UNIVERSIDAD DE CHILE
FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS
DEPARTAMENTO DE GEOLOGÍA

EVIDENCIAS SEDIMENTOLÓGICAS, PALEOCLIMÁTICAS Y PALEOECOLÓGICAS DEL LEVANTAMIENTO DE LA CORDILLERA DE LOS ANDES PATAGÓNICOS DURANTE EL CENOZOICO EN SIERRA BAGUALES, PROVINCIA DE ÚLTIMA ESPERANZA, MAGALLANES, CHILE.

TESIS PARA OPTAR AL GRADO DE DOCTOR EN
CIENCIAS MENCIÓN GEOLOGÍA

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SANTIAGO DE CHILE
2017

RESUMEN DE LA TESIS
PARA OPTAR AL GRADO DE
DOCTOR EN CIENCIAS MENCION GEOLOGIA
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FECHA: 28/03/2017
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EVIDENCIAS SEDIMENTOLÓGICAS, PALEOCLIMÁTICAS Y PALEOECOLÓGICAS DEL LEVANTAMIENTO DE LA CORDILLERA DE LOS ANDES PATAGÓNICOS DURANTE EL CENOZOICO EN SIERRA BAGUALES, PROVINCIA DE ÚLTIMA ESPERANZA, MAGALLANES, CHILE.

Modificaciones del relieve provocados por procesos geológicos de gran escala como el alzamiento de cordilleras tiene importantes efectos en las condiciones climáticas y generan cambios significativos del paisaje. De esta forma, variaciones en las condiciones de temperatura y precipitación de una región afectan directamente la distribución, diversidad y composición de la vegetación.

En la actualidad la dirección de flujo de los ríos en el sur de Sudamérica es principalmente hacia el oriente, sin embargo, aún no es claro cuál fue la dirección de las corrientes y las zonas de proveniencia en el pasado. Cambios en las direcciones de paleocorrientes ocurridos durante el Cenozoico en la Cuenca de Magallanes, junto con cambios de ambientes, pasando de marinos a transicionales y finalmente a ambientes continentales, procesos que fueron identificados en el sector de Sierra Baguales, al norte del Parque Nacional Torres del Paine, podrían vincularse con el levantamiento de los Andes Patagónicos, proceso que a su vez podría asociarse a cambios paleoclimáticos y paleoecológicos que habrían sido provocados por el efecto de sombra de lluvia y apertura del paso Drake durante el Oligoceno, cambios paleogeográficos que a su vez coinciden con modificaciones de las zonas de aporte de sedimentos a la Cuenca de Magallanes y la posición relativa de Península Antártica.

El presente estudio evalúa cual fue el efecto de los procesos tectónicos como el levantamiento de los Andes Patagónicos, apertura del Paso Drake y cambios en las zonas de proveniencia. Se discute el vínculo entre la evolución de la Cuenca de Magallanes y la posición de la Península Antártica. Estos procesos fueron evaluados a partir de la evolución espacio-temporal de las paleocorrientes y el establecimiento de las zonas que aportaron detritos a la Cuenca durante el Cenozoico en Sierra Baguales, adicionalmente, junto con la evolución tectónica y sedimentológica del sector, se analiza la respuesta de la vegetación en términos de diversidad y composición, comportamientos analizados bajo un contexto de cambio climático global durante el Cenozoico donde especialmente se discute la respuesta de la vegetación frente a procesos de enfriamiento como el ocurrido durante el Oligoceno.

DEDICATORIA

A mi esposa Viviana Pedroza Rodríguez

AGRADECIMIENTOS

Agradezco a CONICYT por el financiamiento para el desarrollo de esta investigación mediante la Beca para Estudios de Doctorado en Chile - Dirigida a extranjeros sin permanencia definitiva en Chile.

Agradezco al proyecto ANILLOS ATC-105 por el financiamiento en los terrenos del año 2011, 2012 y 2013.

Agradezco al proyecto FONDECYT 1130006 “**Tertiary successions in Chile**” por el financiamiento de las dataciones y el terreno del año 2014.

Agradezco al proyecto FONDECYT 1150690 “**Leaf traits from Cenozoic to present climate; are there common relationships**“ por el apoyo en el terreno y colecta de fósiles del año 2014.

A mi profesor guía Jacobus Le Roux, por su orientación, conocimientos valiosos aportados para realizar mi trabajo de tesis, adicionalmente, agradezco su buena disposición, tiempo dedicado para el desarrollo de este proyecto y por su amistad, de igual forma agradezco a su esposa, la señora Petrysia Le Roux por su amistad.

A mi profesor co-guía Luis Felipe Hinojosa por sus comentarios apoyo en terreno y recomendaciones, los cuales aportaron nuevos puntos de vista y proporcionaron información que me permitió mejorar y concluir la tesis.

A los profesores miembros de la comisión, Luisa Pinto, Marcelo Farías y Rodrigo Villa por sus recomendaciones y consejos, los cuales fueron fundamentales en esta investigación.

A los profesores del Departamento de Geología: Cesar Arriagada, Reynaldo Charrier, Francisco Hervé, Alfonso Rubilar, Diego Morata, Miguel Ángel Parada y Gabriel Vargas, por sus recomendaciones y consejos aportados durante mi estadía en el programa de Doctorado.

A la Señora Maritza Acuña por su apoyo en los diferentes trámites del Doctorado y también por su valiosa amistad.

A los co-autores del primer y segundo capítulo, por el apoyo en la finalización de los manuscritos.

A los dueños de las estancias Las Cumbres, 3R, Cerro Guido, a José Luis Oyarzun por su apoyo y por facilitarnos el acceso a las estancias y por toda la ayuda prestada en terreno, a Camilo Diaz y Francisco Salinas por su apoyo en la colecta de fósiles.

A mis amigos, Elkin Hernández, José Araos, Emily Soto, Juan Pablo Pino, Ana Vásquez, por su amistad y apoyo.

A mis compañeros del IDIEM, Juan Pablo Vasquez, Carolina Smith, Scarlet Frez, Hector Fuentes,

A mi familia, mi Papá Miguel Gutierrez; Mamá Teresa Duarte; Hermanos Alonso, German, Laura; a la Prima Rosalba Carrero.

Quiero agradecer especialmente a mi esposa Viviana Pedroza por estar siempre a mi lado, acompañándome y disfrutando en las buenas y por su energía, perseverancia y fuerza en las no tan buenas.

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1. INTRODUCCIÓN

Los Andes Patagónicos son producto de colisiones de la Placa de Nazca con el sur de Sudamérica, el cual se manifestó con varios pulsos de levantamiento generados durante el Cretáceo Tardío, Eoceno y Mioceno Tardío (Ramos & Kay, 1992; Ramos, 2005). Cambios del relieve pueden tener importantes efectos en las condiciones hidrodinámicas y en el tipo de sedimentación de una cuenca (Ruddiman et al., 1997; Bossi et al., 2000), el cual en este caso está representado por la Cuenca de Magallanes (Fig. 1. Capítulo I y II). El vínculo directo entre el levantamiento de los Andes Patagónicos y la sedimentología de las formaciones de edad Cenozoico en la Cuenca de Magallanes no ha sido claro. Estimaciones de paleocorrientes en la Provincia de Ultima Esperanza en Patagonia se han restringido al Cretácico Superior en la Formación Cerro Toro y la Formación Dorotea (Scott, 1966; Fildani and Graham, 2015), al Eoceno medio-superior en la Formación Man Aike (Le Roux et al., 2010), y al Mioceno inferior en la Formación Santa Cruz (Bostelmann et al., 2013). De igual forma, son pocas las edades de circón que se han publicado (Bernhardt, 2011; Fosdick et al., 2011, 2015a, 2015b; Bostelmann et al., 2013; Schwartz et al., 2016) y solo un análisis de proveniencia basado en poblaciones de circón detrítico fue llevado a cabo en formaciones de edad post-Cretácico en el sector mas austral de la cuenca (Barbaeau et al 2009), por lo tanto, es necesario realizar estudios de análisis de proveniencia a partir de poblaciones de circón detrítico en las formaciones del Cenozoico. Como resultado, actualmente se considera que las áreas de proveniencia de la Cuenca de Magallanes están localizadas al norte, oeste y suroeste (Bernhardt et al.,2008; Bardeau et al., 2009; Hubbard et al., 2010; Zahid and Barbeau, 2010; Cuitiño, 2011; Schwartz and Graham, 2015;) ignorando así la existencia de posibles fuentes al este.

Simultáneamente con los cambios tectónicos, también se generaron cambios en las condiciones climáticas y ecológicas a escala local y regional (e.g., Zachos et al ., 2001; Le Roux, 2012; Ruddiman et al. 1997; en Blisniuk et al. 2011). Los Andes Patagónicos ejercen un efecto orográfico de bloqueo de los vientos húmedos del oeste, generando un efecto de sombra de lluvia en su vertiente oriental (Blisniuk et al., 2005).

La distribución y composición florística de los bosques del sur de Sudamérica representaría un legado histórico de la interacción entre la biota y procesos geológicos y climáticos ocurridos durante el Cenozoico (Arroyo et al., 1996; Hinojosa, 2003; Hinojosa, 2005; Hinojosa & Villagrán, 1997; Quattrocchio et al., 2013; Romero, 1978; Romero, 1986a; Troncoso & Romero, 1998; Villagrán & Hinojosa, 1997; Wilf et al., 2005a). Durante el Cenozoico se han registrado cuatro momentos de máximas temperaturas superficiales marinas, el Máximo Termal del Paleoceno-Eoceno (59-52 Ma) "MTPE", el Óptimo Climático del Eoceno (52-50 Ma) "OCE", el Calentamiento del Oligoceno tardío "COT" (26-27 Ma) y el Óptimo climático del Mioceno Medio (17-15 Ma) "OCMM", evento último que coincide con la disminución del espesor de la capa de hielo Antártico. Desde el Cretácico Tardío en Sudamérica también se reconocen cinco periodos de enfriamiento (Le Roux, 2012), identificados como el SDC (Santoniano-Daniano: 86-60 Ma), YC (Ypresiano: 55-49 Ma), BRC (Bartoniano-Rupeliano: 41-28 Ma), AC (Aquitaniano: 24-21 Ma), y STC (Serravaliano-Tortoniano: 15-6 Ma). A mediados del BRC fue marcado por una declinación muy abrupta de la temperatura, ampliamente conocida como La Glaciación Oi-1 (Zachos et al., 2001) que coincidió con la apertura del Paso Drake, la creación de la Corriente Circumpolar Antártica, y la iniciación de la Capa de Hielo Antártico alrededor de los 35 Ma (Berker, 2001; Zachos et al., 2001; Liu et al., 2009).

Durante el Optimo Climático del Eoceno, la TMA alcanzó una diferencia de 9-12ºC respecto a la actual TMA, pero desde entonces declinó considerablemente hasta el Oligoceno, alcanzando valores mínimos que solo fueron 0.6-1ºC mas calientes que la actual TMA (Hinojosa et al., 2011; Peppe et al., 2011; Quattrocchio et al., 2013). Esta disminución de la temperatura coincide aproximadamente con el BRC (41-28 Ma) de Le Roux (2012)

Recientes análisis palinológicos en zonas tropicales muestran que cambios de diversidad y composición durante el Cenozoico podrían ser sensibles a variaciones de temperatura a nivel global (Jaramillo et al., 2006). El efecto de cambios climáticos rápidos, como el evento de calentamiento del límite Paleoceno-Eoceno MTPTE, habría generado un incremento de diversidad en la vegetación a partir de palinomorfos. La flora fósil muestra a la vez variaciones en composición, donde las familias Proteaceae, Araceae, Podocarpaceae, y Ctenolophonaceae fueron más abundantes durante el Paleoceno. Las familias Ulmaceae, Rhizophoraceae, Moraceae, Poaceae y Bombacaeae no presentaron cambios de abundancia durante la transición Paleoceno/Eoceno; y las familias Arecaeae, Polypodiaceae, Annonaceae, Onagraceae, Fabaceae, y Convolvulaceae fueron las más abundantes durante el Eoceno (Jaramillo et al., 2010a). El vínculo entre el calentamiento global del límite Paleoceno/Eoceno y la significativa diversificación in situ de palinofloras en el norte de Sudamérica sugiere que los incrementos en la diversidad ocurridos durante el Eoceno, podrían estar mediados por cambios climáticos, caracterizados por altos montos de precipitación y temperaturas elevadas (Rull, 1999; Jaramillo, 2002; Jaramillo, 2006). Simultáneamente durante el Paleoceno y Eoceno medio (65,5-40,4 Ma) la paleoflora del sur de Sudamérica registró un cambio en su composición florística, pasando de una Paleoflora Gondwánica Tropical a una Paleoflora Gondwánica Subtropical (Hinojosa, 2005). Las floras fósiles de Laguna del Hunco y Río Pichileufú (Patagonia Argentina, ~42º-45ºS) durante el Eoceno (52 Ma) muestran altos índices de diversidad (Iglesias et al., 2007; Wilf et al., 2005) en lo que podría constituir evidencia del efecto de cambio climático enunciado por Rull y Jaramillo. Desde finales del Eoceno (35,9 Ma) esta Paleoflora Gondwánica Subtropical primero es reemplazada por una Paleoflora Mixta y luego en Chile central, por una Paleoflora Subtropical Neógena entre 23 y 14 Ma. Dentro de esta última se destaca la dominancia de elementos fitogeográficos termófilos tales como Neotropical, Pantropical, y Australasiático en conjunto con elementos endémicos (Hinojosa et al., 2006; Hinojosa & Villagrán, 1997; Hinojosa & Villagrán, 2005b; Quattrocchio et al., 2013).

El alzamiento andino en la zona de Magallanes habría producido cambios en la composición y diversidad de unidades de bosque, pasando de una Paleoflora Mixta a una Paleo-fitogeoprovincia Transicional durante el Mioceno medio al Mioceno tardío (Barreda & Palazzesi, 2007; Barreda et al., 2010; Hinojosa et al., 2006; Hinojosa & Villagrán, 1997; Hinojosa & Villagrán, 2005b; Quattrocchio et al., 2013; Wilf et al., 2005).

Considerando la relación que existe entre el aumento en la diversidad de plantas con los incrementos en temperatura y precipitación (Jaramillo & Cadena Rueda, 2006) es posible predecir que se puede encontrar altos niveles de diversidad en la vegetación durante intervalos de calentamiento, parecidos al ocurrido durante el Eoceno 50-53 Ma, el cual alcanzó 12°C de diferencia en las temperaturas marinas profundas. Sin embargo en el sur de Sudamérica, son pocos los estudios que muestran el comportamiento en términos de diversidad y cambios en la composición en la vegetación durante intervalos de enfriamiento global como el ocurrido durante el Oligoceno, donde se registró la disminución de temperatura más drástica después del Calentamiento ocurrido durante el Eoceno.

¿Cuál es el vínculo entre los procesos tectónicos y la evolución de la Cuenca de Magallanes en términos sedimentológicos, paleoclimáticos, paleoambientales y paleogeográficos durante el Cenozoico en Sierra Baguales bajo un escenario de cambio climático global?

Afloramientos de origen sedimentario de edad cenozoica regionalmente continuos en el sur de Sudamérica son escasos; sin embargo, Sierra Baguales es la única región de la Cuenca de Magallanes, donde aflora una de las más completas e ininterrumpida secuencia sedimentarias de edad Mesozoica-Cenozoica. El espesor aproximado de la sucesión es 1300 m e incluye las formaciones Tres Pasos y Dorotea ambas de edad cretácica tardía, también afloran formaciones cenozoicas, como la Formación Man Aike (Eoceno Medio-Superior), la Formación Río Leona (Oligoceno-Mioceno Inferior), la Formación Estancia 25 de Mayo (Mioceno Inferior), y la Formación Santa Cruz (Mioceno Inferior–Mioceno Medio). A pesar de estudios previos (Piatnitzky, 1938; Feruglio, 1938; Cecioni, 1957; Hoffstetter et al., 1957; Furque, 1973; Malumián, 1990; Marenssi et al., 2000, 2002, 2005; Le Roux et al., 2010; Malumián & Náñez, 2011; Cuitiño et al., 2012; Le Roux, 2012; Bostelmann et al., 2013), en esta área no se ha llegado a un consenso sobre la distribución geográfica ni las relaciones de contacto de las diferentes unidades estratigráficas propuestas para la zona. En Sierra Baguales, el mapa más detallado de la región se encuentra en una escala de 1:100.000 y muestra nomenclaturas estratigráficas obsoletas como La Formación Río Bandurrias, Formación Río Baguales y La Formación Las Flores (Muñoz, 1981; Le Roux et al., 2010).

El presente estudio evalúa cuál fue el efecto de los procesos tectónicos como el levantamiento de los Andes Patagónicos, apertura del Paso Drake y cambios en las zonas de proveniencia. Se discute el vínculo entre la evolución de la Cuenca de Magallanes y la posición de la Península Antártica. Estos procesos fueron evaluados a partir de la evolución espacio-temporal de las paleocorrientes y el establecimiento de las zonas que aportaron detritos a la Cuenca durante el Cenozoico en Sierra Baguales, adicionalmente, junto con la evolución tectónica y sedimentológica del sector, se analiza la respuesta de la vegetación en términos de diversidad y composición, comportamientos analizados bajo un contexto de cambio climático global durante el Cenozoico donde especialmente se discute la respuesta de la vegetación frente a procesos de enfriamiento como el ocurrido durante el Oligoceno.

1.1 Hipótesis.

1.- Dados los cambios tectónicos (i.e levantamiento andino, apertura del Paso Drake) ocurridos durante el Cenozoico, en Sierra Baguales se espera que las fuentes de aporte de la Cuenca de Magallanes estén localizadas al norte y occidente; que la edad de las poblaciones de circones detríticos identificados en las unidades cenozoicas sean similares con las edades de los plutones datados en los Andes Patagónicos.

2.- Dado el levantamiento de la Cordillera de los Andes Patagónicos y el bloqueo de los westerlies, y el correspondiente efecto de sombra de lluvia a los vientos del oeste, se espera en la flora fósil de Sierra Baguales una disminución en términos de diversidad de morfoespecies junto con una disminución del área foliar de las floras fósiles en concordancia con el descenso de las precipitaciones.

3.- Dado el proceso de enfriamiento global ocurrido desde el Optimo Climático del Eoceno, se espera en la flora de Sierra Baguales encontrar una mayor proporción de hojas de dicotiledóneas con borde dentado en comparación al Eoceno.

1.2 Objetivo general

Determinar el vínculo entre los procesos tectónicos en la evolución de la Cuenca de Magallanes en términos sedimentológicos, paleoclimáticos, paleoambientales y paleogeográficos durante el Cenozoico en Sierra Baguales bajo un escenario de cambio climático global.

Objetivos específicos

1.-Determinar la geología, estratigrafía, tipo de ambientes y direcciones de paleocorrientes de las Formaciones Dorotea, Man Aike, Río Leona, Estancia 25 de Mayo, Santa Cruz; y relacionar la evolución espacio temporal de estas formaciones con el levantamiento de los Andes Patagónicos en la zona de Sierra Baguales durante el Cenozoico.

2.- Determinar la diversidad y composición de hojas fósiles del Oligoceno-Mioceno de la Formación Río Leona.

3.- Determinar la fisionomía foliar de las hojas fósiles de la Formación Rio Leona. A partir de la fisionoía foliar presente en la Formación Rio Leona se estimará el paleoclima en término de temperatura y precipitaciones utilizando métodos uni y multivariados.

2. METODOLOGÍA

Geología de Sierra Baguales. Los procedimientos desarrollados y análisis geológicos, estructurales se detallan en el Capítulo I. Sin embargo, se realizó un mapeo a escala 1:10.000 y describieron las características geológicas, estructurales de Sierra Baguales para reconstruir la cartografía geológica a partir de datos en terreno de las Formaciones Dorotea, Man Aike, Río Leona, Estancia 25 de Mayo y Santa Cruz.

La geología de Sierra Baguales fue cartografiada, descrita, clasificada e interpretada utilizando fotografías aéreas, imágenes satelitales Landsat TM y ETM Plus, además de modelos de elevación digital ASTER Global Digital Elevation Model. Los rasgos mapeados fueron validados en terreno y posteriormente fueron cartografiados en un mapa geológico a escala 1:10.000.

Estratigrafía, sedimentología y edades de las formaciones cenozoicas en Sierra Baguales. Los procedimientos desarrollados y análisis estratigráficos, sedimentológicos, edades y análisis de proveniencia se detallan en el Capítulo I. La selección de los lugares donde se levantaron las cinco secciones estratigráficas se estableció según el análisis de fotointerpretación donde se identificaron afloramientos continuos y accesibles. La descripción de las sucesiones estratigráficas en terreno se llevó a cabo siguiendo procedimientos estratigráficos estándar.

Se midieron un total de 195 paleocorrientes en areniscas con estructuras como artesas, costillas y surcos.

Se realizaron cinco dataciones $^{238}U/^{206}Pb$ en circón detrítico de muestras colectadas en las unidades cenozoicas de Sierra Baguales.

Estudio Paleobotánico. La metodología desarrollada en la colecta, curado y análisis de los fósiles de hojas de la Formación Río Leona se detallan en el Capítulo II.

En la Formación Río Leona se identificaron cinco localidades con fósiles de hojas, sin embargo, solo en dos localidades el grado de preservación de los fósiles permitió realizar la colecta, descripción y posterior análisis de la morfología foliar. En la

Formación Río en Sierra Baguales, fueron muestreadas, curadas y analizadas 3746 fósiles de hojas.

Morfología foliar-clima

Se correlacionó la fisonomía de las hojas con el clima. Específicamente se aplicó las metodologías que vinculan la forma y tamaño de las hojas con la temperatura y precipitación (Burnham et al., 2001; Gregory-Wodzicki, 2000; Herman, 1996;1997; Hinojosa, 2005; Hinojosa et al., 2011; Jacobs,1999; 2002, Kowalski, 2002; Peppe et al., 2011; Wilf, 1997; Wing, 1998; 2000, Wolfe, 1979;1995). Se utilizó la relación que existe entre el porcentaje de hojas con borde entero (pE) y la temperatura media anual (MAT) (Bailey, 1916, 1917). La ecuación utilizada fue: MAT = 26.03pE + 1.31 (Hinojosa et al., 2011). Adicionalmente se aplicó la relación entre el área foliar promedio y la precipitación media anual (MAP), dada por la ecuación: Ln (MAP) = 1,63 + 0,49*MLaA.

Cálculos de diversidad. Los análisis estadísticos realizados sobre los morfotipos de hojas fósiles colectados en las localidades de Barranca de las Hojas y Alto Río Bandurrias fueron: Cálculo de la estimación no paramétrica CHAO 1 (Chao. A, 1984) para establecer la riqueza esperada de morfoespecies de hojas fósiles de la Formación Río Leona. Riqueza de especies (Whittaker, 1972) y análisis de rarefacción para las dos floras fósiles colectadas. Análisis de correspondencia canónica (CCA) se usará para evaluar la relación entre las variables climáticas actuales y las características morfológicas del ensamble fósil.

3. RESULTADOS

Esta tesis es una compilación de dos manuscritos (capítulos I y II) que corresponden a los siguientes estudios:

Capítulo I: “Tectonic events in southern Patagonia as reflected by paleocurrent directions, detrital zircon ages, and palaeobotanical evidence in the Baguales Mountain Range, Chile”. Este articulo muestra la evolución de los estilos sedimentológicos y tendencias, cambios paleoclimáticos y eventos tectónicos durante el Cenozoico en la Cordillera Baguales, situado al norte del Parque Nacional Torres del Paine, en la región de Magallanes en el sur de Chile. Mediciones de paleocorrientes en esta sucesión Mesozoico-Cenozoico indican cambios en las zonas de origen de los sedimentos, pasando de fuentes de aporte situadas al noreste y el sureste durante el Cretácico superior y Eoceno medio, a proveniencias del suroeste durante el Oligoceno temprano a principios del Mioceno. Esto es confirmado por poblaciones de edades de circón detrítico en las diferentes unidades, que pueden estar vinculados a las probables fuentes con edades similares en esta área. La procedencia del sudeste se identifica aquí como la Península Antártica, mientras que las fuentes del suroeste y oeste posteriores fueron exhumados durante la elevación gradual de los Andes Patagónicos del Sur. Este proceso coincidió con el cambio de condiciones marinas a condiciones continentales en la Cuenca de Magallanes, así como una disminución de la temperatura media anual y precipitación indica por las hojas fósiles en la Formación Río Leona. El efecto de sombra de lluvia hacia el oriente de los Andes habría iniciado a desarrollarse en Sierra Baguales durante el Oligoceno temprano (~ 34 Ma), mucho antes que la "Fase Quechua" (19 - 18 Ma).

Capítulo II: “Evidence for Microthermal forest dominated by Nothofagus in Patagonia: Palaeotemperature, palaeoprecipitation and palaeodiversity during the Oligocene as reflected by plant macrofossils in the Sierra Baguales, Chile”. Este articulo muestra el análisis de más de 3.700 hojas fósiles de la Formación Oligoceno Río Leona en la Cordillera Baguales de la Patagonia chilena donde la asociación está dominada por la familia Nothofagaceae, que constituye el 65% del total. La Paleoflora de la Formación Río Leona indica una disminución de diversidad y riqueza de morfoespecies acompañada a su vez por un recambio de morfoespecies. También se identifica una marcada disminución de la diversidad en comparación con morfoespecies de dicotiledóneas en la Patagonia durante el Cenozoico. La morfología foliar indica condiciones climáticas frías y de menor humedad comparada con otras floras del Cenozoico, con una temperatura anual promedio de 9.18 ° C, una alta estacionalidad de la temperatura y la precipitación, y una precipitación anual promedio de 120 cm. Condiciones microclimáticas bajo las cuáles *Nothofagus* se adaptó y se convirtió en un elemento dominante en el sureste de la Patagonia durante el Rupeliano. Las estimaciones plaoclimáticas a partir de hojas fósiles coinciden con un marcado período de enfriamiento global relacionado con el inicio de la glaciación de la Antártida. Sin embargo, la disminución de las precipitaciones a partir de los 34 Ma se atribuye al efecto de sombra de lluvia provocado por el levantamiento de los Andes Patagónicos del Sur.

