



Stratigraphy, geochronology, and paleoenvironments of Miocene - Pliocene boundary of San Fernando, Belén (Catamarca, northwest of Argentina)



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ABSTRACT

The Santa María-Hualfín Basin was proposed as a regional synchronous lithostratigraphic depocenter in the geological province of Northwestern Pampean Ranges, Northwestern Argentina. However, new ⁴⁰Ar–³⁹Ar dating indicates that deposits toward the east, in Santa María Valley (Santa María Department), are younger than the western depocenter in San Fernando (Belén Department). Therefore, it would be more appropriate to study these valleys as separate basins, each one with its own tecto-sedimentary features. The east basin, named in this paper Villavil-Quillay, constitutes an elongated independent basin that developed along the front of the eastern Puna bordering with Papachacra and Durazno Ranges. This basin is composed of more than 3000 m of mudstone, sandstone, conglomerates, volcanoclastic and pyroclastic deposits. Villavil-Quillay basin develops onto a peneplain of Precambrian and lower Cambrian rocks, most of which are metamorphic and granites rocks. The sedimentary fill consists of Cretaceous? and Cenozoic continental deposits. The Cenozoic record is composed of a) the Santa María Group (Miocene-Pliocene), formed by Las Arcas, Chiquimil, Andalhuala and Corral Quemado Formations, and b) the *Punaschotter* unit (Puna's Gravels in German, Pleistocene). This study involves the Andalhuala, Corral Quemado and *Punaschotter* deposits cropping out in San Fernando area. The set of identified facies assemblage corresponding to the Andalhuala Formation shows a vertical variation of fluvial sub-environments, varying from permanent sandy braided rivers to gravel rivers and aeolian dunes culminating in an alluvial dry cycle. While facies assemblages of the Corral Quemado Formation allow inferring the development of ephemeral water bodies from secondary channels on the floodplain, the *Punaschotter* conglomerates indicate the development of gravel channels and bars. Three samples of tuffs interbedded in the sedimentary levels of Andalhuala Formation were dated indicating that the Miocene-Pliocene boundary is represented in this area. The lower tuff beds, outcropping at the southwest of San Fernando Sur, provided an age of 5.59 ± 0.04 Ma (late Miocene, Messinian). The others tuffs beds, both outcropping at the west-northwest of San Fernando Norte and overlaying the first one, gave an age of 4.79 ± 0.15 Ma and 4.72 ± 0.08 Ma (early Pliocene, Zanclean), respectively. These absolute ages, together with the results of a sedimentological analysis, indicate that westward from San Fernando River, much of the areas mapped as Corral Quemado Formation correspond to the Andalhuala Formation; while part of the area considered as *Punaschotter* unit must be assigned to Corral Quemado Formation. Also, a thick tuff bed, recognized at the contact of Corral Quemado and *Punaschotter*, was considered as the previous one dated in 3.66 Ma, in Puerta de Corral Quemado locality.

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1. Introduction

A Neogene sedimentary sequence of over 3000 m of thickness develops in the Catamarca Province (Northwestern Argentina), into the Northwestern Pampean Ranges geological province and is mainly recognized for bearing large and diverse vertebrate fossil faunas (Marshall and Patterson, 1981). This depocenter, formed by clastics, volcanoclastics, and pyroclastic sediments is largely extended in the tectonic intermountain valleys from Cafayate (Salta) to Sierra de Belén (Catamarca) and was considered by Bossi et al. (1993) as the Santa María-Hualfín basin, due to synchrony in the outcropping sedimentary deposits in this region. However, new radioisotope dating suggests that the Santa María Valley deposits are younger than those of Villavil-Quillay sin (Fig. 1) (Spagnuolo et al., 2010, 2013, 2015; Georgieff et al., 2012a,b; Georgieff and Díaz, 2014; Bonini, 2014), therefore is more appropriate to consider these areas (Santa María Valley and Villavil-Quillay basin) as basins with their own and independent tecto-sedimentary features.

Initially, the Neogene outcrops from the intermountain valleys from the north of Catamarca Province have been described as a single unit called indistinctly “Araucano”, “Araucanense”, “formación araucana”, “piso araucano”, “estratos araucanos”, or “Araucaniano” (e. g. Doering, 1882; Ameghino, 1889, 1919; Rovereto, 1914; Frenguelli, 1937; Cabrera, 1944). These terms were applied equally to rocks or faunas, which were considered synchronous. Subsequently, Stahlecker (in Riggs and Patterson, 1939) was pioneer in proposing a stratigraphic scheme for two of the most important fossiliferous localities of Catamarca Province (i.e. Chiquimil = Entre Ríos and Puerta de Corral Quemado areas). Since the 80's, a new interpretation of the Neogene sequences outcropping in these areas has been proposed after a series of contributions at the “Santa María-Hualfín basin” (Bossi and Palma, 1982; Bossi et al., 1987; Georgieff, 1998; Muruaga, 1998, 2000, 2001a, b; 2003; Bossi and Muruaga, 2009). These authors recognized that the Neogene sequence is represented basically by the lithostratigraphic units that compose the Santa María Group (i. e. San José, Las Arcas, Chiquimil, Andalhuala and Corral Quemado formations), originally proposed by Galván and Ruiz Huidobro (1965) for the Santa María Valley.

In this contribution, we carry out stratigraphic, geochronologic, and paleoenvironmental analyses of the Andalhuala and Corral Quemado formations outcrops around San Fernando town (Belen Department, Catamarca Province).

The objectives of this work are: (1) to carry out a paleoenvironmental interpretation of the Andalhuala and Corral Quemado formations outcropping in San Fernando, Belén area; (2) to reconsider the stratigraphy of the sediments outcropping around San Fernando Norte and at the west of San Fernando River; and (3) make the results known of three new absolute dates (^{40}Ar – ^{39}Ar by deep-heating).

2. Geologic setting and stratigraphy

The study area is located within the Northwestern Pampean Ranges geological province, approximately 50 km north-northeast of Belén city, in northwestern Catamarca province. The locality is divided into two villages: San Fernando Sur (SF) or Capillanía (27° 20' S; 67° 53' W) and San Fernando Norte (SFN) or La Villa (27° 16' S; 66° 54' W). The area limits are approximately the Hualfín-Las Cuevas Ranges to the north, the Campo el Arenal, Complejo Volcánico Farallón Negro and cerro Pampa to the east, the Belén Ranges to the south, and the cerro El Durazno to the west (Fig. 1.B–C). The outcrops of the Andalhuala and Corral Quemado Formations, and *Punaschotter* unit to the west of San Fernando River represent the better and larger exposures of these units in the area.

Considering the tecto-sedimentary evolution of the North-western Pampean Ranges, some researchers propose that during the early Miocene there was an extension (Muruaga, 1998; Bossi et al., 2001; Ramos et al., 2002; Dávila and Astini, 2003; Bossi and Muruaga, 2009) or an undeformed foreland (Mortimer et al., 2007) prior to the shortening that occurred in the late Miocene-Pliocene (Georgieff, 1996, 1998; Georgieff and Ibañez, 1999; Kleinert and Strecker, 2001). This behavior would explain the location of the asymmetrical depocentres (Bossi et al., 2001; Mortimer et al., 2007), the vergence of the main faults (Strecker et al., 1989; Georgieff, 1996, 1998; Muruaga, 1998), the paleo-environmental changes (Georgieff et al., 2012a) and the discontinuities recorded in different sectors of the region (Georgieff, 1998; Bossi et al., 1999; Segovia, 2004; Bossi and Muruaga, 2009).

