrops restricted to the area between Lago Posadas to the North and Lago San Martín to the South (Fig. 1; Aguirre-Urreta and Ramos, 1981). The depocenter consist of basal sandstones with interspersed shales and limestones from the Río Belgrano Formation, topped by up to 350 m of conglomerates and tuffs of the Río Tarde and Kachaike formations (Fig. 2; Aguirre-Urreta, 1990; Ramos, 1989). Sedimentological studies from Arbe (1986) determine a shallow marine depositional environment near to shoreline, followed by deltaic to fluvial regressive sequences. The Río Belgrano Formation has Hauterivian-Barremian ammonites (Aguirre-Urreta, 1990, 2002), and yielded a ~122 Ma maximum depositional age from detrital zircons (Ghiglione *et al.*, 2014a, 2015). The Río Tarde Formation is constrained to the Aptian-Cenomanian by a ~121.5 Ma peak of detrital zircons at its base, a U-Pb ~112 ± 2 Ma age for a tuff in its mid section (Ghiglione *et al.*, 2015), and tuffs at the top with K-Ar ages of ~99-97 Ma (Ramos and Drake, 1987).

There are currently two main different hypotheses to explain the geodynamic context of this littoral to continental confined depocenter on top of the marine sag. The coarse-grained sandstones could be a response to basement uplift along the Southern Patagonian Andes (Ramos, 1979, 1989; Aguirre-Urreta and Ramos, 1981), and therefore indicate the beginning of the foreland stage in the northern Austral basin. However, in a recent U-Pb study in detrital zircons Ghiglione *et al.* (2014a, 2015) detected Paleozoic basement sources mixed with Lower to Middle Jurassic volcanic detritus, characteristic of Central Patagonia. The latter study related the coarse grained sequences, and the onset of littoral to continental conditions, to uplift and exhumation of the Deseado massif during Aptian post-breakup deformation (Giacosa *et al*., 2010; Dalziel *et al.*, 2013; Heine *et al.*, 2013). Recently, intracontinental deformation in the extra-Andean Patagonia has been related to the development of a broken foreland system in Aptian times (Gianni *et al*., 2015).

First uplift along the Southern Patagonian Andes took place afterwards, during the Late Cretaceous, with deformation concentrated south of Lago San Martín (Fig. 1; Arbe, 1986, 2002; Kraemer, 1998; Ghiglione *et al.*, 2014b). Andean uplift on those sectors produced the onset of the foreland stage in the Austral basin, as is indicated by the appearance of Cenomanian-Turonian coarse sandstones (Fildani *et al.*, 2003; Fosdick *et al.*, 2011, Varela *et al.*, 2012) on top of the sag deposits (Wilson, 1991). Foreland deposits in the Última Esperanza region (Fig. 1; Katz, 1963; Wilson, 1991) contain grains clearly derived from Andean sources, including Paleozoic-Mesozoic metamorphic and ophiolitic complexes, and Upper Jurassic volcanic units (Fildani and Hessler, 2005; Romans *et al.*, 2011). However, between Lagos Viedma and Argentino there are Late Cretaceous sequences with quartzose-recycled sources, most probably from extra-Andean Patagonia origin (Manassero, 1988; Macellari *et al.*, 1989).

We analyzed in this paper the sedimentary petrography of 37 thin sections in four stratigraphic profiles covering the whole Early Cretaceous continental depocenter (see location on Fig. 2), and compare them with the detrital zircons chronological data from Ghiglione *et al.* (2015). The modal composition of the sandstones is not only useful to classify the sedimentary rocks (Folk *et al.*, 1970), but also to establish the composition of provenance areas (Scasso and Limarino, 1997; Tunik *et al.*, 2004; Tunik *et al.*, 2010; Spalletti *et al.*, 2008). Sandstones petrography composition is also a powerful tool to establish the related tectonic setting and to study the geodynamic evolution of the basins (Dickinson and Suczek, 1979; Spalletti *et al.*, 1986). Furthermore, detrital modes are influenced by climate, transportation, diagenesis and depositional environment (Ingersoll, 1978; Dickinson and Suczek, 1979). The objective of the present work is to determine the sedimentary sources of the Lower Cretaceous regressive sequences from the northern Austral basin based on its petrographic composition and its tendency-variations along the stratigraphic column.

2. Geological setting

The Austral Basin, located in southern Patagonia and along the Southern Patagonian Andes, is characterized by three main Mesozoic-Cenozoic tectonic stages: rift, thermal subsidence and foreland stage (Biddle *et al.*, 1986; Robbiano *et al.*, 1996; Ramos, 2002; Kraemer *et al.*, 2002; Peroni *et al.*, 2002).

The rift stage was originated during a Jurassic extensional phase, related to the opening of the South Atlantic Ocean and Gondwana breakup (Uliana and Biddle, 1988; Pankhurst *et al.*, 2000). This phase is represented by volcanic rocks of the Middle to Upper Jurassic El Quemado Complex (Pankhurst *et al.*, 2000). To the southwest the rift stage developed Upper Jurassic oceanic crust in the Rocas Verdes basin (Fig. 1; Calderón *et al.*, 2012). A sag stage followed, represented by the Berriasian-Valanginian siliciclastic sandstones of the Springhill Formation covered by black shales of the Río Mayer Formation (Uliana and Biddle, 1988). The last tectonic stage corresponds to up to 5000 m thick Cenomanian-Miocene foreland deposits on top of the sag units present south of Lago San Martín (Fig. 1; Kraemer and Riccardi, 1996; Fildani *et al.*, 2003; Fosdick *et al.*, 2011, Varela *et al.*, 2012).

3. Stratigraphy

The oldest exposed unit along the northern segment of the Southern Patagonian Andes corresponds to the metasedimentary basement of the Río Lácteo Formation (Bianchi, 1967) of Devonian to Carboniferous age (Giacosa and Márquez, 2002; Augustsson *et al.*, 2006; Hervé *et al.*, 2007). Unconformably or in tectonic contact with the metamorphic basement are the volcanic rocks of the El Quemado Complex (Riccardi, 1971), related to the Jurassic rift stage. The volcanic rocks are conformably covered by a marine platform with siliciclastic sandstones and conglomerates from the Springhill Formation (Thomas, 1949) and black shales from Río Mayer Formation (Riccardi, 1971). The marine sediments represent the Lower Cretaceous sag stage. The latter succession is conformably covered by green sandstones and conglomeratic rocks from the Río Belgrano and Río Tarde formations (Ramos, 1979) of Barremian-Albian age. The Río Tarde Formation is divided into two members based on its pyroclastic content. The lower member is characterized by red conglomerates and sandstones, interpreted as a continental fluvial system of high energy. The upper member is dominated by reworked tuffs, ignimbrites and sandstones deposited in a floodplain (Arbe, 1986).

The Upper Cretaceous is poorly represented north of 50°S, and consists of red continental deposits of the Cardiel Formation (Russo and Flores, 1972) less than 100 m thick. The Cenozoic deposits are around 1500 m thick, and consist of the Eocene Posadas Basalt (Riggi, 1957), followed by the Oligocene marine Centinela Formation (Furque and Camacho, 1972), the thick Miocene synorogenic deposits of the Santa Cruz Formation (Hatcher, 1897, 1900) and the Belgrano Basalt (Riggi, 1957). Quaternary deposits cover widely the piedmont with glacial, fluvial, lacustrine and alluvial deposits.

3.1 Río Belgrano Formation

The Río Belgrano Formation is developed significantly from Lago Pueyrredón to the Arroyo Potranquitas (Fig. 3; Aguirre-Urreta and Ramos, 1981; Relañez, 2014). However, we recognized the northernmost outcrops in the Río Zeballos bridge (46°50´S), consisting of green sandstones in contact above grey shales with parallel lamination, characteristic of the transition between Río Mayer and Río Belgrano formations. The thickness diminish to the south: from 117 m measured in the Río Belgrano stratotype section to 40 m measured in Ea Los Ñires. Other described profiles in the northern sector are 133 m thick at the Río Tarde canyon (Homovc, 1980), and 160 m in the southwestern coast of Lago Pueyrredón (Aguirre-Urreta, 2002).