Finalmente en ambos capítulos se analiza estable el vínculo entre los procesos tectónicos y su efecto en la evolución de la Cuenca de Magallanes en términos sedimentológicos, paleoclimáticos, paleoambientales y paleogeográficos durante el Cenozoico en Sierra Baguales bajo un escenario de cambio climático global.

3.1 Capítulo I:

Tectonic events reflected by palaeocurrents, zircon geochronology, and palaeobotany in the Sierra Baguales of Chilean Patagonia.

Artículo publicado en la revista Tectonophysics

Tectonophysics 695 (2017) 76–99

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Tectonic events reflected by palaeocurrents, zircon geochronology, and palaeobotany in the Sierra Baguales of Chilean Patagonia

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ARTICLE INFO

Article history:
Received 23 August 2016
Received in revised form 6 December 2016
Accepted 9 December 2016
Available online 13 December 2016

Keywords:
Andean tectonics
Patagonian Transgression
Zircon provenance
Gondwana reconstruction
Antarctic Peninsula

ABSTRACT

The Sierra Baguales, situated north of the Torres Del Paine National Park in the Magallanes region of southern Chile, shows a well-exposed stratigraphic sequence ranging from the Late Cretaceous to late Pliocene, which presents a unique opportunity to study the evolution of sedimentological styles and trends, palaeoclimate changes, and tectonic events during this period. The depositional environment changed from a continental slope and shelf during the Cenomanian-Campanian (Tres Pasos Formation) to deltaic between the Campanian-Maastrichtian (Dorotea Formation) and estuarine in the Lutetian-Bartonian (Man Aike Formation). During the Rupelian, a continental environment with meandering rivers and overbank marshes was established (Río Leona Formation). This area was flooded in the early Burdigalian (Estancia 25 de Mayo Formation) during the Patagonian Transgression, but emerged again during the late Burdigalian (Santa Cruz Formation). Measured palaeocurrent directions in this Mesozoic-Cenozoic succession indicate source areas situated between the northeast and east-southeast during the Late Cretaceous, east-southeast during the middle Eocene, and southwest during the early Oligocene to early Miocene. This is confirmed by detrital zircon age populations in the different units, which can be linked to probable sources of similar ages in these areas. The east-southeastern provenance is here identified as the Antarctic Peninsula or its northeastern extension, which is postulated to have been attached to Fuegian Patagonia during the Eocene. The southwestern and western sources were exhumed during gradual uplift of the Southern Patagonian Andes, coinciding with a change from marine to continental conditions in the Magallanes-Austral Basin, as well as a decrease in mean annual temperature and precipitation indicated by fossil leaves in the Río Leona Formation. The rain shadow to the east of the Andes thus started to develop here during the late Eocene-early Oligocene (~34 Ma), long before the "Quechua Phase" of Andean tectonics (19–18 Ma) that is generally invoked for its evolution at lower latitudes.

1. Introduction

The Southern Patagonian Andes resulted from collision of the Nazca Plate with southernmost South America, which was manifested in various pulses of uplift during the Late Cretaceous, Eocene and late Miocene (Ramos and Kay, 1992; Ramos, 2005). Such changes in the source topography can have important effects on hydrodynamic conditions and sedimentation styles within the adjoining depocenters (Ruddiman et al., 1997; Bossi et al., 2000), which in this case are represented by the Magallanes-Austral Basin (Fig. 1A).

The link between Andean tectonics and the sedimentology of Cenozoic successions in the Magallanes-Austral Basin has only been partially investigated to date. Palaeocurrent measurements in the Última Esperanza Province of Patagonia have been restricted mostly to the Upper Cretaceous Cerro Toro and Dorotea Formations (Scott, 1966; Fildani and Hessler, 2005; Crane and Lowe, 2008; Romans et al., 2010; Schwartz and Graham, 2015), the middle – upper Eocene Man Aike Formation (Le Roux et al., 2010), and the lower Miocene Santa Cruz Formation (Bostelmann et al., 2013). Similarly, relatively few zircon ages have been published (Bernhardt, 2011; Fosdick et al., 2011, 2015a, 2015b;

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http://dx.doi.org/10.1016/j.tecto.2016.12.014
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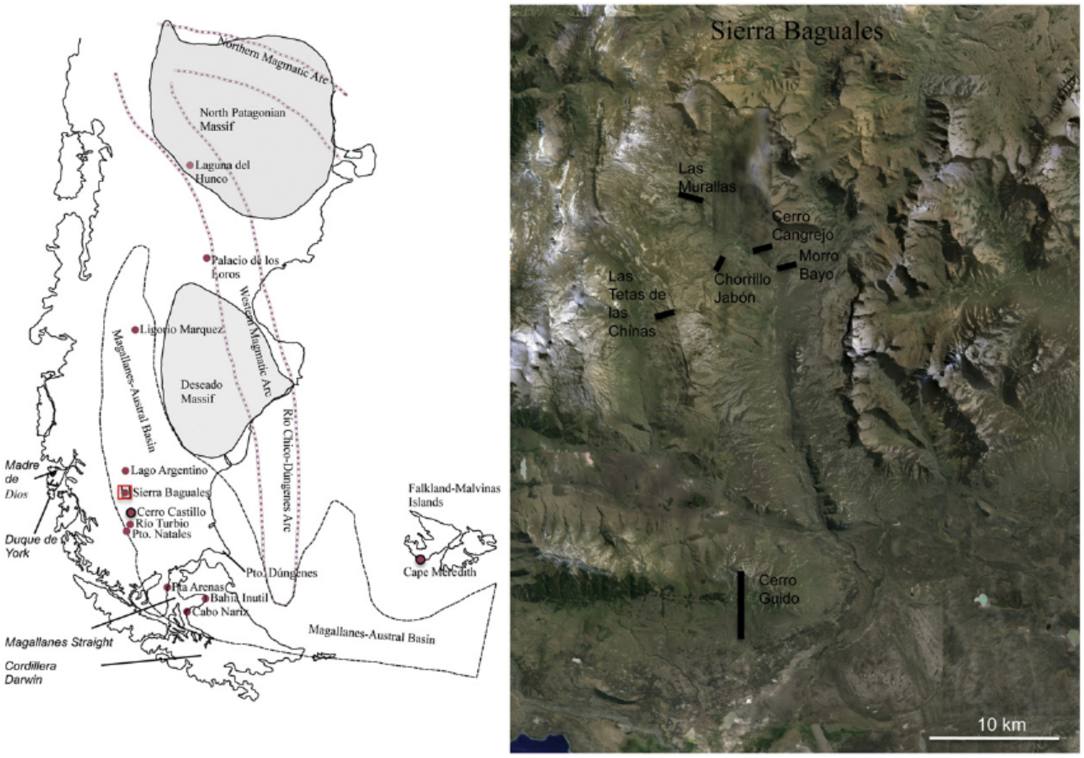

Fig. 1. Locality map of South America and the Sierra Baguales showing tectonic elements and Tertiary fossil leaf localities.

Bostelmann et al., 2013; Schwartz et al., 2016, and references therein), and only one provenance study based on zircon populations was carried out for the post-Cretaceous formations in the southernmost part of the basin (Barbeau et al., 2009). A comprehensive provenance study based on zircon populations has therefore been lacking for the post-Cretaceous formations. As a result, most previous authors (e.g., Bernhardt et al., 2008; Hubbard et al., 2010; Cuitiño, 2011; Schwartz and Graham, 2015) considered the provenance areas of the Magallanes-Austral Basin to have been located to the north, west, and southwest (Barbeau et al., 2009; Zahid and Barbeau, 2010) thus ignoring the existence of possible sources to the east.

In the Sierra Baguales, located about 100 km north of Puerto Natales (Fig. 1A), the stratigraphic succession includes all the formations mentioned above as well as the Rupelian Estancia 25 de Mayo Formation, but with the exception of the Cerro Toro Formation. In spite of previous studies in this and surrounding areas (Feruglio, 1938; Piatnitzky, 1938; Cecioni, 1957; Hoffstetter et al., 1957; Furque, 1973; Malumián, 1990; Marenssi et al., 2000, 2002, 2005; Le Roux et al., 2010; Malumián and Nañez, 2011; Cuitiño et al., 2012; Bostelmann et al., 2013), there has been no consensus about the geographic distribution of the different stratigraphic units and their contact relationships. For the Sierra Baguales, in fact, the most detailed geological map presently existing is at a scale of 1:100,000, showing obsolete nomenclature such as the "Río Bandurrias", "Calafate" and "Las Flores" Formations (Muñoz, 1981). Here we present a new geological map at a scale of 1:10,000 (Fig. 2), updating the nomenclature according to international stratigraphic principles and correcting the spatial distribution of the different stratigraphic units. However, our main objective has been to determine the link between sedimentation in the Magallanes-Austral Basin and its tectonic context. With this in mind, we investigated the depositional environments of the different units and their palaeocurrent patterns, backed up by a study of zircon age populations. Six new detrital zircon U-Pb ages are presented, of which three are from the Dorotea Formation, one from the Man Aike Formation, and two from the Río Leona Formation. Bearing in mind the well-established relationship between tectonics and local climate, we also carried out a palaeobotanical analysis based on fossils leaves from the Río Leona Formation, comparing these results with those of similar studies on older successions in Patagonia.

2. Methodology

Field work in the Sierra Baguales consisted of geological mapping, the measurement of stratigraphic columns and palaeocurrent directions, sampling for petrographic work and detrital zircon dating, and the collection of fossil leaves for palaeobotanical and palaeoclimatic studies.

Geological mapping of the Sierra Baguales was carried out on a scale of 1:10,000 between Cerro Cono in the north, Cerro Ciudadela and the Chilean-Argentinean border in the east, Cerro Guido in the south, and the Río Las Chinas in the west (Fig. 2).

Seven stratigraphic columns (some composite) were measured at 10 different localities (Fig. 1B). In the Tres Pasos Formation, a 380 m thick composite section was surveyed at Cerro Guido and Estancia Las Chinas. Towards the west, at Las Tetas de las Chinas, a 200 m thick profile was surveyed in the Dorotea Formation. The stratigraphy of the Man Aike Formation was described in 3 different sections comprising its basal, middle and upper parts, respectively. The basal section, measured in the vicinity of Las Tetas de las Chinas, has a thickness of 40 m, while the middle section comprised 240 m measured by Le Roux et al. (2010) on Estancia 3R, which was correlated with the section described by Ugalde (2014) and Cecioni (1957) in the sector Las Flores. The upper part has a thickness of 50 m measured at Chorrillo Jabón. In the Río Leona Formation, two 115 m thick profiles were surveyed. The basal

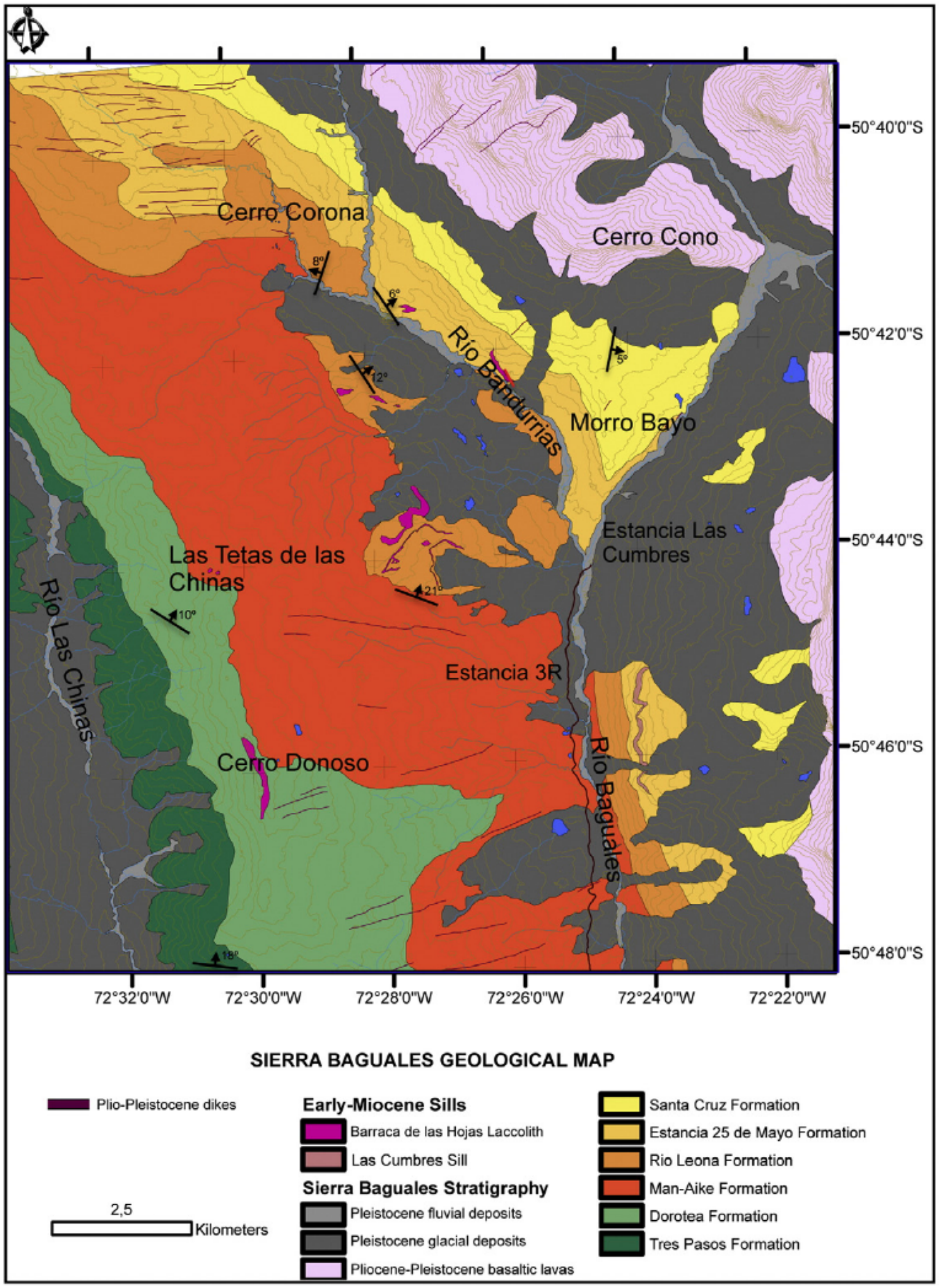

Fig. 2. Geological map of the Sierra Baguales.

part of this formation, which conformably overlies the Man Aike Formation in this area, was measured in the sectors Barranca de las Hojas and Chorrillo Jabón, whereas the upper part was measured at Las Murallas west of the Bandurrias River (Fig. 2). Two stratigraphic columns were also measured in the Estancia 25 de Mayo Formation, the first at the locality of Las Murallas and the second at Cerro Cangrejo. The profile of the Santa Cruz Formation at Cerro Cono, measured by the first four authors of this paper and published in Bostelmann et al. (2013), was included as part of the data base.

A total of 192 palaeocurrent directions were measured, including planar and trough cross-lamination, streaming and parting lineation, rib-and-furrow structures, ripple marks, and the elongation of nodules and concretions where such structures showed a preferred orientation at any particular locality. The growth of concretions is controlled by the grain orientation of their host beds and like streaming and parting lineation do not yield vectors, but can be used in conjunction with other associated structures such as cross-bedding to find the palaeocurrent trends. The recorded directions were distributed as follows: 55 in the Dorotea Formation, 9 in the Man Aike Formation, 18 in the Río Leona Formation, 37 in the Estancia 25 de Mayo Formation, and 73 in the Santa Cruz Formation. Although the beds in this particular area are generally sub-horizontal, tilt corrections were carried out to obtain the original palaeocurrent directions using the methodology of Le Roux (1991). These were further analyzed by directional statistics (Le Roux, 1992, 1994), to obtain the vector mean azimuth, magnitude, and channel sinuosity of each data set. In the Tres Pasos and Estancia 25 de Mayo Formations no measurable directions were encountered. However, published palaeocurrent data from the Estancia 25 de Mayo Formation at Lago Argentino (Cuitiño, 2011) were also incorporated into this data set.

Eight samples from the Sierra Baguales succession were selected for detrital zircon dating. The first of these was taken from the Dorotea Formation close to its basal contact with the Tres Pasos Formation near Cerro Guido (Fig. 1B), whereas the second and third are from the upper part of the Dorotea Formation at Las Tetas de las Chinas. One sample was dated from near the top of the overlying Man Aike Formation at Chorrillo Jabón (Fig. 1B). For the Río Leona Formation, two samples were dated, one from Chorrillo Jabón close to its basal contact with the Man Aike Formation, and the other from Cerro Ciudadela, where it was previously attributed to the "Las Flores Formation" and correlated with the Man Aike Formation (Ugalde, 2014). These 6 samples were analyzed in the Mass Spectrometry Laboratory of the Andean Geothermal Centre of Excellence (CEGA) at the University of Chile. Two other samples, previously dated at the Australian National University in Canberra (Bostelmann et al., 2012) were collected from near the base and top of the Santa Cruz Formation, respectively.

More than 3700 fossil leaves recovered from the Río Leona Formation were identified, classified, and subjected to multi- and univariate analysis to determine temperature and precipitation conditions as well as their morphospecies diversity. Palaeoclimatic analysis was performed using the models and datasets of Hinojosa and collaborators (Hinojosa, 2005; Hinojosa et al., 2006, 2011).

3. Geological setting

The Rocas Verdes Basin, a predecessor of the Magallanes-Austral Basin, developed as a backarc or marginal basin during a Middle to Late Jurassic extensional episode associated with the initial breakup of Gondwanaland (Dalziel et al., 1974; Gust et al., 1985; Biddle et al., 1986; Pankhurst et al., 2000; Calderón et al., 2007). Inversion converted its eastern part into a foreland basin and caused flexural loading, thus creating the north-south orientated Magallanes-Austral Basin (Natland et al., 1974; Dalziel, 1986).

The Sierra Baguales represents the region in the Magallanes-Austral Basin with the most complete, uninterrupted Mesozoic-Cenozoic stratigraphic succession, reaching a total approximate thickness of 1300 m. It includes the Tres Pasos and Dorotea Formations, both of Late Cretaceous age, as well as the Man Aike Formation (middle to late Eocene), Río Leona Formation (early Oligocene), Estancia 25 de Mayo Formation (early Miocene), and the Santa Cruz Formation (middle Miocene).

The basal part of the Tres Pasos Formation is partly contemporaneous with the underlying Cerro Toro Formation, which represents large, conglomerate-filled submarine channels prograding towards the south along the Magallanes-Austral axis (Katz, 1963; Natland et al., 1974; Hubbard et al., 2008). The Tres Pasos Formation is of late Campanian age in its uppermost part, as indicated by the ammonites *Hoplitoplacenticeras plasticus* and *H. semicostatus* at Cerro Cazador (Paulcke, 1907). Its contact with the overlying Dorotea Formation is concordant, as revealed in the upper part of Cerro Guido (Fig. 1B). The latter formation reaches a thickness of about 200 m in the study area, consisting mainly of medium to coarse sandstones. The Man Aike Formation, previously referred to as the Río Baguales or Las Flores Formation in different parts of the study area (Le Roux et al., 2010; Ugalde, 2014), overlies the Dorotea Formation paraconformably to unconformably, consisting of about 300 m of medium- to coarse-grained sandstones and conglomerates. Apart from fossils clearly reworked from the underlying Dorotea Formation, late Eocene shark teeth, fish fossils and invertebrates are present (Otero et al., 2013). The Río Leona Formation overlies the Man Aike Formation concordantly at Chorillo Jabón, where it reaches an approximate thickness of 200 m. It is here composed mainly of mudstones and medium-grained sandstones with intraformational conglomerate lenses. Thin lignite beds, as well as fossil wood and leaves are common (Barreda et al., 2009; Torres et al., 2009). The Estancia 25 de Mayo Formation concordantly overlies the Río Leona Formation and represents the Patagonian or "Superpatagonian" Transgression (Feruglio, 1949; Malumián, 1999), which took place during the early Miocene between 20 and 18 Ma (Parras et al., 2012; Bostelmann et al., 2013; Cuitiño et al., 2013). Its fossil assemblage includes oyster banks (*Ostrea hatcheri*), bivalves, typical Leonenses gastropods such as *Perissodonta ameghinoi*, and crabs (*Chaceon peruvianum*) (Gutíerrez et al., 2013). A prominent, 2 m thick pyroclastic horizon of rhyodacitic composition is present in the middle of this unit at Cerro Corona (Figs. 2, 3). It was also reported in the Lago Argentino succession, where it was identified as "LPL" and dated by U—Pb at 19.14 ± 0.5 Ma (Cuitiño et al., 2013). The Santa Cruz Formation lies conformably upon the Estancia 25 de Mayo Formation (Bostelmann et al., 2013) at Cerro Cono (Fig. 2), where it reaches a thickness of about 100 m. It consists of multi-coloured mudstones with medium to coarse sandstones and conglomerates. Terrestrial vertebrate fossils indicate a post-Colhuehuapense to pre-Santacrucian age, which is supported by a population of detrital zircons with a mean age of 18.23 ± 0.26 Ma (Bostelmann et al., 2013). However, the dated sample also contained several zircons with ages of about 16 Ma, which indicated that the latter may have to be revised downward.

Olivine-rich dolerite intrusions are common in the Sierra Baguales, forming huge, laccolite-like sills reaching many tens of meters in thickness, as well as dikes up to 3 m thick (Fig. 3). Field evidence shows that none of these sills penetrates the Santa Cruz Formation, suggesting that their intrusion occurred before the deposition of this unit.

The "Andesitic Lavas of Sierra Baguales" (Muñoz, 1981) are of late Pliocene age and overlie the Santa Cruz Formation, forming prominent cliffs in the high mountains to the north and east of the Río Baguales. These lavas, as well as all the Cretaceous and Miocene successions below, have been intruded by younger dioritic and basaltic dikes with an E-W trend.

In spite of its location close to the fold-and-thrust belt of the Rocas Verdes Basin, the Sierra Baguales area is relatively undeformed, with very gentle folding and faults being almost absent. Our measurements throughout the study area indicate a mean strike and dip of 303°/10°NE.

4. Lithostratigraphy and depositional environments

4.1. Tres Pasos Formation

This formation is described by Bernhardt (2011) and Macauley and Hubbard (2013) as a continental slope system. In the vicinity of the Río Las Chinas and Cerro Guido the succession consists of decimeter-scale intercalations of fine-grained sandstones, siltstones, and organic-rich shales (Fig. 4A) in occasional fining-upward cycles. The sandstones show lower flow regime horizontal lamination and rare flutes at the base (facies 11 in Table 1). *Rusophycus* trace fossils, probably formed by arthropods, are abundant. This facies is typical of distal turbidites and suggests a continental slope environment. Towards the top of this formation there is a coarsening-upward trend with fine- to very coarse sandstone beds showing high-angle tabular and trough cross-lamination, in which trace fossils of *Rusophycus*, *Palaeophycus* (Fig. 4B), *Cruziana* (Fig. 4C), fish trails or undichnia (Fig. 4D), *Psilonichnus* (Fig. 4E), and *Skolithos* (Fig. 4F) are present. This facies assemblage (mainly facies 10 in Table 1, but elements of facies 9 are also present)

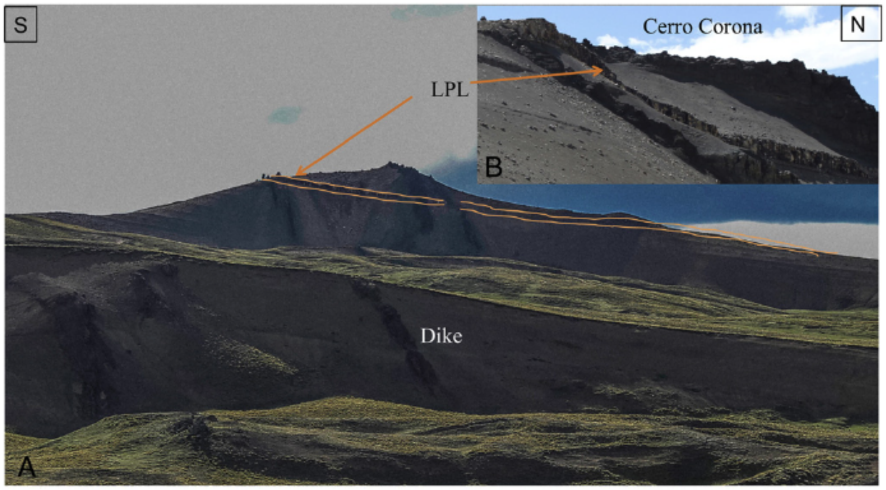

Fig. 3. A) Vertical dike intruding Estancia 25 de Mayo Formation. B) Pyroclastic bed (LPL) in the Estancia 25 de Mayo Formation.

suggests a transition to shallow marine conditions ranging from the shelf or lower shoreface to an upper shoreface with ridges and runnels. There is a thus a gradual transition into the deltaic facies of the Dorotea Formation.

