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Stratigraphy, sedimentology, and geothermal reservoir potential of the volcaniclastic Cura-Mallín succession at Lonquimay, Chile

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ABSTRACT

The Tolhuaca Volcano near Lonquimay in south-central Chile has been the subject of several studies due to its geothermal manifestations, but little is known about the stratigraphy and reservoir potential of the Cura-Mallín Formation forming its basement. Field work and U-Pb dating of detrital zircons allow us to redefine this succession as the Cura-Mallín Group, consisting of the volcano-sedimentary Guapitrío Formation, sedimentary Río Pedregoso Formation, and volcano-sedimentary Mitrauquén Formation. The Río Pedregoso Formation can be subdivided into three formal units, namely the Quilmahue Member, Rucañanco Member, and Bío-Bío Member. The base of the Quilmahue Member interfingers laterally with the base of the Guapitrío Formation, for which a previous K/Ar date of 22.0 ± 0.9 Ma was apparently discarded by the original authors. However, this date is consistent with the stratigraphic position of the Quilmahue Member and new zircon dates from the overlying units, also coinciding with the initiation of an extensional phase in the Bíobío-Aluminé Basin. Deposition of the Quilmahue Member continued throughout the early Miocene, as confirmed by dates of 17.5 Ma reported by previous authors and 16.5 Ma obtained in this study. The Rucañanco Member was deposited during the Serravalian around 12.6 Ma, whereas the Bío-Bío Member was dated at the Serravalian-Tortonian limit (11.6 Ma). Although all three members were deposited in a fluvio-lacustrine environment, they were dominated respectively by flood plains with crevasse splays, lake margins with distributary mouth bars and Gilbert-type deltas, and distal braided and meandering rivers. Whereas the Quilmahue Member was deposited during basin extension, the Rucañanco Member was formed during a period of basin inversion and compression. Temporary tectonic quiescence during deposition of the Bío-Bío Member allowed denudation of the landscape, but around 9.5 Ma tectonism was renewed again during deposition of the Mitrauquén Formation. From a geothermal point of view, the Guapitrío Formation has a low potential to host significant reservoirs due to extensive hydrothermal alteration that produced secondary minerals clogging pore spaces and fractures. In the Río Pedregoso Formation, on the other hand, the Rucañanco Member seems to have the best reservoir potential, as it has relatively thick, semi-permeable sandstones and conglomerates deposited in a lake-margin environment.

1. Introduction

The Tertiary Cura-Mallín succession is located between 36° and about 40°S (Fig. 1). It occurs in 6 as yet unmapped basins, namely the Valle Central Basin, Cura-Mallín Basin, an as yet unnamed sub-basin to the northeast of the latter (here referred to as the Andacollo Sub-basin), the Bíobío-Aluminé Basin, Loncopué Basin, and the Collón Cura Basin, the last two being located in Argentina (Radic et al., 2002; Spalletti et al., 2013). Flynn et al. (2008) considered the Cura-Mallín succession to be a possible southern extension or lateral equivalent of the volcano-sedimentary Abanico Formation between 32° and 36°S.

The sedimentary fill of these basins has received much attention lately, due to the fact that they form the basement underlying Quaternary volcanoes such as Lonquimay and Tolhuaca (Fig. 1). The latter is considered to be a potentially commercial geothermal

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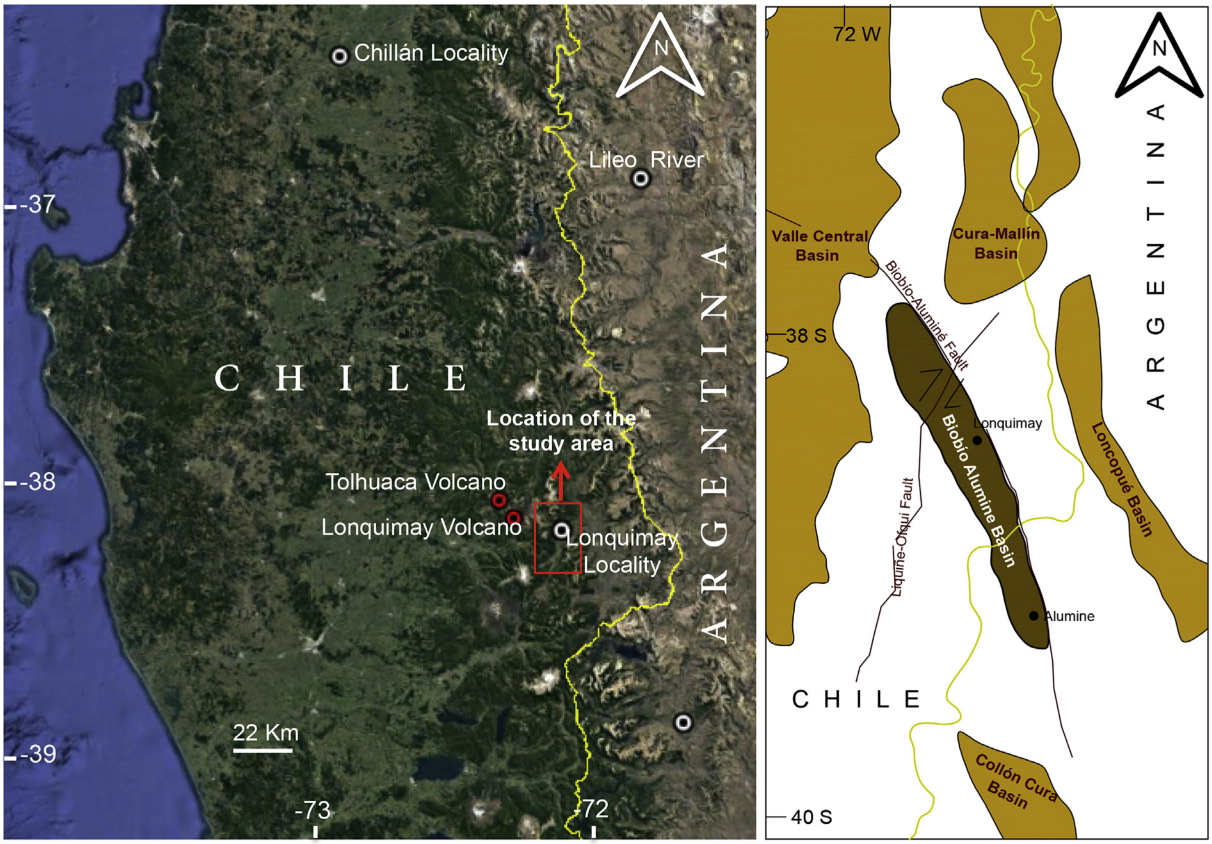

Fig. 1. a) Location of study area with some localities mentioned in the text. b) Distribution of the different basins hosting the Cura-Mallín Group (modified from Spalletti et al., 2013).

system and has been the subject of various recent studies (Risacher et al., 2011; Melosh et al., 2012; Sánchez et al., 2012; SKM, 2012; Iriarte, 2013; Lizama, 2013; Vicencio, 2015; Aravena et al., 2016). A flow test on one of the deep exploration wells performed by the company Mighty River Power Chile, confirmed that it can already be considered as an indicated resource (Aravena et al., 2016). Melosh et al. (2012) reported the existence of a two-level reservoir with steam and steam-heated waters at a shallow depth of about 500 m, and a deep liquid reservoir at 1100–2500 m depth, consistent with a high temperature propylitic alteration zone (>250 °C) observed in other wells (Iriarte, 2013). The minimum horizontal extent of the reservoir is constrained by a low resistivity conductive anomaly associated with a 7–8 km^2 clay cap (Melosh et al., 2012).

Interpretation of a seismic line northeast of Andacollo in Argentina at 37°S, indicates that the Cura-Mallín basins subsided along normal faults (Jordan et al., 2001; Spalletti et al., 2013) and that the deposits initially filling these half-grabens (Radic et al., 2002) accumulated during an extensional tectonic phase from the late Oligocene to middle Miocene (Jordan et al., 2001; Folguera et al., 2003). This extension was followed by a compressive tectonic regime that caused basin inversion along inverse faults during the late Miocene (Burns and Jordan, 1999; Carpinelli, 2000; Radic et al., 2000, 2002; Folguera et al., 2003; Melnick et al., 2006; Radic, 2010).

In the Cura-Mallín Basin around Laguna del Laja (Spalletti et al., 2013), the Cura-Mallín Formation is composed of the mainly volcanic Río Queuco Member (Niemeyer and Muñoz, 1983; Carpinelli, 2000) and the overlying sedimentary Malla Malla Member (Carpinelli, 2000; Radic et al., 2000). Drake (1976) obtained a K-Ar age of 14.5 ± 1.4 Ma from the top of the Río Queuco Member, but the Trapa Trapa Formation overlying the Cura-Mallín Formation in this basin area yielded K-Ar ages between 18.2 ± 0.8 and 14.7 ± 0.7 Ma (Flynn et al., 2008), which is clearly contradictory. Furthermore, it should be noted that the Trapa Trapa Formation as originally defined is largely volcanic (Muñoz and Niemeyer, 1984), and that the granular conglomerate considered by Flynn et al. (2008) and others to mark the onset of Trapa Trapa sedimentation could just as well be grouped with the Malla Malla Member of the underlying Cura-Mallín Formation. In the Andacollo Sub-basin immediately to the east of Laguna del Laja, studies integrating published geochronological data with field observations suggest that the age of the Trapa Trapa Formation ranges from 20 to about 12 Ma (Radic et al., 2002; Melnick et al., 2006). This largely coincides with the dates of the Trapa Trapa Formation in Chile obtained by Flynn et al. (2008), but suggests that the Río Queuco Member is probably older than 14.5 Ma. In fact, the base of the lower pyroclastic series of the Cura-Mallín Formation in Argentina has yielded an ^{40}Ar-^{39}Ar age of 24.6 ± 1.8 Ma (Jordan et al., 2001). Such apparently contradicting ages are also recorded further south in the Bíobío-Aluminé Basin, and reflect some of the current geochronological and stratigraphic uncertainties in the Cura-Mallín succession.

The Bíobío-Aluminé Basin (Spalletti et al., 2013) is located between the Copahue-Callaqui Volcanic Complex and the Sollipulli Volcano. In this area, the volcaniclastic succession was described for the first time by Burckhardt (1900), and since then has been studied by various authors, including Sandoval (1977), Cisternas and Díaz (1985), Suárez and Emparan (1988, 1995, 1997), Wall et al. (1991), and Vicencio (2015). Suárez and Emparan (1988) first referred to the succession at Lonquimay as the Bíobío Group, but it was later redefined and reclassified as the Cura-Mallín Formation, composed of the volcanic Guapitrío Member and the sedimentary Río Pedregoso Member (Fig. 2; Suárez and Emparan, 1995, 1997). The Guapitrío Member probably correlates with the Río Queuco Member of the Valle Central Basin, whereas the Malla Malla Member of the latter is a likely lateral equivalent of part of the Río Pedregoso Member (Flynn et al., 2008).

Suárez and Emparan (1995, 1997) obtained K-Ar ages between 20.3 ± 4.0 and 19.1 ± 2.8 Ma for volcanic facies near the base of the Guapitrío Member (Fig. 2). An age-diagnostic notoungulate, *Nesodon conspurcatus*, recovered from the Río Pedregoso Member (Croft et al., 2003b) indicates a Santacrucian to Friasian SALMA assignment (17.5–15.5 Ma; Flynn and Swisher, 1995), which is confirmed by at least one K-Ar date of 17.5 ± 0.6 Ma in beds immediately overlying the strata from which this specimen was recovered (Suárez and Emparan, 1995, 1997). However, the present stratigraphic scheme for the Cura-Mallín Formation at Lonquimay postulates an age of 20.3–10.7 Ma for the Guapitrío Member and 17–13 Ma for the Río Pedregoso Member (Suárez and Emparan, 1997), so that the two members are considered to be roughly time-equivalent (Fig. 2). The environmental interpretation contemplates a change from lacustrine at 17 Ma to deltaic around 13 Ma at Piedra Parada and Cerro Rucañanco (Fig. 3), respectively (Suárez and Emparan, 1997).