The latest stratigraphic framework for the study area was proposed by Muruaga (1998, 2000, 2001a, b) and Muruaga et al. (2003) for Cretaceous? and Neogene outcrops among the Villavil Village (3,500 m thick at the north), El Durazno Hill (2,300 m thick at the south) and those surrounding Hualfín Ranges at the east. According to Bossi et al. (1987) and Muruaga (1998, 2001a), the Neogene sedimentary deposits in this area are lithostratigraphically equivalent to those Neogene deposits in the Santa María Valley; these deposits were originally described and grouped under the name of Santa María Group (Galván and Ruiz Huidobro, 1965).

The sedimentary succession at the western flank of the Belén Ranges was analyzed by Bossi et al. (1999), Muruaga et al. (2003) and Bossi and Muruaga (2009). This sequence, named by these authors as cerro Pampa, is exposed at 10 Km from the southeast of SFS and presents a thickness of 1900 m; it also shows a greater number of discontinuities with respect to other outcrops of this basin (Bossi et al., 1999; Segovia, 2004). Even though the authors of the aforementioned contributions recognized that the stratigraphic and sedimentological similarity with the Santa María Group extends to Quillay River, they also found a significant influence of the Complejo Volcánico Farallón Negro in petrology of the El Áspero Member of Chiquimil Formation (ca. 9 Ma). Besides, they indicated that the sediments of the Andalhuala Formation present two different sections, a lower one of coarser grain size, conglomeratic, and an upper one of thinner lime-sandy sediments. This difference is likely indicating a change in the regional climatic conditions at the time of deposition and it allowed inferring aridity in the environment (Galli et al., 2011; Starck and Anzótegui, 2001; Bossi et al., 1999; Muruaga et al., 2003).

3. Methodology

Six field works, between 2010 and 2015, were performed around San Fernando Town. A review of the geological units leads to propose a new geological map (Fig. 1.C). Several tuff beds were sampled and three of them identified as T-SE-SF1, TB-SFN1, and TT-SFN2 were dated by ^{40}Ar – ^{39}Ar method (step-heating in biotites, see below) in the SERNAGEOMIN laboratories (Servicio Nacional de Geología y Minería, Chile). The descriptions of detailed stratigraphic logs (1:50) (Fig. 2.A–B) are the base to paleoenvironmental interpretations presented below. These profiles involved the upper section of Andalhuala Formation and all Corral Quemado Formation, and “*Punaschotter*” informal unit. One of these stratigraphic logs was measured near to SFN, where the outcrops are recognized on both sides of San Fernando River, at the northwest of the National Route 40. This stratigraphic log was surveyed through a transect: since 27°17'5.92"S/66°54'30.88"W to 27°17'42.94"S/66°55'15.99"W and comprises a total thickness of 385 m (Figs. 1.C and 2.A). The second log was performed close to SFS, where the lithostratigraphic units prospected were recognized on the east side of San Fernando River, at the southeast of National Route 40. In this area, the log was done across a

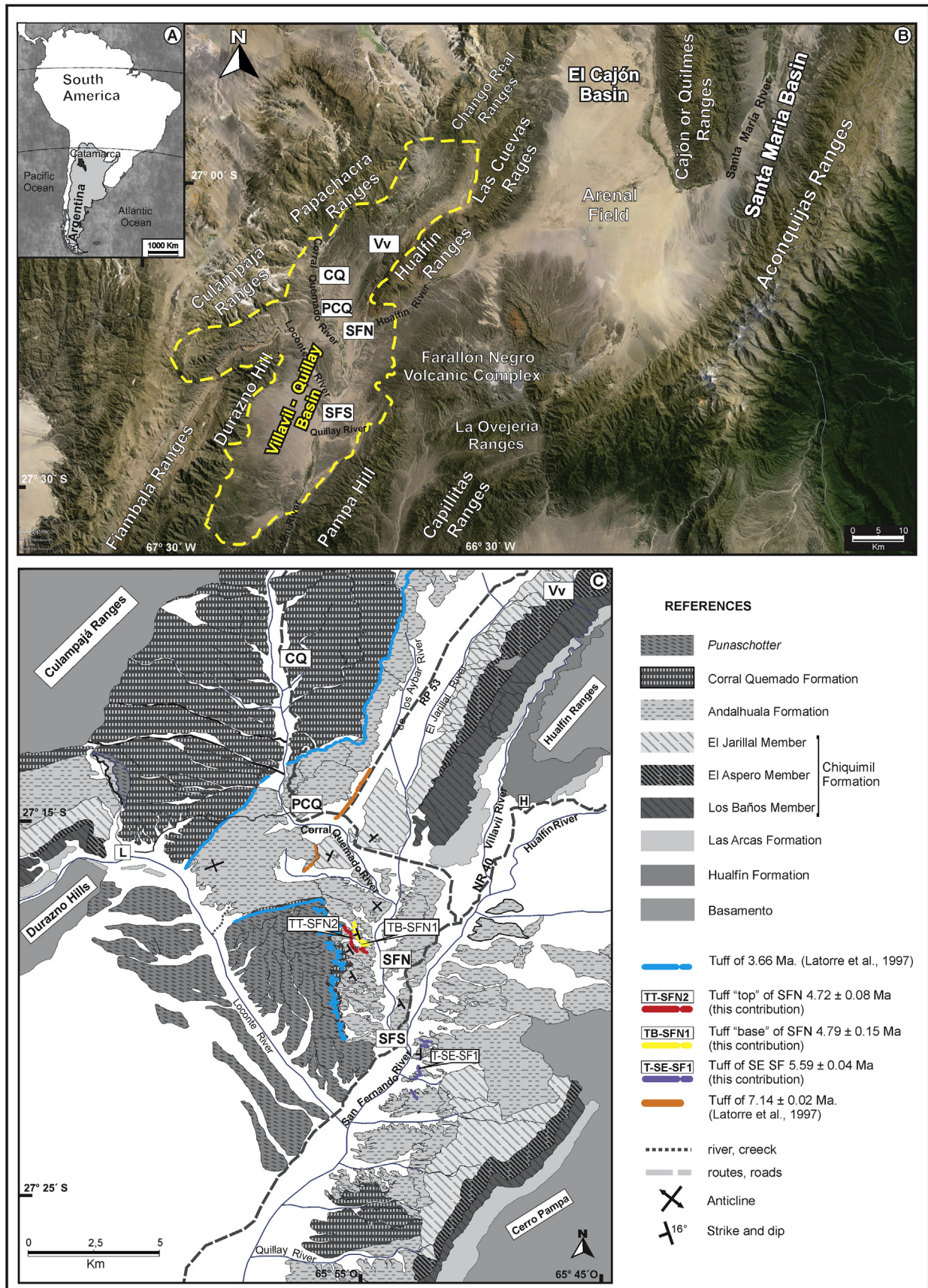


Fig. 1. A. South America map showing the location of Catamarca province, Argentina; B. Regional location map showing the basins recognized at the intermountain valleys of the north of Catamarca, highlighting the limits of Villavil–Quillay basin; C. Representative map of the exposed lithostratigraphic units in the Villavil–Quillay Basin. **Abbreviations:** CQ, Corral Quemado; L, Loconte; PCQ, Puerta de Corral Quemado; SFN, San Fernando Norte; SFS, San Fernando Sur; Vv, Villavil.

