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ESTRATIGRAFÍA, SEDIMENTOLOGÍA Y ESTIMACIÓN DE LA PERMEABILIDAD EN ROCAS SEDIMENTARIAS DE LA SUCESIÓN VOLCANOCLÁSTICA DE CURA-MALLÍN

TESIS PARA OPTAR AL GRADO DE MAGÍSTER EN CIENCIAS MENCIÓN GEOLOGÍA

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RESUMEN DE LA TESIS
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Los trabajos de terreno y nuevas datación de U-Pb en circón detrítico en la Formación Cura-Mallín alrededor de Lonquimay, Chile sur-central, nos permiten redefinir esta sucesión como Grupo Cura-Mallín, compuesto por la Formación Guapitrío (volcano-sedimentaria), Formación Río Pedregoso (sedimentaria), y la Formación Mitrauquén. La Formación Río Pedregoso se puede subdividir en tres unidades formales, de base a techo Miembro Quilmahue, Miembro Rucañanco y Miembro Bío-Bío. La base del Miembro Quilmahue tiene un contacto lateral interdigitado con la Formación Guapitrío que aflora entre las localidades de paso Caracoles y paso Rahue esta última localidad datada en trabajos anteriores en 22,0±0,9 Ma por el método K-Ar, la cual fue aparentemente descartada por los mismos autores, quienes no la mencionan en publicaciones posteriores. Sin embargo, esta edad es consecuente con la posición estratigráfica del Miembro Quilmahue y nuestras nuevas dataciones de circón detrítico en las unidades suprayacentes, y coincide con el comienzo de una fase extensional en la Cuenca Cura-Mallín. La deposición del Miembro Quilmahue continuó durante todo el Mioceno temprano, como indican una edad de 17,5 Ma obtenida en trabajos previos y una nueva datación de 16,5 Ma en el estudio actual. La deposición del Miembro Rucañanco ocurrió alrededor de 12,6 Ma durante el Serravaliano, y la del Miembro Bío-Bío en el límite entre el Serravaliano y Tortoniano a los 11,6 Ma. Aunque los tres miembros fueron depositados en un ambiente fluvio-lacustre, han sido dominados por lagos, llanuras de inundación con derrames de llanura, márgenes lacustres con barras de desembocadura, deltas tipo Gilbert y ríos entrelazados distales y meándricos. Los restos de un ave fósil (*Meganhinga chilensis*) y un mamífero (*Protypotherium* sp.) han sido vinculados a una edad Mamífero Santacrucense (17.5 – 16.3 Ma), sin embargo nuevos datos geocronológicos e interpretaciones estratigráficas de este estudio indican que son evidentemente más jóvenes (~13 Ma). Adicionalmente datos de permeabilidad y porosidad en capas de arenisca del Miembro Rucañanco y una posición estratigráfica favorable permiten considerarlo como un potencial reservorio geotérmico.

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Dedico este trabajo de tesis a mi esposo, mi mejor amigo y colega Mauricio Gutiérrez Duarte, por su amor y apoyo incondicional. Hace siete años emprendimos un viaje lejos de nuestro querido Colombia, hoy puedo decir que nuestro hogar no está en un lugar geográfico, existirá en cualquier lugar donde estemos juntos.

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CAPÍTULO I

INTRODUCCIÓN

Chile cuenta con cerca de 3000 volcanes de los cuales 500 se mantienen activos o han tenido actividad en los últimos 10.000 años (Morata., 2014) los cuales se distribuyen en dos zonas, la Zona Volcánica Norte (17ºS - 28ºS) y la Zona Volcánica Centro-Sur (33ºS - 46ºS) posicionando al país como un territorio con alto potencial geotérmico. Dentro de la Zona Volcánica Centro-Sur se encuentran los volcanes Tolhuaca y Lonquimay (Fig.1) este último registró su más reciente actividad en el año 1988 (Moreno y Gardeweg, 1989). El volcán Tolhuaca, representa uno de los volcanes más activos de la Cuenca de Cura-Mallín y ha sido considerado como un potencial sistema geotérmico de interés comercial (Risacher et al., 2011; Melosh et al., 2012; Sánchez et al., 2012; SKM, 2012; Iriarte, 2013; Lizama, 2013; Vicencio, 2015; Aravena et al., 2016).

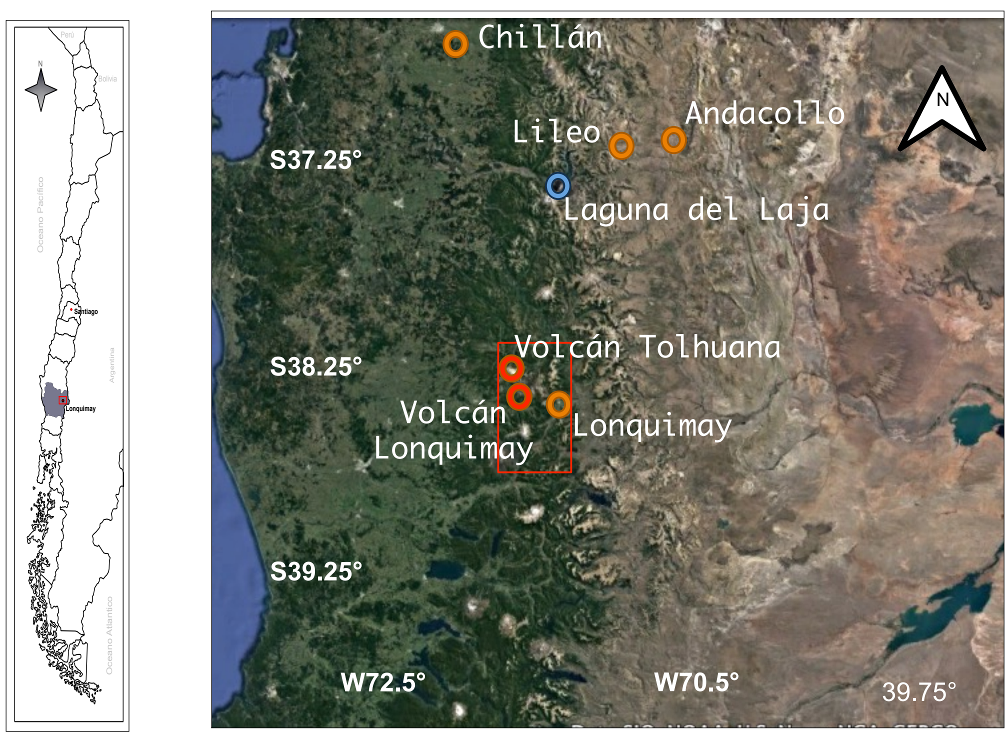

Figura 1. a) Localización general de la zona de estudio, Región de la Araucanía. b) Sub-cuenca Lonquimay en el recuadro rojo.

El relleno sedimentario de la Cuenca de Cura-Mallín forma parte del basamento de los volcanes activos Lonquimay y Tolhuaca, conocer la historia geológica de la cuenca, modo de sedimentación y cambios litológicos permite prever posibles variaciones y orientar la exploración geotérmica hacia zonas más favorables.

En el sector norte de la cuenca en los alrededores de la laguna del Laja, la Formación Cura-Mallín está compuesta por el Miembro Volcánico Río Queuco (Niemeyer y Muñoz, 1983; Carpinelli, 2000) y el Miembro Sedimentario suprayacente Malla Malla (Carpinelli, 2000; Radic et al., 2000). Drake (1976) obtuvo una edad K-Ar de 14.5 ± 1.4 Ma en el techo del Miembro Río Queuco, pero la Formación Trapa Trapa que recubre la Formación Cura-Mallín en esta área muestra edades K-Ar entre 18,2 ± 0,8 y 14,7 ± 0,7 Ma (Flynn et al., 2008), estas edades son claramente contradictorias.

En la zona de Andacollo de Argentina, inmediatamente al Este de la Laguna del Laja, los estudios publicados sugieren que la edad de la Formación Trapa Trapa tienen un rango entre 20 Ma y alrededor de 12 Ma (Radic et al., 2002, Melnick et al., 2006). Esto coincide con las edades de la Formación Trapa Trapa en Chile obtenida por Flynn et al. (2008), pero sugiere que el Miembro Río Queuco es probablemente más antiguo que 14.5 Ma. De hecho, la base de la serie piroclástica inferior de la Formación Cura-Mallín en Argentina ha dado una edad de ^{40}Ar-^{39}Ar de 24.6 ± 1.8 Ma (Jordan et al., 2001).

La Figura 2 muestra la distribución y edades asignadas a los Miembros Sedimentarios y Volcánicos que constituyen la Formación Cura-Mallín en la zona Norte, Sur y Este de la cuenca de Cura-Mallín.

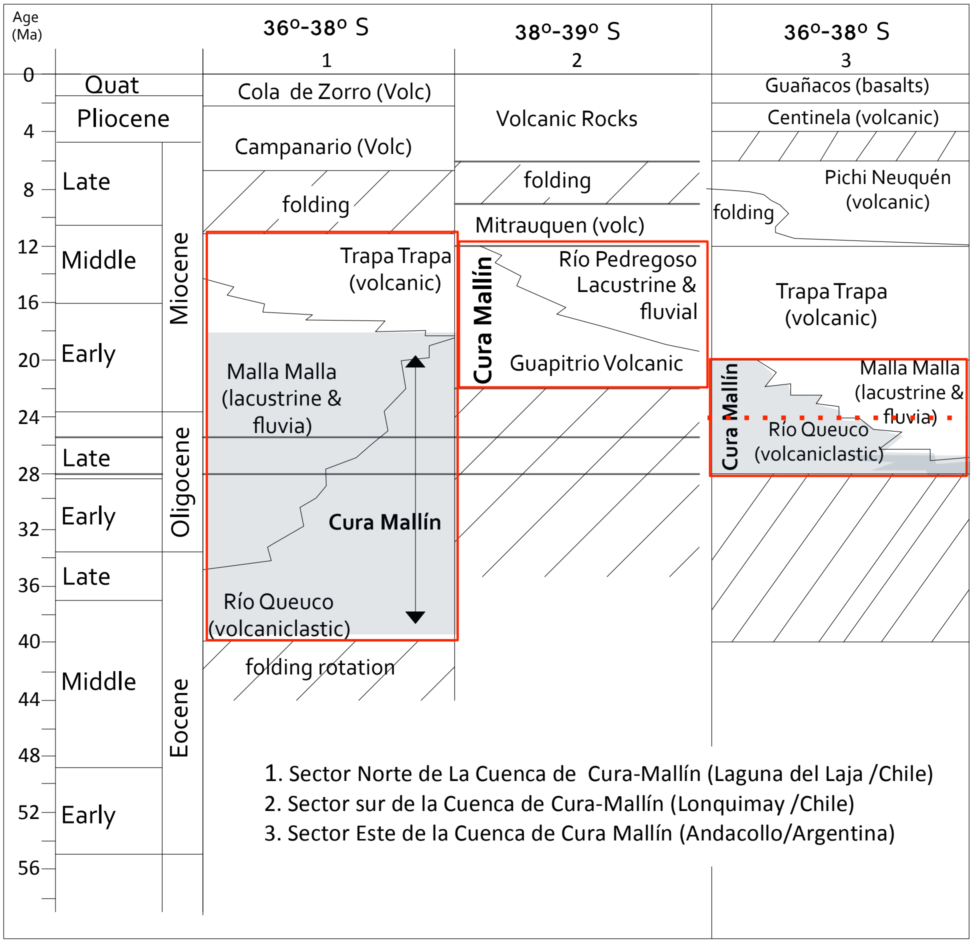

Figura 2: Edades y distribución de la Formación Cura-Mallín (Modificado Jordan et al., 2001).

La Formación Cura-Mallín en la zona de Lonquimay (sector sur de la Cuenca de Cura-Mallín) fue descrita por primera vez en Chile por Burckhardt (1900) reconociéndola como una unidad lacustre, posteriormente fue descrita por diferentes autores (Cisternas y Días, 1986; Sandoval., 1977; Suarez y Emparan, 1988, 1994 y 1997; Vicencio, 2015; Wall et al., 1991) y nombrada como Grupo Biobío (Suarez y Emparan, 1988). Finalmente el Grupo Biobío fue redefinido y reclasificado como la Formación Cura-Mallín (Suarez y Emparan 1994, 1997), conformada por el Miembro Guapitrío de origen principalmente volcánico y el Miembro Río Pedregoso de origen sedimentario el cual presenta un registro fósil diverso, identificándose peces, moluscos y ostrácodos dulceacuícolas (Sandoval., 1977; Osorio et al.,1982; Rubilar., 1990, 1994) además de fósiles de aves y mamíferos (Suarez et al., 1990; Wall et al., 1991; Croft et al., 2003; Buldrini et al., 2011).

Suarez y Emparan (1997) indican que los depósitos lacustres del Puente Lolén y Cerro Tallón datado en 17 Ma (K-Ar en biotitas) y los depósitos fluviodeltaicos del Cerro Rucañanco y de Piedra Parada datado en 13 Ma (K-Ar en roca total) coexistieron durante el Mioceno. También señalan que existe una correlación estratigráfica entre los depósitos del Cerro Rucañanco y los depósitos de Piedra Parada, por lo que ambos son asignados a una edad de 13 Ma. Nosotros consideramos que no existe una correlación entre estas dos unidades. El Cerro Rucañanco se ubica a 21 Km al Sur-Este de Piedra Parada y se desconoce cual es su posición estratigráfica con respecto a los depósitos de Piedra Parada de 13 Ma. Consideramos que no es preciso asignarles la misma edad a estas unidades, teniendo en cuenta sólo la similitud de facies. Además los capas conglomeráticas de Piedra Parada están representadas por tres niveles que no superan los 5 m de espesor cada uno, mientras que en el Cerro Rucañanco los niveles conglomeráticos se distribuyen ampliamente en una sección de 180m, donde se observan múltiples niveles conglomeráticos de hasta 10m de espesor y podrían representar facies distintas. Por otro lado, consideramos que la datación de 13 Ma de K-Ar en roca total realizada en un conglomerado en la localidad de Piedra Parada no es confiable, debido a que la muestra (roca total) no es homogénea, por lo tanto no es ideal para este tipo de análisis.

Suarez et al (1990) y Wall et al (1991) identifican los restos fósiles de un ave del terciario (*Meganhinga chilensis)* en la localidad de Cerro Rucañanco (Fig. 1), y un mamífero (*Protypotherium sp)* en la localidad de Puente Tucapel (Fig. 1). Ambos fósiles son asignados a la edad Mamífero Santacrucense entre 16,3 Ma -17,5 Ma (Wall et al., 1991, Buldrini et al., 2011), edades sustentadas a partir de la datación de 17,5 Ma obtenida en los depósitos sedimentarios lacustres del Cerro Tallón ubicada a 10 Km al NW del Puente Tucapel y 15 Km al NW del Cerro Rucañanco (Fig 1). Consideramos que la edad Mamífero Santacrucense asignada a estos restos fósiles no es correcta, debido a que se desconoce la relación estratigráfica entre las localidades fósiles y la localidad datada. Además existe una diferencia en la edad asignada al fósil y la edad asignada a las unidad sedimentaria que lo contiene.

Estas edades aparentemente contradictorias de los depósitos y restos fósiles de la Formación Cura-Mallín reflejan algunas de las incertidumbres geocronológicos y estratigráficas actuales del relleno de la Cuenca de Cura-Mallín.