The Río Pedregoso Member contains a diverse fossil record, including freshwater fish, mollusks, and ostracods (Sandoval, 1977; Osorio et al., 1982; Rubilar and Wall, 1990; Rubilar, 1994), as well as birds and mammals (Suárez et al., 1990; Wall et al., 1991; Croft et al., 2003a, 2003b; Buldrini et al., 2011). The main vertebrate fossil finds have been reported from Piedra Parada, Puente Lolén, Cerro Tallón, Puente Tucapel, Bío-Bío and Cerro Rucañanco (Fig. 3). At Piedra Parada there is a register of Gliptodontidae, mammals without a definite age range (Suárez et al., 1990). Remains of the fish Characidae *indet.* of Miocene age were recovered from Puente Lolén (Rubilar, 1994). Cerro Tallón yielded fragments of *Nesodon conspurcatus* (Croft et al., 2003b), as well as five types of fish, including *Percichthys lonquimayiensis*, *Percichthys sandovali* (Arratia, 1982) and unidentified species of *Percichthys*, *Santosius,* and Characidae, all assigned to the Miocene (Suárez et al., 1990; Rubilar, 1994). At Puente Tucapel, in situ fragments of *Macrauchenia litopterna*, a mammal without a definite age range, were found (Suárez et al., 1990). From this locality additional, displaced fragments of *Protypotherium* sp. were also reported (Suárez et al., 1990). The latter fossil was assigned to the Santacrucian Land Mammal Age by Buldrini et al. (2011). At the Bío-Bío locality, *Nematogenys cuivi*, a fish assigned to the Miocene, was recovered (Azpelicueta and Rubilar, 1998), while fragments of Characidae and Serrasalminae, both Miocene fishes (Rubilar, 1994), were found at Cerro Rucañanco. Finally, at the latter locality, the first Tertiary terrestrial bird fossil identified in South America was discovered, namely *Meganhinga chilensis* (Alvarenga, 1995). It was assigned to the late Burdigalian by Suárez et al. (1990) and was also considered to be linked to the Santacrucian Land Mammal Age (Wall et al., 1991). However, at Cerro Rucañanco there is a discrepancy between the age of 13 Ma

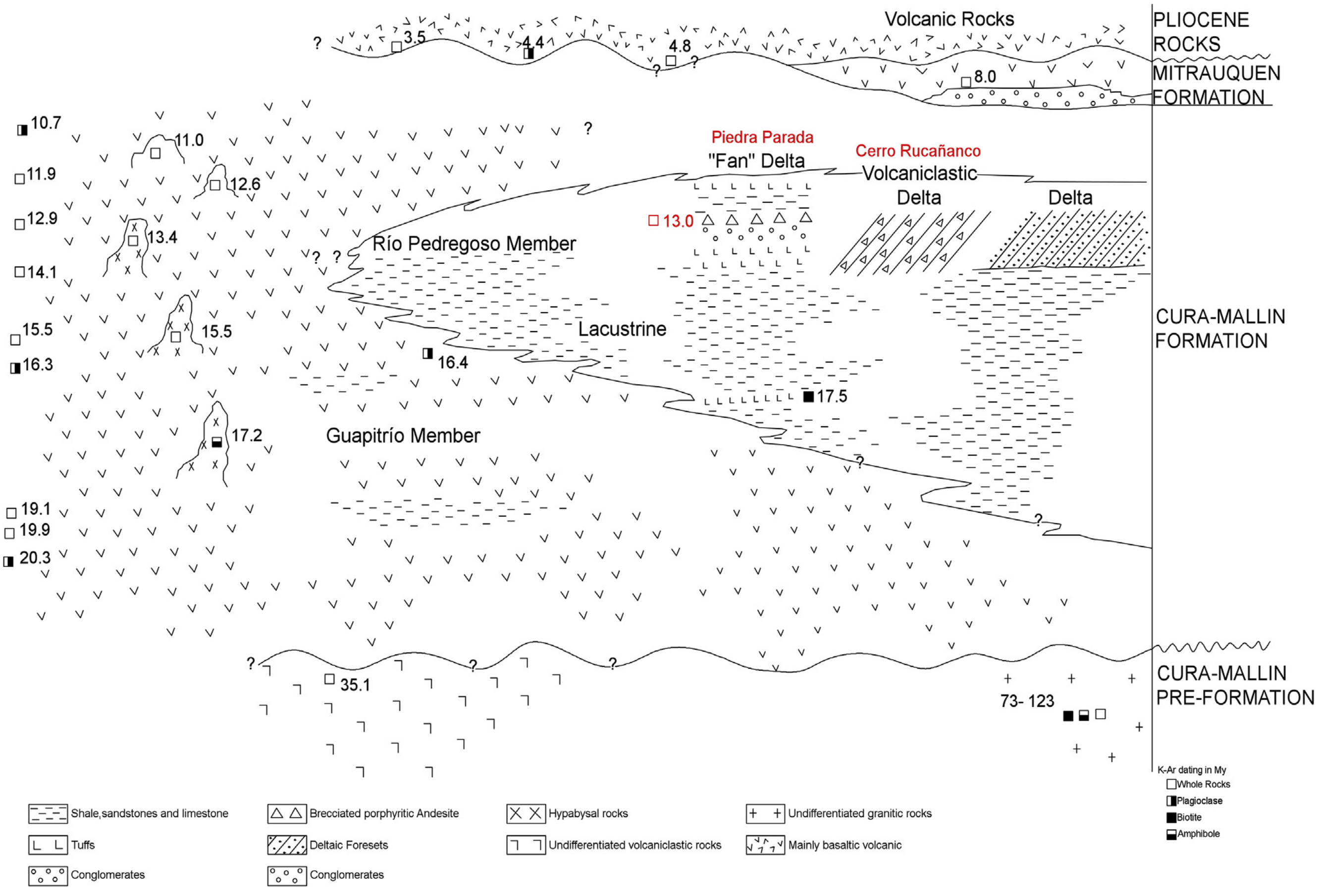

Fig. 2. Original stratigraphic scheme of Suárez and Emparan (1995), showing that the Guapitrío and Río Pedregoso "Members" co-existed.

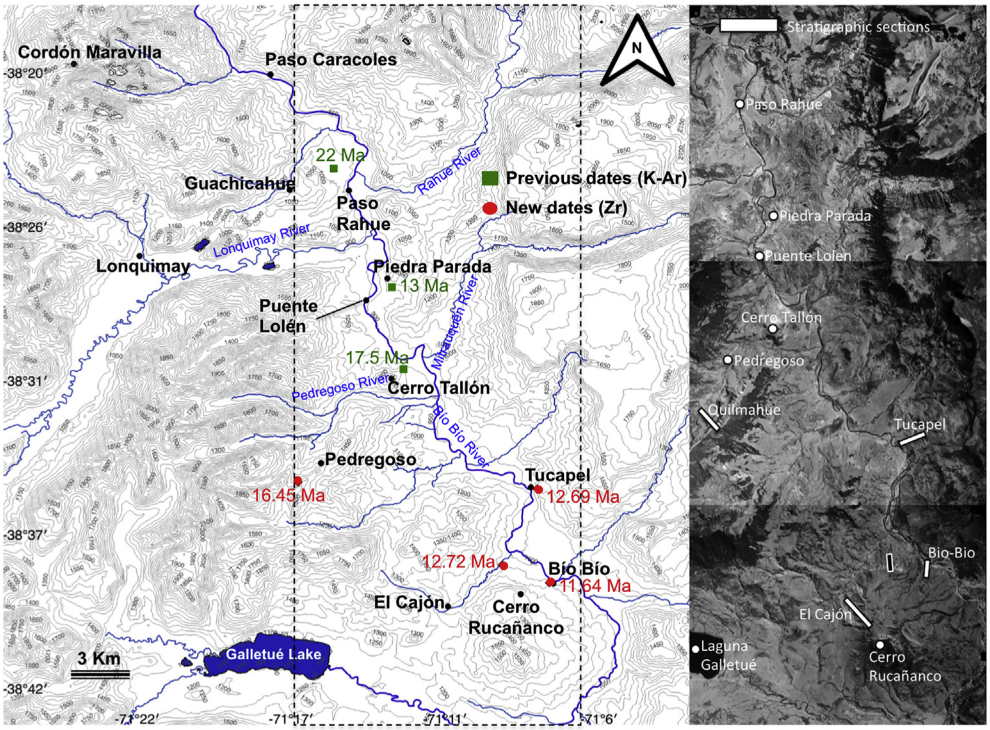

Fig. 3. Topography of the Bíobío-Aluminé Basin, showing localities mentioned in text, location of measured stratigraphic sections, and dated samples.

ascribed to the sedimentary deposits and the Santacrucian Land Mammal Age of 17.5–16.3 Ma. This again reflects some of the existing ambiguities in the stratigraphic interpretation and indicates that a revision of the latter is urgently required, as it is vital for successful geothermal exploration in the area.

In this paper we report five new detrital zircon U-Pb ages and present a revised sedimentological and geochronological interpretation of the Cura-Mallín succession, which allows us to propose a new stratigraphic scheme. The stratigraphic relationship between the Guapitrío and Río Pedregoso units is also clarified, which has long been a subject of dispute. Finally, we present a preliminary assessment of the potential of the Cura-Mallín succession to host geothermal reservoirs, a key factor if these systems are ever to be exploited commercially.

2. Methodology

Field work in the Lonquimay area consisted of geological mapping, outcrop description (lithology, sedimentary structures and palaeocurrent directions), and the measuring of five stratigraphic sections using a tape and Brunton compass in order to make corrections for variations in dip and strike (Fig. 3). This was backed up by photogeological interpretation. Samples were also collected for detrital zircon U-Pb dating, thin section studies, and permeability measurements.

Geological mapping was carried out at a scale of 1:10,000 between Paso Caracoles to the north and the Galletué Lake to the south, following the outcrops along the Bío-Bío River (Figs. 3 and 4). Of the 5 measured stratigraphic sections, 2 were at the locality of Pedregoso, where total thicknesses of 86 and 116 m were recorded, and 1 each at Puente Tucapel, El Cajón and Bío-Bío, with total thicknesses of 96, 102, and 78 m, respectively (Fig. 3).

Based on this information, facies associations were identified, an interpretation of sedimentary environments was made, and a new stratigraphic subdivision was established for the Río Pedregoso Formation.

The mineralogy and hydrothermal alteration of the Guapitrío Formation was studied using optical microscopy, cathodoluminescence, SEM, XRDS, and XRD (Vicencio, 2015). We also carried out permeability studies at IDIEM (Universidad de Chile) on 11 samples collected from the Río Pedregoso Formation, using a standard constant head test (Das, 2001) and a portable permeameter, *TinyPerm*. The formula

$$K = \frac{\Delta VL}{A\Delta h\Delta t}, \tag{1}$$

where ΔV is the volume of fluid (m^3) measured over a determined time interval Δt, L is the length of the sample (m), A is the transverse surface area of the sample (m^2), and Δh is the head (m), was used to calculate the hydraulic conductivity K in m s^{-1}. *TinyPerm* was also used under laboratory conditions on the same samples to check the results. This method utilizes a microcontroller to monitor the vacuum replenishing rate after extracting a certain volume of air from the sample with a hand pump mechanism. It yields a value T that is related to the permeability through the equation

$$T = -0.8206\log_{10}(k) + 12,8737, \tag{2}$$

where k is the intrinsic permeability expressed in m^2. To guarantee a more constant reading, *TinyPerm* was mounted vertically on a universal metal stand in order to prevent possible pressure loss during the procedure. The average of ten measurements performed on each of the 11 samples was used.

The results of this method were compared to that of the constant head reading through the equation of Langguth and Voigt (1980):

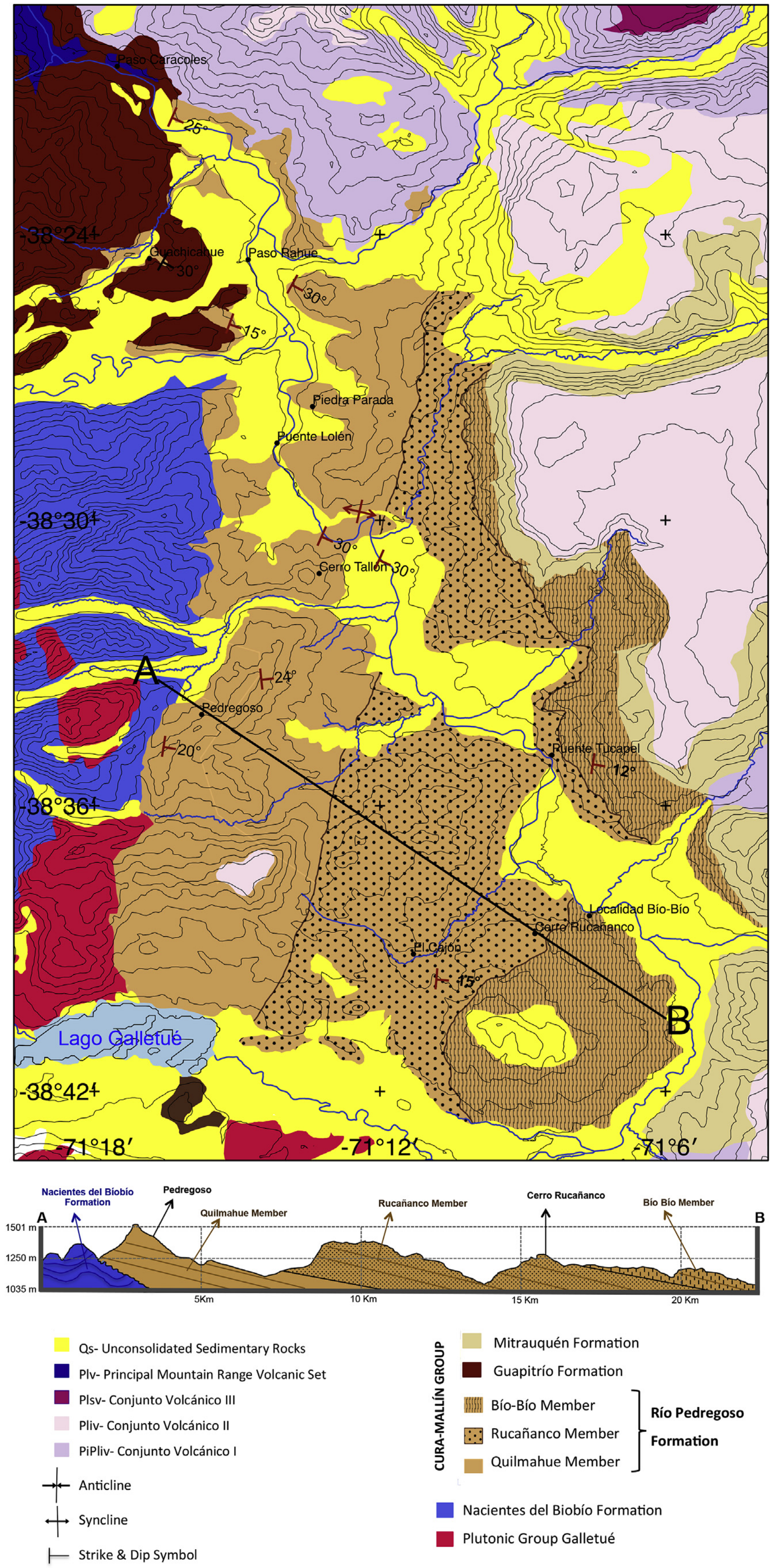

Fig. 4. Geological map of the Bíobío-Aluminé Basin.

$$K = \frac{k\rho g}{\mu}, \tag{3}$$

where ρ and μ are the fluid density and dynamic viscosity, respectively, and g is the acceleration due to gravity (9.81 m s^{-2}).