4.2. Dorotea Formation

According to previous authors (Katz, 1963; Riccardi and Rolleri, 1980; Schwartz and Graham, 2015), this formation was deposited in a

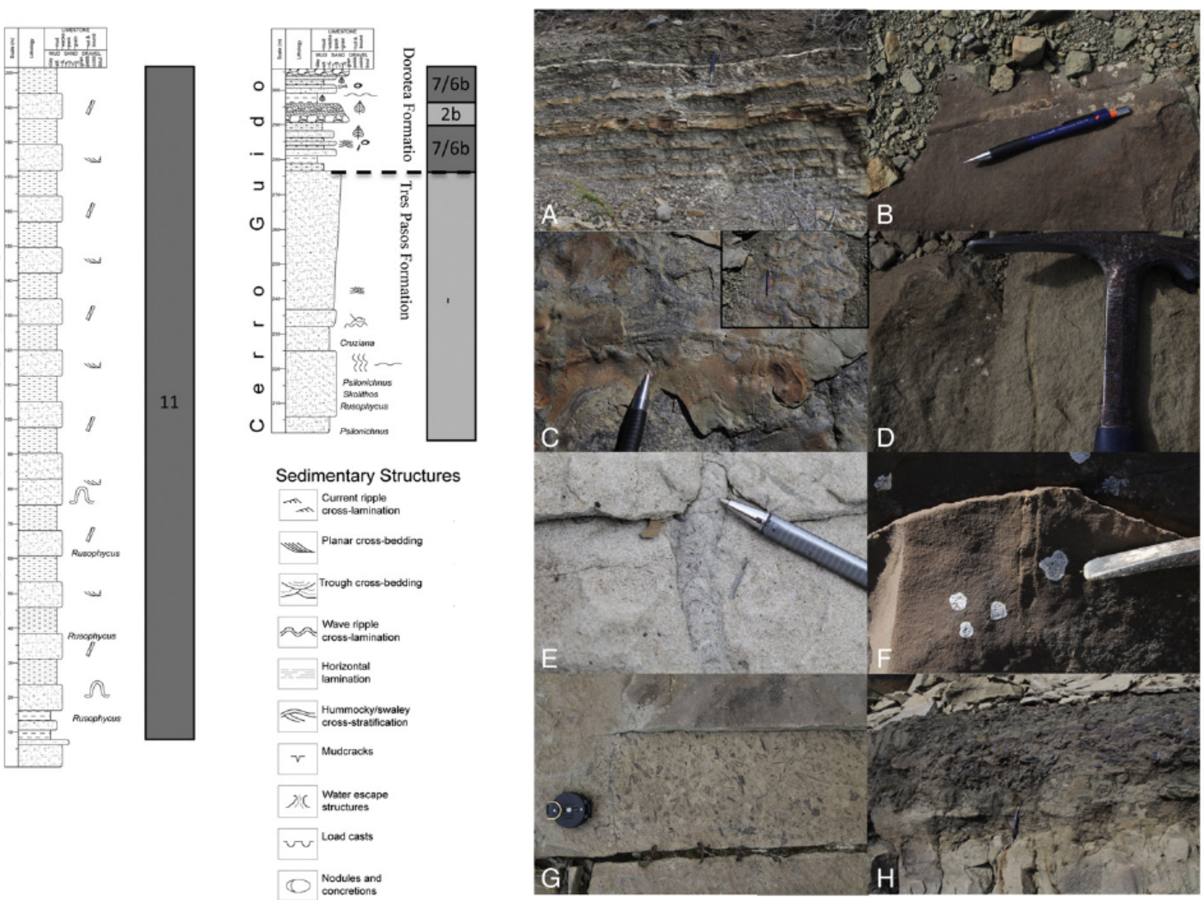

Fig. 4. Measured stratigraphic column of the Tres Pasos and Dorotea Formations in Cerro Guido. A) Turbidites; B); Palaeophycus; C) Cruziana; D) Fish trails (undichnia); F) Oyster bank; G) Wood and leaf fragments; H) *Psilonichnus*; H) *Skolithos*.

Table 1
Depositional facies recognized in the Upper Cretaceous to middle Miocene stratigraphic succession of the Sierra Baguales.

Id	Facies	Formation	General description
1	1a. Braided rivers with abandoned channels. 1b. Braided rivers proximal to ocean.	Santa Cruz, Río Leona. Man Aike	**Lithology:** Fining- and coarsening-upward, medium- to coarse, greenish sandstones and conglomerates with mud clasts; mudstone and calcareous, very fine-grained sandstone lenses within sandstones. **Sedimentary structures:** High-angle tabular and trough cross-lamination. **Fossils:** High content of tree trunks and poorly preserved leaf fragments; shark teeth in 1b.
2	2a. Point bars in meandering rivers. 2b. Point bars in meandering distributary channels.	Río Leona, Santa Cruz. Tres Pasos, Dorotea, Man Aike.	**Lithology:** Three types of fining-upward cycles: Medium-grained sandstone to nodular mudstone; coarse- and medium-grained sandstone to fine- and very fine-grained sandstone; coarse, clast-supported, monomictic conglomerate to fine conglomerate. Conglomerates contain very fine-grained sandstone lenses. **Sedimentary structures:** High-angle tabular and trough cross-lamination; upper flow regime parallel lamination; rib-and-furrow structures; current ripple marks in 2a; wave ripples in 2b. **Fossils:** Bivalves, oysters, shark teeth in 2b, vertebrates, arthropods, tree trunks and leaves in 2a. **Ichnofossils:** *Arenicolites*, arthropod trails in 2b.
3	Levees	Santa Cruz	**Lithology:** Thin, intercalated beds of siltstone and very fine-grained sandstone.
4	Subaerial flood plains.	Dorotea, Río Leona, Santa Cruz.	**Lithology:** Multicoloured mudstones with thin, grey to brown shale, reddish siltstone and fine-grained sandstone beds and lenses. **Fossils:** Wood fragments, leaves, pollen, vertebrates.
5	Overbank swamps.	Río Leona.	**Lithology:** Sapropelite interbedded with black mudstone. **Fossils:** Wood fragments and leaves.
6	6a. Crevasse splays on flood plains. 6b. Crevasse splays in interdistributary bays	Río Leona, Santa Cruz. Tres Pasos, Dorotea, Man Aike, Estancia 25 de Mayo.	**Lithology:** Fine- to medium-grained sandstone; quartz and chert clasts; calcareous sandstone beds with $CaCO_3$ nodules in 6b. **Fossils:** Tree trunks, leaves, vertebrate fragments in 6a. Bivalves, gastropods, oysters, shark teeth, leaves, tree trunks, vertebrate fragments in 6b.
7	Estuaries and interdistributary bays.	Dorotea, Man Aike, Estancia 25 de Mayo.	**Lithology:** Greenish grey mudstones and grey to brown shales with thin interbeds of siltstone and fine-grained sandstone. **Fossils:** Wood fragments, leaves, bivalves, oysters, shark teeth.
8	8a. Low-sinuosity meandering rivers. 8b. Tidal channels	Santa Cruz. Dorotea, Man Aike.	**Lithology:** Coarse- to medium-grained sandstones and clast-supported, monomictic conglomerates; beds and lenses have erosional bases; $CaCO_3$ nodules. **Sedimentary structures:** Upper flow regime horizontal lamination; high-angle tabular and trough cross-lamination; herringbone cross-lamination in 8b. **Fossils:** Burnt wood fragments in 8a. Burnt wood fragments, shark teeth in 8b. **Trace fossils:** *Skolithos* in 8b.
9	Upper shoreface with shoals, ridges and runnels, occasional distributary mouth bars.	Tres Pasos, Dorotea, Man Aike, Estancia 25 de Mayo.	**Lithology:** Coarse- to very coarse-grained sandstones and conglomerates in coarsening-upward cycles; sandstones contain fine-grained sandstone lenses. **Sedimentary structures:** High-angle tabular and trough cross-lamination. **Fossils:** Wood and leaf fragments, *Turritella*, gastropods, oysters, crabs. **Ichnofossils:** Fish trails (undichnia), *Psilonichnus*, *Skolitos*, *Rusophycus*, *Palaeophycus*, *Cruziana*
10	Shelf to lower shoreface	Estancia 25 de Mayo.	**Lithology:** Fine- to medium-grained sandstone interbedded with shale; $CaCO_3$ nodules and concretions. **Sedimentary structures:** Lower flow regime horizontal lamination. **Fossils**: Gastropods, brachiopods, crabs, leaves.
11	Continental slope, turbidity currents	Tres Pasos.	**Lithology:** Medium- to fine-grained sheet sandstones interbedded with thin, organic-rich shales; occasional fining-upward cycles. **Sedimentary structures:** Lower flow regime horizontal lamination, rare flute marks. **Ichnofossils:** *Rusophycus*.

transitional, shallow marine to deltaic environment. It contains invertebrate, vertebrate, insect and plant fossils, while traces of *Skolithos* and *Thalassinoides* are common.

In the Cerro Guido section (Fig. 4, left) this formation concordantly overlies the Tres Pasos Formation, consisting of greenish grey mudstones and grey to brown shales with thin interbeds of siltstone and fine-grained sandstone (facies 7 in Table 1). Fining-upward conglomerates filling channels also occur (facies 2), while fossils are represented by wood and leaf fragments (Fig. 4G), bivalves, shark teeth and oyster accumulations (Fig. 4H). This section is interpreted as representing estuaries or interdistributary bays with oyster banks.

Five depositional facies were recognized in the profile of the Dorotea Formation measured at Las Tetas de las Chinas (Fig. 5). The first (facies 4; Table 1) consists of up to 40 m of reddish to greenish and grey mudstones with bed thicknesses between 10 and 30 cm, intercalated with cm-scale horizons of grey to brown shale. Thin lenses of fine- to medium-grained sandstone are also present. These deposits contain fossil wood and leaves, pollen, and vertebrate fragments, being interpreted as representing overbank flood plains with small channels and shallow ponds.

The second (facies 2; Table 1) is represented by 2–5 m thick, grey, medium- to coarse-grained sandstones with erosional bases, separated by mudstones. The sandstones display trough and high-angle planar cross-lamination as well as upper flow regime parallel lamination (Fig. 5K), rib-and-furrow structures (Fig. 5I), and wave ripples (Fig. 5G). Trace fossils are represented by *Arenicolites* (Fig. 5C, D) and arthropod trails (Fig. 5E, F). Meter-scale lenses of brown, very coarse-grained sandstones with high-angle planar cross-lamination are also present. This facies reflects low-sinuosity distributary channels with lunate and straight-crested bars under the influence of wave action.

The third (facies 6; Table 1) is up to 5 m thick, being composed of brown, calcareous, fine- to medium-grained sandstones with chert and quartz clasts as well as carbonate nodules. Bivalves and gastropods are present. They are interpreted as crevasse splay deposits partially filling interdistributary bays, as they are interbedded with facies 7.

The fourth (facies 9; Table 1) consists of up to 5 m thick cycles of coarse to very coarse sandstones grading upward into conglomerates with chert and quartz clasts reaching 14 cm in diameter. The sandstones display trough- and high-angle planar cross-lamination (Fig. 5J) and contain fine-grained sandstone lenses. Fossil leaves and wood fragments are present. These characteristics suggest prograding upper shoreface deposits with ridges and runnels, or possibly distributary mouth bars.

The fifth association (facies 2b; Table 1), displays three types of fining-upward cycles: up to 8 m of medium sandstone grading into mudstone with calcareous nodules; medium sandstone grading into fine

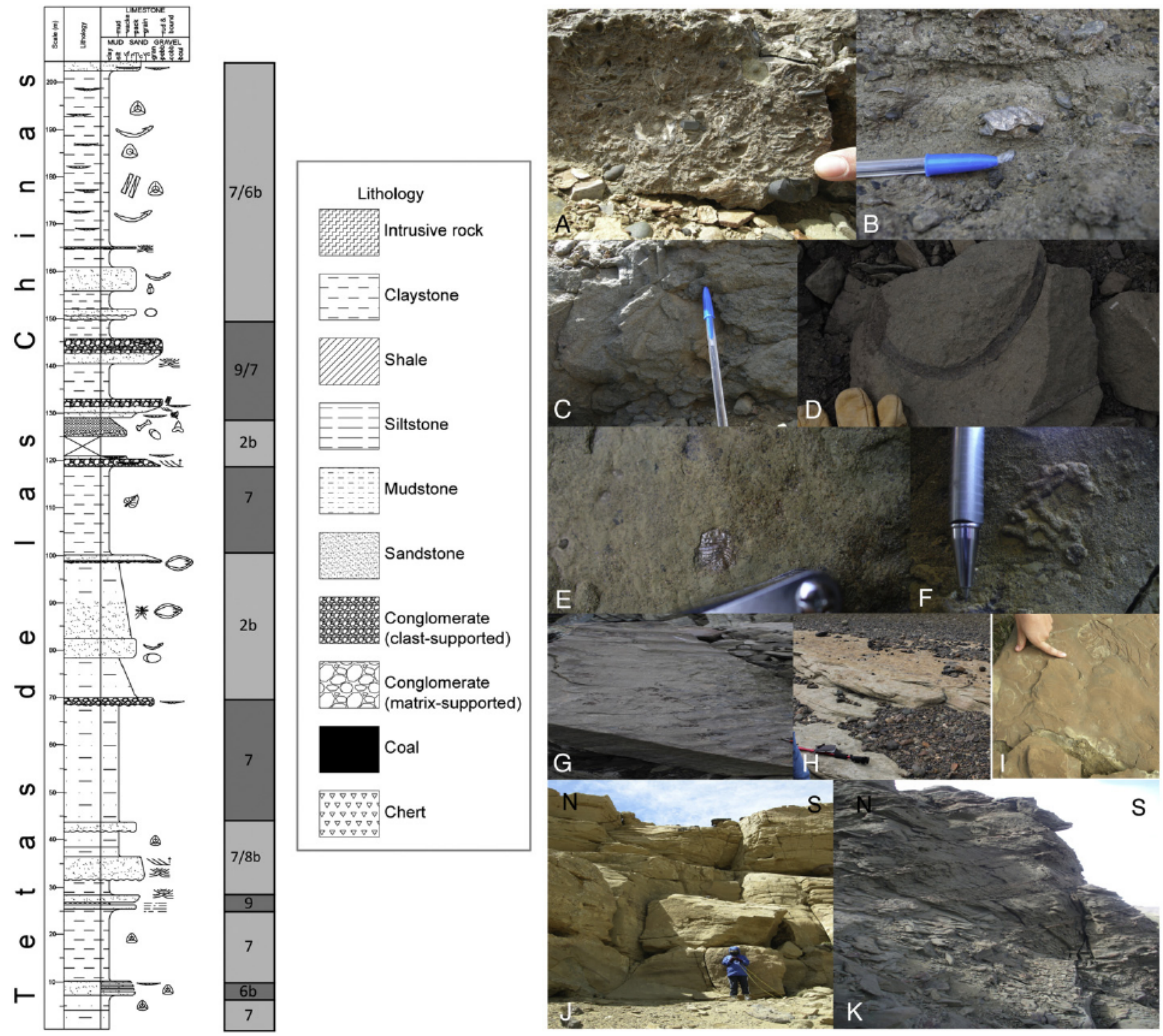

Fig. 5. Measured stratigraphic column of Dorotea Formation at Las Tetas de las Chinas. A) Bivalves; B) Oysters; C and D) *Arenicolites*; E) Arthropod; F) Arthropod trails; G) Wave ripples; H) Trough cross-lamination; I) Rib-and-furrow structures; J) High-angle tabular and trough cross-lamination; K) upper flow regime horizontal lamination.

sandstone over a total thickness of 20 m; and up to 2 m thick cycles of coarse conglomerate grading into monomictic, clast-supported conglomerates with rounded chert clasts reaching 10 cm in diameter. In the latter cycles, the conglomerates show high-angle cross-bedding and contain fine-grained sandstone lenses. Fossils include shark teeth, vertebrate fragments, insects, bivalves and oysters. This facies is interpreted as representing meandering distributary channels directly connected to the open sea.

The characteristics described above therefore indicate a shallow marine, deltaic environment for the Dorotea Formation, in which subaerial delta plains with low to higher sinuosity distributary channels and overbank sediments graded laterally into interdistributary bays with crevasse splays. Distributary mouth bars developed on the upper shoreface where the channels entered the underwater platform. This interpretation coincides with those of Gutíerrez et al. (2013), González (2015), and Schwartz and Graham (2015), based on other profiles measured in the Dorotea Formation.

4.3. Man Aike Formation

The middle part of the Man Aike Formation was deposited in a mainly wave-dominated estuary, but with extensive tidal flats (Le Roux et al., 2010). A 50 m thick profile was measured in the Chorrillo Jabón sector and 40 m in the Las Tetas de las Chinas sector (Fig. 6). The first is complementary to the top of the Man Aike Formation measured by and referred to as the Río Baguales Formation by Le Roux et al. (2010), whereas the second corresponds to the base of this column. In the measured base and top of the Man Aike Formation, three different facies were recognized, all containing shark teeth. The first (facies 1a; Table 1) consists of medium to coarse sandstone with both coarsening- and fining-upward trends, displaying high-angle tabular and trough cross-lamination and decimeter-scale mudstone lenses. Poorly preserved wood and leaf fragments are present. It is interpreted as representing braided streams in a general estuary environment. The presence of shark teeth indicates proximity to the ocean. The second

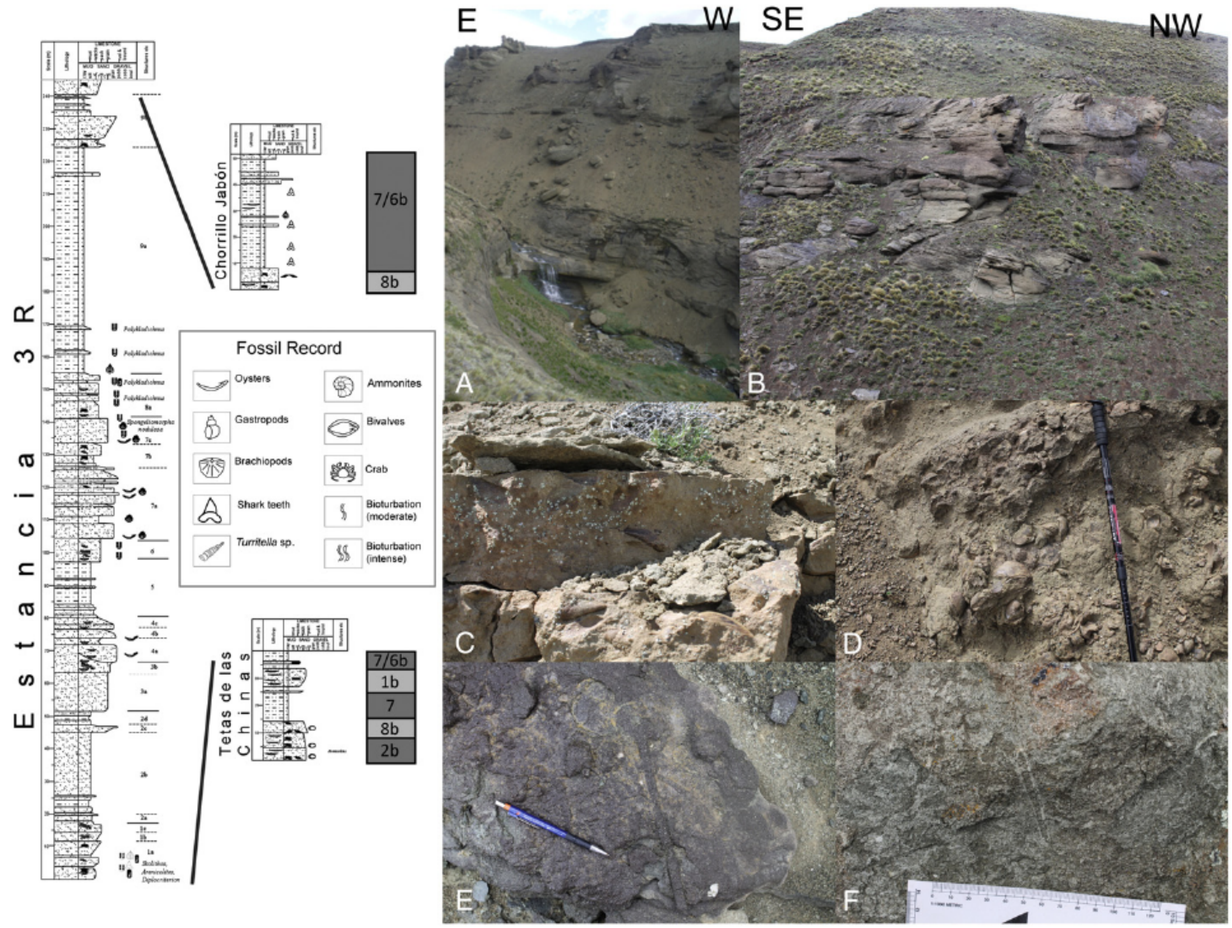

Fig. 6. Measured stratigraphic columns of Man Aike Formation at Las Tetas de las Chinas and Chorrillo Jabón. A) Outcrop of Man Aike Formation at Chorillo Jabón; B) Herringbone cross-lamination; C) Bivalves; D) Gastropods; E) and F) *Skolithos.*

facies (facies 7; Table 1) is dominated by mudrocks interbedded with fine- to medium-grained sandstone beds and lenses. Bivalves and gastropods are present (Fig. 6C, D) in addition to shark teeth. This facies is considered to reflect an estuary. The third facies (facies 8b; Table 1) is represented by medium- to coarse-grained sandstones with erosional bases showing herringbone (Fig. 6B) and trough cross-lamination. Trace fossils are represented by *Skolithos* (Fig. 6E, F). This facies reflects tidal channels subjected to ebb and flow. The association is thus typical of tide-dominated estuaries, which is consistent with the interpretation of Le Roux et al. (2010).

4.4. Río Leona Formation

The Río Leona Formation was deposited in a fluvial environment characterized by meandering and anastomosing rivers with wide overbank flood plains (Marenssi et al., 2000, 2005).

A composite section of the Río Leona Formation was measured at Chorrillo Jabón and Las Murallas, respectively (Fig. 7), in which 6 depositional facies were identified. The first (facies 4; Table 1) consists of brown to greenish, massive mudstones interbedded with siltstones and very fine-grained, grey to dark grey sandstones. Its thickness varies between 5 and 20 m. Fossil tree trunks and leaves were also recorded. This facies is attributed to a subaerial, overbank environment.

Buff, fine to medium-grained sandstones up to 1 m thick intercalated with buff to brown mudstones compose the second facies (facies 6a, Table 1). Fossil roots, trunks and leaves (Fig. 7C–F) are present, indicating a subaerial environment. This facies reflects crevasse splays in an overbank environment.

The third association (facies 2a, Table 1) is composed of coarse- to fine-grained sandstones forming 2–5 m thick, fining-upward cycles. Current ripple marks occur at the top of some cycles, with fossil wood fragments and leaves also present. These are interpreted as point bars in meandering channels.

The fourth facies (facies 1a; Table 1) displays greenish, medium- to coarse-grained sandstones with intraformational mud-clast conglomerates. Both coarsening- and fining-upward cycles are present. Sedimentary structures include trough and high-angle tabular cross-lamination. Mudstone lenses with erosional basal and upper contacts and some calcareous sandstone lenses were also recorded. There are abundant, but poorly preserved fossil tree trunks and leaves. This facies represents braided streams with abandoned channels.

Facies 5 (Table 1) consists of sapropelite interbedded with black mudstones, indicating a high organic content that coincides with the presence of abundant fossil wood fragments and leaves. It is interpreted as representing swampy, reducing conditions within an overbank environment.

The overall sedimentological characteristics of the Río Leona Formation thus suggest a coastal plain with meandering and locally braided channel systems. Flood plain swamps created reducing conditions in which wood and leaf fragments were well preserved. This

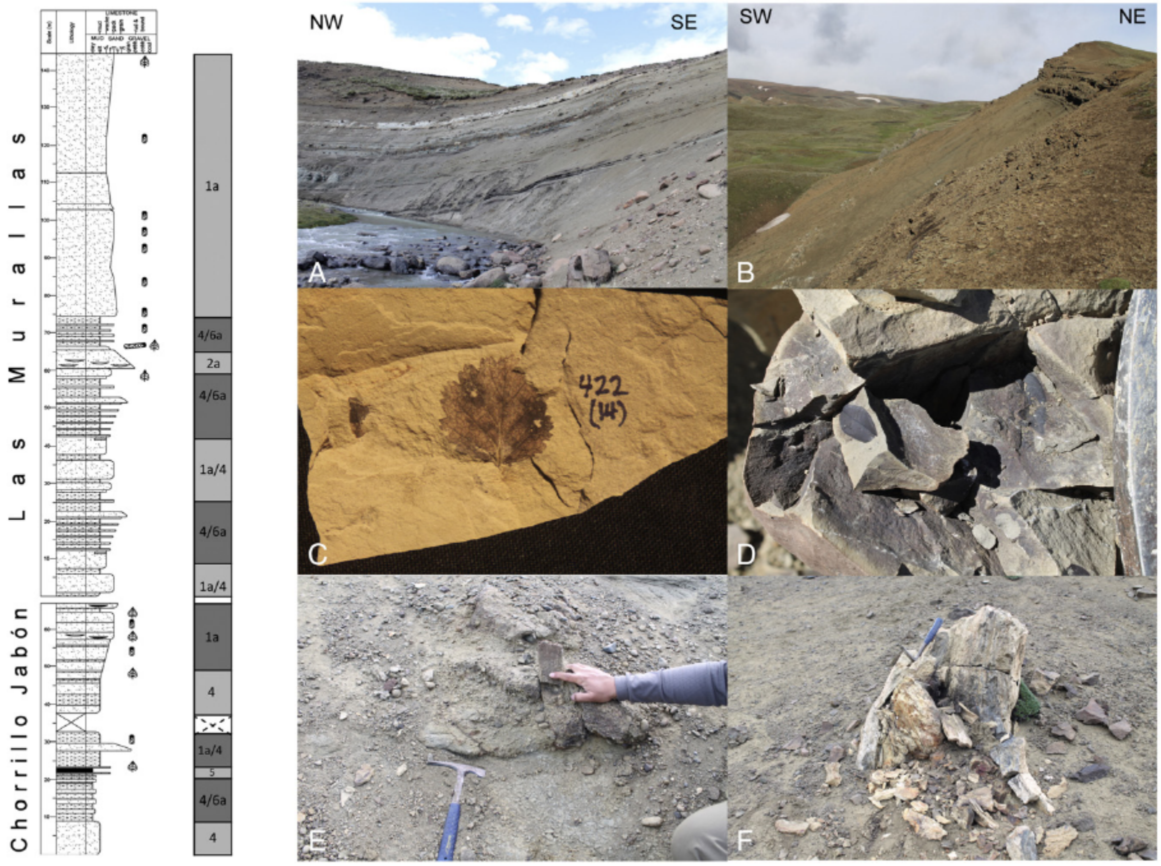

Fig. 7. Measured stratigraphic columns of Río Leona Formation at Las Murallas and Chorrillo Jabón. A) and B) Outcrops of Río Leona Formation at Las Murallas and Chorillo Jabón; C) and D) Well preserved fossil leaves; E) Wood fragment in conglomerate; F) tree trunk in life position.

interpretation of the Río Leona Formation is consistent with previous studies of this formation in Argentina and Chile (Malumián, 1990; Marenssi et al., 2000, 2002, 2005; Le Roux et al., 2010; Malumián and Nañez, 2011; Cuitiño et al., 2013).