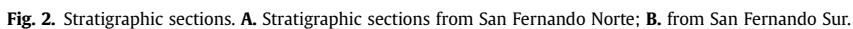


Fig. 2. Stratigraphic sections. **A.** Stratigraphic sections from San Fernando Norte; **B.** from San Fernando Sur.

transect from 27°20'6.8"S/66°52'9.2"W to 27°20'10.1"S/66°53'27.5"W, and it has a thickness of 155 m (Figs. 1.C and 2.B). The lithology, grain size, contacts (lateral geometries), biogenic and/or sedimentary structures, fossils and color (Rock-Color Chart Committee, 1991) of each bed were recorded. The regional strike and dip, and paleocurrent directions in imbricated clasts were measured with Brunton compass. Likewise, the presence of tuffaceous levels of the large lateral extension was tracked with GPS (navigator, Garmin e-Treck Vista HCx) and those strata were used as markers to correlate different sections of the profiles.

With the aim of interpreting the depositional environments, the surveyed sequences in both profiles were subdivided in facies (Table 1), which were subsequently grouped into the facies assemblages (Table 2). The identified lithofacies in the stratigraphic sequence were coded adapting the proposal of Miall (1985, 1996, 2014), capital letter for grain size classes and lower case for sedimentary structures were used: (A) Claystone, (L) Limestone, (S) sandstone, [(f) fine; (m) medium and (g) coarse], (G) conglomerates, (T) Tuffs; (a) trough cross-stratified, (m) massive, (p) parallel laminated, (o) ripple stratified, (c) cemented, (l) lenticular, (t) tabular, (q) cuneiform (see Table 1; Reineck and Singh, 1980).

For the identification of the facies assemblages (FA), the vertical arrangement of the succession and the lateral continuity of the sedimentary bodies were considered, as well as the criteria of changes in the intensity (energy) of the sedimentology process, which was identified by: wavy or irregular contacts associated with abrupt changes of granulometry, occurrence of intraformational clasts, undulated or flat contacts with changes in granulometry as indicator of primary structures of higher transport velocities, among others. The FA (Table 2) allowed to interpret the sedimentary processes and to link them with the subenvironment where they developed.

4. Sedimentological and paleoenvironmental analysis

4.1. Recognized facies

A total of 20 facies were identified in the deposits of Andalhuala and Corral Quemado formations and *Punaschotter* outcrops near to the locality of San Fernando (Bonini and Georgieff, 2013; Bonini, 2014). The nomenclature used in the identification of the lithofacies is indicated in Table 1, together with the primary and secondary structures that characterize each one. The different lithofacies recognized in the outcrops of SFS and SFN are listed and described briefly below:

4.2. Facies assemblages

The different subenvironments that were inferred from the identified facies associations are listed and briefly described below (see Table 2).

4.2.1. Facies assemblage I: (Fig. 3.A-B)

Description: it is constituted by sets from 2 to 12 m of thickness, represented by brownish and reddish sandstone with tabular and trough cross-strata [S(f)a, S(m)a, S(f)t y S(m)t]. This facies assemblage shows secondary features that evidence periods of seasonal dryings, such as calcretes, rhizoconcretions, and burrows.

Interpretation: the same lithological characteristics allow the interpretation of two different subenvironments can be interpreted, both of which constitute filling channels but according to the geometry and internal arrangement of the deposit, they can be identified as channel deposits and/or fluvial sandy bars (Bridge and Demico, 2008; Bridge et al., 2000). The sets of the rocks interpreted as main channels or channel belts are characterized by irregular base geometry, flat top and fining upward internal arrangement;

Table 1
Table of facies and their codes adapting from the proposal by Miall (1985, 1996, 2014).

Code	Description	Thickness	Others structures/fossils	Litostrat. unit and log
Atm	Tabular massive claystones with thin laminae of massive tabular siltstones	<1 m		Corral Quemado Formation (SFN)
Ltm	Tabular massive siltstones and thin lenses of small cross-stratified sandstones	1 to 18 m	calcretes, burrows, rhizoconcretions and vertebrate fossils	Andalhuala and Corral Quemado formations (SFN); Andalhuala Formation (SFS)
Lto	Tabular reddish siltstones with ripple marks	<6 m	calcretes, rhizoconcretions	Andalhuala Formation (SFN)
Lp	Parallel laminated reddish siltstones	1 to 1.5 m		Andalhuala Formation (SFN and SFS)
Sa	Trough cross-strata sandstones and lenses of reddish siltstones	<1–8.5 m; sets of 0.5–1.5 m	rhizoconcretions, burrows, calcretes, magnetite laminae, desiccation cracks, pebble clusters, flame structures, and vertebrate fossils	Andalhuala Formation (SFN and SFS)
So	Ripple marks sandstones	2 to 12 m	calcretes, rhizoconcretions	Andalhuala Formation (SFN and SFS)
[S(f,m)o]				
Sl	Lenticular cross stratification sandstones	0.3–1 m	Magnetite laminae	Andalhuala and Corral Quemado Formations (SFN and SFS)
[S(f,c)l]				
St	Tabular massive sandstones with thin laminae of massive siltstones	2 to 13 m	calcretes	Andalhuala Formation (SFN and SFS)
[S(f,m)t]				
Sq	Cuneiform cross-strata sandstones	1 to 10 m; sets of 1.5–2 m	desiccation cracks, deformations	Andalhuala Formation (SFN)
[S(f,m)q]				
Sp	Parallel laminated brownish sandstone	Approx. 9 m		Corral Quemado Formation (SFN)
[S(f)p]				
Gla	Lenticular trough cross-strata gravels	1 to 3 m	calcretes, rhizoconcretions and vertebrate fossils	Andalhuala Formation (SFN and SFS)
Gm	Massive gravel with imbricated blocks	Sets of 3 m	normal stratification	Punaschotter (SFN)
Tl	Laminated tuff	0.8–2 m		Andalhuala and Corral Quemado Formations (SFN and SFS)
Tm	Massive tuff	1 to 3 m		Andalhuala and Corral Quemado Formations (SFN and SFS)

Table 2

Table of facies assemblage and their main interpretations.

Facies assemblages	constituent facies	Interpretations	litostratigraphic unit
FA I (Fig. 3. A-B)	S(f)a, S(m)a, S(f)t, S(m)t	- sandy bars (normal contact, tabular) - channel deposits (irregular contact, fining-upward)	Andalhuala and Corral Quemado Formations
FA II (Fig. 3. C)	Atm, Lp, Lto, Ltm, S(f)o, S(f)t	- distal floodplains to the channel, deposits by settling	Andalhuala Formation
FA III (Fig. 3. D)	Ltm, Lp, S(f)l, S(f)a	- intermediate floodplains to the channels with develop of incipient secondary channels. - mud and silt deposited by decantation	Andalhuala and Corral Quemado Formations
FA IV (Fig. 3. E)	Ltm, S(f)l	- proximal floodplain to the channel (greater involvement of sand)	Andalhuala and Corral Quemado Formations
FA V (Fig. 3. F)	S(f)a, Ltm	- Overbank deposits	Andalhuala Formation
FA VI (Fig. 3. G)	Gla, S(c)l, Gm, S(c)a	- Deposits of gravel channel (channel and gravel bars)	Punaschotter
FA VII (Fig. 3. H)	S(f)q, S(m)q, S(m)a	- Wind dunes	Andalhuala Formation
FA VIII (Fig. 3. I)	Ltm, S(f)p	- crevasse splay and/or splays	Corral Quemado Formation

while those interpreted as fluvial sandy bars show flat or slightly convex base, convex top and tabular strata (no grading beds). These deposits usually present scattered and lineation of pebbles or laminae with magnetite grains.