The age based on fossils is Barremian to Aptian (Aguirre-Urreta, 1990; 2002), in agreement with a ~122 Ma maximum depositional age from detrital zircons (Ghiglione *et al.*, 2015). The Río Belgrano Formation is characterized by green sandstones with limestone intercalations and calcareous sandstones. The sedimentary environment is defined as a marine platform near coastline (Ramos, 1979) to deltaic (Pöthe de Baldis, 1981; Arbe, 2002).

3.2 Río Tarde Formation

The Río Tarde Formation overlies the Río Belgrano Formation in concordance or erosive discordance. The formation is divided into two members: the lower member is characterized by red conglomerates and sandstones, and the upper member is dominated by tuffs and tuffaceous sandstones. The age of this unit can be constrained to the Aptian-Cenomanian by a ~121 Ma age from detrital zircons at its base, a U-Pb ~112 ± 2 Ma age for a tuff in its mid section (Ghiglione *et al.*, 2015), and tuffs at the top with K-Ar ages made in biotite and plagioclase of ~99-97 Ma (Ramos and Drake, 1987), in agreement with previous stratigraphic considerations (Aguirre-Urreta and Ramos, 1981; Arbe, 2002). To the south a correlation can be made with the late Aptian - early Cenomanian Kachaike Formation (Fig. 3; Riccardi, 1971; Ramos, 1979; Riccardi and Rolleri, 1980). The upper member is also regarded as equivalent to the volcanic Divisadero Formation of the Northern Patagonian Andes (Ghiglione *et al.*, 2015), geochronologically constrained between 118 and 116 Ma (Pankhurst *et al.*, 2003).

3.3 Kachaike Formation

This unit is recognized from Ea. Los Ñires to the north, in concordance and net contact over the Río Belgrano Formation (Figs 2 and 3), while the southernmost outcrops are south of Lago San Martín (Fig. 1). Dominated by varicolored tuffaceous sandstones, it preserves trunks, leaves, ammonites and bivalves. Rebassa (1982) assigned the environment to a coarse-grained deltaic plain with interbedded prodelta shales. The abundant palynological assemblages are late Aptian - early Cenomanian (Archangelsky and Llorens, 2005; Guler and Archangelsky, 2006), and the ammonites fauna is late Aptian (Aguirre-Urreta, 2002).

3.4 Stratigraphic profiles

We present four new stratigraphic profiles covering the whole Early Cretaceous continental depocenter (Figs 3 and 4), and studied its sandstone petrography in an attempt to determine the sources of the sediments and the related geodynamic setting. The contact between the black shales of Río Mayer Formation and the sandstones of Río Belgrano Formation is transitional. Note that in “Estancia Los Ñires” and “Arroyo Potranquitas” profiles, Kachaike Formation is considered as equivalent to Río Tarde Formation.

a) Río Oro profile

The sedimentary profile on the SE side of Río Oro includes the Río Belgrano and lower Río Tarde formations (Figs 2 and 4). The measured section of Río Belgrano Formation is composed of 40 m thick green sandstones of fine to medium grain sizes and interspersed fine conglomerates (Fig. 4): The first 9 m includes medium to fine sandstones, with flaser, wavy and cross bedding, and intercalated conglomeratic sandstones with erosive bottoms. A continuous 2 m thick bed of conglomeratic sandstones follows, containing pelecypods, gastropods and corals. The section continues with 8 m of thinning-upwards medium sandstones in 50 cm thick banks, whose grain size continuously decreases to shale, followed by 6 m of shale and 5 m of fine massive sandstones. The section ends with 10 m of conglomeratic to sandstone thinning-upwards banks with erosive base and parallel to cross bedding.

The measured thickness of the overlying Río Tarde Formation includes the basal 40 m of the lower member (Fig. 4): the first 12 m are thinning-upwards banks of red conglomerates to medium sandstones, with erosive base, parallel and cross-bedding. The section continues with 11 m of coarse to medium sandstones and tuffs, and 9 m of thinning-upwards red conglomeratic banks, with erosive base. The measured section ends with 7 m of sandstones with silicified trunks.

b) Río Belgrano profile

The profile includes only the Río Belgrano Formation, since the lower Río Tarde Formation is covered. We precisely measured a 117 m high profile (Fig. 4):

The first 26 meters include 5 m of alternating banks of medium sandstones and silt at the base, and 7 meters of green medium sandstones with parallel lamination to the top. Above, follows 2 meters of medium sandstones with parallel lamination, and 5 m of fine to medium sandstones.

The section continues with 56 m of beds between 2 and 5 m thick, showing cross ripple lamination at the bottom and parallel lamination, planar, sigmoid and tangential stratification toward the top. Levels of concretions can be identified.

The last 35 m are coarser, starting with 6 m of medium sandstones with trough cross-bedding and concretions at the base, topped by 1 m of fine conglomerates. 14 m of medium to coarse sandstones with parallel lamination follows, topped by a thin level of limestone with concretions. The sections ends with 5 m of conglomerates and a thinning-upwards bank from coarse to very fine sandstones with parallel lamination.

c) Estancia Los Ñires profile

The measured thickness in Estancia Los Ñires is 179 m, and includes the Río Mayer, Río Belgrano and Kachaike formations.

The 86 m thick Río Mayer Formation is dominated by shales including concretions and ammonites, and interspersed fine sandstones.

The Río Belgrano Formation overlies in concordance, with 12 m of fine sandstones with parallel lamination, concretions and remnants of bivalves. The section continues with 2 m of fine laminated sandstones with bivalves and trunks. In erosive contact there is 0.5 m of conglomerates at the base of a 2 m thick bank of medium sandstones with remnants of bivalves. A 7 m bank of fine sandstones with fossils trace follows. The section continues with 6 m of medium sandstones with trough cross bedding and carbon, and 8 m of coarse sandstones with concretions. The section ends with 3 m of medium sandstones with trough cross bedding and two thin banks of conglomerates.

The Kachaike Formation overlies in net contact. Its total thickness is 53 m made of tuffaceus sandstones with intercalations of shales and carbon, and abundant remnants of vegetation.

d) Arroyo Potranquitas profile

The measured thickness of Arroyo Potranquitas profile is 350 m, including the Río Mayer, Río Belgrano and Kachaike formations.

The Río Mayer Formation is dominated by shales with thin intercalations of very fine sandstones. The proportion of sandstones increases to the top.

We follow the 47 m thick profile of Relañez (2014) for the Río Belgrano Formation: The profile starts with 5 m of massive fine sandstones with a level of medium sandstones, concretions and ripple cross lamination, along with remnants of bivalves. There is a thin level of carbon, of centimeters range, with horizontal lamination. It is followed by 8 meters of limestones to fine sandstones with horizontal lamination and rests of bivalves. The section continues with 9 meters of limestones, and a thickening-upwards 16 m bank of fine to medium sandstones, with levels of concretions, ripple lamination and remnants of bivalves. The Río Belgrano Formation culminates with 4 meters of medium sandstones with horizontal lamination and concretions to the top.

In concordance continues the Kachaike Formation, where 140 m of medium to coarse sandstones tuffs, level of shales and remnants of leaves have been measured.

4. Samples and analytical methods

To characterize the petrographic composition, 37 samples of coarse to fine grained sandstones were collected (Fig. 4). The samples were studied under a polarized microscope (Fig. 5) and classified following the scheme of Folk *et al.* (1970), using monomineral quartz (Qm), feldspars (F), and lithics plus polycrystalline quartz (Lt) components (QmFLt diagram, Fig. 6). Approximately 500 framework grains and intergranular space components were counted per thin section for quantitative petrographic analysis, with spacing greater than average grain size. Following the Gazzi-Dickinson method (Ingersoll *et al.*, 1984), fragments monominerals >62 µm within lithoclasts were counted as monomineral clasts. The count was made on 37 thin sections, using a Swift point counter.