4.5. Estancia 25 de Mayo Formation

Two facies were recognized in this formation. The first (facies 10, Table 1) consists of thin (1–2 m), sheet-like beds of greenish, fine- to medium-grained, calcareous sandstones. These are intercalated with ochre to brown, calcareous shales, also between 1 and 2 m thick, in which cm-scale, calcareous nodules and fossiliferous concretions are present. Among the fossils are gastropods and crabs, as well as brachiopods and leaves. This facies represents a lower shoreface environment.

The second facies (facies 9; Table 1) is composed of massive, medium- to coarse-grained, calcareous sandstones showing ochre to greenish colours, calcareous nodules and concretions containing gastropods (including *Turritella*), crabs (Fig. 9B), articulated brachiopods (Fig. 8B), and oysters (Fig. 8F). The presence of *Turritella* and oysters suggests a nearshore environment in the vicinity of river mouths, so that this facies is interpreted as representing sandy shoals in an upper shoreface environment.

4.6. Santa Cruz Formation

This formation was deposited in meandering rivers on a flood plain with local small lakes. No new stratigraphic profiles were measured in the Santa Cruz Formation, as this had already been done by the present authors in a previous publication (Bostelmann et al., 2013). The facies recognized in that study (Morro Bayo section; Fig. 9A) included 2–10 m thick units of multicoloured mudstones with abundant vegetal remains, showing metric-scale, reddish siltstone lenses in the thicker units. Vertebrate fossils (Fig. 9B) and pollen are abundant, with occasional insect traces (Fig. 9D). This association (facies 4; Table 1) represents overbank flood plain deposits. Fine- to medium-grained sandstones reflecting crevasse splays (facies 6a; Table 1) are between 1 and 1.5 m thick and interbedded with the mudstone. Meandering channels with point bar deposits (facies 2a; Table 1) are represented by 2–5 m thick, fining-upward, coarse- to fine-grained sandstone with epsilon (Fig. 9F), high-angle tabular (Figs. 9C, 10) and trough cross-lamination (Fig. 9E, H), whereas levees (facies 3; Table 1) are indicated by thin beds (less than 1 m) of siltstone intercalated with very fine sandstone. Somewhat straighter channels (facies 8a; Table 1) are represented by clast-supported, monomictic conglomerates showing erosional basal contacts and trough cross-bedding. Burnt wood fragments are also present. These characteristics indicate a fluvial system dominated by meandering streams, with local minor braided systems.

5. Palaeocurrent directions

5.1. Tres Pasos Formation

Previous palaeocurrent studies in the Cerro Toro and lower parts of the Tres Pasos Formation indicated a consistent southward-directed

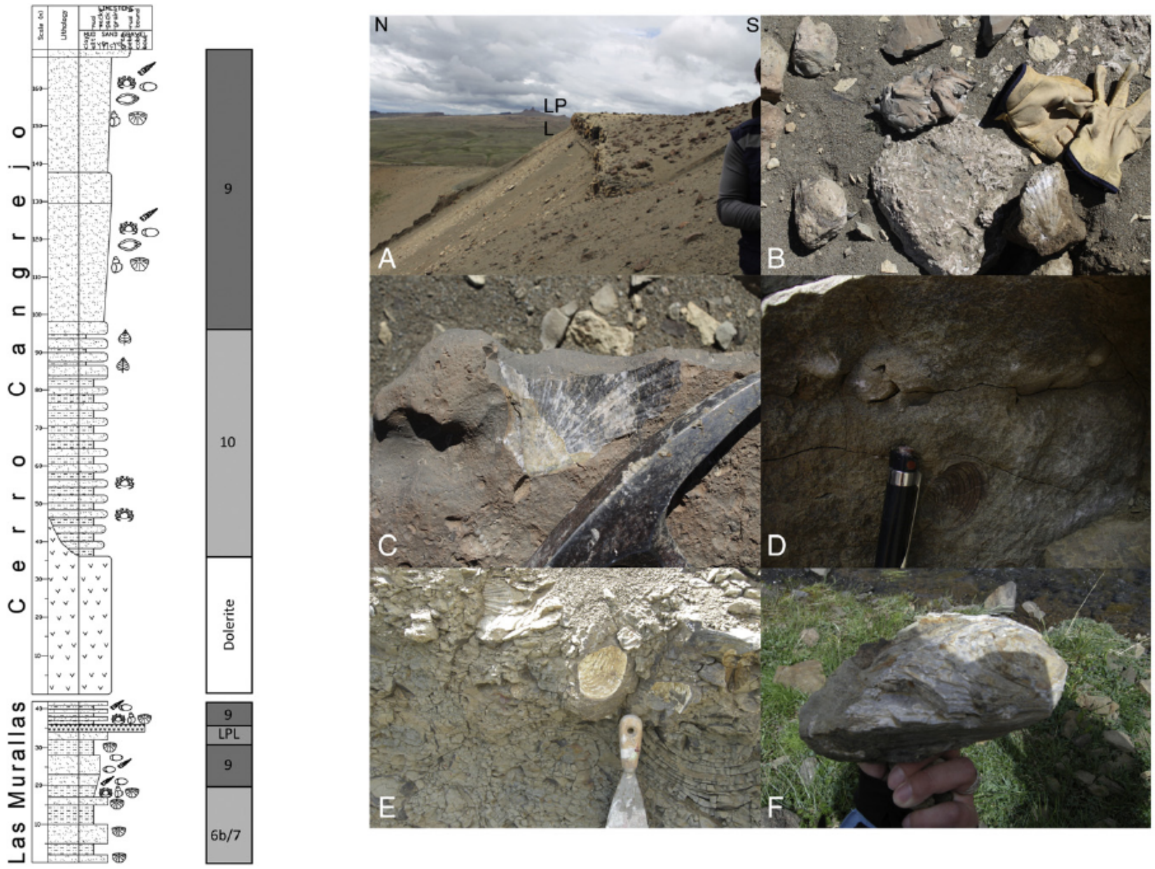

Fig. 8. Measured stratigraphic columns of Estancia 25 de Mayo Formation at Las Murallas and Cerro Cangrejo. A) Outcrop of Estancia 25 de Mayo Formation and LPL bed at Las Murallas. B) Gastropods, *Turritella* and crabs; C)–E) Brachiopods; F) Oysters.

dispersal pattern (Scott, 1966; Fildani and Hessler, 2005; Crane and Lowe, 2008; Hubbard et al., 2008, 2010; Bernhardt et al., 2008, 2011; Jobe et al., 2010; Romans et al., 2010). Palaeocurrent directions in the Tres Pasos Formation were mainly derived from the inclination direction of slope clinoforms, lateral facies changes indicating southward progradation, and sole structures such as tool and flute marks. Measured directions vary between 160 and 180° (Hubbard et al., 2010). Our identification of shelf to lower shoreface facies in the upper part of the Tres Pasos Formation in the Sierra Baguales concurs with these studies, in that it represents a more proximal, shallow marine environment in comparison with the continental slope facies identified further south by Bernhardt (2011) and Macauley and Hubbard (2013). The source area was therefore located mainly to the north.

5.2. Dorotea Formation

In the Dorotea Formation (Campanian to Maastrichtian), the 55 measured palaeocurrent directions in the Sierra Baguales are towards the west with a range between southwest and northwest (Fig. 10A). This is consistent with the type of depositional environment, being a tide-dominated delta. However, the vector mean is 269° with a vector magnitude of 84%, suggesting that the source area was situated mainly to the east. Forty-one palaeocurrents measured by us further south at Cerro Castillo (Fig. 1) gave a vector mean of 241° with a vector magnitude of 32%.

5.3. Man Aike Formation

Only 9 measurements were taken in the Man Aike Formation (Lutetian to Bartonian) in the Sierra Baguales, which display two trends. The main trend is towards the west-northwest and the second towards the east (Fig. 10B). The vector mean is 295° with a magnitude of 43%. This coincides with an estuary environment (Le Roux et al., 2010) subjected to ebb and flow tides as shown by herringbone cross-lamination. We also measured 32 palaeocurrent directions in the time-equivalent Loreto Formation west of Punta Arenas (Fig. 1), yielding a vector mean of 291° with a vector magnitude of 18%. This set also shows two modes, one with a vector mean of 289° (n = 19) and another (n = 13) with a vector mean of 104°.

5.4. Río Leona Formation

The Río Leona Formation (Rupelian) yielded 18 measurements with three preferential directions towards the south, northwest and northeast, respectively (Fig. 10C). The last concentrates the majority of readings, with a vector mean of 56° and a magnitude of 63%.

5.5. Estancia 25 de Mayo Formation

In the Estancia 25 de Mayo Formation (early Burdigalian), 37 palaeocurrent directions were recorded, which are dominated by two

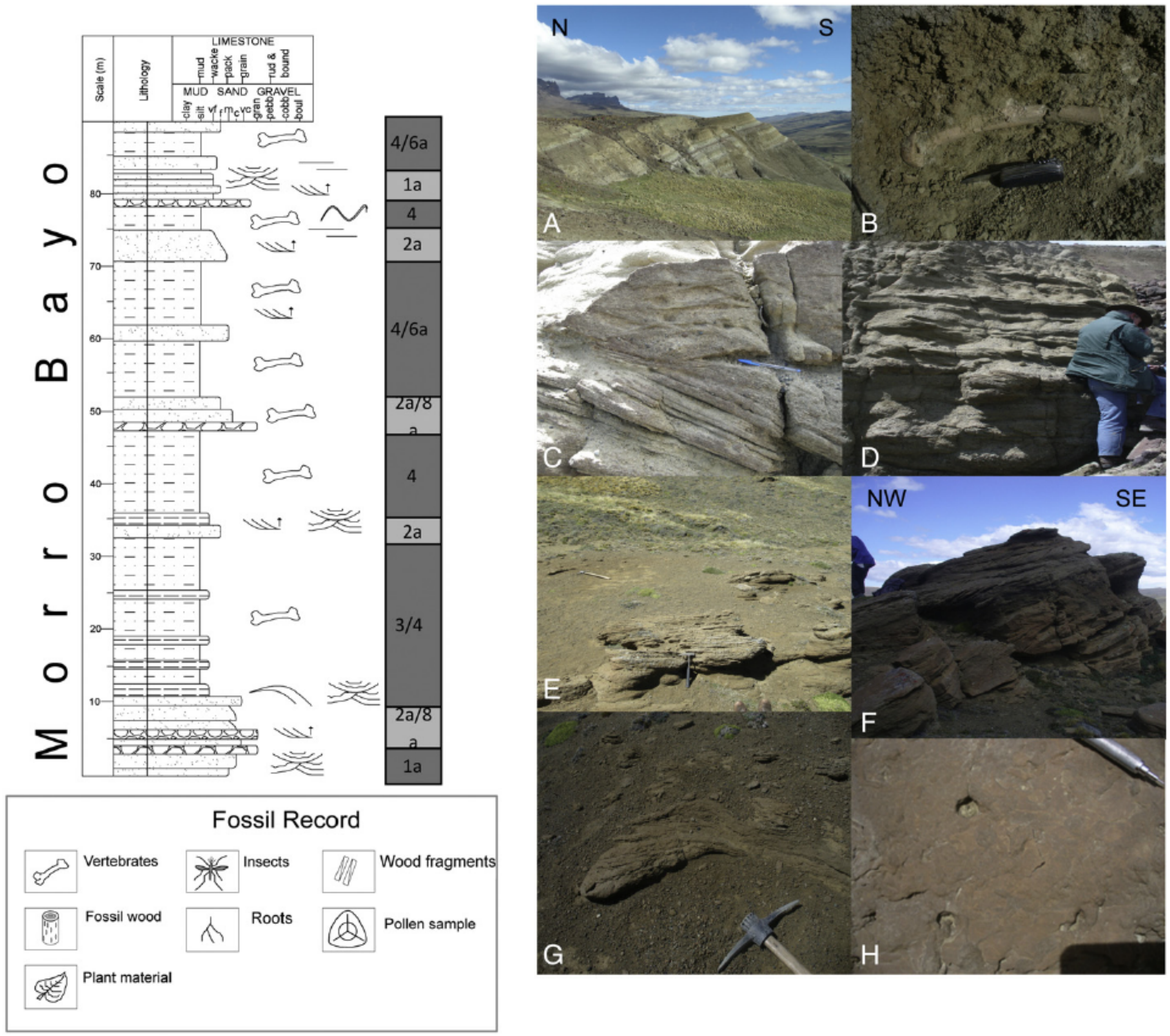

Fig. 9. Measured stratigraphic column of Santa Cruz Formation in Morro Bayo (after Bostelmann et al., 2013). A) Outcrops of the Santa Cruz Formation; B) Vertebrate bone; C–D) Tabular cross-lamination; E–F) Trough cross-lamination; G) Epsilon cross lamination; H) Insect trails.

trends, namely north and southeast (Cuitiño, 2011). The vector mean is 55° with a magnitude of 36% (Fig. 10D).

5.6. Santa Cruz Formation

In the Santa Cruz Formation (late Burdigalian), 73 palaeocurrents were recorded with a vector mean of 65° and a magnitude of 83% (Fig. 10E).

5.7. Summary of palaeocurrent directions

Our measured palaeocurrent directions and vector magnitudes in the Sierra Baguales indicate that they were directed mainly towards the west (269°) between the Cenomanian and Maastrichtian, varying from southwest to west-northwest. This is consistent with 86 palaeocurrent directions measured by us in the Thanetian (57.6 ± 1 Ma; Sánchez et al., 2010) "Cabo Nariz Beds" on Tierra del Fuego in the southern part of the Magallanes-Austral Basin, which gave a vector mean of 300°. The northwesterly trend was maintained at least until the Bartonian-Priabonian, when a vector mean of 295° was recorded in the Man Aike Formation. However, during the Rupelian and early Chattian an abrupt swing to the northeast (055°) occurred, shifting to east-northeast (065°) during the Burdigalian. Additionally, the data show a decrease in the vector magnitude between the Río Leona and Estancia 25 de Mayo Formations, changing from 63% to 36%. This decrease coincides with a change in the depositional environment, passing from meandering and braided rivers in the Río Leona Formation to a shoreface environment in the Estancia 25 de Mayo Formation. After deposition of the latter, there was an increase in the vector magnitude from 36% to 86%, which coincides with a new change in depositional environment from shoreface to continental, fluvial conditions in the Santa Cruz Formation.

6. Detrital zircons and radiometric ages

6.1. Tres Pasos Formation

The Tres Pasos Formation was dated by Bernhardt (2011) in the Silla Syncline to the south of the Sierra Baguales between 89.5 ± 1.9

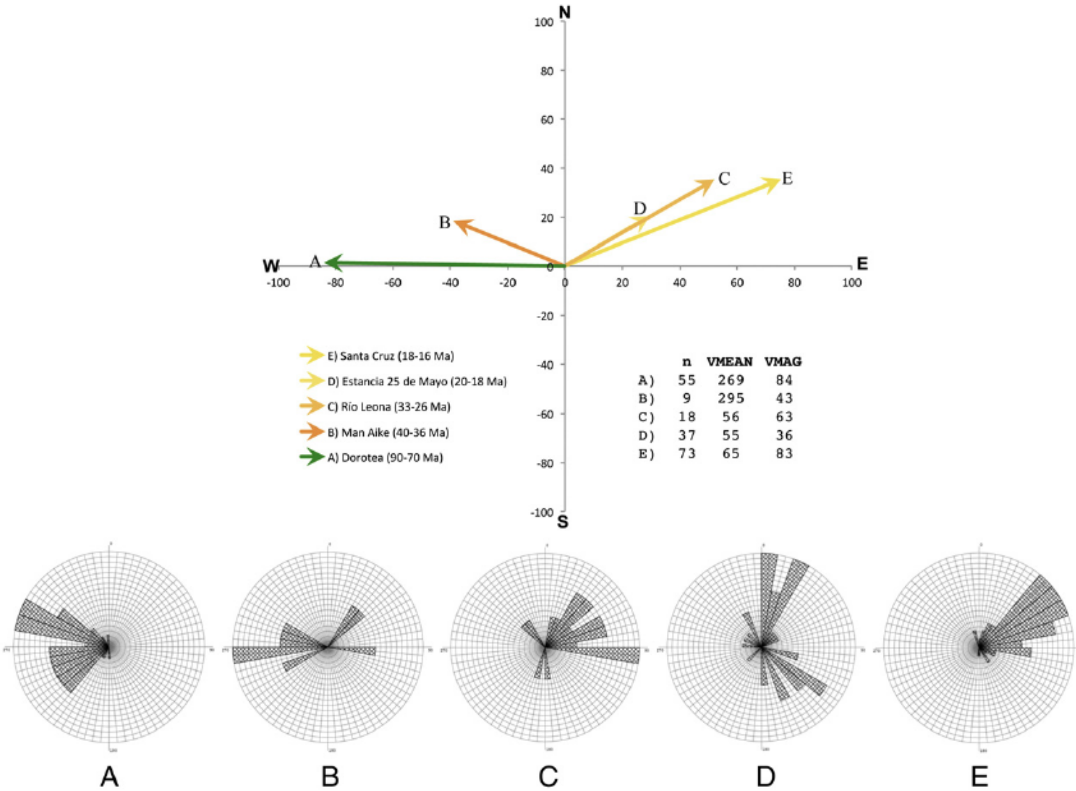

Fig. 10. Rose diagrams of palaeocurrent directions in the different formations of the Sierra Baguales. A) Dorotea Formation; B) Man Aike Formation; C) Estancia 25 de Mayo Formation; D) Río Leona Formation; E) Santa Cruz Formation.

(Turonian) and 81.7 ± 1.7 Ma (Campanian), using Sr isotopes as well as detrital and volcanic zircons. The last age is supported by the presence of *Hoplitoplacenticeras plasticus* and *H. semicostatus* ammonites at Cerro Cazador (Paulcke, 1907). Her sample SdT-Wc, collected from just north of Lago del Toro about 40 km south of the Sierra Baguales, contained 2 detrital zircons with ages exceeding 1000 Ma, 13 with ages between 672 and 251 Ma, and 16 between 155 and 93 Ma. These are here assigned to groups I, IIe and IIIe, respectively.

6.2. Dorotea Formation

Sample Zr-PTO-123 (Fig. 11, top) was collected from the base of the Dorotea Formation at Cerro Guido. The results of detrital zircon dating show 5 populations with ages ranging from 636–480 Ma, 423–310 Ma, 270–171 Ma, 151–139 Ma, and finally 127–84 Ma. The latter population has a mean maximum depositional age of 92.78 ± 0.76 Ma. However, the youngest zircon yielded a date of 83.9 ± 2.6 Ma (late Santonian). Two further samples, Zr-FB-1 (Fig. 11, bottom) and Zr-FB-2 (Fig. 12, top), were collected in the sector Las Tetas de las Chinas, from the middle and upper part of the Dorotea Formation, respectively. Detrital zircon dating of sample Zr-FB-1 shows 3 populations: the first with ages ranging from 578 to 390 Ma, the second with dates between 158 and 123 Ma, and the third group of 31 zircons varying between 112 and 71 Ma. The mean maximum depositional age is 95.1 ± 1.5 Ma (Cenomanian). Similarly, 3 populations were also identified in sample Zr-FB-2, the first between 512 and 406 Ma, the second from 380 to 268 Ma, and the final group ranging from 152 to 72 Ma. In this case the mean maximum depositional age is 93.7 ± 1.2 Ma. However, two zircons in sample Zr-FB-1 have ages of 74.9 ± 2.1 and 71.0 ± 1.2 Ma (Campanian), respectively, whereas one zircon in sample Zr-FB-2 has an age of 71.7 ± 1.2 Ma. The latter dates are supported by the presence of *Gunnarites sp.*, *Pachydiscus aff. gollevilensis*, and *Pachydiscus cazadoriana* in the Dorotea Formation in the vicinity of Las Tetas de las Chinas (González, 2015). The first two fossils are of Maastrichtian age (Martínez-Pardo, 1965), while the last is from the Campanian-Maastrichtian (Otero et al., 2009). A vertebrate fragment of an *Aristonectes* sp. (Plesiosauria, Elasmosauridae) reported by Otero et al. (2015) at the same locality also indicates a late Maastrichtian age, while the presence of *Hoplitoplacenticeras* ammonite species at Cerro Cazador suggests a Campanian age for the basal part of the Dorotea Formation (Macellari et al., 1989). In addition, in the Cordillera Chica and Sierra Dorotea, where the Dorotea Formation also crops out, maximum depositional ages between 72 Ma and 67 Ma were obtained from detrital zircons (Hervé et al., 2004; Fosdick et al., 2015a, 2015b). Therefore, although the possible age of the Dorotea Formation ranges from the late Cenomanian to Maastrichtian (Late Cretaceous), the youngest zircons as well as ammonite fossils indicate a Campanian-Maastrichtian age.

Taking account of the overlapping ages of the populations from different samples, two general groups can be distinguished, namely IIe, between 636 and 171 Ma, and IIIe, between 158 and 67 Ma.

6.3. Man Aike Formation

A sample from the top of this formation, Zr-PTO-77 (Fig. 12, bottom), from the locality of Chorrillo Jabón shows 3 zircon age populations ranging from 550–450 Ma, 143 Ma–72 Ma, and 49 Ma–35 Ma, respectively. The first two populations therefore correspond to the broad groups IIe and IIIe defined in the Dorotea Formation, while the third, here referred to as IV, is younger. The maximum depositional age of a population with 39 zircons is 40.30 ± 0.47 Ma. A mean maximum zircon age of 40.48 ± 0.37 Ma was also reported by Le Roux (2012a), Bostelmann et al. (2012)

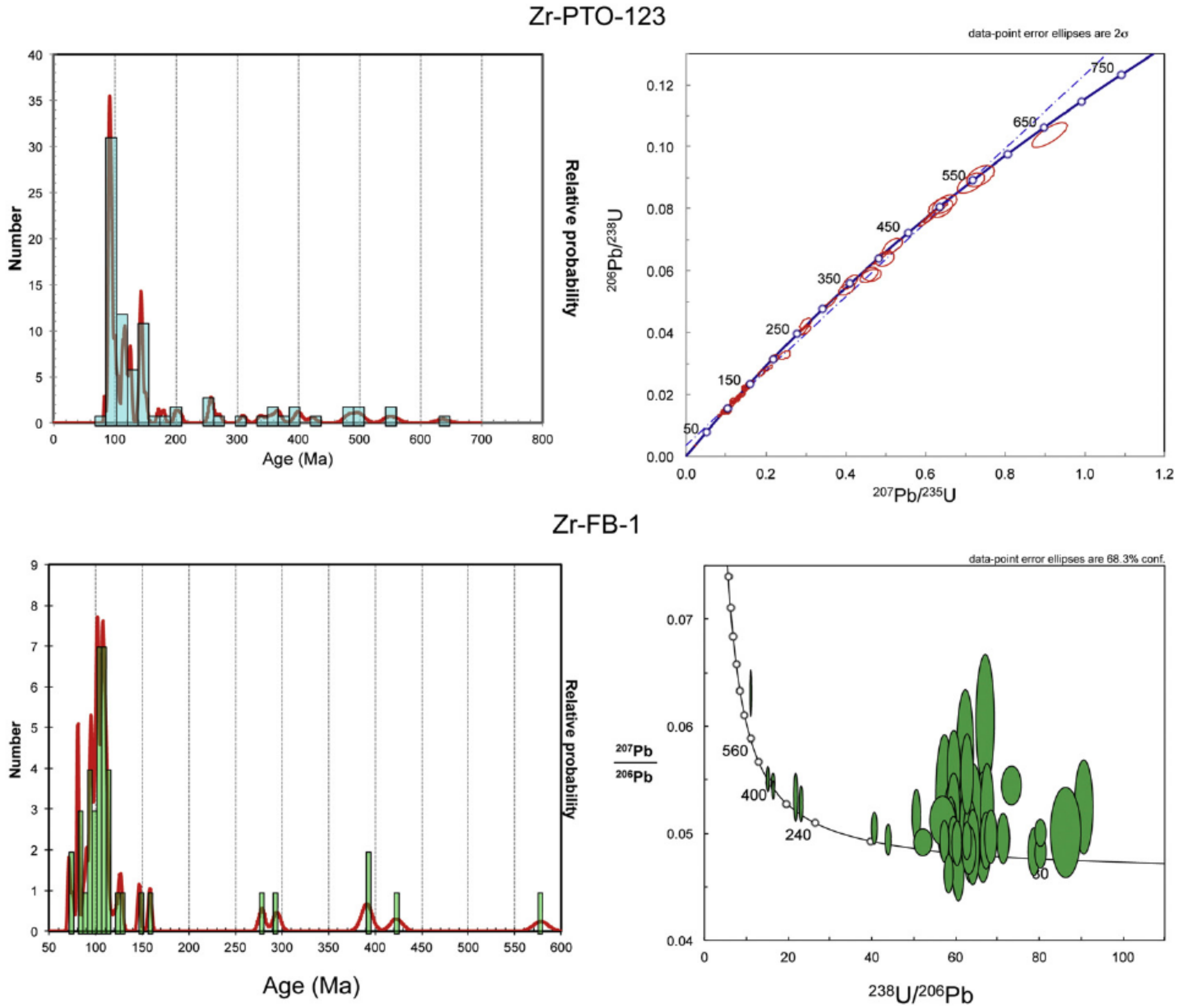

Fig. 11. U-Pb detrital zircon ages in sample PTO-123 and ZR-FB-1 from the Dorotea Formation.

and Otero et al. (2013), so that a latest Lutetian to Bartonian (middle Eocene) age can be accepted. Although Le Roux (2012a) and Bostelmann et al. (2012) never published the details of this sample collected from the top of the Man Aike Formation in a stratigraphic profile measured on Estancia 3R (Le Roux et al., 2010), the results are consistent with those of sample Zr-PTO-77.