4.2.2. Facies assemblage II: (Fig. 3.C)

Description: FA II is constituted by mudstones, reddish siltstones and reddish and brownish sandstones [Atm, Ltm, Lp, Lto, S(f)t and S(f)o], which reaches from 1 to 13 m of thickness, with flat bases and tops. In this facies assemblage calcretes, burrows, rhizoconcretions and vertebrate fossils can also be recognized as secondary features.

Interpretation: FA II can be interpreted as floodplains deposits placed distant to intermediate with respect to the channel (Kraus and Aslan, 1999; Kraus and Hasiotis, 2006; Georgieff, 1998).

4.2.3. Facies assemblage III: (Fig. 3.D)

Description: FA III is constituted by reddish siltstones with massive and parallel lamination (Ltm, Lp), which compose tabular strata with a flat base and top from 3 to 12 m of thickness, interbedded with lenticular trough cross-strata of fine sandstones [S(f)l and S(f)a].

Interpretation: sedimentary deposits of FAIII would have formed in intermediate floodplains with a development of incipient secondary channels (*crevasse or splay channels*) (Kraus and Aslan, 1999; Kraus and Hasiotis, 2006; Georgieff, 1998).

4.2.4. Facies assemblage IV: (Fig. 3.E)

Description: this assemblage is characterized by massive siltstones with tabular stratification (Ltm), with flat bases and tops, and are often interbedded by facies of fine sandstones with laminar stratification [S(f)l]. This assemblage shows more numerous and thicker interbedded strata than the intermediate plains (FA III).

Interpretation: FA IV deposits can be interpreted as floodplains close to the channel (Kraus and Aslan, 1999; Kraus and Hasiotis, 2006; Georgieff, 1998).

Observations: FA II, III and IV (Fig. 3.C-F) are interpreted as floodplains, but they differ in the variation of their relative distance with respect to the channel. This distance is inferred through the presence of sandy sediments in the configuration of the facies assemblage. In FA III and IV (interpreted as intermediate and distant floodplains), the fine sandstones with lenticular trough cross-strata represent small secondary channels developed on the floodplains.

In these facies assemblage, secondary features and structures

that evidence temporary flood of the plains are recognized, as well as the water table fluctuation, a result of the rainfall seasonality (dry season). Several of the secondary subaqueous features recognized are: a) ripple lamination of siltstones and fine sands, which are inferred as the result of the subaqueous ripple migration on the floodplain; b) horizontal lamination of muds formed from settling of fine sediments (mud and silt), suspended in ephemeral water bodies developed on the floodplain; c) water table fluctuation; d) presence of calcretes, rhizoconcretions and vertical bioturbations with meniscus structures; and e) small and medium sized mammal remains (rodents, pachyrukhines; Bonini, 2014) which were found in the siltstones and lenticular cross strata of sandstones.

4.2.5. Facies assemblage V: (Fig. 3. F)

Description: this assemblage is formed by massive siltstones and fine sandstones [Ltm and S(f)a], which developed deposits from 4 to 8 m of thickness.

Interpretation: FA V deposits can be interpreted as overbank deposits (Miall, 1996; Bridge, 2006; Viseras and Fernández, 2010).

4.2.6. Facies assemblage VI: (Fig. 3.G)

Description: this assemblage is represented by sets from 1 to 25 m of thickness, composed of gravels and coarse sandstones with lenticular trough cross-stratified [Gla, S(c)l, S(c)a, Gm]. Here, as in FA I, two different, although associated, subenvironments can be interpreted. The main characteristic is the geometry of the sets: a) flat to softly undulated and concave base (type channel geometry); b) convex top and a base from flat to slightly undulated (lobed geometry). Disarticulated and fragmented fossils remains (osteoderms of cingulata, loose and fragmented bones elements and teeth of great mammals; Bonini, 2014) represent secondary features that can be found in these deposits. These fossiliferous levels are represented by lenticular strata of pebbles with granules interbedded, which may have accumulated by the hydraulic action of the channel.

Interpretation: these deposits can be interpreted as bars deposits and gravel channels (Miall, 1985, 1996; Ibañez, 2001; Georgieff and González Bonorino, 2002) according to its different sedimentary structure associated with the geometry of the strata.

4.2.7. Facies assemblage VII: (Fig. 3.H)

Description: FA VII is formed by deposits of fine to medium sandstones [S(m)a, S(f)q and S(m)q].

Interpretation: these deposits could represent the development

of sand dunes and eolian deposits (Prothero and Schwab, 1996) developed in the floodplains during the dry season. These features are also evidence related to the beginning of aridity and seasonal precipitation.

4.2.8. Facies assemblage VIII: (Fig. 3.I)

Description: FA VIII is formed by sets of approximately 8 m of thickness constituted by fines sandstones with parallel lamination interbedded with tabular stratification of massive mudstones [Ltm and S(f)p].

Interpretation: these deposits would be generated from a mantiform flow, during flood seasons in low energy conditions, which are interpreted as crevasse splay and/or splays onto and close to floodplain (Bridge et al., 2000).

4.3. Lithostratigraphic units recognized in the study area

The stratigraphic reallocation of SFN west area proposed in this work (see Figs. 1.C and 4) is based on the lithofacial attributes of the described deposits in the study area and the absolute ages obtained for the lower and middle section of these deposits. Thus, the lithostratigraphic limits of both Andalhuala and Corral Quemado Formations, as well as “Punaschotter” unit, are described and reconsidered. Additionally, the sedimentary deposits recognized in the SFS area are described.

4.3.1. Andalhuala Formation

This is the most extended unit in the study area. This unit is recognized in SFN log from the beginning of stratigraphic succession down to 310 m (Fig. 2.A), and in the whole profile surveyed in SFS (Fig. 2.B). Andalhuala Formation is composed by brownish to reddish sandstones with lenticular, trough cross-stratification, ripple marks, and cuneiform cross-stratification, which often present calcium carbonate as cement, rhizoconcretions, calcretes, desiccation cracks and other secondary features that evidence the subaerial exposure and water table fluctuations. In this unit, there are typically sandstones strata interbedded by siltstones with tabular massive or ripple laminations. Moreover, several levels of tuffs were recorded, three of which were sampled for radio isotopic dating (^{40}Ar – ^{39}Ar ; see below).

4.3.2. Corral Quemado Formation

This unit was recognized between 310 and 360 m of the surveyed outcrops in SFN (Fig. 2.A and Fig. 6). Corral Quemado Formation is characterized by claystone deposits, dark reddish tabular siltstones, and lenses of sabulites interbedded between claysiltstone strata, in contrast to others localities where this unit was mainly identified by gravel and coarse sands deposits. At the top of this unit, a massive tuff of about 2.6 m thick was described, which was considered as the of 3.66 Ma tuff (Latorre et al., 1997; Bonini and Georgieff, 2014).