Modal components taken into account were of second order, therefore quartz separates in monocrystalline and polycrystalline quartz, feldspars were distinguished between potassic feldspar and plagioclase, and the lithic fragments were differentiated in volcanic, sedimentary and metamorphic (Fig. 5). These components are used to discriminate the tectonic source area as proposed by Dickinson and Suczek (1979) (Fig. 7). Modal composition was determined on the 37 thin sections: 3 from Río Mayer Formation, 28 from the Río Belgrano Formation, 2 from the Río Tarde Formation and 4 from the Kachaike Formation.

A complementary clast composition study was made in conglomerates from the lower member of Río Tarde Formation, in Río Oro profile. They are illustrated separately in Figure 8a, because they do not meet the standard for sandstone petrography.

5. Sandstones and conglomerate petrography

The basic petrographic characteristics are described in Table 1. The recalculated framework modes are presented in Table 2. Most samples are classified as litharenites and feldspathic litharenites following the classification of Folk *et al.* (1970). According to the textural definitions of sandstones by Dott (1964), all samples are arenites.

Most of the samples are clast-supported and moderately sorted, with straight to convex-concave grain contacts, while porosity is low to absent. The predominant cements in the two northern sections are oxides and carbonates. In the southern profiles, ferromagnesian and magnesian phyllosilicates can be found in the cements, in addition to iron oxides and carbonates.

Sandstones of the Río Belgrano Formation are very fine to coarse, moderately sorted and contain subangular to subrounded clasts. Based on Folk *et al.* (1970) (Fig. 6, Table 2) the sandstones of Río Belgrano Formation are mostly feldespatic litharenites to litharenites, with one litharenite feldspatic and one sublitharenite in the Río Belgrano profile.

The Río Mayer Formation is composed of sublitharenites and litharenites. The lower member of Río Tarde Formation and Kachaike Formation are mostly litharenites, with one lithic feldsarenite.

Conglomerates from the basal Río Tarde Formation are polymictic with well rounded clasts, moderate to well sorted and carbonatic cements. The clasts were separated between metasedimentary (MS), silicic volcanic (SV) and supplementary material (SM). Most clasts derive from low grade metamorphic rocks (Fig. 8a).

6. Provenance analysis

Dickinson and Suczek (1979) have tectonically characterized source areas using ternary diagrams. The diagrams use three basic components (Q-F-L); Q: cherts and quartz including polycrystalline and monomineral; F: feldspars; and L: lithics. The QFL diagram distinguishes three fields: continental blocks, recycled orogens and magmatic arcs. The Qm-F-Lt diagram, previously used for sandstone classification, subdivides the recycled orogen field into quartzose, transitional, and lithics recycled with most differences between monocrystalline quartz and total lithics, and adds a so-called “mixed” field (Fig. 7b). It is important to note that detrital modes are the result of several factors as climate driving erosion processes, transport mechanism, distance from source area, and diagenesis (Dickinson and Suczek, 1979; Marsaglia and Ingersoll, 1992; Ingersoll *et al.,* 1993).

The littoral and marine environments studied in this paper are effective to determine the tectonic conditions of provenance (Dickinson and Valloni, 1980). Furthermore, Ingersoll *et al.* (1993) states that in specific types of basin such as volcanic arcs of foreland basins, the local scale sample of first and second order is appropriated. Table 2 shows the results of the detrital modes (point counting) obtained for the 37 thin sections we analyzed. We built the ternaries diagrams (Fig. 7) proposed by Dickinson and Suczek (1979) to characterize the possible source area for the Río Belgrano, Río Tarde and Kachaike formations.

7. Results

We analyze first the results of the counting from each profile, from base to top, according to each formation. Then we look for tendencies from North to South in an attempt to determine the sedimentary sources. Figure 7 shows the ternary diagrams proposed by Dickinson *et al.* (1983) and the modal components of the analyzed samples plotting.

Río Oro profile

In the QFL diagram the samples of Río Belgrano Formation show a strong tendency since most of them plot in the recycled orogen field (Fig. 7a). There are two samples in the dissected and transitional arc fields. In the Qm-F-Lt diagram most of samples lay in the quartzose recycled field, while there are one in each of the dissected arc, transitional arc and transitional recycled orogen fields (Fig. 7b).

In this profile, the petrographic analysis revealed a higher percentage of sedimentary and metamorphic lithics than of volcanics lithics.

Río Belgrano profile

The samples of Río Belgrano plotted in the diagram QFL are also concentrated in the recycled orogen field, although three samples plot in the transitional arc and dissected arc fields (Fig. 7a). In the Qm-F-Lt diagram the samples vary from dissected arc, mixed, transitional to quartzose recycled fields, without a clear tendency (Fig. 7b).

The relation between lithic fragments shows mainly a volcanic and metamorphic origin in a variable proportion, and subordinated sedimentary lithics.

Estancia Los Ñires profile

The diagram QFL shows clustering in the recycled orogen field for the Río Mayer and Belgrano formations (Fig. 7a). The samples from the Kachaike Formation are in the recycled orogen and transitional arc fields. On the Qm-F-Lt diagram the samples from the Río Mayer and Río Belgrano formations lay in the quartzose recycled to transitional recycled orogen fields (Fig. 7b). Samples from Kachaike Formation plot in the transitional recycled orogen and transitional arc fields.

The lithic fraction is dominated by sedimentary and volcanic fragments, and subordinated clasts of metamorphic origin.

Arroyo Potranquitas profile

Río Mayer and Río Belgrano formations lay in the field of recycled orogen for the QFL diagram (Fig. 7a) and quartzose recycled orogen field for the Qm-F-Lt diagram (Fig. 7b). Kachaike Formation samples plot between recycled orogen and dissected arc fields.

The volcanic fragments compose around ~85% of the lithic fraction, with subordinated low-grade metamorphic and sedimentary lithics.

General tendencies

The Río Mayer Formation is clearly clustered in the recycled orogenic (QFL) - quartzose recycled (QmFLt) fields. The Río Belgrano Formation is clustered in two clear groups when all the profile are considered (Fig. 7): Group one, with a predominant content of quartz plot in the recycled orogenic (QFL) and quartzose recycled (QmFLt) fields; a Group two with a greater proportion of lithics and feldspars is dispersed between the arcs fields and transitional recycled fields. Samples from the Río Tarde and Kachaike formations can also be divided in those two groups defined for the Río Belgrano Formation (Fig. 7).

We therefore define two evident groups, interspersed along the stratigraphic column. Group one with a great proportion of quartz, is clustered on the upper fields of the diagrams, indicating quartzose recycled orogen sources. Group two with greater proportion of lithics and feldspars, indicate mixed sources that also includes a magmatic arc and a recycled orogen. The fluctuating proportions of components are shown in the Table 2, where samples are arranged in stratigraphic order for each profile.

We recognized an increase of the relative proportion of lithics volcanic fragments toward the southern profiles.

8. Discussion and conclusions

The detailed petrographic analysis of the Lower Cretaceous depocenter for the northern Austral basin of Patagonia indicates predominant metamorphic basement sources with provenance field from a quartzose recycled orogen. We also detected interspersed events were the proportion of lithics fragments increased. The recognized lithics are predominantly metamorphic in the northern profiles and volcanic to the south.

Possible detritus sources from metamorphic origin correspond to the sedimentary and metasedimentary late Paleozoic basement. Known as Río Lácteo or Bahía La Lancha formations in Argentina and Eastern Andes Metamorphic Complex (EAMC) in Chile, these low grade metamorphic rocks contain quartz, albite, white mica, and chlorite (Hervé *et al*., 2008).

The metamorphic lithics further corroborates the basement source for the northern profiles and the Lago Posadas and Río Belgrano area, in agreement with the previously proposed uplift and exhumation of the surrounding basement blocks. In the northern Patagonian Andes there is a contractional phase during the Aptian evidence by a regional unconformity (Folguera and Iannizzotto, 2004; Suárez *et al*., 2010) that also could have exposed methamorphic rocks.