6.4. Río Leona Formation

Sample Zr-PTO-81 (Fig. 13, top) was collected from Chorrillo Jabón, being a feldspathic wacke located at the base of the Río Leona Formation. The zircons show three populations, the first with ages exceeding 120 Ma and the second dating between 100 Ma and 76 Ma. Both populations belong to group IIIw. The third population has ages between 43 Ma and 30.8 Ma, therefore belonging to group IV, with a mean calculated age of 35.33 ± 0.57 Ma. Again, the 17 youngest zircons have ages less than 35 Ma, forming a sub-population with a mean of 33.0 ± 2.8 Ma, which is thus taken as the maximum depositional age.

Sample Zr-BAG-25 (Fig. 13, bottom) was collected from Chorrillo las Flores (Fig. 1B) by Ugalde (2014) in the stratotype section of the former Las Flores Formation of Cecioni (1957), which was redefined by the first author as being from the top of the Man Aike Formation. The sample is a feldspathic wacke. The detrital zircon dates show 4 populations, the first with ages exceeding 117 Ma, the second with dates between 108 Ma and 93 Ma, and the third with ages ranging from 80 Ma to 68 Ma. These therefore correspond to group IIIw. The final population lies between 46 Ma and 30 Ma, extending the lower range of group IV by 5 Ma. Although the calculated maximum depositional age for the latter population is 37.0 ± 0.27 Ma (Priabonian), the 16 youngest zircons are all less than 35 Ma old. Taking these as a sub-population, they yield a mean age of 32.83 ± 0.65 Ma, which is here taken to represent the maximum depositional age, i.e. Rupelian (early Oligocene). The presence of fossil leaves of Nothofagaceae, fossil wood belonging to the Araucariaceae, and palynological records of pollen, spores and organic material of plant origin, deposited in an environment of tidal bars and flats (Ugalde, 2014), suggests that this section in fact corresponds to the base of the Río Leona Formation (see Fig. 13, modified from Ugalde, 2014).

The lithological similarity between samples Zr-PTO-81 and Zr-BAG-25, together with the fact that they show very similar zircon population groups and have coinciding maximum depositional ages of 33 Ma, supports the idea that both are from the base of the Río Leona Formation, which is therefore considered to be of Rupelian age.

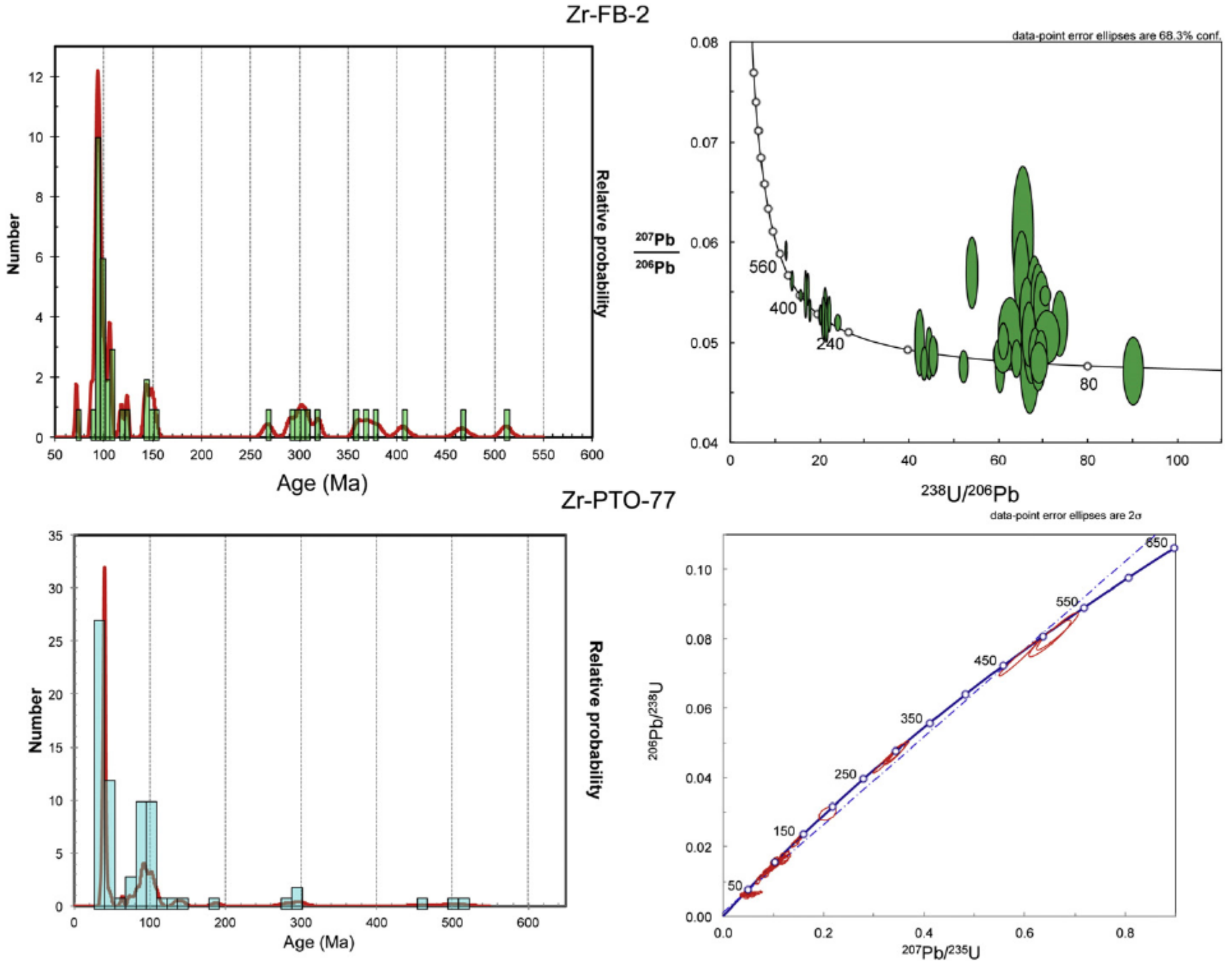

Fig. 12. U-Pb detrital zircon ages in sample Zr-FB-2 from the Dorotea Formation and U-Pb detrital zircon ages in sample Zr-PTO-77 from the Man Aike Formation.

6.5. Estancia 25 de Mayo Formation

It was not possible to date the Estancia 25 de Mayo Formation using detrital zircons in Sierra Baguales. Nevertheless, in the middle part of the stratigraphic section measured in the Alto Río Bandurrias sector, a 2 m-thick pyroclastic bed with a rhyodacitic composition was identified. This pyroclastic event was also recorded in the Quien Sabe Member of the Lago Argentino sector, where it was referred to as "LPL" by Cuitiño et al. (2012), and yielded a zircon U-Pb age of 19.14 ± 0.5. Cuitiño et al. (2015) subsequently dated the stratigraphically equivalent El Chacay Formation in the northern Magallanes-Austral Basin at 20.3–18.1 Ma using strontium isotopes. The Estancia 25 de Mayo Formation is therefore of early Burdigalian age.

6.6. Santa Cruz Formation

Two samples were dated from this formation by Bostelmann et al. (2013) using the SHRIMP U-Pb method. Sample Zr-LF-002 (Fig. 14), located stratigraphically 65 m below Zr-LF-001, yielded 70 zircons. The oldest population showed ages exceeding 1000 Ma, here classified into group I. The second ranged from 700 Ma to 500 Ma, in this paper being considered as part of group IIw because palaeocurrents indicate a source to the southwest instead of the east. The third population, with an age range between 450 Ma and 250 Ma, and the fourth showing ages clustered around 200 Ma, would also form part of group IIw. The fifth population, with ages of 154 Ma – 130 Ma, together with the sixth between 92 Ma and 88 Ma, would belong to group IIIw, distinguished from group IIIe because palaeocurrents indicate a different source area. No younger zircons were present (Fig. 14).

Sample Zr-LF-001 (Fig. 15) was collected from near the top of the exposed Santa Cruz Formation. It contained a total of 70 zircons, of which the oldest 42 could be grouped into 6 populations. The first group has ages between 2927 Ma and 1656 Ma and is here classified into group I. The second population lies between 695 Ma and 560 Ma, the third between 397 Ma and 303 Ma, and the fourth between 299 Ma and 270 Ma, all belonging to group IIw. The fifth population consists of 4 zircons ranging in age between 153 Ma and 142 Ma, and the sixth has 18 zircons dating from 108 Ma to 79 Ma. Both populations belong to group IIIw. For the youngest population of 28 zircons, all falling in group V (with ages less than 25 Ma), Bostelmann et al. (2013) reported a mean calculated age of 18.23 ± 0.22 Ma. However, a new interpretation of these data suggests that the maximum depositional age of the Santa Cruz Formation in the Última Esperanza Province is in fact 16.8 ± 0.22 Ma (late Burdigalian), which is the mean age of a subpopulation of the 8 youngest zircons.

Except for the absence of zircons younger than 25 Ma from sample Zr-LF-001, there is a clear similarity between the population groups of

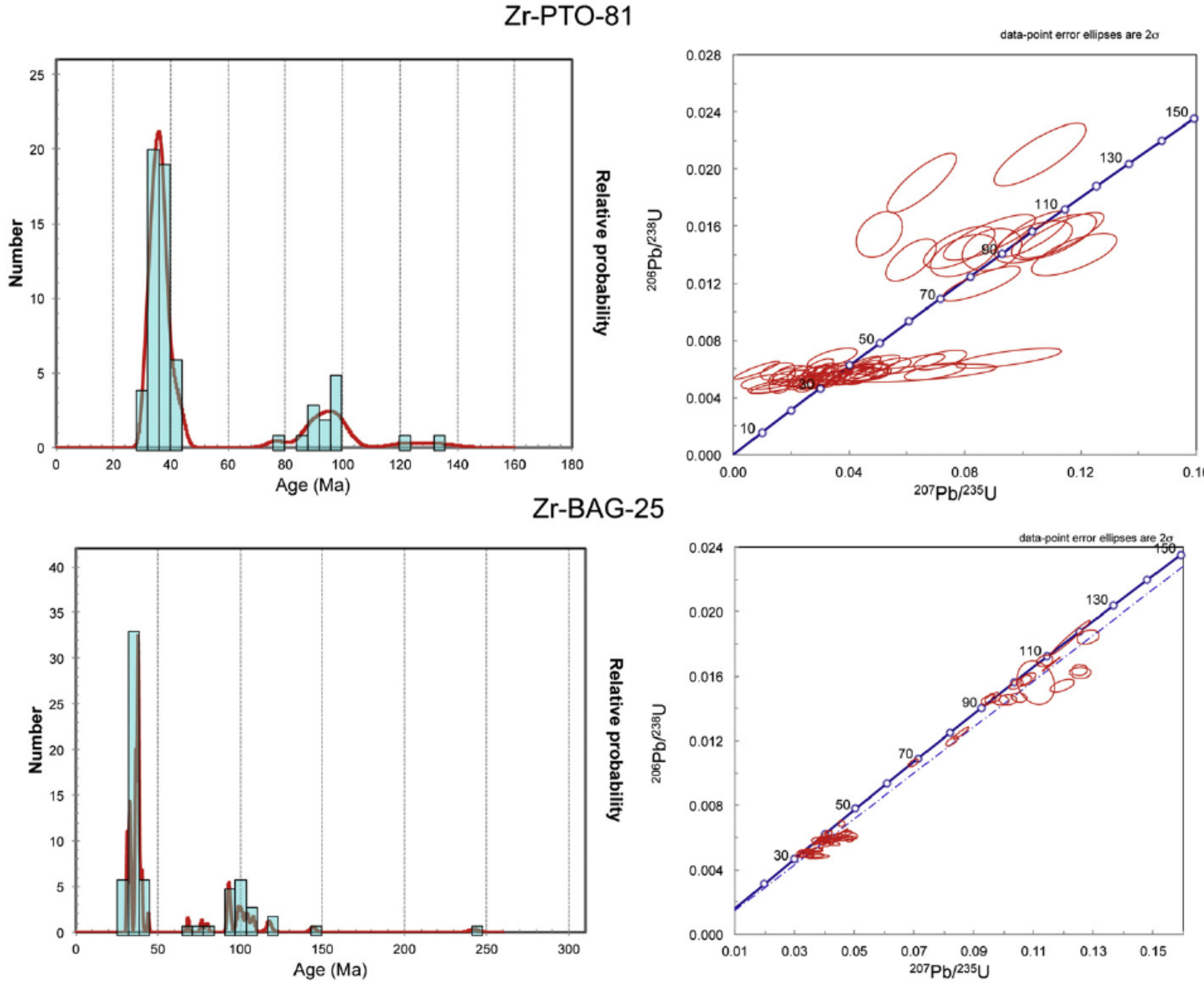

Fig. 13. U-Pb detrital zircon ages in sample Zr-PTO-81 from the Río Leona Formation and U-Pb detrital zircon ages in sample Zr-Bag-25 from the Río Leona Formation (after Ugalde, 2014).

samples Zr-LF-001 and Zr-LF-002, suggesting that the source of the Santa Cruz Formation did not change, but that the younger pluton had either not been exhumed when the base of the formation was being deposited or were not specifically eroded by the rivers delivering detritus to the basin.

7. Zircon provenance areas

Romans et al. (2010) summarized the available evidence from detrital zircon ages that indicate potential source areas for the Late Cretaceous deposits in the Magallanes-Austral Basin, based mostly on the work of Pankhurst et al. (2000), Hervé and Fanning (2003) and Hervé et al. (2007). According to the latter authors, detrital zircons older than 168 Ma were derived from metasediments of the Eastern Andean Metamorphic Complex and the Duke de York Complex, both located to the west of the Magallanes-Austral Basin, while Pankhurst et al. (2000) proposed that volcanic rocks of the Tobífera Formation contributed Early to Late Jurassic zircons (201–145 Ma). The Southern Patagonian Batholith along the southwestern and western side of the basin experienced 3 plutonic episodes dating between 144 and 137 Ma, 136–127 Ma, and 126–75 Ma, providing zircons of these ages (Hervé et al., 2007).

Zircon populations in the Sierra Baguales can be broadly classified into 7 groups, namely I, between 3000 and 1000 Ma; IIe, between 700 and 250 Ma; IIw, between 700 and 200 Ma; IIIe, between 160 and 65 Ma; IIIw, between 155 and 75 Ma; IV, between 50 and 30 Ma; and V, between 25 and 15 Ma. The designations e (east) and w (west) indicate zircons of similar age ranges but different source areas as suggested by palaeocurrent directions. In the western source area groups, there are gaps between 1000–700 Ma, 200–155 Ma, 75–50 Ma, and 30–25 Ma, whereas the eastern provenance area groups show gaps between 250–160 Ma, and 65–50 Ma. In the southern part of the Magallanes-Austral Basin, the zircons dated by Sánchez et al. (2010) from the "Cabo Nariz Beds" range between 165 and 57 Ma, thus roughly coinciding with group IIIe zircons. Three zircon ages fall in group II and two in group I. In the Chorillo Chico Formation near Punta Arenas, which is chronostratigraphically equivalent to the "Cabo Nariz Beds", we only found group IIIe zircons.

The Tres Pasos Formation hosts zircons belonging to groups I, IIe and IIIe, which according to palaeocurent studies and lateral facies changes were derived from source areas to the north of the Magallanes-Austral Basin. Bernhardt (2011) also considered some input from the Andean Fold-and-Thrust Belt to the west. As far as group I zircons is concerned, outcrops of basement rocks with ages exceeding 1000 Ma are scarce in southern South America, currently only known to be present northeast

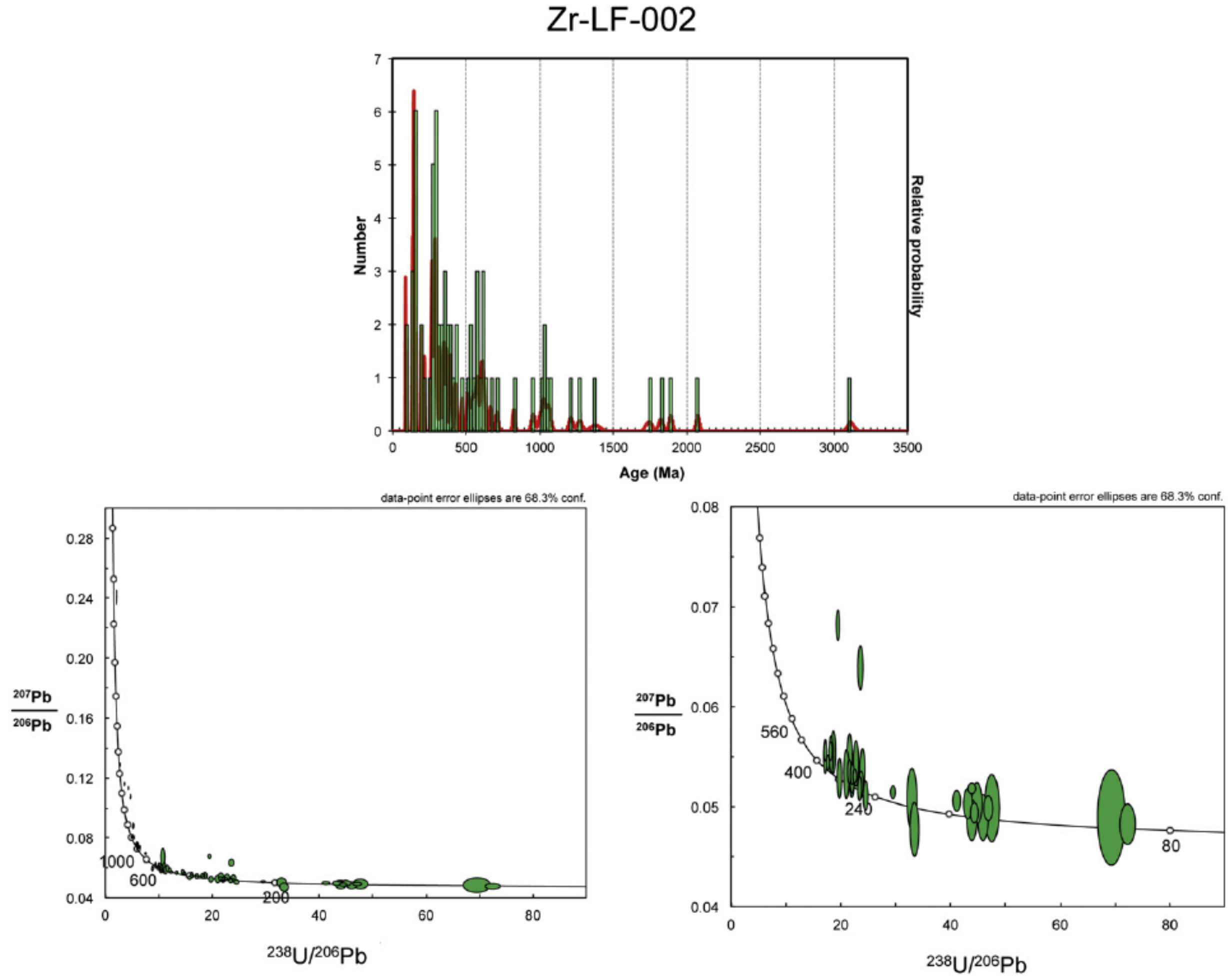

Fig. 14. U-Pb detrital zircon ages in sample ZR-LF-002 from the Santa Cruz Formation (after Bostelmann et al., 2013).

of the Magallanes-Austral Basin in the Río de la Plata Craton where ages between 2200 and 2000 Ma are recorded (Santos et al., 2003; Ramos et al., 2014a, 2014b), and in the North Patagonia Massif where relatively high-grade schists and gneisses with Rb-Sr ages of up to 1190 Ma (Linares et al., 1988) are intruded by Paleozoic granites (Pankhurst et al., 1998). The Kalahari Craton of southern Africa also has Mesoproterozoic rocks (1600–1000 Ma), whereas the Proto-Kalahari Craton dates back to the Archaean (Jacobs et al., 2008). The Magallanes-Austral Basin was at about the same distance from the Kalahari and Río de la Plata Cratons during the Jurassic, so that detritus derived from the northeast could have been diverted into its north-south trending axis.

Some of the group IIe zircons in the Tres Pasos Formation could have been sourced by the Deseado Massif (Fig. 1; 16), where small windows in the Jurassic sequence reveal micaceous and amphibolitic schists of very late Precambrian or Cambrian age, as well as Permo-Triassic plutonic rocks located to the north of the Magallanes-Austral Basin at 40°S (Pankhurst et al., 1998).

The Dorotea Formation, despite being the oldest unit for which zircon data are available in the Sierra Baguales, did not yield zircons representing group I, and obviously also lacks groups IV and V. However, 3 zircons belonging to group I were dated by us in samples from Cerro Castillo. This formation therefore contains groups I, IIe and IIIe. On the other hand, group I zircons do appear to be absent from the Man Aike Formation, as we found only groups IIe, IIIe and IV in Sierra Baguales, whereas the time-equivalent Loreto Formation in the vicinity of Punta Arenas yielded only groups IIIe and IV. It therefore seems that the Dorotea Formation still received some detritus from the Río de la Plata Craton or time-equivalent rocks to the north-northeast, but that this source area became obsolete during deposition of the Man Aike Formation, in which groups IIe, IIIe, and IV are strongly represented.

Although group IIe zircon ages (636–268 Ma) partially overlap with the maximum recorded ages (451–267 Ma) in the Eastern Andes Metamorphic Complex, 62% of the published ages of metamorphic complexes west of the Magallanes-Austral Basin (Hervé et al., 2008; fig. 1) fall in the gap of 250–160 Ma between groups IIe and IIIe. Moreover, zircons between 636 and 451 Ma are represented neither in these metamorphic complexes nor in the Southern Patagonian Batholith. Although group IIIe (160–65 Ma) zircons could have been derived from the latter, where the oldest recorded intrusion age is 157 Ma (Hervé et al., 2007), a source located to the west would contradict the majority of measured palaeocurrent directions.

The region northeast and east of the Magallanes-Austral Basin has a magmatic and metamorphic belt with Paleozoic basement and sedimentary rocks as well as granitoid intrusions, which could have contributed some of the group IIe zircons to the Dorotea and Man Aike Formations (Fig. 16). This prominent geomorphological feature, the

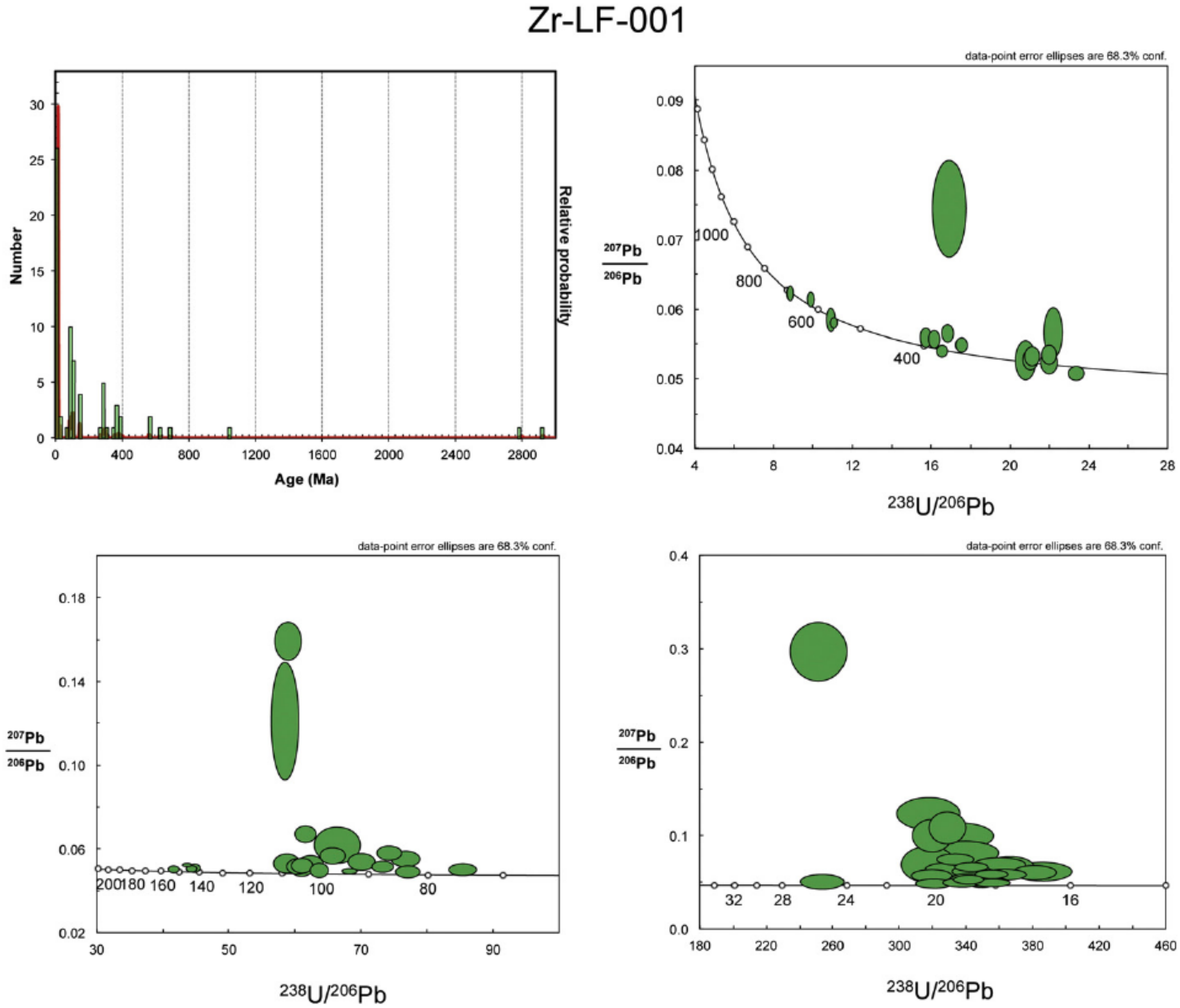

Fig. 15. U-Pb detrital zircon ages in sample ZR-LF-001 from the Santa Cruz Formation (after Bostelmann et al., 2013).