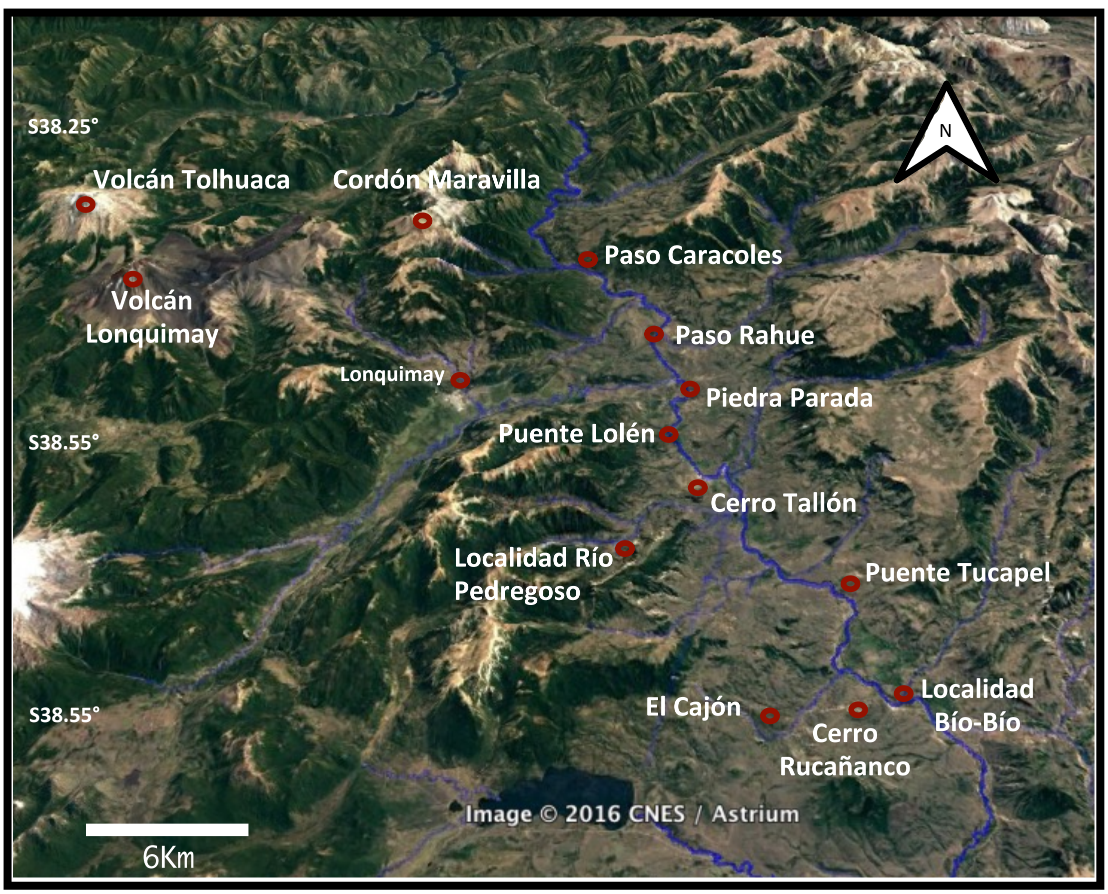

Figura 3. Zona de estudio detallada y localidades mencionadas en el texto.

En este trabajo se presenta la descripción de facies e interpretación de ambientes sedimentarios de cinco columnas estratigráficas, así como cinco nuevas dataciones de U-Pb en circón detrítico. Además se incluyen nuevas interpretaciones estratigráficas de las unidades sedimentarias del Miembro Río Pedregoso y se aclara la relación de contacto con el Miembro Guapitrío, finalmente se propone un nuevo esquema estratigráfico donde se identifican unidades arenosas con potencial para albergar un reservorio geotérmico.

1. Planteamiento del problema

En el área de estudio recientes trabajos indican que el sistema geotérmico Tolhuaca se considera como un campo geotérmico comercialmente explotable y se clasifica como un recurso indicado según las pruebas de flujo realizadas en uno de los pozos exploratorios (Aravena et al., 2016). Establecer el orden estratigráfico correcto de la sucesión volcano-sedimentaria del relleno de la Cuenca de Cura-Mallín y establecer su vinculo con fuentes de calor activas, como los volcanes Lonquimay y Tolhuaca, es la base fundamental en la fase de exploración y en la interpretación de zonas de interés geotérmico .

Existen diferencias litológicas entre las rocas que componen los miembros de la Formación Cura-Mallín, existe un miembro principalmente volcánico Guapitrío y otro de carácter sedimentario Río Pedregoso, en la actualidad el modelo estratigráfico más aceptado para los depósitos volcano-sedimentarios Oligo-Miocenos en la zona de Lonquimay es el propuesto por Suarez y Emparan (1995, 1997). Sin embargo se desconoce la posición estratigráfica, correlación y la edad de los depósitos sedimentarios que afloran en las localidades paso Caracoles, paso Rahue, Puente

Lolén, Pedregoso, Puente Tucapel, El Cajón, Cerro Rucañanco y Bío-Bío en relación con las unidades datadas Piedra Parada de 13 Ma y Cerro Tallón de 17 Ma , así mismo no existe un consenso entre las edades radiométricas de los depósitos del Cerro Rucañanco y Puente Tucapel y las edades mamífero asignadas al *Meganhinga chilensis* y al *Protypotherium sp* respectivamente. Adicionalmente se desconoce la relación de contacto entre las unidades sedimentarias y las unidades volcánicos del Miembro Guapitrío.

1.1. Hipótesis

Dados los antecedentes estratigráficos y sedimentológicos expuestos, se postula que:

H1. Si la correlación estratigráfica entre los depósitos sedimentarios de Piedra Parada de 13 Ma y los depósitos sedimentarios del Cerro Rucañanco es correcta, ambas unidades deberán ser más jóvenes que los depósitos sedimentarios del Cerro Tallón de 17 Ma.

H2. Alternativamente, si se presenta una coexistencia de los ambientes sedimentarios, los depósitos fluviolacustres de las localidades del Cerro Tallón de 17 Ma, Puente Lolén y Piedra Parada se deberían correlacionar estratigráficamente, y deberían ser más antiguas que las unidades fluvio-deltaicos como las del Cerro Rucañanco y Piedra Parada.

2. OBJETIVOS

Objetivo general:

Actualizar y complementar la información estratigráfica, sedimentológica de la Formación Cura-Mallín y determinar el vínculo entre la estratigrafía y la variación de los valores de permeabilidad.

Objetivos específicos:

- Definir las facies, ambientes y posición estratigráfica de los depósitos que conforman el Miembro Rio Pedregoso.
- Establecer la edad y la relación de contacto entre el Miembro Río Pedregoso y el Miembro Guapitrio.
- Determinar la variación de la permeabilidad en muestras de la Formación Cura Mallín y su relación con la estratigrafía.

3. UBICACIÓN DEL ÁREA DE ESTUDIO

La zona de estudio se localiza en la IX Región de Chile, Región de la Araucanía, próxima a la localidad de Lonquimay y a lo largo del río Bío-Bío, entre las latitudes 38,3°S - 38,7°S y longitud 71,4°W - 71,0°W. En esta zona se destacan las localidades de paso Caracoles, paso Rahue, Piedra Parada, Puente Lolén, Cerro Tallón, Río Pedregoso, Puente Tucapel, El Cajón, Cerro Rucañanco y Bío-Bío (Fig. 3).

4. METODOLOGÍA

- <u>Recopilación de información:</u> sobre la geología existente del área de estudio, además de planos topográficos, fotografías aéreas, imágenes satelitales y la carta geológica publicada por el Servicio Nacional de Geología y Minería en Chile.
- <u>Reconocimiento previo de la zona de estudio</u>: se utilizaron fotografías aéreas e imágenes satelitales Landsat TM y ETM Plus, además de modelos de elevación digital ASTER Global Digital Elevation Model, donde se establecieron zonas aptas para el levantamiento de secciones estratigráficas e identificación de afloramientos y zonas de acceso.
- <u>Trabajo de terreno</u>: consistió en tres salidas de terreno, la primera del 4 - 20 de enero de 2014, la segunda del 11 - 17 de enero del 2015 y la última del 2 - 5 de septiembre del 2015. Se realizó el reconocimiento detallado de la zona de estudio y se determinaron zonas aptas para la descripción de afloramientos y levantamiento de columnas estratigráficas siguiendo procedimientos estratigráficos estándar, además se registraron datos estructurales, se recopilaron muestras para datación $^{238}U/^{206}Pb$ en circón detrítico y muestras para ensayos de permeabilidad y cortes transparentes. Se realizó un registro fotográfico de estructuras sedimentarias, fósiles y litologías, adicionalmente se estableció la relación estratigráfica entre los distintos afloramientos y el contacto con el Miembro Guapitrío.
- <u>Registro de datos en laboratorio</u>: a partir de muestras de mano y testigos de roca se estimaron parámetros de permeabilidad a partir de dos métodos directos. El primero corresponde a pruebas de carga constante realizadas en el laboratorio de rocas del IDIEM, adicionalmente se realizaron ensayos de porosidad y absorción en cada una de las muestras. En el segundo método se registraron datos de permeabilidad a partir del

permeámetro portátil (*TinyPerm*), las medidas se realizaron en el laboratorio de sedimentología utilizando un soporte metálico y testigos con caras planas, para garantizar un mayor control en el registro de datos y disminuir las probabilidades de error en la lectura.

- <u>Conteo modal de partículas:</u> se realizó un conteo de aproximadamente 300 partículas en cada uno de los cortes transparentes, se midió el área y se calculó un diámetro equivalente para cada partícula. Con esta información se estimó la distribución de tamaños de partículas en las diferentes muestras analizadas.
- <u>Análisis e interpretación de la información</u>: se realizó el esquema gráfico de cinco columnas estratigráficas, donde se interpretó las diferentes facies, ambientes de depósito y se estableció el orden estratigráfico correcto entre las unidades de acuerdo con las nuevas evidencias de terreno, dataciones y datos estructurales, adicionalmente se estimaron valores de permeabilidad y porosidad en algunas facies arenosas del Miembro Río Pedregoso.

CÁPITULO II

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 Cura-Mallín 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 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 to best reservoir potential, as it has relatively thick, semi-permeable sandstones and conglomerates deposited in a lake-margin environment.

Keywords: Tolhuaca Volcano, Cura-Mallín Formation, geothermal reservoir, Gilbert-type delta.

1. Introduction

The Cura-Mallín Basin is located between 36° and 39°S in both Chilean and Argentinian territory (Fig. 1), being composed of 3 partly connected (but as yet unmapped) sub-basins around Chillán, Lileo, and Lonquimay from north to south (Radic et al., 2002; Spallettti 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 this basin has received much attention lately, due to the fact that it forms the basement underlying Quaternary volcanoes such as Lonquimay and Tolhuaca (Fig. 1). The latter is considered to be a potentially commercial geothermal 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 to 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).

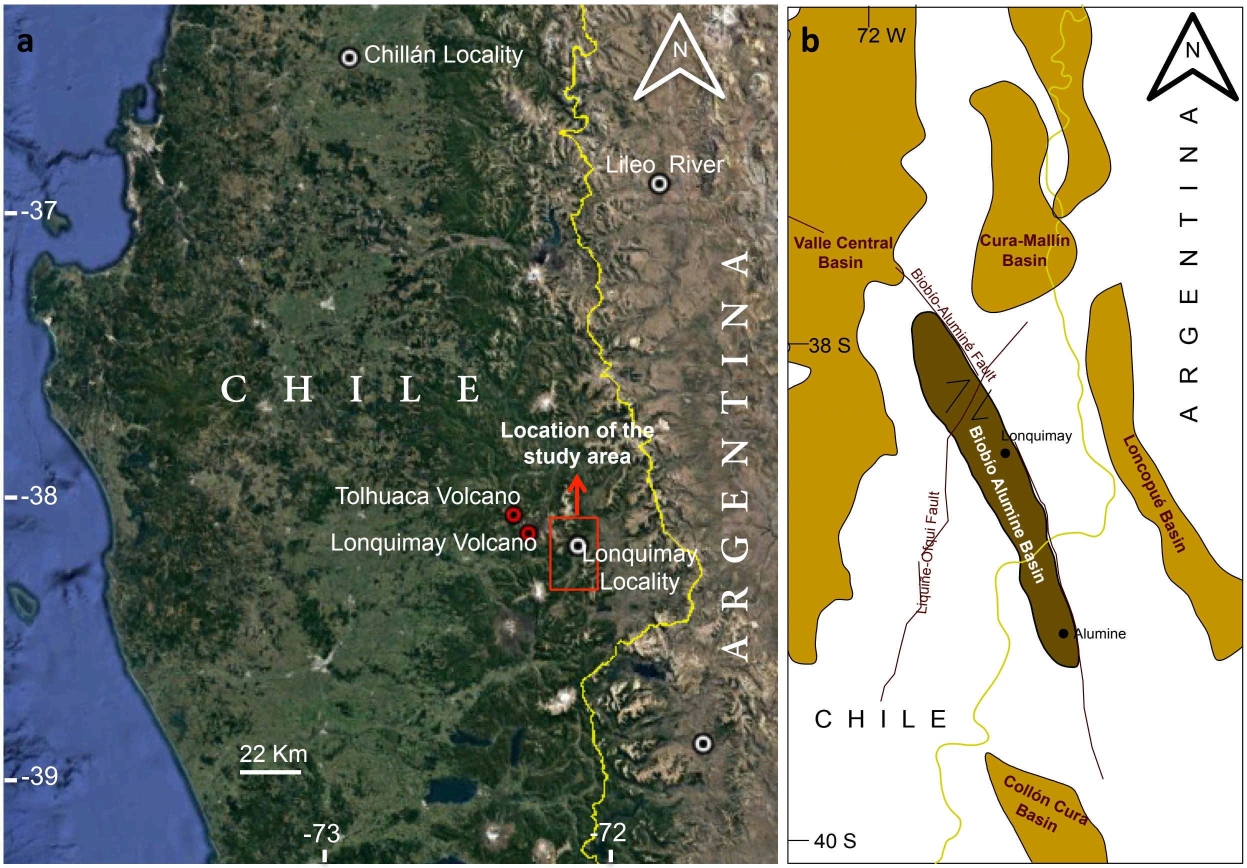

Figure 1. a) Generalized location and extension of the Cura-Mallín Basin in Chile and Argentina, with some localities mentioned in the text. b) Distribution of the Sub-basin Biobío Alumine in the Cura-Mallín Basin (Modified from Spalletti et al., 2013)

Interpretation of a seismic line northeast of Andacollo in Argentina at 37ºS, indicates that the Cura-Mallín sub-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 northern sub-basin around Laguna del Laja, referred to by Spalletti et al. (2013) as the Cura Mallín Basin, 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 sub-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 area of Argentina, 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 Lonquimay area, and reflect some of the current geochronological and stratigraphic uncertainties in the Cura-Mallín Basin.

The Lonquimay Sub-basin (Bíobio-Aluminé Basin according to 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 Chillán Sub-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. 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, 1995a), 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).