4.3.3. Punaschotter unit (Conglomerates from the Puna; Penck, 1920)

This unit is located up above of the tuff bed considered as 3.66 Ma. In the San Fernando Norte log (Fig. 2.A), the last 25 m of thickness recorded were represented by eight conglomerate bodies of cobble and clast-support massive blocks coarsening upward from 3 to 5 m of thickness, with coarse sandstone with lenticular cross stratification and massive gravels.

5. New datings from the area

Sedimentary beds of Andalhuala Formation, cropping out around the locality of San Fernando, are characterized by several

tuff beds. In this area, at least six tuff strata with an extensive lateral continuity were recognized and mapped, which have been used for the stratigraphic correlation of the different logs.

The sample identified as T-SE-SF1 ($27^{\circ}20'42.18''\text{S}$ / $66^{\circ}53'20.73''\text{W}$; $270/15^{\circ}$), interbedded between siltstones-sandstones facies of Andalhuala Formation, outcropping at the southwest of SF and at the east of the homonymous river (see Fig. 1.C), has an age of 5.59 ± 0.04 Ma. Whereas the samples TB-SFN1 ($27^{\circ}16'48.17''\text{S}/66^{\circ}54'56.40''\text{W}$; $240/16^{\circ}$) and TT-SFN2 ($27^{\circ}16'50.54''\text{S}/66^{\circ}55'3.52''\text{W}$; $250/10^{\circ}$), interbedded in the upper beds of Andalhuala Formation, at the west-northwest of SFN, and to the west of the homonymous river, have ages of 4.79 ± 0.15 Ma and 4.72 ± 0.08 Ma, respectively. All dates gave similar plateau and integrated ages (see Fig. 5.A–C). These new geochronological data allow considering these ages as very early records of arid conditions for this area, although Schoenbohm et al. (2014) propose a gentle onset of aridification at 8Ma and the climax at 4Ma. In Santa María Valley, Kleinert and Strecker (2001) consider the onset of aridification between 3 and 2.5Ma, Schoenbohm et al. (2014) partially agree with this age for the beginning of a major cycle of arid condition but they also propose the dry conditions between 7 and 5Ma. In Fiambalá Basin (toward East of the study area), Schoenbohm et al. (2014) propose the beginning of semi-arid conditions at 8Ma.

6. Discussion

The observations and descriptions from the field work, the facies analysis, and the mapping of lithostratigraphic units show lithofacial differences with previous researches (Muruaga, 1998, 1999; Bossi et al., 1999; Bossi and Muruaga, 2009). Moreover, the stratigraphic data and the new ages of the tuffaceous strata allow reconsidering the areal distribution of the units compared to previous proposals.

The tecto-sedimentary evolution proposed for the studied area recognized five stages (stages 1–5: Muruaga, 1998, 1999; Bossi et al., 1999; Bossi and Muruaga, 2009), of which the last three (stages 3–5) are involved in the deposition of units recognized in the localities of San Fernando. The stage 3 involves thermal subsidence and is defined by the deposition of thick clastic succession, which is represented by the Andalhuala Formation, with the development of a braided of low sinuosity permanent rivers system; probably in this stage the Aconquija Ranges could have been already rising and producing early dry conditions, a similar behaviour for Quilmes Ranges was pointed out by Kleinert and Strecker (2001). The dry conditions installed with the incipient eastern barrier were increased by the uplifting of western mountains located in Fiambalá Basin (Carrapa et al., 2008); stage 4 consists of an abrupt change to alluvial fans sequence of the Corral Quemado Formation; and stage 5 constitutes thin deposits of piedmont gravels, as a result of the uplift of surrounding ranges, represented by The Punaschotter unit. The sedimentological analysis of the Andalhuala Formation cropping out in both localities, those located at the west of SFN and which were previously considered by Muruaga (1998, 2001a, b) and Bossi and Muruaga (2009) as Corral Quemado Formation, allows recognizing seven of the eight identified facies assemblages (see Table 2). The set of identified facies assemblages shows a vertical variation of fluvial subenvironments. In several strata, along the sequence interpreted as floodplains, fluvial bars and channel deposits, secondary features were observed, such as calcretes, calcium carbonate cement and mud cracks, features that should be indicating periods of subaerial exposure and water table fluctuations. Also, features such as rhizoconcretions and burrows could indicate vegetation encroachment into the dry riverbeds during the periods of seasonal desiccation. Moreover, in several sandstone bodies interpreted as