The volcanic lithics are potentially linked to the synrift Jurassic magmatism or the active volcanic arc. These volcanic rocks could come from thrusts located to the West of the depocenter that exposed the Quemado Complex or may be related to an increase in volcanic activity. The volcanic rocks could also come from the synrift of the Deseado Massif, since both sequences has the same lithology (Pankhurst *et al*., 2000). To the West, the contemporaneous volcanism is from Ibañez and Tobífera formations during the Jurassic. To the North Patagonian Massif, an equivalent volcanic unit for the V1 stage corresponds to the Lonco Trapial Formation (Feraud *et al*., 1999; Zaffarana and Somoza, 2012; Cúneo *et al*., 2013). To the North Patagonian Andes, the Batholith in the Bariloche area has U-Pb zircon ages between 170-150 Ma (Castro *et al*., 2011). Based on the volcanism links, we consider the Quemado Complex and the Deseado Massif as the main sources because of their spatial locations: they're the closest potential sources at the regional scale.

We found very low proportions of potassium feldspars in the petrographic analysis of the sandstones, neither plutonic texture in the studied conglomerates clasts (Fig. 8a). These features allow us to discard the Early Jurassic Subcordilleran Batholith (Gordon and Ort, 1993; Rapela *et al*., 2005) as source for the lithics of the recycled orogen field. Also, we couldn´t assigned them to the contemporaneous volcanic acid suites because of the scarce samples with magmatic arc provenance (Fig. 7).

Recent U-Pb ages of detrital zircon samples obtained in the same units (Ghiglione *et al*., 2015) suggests a strong correlation with the petrographic analysis. According to patterns of U-Pb ages on zircon, three groups are distinguished (Fig. 8b): a group between 140 and 120 Ma assigned to a volcanic arc active during Lower Cretaceous sedimentation; a group between 188 and 145 Ma corresponding to volcanics from El Quemado Complex, and a third Paleozoic-Precambrian group from basement sources. The two younger groups represent the volcanic lithics, and the older group the metamorphic lithics as described in our petrographic analysis.

In summary, our study shows that the particular Lower Cretaceous continental depocenter developed in the northern Austral basin received mainly basement detritus consistent with its previously proposed synorogenic character (Suárez *et al*., 2010). Even though the orogen recycled samples could also come from the northern Patagonian or the Subcordilleran Batholith, we dismiss such source of sediments because of the low percentage of potassium feldspars and the absence of plutonic textures. The sporadic apparition of volcanic detritus is most likely associated to episodic contemporaneous source from the volcanic arc.

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FIGURE CAPTIONS

Figure 1: Location of the study zone (black square) from high-resolution digital elevation model (DEM; Mercator projection, NASA-SRTM) showing sediment distribution from Austral basin. Patagonian basins and site locations mentioned in the text are also shown. Contours indicate foreland sediment thickness within the undeformed depocenters from seismic information in kilometers (from Heine, 2007; www.basinatlas.com). MFFS, Magallanes-Fagnano fault zone; RVB, Rocas Verdes Basin; TJ, Triple Junction.

Figure 2: Geological map of the western Austral Basin (Panza *et al*., 2003) showing the location of measured sections and sampling localities: (1) Río Oro (2) Río Belgrano, (3) Ea. Los Ñires, and (4) Arroyo Potranquitas.

Figure 3: Lower Cretaceous continental basin between Lago Posadas and Arroyo Potranquitas (modified from Aguirre-Urreta and Ramos, 1981). The profiles are spatially located, with fossil data and U-Pb ages in zircons. Green line correlates the Río Belgrano Formation along the northern depocenter showing the first coarse grained deposits in the foreland.

Figure 4: Measured stratigraphic sections from north to south: Río Oro, Río Belgrano, Ea Los Ñires and Arroyo Potranquitas. See Fig. 2 for location. Red line correlates Río Belgrano Formation along the profiles.

Figure5: Thin section photomicrographs of the Río Belgrano Formation sandstones in Río Oro profile: a) Metamorphic lithic (Lm), b) Volcanic lithic (Lv), c) and d) Volcanic lithic (Lv), with and without polarizer respectively. Cc: calcite cement. Red scale-bar is 0,1 mm.

Figure 6: Sandstone classification diagram (from Folk *et al.*, 1970) of the 37 thin-sections analyzed.

Figure 7: Provenance ternary Q-F-L (a) and Qm-F-Lt (b) diagrams (from Dickinson *et al.*, 1983) of the Río Mayer, Río Belgrano, Río Tarde and Kachaike formations sandstones from the 37 thins sections analized. Q: total quartz; F: feldspars; L: unstable lithics; Qm: monocrystalline quartz; Lt: total lithics.

Figure 8: a) Clast composition in the basal conglomerate of Río Tarde Formation, Río Oro profile. **b)** Pie chart showing percentage of detrital zircon ages and their possible source areas in the Patagonian Andes and extra-Andean Patagonia constructed with data from Ghiglione *et al.* (2015). V1, V2, V3: volcanic episodes (Pankhurst *et al*., 2000). LC: Lower Cretaceous.

Table 1: Petrographic composition of the sandstones and key to recalculates modal parameters.

Table 2: Recalculated point-count data from the Río Mayer, Río Belgrano, Río Tarde and Kachaike formations.

Figure

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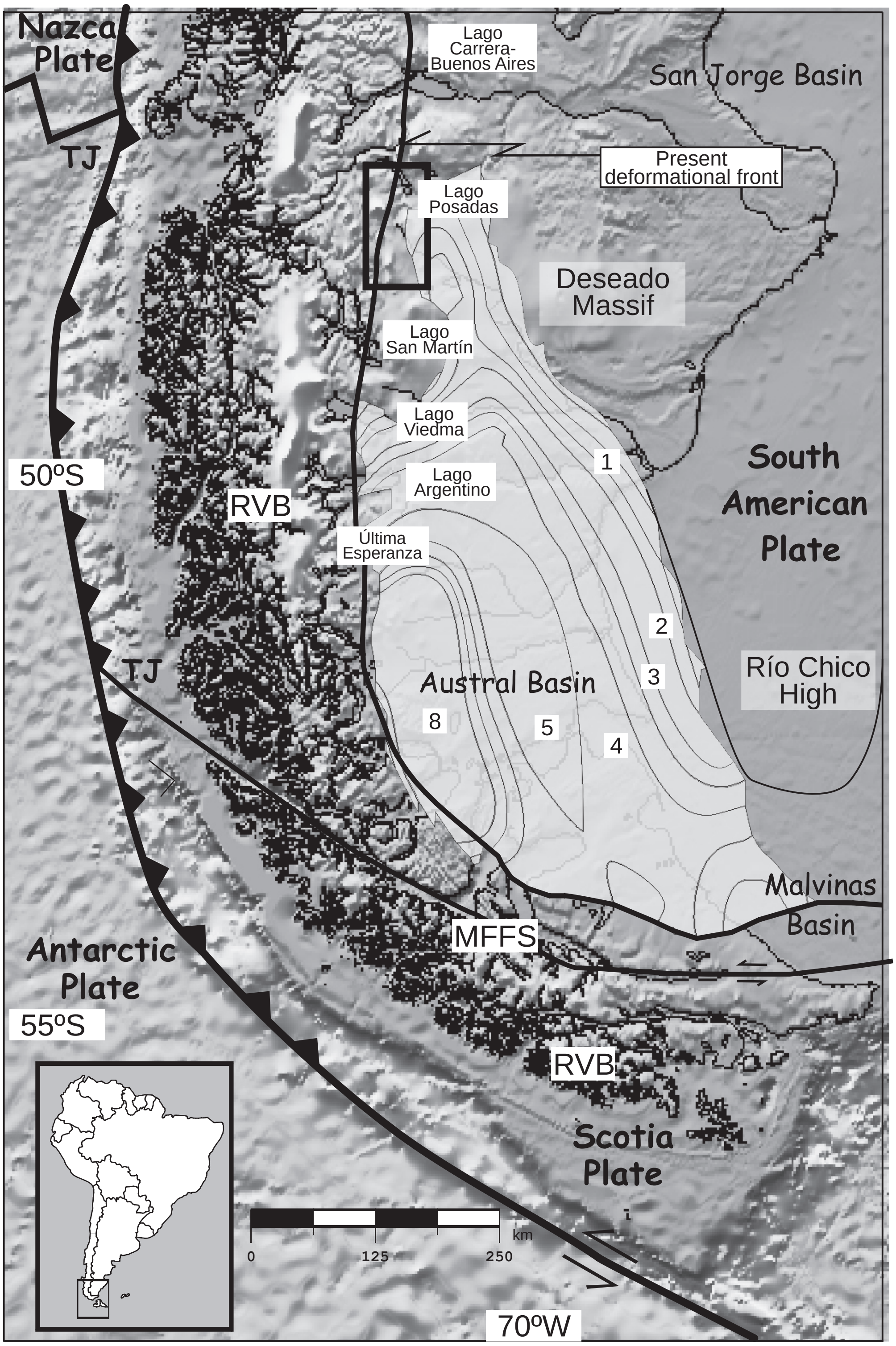