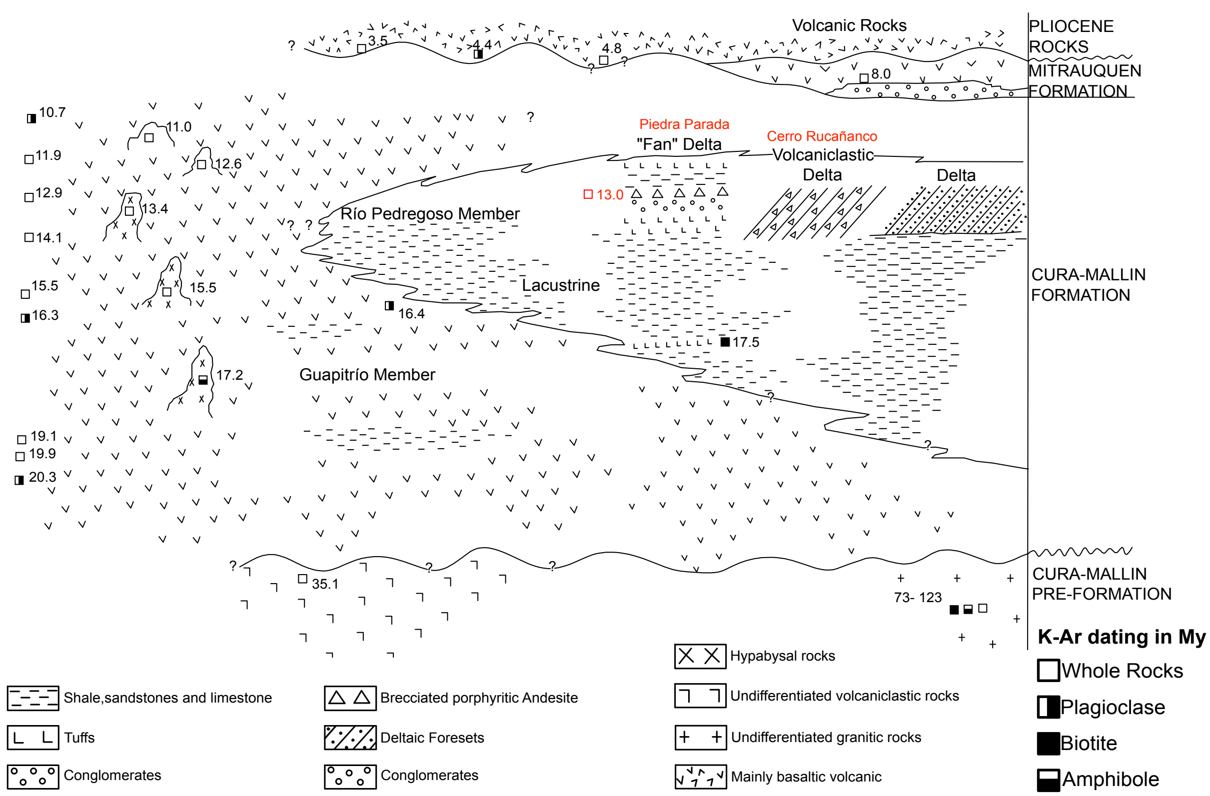

Fig. 2. Original stratigraphic scheme of Suárez and Emparan (1995), showing that the Guapitrío and Río Pedregoso "Members" co-existed.

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 (Suarez 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 ascribed to the sedimentary deposits and the Santacrucian Land Mammal Age of 17.g – 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.

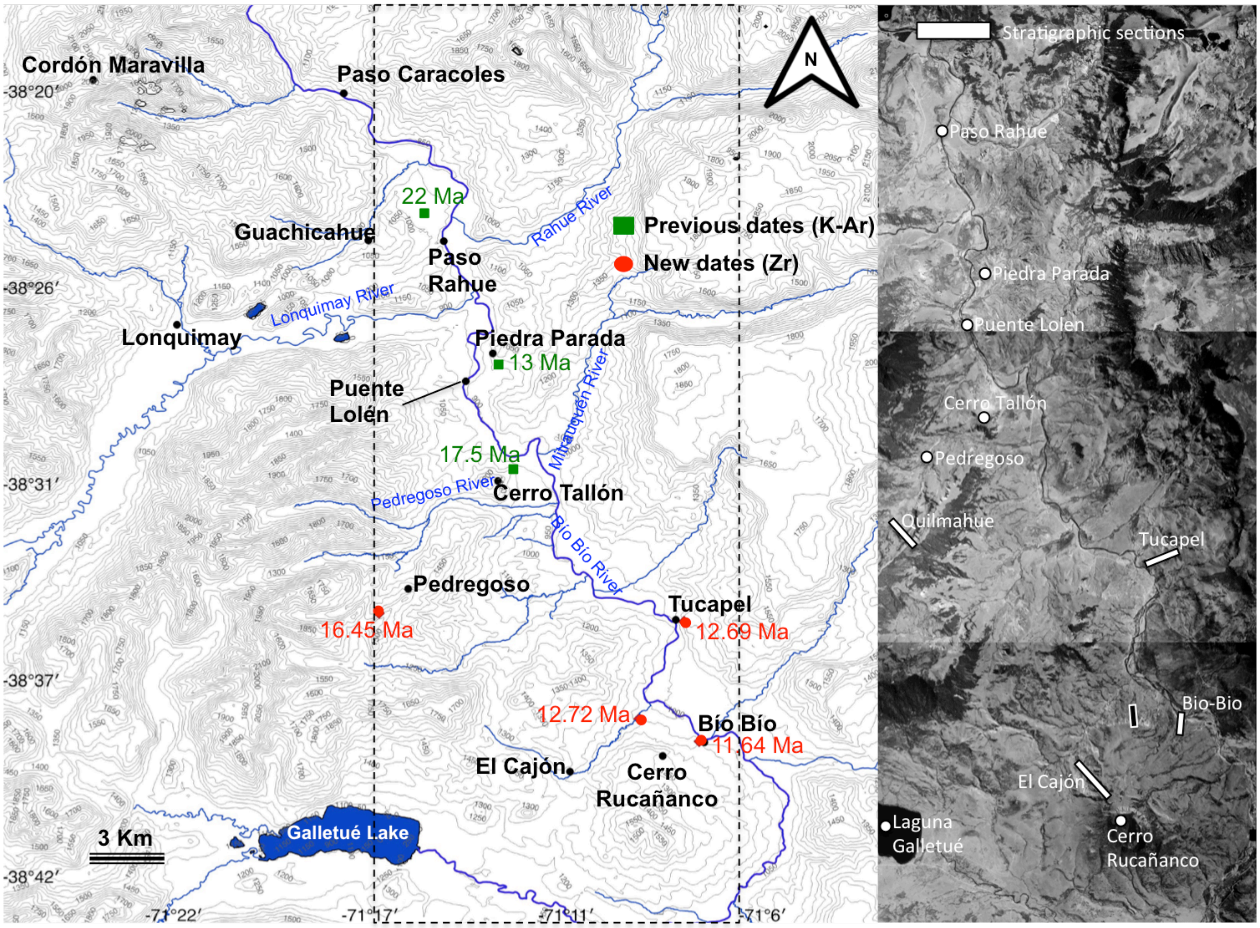

Fig. 3. Topography and aerial photos of the Lonquimay Sub-basin, showing localities mentioned in text, measured stratigraphic sections, and dated samples.

2. Methodology

Field work in the Lonquimay area consisted of geological mapping, outcrop description (lithology, sedimentary structures and paleocurrent 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. 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 (Fig. 3). 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

$$K = \frac{\Delta VL}{A\Delta h\Delta t}, \quad (1)$$

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

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

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):

$$K = \frac{k\rho g}{\mu}, \qquad (3)$$

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 (Suarez 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 (Fig. 3). 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. 4).

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. 4). 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.

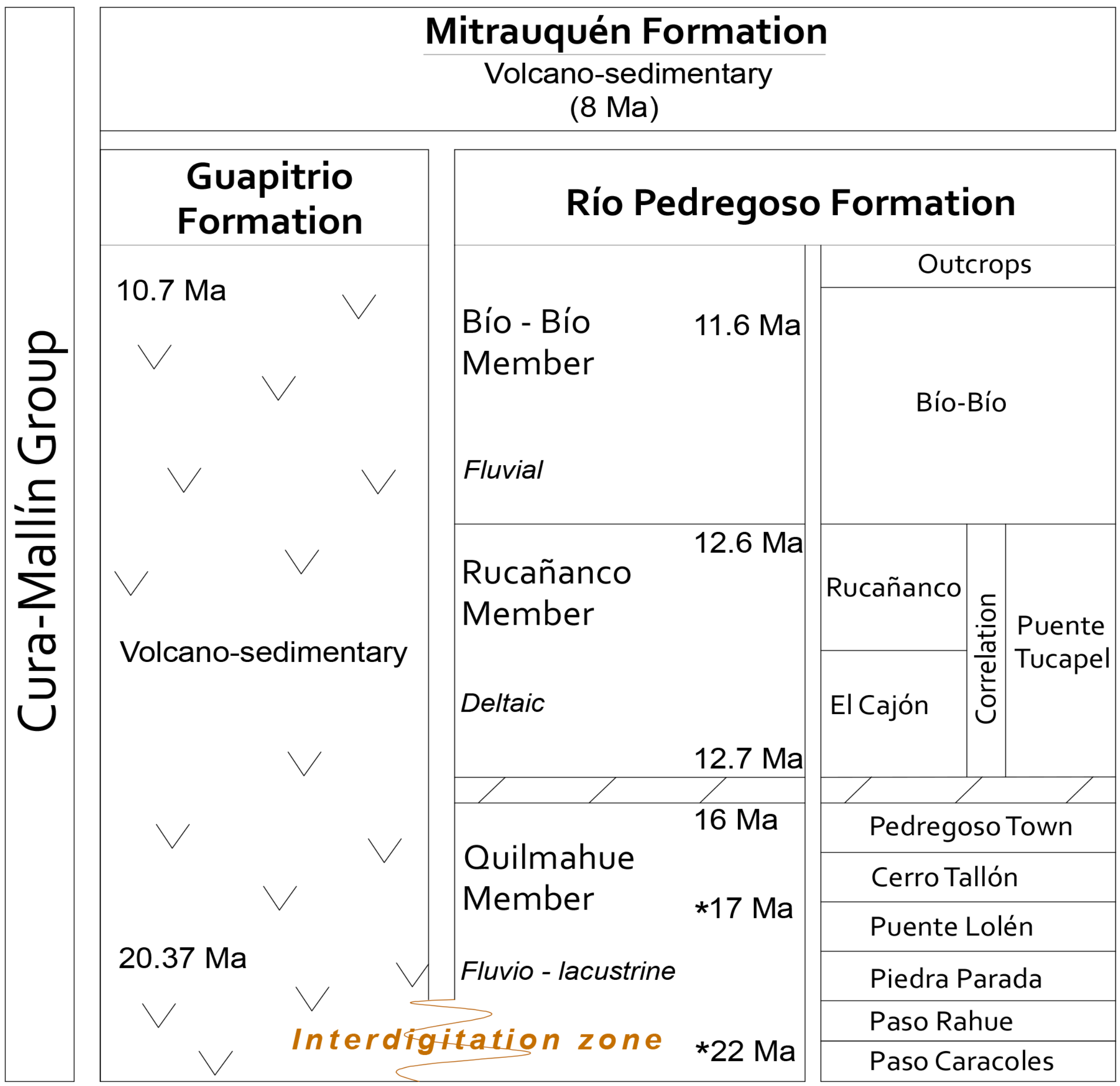

Fig. 4. New stratigraphic subdivision of the Cura-Mallín Group as proposed in this paper.

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 Lonquimay (Fig. 5).

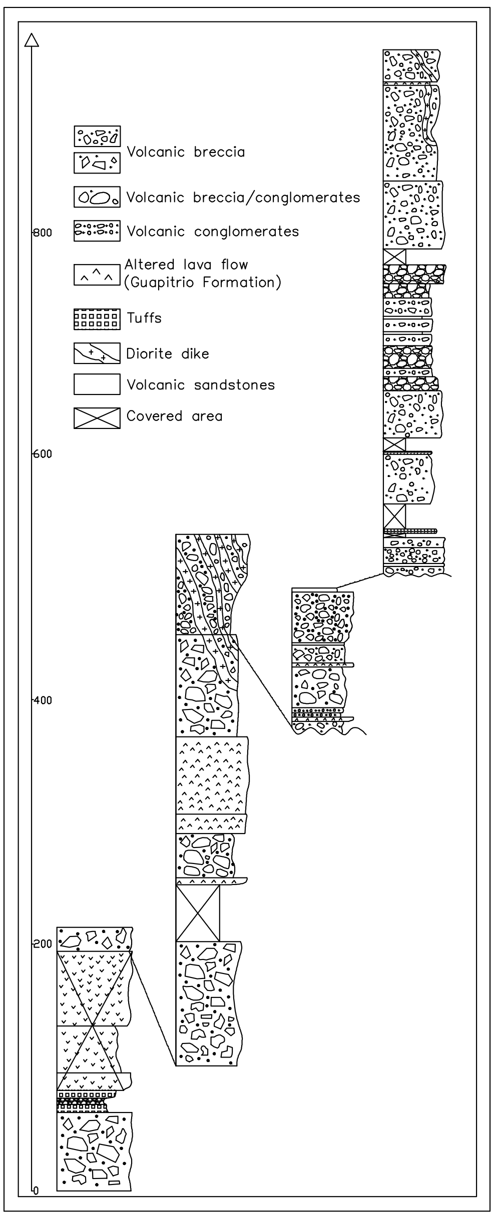

Fig. 5. Stratigraphic succession in the Guapitrío Formation measured by Vicencio (2015) at Cordón Maravilla.

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. Colors 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. 4).

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. 6 and 7). 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. 8e) 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. 8a), oölites (Fig. 8d), and raindrop marks (Fig. 8b). Small channels are locally present. Fossils are represented by wood and leaf fragments (Fig. 8f) as well as fresh-water gastropods and bivalves. Locomotion traces of the latter are also present (Fig. 8c).

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 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 (Fig. 9). The entire Quilmahue Member was therefore deposited during the early Miocene.

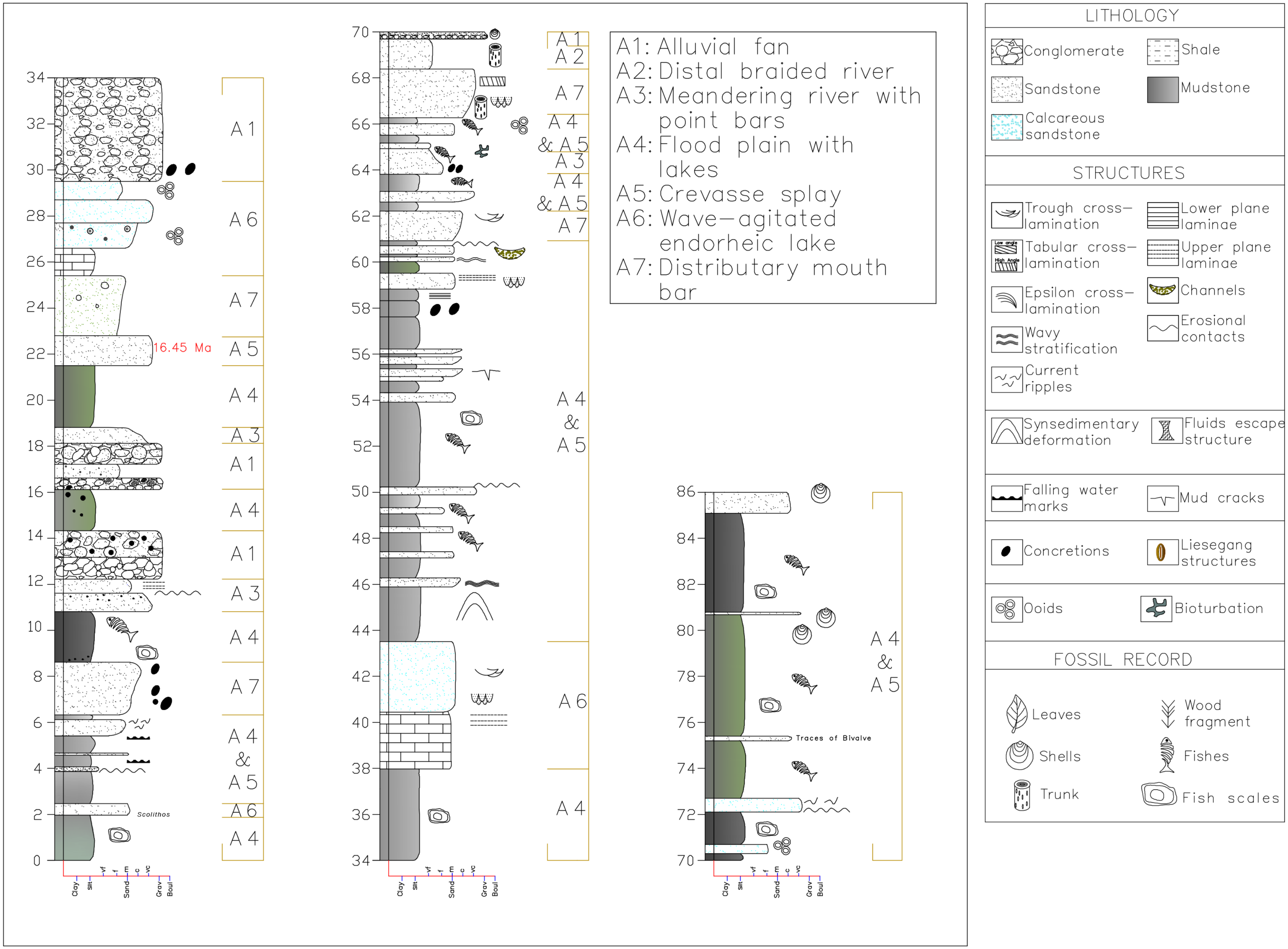

Fig. 6. Stratigraphic section measured in the Quilmahue Formation (Lower Quilmahue).