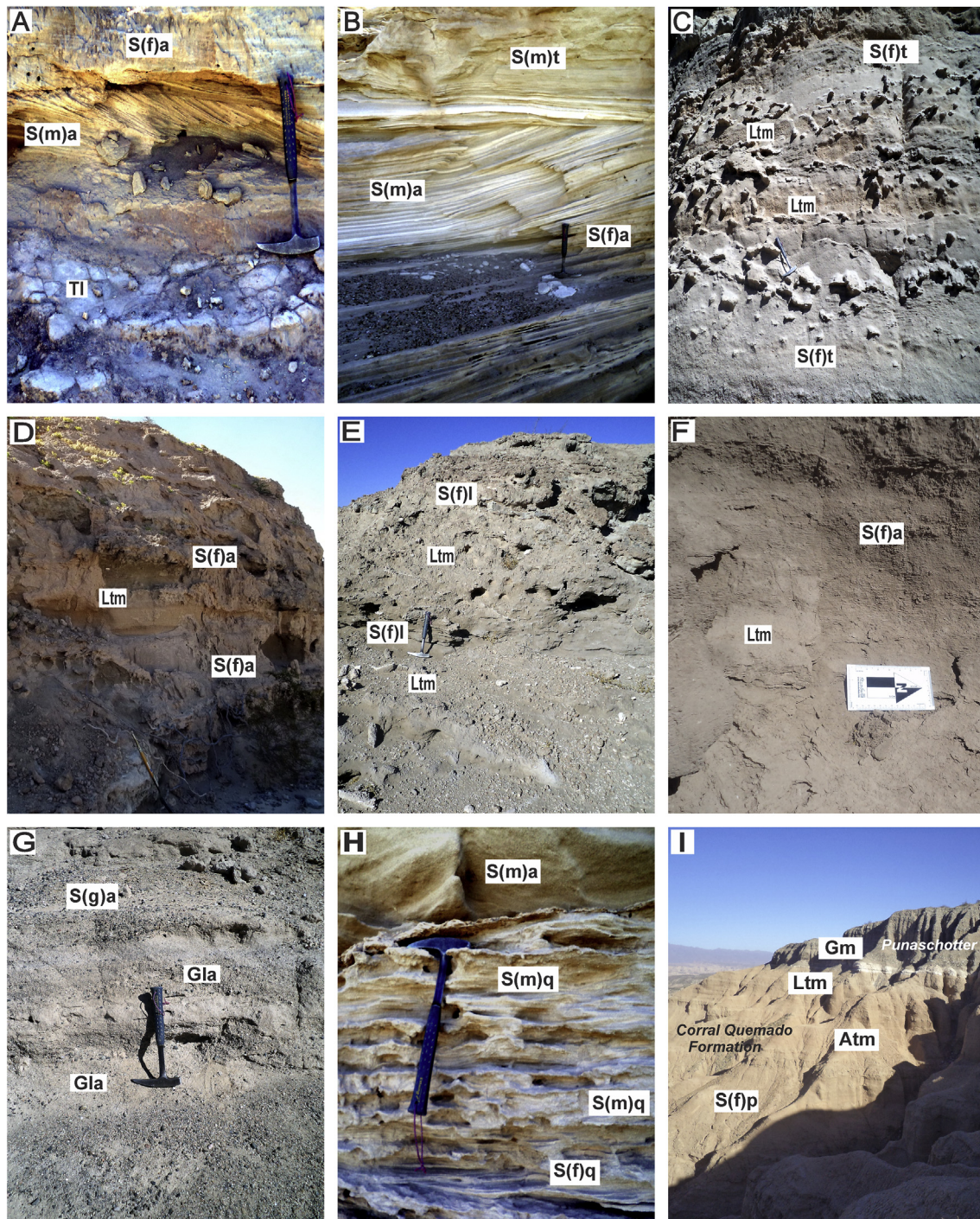


Fig. 3. Examples of facies assemblages recognized in the study area. **A–B.** Facies Assemblages I; **C.** Facies Assemblages II; **D.** Facies Assemblages III; **E.** Facies Assemblages IV; **F.** Facies Assemblages V; **G.** Facies Assemblages VI; **H.** Facies Assemblages VII; **I.** Facies Assemblages VIII.

sands bars deposits, evidence of the development of subaqueous bed form (ripple lamination) can be identified, and toward to the top, sandy levels with cuneiform stratification were observed, which can be associated with the development of eolian dunes during a temporally dry surface. From this set of facies assemblages it can be inferred a fluvial subenvironment with permanent sandy braided rivers, which passes through a hierarchical system of minor channels, and toward to the top aeolian dunes culminating in a dry cycle can be observed. This interpretation agrees with previous tecto-sedimentary evolution proposed for the similar stratigraphic

successions near to the study area (Muruaga, 2001a; Muruaga et al., 2003). The paleoenvironmental changes recorded in the studied sections have also been documented in other localities of NW Argentina, which were related to regional and global climatic phenomena (e. g. Bywater-Reyes et al., 2010; Carrapa et al., 2011; Coutand et al., 2006; Starck and Anzotegui, 2001; Strecker et al., 2007; Hynek et al., 2012; Zachos et al., 2001).

The noticeable changes in the lithology and color of the sediments observed in the sedimentary sequence of SFN allowed to identify the base of a different unit, the Corral Quemado Formation,

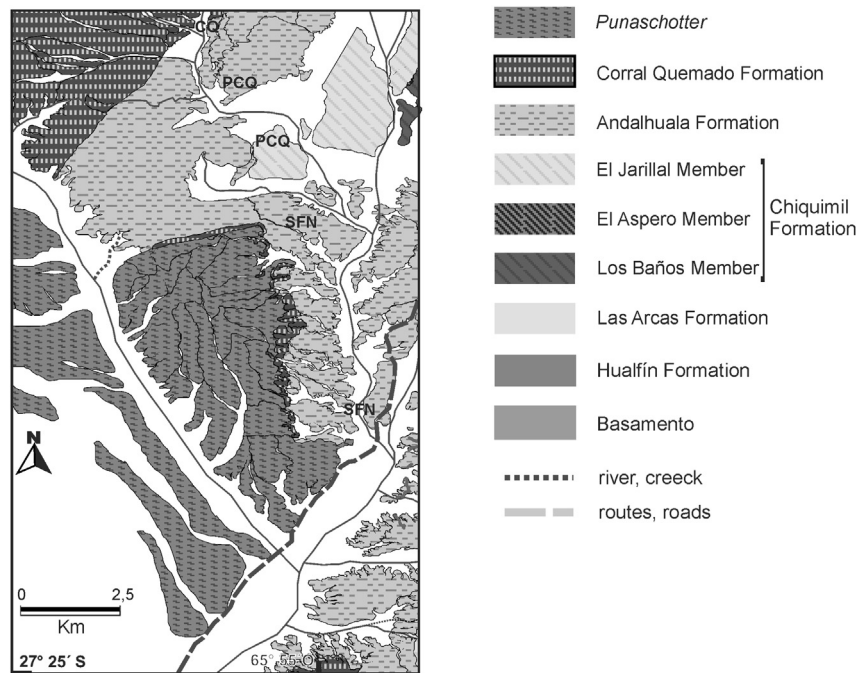


Fig. 4. Maps showing the stratigraphic reallocation proposed in this contribution, at west of San Fernando River. **Abbreviations:** CQ, Corral Quemado; PCQ, Puerta de Corral Quemado; SFN, San Fernando Norte; SFS, San Fernando Sur.

where three facies assemblages were recognized. As was indicated above, these sediments were previously assigned to *Punaschotter* unit by Muruaga (1998, 2001a, b) and Bossi and Muruaga (2009). In these deposits it can be identified the FA II and III can be identified, which allowed to infer the possible development of a) distant and intermediate floodplain deposits, which are identified by different involvements of fine brownish sands; b) the existence of ephemeral water bodies (lagoons or ponds) over the floodplains in which the mud and silt were deposited by settling; c) secondary channels on the floodplain, and the FA VIII facies with more energy than the previous ones, although still very low, in which the fine sandstones present parallel lamination, are interpreted as runoff or spays deposits. This interpretation contrast with other near localities (Villavil or Quillay River; Bossi et al., 1999, 2001; Muruaga, 1998, 2001) or other regions (Santa María Valley; Kleinert and Strecker, 2001) because generally the Corral Quemado Formation was described as deposits of gravels and coarse sandstones interpreted as gravel channels or alluvial fans deposits.

Finally, the last 25 m of SFN log allows recognizing the *Punaschotter* unit, characterized by the FA VI, which is represented by grading deposits of massive gravel with imbricated blocks interpreted as gravel channel and bars. This interpretation agrees with the indicated in the previous proposal (see above).

From the geochronological point of view, the intermountain valleys of North Catamarca represent one of the areas with late Neogene outcrops in Argentina of which there is the most information (see Table 3). The new stratigraphic and geochronological data presented here provides new information to complete our knowledge of the precise age of the mammalian assemblages recovered from Neogene units of Catamarca Province. The fossil mammals recovered from Santa María Valley (in Santa María basin) and Corral Quemado area (in Villavil-Quillay basin) were traditionally correlated and considered coetaneous as they came from the same lithostratigraphic unit (see Riggs and Patterson, 1939; Simpson, 1940; Marshall and Patterson, 1981; Pascual and

Odreman Rivas, 1971). However, the numerous strata interbedded between sediments of Santa María Group have been analyzed radiometrically in many opportunities and these analyses have shown a depositional differential time of the sedimentary sequence for the different basins (Spagnuolo et al., 2010, 2013, 2015; Georgieff et al., 2012a, b; Georgieff and Díaz, 2014; Bonini, 2014; Bonini et al., 2015;). So, the new information is presented as a good opportunity for calibrating the Neogene faunas of Catamarca, and it can provide a reliable base to infer the evolutionary process (see Bonini, 2014; Esteban et al., 2014).