Western Magmatic Arc (e.g. Ramos, 2008), is known as the Río Chico-Punta Dúngenes Arc in its offshore, southeastern extension (Galeazzi, 1996; fig. 1; 16). The Western Magmatic Arc has plutonic and metamorphic rocks in which ages between 476 Ma and 344 Ma have been recorded (Ramos, 2008), and according to this author (Fig. 10) shed detritus westward into the Magallanes-Austral Basin. Another granite pluton in the Western Magmatic Arc with an age of 280 Ma (Ramos, 2008) could have contributed some of the younger zircons to group IIe. On the other hand, older zircons could have been derived from the Deseado Massif, which is situated between the Western Magmatic Arc and Magallanes-Austral Basin (Fig. 16) and where ages between 580 and 346 Ma have been recorded (Permuy Vidal et al., 2014). Basement rocks with ages between 536 and 527 Ma also occur to the southwest of Puerto Dúngenes (Fig. 16) (Hervé et al., 2008; Dickinson, 2009).

Alternatively, Jurassic and Cretaceous zircon populations identified in the Dorotea and Man Aike Formations could have been eroded from the rhyolitic Chon-Aike Province (Fig. 16), which overlaps with the Magallanes-Austral Basin and has plutons with the same ages (Gust et al., 1985; Pankhurst and Rapela, 1995). Some of the zircons in the Man Aike Formation could also have been reworked from the underlying Dorotea Formation, because it shows ample evidence of reworked fossils (e.g. shark teeth) from the latter formation and their contact is a prominent erosional unconformity.

The origin of group IIIe zircons (160–65 Ma) in the Dorotea, Man Aike, and Chorillo Chico Formations is more problematic if sources southeast of the Magallanes-Austral Basin are to be considered because of the recorded palaeocurrent directions. The basin does extend southeastward to the Magallanes-Fagnano Fault System in Fuegian Patagonia where it links up with the Falkland-Malvinas Basin, so that transport could easily have taken place along the basin axis (Fig. 16). However, this implies the existence of a hitherto unidentified point source in the vicinity of the present Cape Horn.

Finally, group IV zircons (50–30 Ma) in the Man Aike Formation were possibly eroded from intrusions of this age around the western exit of the Magellan Strait (Hervé et al., 2007), as some palaeocurrents suggest a possible source to the southwest (Fig. 10B).

In the Río Leona Formation both groups I and II zircons are absent, while groups IIIw and IV are well represented. Plutons with Jurassic-Cretaceous ages that could have provided group IIIw zircons (155–75 Ma) to the Río Leona Formation are common west of the Magallanes-Austral Basin (Fildani et al., 2003; Hervé et al., 2007). The majority are emplaced into the western flank of the Southern Patagonian

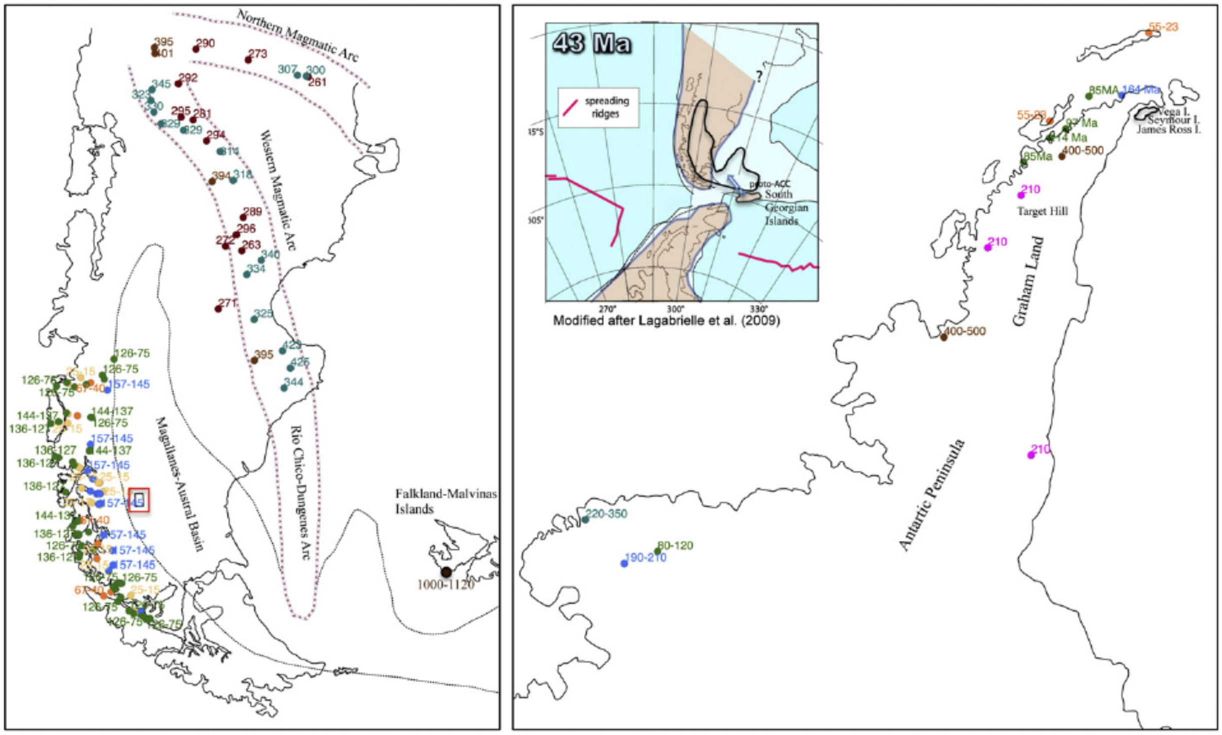

Fig. 16. Distribution of possible detrital zircon source rocks in southern South America and the Antarctic Peninsula. See text for references.

Andes where they form part of the Southern Patagonian Batholith, for example east of the Madre de Dios Archipelago and Duke de York Island around 50°–51°S, at the same latitude as the Sierra Baguales (Fig. 16). In this sector the vast majority of the plutons are of Jurassic to Cretaceous and Neogene age, with only one Paleogene date, which coincides with the zircon age gap between 67 and 49 Ma in the Río Leona Formation.

The absence of group IIe, having been replaced by group IIw in the Río Leona Formation, suggests that the source area had begun to shift by this time, but that group IV was still being contributed. The source of the latter was probably situated between the Pacific end of the Magallanes Strait and the Guadalupe Channel to the north, i.e. to the southwest of the Sierra Baguales (Fig. 16).

The Estancia 25 de Mayo Formation lacks groups I, IIw and IIIw, hosting only group IV, which reflects the dominance of the southwestern provenance that contributed to the Río Leona Formation.

The Santa Cruz Formation has zircons of group I, IIw, IIIw and V, being the only formation in the Sierra Baguales with group I zircons. In this case the Kalahari and Río de la Plata Cratons can be discarded as direct sources due to the recorded northwesterly palaeocurrent trend in the Santa Cruz Formation. However, the reworking of Jurassic and Cretaceous successions, such as the Tobífera, Zapata, Punta Barrosa and Cerro Toro Formations, which do have outcrops to the southwest and west of the Sierra Baguales, could have provided detrital zircons of Precambrian age, as such zircons are known to be present within these rocks. The erosion of these successions implies significant uplift and probably folding to the southwest and west of the Sierra Baguales, which would coincide with the observed change in palaeocurrent directions.

Finally, zircons of Neogene age ranging from 25 Ma to 15 Ma (group V) coincide with early to middle Miocene plutons dated by Hervé et al. (2007) in the Southern Patagonian Batholith between 50° and 51°S, directly to the west of the Sierra Baguales (Fig. 16).

8. Palaeobotany and palaeoclimate

A quantitative reconstruction of terrestrial paleoclimate can be made using fossil leaf morphology (e.g. Wolfe, 1995; Wilf, 1997; Mosbrugger and Utescher, 1997; Mosbrugger, 1999; Kowalski, 2002; Uhl et al., 2007). Estimations of the mean annual precipitation (MAP), mean annual temperature (MAT), and diversity according to the number of morphospecies, were based on 3746 fossil leaves collected at the localities of Barranca de las Hojas and Alto Río Bandurrias in the Río Leona Formation (Fig. 1). The fossil flora of this formation were compared to 4 fossil flora sites (Fig. 1) in Patagonia ranging in age from Paleocene to Eocene, which had been used previously to estimate the MAP and MAT as well as the diversity conditions (Wilf et al., 2005; Hinojosa et al., 2006; Iglesias et al., 2007). The Palacio de los Loros fossil flora of Paleocene age (61.7 Ma) represent a MAP of 166.3 cm, a MAT of 12.2 °C, and a diversity of 39 morphospecies (Hinojosa et al., 2006; Iglesias et al., 2007). The Early Eocene fossil flora of Ligorio Marquez (Hinojosa et al., 2016) indicate a MAP of 108–153 cm and a MAT between 17.2 °C and 20.9 °C, with a diversity of 55 morphospecies (Hinojosa et al., 2006, 2016). At Laguna el Hunco, the fossil floras are of early Eocene age (52 Ma), reflecting a MAP of 193.8 cm, a MAT between 14.8° and 17.7 °C, and a diversity of 122 morphospecies (Wilf et al., 2005; Hinojosa et al., 2011; Peppe et al., 2011; Quattrochio et al., 2013). Finally, the fossil flora of Río Turbio, with a middle Eocene age (45 Ma) indicate a MAP of 152.5 cm, a MAT between 16.1 and 18 °C, and a diversity of 45 morphospecies (Hinojosa, 2005; Hinojosa et al., 2011; Peppe et al., 2011; Quattrochio et al., 2013).

Our data indicate that the Río Leona Formation, with a Rupelian (early Oligocene) age, reflects a MAP of 55–74 cm based on multivariate analysis, and 92–96 cm according to the univariate method. As concerns the MAT, we estimate a range of 6.7 °C–7.7 °C according to the standard equations for Chile ($MAT = 18.85 * pE + 3.83$) and South America ($MAT = 26.03 * pE + 1.31$) (Hinojosa et al., 2011) and between 7.6

and 11 °C according to CLAMP (Climate Leaf Analysis Multivariate Program) (Wolfe, 1993, 1995; Kovach and Spicer, 1995; Wolfe and Spicer, 1999; Spicer, 2000; Spicer et al., 2004) including the CLAMP3bSA dataset (Hinojosa, 2005). Diversity in the Río Leona Formation includes a total of 24 dicotyledoneous morphospecies, in which the families *Nothofagacea*, *Mirtaceae*, *Cunoniacea*, *Sapindaceae*, *Gesneriaceae*, *Leguminosae*, *Monimiaceae*, *Grosulariaceae*, *Berberidaceae*, *Blechnaceae*, and *Podocarpaceae* stand out. These have a typical Mixed Flora phytogeographic character and indicate the oldest cold and dry forests in Patagonia.

The MAP, MAT and diversity conditions mentioned above illustrate the palaeoclimatic evolution and composition of forests in Patagonia, where Paleocene-Eocene, high-diversity forests flourishing under high precipitation and temperature conditions during the Eocene were replaced by low-diversity forests with low MAP and MAT conditions during the early Oligocene (Fig. 17).

The decrease in temperature recorded in the fossil flora of the Río Leona Formation between the Lutetian/Bartonian and early Oligocene coincides with the opening of the Drake Passage, which caused the first influx of Pacific sea-water into the Atlantic Ocean (Scher and Martin, 2006) and the development of the Antarctic Circumpolar Current (Barker, 2001). This event rang in the start of glaciation in Antarctica, as manifested in the global Oi-1 sea level fall (Zachos et al., 1996), an increase in deep-sea $\delta^{18}O$, and a decrease in atmospheric CO_2 (Zachos et al., 2001; Beerling and Royer, 2011). This cooling period, referred to as the Bartonian-Rupelian Cooling by Le Roux (2012a, 2012b), was not only subcontinent-wide but global. Independent records of palynomorph species diversity in the Río Leona Formation (Barreda et al., 2009) also indicate a decrease in temperature, and a similar trend is observed during the Cenozoic at tropical latitudes (Jaramillo et al., 2006).

On the other hand, the precipitation registers a decrease from 150 to 200 cm during the Paleocene and Eocene to less than 80 cm (55–70 cm) during the Oligocene. This decrease in precipitation went hand-in-hand with a decrease in morphospecies diversity in Patagonia, passing from 39 to 131 in the Paleocene fossil flora of Palacio de los Loros and the Eocene fossil flora of Laguna el Hunco, to only 29 morphospecies in the palaeoflora of the Río Leona Formation. The decrease in precipitation and morphospecies diversity in the Sierra Baguales can be related to the rise of the Southern Patagonian Andes as an orographic barrier to the Westerly Winds and creating a rain shadow to the east thereof, which is consistent with the abrupt change in palaeocurrent directions and zircon source areas between the Priabonian and Rupelian (~34 Ma). Topographic forcing on climate only begins to take effect at around 1000 m (Browning, 1980), so that this amount of uplift would have represented a major pulse in the Andean tectonic cycle. Palaeocurrents from the southwest at this time also agree with the present strike and dip of the Sierra Baguales strata, which are mainly tilted towards the northeast. It can therefore be postulated that tectonic compression at this time was directed from the southwest. At Cabo Nariz in Bahía Inútil (Fig. 1), our measured mean strike of 292° is consistent with this trend.

9. Discussion and conclusions

The different lines of evidence presented above, including the recorded changes in depositional environments, palaeocurrent directions, zircon source areas, and palaeoclimate, all coincide in the following sequence of tectonic events:

During the Late Cretaceous the depositional environment changed from a continental slope system with turbidites in the Tres Pasos Formation to deltaic conditions in the overlying Dorotea Formation. This shallowing-upward succession suggests that tectonic uplift started during the late Campanian. Palaeocurrents were rather variable with a full range between northeast and southeast, but being mainly from the east. The most probable source consisted of the Western Magmatic and Río Chico-Punta Dúngenes Arcs (as previously proposed by Ramos, 2008), as well as the rhyolitic Chon-Aike Province.

Tectonic uplift continued after deposition of the Dorotea Formation, causing a 30 m.y.-long period of erosion that lasted throughout the Paleocene and most of the Eocene (~70–40 Ma), ending with the deposition of the Man Aike Formation. The latter succession still received its detritus from the east and southeast, suggesting that the erosion was caused by tectonic uplift focused in this area. Although the eastern provenance can possibly still be attributed to the Río Chico-Punta Dúngenes Arc, the southeastern source needs another explanation. We propose that a local continental plate fragment was attached to the eastern end of Fuegian Patagonia and immediately to the south of the Falkland-Malvinas Plateau Basin. Our zircon data suggest that it may have formed part of the Antarctic Peninsula and/or its northeastern extension.

Zircon ages between 120 Ma and 80 Ma have been registered from the northern tip of the Antarctic Peninsula (Fig. 16) (Pankhurst, 1990). This area could also have contributed some group IIe zircons, as crystalline basement crops out at Target Hill and elsewhere in Graham Land (Fig. 16), where whole-rock ages of 410 ± 15 and 426 ± 12 Ma have been obtained (Milne and Millar, 1989).

The relative position of the Antarctic Peninsula with respect to southern South America during the Mesozoic and Cenozoic is still problematic (Miller, 2007), although many accept that it was located west of South America from the Middle to Late Jurassic (e.g., Grunow et al., 1987; Lawver and Scotese, 1987; Hanson and Wilson, 1991; Ghidella et al., 2002; Hervé and Fanning, 2003; Hervé et al., 2008; Breitsprecher and Thorkelson, 2009) and from there drifted southward along the South American Plate boundary. A problem with this interpretation is that Late Cretaceous and Cenozoic strike-slip faults in the Southern Patagonian Andes as well as on the eastern side of the Antarctic Peninsula are dominantly right-lateral (Storey and Nell, 1988; Diraison et al., 2000), which contradicts this notion. On the other hand, Seton et al. (2012; figs. 18–22) show the position of the Antarctic Peninsula as essentially unchanged to the south-southwest of Patagonia between 200 and 120 Ma, from where it drifted north and east, almost becoming a southward continuation of Fuegian Patagonia by 60 Ma. Diraison et al. (2000; fig. 3b and c) indicate this position to have been reached between 90 and 50 Ma, and that by the latter date, South Georgia was located along the northern boundary of the Scotia Plate. Several other authors have also indicated the position of the Antarctic Peninsula immediately to the south of Fuegian Patagonia during the Late Cretaceous (Barker and Lawver, 1988; Lagabrielle et al., 2009; Eagles, 2016a). It has also been suggested that the Antarctic Peninsula was a continuation of Fuegian Patagonia and Cordillera Darwin (Veevers et al., 1984; Pankhurst, 1990; Reguero et al., 2013) extending southeast of the Magallanes-Austral-Falkland-Malvinas Basin even during the Jurassic. However, Eagles (2016b) disputed the proximity of South Georgia to Tierra del Fuego during the Early Cretaceous.

An alternative northeastern extension of the Antarctic Peninsula is the small subsided banks of the Scotia Sea, including Terror Rise, Pirie Rise, and Bruce Bank, which Eagles and Jokat (2014) referred to as Omond Land. Given their present proximity to the Antarctic Peninsula and the South Orkney microcontinent, these could perhaps be more easily reconciled with the postulated southeastern source, which would have been removed by extension, rupture and subsidence during the Eocene.

If our proposal is correct that the northernmost tip of the Antarctic Peninsula and/or its northeastern extension was located immediately southeast of the Magallanes-Austral Basin during the Lutetian, this could have provided detritus to the Man Aike Formation along the northwest-trending basin axis. Uplift here could have been caused by the development of a transform fault with accompanying shoulder elevation, which can easily reach more than 1 km (Buck, 1986; Basile and Allemand, 2002). The most likely candidate here is the North Scotia Ridge, a left-lateral transform boundary forming the eastward extension

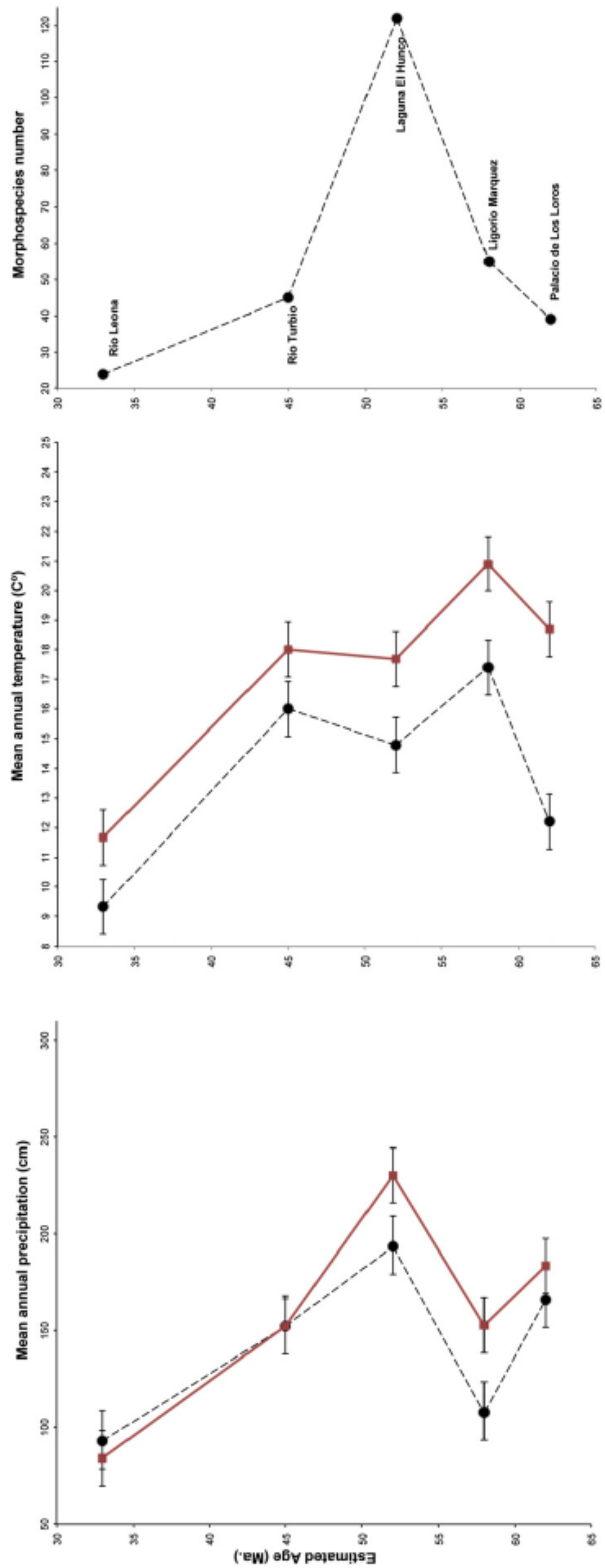

Fig. 17. Palaeoclimatic and palaeodiversity evolution in Patagonia as derived from fossil leaf morphology.

of the Magallanes-Fagnano Fault System in Fuegian Patagonia and stretching east to South Georgia, with a series of shallow banks in between (Eagles and Jokat, 2014). Geophysical surveys indicate that this ridge consists of mainly continental blocks, suggesting post-Cretaceous fragmentation of a formerly continuous continental area (Barker and Griffiths, 1972). It is still unclear whether the South Georgian Islands, presently located on the South American side of the plate boundary, are part of the Scotia Plate or have been recently accreted to the South American Plate (Thomas et al., 2003), but they could present vestiges of such an uplift shoulder. The original position of the South Georgia microcontinent was south of the Burdwood Bank and south of the Falkland-Malvinas Islands, from where it moved further east during the ongoing lengthening of the North Scotia Ridge (Dalziel et al., 2013). Considering the left-lateral movement along this ridge, this would imply that it was originally part of the Antarctic/Scotia Plate and could thus have formed, together with the submerged banks mentioned above, the northeastern extension of the Antarctic Peninsula. The Scotia Plate was formed mainly since a change in relative motion between the South American and Antarctic Plates during the Ypresian (~50 Ma) according to Pelayo and Wiens (1989). Marine geophysical data indicate that motion between the South American and Antarctic Plates at that time shifted from N-S to WNW-ESE, which was accompanied by an eightfold increase in the separation rate (Livermore et al., 2005).

There are many palaeontological similarities between the Antarctic Peninsula and the Magallanes-Austral Basin. For example, Aristonectinae (Plesiosauria) found in the Sierra Baguales are also found on Seymour Island (Gasparini et al., 1984; Chatterjee and Small, 1989; Fostowicz-Frelik and Gaździcki, 2001), James Ross Island (Otero et al., 2014) and Vega Island (O'Gorman et al., 2010) of the Antarctic Peninsula. South Pacific records are so far restricted to the Quiriquina Basin of central Chile, which according to Cecioni (1970) and Le Roux (2012a) was connected to the Magallanes-Austral Basin during the Late Cretaceous. However, plesiomorphic elasmosaurids were present in both the latter basin and the Antarctic Peninsula during the early Campanian, but only appeared in the Quiriquina Basin during the early Maastrichtian (Otero et al., 2015). Furthermore, palaeoichtyofauna of North Atlantic affinity present in both the Magallanes-Austral Basin and on Seymour Island include the chondrichtyan genera *Squatina*, *Pristiophorus*, and *Carcharocles* (Otero et al., 2013; Kriwet et al., 2016). Chondrichthyans were dominant elements in the Antarctic fish fauna during the Paleogene, but decreased in abundance from the middle to late Eocene, during which time bony fishes increased. This decline of chondrichthyans as registered in the Eocene La Meseta Formation on Seymour Island was related to the sudden cooling of seawater, reduction in shelf area, and increasing shelf depth according to Kriwet et al. (2016). Although these authors attributed their disappearance during the late Eocene to climatic conditions rather than plate tectonics, it could also be due to the development of a transform fault and ridge between southernmost South America and the northern tip of the Antarctic Peninsula. Lagabrielle et al. (2009) in fact show the latter immediately to the south of Patagonia at 43 Ma, from where it drifted to the east until 32 Ma, accompanied by strengthening of the Antarctic Circumpolar Current. Up to 25 Ma it was still drifting eastward along the Magallanes-Fagnano Transform Fault-Northern Scotia Ridge stretching from Fuegian Patagonia to the southern border of the Falkland-Malvinas Plateau, from where it began to move south with the development of an ocean ridge in the Drake Passage.

Palaeomagnetic studies indicate that the Antarctic Peninsula-block was located at or near its present-day position with respect to East Antarctica by ~130 Ma, while Antarctic Peninsula-block ~110 and ~85 Ma poles are similar to equivalent age poles from the East Antarctica-block, indicating that little or no relative motion between these two blocks occurred (Grunow, 1993). Poblete et al. (2011) also concluded from their palaeomagnetic studies in the Antarctic Peninsula that the small displacement between the latter and the East Antarctica-block during the Tertiary is probably not discernible by palaeomagnetism. Furthermore, Mid-Cretaceous poles in the northern and southern parts of the Antarctic Peninsula are alike, suggesting that the "S" shape of the peninsula was not due to oroclinal bending since 110 Ma (Grunow, 1993). Fitting the Antarctic Peninsula along the western border of the South American Plate during the Late Cretaceous would therefore require considerable counterclockwise rotation of both the former and East Antarctica to bring them into their present position and orientation. This should also be manifested in left-lateral instead of the observed right-lateral strike-slip faulting along the western side of South America and the eastern side of the Antarctic Peninsula. However, if the Antarctic Peninsula was initially located south-southwest of South America and then drifted north-northeast to become attached to the southeastern tip of Patagonia, it would explain the left-lateral strike-slip direction along the Magallanes-Fagnano Fault System and North Scotia Ridge. The right-lateral strike-slip faulting observed at the eastern side of the Antarctic Peninsula could be due to its southwestward drift along the South Scotia Ridge after separation from the South Georgian-Falkland-Malvinas continental fragment. This whole process would require very little rotation to bring it into its present orientation, which would agree with the 10° postulated by Poblete et al. (2011).The Man Aike Formation was deposited in a coastal (estuarine) environment, which indicates that uplift of the postulated ridge shoulder between the Scotia and South American Plates had come to an end by 40 Ma and that denudation or minor subsidence brought the region closer to base level.