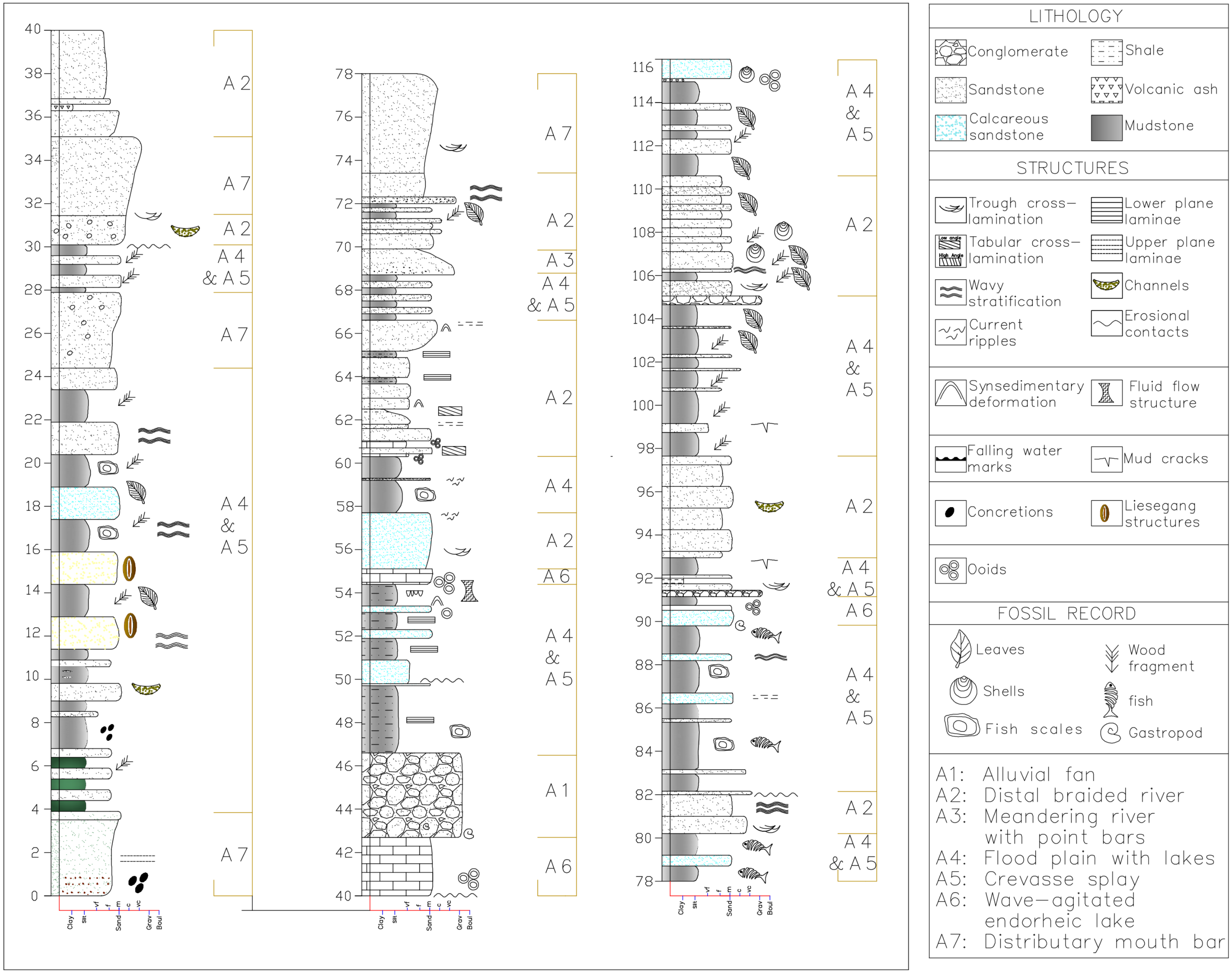

Fig. 7. Stratigraphic section measured in the Quilmahue Formation (Upper Quilmahue).

Id	Lithology	Sedimentary structures/textures	Fossils	Depositional environment
A1	Polymictic, matrix-supported conglomerate with subrounded clasts.	Nodules 2 mm in diameter.		Alluvial fans.
A2	Fine- to coarse-grained, upward-coarsening sandstones; very fine-grained sandstone interbedded with medium to coarse-grained sandstone.	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 rivers.
A3	Fining-upward, coarse- to medium-grained sandstone.			Meandering rivers with point bars.
A4	Light grey and green mudstones and mudstone laminated, rich in phosphorus (1-2 m thick)	Lower flow-regime planar lamination, raindrop marks, mud cracks, sedimentary dikes, load casts.	Leaves, vegetal organic matter and abundant fish scales	Flood plains lakes.
A5	Medium- to coarse-grained sandstones.	Undulose stratification, wave ripples, mud cracks, liesegang structures.	Leaves and vegetal organic matter.	Crevasse splays
A6	Light to dark grey and green mudstones with fetid odor, limestones, calcareous sandstones, fine- to medium-grained sandstones.	Oölites in limestones and calcareous sandstones, undulose stratification, current ripple marks, bivalve traces, *Skolithos*.	Abundant fish scales and spines, gastropods, bivalves.	Shallow overbank and playa lakes.
A7	Coarsening-upward, fine- to medium-grained sandstone (1-3 m thick)	Trough cross-lamination, concretions.		Distributary mouth bar

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

Fig. 8. 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.

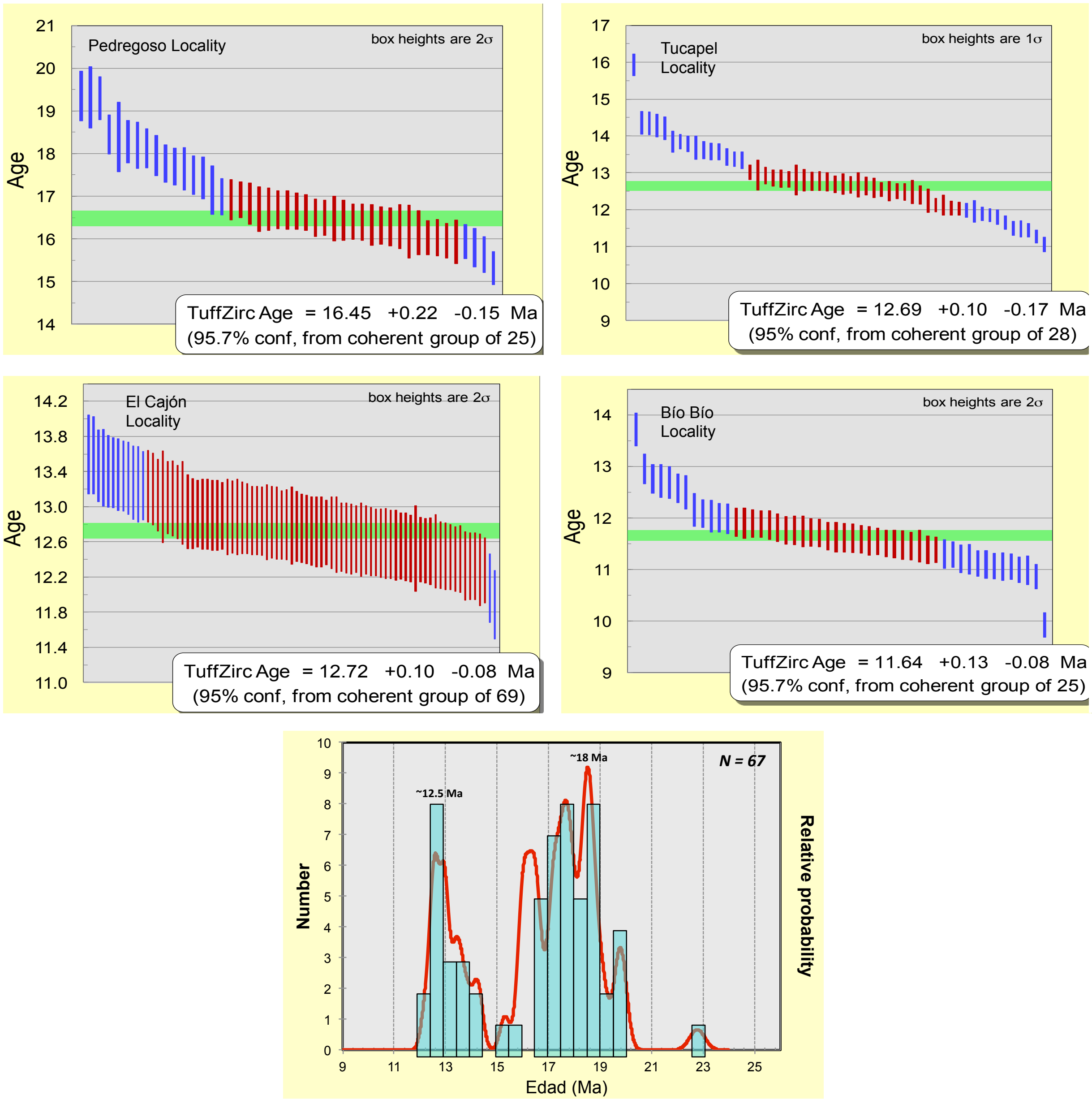

Fig. 9. Detrital zircon ages for the Quilmahue Member (Río Pedregoso), Rucañanco Member (Puente Tucapel, El Cajón) and Bío-Bío Member (Bío-Bío locality).

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, 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, 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 (Figs. 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 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 sub-cycles 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. 9).

The fossil record from Cerro Rucañanco includes fish teeth (Rubilar, 1994), the terrestrial bird Meganhinga chilensis (Wall et al., 1991; Alvarenga, 1995), freshwater bivalves, and a Miocene catfish, Nematogenys cuivi, found together with Serrasalminae teeth (Rubilar, 1994; Azpelicueta and Rubilar, 1998). Remains of the land mammal Protypotherium Ameghino were recovered from the Puente Tucapel locality (Suárez and Emparan, 1995; Buldrini et al., 2011).

d	Lithology	Sedimentary structures	Fossils	Depositional environment
A1	Polymictic, matrix-supported conglomerates; clast-supported, imbricated conglomerates with rounded, centimetric clasts.		Armadillo plates	Alluvial fans with debris flows and stream channels
A2	Coarsening-upward, medium- to very coarse-grained sandstone (2-12 m thick)	High-angle tabular cross-lamination, synsedimentary deformation structures, concretions.		Distributary mouth bar
A3	Grey mudstones.			Overbank flood plains.
A4	Medium-grained sandstones up to 1 m thick.			Crevasse splays.
A5	Shales with thin, fine-grained sandstone interbeds.			Shallow overbank lakes

Table 2. Lithofacies description at El Cajón.

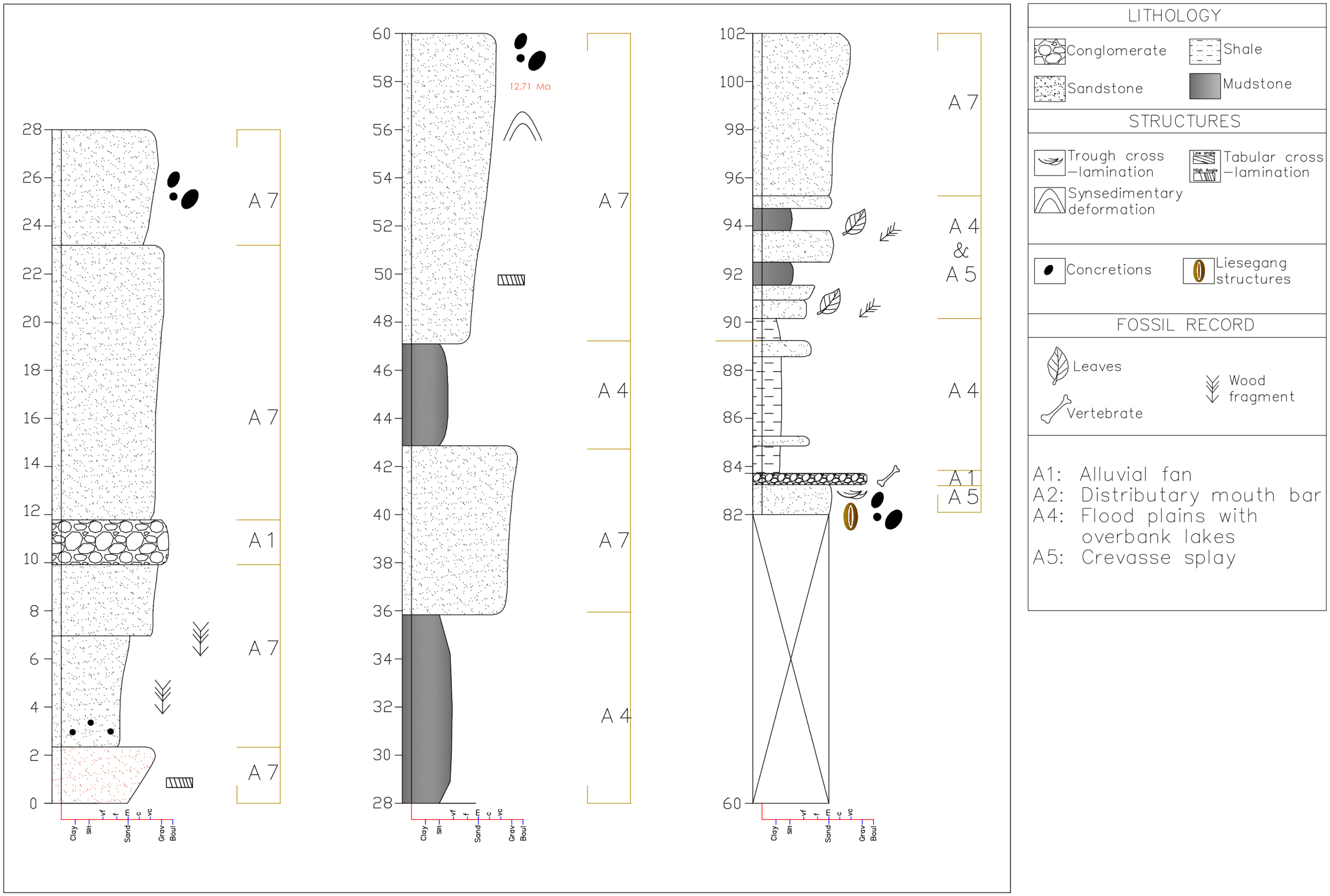

Fig. 10. Stratigraphic section measured in the Rucañanco Member at El Cajón.