In many opportunities, the absolute ages were used to determine the lithostratigraphic boundaries (Bossi and Muruaga, 2009; Hynek et al., 2012; Esteban et al., 2014). However, a regional visualization of them shows that these guides levels are not a stratigraphic markers (see Fig. 6).

Close to the Villavil Village, Sasso (1997) obtained an age of 9.14 ± 0.09 Ma from andesitic-basaltic rocks from the El Áspero Member of the Chiquimil Formation. These rocks were considered by Muruaga (1998, 2001a, b) as the correlation marker between the Río Villavil and Cerro El Durazno outcrops, nevertheless, this strata disappears southwards in the Puerta de Corral Quemado (PCQ) area. On the other hand, the conspicuous tuff outcrops in the surroundings of PCQ locality, called “Tefra del Puerto”, was considered by some authors as belonging to lower strata of Andalhuala Formation (e.g. Riggs and Patterson, 1939; Marshall and Patterson, 1981; Bossi and Palma, 1982; Bossi et al., 1987); while for others researchers this bed constitutes the boundary between the Chiquimil and Andalhuala Formations (e.g. Bossi and Muruaga, 2009; Esteban et al., 2014). In the same way, Muruaga (1999, 2001a, b) recognized a thick tuff in Villavil outcrops, inferred as the “Tefra del Puerto”, but positioned 300 m above the Chiquimil-Andalhuala boundary, and pointed it out as the diachronic limit between these units. The “Tefra del Puerto” was analyzed in two opportunities by different authors with different radiometric analysis techniques, providing the ages of 6.68 ± 0.02 Ma (Marshall et al.,

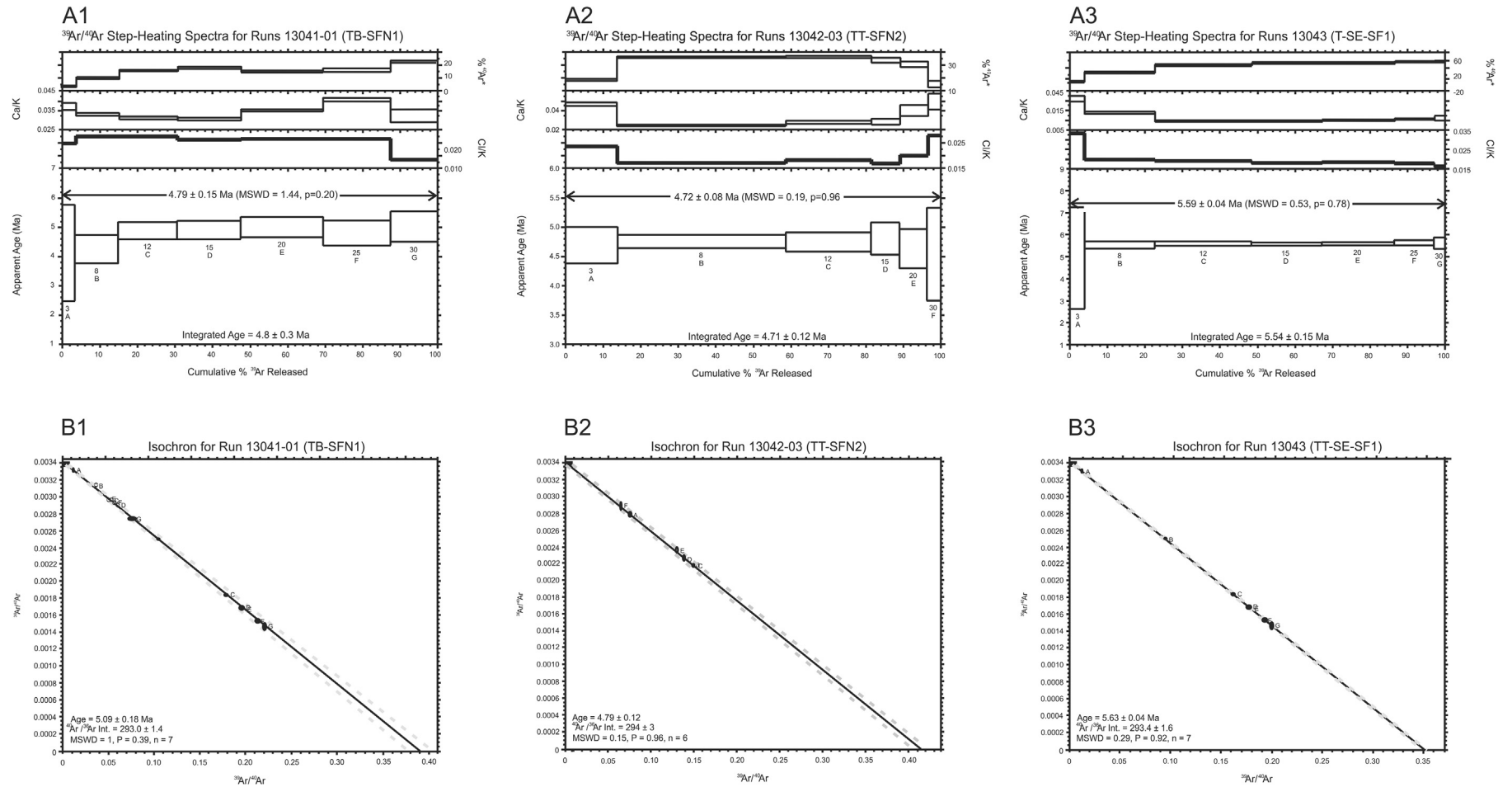


Fig. 5. A. ^{40}Ar – ^{39}Ar Step-Heating Spectra for the tuff; **A1**, for Runs 13041-01 (TB-SFN1); **A2**, for Runs 13042-03 (TT-SFN2); **A3**, for Runs 13043 (T-SE-SF1); **B.** Isochron information for the tuff; **B1**, for Run 13041-01 (TB-SFN1); **B2**, for Run 13042-03 (TT-SFN2); **B3**, for Run 13043 (TT-SE-SF1).