3. Stratigraphy and sedimentology

The stratigraphic scheme currently accepted for the Cura-Mallín Formation is that the deltaic and lacustrine environments of the Río Pedregoso Member were contemporaneous between 17 and 13 Ma (Fig. 2) and that the Piedra Parada outcrops are younger than the Cerro Tallón succession (Suárez and Emparan, 1988; 1995, 1997). However, new structural data obtained during this study indicate that the beds dip mainly towards the southeast. Consequently, the oldest outcrops are in the northwest around Paso Caracoles and Paso Rahue, whereas the youngest are exposed in the southeast at the Bío-Bío locality (Figs. 3 and 4). The deposits at Piedra Parada are therefore located towards the base of the succession, those at Cerro Tallón are in the middle of the stratigraphic sequence, and those at Cerro Rucañanco are near the top (Fig. 5).

Our field work indicates that the Río Pedregoso Member can be subdivided into three distinct units that comply with international regulations for their definition as formal members (Hedberg, 1980). We therefore propose that the Cura-Mallín Formation be elevated to group status, and that its former Guapitrío and Río Pedregoso Members be given formation status. This preserves the essence of the previous descriptions (Suárez and Emparan, 1995, 1997; Vicencio, 2015), but allows us to further subdivide the Río Pedregoso Formation into the Quilmahue, Rucañanco, and Bío-Bío Members (Fig. 5). The Guapitrío Formation, being of volcanic character, is lithologically too different from the Río Pedregoso Formation to be included in the latter as a member, and also partially overlaps with it in time. It therefore maintains its independent status as a different formation as proposed in the earlier studies of Suárez and Emparan (1995, 1997) and Vicencio (2015).

The Mitrauquén Formation, cropping out to the east of the Bío-Bío River and south of the Mitrauquén River (Sandoval, 1977; Suárez and Emparan, 1997), overlies the Bío-Bío Member concordantly and is composed of conglomerates, ignimbrites and andesitic lavas. We propose that it should be incorporated as the third formation of the Cura-Mallín Group, having been dated between 9.5 ± 2.8 and 8.0 ± 0.3 Ma (Suárez and Emparan, 1997) and being overlain discordantly by Pliocene volcanic rocks.

3.1. Guapitrío Formation

Suárez and Emparan (1988, 1995, 1997) described the Guapitrío Formation as a volcanic association of intermediate to acid composition, including pyroclastic falls and flows in volcanic breccias and tuffs. These are interbedded with andesitic lavas as well as lacustrine and fluvial sedimentary units. They also included hypabyssal dikes and sills in this formation, which they dated between 22.0 ± 0.9 Ma and 11.0 ± 1.6 Ma.

The latest study is that of Vicencio (2015), who described five volcaniclastic lithofacies in addition to lavas and dikes in the 900 m thick Cordón Maravilla succession about 10 km northwest of

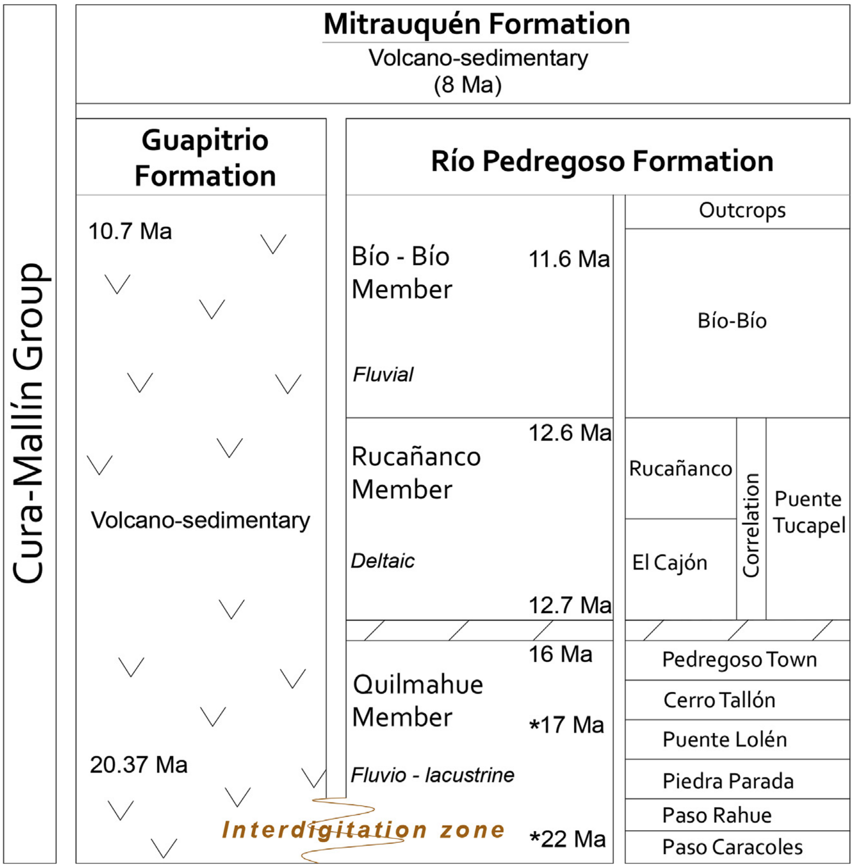

Fig. 5. New stratigraphic subdivision of the Cura-Mallín Group as proposed in this paper.

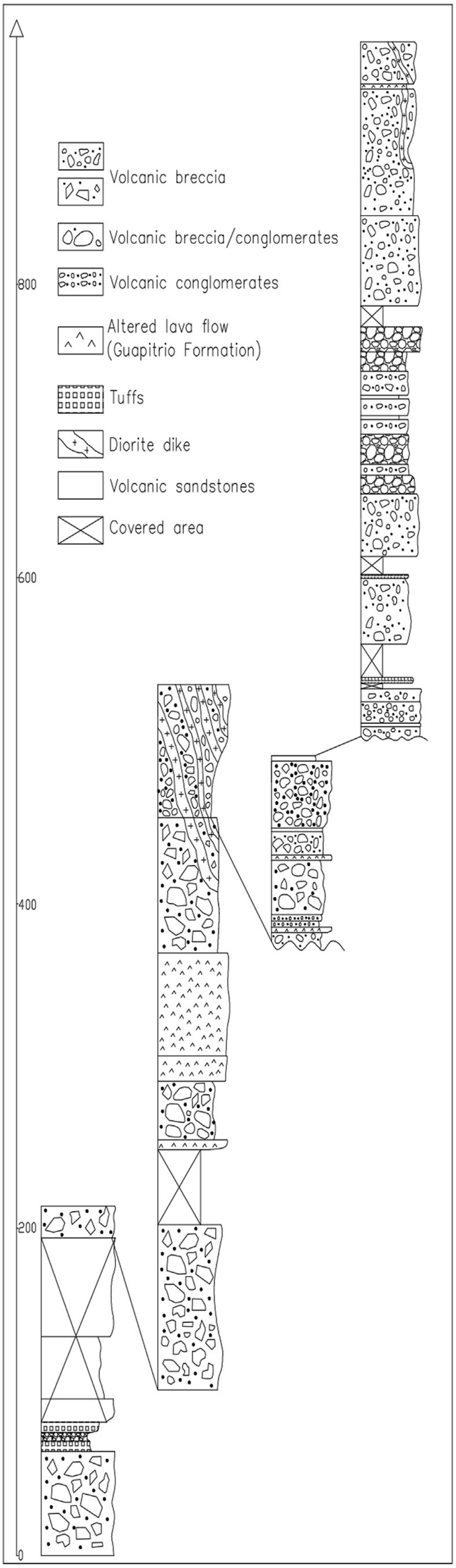

Fig. 6. Stratigraphic succession in the Guapitrío Formation measured by Vicencio (2015) at Cordón Maravilla.

Lonquimay (Fig. 6).

The first volcaniclastic facies, a volcanic breccia, is composed of poorly sorted, matrix-supported clasts of variable composition. At least 10% of these clasts, which are sub-angular to sub-rounded, are of andesitic origin. Texturally, they show partially altered plagioclase phenocrystals and fragments between 0.1 and 2.0 mm in diameter, forming a porphyritic texture. Contacts are generally erosional.

A volcanic conglomerate with similar characteristics to that described above constitutes the second facies, but it has better rounded clasts, a larger percentage of matrix, and lithic tuff fragments. It occurs as transitional zones within volcanic breccias or other facies.

The third facies consists of coarse to very coarse, poorly to well sorted volcanic breccia or conglomerate, which is variably matrix- or clast-supported. Colours range between green and brown to reddish. The matrix is also variable, showing lithic and crystal fragments with a porphyritic texture and tabular plagioclase.

The fourth facies is made up of lithic, glassy and crystalline tuffs up to 5 m thick. These may be altered to clays, although preserving a porphyritic texture. Some samples show an anomalous amount of plagioclase fragments.

Finally, the fifth facies is formed by meter-thick lavas with amygdaloid, porphyritic textures and pervasive alteration. The latter is particularly prominent in fractured or contact zones. These lavas overlie volcanic breccias with concordant or erosional contacts. The primary and alteration mineralogy indicate an intermediate composition with scarce mafic minerals (clinopyroxene). The alteration is best observed in irregular and amygdale cavities, fissures, and zones with increased fracturation. The plagioclase exhibits a high percentage of smectite replacement and shows albitization in disequilibrium, as evidenced by zonation, sieve textures and absorbed boundaries.

Sandstones interbedded with the deposits above are between 1 and 2 m thick, being composed of moderately to well sorted, grey, green and brown lithic fragments with moderate rounding and sphericity. These beds overlie volcanic breccias with erosional contacts, displaying marked vertical and lateral changes in grain size, upper plane lamination, and synsedimentary folds.

Dikes, sills and intrusive subvolcanic rocks of dioritic composition within this succession are oriented approximately between NE, NS and NW.

3.2. *Río Pedregoso Formation*

3.2.1. *Quilmahue Member*

This member is exposed sporadically at different localities, described here in ascending stratigraphic order. Between Paso Caracoles and Paso Rahue north of the Bío-Bío River, black to grey shales and mudstones towards the base of the Quilmahue Member interfinger laterally with andesitic lavas of the Guapitrío Formation (Fig. 5).

Three kilometers to the west of Paso Rahue, at the Guachicahue River (Fig. 3), monomictic, clast-supported conglomerates with rounded clasts between 1 and 15 cm in diameter are intercalated with thin, fine-to medium-grained sandstones showing trough cross-lamination.

At Piedra Parada (Fig. 3), stratigraphically higher than the deposits at Paso Caracoles and the Guachicahue River, there are well-stratified, very fine-to medium-grained sandstones with numerous freshwater bivalve fossils. These are overlain by matrix-supported, polymictic conglomerates with poorly sorted, subrounded to angular clasts. The recorded thickness of the Quilmahue Member at this locality is about 900 m (Carpinelli, 2000).

Stratigraphically above the Piedra Parada deposits, at Puente Lolén, there are mudstones intercalated with fine-to medium-grained sandstones similar to those at Pedregoso. They have a high content of fragmented fish bones, scales, and spines.

The deposits at Cerro Tallón (Fig. 3) are younger than those at Puente Lolén. Here, shales and carbonaceous shales with a high content of fish scales and spines are intercalated with fine-to medium-grained, carbonaceous sandstones showing lower flow regime plane lamination, undulose stratification, and synsedimentary folds. Oölites are present in some sandstones, while fossils are represented by gastropods and wood fragments.