Renewed uplift followed during deposition of the Río Leona Formation, maintaining a continental environment close to base level until the Rupelian (early Oligocene). The source areas by now had shifted to the southwest, reflecting the initial uplift of the Southern Patagonian Andes at around 34 Ma. This uplift led to the development of a rain shadow to the east of the latter, causing a marked decrease in precipitation. It was accompanied by a drop in temperature and a decrease in morphospecies diversity, which was also reflected globally at the time. This can be attributed to the complete separation of the Antarctic Peninsula from South America, with the final opening of the Drake Passage that allowed the generation of the Antarctic Circumpolar Current and the Bartonian-Rupelian Cooling period leading to the glaciation of Antarctica (Le Roux, 2012a).

A period of crustal subsidence occurred at around 19 Ma that caused the Patagonian Transgression, as reflected in the marine Estancia 25 de Mayo Formation. This was followed by a period of accelerated plate convergence together with slab detachment at around 17 Ma, causing another period of rapid uplift in the Southern Patagonian Andes. Apatite fission track ages from the western flank of the Andean segment suggest that 3–4 km of denudation occurred in this region since 17 Ma (Blisniuk et al., 2006). This uplift bought the Sierra Baguales area above base-level and led to the establishment of the continental depositional environment of the Santa Cruz Formation. Zircons probably derived from older, underlying formations were now being exposed to the west, suggesting that folding accompanied this uplift.

Acknowledgements

This research was financially supported by Project ANILLOS ATC-105 and Projects FONDECYT 1130006 and 1150690, being carried out under the auspices of Project CONICYT/FONDAP 15090013. N.M.G. is grateful for the grant "Beca CONYCYT de Estudios de Doctorado para Extranjeros en Chile". Detrital zircon dating was carried out by Mathieu Leisen in the Mass Spectrometry Laboratory of the Andean Geothermal Centre of Excellence. Victor Ramos and an anonymous reviewer provided much-appreciated comments which helped to improve this manuscript considerably.

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3.2 Capítulo II:

Evidence for Microthermal forest dominated by *Nothofagus* in Patagonia: Palaeotemperature, palaeoprecipitation and palaeodiversity during the Oligocene as reflected by plant macrofossils in the Sierra Baguales, Chile.

Articulo enviado a la revista Palaeogeography, Palaeoclimatology, Palaecology, el manuscrito presenta observaciones mayores, modificaciones que fueron consideradas en el presente capítulo, actualmente el manuscrito se encuentra sometido nuevamente.

Evidence for microthermal forest dominated by *Nothofagus* in Patagonia: Palaeotemperature, palaeoprecipitation and palaeodiversity during the Oligocene as reflected by plant macrofossils in the Sierra Baguales, Chile

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Abstract

The morphology of more than 3,700 fossil leaves from the Oligocene Río Leona Formation in the Sierra Baguales of Chilean Patagonia was analyzed using different statistical techniques. The association is dominated by *Nothofagus* genera, which constitutes 65% of the total in comparison with 7.5% of the second most abundant morphospecies. The collection can be classified as Mixed Palaeoflora of the Austral-Antarctic association. Of the 29 different morphospecies identified, 24 are dicotyledons. Samples from two sites at the base and upper middle part of the Río Leona Formation, indicate a decrease in morphospecies diversity and richness with time, which was accompanied by a turnover of species. There is also a marked decrease in diversity compared to dicotyledon morphospecies from Eocene rocks elsewhere in Patagonia. The foliar morphology indicates cold and dry climatic conditions, with a mean annual temperature of 9.2°C, a relatively high seasonality in temperature and precipitation, and a mean annual precipitation of 120 cm. *Nothofagus* only became dominant in southeastern Patagonia during the Rupelian, coinciding with a marked global cooling period linked to the initiation of glaciation in Antarctica. However, the decrease in precipitation since 34 Ma is attributed to the development of a rain shadow to the east of the rising Southern Patagonian Andes, which must have been of the order of 1000 m or more for topographic climate forcing to take effect. This contrasts with the rain shadow development east of the Andes at lower latitudes, which was mainly manifested after the middle Miocene.

Keywords: Río Leona Formation; palaeoclimate; Andean tectonics; Bartonian-Rupelian cooling

1. Introduction

During the Cenozoic, various periods of maximum sea-surface temperatures have been recorded worldwide. Many authors (e.g. Vincent and Berger, 1985; Martínez-Pardo, 1990; Tsuchi, 1990, 1992; Dickens et al., 1995; Zachos et al., 2001; Thomas et al., 2002; Bohathy and Zachos, 2003) recognized four of these events, namely the Paleocene-Eocene Thermal Maximum (59–52 Ma), the Eocene Climatic Optimum (52–50 Ma), the Late Oligocene Warming (27–26 Ma), and the Middle Miocene Climatic Optimum (17–15 Ma). Around southern South America and the Antarctic Peninsula, Le Roux (2012) identified five warming periods, which he referred to as the TYW (Thanetian-Ypresian: 60–55 Ma), LW (Lutetian: 49–41 Ma), CW (Chattian: 28–24 Ma), BLW (Burdigalian-Langhian: 21–15), and MPW (Messinian-Pliocene: 6–2.8 Ma). These episodes were apparently linked to an acceleration in ocean plate spreading rates, during which ocean currents were warmed by increased volcanic activity along the mid-oceanic ridges (Le Roux, 2012).

Five cooling periods have also been identified in this region since the Late Cretaceous (Le Roux, 2012), namely the SDC (Santonian-Danian: 86–60 Ma), YC (Ypresian: 55–49 Ma), BRC (Bartonian-Rupelian: 41–28 Ma), AC (Aquitanian: 24–21 Ma), and STC (Serravalian-Tortonian: 15–6 Ma). The middle of the BRC was marked by a very abrupt temperature decline, widely known as the Oi-1 Glaciation (Zachos et al., 2001) that coincided with the opening of the Drake Passage, the creation of the Antarctic Circumpolar Current, and the initiation of the Antarctic Ice Cap around 35 Ma (Barker, 2001; Zachos et al., 2001; Liu et al., 2009).

The distribution and floral composition of the present southern South American forests result from a long history of interaction between the biota, geological processes and climate changes during the Cenozoic (Romero, 1978; Romero, 1986; Arroyo et al., 1996; Hinojosa and Villagrán, 1997; Villagrán and Hinojosa, 1997; Troncoso and Romero, 1998; Hinojosa, 2003, 2005; Wilf et al., 2005; Quattrocchio et al., 2013). Paleoclimate estimates of the Mean Annual Temperature (MAT) based on the relationship between plant leaf physiognomy and climate (Wolfe, 1979, 1995; Wilf, 1997; Wing, 1998; Jacobs, 1999; Gregory-Wodzicki, 2000; Burnham et al., 2001; Hinojosa, 2005; Hinojosa et al., 2011; Peppe et al., 2011) showed that during the Paleogene, MAT values were 0.6–12ºC warmer than the present MAT in southern South America (Wilf et al., 2005; Hinojosa, 2005; Iglesias et al., 2007; Quattrochio et al., 2013; Hinojosa et al., 2016; Gutiérrez et al., 2017) . During the Eocene Climatic Optimum, the MAT reached a difference of 9–12ºC with the present MAT, but since then declined considerably until the Oligocene, reaching minimum values that were only 0.6–1ºC warmer than the present MAT (Hinojosa et al., 2011; Peppe et al., 2011; Quattrocchio et al., 2013). This decline in temperature coincides roughly with the BRC (41–28 Ma) of Le Roux (2012).

Palynological analysis in tropical zones has shown that changes in plant diversity and composition during the Cenozoic were sensitive to global temperature changes (Jaramillo et al., 2006). For example, fossil palynomorphs show that the very rapid climate warming experienced around 56 Ma during the TYW or Paleocene-Eocene Thermal Maximum, triggered an increase in plant diversity, which accompanied high amounts of rainfall and elevated temperatures (Rull, 1999; Jaramillo, 2002; Jaramillo et al., 2006).

Between the Paleocene and middle Eocene (65.5–40.4 Ma) the palaeoflora of southern South America registered a change in its floral composition, passing from Tropical Gondwana Palaeoflora to Subtropical Gondwana Palaeoflora. The fossil floras of Laguna del Hunco and Río Pichileufú (Argentinian Patagonia; ~42°– 45ºS), for example, show high diversity indices at around 52 Ma during the Eocene (Wilf et al., 2005; Iglesias et al., 2007) in what may constitute evidence of the climate change proposed by Rull (1999) and Jaramillo (2002) for this moment in geological time. Since the end of the Eocene (35.9 Ma), however, the Subtropical Gondwana Palaeoflora was replaced by Mixed Palaeoflora (Hinojosa and Villagrán, 1997, 2005; Hinojosa et al., 2006; Quattrocchio et al., 2013). The first South American Mixed Palaeoflora appeared for the first time in Antarctica during the Paleocene (Dusén, 1916) and expanded towards the north to reach 30ºS during the Eocene. In the Oligocene, the Mixed Palaeoflora remained restricted to subtropical latitudes between 38º and 30ºS (Romero, 1978; Romero, 1986; Hinojosa and Villagrán, 1997; Villagrán and Hinojosa, 1997; Troncoso and Romero, 1998; Hinojosa, 2003, 2005; Quattrocchio et al., 2013).

In South America, there are very few studies showing the behavior of vegetation during cooling episodes, such as that which occurred during the BRC. Floras of Oligocene age in South America are scarce and records only exist in Patagonia, in the late Eocene to early Oligocene Río Guillermo Formation near Santa Cruz (Panti et al., 2011) and in the Lago Argentino sector in the late Oligocene Río Leona Formation (Césari et al., 2015). For both floras, cold-temperate, humid climates are assumed (Panti et al., 2011; Césari et al. 2015).

In the Sierra Baguales (SB) of the Última Esperanza Province, we collected fossil leaves from the Río Leona Formation, which is of Rupelian age (Gutiérrez et al., 2017). These were used to investigate the response of vegetation, in terms of diversity and composition, to tectonic and climatic changes such as the opening of the Drake Passage to the east and south, uplift of the Southern Patagonian Andes to the west, and global climatic variations during the Oligocene.

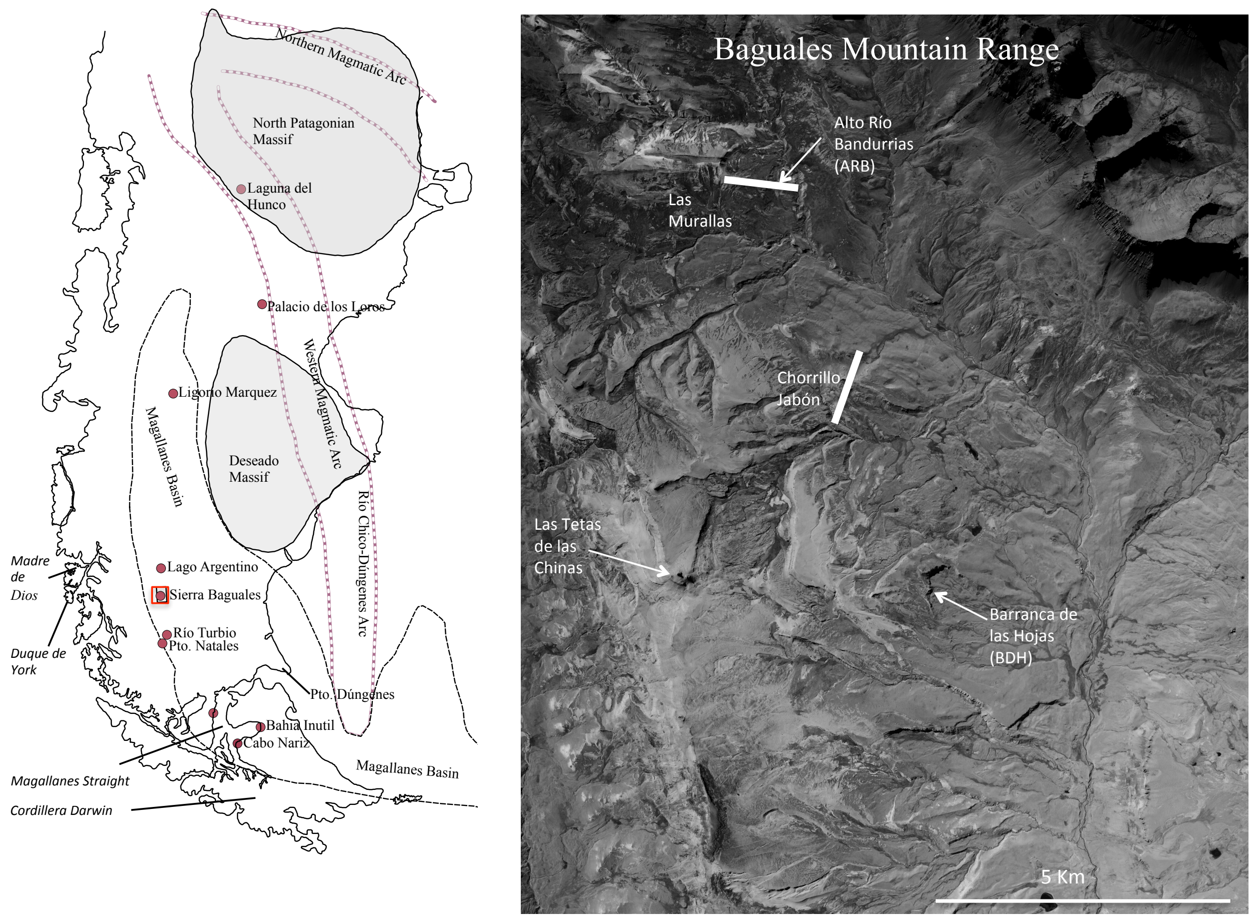

Fig. 1. Locality map of South America and the Sierra Baguales showing tectonic elements and Tertiary fossil leaf localities.

2. Methodology

2.1. Collection and preparation of fossils

During the field campaign, a total of 3,746 fossil leaves were collected, 3,000 at Barranca de las Hojas (BDH) and 746 at Alto Río Bandurrias (ARB), which were studied at the Geology Department of the University of Chile. Each fossil imprint was revealed using a Dremel pneumatic tool, and a code was assigned showing its locality and number.

2.2. Identification and classification

The morphological characterization and description of fossils were carried out using the terminology in the "Foliar Architecture Manual" (Leaf Architecture Working Group; Ellis et al., 1999). Diagnostic morphological characteristics were thus highlighted to allow the individualization of each morphotype and distinguish it from other similar morphotypes. The identification and assignation of the possible taxonomic affinities of the species were based on the comparison between morphotypes of the Baguales fossil flora (BFF) and those of other fossil flora previously described for the Oligocene and Eocene in South America. In addition, for the Nothofagaceae we used the literature on fossil and extant *Nothofagus* taxonomy erected by Hill and Read (1991), although Heenan and Smissen (2013) recently suggested that morphological and molecular differences between the four subgenera are sufficient for these to be recognized as separate genera. However, we do not adopt this revision in the present study, in order to avoid confusion between modern taxonomy and the fossil record (Hill et al., 2015; Hinojosa et al., 2016). Finally, morphological similarities to family level were established between the BFF morphospecies and living species of modern-day Chilean forests.

2.3. Univariate analysis

Univariate methods were used to estimate palaeoclimatic variations based on single foliar morphologies. The "Leaf Margin Analysis" (LMA) was employed to calculate mean annual temperatures, which considers the positive relationship between the percentage of woody dicotyledonous species with entire margins and the mean temperatures at present-day sites (Bailet and Sinot, 1915, 1916). However, variations in this relationship have been detected that depend on the geographic region, as for example in Africa (Jacobs and Deino, 1996), Asia (Wolfe, 1979), Australia (Greenwood et al., 2004), North America (Wolfe, 1993), Europe (Traiser et al., 2005), and South America (Gregory-Wodzicki, 2000; Kowalski, 2002; Hinojosa et al., 2011). In the estimation of mean annual temperatures for the fossil leaves of the BFF, regression analysis of the climatic and morphological variables of 161 sites in the CLAMP 3bSA database (Hinojosa, 2005) was carried out, employing the equations proposed for the South American model (Hinojosa et al., 2011) as well as the global model of mean annual temperature (Peppe et al., 2011). The "Leaf Area Analysis" (LAA) was used to estimate the mean annual precipitation, which is based on the positive relationship between the mean of the natural log of foliar surface areas and the natural log of the mean annual precipitation (Hinojosa, 2005; Wilf et al., 1998).

2.4. CLAMP analysis

The "Climate Leaf Analysis Multivariate Program" (CLAMP; Wolfe, 1990, 1993) establishes the relationship between 31 morphological foliar characteristics of modern-day woody dicotyledonous species and the climatic variables associated with each site. The climatic variables include a dataset with 8 climatic variables, namely mean annual temperature (MAT), warmest month mean temperature (WMMT), coldest month mean temperature (CMMT), length of the growing season, which is the number of months with temperatures exceeding 10°C (GROWSEAS) (Wolfe, 1993), precipitation during the growing season (GSP), mean monthly precipitation during the growing season (MMGSP), precipitation during the three wettest months (3WET), and precipitation during the three driest months (3DRY). The CLAMP analysis uses canonical correspondence analysis as its statistical base (Ter Braak, 1986), which is a direct ordering method placing the site in a multivariate space based on the morphological characteristics of the species that characterized the site and its climatic conditions.

2.5. Rarefaction analysis

The rarefaction method (Gotelli and Colwell, 2011) is used to compare the number of species when the samples differ in size. The species richness is estimated as a function of the size of the smallest sample (Gotelli and Entsminger, 2001).

In the SB the species richness was estimated using rarefaction curves. The morphospecies diversity between the two sites was compared; additionally, a diversity analysis reaching "cutoff" was carried out, in this case using values of 200, 300, and 746 sample counts.

2.6. Diversity analysis

At localities BDH and ARB the Shannon and Simpson diversity indices were estimated, as well as three species richness indices, namely CHAO2, Jackknife 1 and Jackknife 2.

The Shannon index, abbreviated as "H", also known as the Shannon-Wiener or Shannon-Weaver index, expresses the uniformity of the most important values as a function of all the sample species, measuring the mean uncertainty factor in predicting to which species an individual leaf belongs that is chosen randomly from a collection (Peet, 1974; Magurran, 1988; Baev y Penev, 1995). It thus assumes that the individual leaves are selected by chance and that all the species are represented in the sample, having a value of zero when there is only one species.

The Simpson's index of diversity, abbreviated as "λ", shows the probability that two individuals chosen randomly from a sample are the same species. This is strongly influenced by the importance of the dominant species (Peet, 1974; Magurran, 1988). As its value is inverse to equality, the diversity can be calculated as 1- λ (Lande, 1996).

CHAO 2 is an estimator of richness based on the abundance or incidence of species, taking account their presence/absence, in which the number of expected species is estimated considering the relationship between the number of unique species (occurring in one sample) and the number of duplicate species (appearing in two samples).

The Jackknife estimation technique was introduced by Quenouille (1949, 1956). One of its most important applications is the reduction of bias, which can be summarized in two groups, namely bias reduction in punctual estimation, and the construction of confidence limits. The first-order Jackknife estimation (Jackknife 1) is based on the number of species present in only one sample, whereas second-order Jackknife (Jackknife 2) is similar to Jackknife 1, but also considers the number of species in two samples (Magurran, 2004).

3. Geological setting

The analyzed fossil floras are from the Rupelian Río Leona Formation, which crops out in the SB northeast of the Torres del Paine National Park. This area forms part of the Magallanes or Austral Basin, as it is known in Chile and Argentina, respectively.

The sediments of the Magallanes-Austral Basin accumulated between the Jurassic and Pliocene, forming a thick, slightly folded succession. In the SB, the oldest deposits belong to the Cretaceous, starting with the Tres Pasos Formation (Campanian-Maastrichtian), in turn succeeded by the Dorotea Formation (Maastrichtian), Man Aike Formation (early Eocene), Río Leona Formation (early Oligocene), Estancia 25 de Mayo Formation (early Miocene), and Santa Cruz Formation (middle Miocene). The succession is capped by Pliocene lavas with an andesitic composition.

At the Chorrillo Jabón and Alto Rio Bandurrias sites in the SB, a 210 m composite stratigraphic section was measured in the Río Leona Formation (Figs. 1; 2). The deposits formed on a coastal plane with meandering and braided river systems. The fossil record includes tree trunks, some in upright (life) position, and well-preserved leaves that accumulated in swamps and on overbank flood plains with reducing conditions.

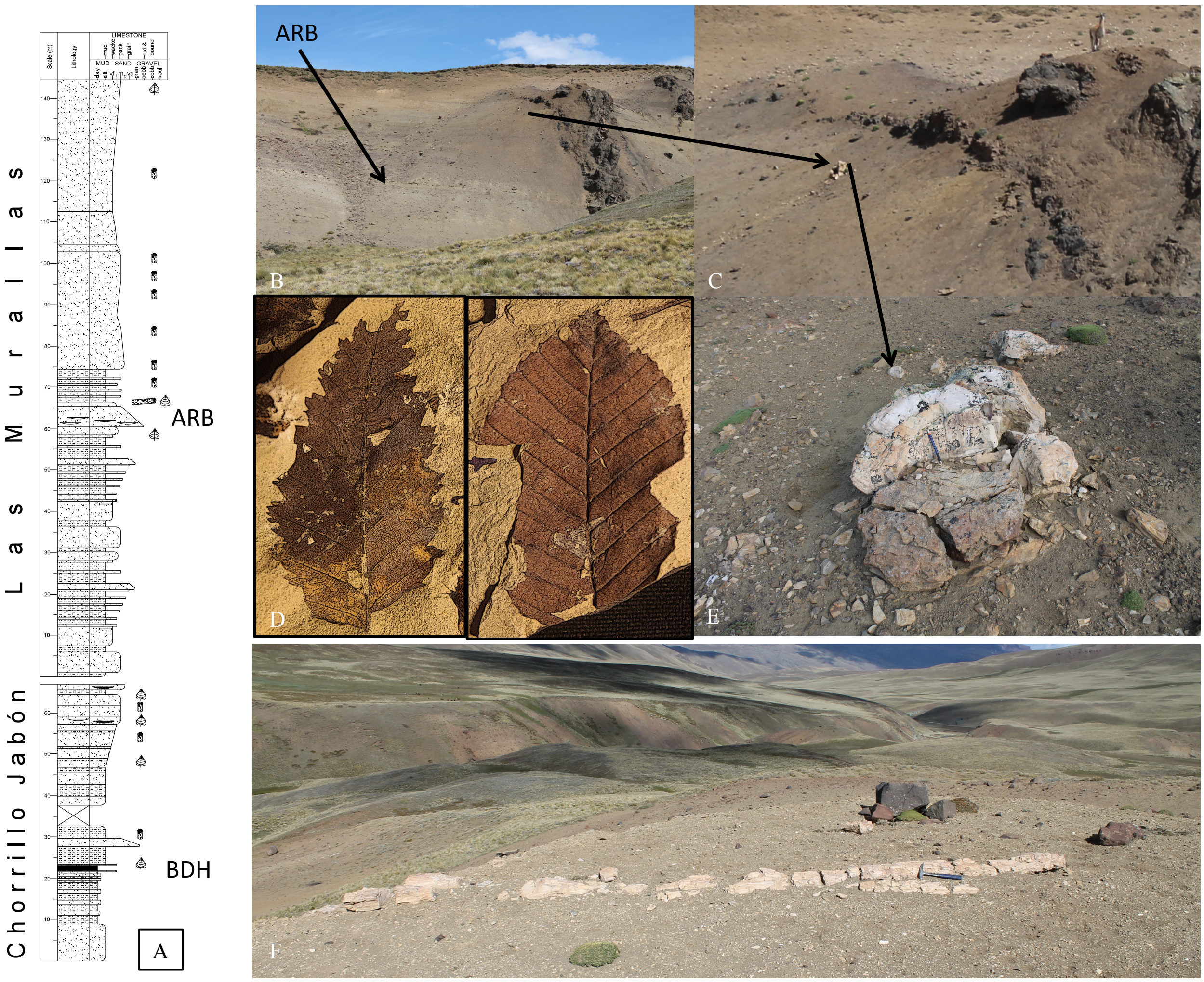

Fig. 2. Measured stratigraphic columns of Río Leona Formation at Las Murallas and Chorrillo Chico. A) Stratigraphic position of Alto Río Bandurrias (ARB) and Barranca de las Hojas (BDH); B) and C) Outcrosps of Río Leona Formation at Las Murallas; D) Well preserved fossil leaves; E) Tree trunk in life position; F) Well preserved big tree trunk

Within the Río Leona Formation, the stratigraphically oldest collection site is at BDH, where the leaves were collected close to its contact with the underlying Man Aike Formation. The ARB locality represents the middle part of the Río Leona Formation.

4. Results

4.1. Diversity and richness estimation

The paleofloral diversity in the BFF totals 29 morphospecies. These paleoflora are composed of 746 fossils collected from the BDH locality at the base of the Río Leona Formation, and 3,000 fossils from the ARB site, stratigraphically above the BDH in the upper middle part of the formation (Fig. 2).