Figure 1

Barberón et al submitted

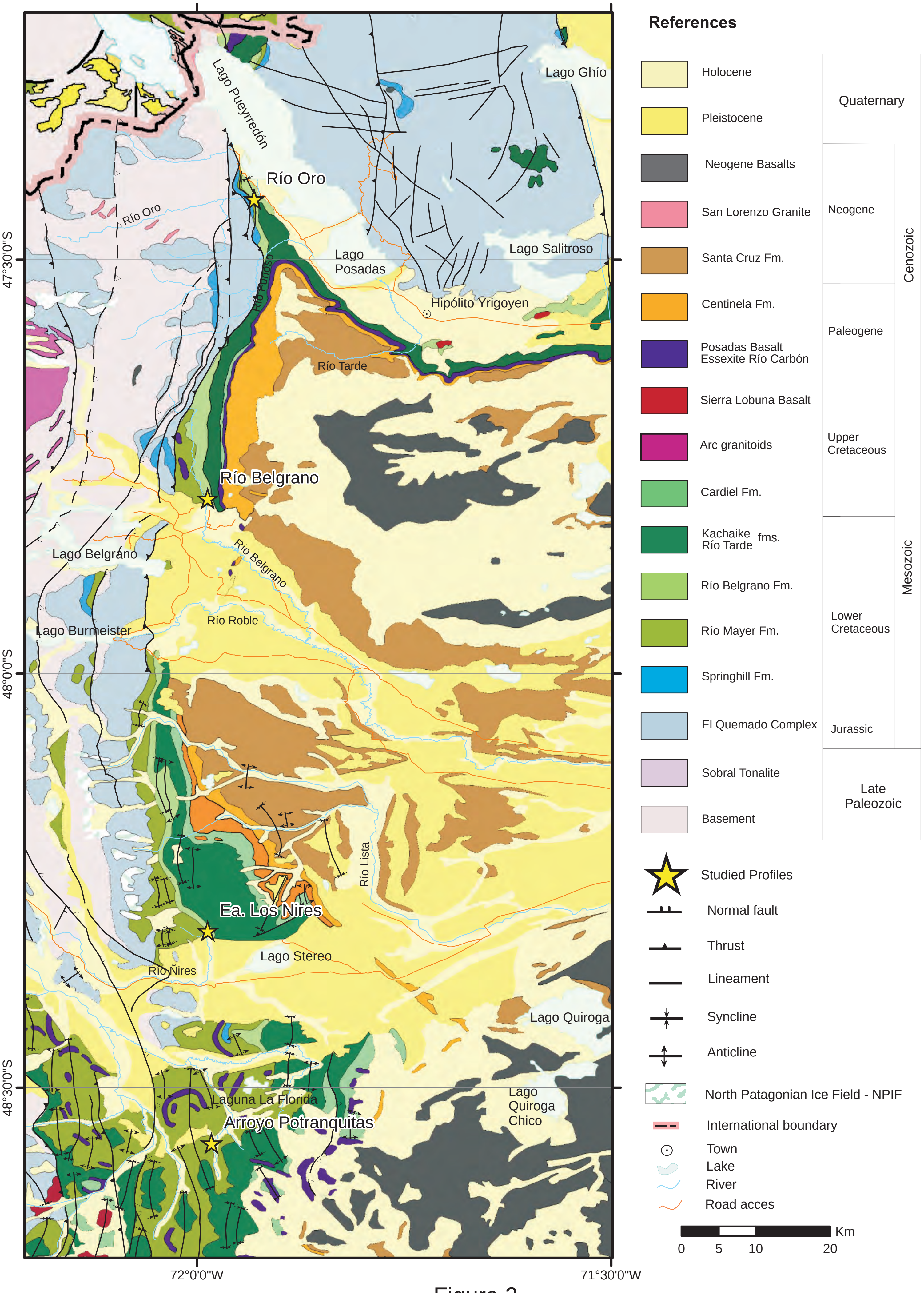
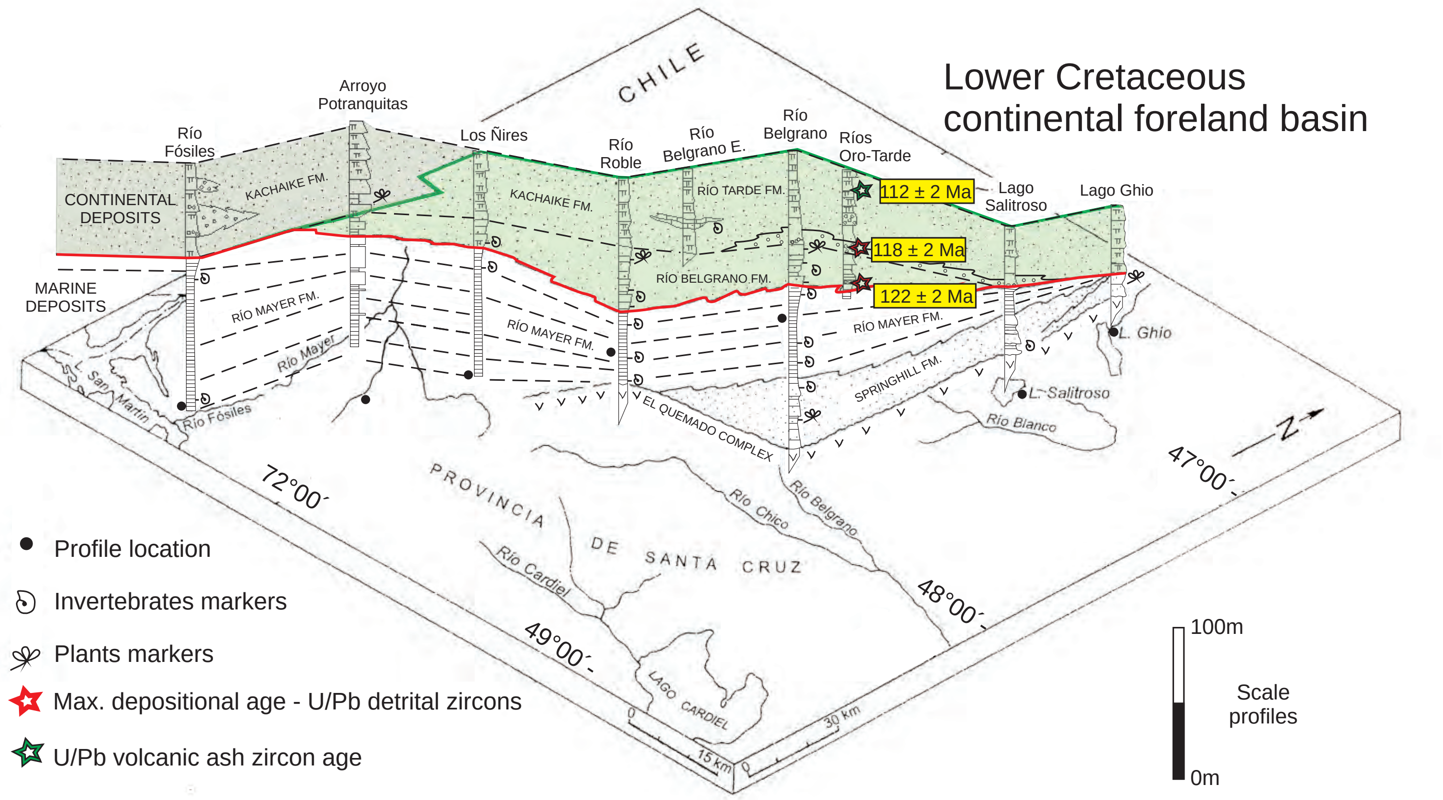