Two stratigraphic sections were measured near Pedregoso (Fig. 3), here referred to as Lower Quilmahue and Upper Quilmahue (Figs. 7 and 8). These are accessible via a rural road that links up with the Ruta 181 highway. The Lower Quilmahue section has a total thickness of 86 m, compared to 116 m measured in the Upper Quilmahue profile. Both sections are dominated by mudstones, minor shales and very fine-to very coarse-grained sandstones, with occasional conglomerate beds up to 4.5 m thick and rare limestone beds slightly exceeding 2 m in thickness. The shales show abundant fish bone fragments (Fig. 9e) and scales as well as occasional wavy lamination, whereas the sandstones display trough, high-angle tabular, and ripple cross-lamination, wavy stratification, upper and lower flow-regime plane lamination, occasional falling water-level marks, mud cracks (Fig. 9a), oölites (Fig. 9d), and raindrop marks (Fig. 9b). Small channels are locally present. Fossils are represented by wood and leaf fragments (Fig. 9f) as well as freshwater gastropods and bivalves. Locomotion traces of the latter are also present (Fig. 9c).

Table 1 shows the 7 sedimentary facies identified in these measured sections, together with their interpretation. These include alluvial fans and proximal braided rivers, distal braided streams, meandering rivers with point bars, flood plains with lakes, crevasse splays, wave-agitated, endorheic lakes, and prograding distributary mouth bars. The general environment is therefore interpreted as fluvial with wide flood plains and shallow overbank lakes. The presence of oölites in limestones and calcareous sandstones indicate endorheic lakes wide enough for significant waves to be generated. This interpretation of a fluvio-lacustrine environment, dominated by extensive flood plains with crevasse splays, is supported by fossils described from other localities in this member. In the Cerro Tallón, Piedra Parada and Puente Lolén sectors, for example, there have been reports of freshwater fish (Sandoval, 1977; Chang et al., 1978; Rubilar, 1994; Suárez and Emparan, 1995), armadillo plates (Suárez et al., 1990), mammals (Croft

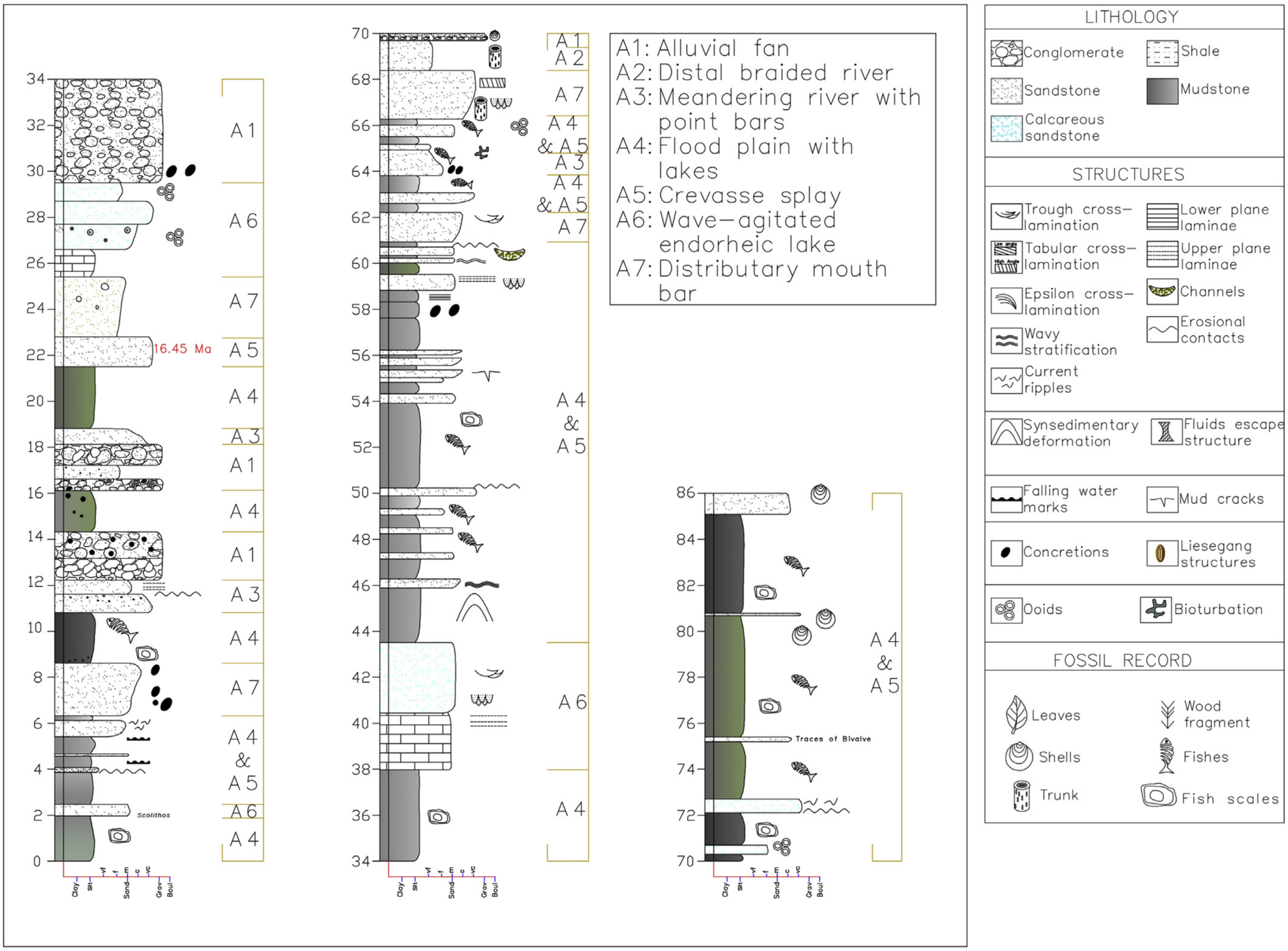

Fig. 7. Stratigraphic section measured in the Quilmahue Formation (Lower Quilmahue). For location see Fig. 3.

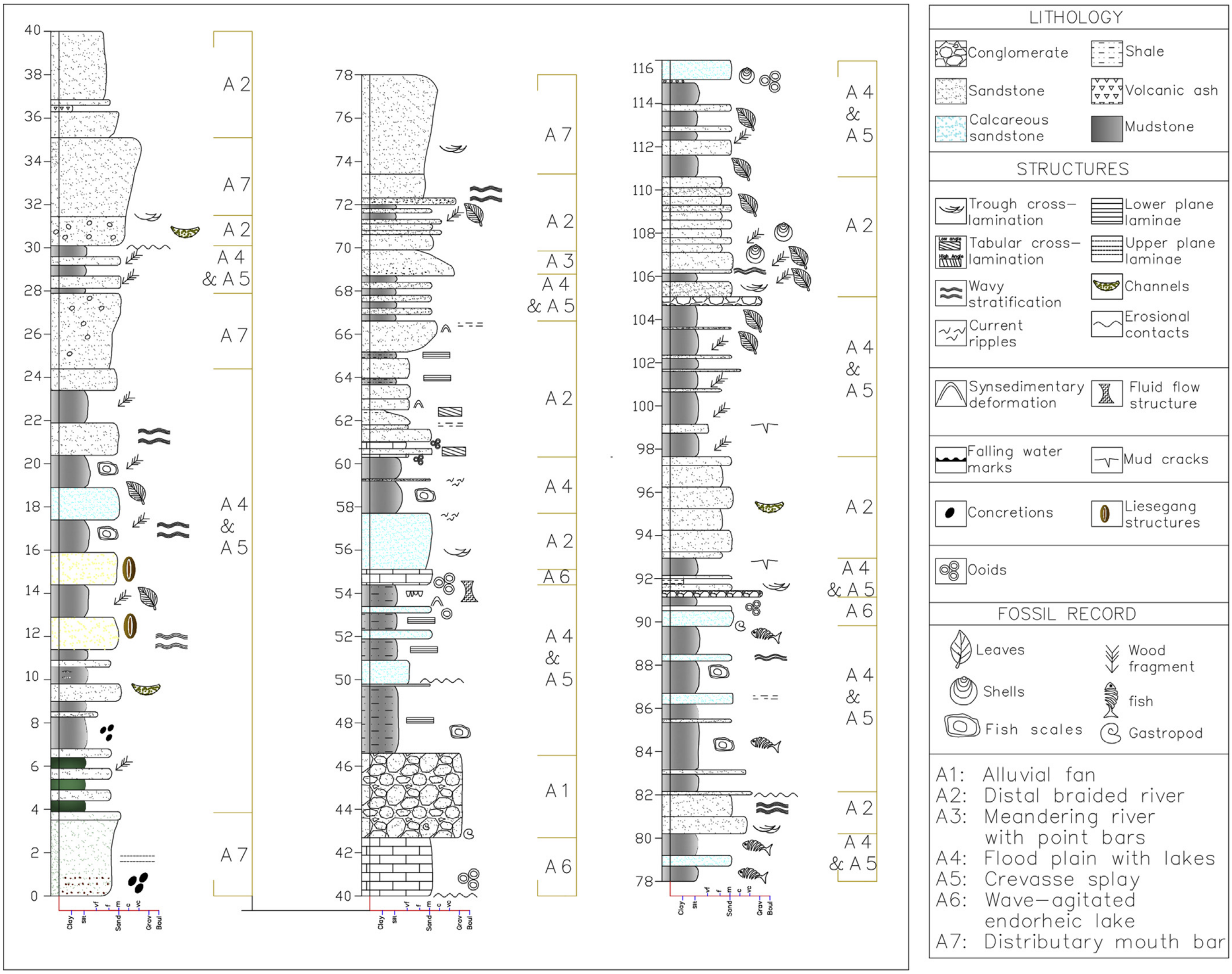

Fig. 8. Stratigraphic section measured in the Quilmahue Formation (Upper Quilmahue). For location see Fig. 3.

et al., 2003a, 2003b), fresh-water pelecypods, brachiopods, and ostracods, as well as fossil wood (Sandoval, 1977; Osorio et al., 1982), and pollen (Palma-Heldt, 1983).

A K-Ar date of 22 ± 0.9 Ma was obtained by Suárez and Emparan (1988) on andesitic, porphyritic lava from the Guapitrío Formation in the Paso Rahue sector where it forms part of the interfingering zone with the Quilmahue Member. By implication, therefore, this age can be assigned to the base of the latter. Additionally, Suárez and Emparan (1995) determined an age of 17.5 ± 0.6 Ma for the deposits at Cerro Tallón, which agrees with our field interpretation of the latter locality being stratigraphically above the Paso Rahue sector. Detrital zircons dated by us from a pebbly sandstone sample collected in the Pedregoso locality, in turn stratigraphically higher than the Cerro Tallón sector, gave an age of 16.45 ± 0.18 Ma. The entire Quilmahue Member was therefore deposited during the early Miocene.

3.2.2. *Rucañanco Member*

Outcrops of the Rucañanco Member were studied by us in the El Cajón and Puente Tucapel sections (Figs. 3, 10 and 11; Tables 2 and 3). A previous profile was also measured at Cerro Rucañanco (Fig. 12) by Wall et al. (1991), which was subsequently described in more detail by Suárez and Emparan (1995). Our data indicate that the deposits at El Cajón underlie those at Cerro Rucañanco, but that both these sections are represented stratigraphically in the Puente Tucapel section.

The stratigraphic sequence at El Cajón (Figs. 10 and 13a), with a measured thickness of 116 m, is located east of Cerro Rucañanco and represents the base of this member. Polymictic, matrix-supported conglomerates with cm-scale clasts, as well as clast-supported, well-imbricated conglomerates with armadillo plate fragments are present. These were deposited in alluvial fans characterized by both debris and braided stream flows (Table 2). Thick (up to 13 m), coarsening-upward, medium-to very coarse-grained sandstones with high-angle planar cross-lamination (Fig. 13b) and synsedimentary deformation structures are interpreted as distributary mouth bars at the margins of deeper lakes. Grey mudstones and shales interbedded with thin sandstones represent flood plains with crevasse splays and ephemeral lakes.