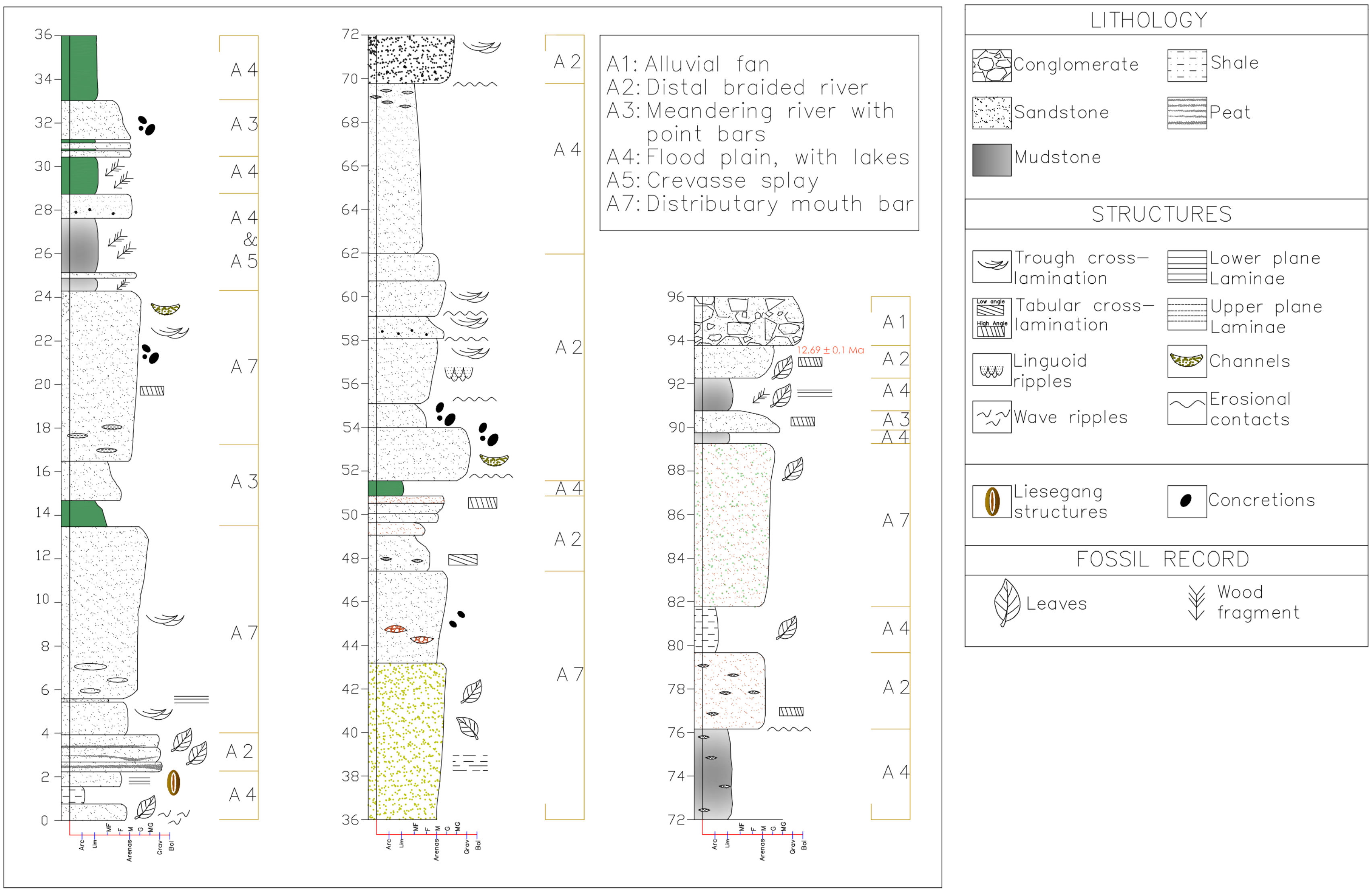

Fig. 11. Stratigraphic section measured in the Rucañanco Member at Puente Tucapel.

Id	Lithology	Sedimentary structures	Fossils	Depositional environment
A1	Polymictic, matrix-supported conglomerates with angular to sub-rounded clasts.			Alluvial fans.
A2	Coarsening-upward, medium- to very coarse-grained sandstone (3-8 m thick)	High-angle tabular cross-lamination and concretions.	Leaves	Distributary mouth bar
A3	Coarsening- and fining-up, fine- to coarse-grained sandstones with mudstone lenses	Trough and high-angle tabular cross-lamination, upper flow-regime planar lamination, linguoid ripples, concretions.	Leaves	Distal braided rivers.
A4	Fining-upward, medium- to fine-grained sandstones with erosional bases.	High-angle tabular cross-lamination, concretions.	Vegetal organic matter.	Meandering rivers with point bars.
A5	Grey and green mudstones, fine-grained sandstone lenses.		Vegetal organic matter.	Overbank flood plains.
A6	Medium-grained sandstones with small, scattered clasts, beds approximately 1 m thick.			Crevasse splays.
A7	Shales interbedded with very fine-grained sandstone.	Lower flow-regime planar lamination, liesegang.	Leaves.	Shallow overbank lakes.
A8	Shales in units up to 1 m thick.		High content of well-preserved wood fragments and leaves.	Oxbow lakes.

Table 3. Lithofacies description at Puente Tucapel.

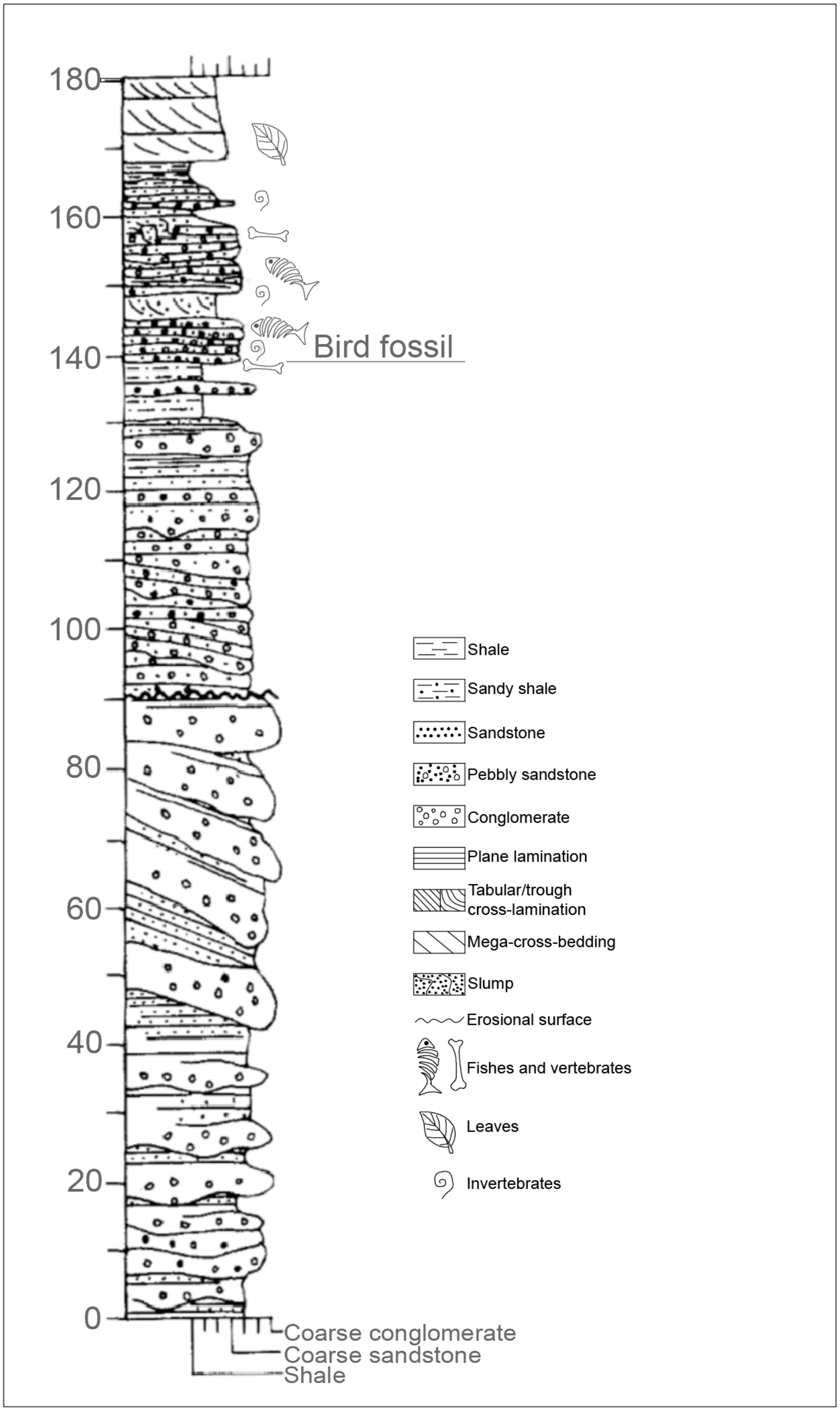

Fig. 12. Stratigraphic section measured at Cerro Rucañanco by Wall et al. (1991), subsequently described in more detail by Suárez and Emparan (1995).

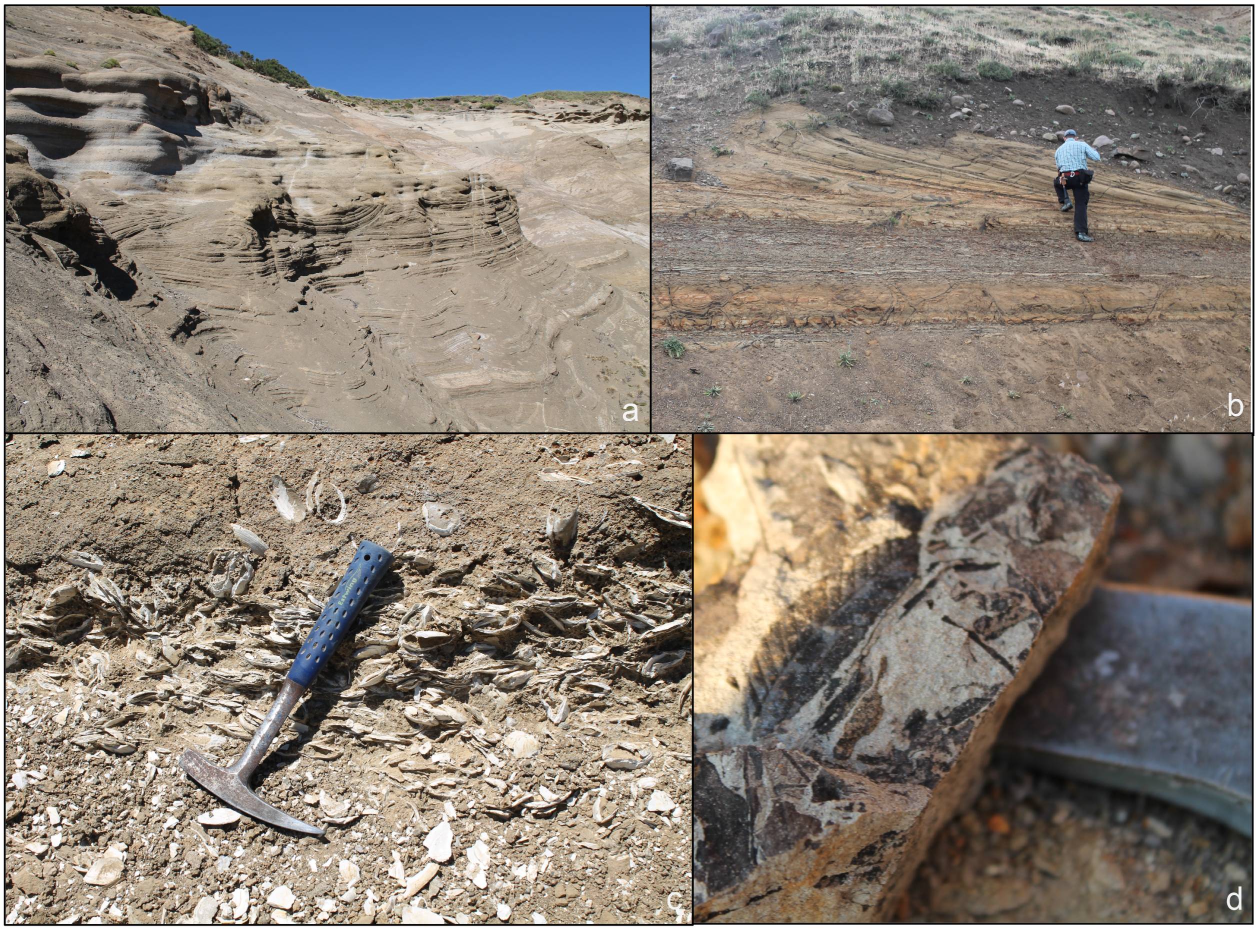

Fig. 13. Sedimentary features in the Rucañanco Member. a) Strata at El Cajón showing large-scale troughs and synsedimentary deformation structures; b) Distributary mouth-bar deposits with high-angle tabular cross-lamination; c) Bivalves in sandstones overlying delta topset deposits; d) Fossil leaves.

3.2.3. Bío-Bío Member

The definition of this member is based on a section along the Bío-Bío River (Figs. 3, 14) 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. 15a), 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. 15b), and concretions (Fig. 15c). 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 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. 9).