Figure 2


Lower Cretaceous
continental foreland basin
CHILE
Arroyo Potranquitas
Río Fósiles
Los Ñires
Río Roble
Río Belgrano E.
Río Belgrano
Ríos Oro-Tarde
Lago Salitroso
Lago Ghio
CONTINENTAL DEPOSITS
MARINE DEPOSITS
KACHAIKE FM.
RÍO MAYER FM.
RÍO TARDE FM.
RÍO BELGRANO FM.
SPRINGHILL FM.
EL QUEMADO COMPLEX
112 ± 2 Ma
118 ± 2 Ma
122 ± 2 Ma
PROVINCIA DE SANTA CRUZ
72°00´
49°00´
48°00´
47°00´
N
L. Ghio
L. Salitroso
Río Blanco
Río Chico
Río Belgrano
Río Cardiel
LAGO CARDIEL
Río Mayer
Río Fósiles
L. San Martín
0
15 km
30 km
100m
0m
Scale profiles
Profile location
Invertebrates markers
Plants markers
Max. depositional age - U/Pb detrital zircons
U/Pb volcanic ash zircon age

Barberón et al submitted

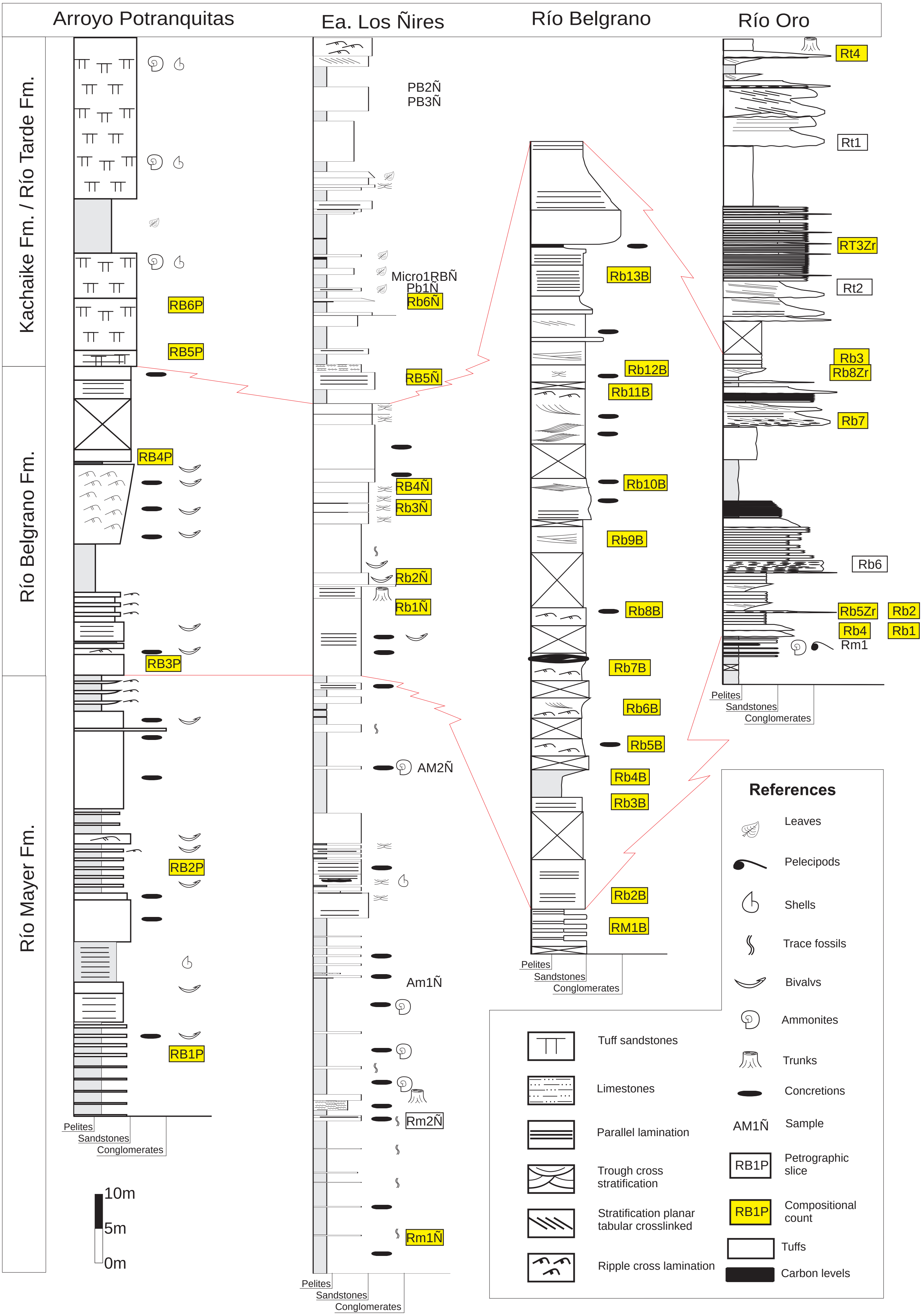


Figure 4

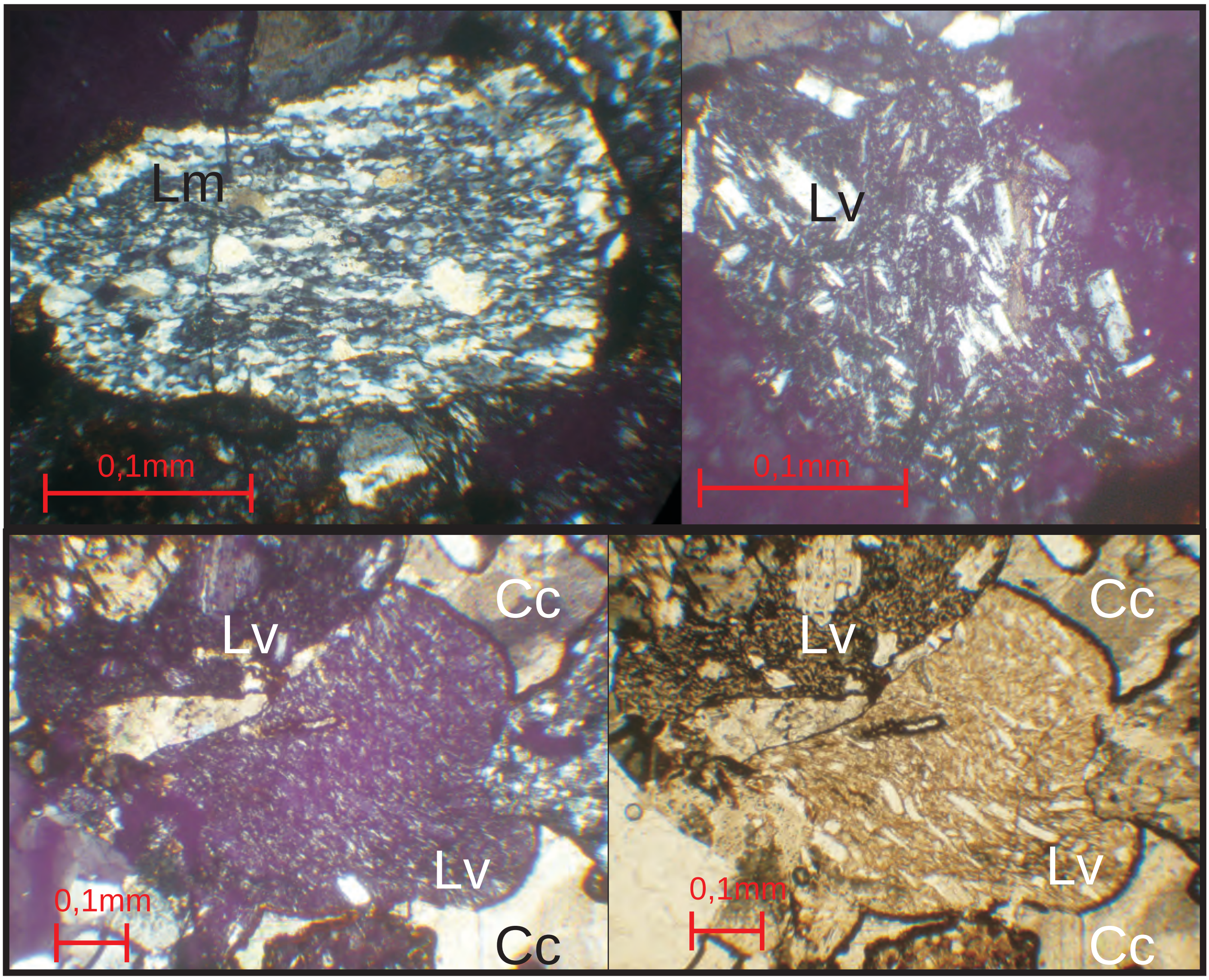


Figure 5

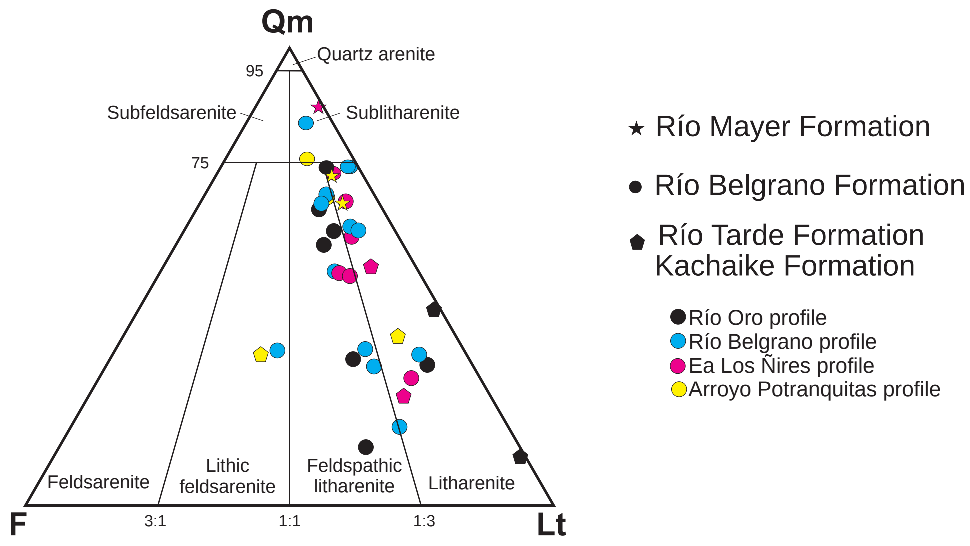

Qm
Quartz arenite
95