The section at Puente Tucapel (Fig. 3; 11) was measured about a kilometer north of the Tucapel Bridge, at a locality known as Pichipehuenco. Comprising a total thickness of 96 m, it is

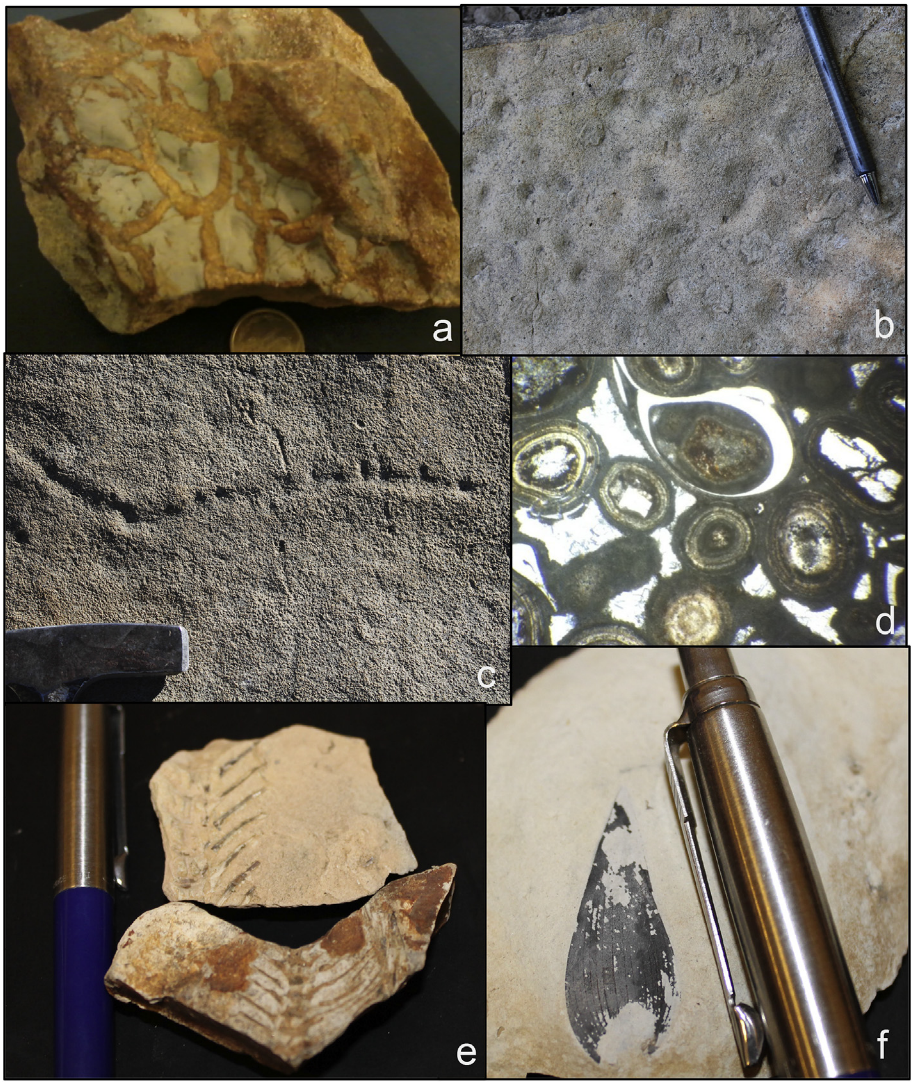

Fig. 9. Sedimentary features in the Quilmahue Member. a) and b) Sand-filled mud cracks and raindrop marks indicating subaerial exposure; c) Bivalve locomotion traces suggesting shallow water bodies such as overbank lakes; d) Calcareous oölites in sandstones at Cerro Tallón indicating wave-agitated, endorheic lakes; e) Fish bones; f) Fossil leaf.

Table 1
Lithofacies description at Pedregoso (Upper and Lower Quilmahue profiles).

Id	Lithology	Sedimentary structures/textures	Fossils	Depositional environment
A1	Polymictic, matrix-supported conglomerate with sub-rounded clasts (1–4 m thick).	Nodules 2 mm in diameter.		Alluvial fan, proximal braided river.
A2	Fine- to coarse-grained, upward-coarsening sandstone; very fine-grained sandstone interbedded with medium to coarse-grained sandstone (<3 m thick).	Trough cross-lamination, high-angle planar cross-lamination, upper flow-regime planar lamination, linguoid ripples, synsedimentary folds, concretions, liesegang structures.	Tree trunks, wood fragments, leaves, bivalves.	Distal braided river.
A3	Fining-upward, coarse- to medium-grained sandstone (<1 m thick).			Meandering river with point bars.
A4	Light grey and green mudstone and shale, rich in phosphorus (1–2 m thick)	Lower flow-regime parallel lamination, raindrop marks, mud cracks, sedimentary dikes, load casts.	Leaves, vegetal organic matter, abundant fish scales	Flood plain with lakes.
A5	Medium- to coarse-grained sandstone (<1 m thick).	Undulose stratification, wave ripples, mud cracks, liesegang structures.	Leaves and vegetal organic matter.	Crevasse splay.
A6	Limestone, calcareous sandstone, fine- to medium-grained sandstone (<2.5 m thick).	Oölites in limestone and calcareous sandstone, undulose stratification, current ripple marks, bivalve traces, *Skolithos*.	Abundant fish scales and spines, gastropods, bivalves.	Larger endorheic lake subjected to wave action.
A7	Coarsening-upward, fine- to medium-grained sandstone (2–5 m thick)	Trough cross-lamination, concretions.		Distributary mouth bar.

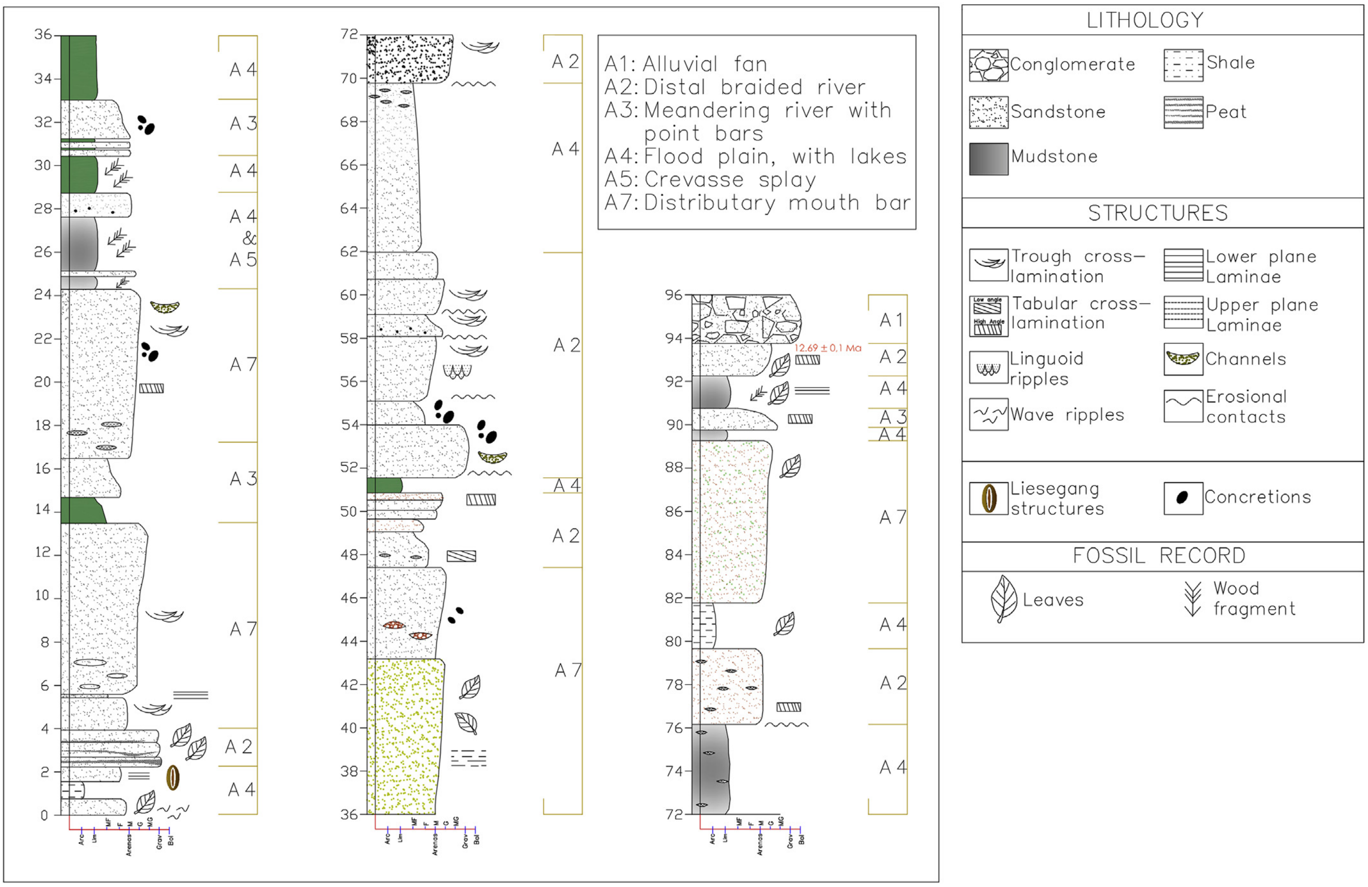

Fig. 10. Stratigraphic section measured in the Rucañanco Member at El Cajón. For location see Fig. 3.

dominated by sandstones with minor mudrocks and conglomerates. Trough and high-angle tabular cross-laminated sandstones occurring in coarsening-upward cycles up to 8 m thick are interpreted as distributary mouth bars. Other sandstone packages, up to 10 m thick, consist of both coarsening- and fining-upward subcycles of fine-to coarse-grained, sometimes pebbly sandstones showing high-angle planar and trough cross-lamination, upper flow-regime planar lamination, and linguoid ripples. They represent distal braided rivers, whereas fining-upward sandstones in cycles up to 2 m thick were deposited in meandering streams. Overbank flood plains and lakes are represented by mudstones and shales reaching 4 m in thickness. They contain fossil wood fragments, leaves (Fig. 13d), fine organic matter, and up to 1 m thick crevasse splay sandstones. Finally, polymictic, matrix-supported conglomerates with angular to sub-rounded clasts were formed in alluvial fans and proximal braided rivers (Table 3).

At Cerro Rucañanco, Wall et al. (1991) and Suárez and Emparan (1995) described a 180 m thick profile (Fig. 12) in which they recognized a fan delta deposit. At the base are bottomset beds overlain by mega-cross-beds that are typical foreset facies of Gilbert-type deltas. These are overlain by coarse, cross-bedded conglomerates interpreted as delta topset facies, in turn succeeded by finer-grained conglomerates and sandstones probably representing a rise in lake level after the original delta progradation. This is suggested by two sandstone beds of approximately 3 m in thickness containing abundant bivalves (Fig. 13c).

Like the Quilmahue Member, the depositional environment of the Rucañanco Member was fluvio-lacustrine, but an abundance of thick distributary mouth bars and Gilbert-type deltas indicate shoreline deposition in a deeper, probably perennial lake environment.

Three samples were dated by detrital zircons, one in the El Cajón sector and two from the base and top of the Puente Tucapel section, respectively. These gave ages with a very narrow range between 12.7 ± 0.3 and 12.5 ± 0.3 Ma (Fig. 14).

3.2.3. *Bío-Bío Member*

The definition of this member is based on a section along the Bío-Bío River (Figs. 3 and 15) 1.7 km northeast of Cerro Rucañanco. This outcrop is reached via the main road and a turn-off to the latter locality, followed by a relatively short walk to the outcrop. Stratigraphically these deposits lie above those at Cerro Rucañanco, thus representing the youngest strata of the Río Pedregoso Formation.

The Bío-Bío Member is here composed of very fine to very coarse-grained sandstones (Fig. 16a), some with erosional bases, which present both fining- and coarsening-upward cycles. Sedimentary structures are represented by trough, high-angle tabular, and epsilon cross-lamination, soft-sediment deformation (Fig. 16b), and concretions (Fig. 16c). Fossils are restricted to leaves, vegetal organic matter and rare fresh-water bivalves. There are also matrix-supported conglomerates with sub-rounded clasts, as well as grey to red mudstones and dark grey shales. Pumice clasts are present both in the sandstones and mudstones.