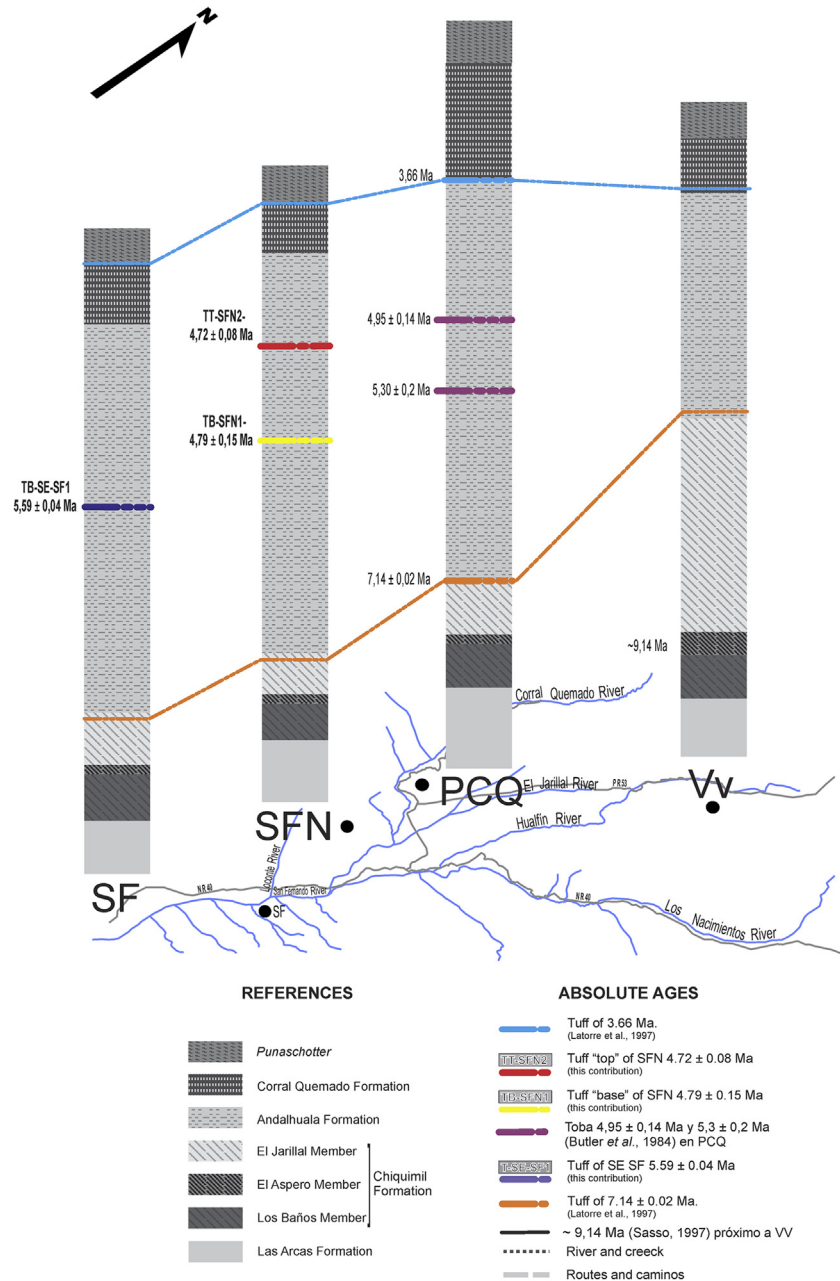


Gráfico fuera de Escala

Fig. 6. Temporal correlation of the sediments outcropping in the Villavil-Quillay basin, indicating some of the absolute ages.

1979), by the method $^{40}\text{K}-^{40}\text{Ar}$, and 7.14 ± 0.02 Ma (Latorre et al., 1997), by $^{40}\text{Ar}-^{39}\text{Ar}$ technic. This tuff bed has not yet been identified in the San Fernando area. Additional ages obtained from tuff beds are listed in Table 3.

A thick stratum of tuff interbedded between gravels deposits identified in PCQ area was considered in different ways by the authors a) interbedded near to the base of Corral Quemado Formation by Marshall et al. (1979) and Marshall and Patterson (1981); b) as the upper levels of Andalhuala Formation by Bossi and Palma (1982), Bossi et al. (1987) and Muruaga (1998, 2001a); c) the contact between Andalhuala and Corral Quemado Formations by others (e.g. Esteban et al., 2014); and d) in SFN log was identified as a thick tuff level in the contact of Corral Quemado and Punaschotter units. This tuff bed recognized in the PCQ area gives the following

absolute ages: 3.54 ± 0.03 Ma (Marshall et al., 1979) and 3.53 ± 0.04 Ma (Butler et al., 1984), both dated by $^{40}\text{K}-^{40}\text{Ar}$; and 3.66 ± 0.05 Ma (Latorre et al., 1997), dated by $^{40}\text{Ar}-^{39}\text{Ar}$.

7. Conclusions

In summary, the results of the sedimentology analyses performed in this contribution indicate that the sedimentary sequence described in the San Fernando area allows recognizing 20 lithofacies and 8 facies assemblages, which correspond to deposits of a fluvial subenvironment with permanent sandy braided rivers, that pass through a hierarchical system of minor channels culminating in a dry cycle of alluvial fans. These deposits correspond to the Andalhuala, Corral Quemado, and Punaschotter units, and were

Table 3

Summary of geochronologic information known from the Villavil-Quillay Basin.

Name	Locality	Age (Ma)	2σ (Ma)	Method	Reference
KA 3343	PCQ	3.53	0.04	^{40}K – ^{40}Ar	Butler et al., 1984
KA 3343	PCQ	3.54	0.03	^{40}K – ^{40}Ar	Marshall et al., 1979
CQ38	CQ	3.65	0.12	^{206}Pb – ^{238}U zircon	Pingel et al., 2016
KA 3343	PCQ	3.66	0.05	^{39}Ar – ^{40}Ar	Latorre et al., 1997
TB-SFN2	SFN	4.72	0.08	^{39}Ar – $^{40}\text{Ar}^a$	This study
TB-SFN1	SFN	4.79	0.15	^{39}Ar – $^{40}\text{Ar}^a$	This study
KA 4368	PCQ	4.95	0.14	^{40}K – ^{40}Ar	Butler et al., 1984
ENTR 909	SMV	5.19	0.01	^{40}K – ^{40}Ar	Hynek et al. (2012)
QJ4	SMV	5.20	0.06	^{40}K – ^{40}Ar	Pingel et al., 2016
QDJ 983	SMV	5.27	0.01	^{39}K – ^{40}Ar	Hynek et al. (2012)
KA 4099	PCQ	5.3	0.2	^{40}K – ^{40}Ar	Butler et al., 1984
T2-R Zr	CV	5.50	0.90	^{40}K – ^{40}Ar f.tr	Strecker et al. (1989)
T-SE-SF1	SFS	5.59	0.04	^{39}Ar – $^{40}\text{Ar}^a$	This study
KA 3386–90	SMV	6.02	0.04	^{40}K – ^{40}Ar	Marshall et al., 1979
VV-1	BL	6.35	0.70	^{206}Pb – ^{238}U zircon	Carrapa et al., 2014
KA 3307	PCQ	6.68	0.02	^{40}K – ^{40}Ar	Marshall et al., 1979
KA 3307	PCQ	7.14	0.02	^{39}Ar – ^{40}Ar	Latorre et al., 1997
CQ40	CQ	7.70	0.10	^{40}Ar – ^{39}Ar	Pingel et al., 2016
CQ12	CQ	8.74	0.53	^{206}Pb – ^{238}U zircon	Pingel et al., 2016
TOBA TUCUMAN	SMV	9.01	0.12	^{39}Ar – ^{40}Ar	Spagnuolo et al., 2015
FAR 262	Vv	9.14	0.09	^{39}Ar – ^{40}Ar	Sasso, 1997

^a New datings made known in this study.

deposited during the upper Miocene (Messinian) to upper Pliocene (Piacenzian). Three new absolute ages from tuffs were obtained using ^{40}Ar – ^{39}Ar method (step-heating in biotite), which are: 5.59 ± 0.04 Ma from lowers beds of Andalhuala Formation cropping out in SFS; and 4.79 ± 0.15 Ma and 4.72 ± 0.08 from the upper beds of Andalhuala Formation cropping out at the west-northwest of SFN. Likewise, it was identified a tick tuff level in the contact of Corral Quemado Formation and *Punaschotter* unit, which apparently matches with the tuff dated in approximately 3.66 Ma at PCQ.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jsames.2017.08.020>.

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