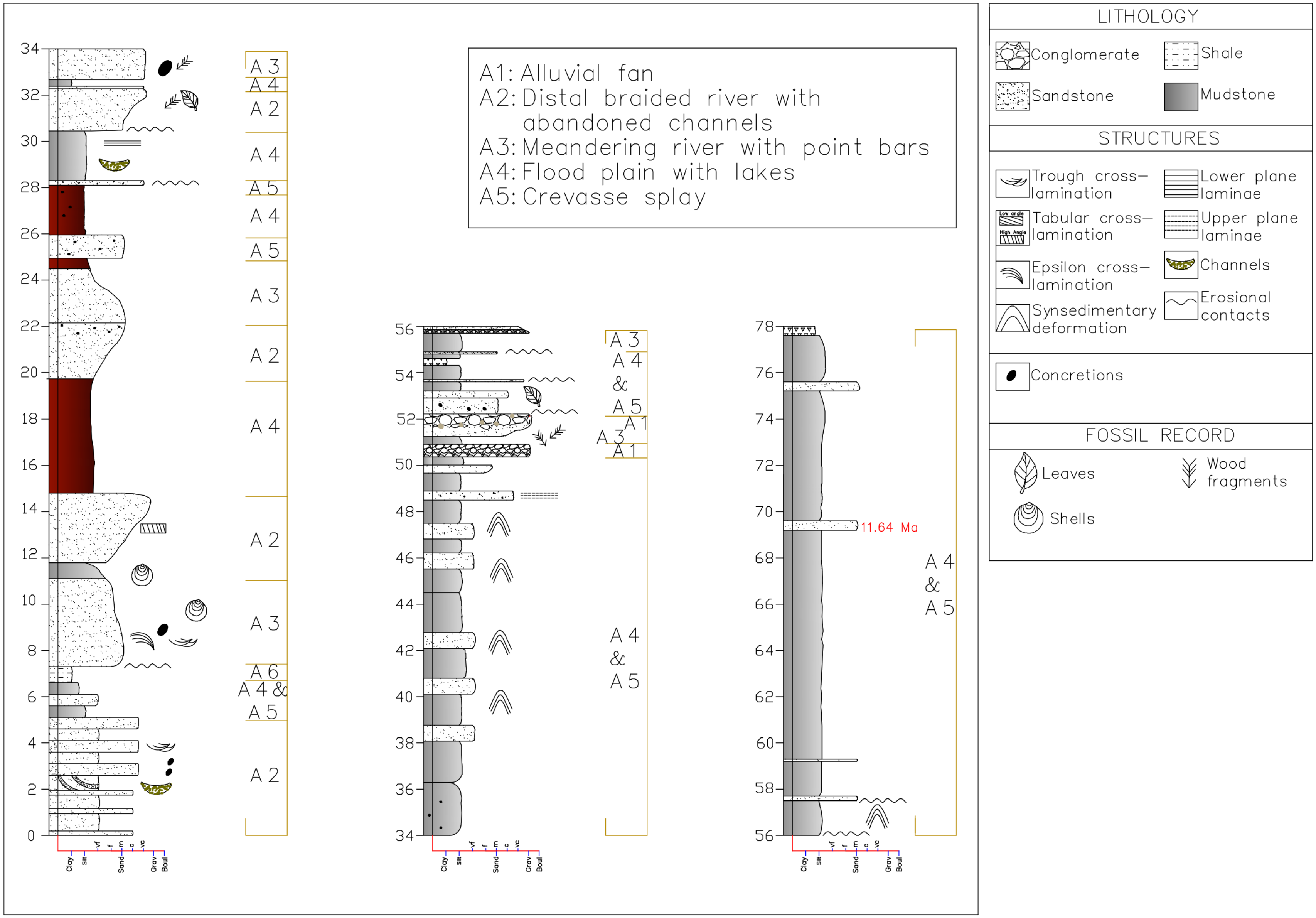

Fig. 14. Stratigraphic section measured in the Bío-Bio Member at homonymous locality.

Id	Description	Sedimentary structures	Fossils	Depositional environment
A1	Matrix-supported conglomerate with subrounded 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 (2-10m thick)		Vegetal organic matter	Flood plains
A5	Fine- to medium-grained sandstones, pumice clasts	Synsedimentary deformation		Crevasse splays
A6	Dark grey shales.			Oxbow lakes

Table 4. Lithofacies description at Bio-Bio

Fig. 15. Sedimentary features in the Bío-Bío Member. a) Sandstones along the Bío-Bío River; b) Synsedimentary deformation structures; c) Concretions.

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. 2). 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 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 Emparán, 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 (Fig. 2) 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. 2) 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 paleocurrent measurements and zircon age data (Figs. 9, 16). Paleocurrent 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. 16b) 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. 16d), which coincides with probable source areas towards the west as indicated by the zircon data. At Cerro Rucañanco, six measured delta foreset orientations (Fig. 16c) were corrected to incorporate the regional dip, using an Excel progam of Le Roux (1991a). Although these indicate sources to the southeast (Fig. 16e), 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 – 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. 16a). 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.

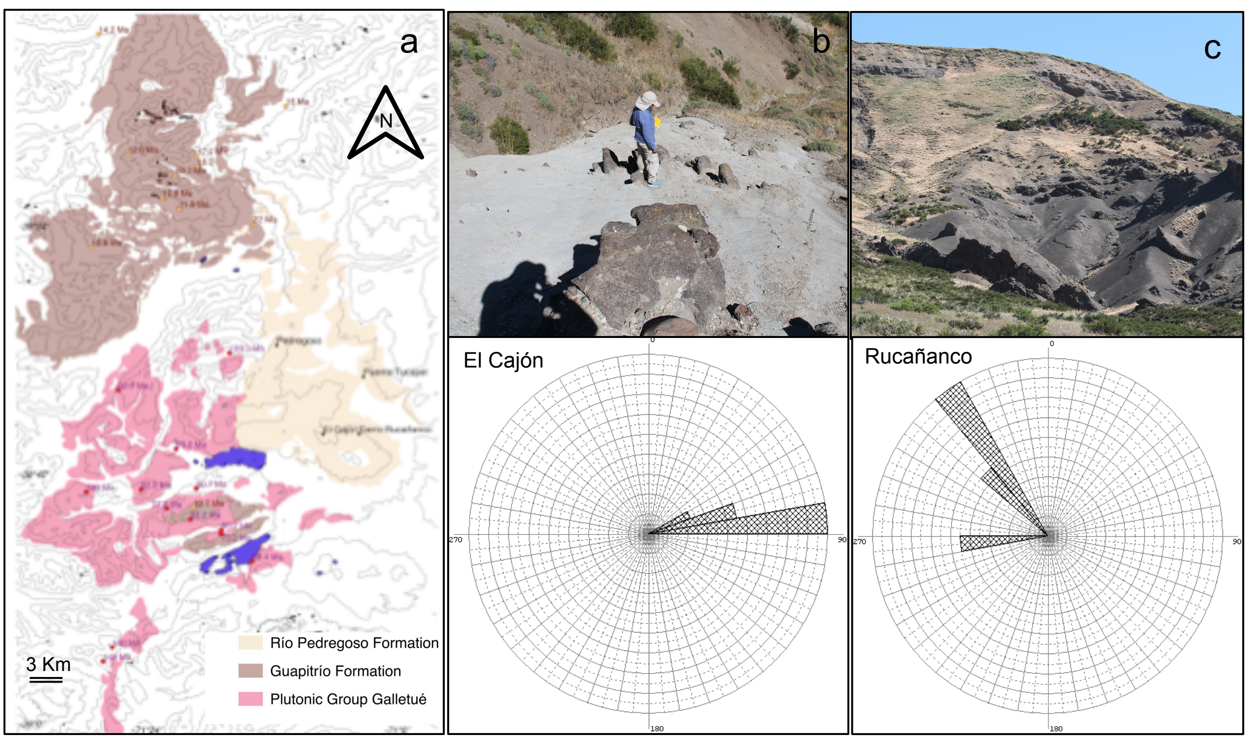

Fig. 16. a) Partial geological map showing distribution of the Guapitrío and Río Pedregoso Formations as well as the Galletué Plutonic Group; b) Oriented concretions; c) Mega-foresets of Gilbert-type deltas at Cerro Rucañanco; d) Rose-diagram of concretion orientations ; e) Rose-diagram of mega-foreset orientations.

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 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. 17) varied between 6.99 x 10^{-7} and 6.81 x 10^{-11} m s^{-1}, i.e. from semi-permeable (1 x 10^{-6} to 1 x 10^{-9} m s^{-1}) to almost impermeable (<1 x 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 x 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 x 10^{-10} and 6.36 x 10^{-10} m s^{-1}, respectively, both being almost 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 x 10^{-8} and 2.31 x 10^{-8} m s^{-1}, respectively.

The *TinyPerm* results for all samples fell within the semi-permeable field (Fig. 17), ranging between 9.09 x 10^{-7} and 8.61 x 10^{-9} m s^{-1}, with the two samples from Puente Tucapel closer to the permeable/semi-permeable limit (6.72 x 10^{-7} and 9.09 x 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.

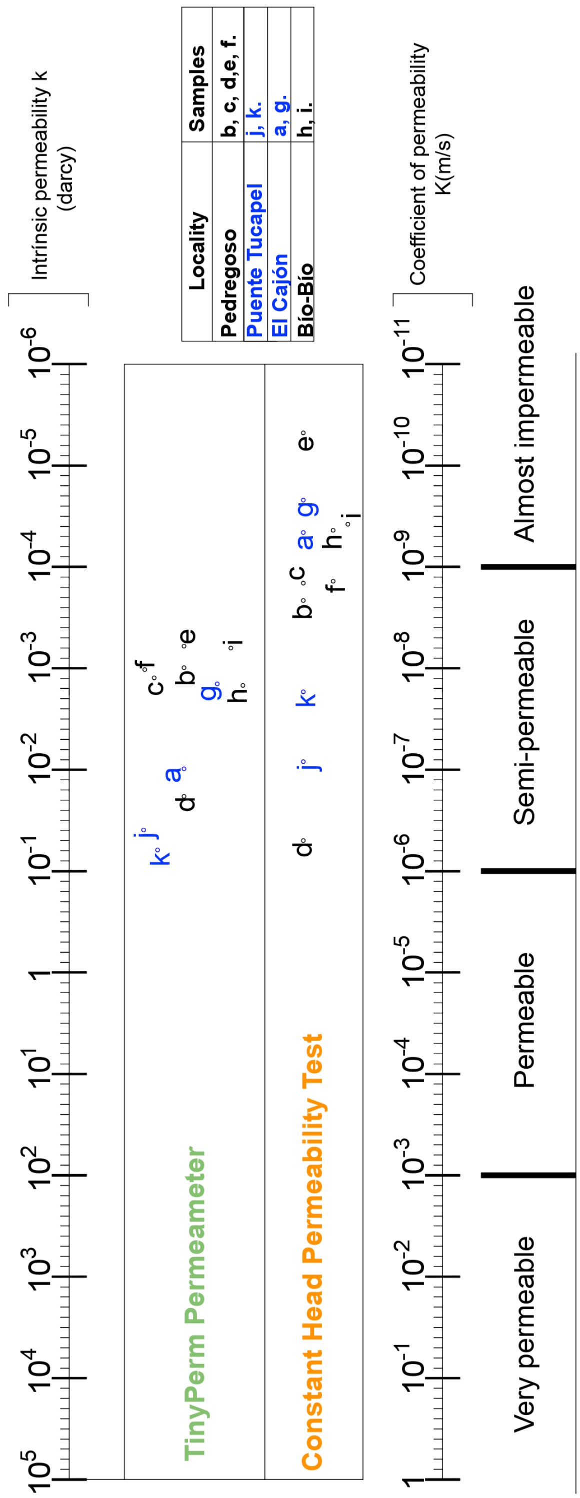

Fig. 17. Permeability of samples from the Río Pedregoso Formation as determined by the constant head and *TinyPerm* methods.

6. Summary and conclusions

Suárez and Emparan (1997) proposed that the Río Pedregoso Member 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 some what 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 in the Cura-Mallín Basin 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 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 region of Argentina. As the basal portion of this formation in the Chillán Sub-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 Cura-Mallín Formation, pending further work. Still further to the southeast in the Lonquimay Sub-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 co-existed 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 Lonquimay Sub-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 – 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 Lonquimay Sub-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.

Acknowledgements

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Bibliography

Alvarenga, H.M.F., 1995. A large and probably flightless anhinga from the Miocene of Chile. Courier Forschungsinstitut Senckenberg, 181, 149-161.

Aravena, D., Munoz, M., Morata, D., Lahsen, A., Parada, M.A., Dobson, P., 2016. Assessment of high enthalpy geothermal resources and promising areas of Chile. Geothermics, 59, 1-13.

Arratia, G., 1982. A review of freshwater percoids from South America (Pisces, Perciformes, Percichthyidae and Perciliidae). Abhandlungen der Senkenbergischen Naturforschenden Gesellschaft, 540, 1-52.

Azpelicueta, M.M., Rubilar, A., 1998. A Miocene Nematogenys (Teleostei: Siluriformes:

Nematogenyidae) from South-Central Chile. Journal of Vertebrate Paleontology, 18(3), 475-483.

Buldrini, K., Bostelmann, E., Soto-Acuña, S., 2011. Taxonomic identity of the Interatheriidae SGO.PV.4004 and SGO.PV.4005, and rectification of collection numbering of *Caraguatypotherium munozi* (Notoungulata; Mesotheriidae). Abstracts, XIV Congreso Geológico Chileno, La Serena, Chile.

Burckhardt, C., 1900. Coupe géologique de la cordillére entre Las Lajas et Curacautin. Museo de La Plata, Anales, Sección Mineralogía y Geología, 1(3), 1-102.

Burns, W.M., Jordan, T.E., 1999. Extension in the Southern Andes as evidenced by an Oligo-Miocene age intra-arc basin. Proceedings of the 4th International Symposium on Andean Geodynamics (ISAG). Editions IRD, Göttingen, Germany, pp. 115-118.

Carpinelli, A., 2000. Análisis estratigráfico, paleoambiental, estructural y modelo tectono-estratigráfico de la cuenca de Cura-Mallín, VIII y IX Región, Chile, Provincia de Neuquén, Argentina. Master's thesis. Departamento de Ciencias de la Tierra, Universidad de Concepción, Chile, 158 p.

Chang, A.G., Arratia G., Alfaro, G.H., 1978. *Percichthys lonquimayiensis* n. sp. from the Upper Paleocene of Chile (Pisces, Perciformes, Serranidae). Journal of Paleontology, 52, 727-736.

Cisternas, M.E., Díaz, L., 1985. Los depósitos terciarios lacustres de Lonquimay, Chile. Zentralblatt für Geologie und Palaeontologie, 1(9-10), 1351-1362.

Croft, D.A., Bond, M., Flynn, J.J., Reguero, M., Wyss, A.R., 2003a. Large archaeohyracids (Typotheria, Notoungulata) from central Chile and Patagonia, including a revision of Archaeotypotherium. Fieldiana (Geology), N.S. 49, 1-38.

Croft, D., Radic, J., Zurita, E., Charrier, R., Flynn, J., Wyss, A., 2003b. A Miocene toxodontid (Mammalia: Notoungulata) from the sedimentary series of the Cura-Mallín Formation, Lonquimay. Revista Geológica de Chile, 30, 285-298.

Das, B., 2001. Fundamentos de Ingeniería Geotécnica. International Thompson Editores S.A., México, 594 pp.

Drake, R., 1976. Chronology of Cenozoic igneous and tectonic events in the Central Chilean Andes-latitudes 35_300–36_000S. Journal of Volcanology and Geothermal Research, 1, 265-284.

Flynn, J.J., Charrier, R., Croft, D.A., Gans, P.B., Herriott, T.M., Wertheim, J.A., Wyss, A.R., 2008. Chronologic implications of new Miocene mammals from the Cura-Mallín and Trapa Trapa formations, Laguna del Laja area, south central Chile. Journal of South American Earth Sciences, 26, 412-423.

Flynn, J.J., Swisher III, C.C., 1995. Chronology of the Cenozoic South American Land Mammal Ages. In: Berggren, W.A., Kent, D.V., Hardenbol, J. (Eds.), Geochronology, Time-Scales, and Global Stratigraphic Correlation, SEPM (Soc. for Sedimentary Geology, Tulsa, Oklahoma). Special Publication, 54, 317-333.

Folguera, A., Ramos, V.A., Melnick, D., 2003. Recurrencia en el desarrollo de cuencas de intra-arco: Colapso de estructuras orogénicas, Cordillera Neuquina (37°30´S). Revista de la Asociación Geológica Argentina, 58(1), 3-19.

Hedberg, H.D., 1980. International Stratigraphic Guide. Wiley Interscience, 200 p.

Iriarte, S., 2013. Jornada Geotérmica Universidad de Concepción, Exploración geotérmica proyecto Tolhuaca.