Table 4 shows the identified lithological facies and their environmental interpretations. The general depositional facies correspond to a fluvial environment of distal braided to meandering

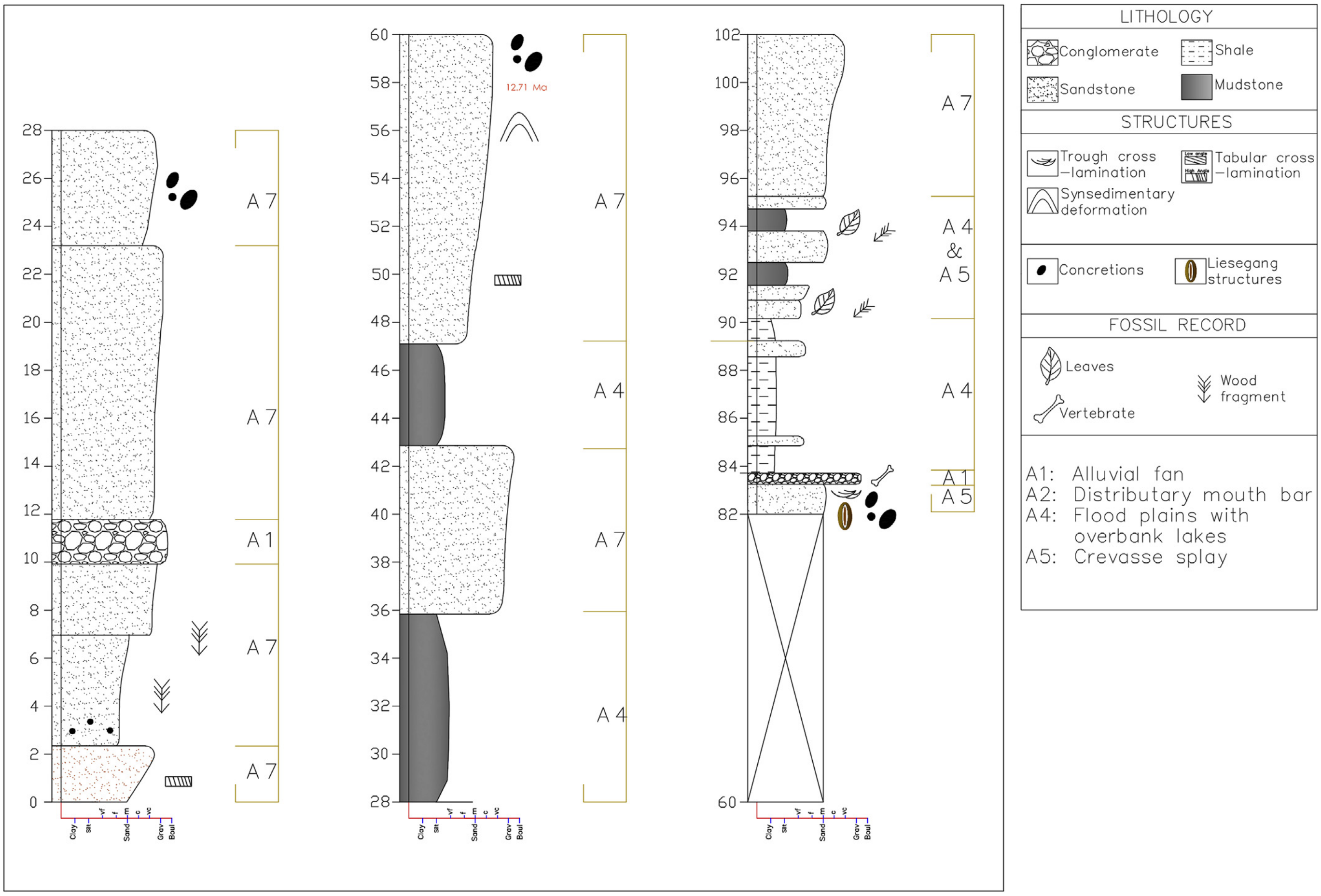

Fig. 11. Stratigraphic section measured in the Rucañanco Member at Puente Tucapel. For location see Fig. 3.

Table 2
Lithofacies description at El Cajón.

Id	Lithology	Sedimentary structures	Fossils	Depositional environment
A1	Polymictic, matrix-supported conglomerate; clast-supported, imbricated conglomerate with rounded, centimetric clasts (<2 m thick).		Armadillo plates	Alluvial fan, proximal braided river.
A4	Grey mudstone; shales with fine-grained sandstone interbeds (1–8 m thick).	Leaves, wood fragments		Flood plain with lakes.
A5	Medium-grained sandstone (<1 m thick).	Leaves, wood fragments, concretions		Crevasse splay.
A7	Coarsening-upward, medium- to very coarse-grained sandstone (2–13 m thick)	High-angle tabular cross-lamination, synsedimentary deformation structures, concretions.	Wood fragments	Distributary mouth bar.

Table 3
Lithofacies description at Puente Tucapel.

Id	Lithology	Sedimentary structures	Fossils	Depositional environment
A1	Polymictic, matrix-supported conglomerate with angular to sub-rounded clasts (~2 m thick).			Alluvial fan.
A2	Coarsening- and fining-up, fine- to coarse-grained sandstone with mudstone lenses (<8 m thick).	Trough and high-angle tabular cross-lamination, upper flow-regime planar lamination, linguoid ripples, concretions.	Leaves	Distal braided rivers, abandoned channels.
A3	Fining-upward, medium- to fine-grained sandstone with erosional base (<2 m thick).	High-angle tabular cross-lamination, concretions.	Vegetal organic matter.	Meandering river with point bars.
A4	Grey and green mudstones and shales, fine-grained sandstone, peat lenses (<8 m thick).	Lower flow-regime plane lamination in sandstone, liesegang structures.	Leaves, vegetal organic matter.	Flood plain with lakes.
A5	Medium-grained sandstones with small, scattered clasts, beds (~1 m thick).			Crevasse splay.
A7	Coarsening-upward, medium- to very coarse-grained sandstone (3–8 m thick)	High-angle tabular cross-lamination and concretions.	Leaves.	Distributary mouth bar.

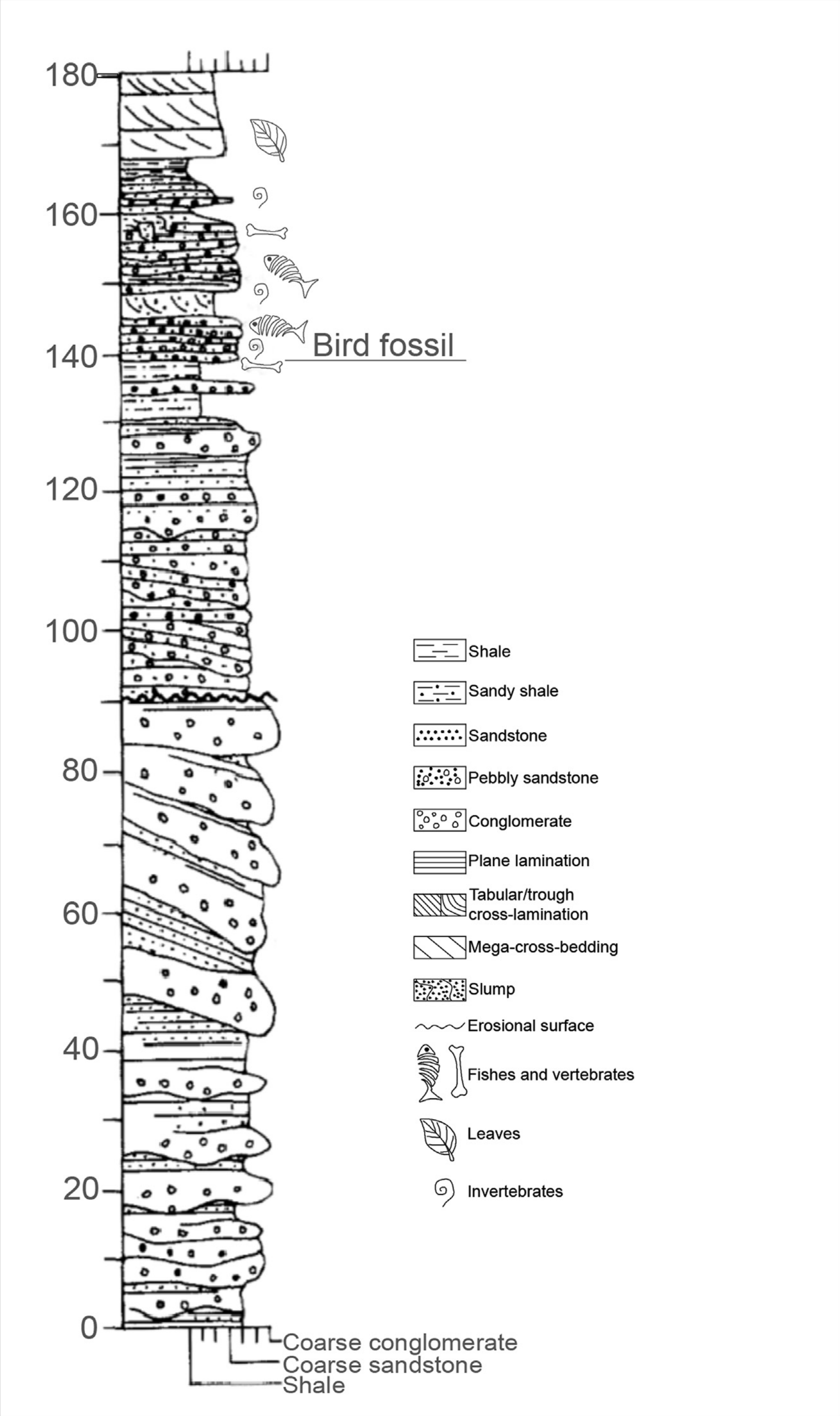

Fig. 12. Stratigraphic section measured at Cerro Rucañanco by Wall et al. (1991), subsequently described in more detail by Suárez and Emparan (1995).

channels with overbank flood plains and crevasse splays. However, although shallow overbank lakes may have existed (as indicated by the presence of freshwater bivalves in thin mudstones), there was an apparent absence of large, deeper lakes, because no distributary mouth bars or Gilbert-type deltas were identified. Fish fossils, scales or spines are also absent.

U/Pb dating of detrital zircons from a sample collected in the upper part of the Bío-Bío Member yielded an age of 11.64 + 0.11 Ma (Fig. 14).

3.3. Mitrauquén Formation

Originally referred to by Sandoval (1977) as the "Estratos de Mitrauquén", this coarsening-upward, 250 m thick succession of conglomerates, ignimbrites and andesitic lavas crops out between the Liucura and Mitrauquén Rivers on the eastern side of the Bío-Bío Valley (Fig. 3). It was deposited partly in braided river systems (Suárez and Emparan, 1997). Melnick et al. (2006) considered this unit to be a syntectonic deposit related to surface uplift caused by

Fig. 13. Sedimentary features in the Rucañanco Member. a) Strata at El Cajón showing large-scale troughs and synsedimentary deformation structures; b) Distributary mouth-bar deposits with high-angle tabular cross-lamination; c) Bivalves in sandstones overlying delta topset deposits; d) Fossil leaves.

the Pino Seco Thrust Fault, and tentatively correlated these beds with the Zapala basalts and conglomerates in the Argentinian foothills to the east. The latter rocks were dated at 8.6 ± 0.4 Ma (Linares and González, 1990), thus coinciding with the age of the Mitrauquén Formation between 9.5 ± 2.8 and 8.0 ± 0.3 Ma (Suárez and Emparan, 1997).

Melnick et al. (2006) confirm the easterly dip of the Mitrauquén Formation, which decreases from 20°E at the bottom of the Mitrauquén Valley to nearly sub-horizontal at the top of the unit. This supports our observations of a general southeasterly dip in the Cura-Mallín Group. Our reconnaissance work along the southern flank of the Mitrauquén Alto River (Figs. 3 and 4) indicated the presence of medium-grained sandstones concordantly underlying tuffs of the Mitrauquén Formation, which are very similar to sandstones in the Bío-Bío Member. Descending the stratigraphy towards Mitrauquén Bajo (Fig. 3) are also Gilbert-type delta deposits of the Rucañanco Member. It is thus clear that the Mitrauquén Formation concordantly overlies the Bío-Bío Member of the Río Pedregoso Formation, and as such should be considered to be part of the Cura-Mallín Group.

4. Palaeocurrent directions and provenance areas

Two main source areas were identified for the Río Pedregoso Formation based on palaeocurrent measurements and zircon age data (Figs. 15 and 17). Palaeocurrent directions were obtained from two localities, namely El Cajón and Cerro Rucañanco. At El Cajón, the orientation of 7 calcareous concretions in a sandstone bed (Fig. 17a) were measured. The aspherical growth of concretions is affected by the grain orientation of the host bed, which in turn is parallel to the depositing flow. Although a vector cannot be obtained directly, this information can be combined with other relevant data such as zircon ages. At El Cajón the concretions are aligned east-west (Fig. 17a), which coincides with probable source areas towards the west as indicated by the zircon data. At Cerro Rucañanco, six measured delta foreset orientations (Fig. 17b) were corrected to incorporate the regional dip, using an Excel program of Le Roux (1991a). Although these indicate sources to the southeast (Fig. 17b), it must be borne in mind that Gilbert-type delta foresets can have a range of orientations due to their relatively small size and shape, so that they are less precise.

A total of 110 individual zircon ages obtained from Pedregoso, Puente Tucapel and El Cajón can be grouped into 5 main populations with ranges from 185 to 171 Ma, 155–146 Ma, 124–105 Ma, 81–70 Ma, and 20–13 Ma, respectively. The first 4 populations coincide with the age of the Galletué Plutonic Group (148 ± 8 Ma – 73 ± 2 Ma), outcrops of which occur to the north-northwest, west and south of Lake Galletué (Fig. 14a). The last population can be attributed to partial reworking of the Guapitrío Formation (22.0 ± 0.9 Ma – 11.0 ± 1.6 Ma), presently exposed mainly to the north and west of Lonquimay. In general therefore, source areas were located along the western side of the basin.

5. Potential geothermal reservoirs in the Cura-Mallín Group

The characteristics of geotermal reservoirs are affected strongly by the primary and secondary permability of the host rocks, which in turn depend on the lithology, sedimentary environment, stratigraphic position, tectonic events, and diagenetic history of the basin. Studies taking account of these factors can thus provide important tools to make geothermal exploration more efficient and cost-effective, by assisting in pre-identifying the most favourable areas and stratigraphic units.