Subfeldsarenite
Sublitharenite
75
Feldsarenite
Lithic feldsarenite
Feldspathic litharenite
Litharenite
F
3:1
1:1
1:3
Lt
Río Mayer Formation
Río Belgrano Formation
Río Tarde Formation
Kachaike Formation
Río Oro profile
Río Belgrano profile
Ea Los Ñires profile
Arroyo Potranquitas profile

Figure 6

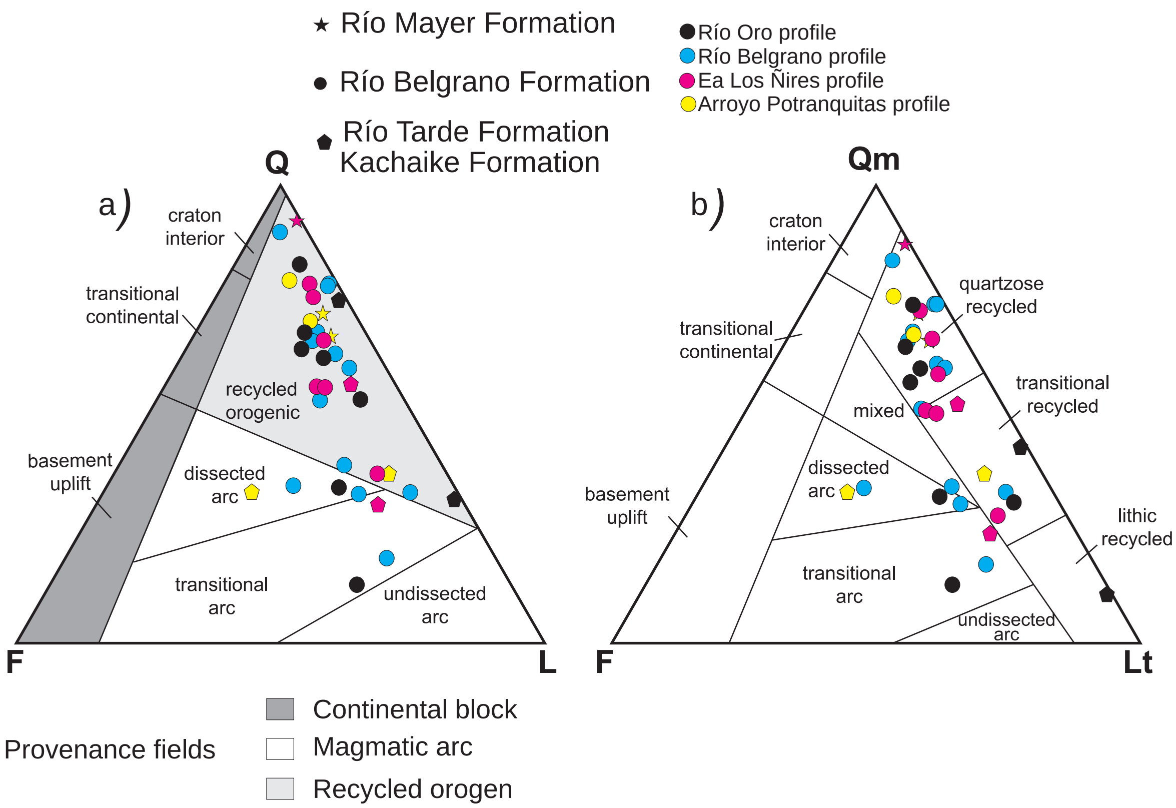

Río Mayer Formation
Río Belgrano Formation
Río Tarde Formation
Kachaike Formation
Río Oro profile
Río Belgrano profile
Ea Los Ñires profile
Arroyo Potranquitas profile
a)
Q
F
L
craton interior
transitional continental
recycled orogenic
basement uplift
dissected arc
transitional arc
undissected arc
b)
Qm
F
Lt
craton interior
quartzose recycled
transitional continental
transitional recycled
mixed
dissected arc
basement uplift
lithic recycled
transitional arc
undissected arc
Provenance fields
Continental block
Magmatic arc
Recycled orogen