Jordan, T., Burns, W., Veiga, R., Pángaro, F., Copeland, P., Kelley, S., Mpodozis, C., 2001. Extension and basin formation in the southern Andes caused by increased convergence rate: a mid-Cenozoic trigger for the Andes. Tectonics, 20, 308-324.

Langguth, H., Voigt, R., 1980. Hydrogeologische Methoden. Springer-Verlag, Berlin, 486 pp.

Le Roux, J.P., 1991a. Paleocurrent analysis using Lotus 1-2-3. Computers & Geosciences, 17(10), 1465-1468.

Le Roux, J.P., 1991b. Flume experiments on permeability and organic matter as related to the genesis of stratiform uranium deposits in the Beaufort Group. South African Journal of Geology, 94(2/3), 212-219.

Linares, E., González, R.R.,1990. Catálogo de edades radiométricas de la República Argentina 1957-1987. Asociación Geológica Argentina, Publicación Especial, Serie B, 19, 1-628.

Lizama, M., 2013. Alteración hidrotermal en el Sistema geothermal Tolhuaca: Caso de studio sondaje TOL-1. Memoria de Título en Geología, Universidad de Chile.

Melnick, D., Rosenau, M., Folguera, A., Echtler, H., 2006. Neogene tectonic evolution of the Neuquén Andes western flank (37° and 39°S). In: Kay, S.M., Ramos, V.A, (Eds.), Evolution of an Andean Margin: A Tectonic and Magmatic View from the Andes to the Neuquén Basin (35° - 39°S latitude). Geological Society of America Special Paper, 407, 73-96.

Melosh, G., Moore, J., Stacey, R., 2012. Natural reservoir evolution in the Tolhuaca geothermal field, southern Chile. Proceedings of the 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.

Morata, D., 2014. ¿Chile: Un País Geotérmico en un Futuro Inmediato? . Revista anales Séptima Serie, No 5, abril 2014 .

Muñoz, J.. Niemeyer, H., 1984. Hoja Laguna de Maule y del Biobio, Carta Geologia de Chile 64, scale 1:250,000, Servicio Nacional de Geología y Minería, Santiago, Chile.

Niemeyer, H.. Muñoz, J., 1983. Hoja Laguna de la Laja, Region del Bío Bío. Carta Geología de Chile 57, scale 1:250,000, Servicio Nacional de Geología y Minería, Santiago, Chile.

Osorio, R., Cisternas S., María E., Díaz, L., 1982. Nuevos antecedentes para la datación de la Formación Lonquimay. III Congreso Geológico Chileno, Concepción, Chile, pp. F389-F395.

Palma-Heldt, S., 1983. Estudio palinológico del Terciario sedimentario de Lonquimay, provincia de Malleco, Chile. Revista Geológica de Chile, 18, 55-75.

Risacher, F., Fritz, B., Hauser, A., 2011. Origin of components in Chilean thermal waters. Journal of South American Earth Sciences, 31, 153-170.

Radic, J., 2010. Las cuencas cenozoicas y su control en el volcanismo de los complejos Nevados de Chillán y Copahue-Callaqui (36°-39°S). Andean Geology, 37(1), 220-246.

Radic, J.P., Carpinelli, A., Zurita, E., 2000. Cuenca Terciaria Cura-Mallín, informe geológico. Informe inédito SIPETROL S.A., Santiago, Chile.

Radic, J.P., Rojas, L., Carpinelli, A., Zurita, E., 2002. Evolución tectónica de la Cuenca de Cura-Mallín, región cordillerana chileno Argentina (36°30´S–39°00´S). Proceedings, XV Congreso Geológico

Argentino, El Calafate, 3, 233-237.

Rubilar, A., 1994. Diversidad ictiológica en depósitos continentales miocenos de la Formación Cura-Mallín, Chile (37°–39°S): implicancias paleogeográficas. Revista Geológica de Chile, 21(1), 3-29.

Rubilar, A., Wall, R., 1990. Primer registro en Chile de Siluriformes (Pisces, Ostariophysi) procedente del Mioceno de Lonquimay. Actas, II Simposio sobre el Terciario de Chile, Concepción, Chile, p. 275-284.

Sánchez, P., Arancibia, G., Cembrano, J., Veloso, E., Lohmar, S., Stimac, J., Reich, M., Rubilar, J., Pérez-Flores, P., 2012. Sampling and detailed structural mapping of veins, fault-veins and faults from Tolhuaca Geothermal System, southern Chile. XIII Congreso Geológico Chileno, Antofagasta, T4, pp. 71-73.

Sandoval, R., 1977. Estudio geológico de la región del Alto Bío-Bío, comuna Lonquimay, depto. Curacautín IX Región, Chile. Memoria de Título, Universidad de Chile, 187 p.

SKM, 2012. Surface reconnaissance of the Callaqui Geotermal Prospect. Unpublished Report, Infinergeo SpA.

Spalletti, L.A., Veiga, G.D., Franzese, J.R., 2013. Procesos gravitacionales-fluviales y preservación de vegetación boscosa en un área volcánica: Formación Rancahué (Oligoceno), Andes neuquinos, Argentina. Andean Geology, 40, 521-538.

Suárez, M., Emparan, C., 1988. Geocronología y asociación de facies volcánicas y sedimentarias del Mioceno de Lonquimay, Chile (lat. 38°- 39°S). Abstracts, II Simposio sobre el Terciario de Chile, Concepción, pp. 311-324.

Suárez, M., Emparan, C., 1995. The stratigraphy, geochronology and paleophysiography of a Miocene fresh-water interarc basin, southern Chile. Journal of South American Earth Sciences, 8, 17-31.

Suárez, M., Emparan, G., 1997. Hoja Curacautín, Regiones de la Araucanía y del Bío-Bío, Carta Geológica de Chile 71, scale 1:250,000, Servicio Nacional de Geología y Minería, Santiago, Chile.

Suárez, M., Emparan, C., Wall, R., Salinas, P., Marshall, L., Rubilar, A., 1990. Estratigrafía y vertebrados fósiles del Mioceno del Alto Biobio. Actas, II Simposio sobre el Terciario de Chile, Concepción, pp. 311-324.

Vicencio, V., 2015. Geología y mineralogía de alteración en una sucesión volcano-sedimentaria en la zona volcánica sur central, Chile: Evidencias de un paleo-sistema volcánico y geotermal en la Formación Cura-Mallin. Masters Thesis, Universidad de Chile, 176 p.

Wall, R., Alvarenga, H., Marshall, L., Salinas, P., 1991. Hallazgo del primer ave fósil del Terciario de Chile: un ánade (Pelecaniformes: Anhingidae), preservado en un ambiente deltaico-fluvial del Mioceno de Lonquimay, Región de la Araucanía, Chile. VI Congreso Geológico Chileno, Viña del Mar, 6, 394-405.

CAPÍTULO III

RESUMEN DE RESULTADOS

1. Formación Río Pedregoso.

La Tabla 1 muestra un resumen de los ambientes, edad y variación de facies de los depósitos que constituyen la Formación Río Pedregoso.

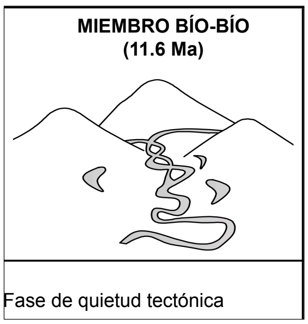
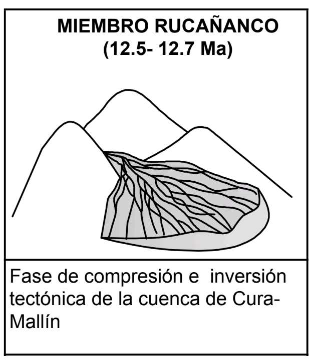
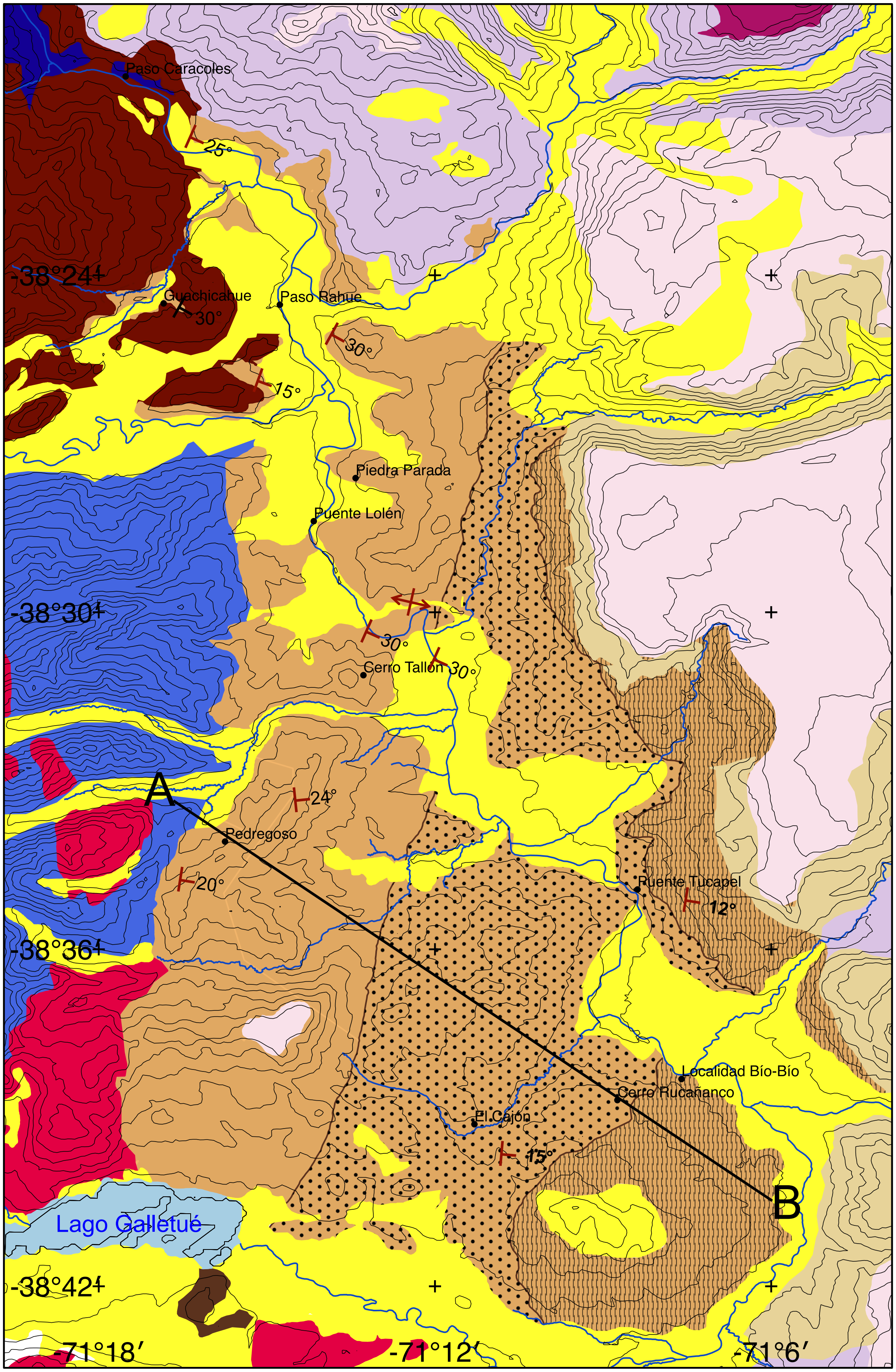
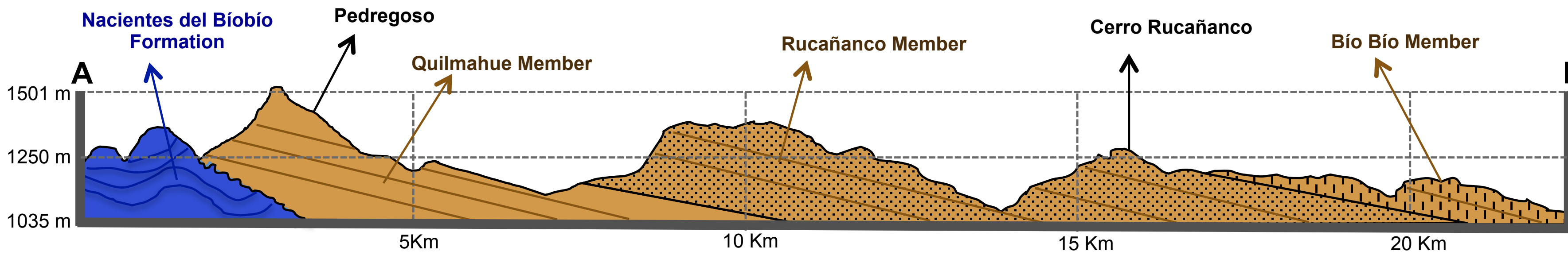
ESQUEMA ESTRATIGRÁFICO FORMACIÓN RÍO PEDREGOSO	
	**Miembro Bío-Bío (Techo)** Constituye un ambiente fluvial de ríos trenzados distales pasando a ríos sinuosos, presenta llanuras de inundación y derrames de llanura, los cuales se depositaron en un periodo de relativa quietud tectónica alrededor de los 11.6 Ma.
	**Miembro Rucañanco (intermedio)** El ambiente está representado por abundantes barras de desembocadura y deltas de tipo Gilbert, depositados en un entorno de margen de lago más profundo durante una fase de inversión tectónica entre 13 y 12 Ma aproximadamente. El ambiente de depósito del Miembro Rucañanco es fluvio-lacustre, con una granulometría mucho más gruesa que la del Miembro Quilmahue.
	**Miembro Quilmahue (Base)** Representa un ambiente fluvio-lacustre, dominado por lagos, grandes llanuras de inundación y derrames de llanura, depositados durante un episodio de extensión tectónica de la cuenca de Cura-Mallín entre 22 - 16 Ma aproximadamente.

Tabla 1: Resumen de ambientes y edad de la formación Río Pedregoso.

El mapa y perfil geológico de la Fig 1, muestra la distribución espacial de los Miembros Quilmahue, Rucañanco y Bío-Bío en la zona de Lonquimay.


Paso Caracoles
25°
-38°24′
Guachicahue
30°
Paso Rahue
30°
15°
Piedra Parada
Puente Lolén
-38°30′
30°
Cerro Tallón
30°
A
24°
Pedregoso
20°
Puente Tucapel
12°
-38°36′
Localidad Bío-Bío
Cerro Rucañanco
El Cajón
15°
B
Lago Galletué
-38°42′
-71°18′
-71°12′
-71°6′

PERFIL GEOLÓGICO



LEYENDA

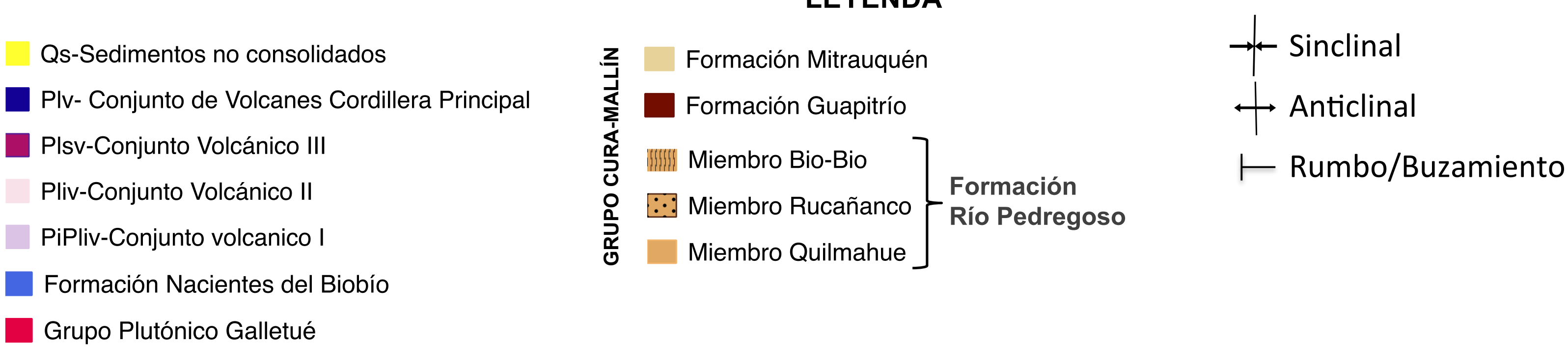


Figura 1. Mapa geológico y perfil de la zona de estudio.