Within the Southern Volcanic Zone (SVZ) of south-central Chile, volcanoes such as Tolhuaca and Lonquimay are among the most active. The Tolhuaca Volcano has an extensive surrounding field of active fumaroles and hot springs that originally attracted the attention of exploration companies, while the Lonquimay Volcano has a record of activity over the last 10,000 years and erupted as late as 1990. As geothermal reservoirs are generally located within

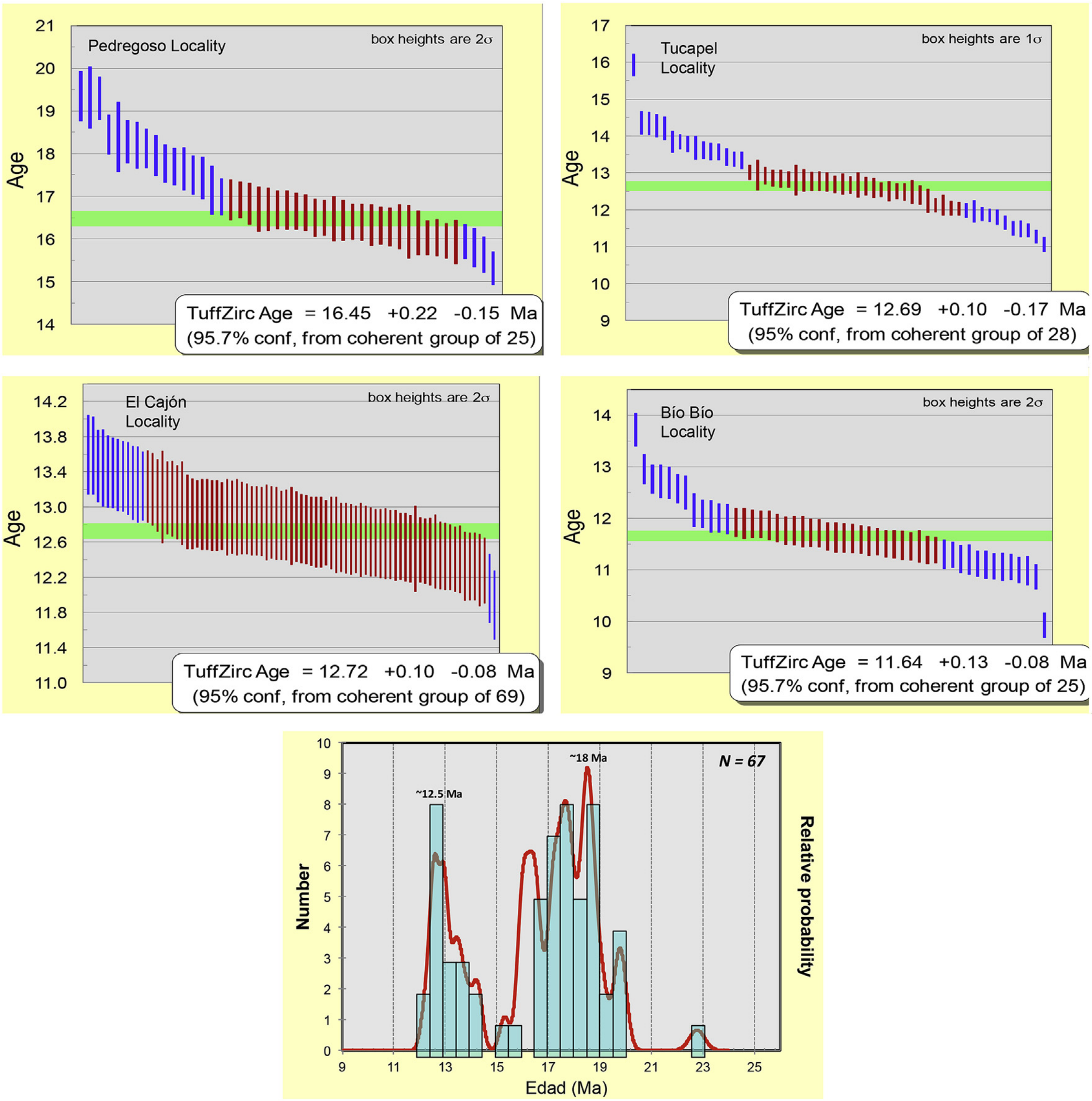

Fig. 14. Detrital zircon ages for the Quilmahue Member (Río Pedregoso), Rucañanco Member (Puente Tucapel, El Cajón) and Bío-Bío Member (Bío-Bío locality).

such active volcanic zones where magmas are close to the surface, the Cura-Mallín Group must be considered to have a high potential because of its proximity to both the Tolhuaca and Lonquimay Volcanoes.

Vicencio (2015), who studied the lithological and mineralogical characteristics of the Guapitrío Formation in a stratigraphic section 8 km northwest of Lonquimay, identified hydrothermal alteration corresponding to the zeolite facies (T° < 180°). It is characterized by the association smectite-chlorite/smectite + mordenite ± heulandite ± clinoptiloit ± quartz ± calcite. These secondary mineral associations fill cavities and fractures in the rocks and are especially common in the upper part of the succession, together with dike swarms suggesting proximity to a heat source. Based on his mineralogical observations, a conceptual model was proposed in which high-temperature hydrothermal fluids rich in Si mixed with cold meteoric water that seeped into a shallow geothermal system associated with a caldera-stratovolcano. The precipitation-dissolution process occurred repeatedly, which significantly reduced the permeability of the rocks during periods of hydrothermal activity or eruptions. It therefore seems unlikely that the Guapitrío Formation could constitute a significant reservoir, at least in the areas affected by hydrothermal fluids.

In the Río Pedregoso Formation, the Quilmahue and Bío-Bío Members contain a large proportion of impermeable shales and mudstones, whereas sandstones and conglomerates are generally thin. The Rucañanco Member, on the other hand, has thick sandstones and conglomerates in distributary mouth bars and Gilbert-type deltas. Permeabilities measured by the constant head method in the sandstones of the Río Pedregoso Formation (Fig. 18) varied between 6.99×10^{-7} and 6.81×10^{-11} m s^{-1}, i.e. from semi-permeable (1×10^{-6} to 1×10^{-9} m s^{-1}) to almost impermeable ($<1 \times 10^{-9}$ m s^{-1}). Samples from the Quilmahue Member had the most variable permeability of the three members, between the two extremes mentioned above, although most were less than 3.3×10^{-9} m s^{-1} (close to or within the almost impermeable field). Two samples from the Bío-Bío Member gave readings of 5.83×10^{-10} and 6.36×10^{-10} m s^{-1}, respectively, both being almost

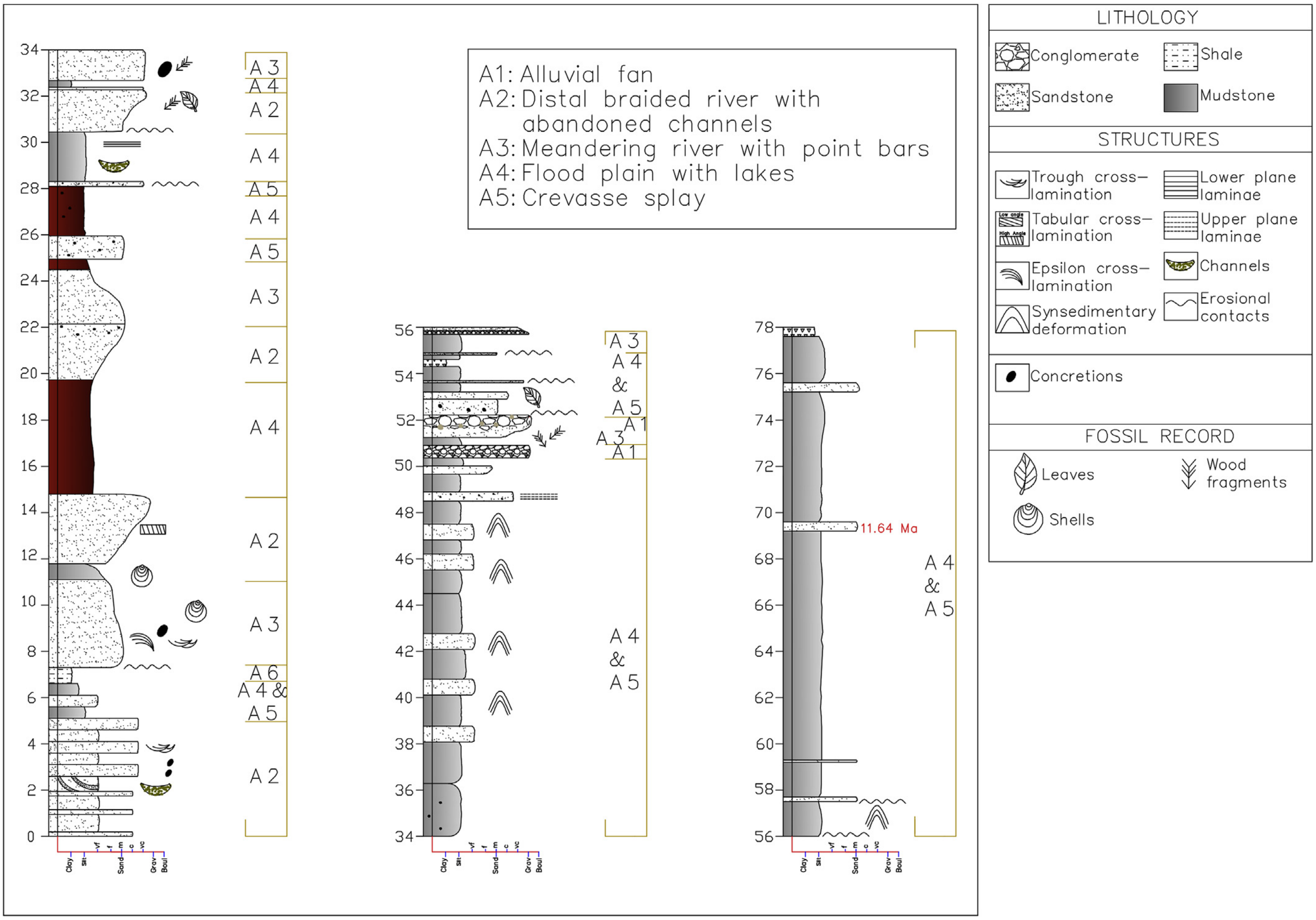

Fig. 15. Stratigraphic section measured in the Bío-Bio Member at homonymous locality. For location see Fig. 3.

Fig. 16. Sedimentary features in the Bío-Bío Member. a) Sandstones along the Bío-Bío River; b) Synsedimentary deformation structures; c) Concretions.

Table 4
Lithofacies description at Bio-Bio.

Id	Description	Sedimentary structures	Fossils	Depositional environment
A1	Matrix-supported conglomerate with sub-rounded clasts.			Alluvial fan, proximal braided rivers
A2	Fine- to very coarse-grained, ungraded to coarsening-upward sandstones with erosional bases, pumice clasts; dark grey mudstone lenses.	Trough and high-angle tabular cross-lamination, some channels structures, concretions	Leaves, vegetal organic matter	Distal braided rivers with abandoned channels.
A3	Fining-upward, medium- to fine-grained sandstones; mudstones	Trough and epsilon cross-lamination, concretions	Fresh-water bivalves	Meandering rivers with point bars
A4	Grey and red mudstones, pumice clasts (2–10 m thick)		Vegetal organic matter	Flood plains
A5	Fine- to medium-grained sandstones, pumice clasts	Synsedimentary deformation		Crevasse splays
A6	Dark grey shales.			Oxbow lakes

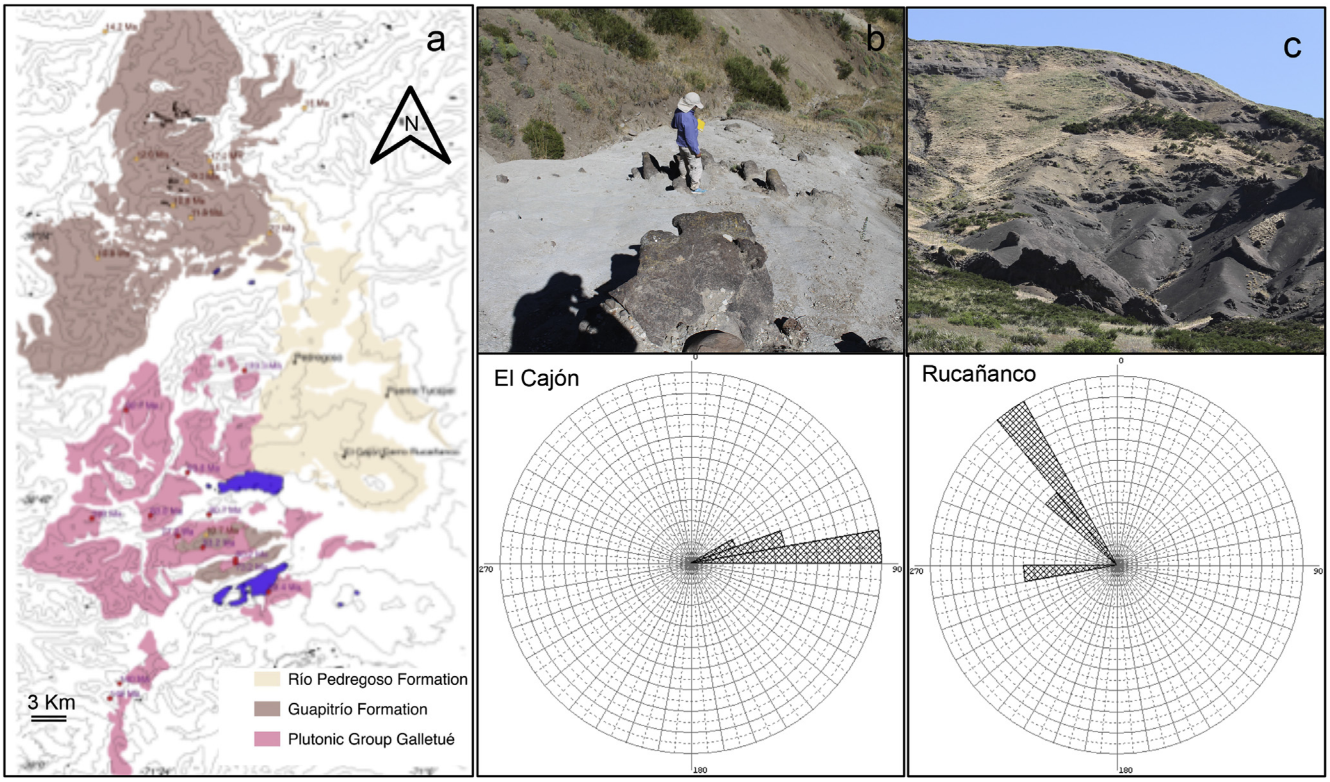

Fig. 17. a) Oriented concretions with rose diagrams (below); b) Mega-foresets of Gilbert-type deltas at Cerro Rucañanco, with rose diagrams (below).