Figure 7

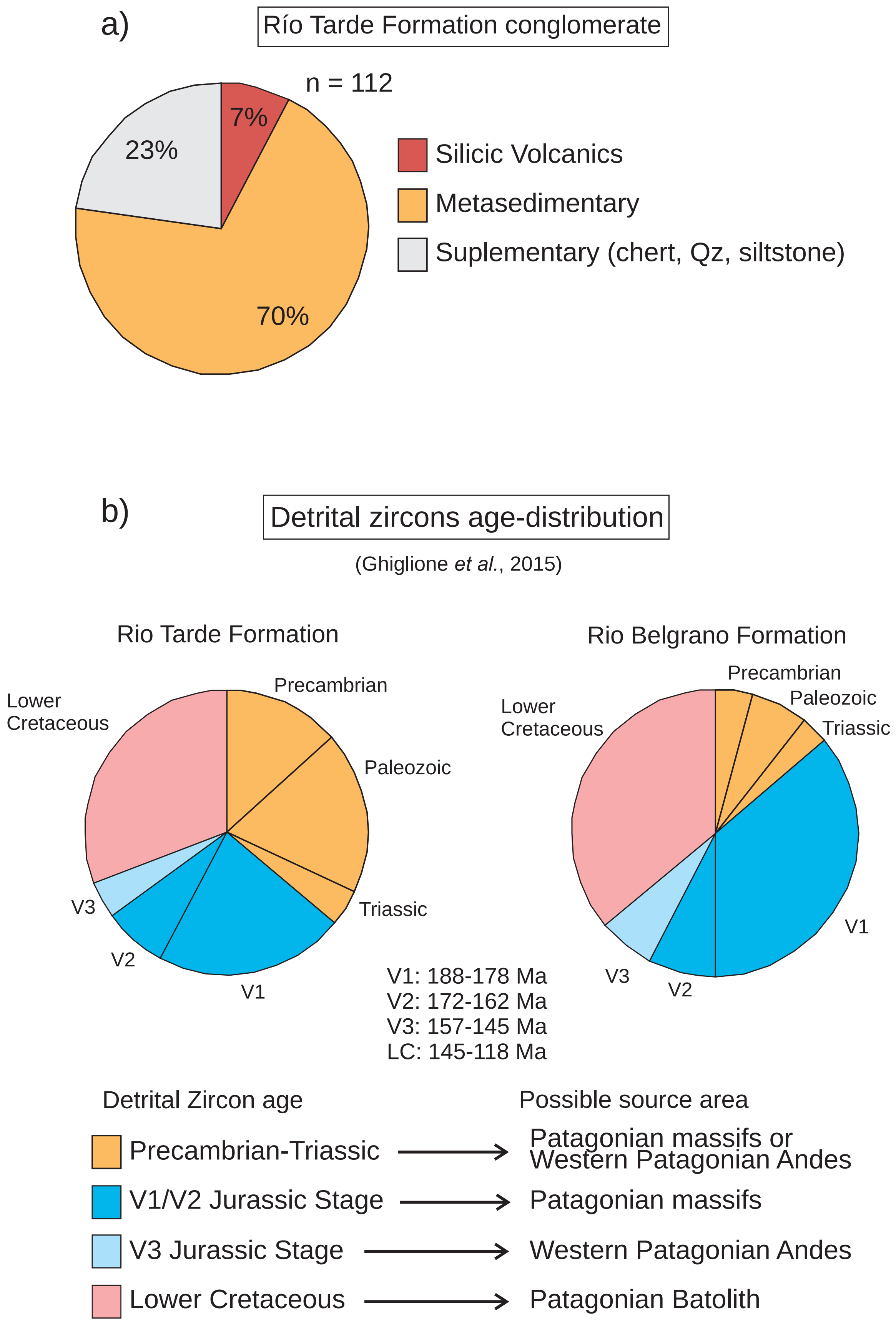

a)
Río Tarde Formation conglomerate
n = 112
7%
23%
70%
Silicic Volcanics
Metasedimentary
Suplementary (chert, Qz, siltstone)
b)
Detrital zircons age-distribution
(Ghiglione *et al.*, 2015)
Rio Tarde Formation
Lower Cretaceous
Precambrian
Paleozoic
Triassic
V3
V2
V1
Rio Belgrano Formation
Precambrian
Paleozoic
Triassic
Lower Cretaceous
V1
V3
V2
V1: 188-178 Ma
V2: 172-162 Ma
V3: 157-145 Ma
LC: 145-118 Ma
Detrital Zircon age
Possible source area
Precambrian-Triassic → Patagonian massifs or Western Patagonian Andes
V1/V2 Jurassic Stage → Patagonian massifs
V3 Jurassic Stage → Western Patagonian Andes
Lower Cretaceous → Patagonian Batolith

Figure 8

Table1

Table 1
Petrographic composition of the sandstones and key to recalculated modal parameters

Symbol	Definition	Description
Qm	Monocrystalline quartz	Most grains are subangular to subrounded with straight to slight undulator extinction. Some quartz shows resorption embayments.
Qp	Polycrystalline quartz	Subrounded grains.
L	Unstable lithic grains	Volcanic clasts composed of quartz or feldspars. Their textures are porphyric with phenocrysts of quartz and feldspars. Matrix textures: pilotaxitic, trachytic and felsitic. Grains composed by quartz–mica with schistose texture are assigned to low-grade metamorphic grains, other with only quartz. Sedimentary clasts are in fewer amounts, they are fragments of limolites where quartz can be recognized.
Plg	Plagioclase feldspar	Subangular to subrounded grains unaltered, twinned.
FK	Potassium feldspar	Subangular grains of slightly altered orthoclase.
M	Minor components	Muscovite, biotite, chlorite, glauconite and dense minerals (opaque minerals, zircon)
Q	Total quartzose grains	Qm + Qp
Lt	Total lithic grains	L + Qp
F	Total feldspar grains	Plg + FK

Table2

Table 2
Recalculated point-count data from the Río Mayer, Río Belgrano, Río Tarde and Kachaike formations sandstones.

Locality	Formation	Sample	Qm–F–Lt			Q-F–L			Classification
			Qm	F	Lt	Qt	F	L	Folk *et al.* (1970)
Río Oro	Río Tarde	RT4	42	1	57	74	1	25	Litharenite
		RT3	10	1	89	31	1	68	Litharenite
	Río Belgrano	RB2	32	22	46	34	22	44	Feldspatic litharenite
		RB1	13	29	58	13	29	58	Feldspatic litharenite
		RB3	59	11	30	61	11	28	Feldspatic litharenite
		RB8	74	6	20	81	6	13	Litharenite
		RB7	30	8	62	51	9	40	Litharenite
		RB5	56	15	29	63	15	22	Feldspatic litharenite
		RB4	63	12	25	66	12	22	Feldspatic litharenite
Río Belgrano	Río Belgrano	RB13B	74	2	24	78	2	20	Litharenite
		RB12B	33	9	58	33	9	58	Litharenite
		RB11B	17	21	62	18	21	61	Litharenite
		RB10B	74	2	24	78	2	20	Litharenite
		RB9B	84	5	11	90	5	5	Sublitharenite
		RB8B	66	11	23	66	11	23	Feldspatic litharenite
		RB7B	34	19	47	39	19	44	Feldspatic litharenite
		RB6B	68	9	23	68	9	23	Feldspatic litharenite
		RB5B	60	7	33	60	7	33	Litharenite
		RB4B	30	19	51	33	19	48	Feldspatic litharenite
		RB3B	61	8	31	63	8	29	Litharenite
		RB2B	34	35	31	35	35	30	Litharenite feldspatic
		RM1	51	16	33	53	16	30	Feldspatic litharenite
Ea. Los Ñires	Kachaike	RB6Ñ	52	9	39	56	9	35	Litharenite
		RB5Ñ	24	16	60	30	16	54	Litharenite
	Río Belgrano	RB10Ñ	28	13	59	37	13	50	Litharenite
		RB9Ñ	59	9	32	66	9	25	Litharenite
		RB4Ñ	50	14	36	56	14	30	Feldspatic litharenite
		RB3Ñ	51	15	34	56	15	29	Feldspatic litharenite
		RB2Ñ	67	6	27	75	6	19	Litharenite
		RB1Ñ	73	5	22	78	5	17	Litharenite
	Río Mayer	RM1Ñ	87	1	12	92	1	7	Sublitharenite
Arroyo Potranquitas	Kachaike	RB6P	33	39	28	33	39	28	Lithic feldarenite
		RB5P	37	11	52	37	11	52	Litharenite
	Río Belgrano	RB4P	76	9	15	79	9	12	Sublitharenite
		RB3P	68	9	23	70	9	21	Feldspatic litharenite
	Río Mayer	RB2P	72	6	22	72	6	22	Litharenite
		RB1P	66	7	27	67	7	26	Litharenite

Qm: monocrystalline quartz; Q: total quartzose grains; F: total feldspar grains; L: unstable lithic grains; Lt: total lithic grains.