2. Antecedentes Paleontológicos

La Formación Río Pedregoso se caracteriza por presentar un diverso registro fósil de peces, aves mamíferos, polen y plantas entre otros (Sandoval., 1977; Chang et al., 1978; Palma., 1983; Cisternas et al., 1985; Suarez et al., 1990; Rubilar., 1994; Suarez y Emparan., 1994; Croft et al., 2003; Buldrini et al., 2011) sin embargo en los trabajos previos existen discrepancias entre las edades asignadas a los fósiles y la posición estratigráfica. La Tabla 2 sintetiza el nuevo esquema estratigráfico vinculado al registro fósil existente y a nuevas edades radiométricas.

Localidades		Registro fósil y edades asignadas				Nuevos rangos de edad
		Mamíferos	Peces	Aves	Polen y Plantas	
Río Bío Bío (Fundo Rucañanco)		--	--	--	--	11 Ma
a) Cerro Rucañanco	Correlación Estratigráfica b) Puente Tucapel	[3,8]*Protypotherium sp/* Edad Mamífero Santacrucense *(b)* [8] Macraucheniidae, Liptopterna /sin edad definida (b)	[7] *Characidae indet*/ Mioceno (a) [7] *Serrasalminae indet*/ Mioceno(a) [2, 7]*Nematogenys cuivi* /Mioceno (a)	[1 y 9]*Meganhinga chilensis* (a)/Mioceno Inferior Tadío (edad Mamífero Santacrucense)	--	12.6 Ma
El Cajón	Correlación Estratigráfica b) Puente Tucapel	--	--	--	--	12.7 Ma
Pedregoso		--	--	--	--	16.45 Ma
Cerro Tallón		[4]*Nesodon conspurcatus/* Edad Mamífero Santacrucense y el Friasense.	[5,7,8] *Percichthys lonquimayiensis/*Mioceno [7 y8]*Percichthys sandovali/* Mioceno [7]*Percichthys sp*/ Mioceno [7]*Santosius sp*/ Mioceno [7]*Characidae indet*/ Mioceno	--	--	*17.5 Ma
Puente Lolén		--	[7] *Characidae Indet*/ Mioceno	--	--	
Piedra Parada		[8] Gliptodontidae/ sin edad definida	--	--	[6]*Podocarpidites cf marwickii*/ Oligoceno (mioceno?)	
Paso Caracoles		--	--	--	--	
Paso Rahue		--	--	--	[6]*Nothofagidites cincta*/ Eoceno [6] Cyathidites patagonicus/ Oligoceno (mioceno?) [6] Trisaccites microsaccatum/ Oligoceno (mioceno?)	*22 Ma

[1]Alvarenga, H.M.F. 1995. A large and probably flightless anhinga from the Miocene of Chile. Courier Forschungsinstitut Senckenberg 181: 149-161.

[2]Azpelicueta, M.M.; Rubilar, A. 1998. A Miocene Nematogenys (Teleostei: Siluriformes: Nematogenyidae) from South-Central Chile. Journal of Vertebrate Paleontology 18(3): 475-483.

[3]Buldrini, K; Bostelmann, E.; Soto-Acuña, S. 2011. Taxonomic identity of the Interatheriidae SGO.PV.4004 and SGO.PV.4005, and rectification of collection numbering of *Caraguatypotherium munozi* (Notoungulata; Mesotheriidae). Abstracts, XIV Congreso Geológico Chileno, La Serena, Chile.

[4]Croft, D.A.; Bond, M.; Flynn, J.J.; Reguero, M.; Wyss, A.R.; 2003a. Large archaeohyracids (Typotheria, Notoungulata) from central Chile and Patagonia, including a revision of Archaeotypotherium. Fieldiana (Geology), N.S. 49: 1-38.

[5]Chang, A.G.; Arratia G.; Alfaro, G.H. 1978. *Percichthys lonquimayiensis* n. sp. from the Upper Paleocene of Chile (Pisces, Perciformes, Serranidae). Journal of Paleontology 52: 727-736.

[6]Palma-Heldt, S., 1983. Estudio palinológico del Terciario sedimentario de Lonquimay, provincia de Malleco, Chile. Revista Geológica de Chile 18: 55-75.

[7]Rubilar, A., 1994. Diversidad ictiológica en depósitos continentales miocenos de la Formación Cura-Mallín, Chile (37–39_S): implicancias paleogeográficas. Revista Geológica de Chile 21 (1): 3-29.

[8]Suárez, M.; Emparán, C.; Wall, R.; Salinas, P.; Marshall, L.G.; Rubilar, A. 1990. Estratigrafía y vertebrados fósiles del Mioceno del Alto Biobío, Chile central (38°- 39°S). In: Simposio sobre el Terciario de Chile, No. 2, Actas, Vol. 1: 311-324.

[9]Wall, R.; Alvarenga, H.M.F.; Marshall, L.G.; Salinas, P. 1991. Hallazgo del primer ave fósil del Terciario de Chile: un ánade (Pelecaniformes; Anhingidae), preservado en un ambiente deltaico-fluvial del Mioceno del Lonquimay, Región de la Araucanía, Chile. In Congreso Geológico Chileno, No. 6, Actas, p. 394-405. Viña del Mar.

Tabla 2: Resumen de antecedentes paleontológicos de la formación Río Pedregoso y nuevas edades.

3. Permeabilidad y Porosidad Formación Río Pedregoso.

De acuerdo a las interpretaciones estratigráficas y datos de permeabilidad, los Miembros Quilmahue y Bío-Bío contienen principalmente una gran proporción de lutitas y fangolitas impermeables, mientras que el Miembro Rucañanco, contiene gruesas capas de areniscas y conglomerados, las cuales representan la mejor unidad con potencial para albergar reservorios geotérmicos debido a su favorable posición estratigráfica y a sus características permeables. En la Tabla 3, se muestra un resumen de los valores de permeabilidad obtenidos en muestras del Miembro Río Pedregoso, en color verde se resaltan las muestras pertenecientes al Miembro Rucañanco.

Muestras		Permeabilidad					Porosidad
		Ensayo de Carga Constante		Permeámetro TinyPerm			
		K cm/seg	K m/s	k mD	D	m^2	%
188	Arenisca gruesa	6,5938E-08	6,5938E-10	9,726200254	0,0097262	9,5998E-15	35,8
253	Caliza oolítica	3,2899E-07	3,2899E-09	1,395868838	0,001395869	1,3777E-15	17,7
257	Caliza oolítica	1,6225E-07	1,6225E-09	1,764456755	0,001764457	1,7415E-15	0,8
260	Arenisca Fina	6,9878E-05	6,9878E-07	36,89290155	0,036892902	3,6413E-14	37,5
269	Caliza	6,8139E-09	6,8139E-11	0,890266577	0,000890267	8,7869E-16	15,2
270	Arenisca gruesa	1,4462E-07	1,4462E-09	1,163992965	0,001163993	1,1489E-15	28,8
277	Arenisca gruesa	3,4175E-08	3,4175E-10	2,62495908	0,002624959	2,5908E-15	32,5
279	Arenisca fina	6,3654E-08	6,3654E-10	3,041466654	0,003041467	3,0019E-15	31,3
280	Ceniza	5,8347E-08	5,8347E-10	0,916288208	0,000916288	9,0438E-16	22,9
284	ceniza	9,1585E-06	9,1585E-08	69,45147171	0,069451472	6,8549E-14	40,8
285	Arenisca media	2,3063E-06	2,3063E-08	94,02213178	0,094022132	9,28E-14	34,3

Tabla 3. Permeabilidad y porosidad en muestras de la Formación Río Pedregoso

4. Descripciones petrográficas del Miembro Rucañanco

- **Muestra 188 Localidad El Cajón**

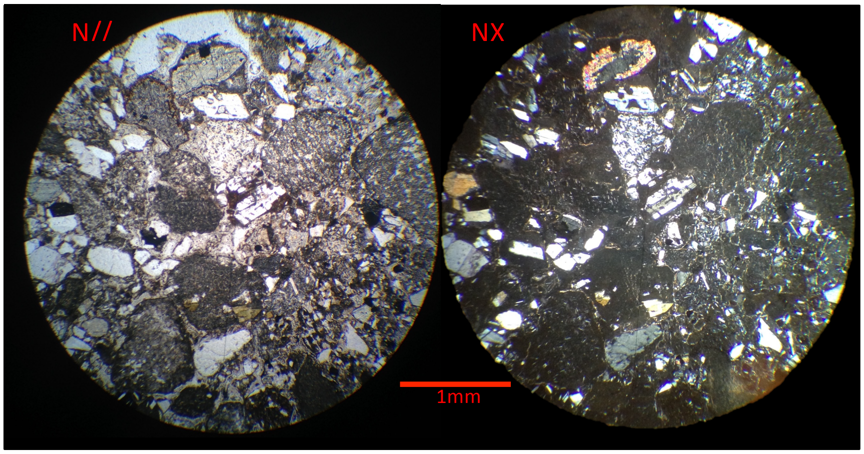


Figura 2. Imagen de corte transparente de la muestra 188 en nicoles cruzados y Paralelos

Tamaño de granos: De un total de 300 puntos medidos en el corte transparente un 22.67% de puntos corresponden a partículas de tamaño muy grueso (≥1mm -<2mm), 34.33% a areniscas de grano grueso (≥0.5mm - <1mm), 13.33% a areniscas de grano medio (≥0.25mm - <0.5mm), 7% a areniscas de grano fino (≥0.125mm - <0.25mm), 2.33% a areniscas de grano muy fino (≥0.0625mm - <0.125mm) y 20.33% corresponde a partículas finas (<0.0625mm, limos y arcillas)..

Componentes principales: La muestra está constituida por 75% fragmentos líticos de composición volcánica, piroclástica, y sedimentaria, menos de 25% corresponde a cristales de plagioclasa y menos de 5% a cristales de cuarzo.

Forma de los granos: La forma de los fragmentos líticos es redondeada a subredondeada, los cristales presentan formas angulosas a subredondeadas y selección moderada.

Clasificación: Wacka lítica.

- **<u>Muestra 277 Localidad El Cajón</u>**

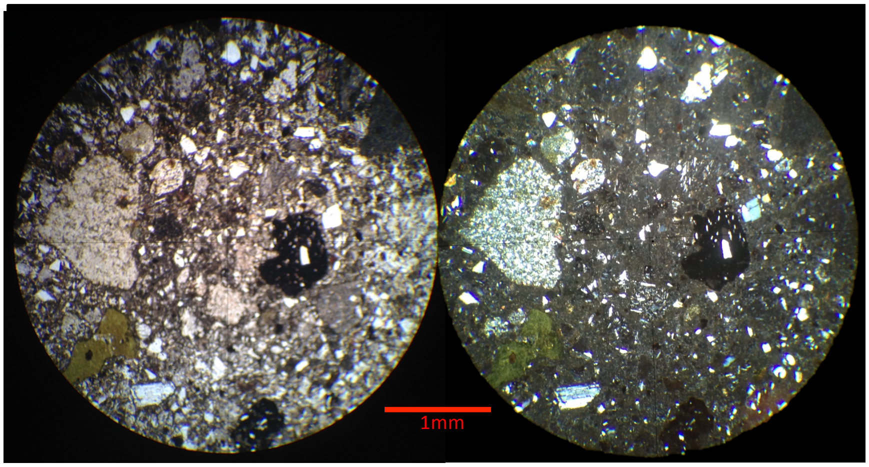


Figura 3. Imagen de corte transparente muestra 277 en nicoles cruzados y paralelos

Tamaño de granos: De un total de 300 puntos medidos en el corte transparente un 25% de puntos corresponden a partículas de tamaño muy grueso (≥1mm -<2mm), 27.33% a areniscas de grano grueso (≥0.5mm - <1mm), 9.67% a areniscas de grano medio (≥0.25mm - <0.5mm), 7.33% a areniscas de grano fino (≥0.125mm - <0.25mm), 4.67% a areniscas de grano muy fino (≥0.0625mm - <0.125mm) y 26% corresponde a partículas finas (<0.0625mm, limos y arcillas).

Componentes principales: la muestra está constituida por 65% fragmentos líticos de composición volcánica y sedimentaria, el 30% corresponde a cristales de plagioclasa y 5% de cristales de cuarzo.

Forma de los granos: La forma de los fragmentos líticos es redondeada a subredondeada, los cristales presentan formas angulosas a subredondeadas, la muestra es moderadamente seleccionada.

Clasificación: Wacka lítica.

- **<u>Muestra 285 Localidad Tucapel</u>**

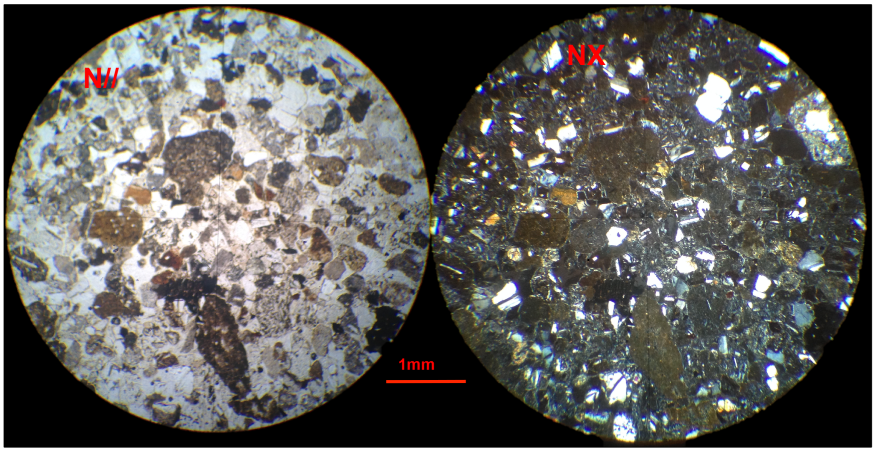


Figura 4. Imagen de corte transparente muestra 285 en nicoles cruzados y paralelos.

Tamaño de granos: De un total de 300 puntos medidos en el corte transparente el 0.35% de puntos corresponden a partículas de tamaño grueso (≥0.5mm - <1mm), 24.21% a areniscas de grano medio (≥0.25mm - <0.5mm), 22.81% a areniscas de grano fino (≥0.125mm - <0.25mm), 8,07% a areniscas de grano muy fino (≥0.0625mm - <0.125mm) y 44,56% corresponde a partículas finas (<0.0625mm, limos y arcillas).

Componentes principales: La muestra está constituida por 65% fragmentos líticos de origen volcánico, 5% de fragmentos líticos de origen sedimentario y 30% de cristales de plagioclasa, olivino y piroxeno.

Forma de los granos: La forma de los fragmentos líticos es subredondeada a angulosa, los cristales presentan formas angulosas, presenta selección moderada.

Clasificación: Wacka lítica.