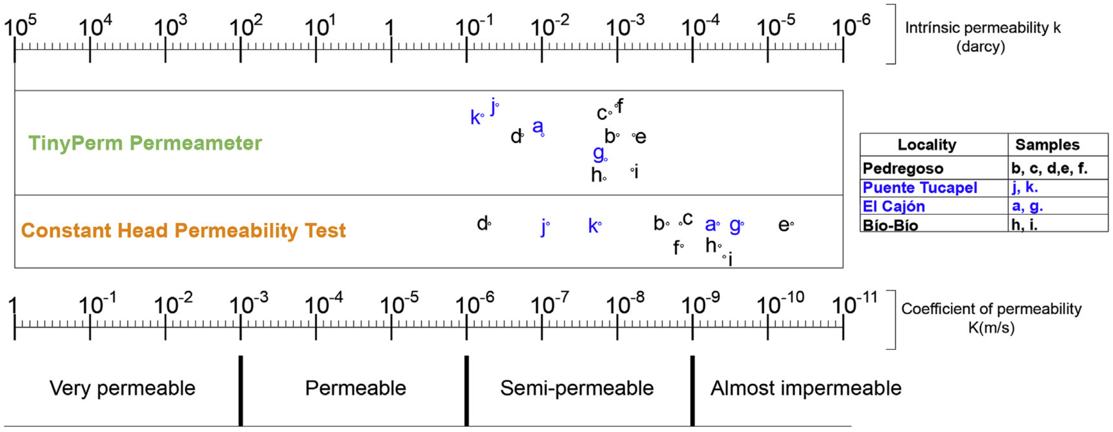

Fig. 18. Permeability of samples from the Río Pedregoso Formation as determined by the constant head and *TinyPerm* methods.

impermeable. The Rucañanco Member had two samples (El Cajón) in the almost impermeable range and two samples (Puente Tucapel) in the semi-permeable range, the latter yielding values of 9.16×10^{-8} and 2.31×10^{-8} m s^{-1}, respectively.

The *TinyPerm* results for all samples fell within the semi-permeable field (Fig. 18), ranging between 9.09×10^{-7} and 8.61×10^{-9} m s^{-1}, with the two samples from Puente Tucapel closer to the permeable/semi-permeable limit (6.72×10^{-7} and 9.09×10^{-7} m s-1, respectively). The difference between the two methods may be due to the fact that permeability tests with the constant head method are conducted under confining pressures of 1–5 kg cm^{-2}, which might therefore reflect conditions at some depth below the surface, whereas *TinyPerm* could represent conditions at the surface itself. However, it cannot be ruled out that *TinyPerm* may be less sensitive to smaller differences in permeability and therefore yields a narrower range of values. Measured effective (absorption) porosities for the two Puente Tucapel samples were 34.3 and 40.8%, respectively, whereas other samples had a mean value of 24.7% and porosities as low as 0.8%.

Both methods therefore indicate that the Rucañanco Member has better permeabilities and effective porosities than the other two members, with the sole exception of one sample from the Quilmahue Member. Furthermore, it has the thickest sandstones. The fact that the Rucañanco Member is sandwiched between the other two, relatively impermeable members, means that it can act as a groundwater trap and might also contain fluids under pressure. Considering the location of source areas mainly to the west of the study area, a general east-west alignment of grains can be expected in the sandstones, especially those with upper plane laminae. Laboratory studies (Le Roux, 1991b) have clearly indicated that the permeability of sands is higher parallel to the grain long axis orientations, which means that groundwater or hydrothermal fluid flow should be preferentially from the western highlands towards the Bío-Bío Valley.

6. Summary and conclusions

Suárez and Emparan (1997) proposed that the Río Pedregoso Member (as previously defined) underlies and interfingers with the Guapitrío Member, but mentioned that the contact zone was covered and could thus be either depositional or tectonic. These studies suggested that the base of the Río Pedregoso Member had an age close to 17 Ma and that its top dated at 13.0 ± 1.6 Ma, in the latter case based on the whole-rock K-Ar ages of volcanic breccias assigned to the Guapitrío Formation (Suárez and Emparan, 1995, 1997). Our studies indicate that, between Paso Rahue and Paso Caracoles, mudstones and shales towards the base of the Quilmahue Member are in lateral contact with volcanic units in the Guapitrío Formation without the intervention of a fault.

As shown in Tables 1–4, the lithology and depositional facies of the three members constituting the Río Pedregoso Formation are somewhat similar in that fluvial channel, floodplain and overbank lake deposits are present in all three members. This, together with the very limited observable contacts between the Guapitrío and Río Pedregoso Formations and the absence of more detailed dating at the time, was possibly the reason why the stratigraphic succession was oversimplified. However, our more detailed observations indicate that the Quilmahue environment was dominated by wide flood plains with crevasse splays, the Rucañanco environment by perennial lake-shoreline deposits of distributary mouth bars and Gilbert-type deltas, and the Bío-Bio environment by distal braided and meandering rivers. The resultant lithological differences are also clearly manifested in the percentage of shale and mudstone of the different measured sections, with an average of 43% in the Quilmahue Member, 12% in the Rucañanco Member, and 54% in the Bío-Bío Member.

In the study area many small folds are present, but the general dip along the Bío-Bío River between Paso Rahue and the locality of Bío-Bío is towards the southeast, as can be verified in different outcrops. Therefore, the youngest depositional cycle (Bío-Bío Member) crops out in the vicinity of Bío-Bío to the southeast, the intermediate cycle (Rucañanco Member) near Cerro Rucañanco, El Cajón and Tucapel, and the oldest cycle (Quilmahue Member) towards the northwest between Pedregoso and Paso Rahue.

This stratigraphic interpretation is consistent with our new detrital zircon dates and also with an earlier K-Ar date of 22.0 ± 0.9 Ma published by Suárez and Emparan (1988) in the vicinity of Paso Rahue, but later apparently discarded by these authors as it was not mentioned in their later publications. If this is taken as the age of the base of the Quilmahue Member due to its interfingering at this locality with the Guapitrío Formation, sedimentation of the Cura-Mallín Group therefore started at around 22 Ma during a period of basin extension (Jordan et al., 2001; Folguera et al., 2003). This also coincides with the age of an upper sedimentary-dominated sequence of 22.8 ± 0.7 Ma in the original Cura-Mallín Formation of Argentina (Jordan et al., 2001), which we therefore correlate tentatively with the Quilmahue Member.

Towards the southeast, in stratigraphically higher horizons, Suárez and Emparan (1995) obtained an age of about 17.5 Ma at Cerro Tallón, while our dating indicates an age of 16.5 Ma at Pedregoso, suggesting that the Quilmahue Member deposition occupied the entire early Miocene. Jordan et al. (2001) also reported a^{40}Ar-^{39}Ar age of 16.2 ± 0.2 Ma for the Trapa Trapa Formation in the Andacollo Sub-basin of Argentina. As the basal portion of this formation in the Valle Central Basin is composed largely of granular conglomerate, lithologically quite distinct from the overlying volcanic succession (Flynn et al., 2008), we propose that this part could eventually be incorporated into the Quilmahue Member of the Río Pedregoso Formation, pending further work. Still further to the southeast in the Bíobío-Aluminé Basin, the Rucañanco Member was dated by us at about 12.6 Ma, while the Bío-Bío Member yielded an age of about 11.6 Ma at its type locality. Again, similar ages have been recorded in the Trapa Trapa Formation, but careful mapping and lithological comparison would be required to establish whether a correlation between these units is valid.

According to our data the outcrops at Piedra Parada underlie those at Cerro Tallón, contradicting the younger K-Ar whole rock age of 13.0 ± 1.6 Ma obtained by Suárez and Emparan (1995) at this locality, which they ascribed to the Guapitrío Formation. However, the reliability of whole-rock K-Ar dating depends on the petrographic homogeneity of the sample, which in this case corresponds to poorly sorted conglomerates with a sandy matrix and angular to sub-rounded volcanic clasts between 5 cm and 2 m in diameter. This is clearly not ideal for whole-rock dating. We also reassign this outcrop to the Río Pedregoso Formation due to its sedimentary character.

Suárez and Emparan (1995, 1997) correlated the alluvial fan facies at Piedra Parada with the Gilbert-type deltas at Rucañanco and concluded that the lakes and rivers in the Lonquimay area coexisted during the Miocene between 17 and 13 Ma. On the other hand, Croft et al (2003b; their Fig. 3). showed a succession passing upward from alluvial-fluvial to lacustrine and finally deltaic-alluvial facies. Although we concur with the co-existence of these environments during the deposition of the Río Pedregoso Formation, our stratigraphic interpretation and dating suggest that there was no temporal correlation between the deposits of Cerro Rucañanco and Piedra Parada, the latter being older than the former. The Santacrucian Land Mammal Age to which *Meganhinga chilensis* was linked (Wall et al., 1991) is also inconsistent with the age of 13 Ma assigned by Suárez and Emparan (1995, 1997) to the beds that hosted this fossil bird, as well as our own age for the Rucañanco Member of about 12.6 Ma. The only mammal in addition to *Nesodon conspurcatus* that was ascribed to the Santacrucian SALMA is a *Protypotherium* sp. discovered more than 35 years ago at Puente Tucapel, originally reported by Suárez et al. (1990). Recently, this specimen was reanalyzed and its classification as a *Protypotherium* sp. was confirmed (Buldrini et al., 2011). However, according to Suárez et al. (1990) it was found in a loose block on the hillside, making any geochronological assignation doubtful. Because our Serravalian age (~12.6 Ma) for the outcrops at Puente Tucapel does not support a Santacrucian Land Mammal Age (17.5–16.3 Ma), we propose a Laventan Land Mammal Age (13.5–11.8 Ma) for this *Protypotherium* sp. and consider *Meganhinga chilensis* to have lived during the same period.

Folguera et al. (2003) identified two tectonic episodes in the Neuquén Mountain Range in Argentina directly east of the Bíobío-Aluminé Basin. The first corresponds to a period of extension from the late Oligocene to early Miocene (Jordan et al., 2001), and the second to tectonic inversion and compression during the late Miocene. Our data indicate that the Quilmahue Member formed between about 22 and 16 Ma during the tectonic extensional episode, whereas the Rucañanco Member corresponds to the tectonic inversion phase between about 13 and 12 Ma. However, the Bío-Bío Member seems to mark a renewed period of tectonic quiescence. These events are reflected in the dominant depositional environments envisaged for the three members. The Rucañanco Member, in spite of having been deposited in a deeper lake-margin environment, is generally much coarser than the Quilmahue Member (88% sandstones and conglomerates in comparison to 57% in the latter), suggesting that the source areas were more mountainous and the intervening valleys deeper. The more distal braided and meandering rivers of the Bío-Bío Formation (46% coarse deposits, of which a very minor proportion are conglomerates) indicate that denudation had greatly reduced this landscape after about 12 Ma, creating wider flood plains in which overbank lakes were scarce and shallow. The first major pulse of tectonic inversion in the Bíobío-Aluminé Basin was therefore restricted to the early Serravalian, but was interrupted by tectonic quiescence around 12 Ma before being resumed again by a second period of active faulting and volcanism after 10 Ma.

The stratigraphic unit with the best potential to host geothermal reservoirs in the Cura-Mallín Group is the Rucañanco Member, due to its relatively thick, semi-permeable sandstones and conglomerates enclosed within two almost impermeable units.

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