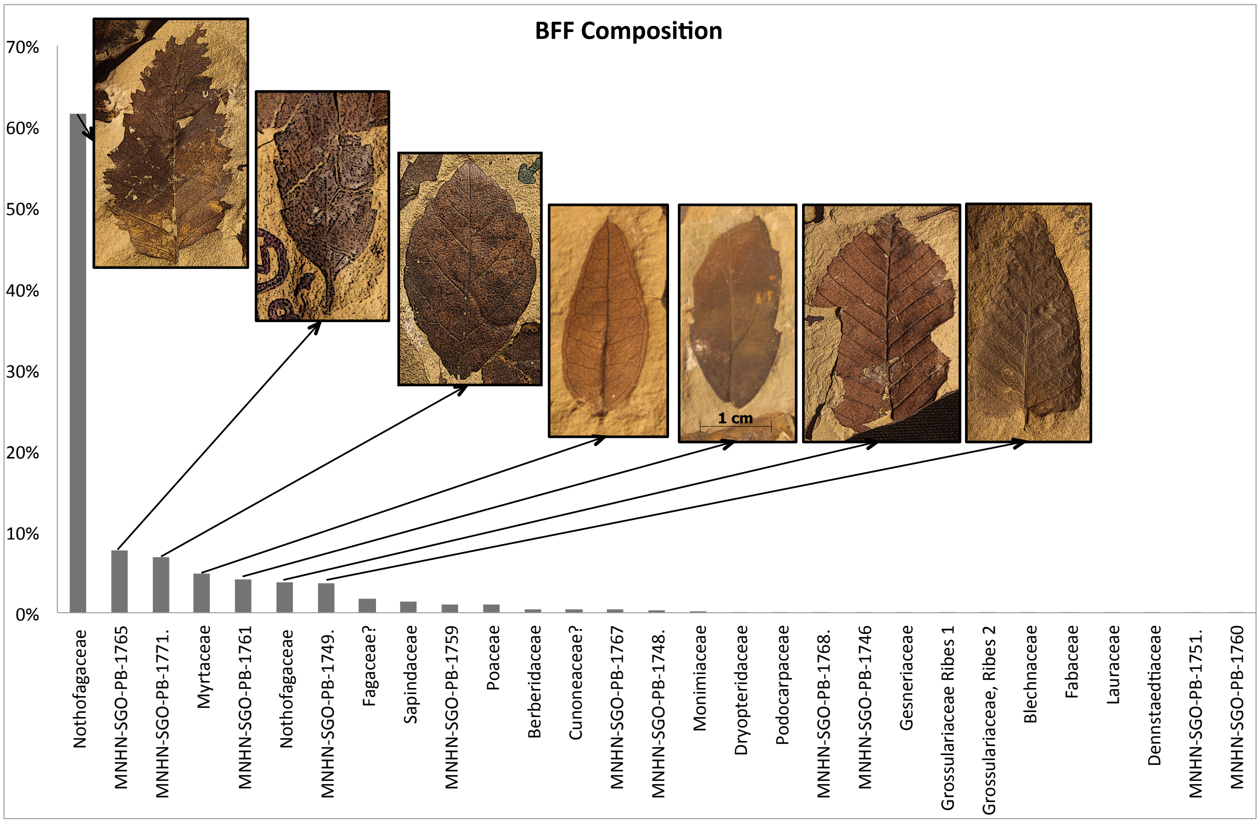

Fig. 3. Relative species abundance and composition of leaves sampled from BFF showing the universal "hollow curve".

Out of the total of 29 identified morphospecies, there are 24 morphospecies of dicotyledons, 3 pteridophytes, 1 monocotyledon, and a gymnosperm. At the family level, an affinity of 18 morphospecies was established, so that the family affinity of only 11 morphospecies could not be assigned (Table 1). In the BFF, the *Nothofagus* genus dominates, reaching almost 65% of the total in comparison with only 7.6% of the second most abundant morphospecies (MNHN-SGO-PB-1765, Fig. 3).

ID MNHN	Division	Affinity (Family)	Genus	Phytogeographic elements.	Oligocene Baguales Flora Fossil
MNHN-SGO-PB-1763.	Magnoliophyta (Dicot)	Nothofagaceae	*Lophozonia*	Austral-Antartico	2307
MNHN-SGO-PB-1765	Magnoliophyta (Dicot)	MNHN-SGO-PB-1765	---	---	286
MNHN-SGO-PB-1771.	Magnoliophyta (Dicot)	MNHN-SGO-PB-1771.	---	---	256
MNHN-SGO-PB-1764.	Magnoliophyta (Dicot)	Myrtaceae	---	---	179
MNHN-SGO-PB-1761	Magnoliophyta (Dicot)	MNHN-SGO-PB-1761	---	---	155
MNHN-SGO-PB-1769	Magnoliophyta (Dicot)	Nothofagaceae	*Fuscospora*	Austral-Antartico	140
MNHN-SGO-PB-1749.	Magnoliophyta (Dicot)	MNHN-SGO-PB-1749.	---	---	138
MNHN-SGO-PB-1758	Magnoliophyta (Dicot)	Fagaceae?	---	---	65
MNHN-SGO-PB-1762	Magnoliophyta (Dicot)	Sapindaceae	*Llagunoa*	Neotropical	50
MNHN-SGO-PB-1759	Magnoliophyta (Dicot)	MNHN-SGO-PB-1759	---	---	40
MNHN-SGO-PB-1753.	Magnoliophyta (Monocot)	Poaceae	---	---	38
MNHN-SGO-PB-1747.	Magnoliophyta (Dicot)	Berberidaceae	*Berberis*	Amplio	17
MNHN-SGO-PB-1770	Magnoliophyta (Dicot)	Cunoneaceae?	---	Austral Asiatica	16
MNHN-SGO-PB-1767	Magnoliophyta (Dicot)	MNHN-SGO-PB-1767	---	---	16
MNHN-SGO-PB-1748.	Magnoliophyta (Dicot)	MNHN-SGO-PB-1748.	---	---	12
MNHN-SGO-PB-1745.	Magnoliophyta (Dicot)	Monimiaceae	*Peumus*	Endémico	5
MNHN-SGO-PB-1755.	Pteridophyta	Dryopteridaceae	*Polystichum*	---	4
MNHN-SGO-PB-1742.	Pinophyta (Gymnosperm)	Podocarpaceae	*Podocarpus*	Pantropical	3
MNHN-SGO-PB-1768.	Magnoliophyta (Dicot)	MNHN-SGO-PB-1768.	---	---	3
MNHN-SGO-PB-1746	Magnoliophyta (Dicot)	MNHN-SGO-PB-1746	---	---	3
MNHN-SGO-PB-1756.	Magnoliophyta (Dicot)	Gesneriaceae	*Mitraria*	Endémico	2
MNHN-SGO-PB-1750	Magnoliophyta (Dicot)	Grossulariaceae Ribes 1	*Ribes*	Amplio	2
MNHN-SGO-PB-1743	Magnoliophyta (Dicot)	Grossulariaceae, Ribes 2	*Ribes*	Amplio	2
MNHN-SGO-PB-1740.	Pteridophyta	Blechnaceae	*Blechnum*	---	2
MNHN-SGO-PB-1757	Magnoliophyta (Dicot)	Fabaceae	*Senna*	Pantropical	1
MNHN-SGO-PB-1744.	Magnoliophyta (Dicot)	Lauraceae	---	Pantropical	1
MNHN-SGO-PB-1741.	Pteridophyta	Dennstaedtiaceae	*Histiopteris*	---	1
MNHN-SGO-PB-1751.	Magnoliophyta (Dicot)	MNHN-SGO-PB-1751.	---	---	1
MNHN-SGO-PB-1760	Magnoliophyta (Dicot)	MNHN-SGO-PB-1760	---	---	1

Table 1. Out of the total of 29 identified morphospecies. At the family level, an affinity of 18 morphospecies was established, so that the family affinity of only 11 morphospecies could not be assigned

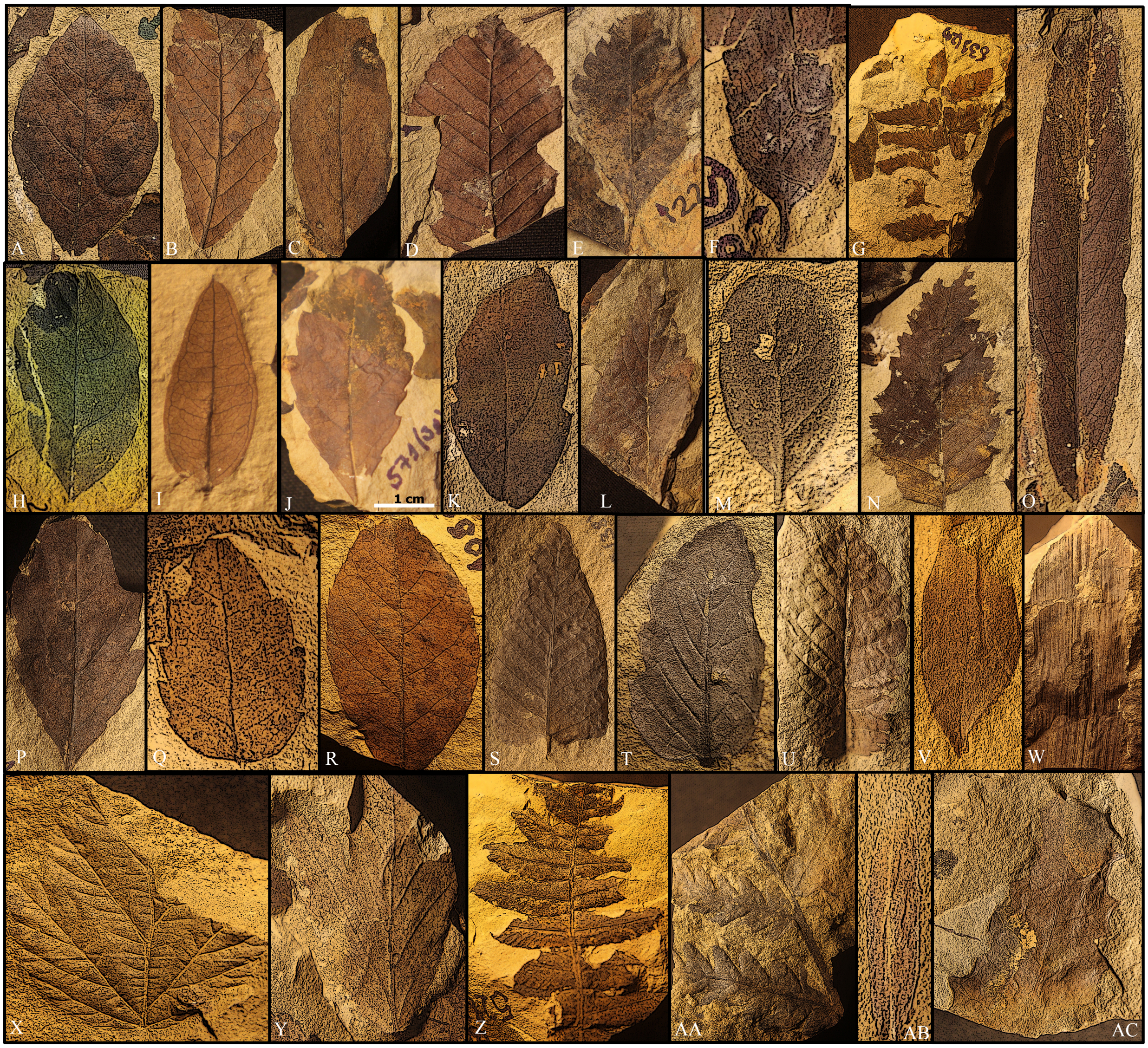

Fig. 4. Identified morphospecies in BFF. A) MNHN-SGO-PB-1771; B) MNHN-SGO-PB-1770 Cunoneaceae?; C) MNHN-SGO-PB-1767; D) MNHN-SGO-PB-1769 *Nothofagus*; E) MNHN-SGO-PB-1768; F) MNHN-SGO-PB-1765; G) MNHN-SGO-PB-1755 Dryopteridaceae; H) MNHN-SGO-PB-1745 Monimiaceae; I) MNHN-SGO-PB-1764 Myrtaceae; J) MNHN-SGO-PB-1762 Sapindaceae; K) MNHN-SGO-PB-1761; L) MNHN-SGO-PB-1760; M) MNHN-SGO-PB-1757 Fabaceae; N) MNHN-SGO-PB-1763 *Nothofagus*; O) MNHN-SGO-PB-1759; P) MNHN-SGO-PB-1758 Fagaceae?; Q) MNHN-SGO-PB-1756 Gesneriaceae; R) MNHN-SGO-PB-1751; S) MNHN-SGO-PB-1749; T) MNHN-SGO-PB-1748; U) MNHN-SGO-PB-1746; V) MNHN-SGO-PB-1744 Lauraceae; W) MNHN-SGO-PB-1753 Poaceae; X) MNHN-SGO-PB-1750 Grossulariaceae; Y) MNHN-SGO-PB-1743 Grossulariaceae Z) MNHN-SGO-PB-1740 Blechnaceae; AA) MNHN-SGO-PB-1741 Dennstaedtiaceae; AB) MNHN-SGO-PB-1742 Podocarpaceae; AC) MNHN-SGO-PB-1747 Berberidaceae.

A cut-off analysis of 300 samples indicates that the BDH site presents a larger diversity than at ARB. In 746 samples, the rarefaction analysis shows that the diversity at BDH totals 17 morphospecies, compared to 15 morphospecies at ARB (Fig. 5). According to the CHAO2 index, richness shows a decrease from 41 at BDH to 29 at ARB, whereas Jackknife indicates 39.5 at BDH and 28.7 at ARB.

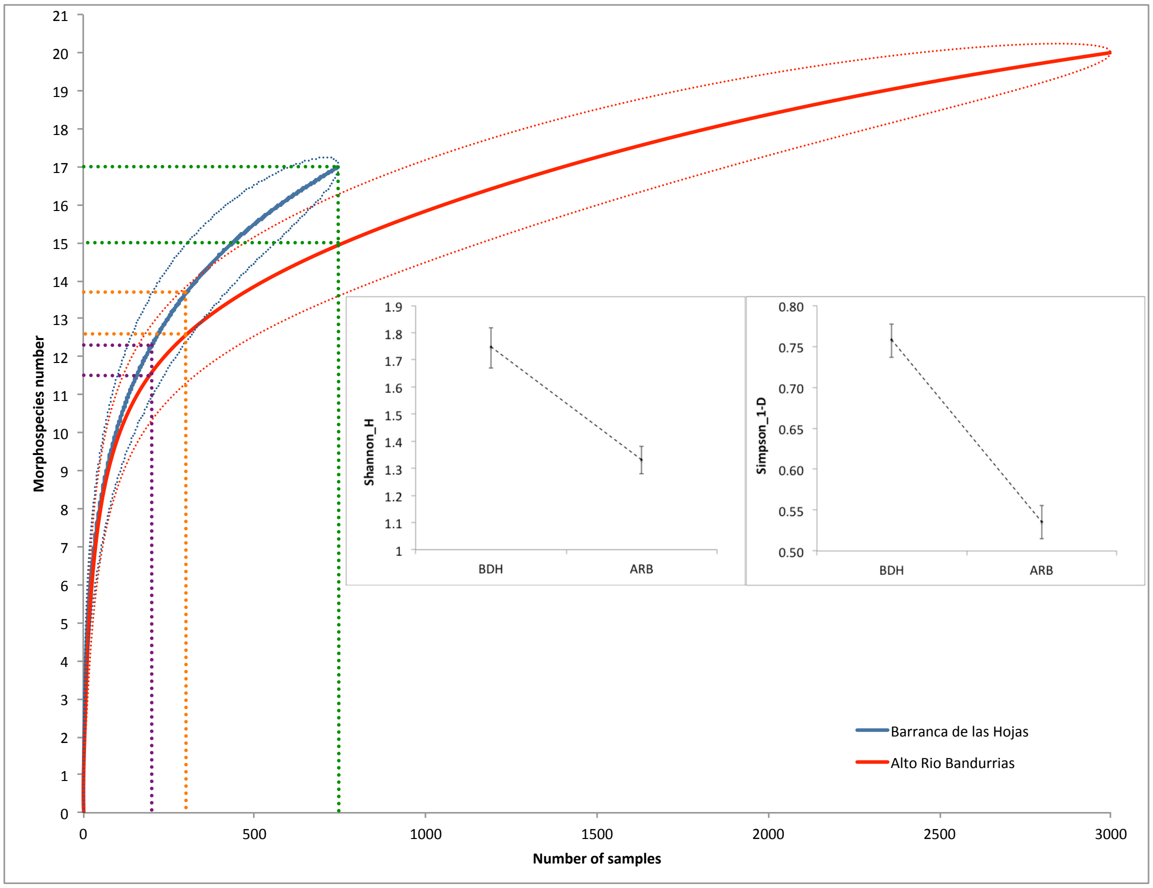

Fig. 5. Rarefaction curves of BFF, in which the number of morphospecies was derived from a sample strength of 3,746 fossil leaves, 3,000 from the ARB and 746 de from the BDH and diversity analysis reaching "cutoff" analysis at 200, 300 and 746 sample. Shannon-H and Simpson-1D diversity indexes for ARB and BDH.

In spite of the fact that ARB has a larger number of taxa, the diversity and richness indexes show a decrease in comparison with BDH. This reduction in diversity is accompanied by a turnover of species. During the Cenozoic, the fossil flora elsewhere in Patagonia registered first an increase and then a decrease in diversity according to the number of dicotyledonous morphospecies identified at each fossil locality (Fig. 9). For example, in the early Paleocene, the fossil flora of Palacio de los Loros had a diversity of 39 morphospecies (Iglesias et al., 2007), but afterwards in the early Eocene, those at Ligorio Márquez registered an increase in diversity reaching up to 55 morphospecies (Hinojosa, 2005; Hinojosa et al., 2016). A peak of diversity of morphospecies was recorded in the fossil flora of Laguna del Hunco, with 122 morphospecies (Wilf et al., 2005). However, after the early Eocene there was a clear reduction in the number of morphospecies, reaching 45 in the middle Eocene Río Turbio Formation (Hunicken, 1967). Finally, during the early Oligocene, only 24 dicotyledonous morphospecies were recorded in the BFF (Gutiérrez et al., 2017).

4.2. Paleoclimate

The Univariate Temperature Model shows that the percentage of morphospecies with an entire margin is 21% (pE). The MAT according to the model proposed by Hinojosa (2011) for South America is 26.03*pE+1.31 = 6.7 ºC. On the other hand, the MAT estimation according to the model of Peppe (2011) is 20.4*pE+4.6 = 8.9 ºC. The Univariate Precipitation Model indicates that the mean annual precipitation according to the Hinojosa (2005) equation, (1.63+0.49*MLnA) gives an estimated MAP of 120 cm.

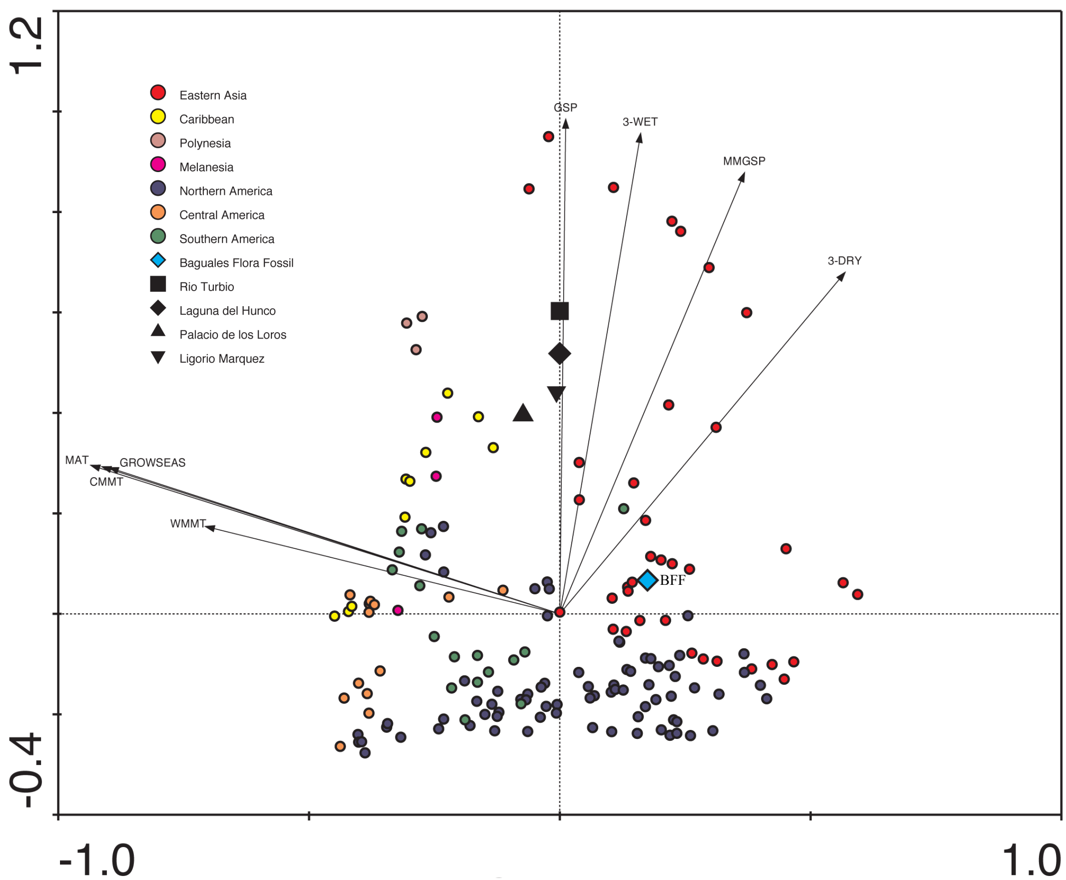

Fig. 6. The canonical correspondence analysis (CCA) indicates that the temperature-related variables are associated with the CCA-1 axis and the precipitation-related variables are associated with the CCA-2 axis. CCA1: 69.8% CCA2: 17.9% and the cumulative variance of the first two axes is 87.7%, n=161.

The canonical correspondence analysis (CCA) indicates that the temperature-related variables are associated with the CCA1 axis whereas the precipitation-related variables are associated with the CCA2 axis (Fig. 6). The existent South American forests show climatic conditions with somewhat higher temperatures than the Rio Leona fossil flora and precipitation conditions within the range of the modern South American forest.

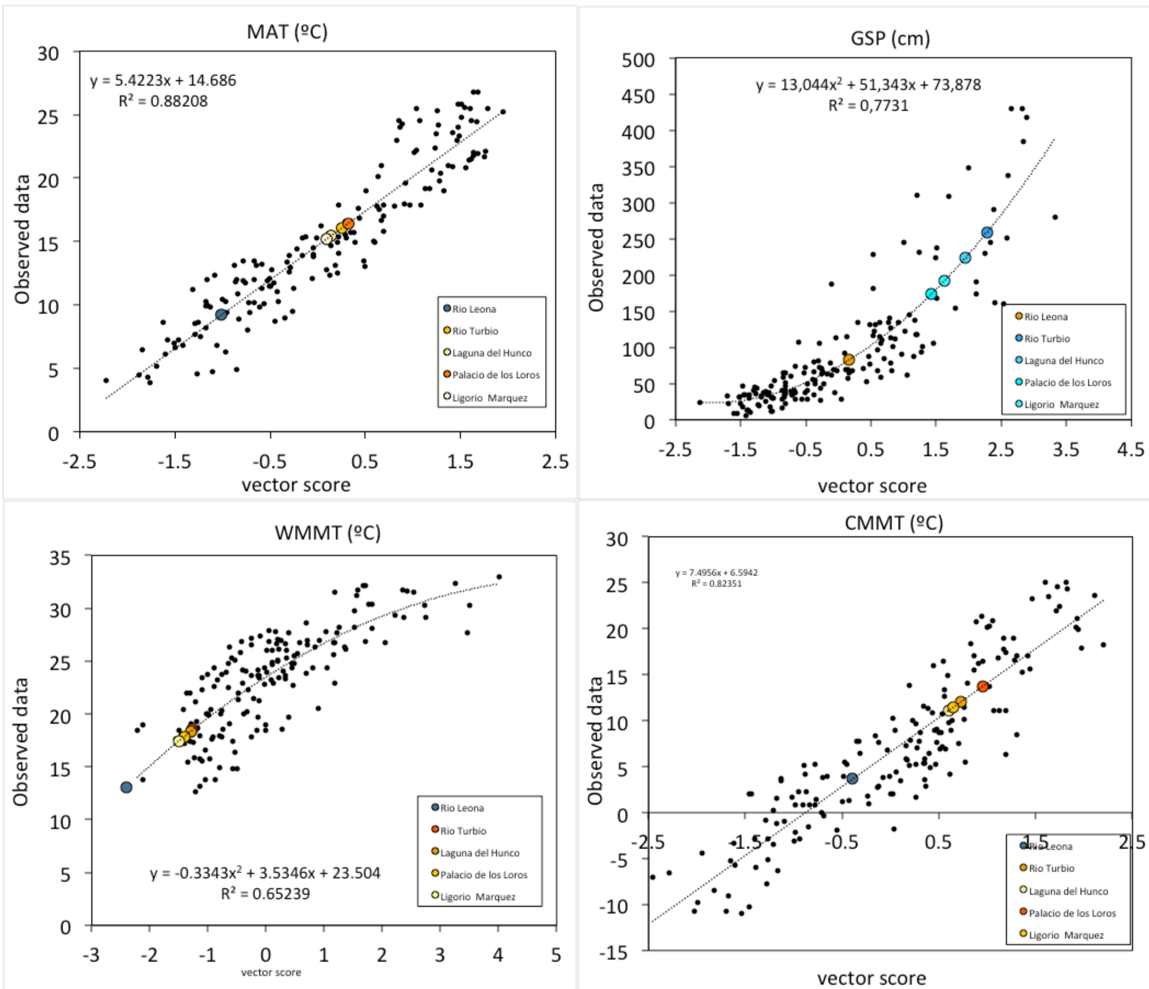

Fig. 7. Temperature results employing multivariate method for Río Leona, Río Turbio, Laguna del Hunco, Palacio de los Loros, and Ligorio Marquez. Mean annual temperature (MAT); Warmest Month Mean Temperature (WMMT); Coldest Month Mean Temperature (CMMT); Number of Months with Temperatures Exceeding 10°C (GROWSEAS).

The estimated climatic results for the BFF are (Figs. 7; 8): Mean annual temperature (MAT): 9.2 ºC; Warmest Month Mean Temperature (WMMT): 11.9ºC; Coldest Month Mean Temperature (CMMT): 3.4ºC; Number of Months with Temperatures Exceeding 10°C (GROWSEAS): 9. The temperature range

(WMMT-CMMT) of 9.4ºC, with a relatively high seasonality gradient, shows that the climate was not equable (Axelrod et al., 1991). Thermal equality refers to a climate with a mean temperature of about 14ºC and a thermal variation of almost zero. As far as precipitation is concerned, the following results were obtained: Growing Season Precipitation (GSP): 82.2 cm; Mean Monthly Growing Season Precipitation (MMGSP): 8.48 cm; Precipitation During Three Wettest Months (3WET): 57.4 cm; Precipitation During Three Driest Months (3DRY): 10.2 cm. The precipitation range (3WET - 3DRY) of 47.2 indicates a high seasonality where close to 70% of the rain-or snowfall was concentrated within the three wettest months.

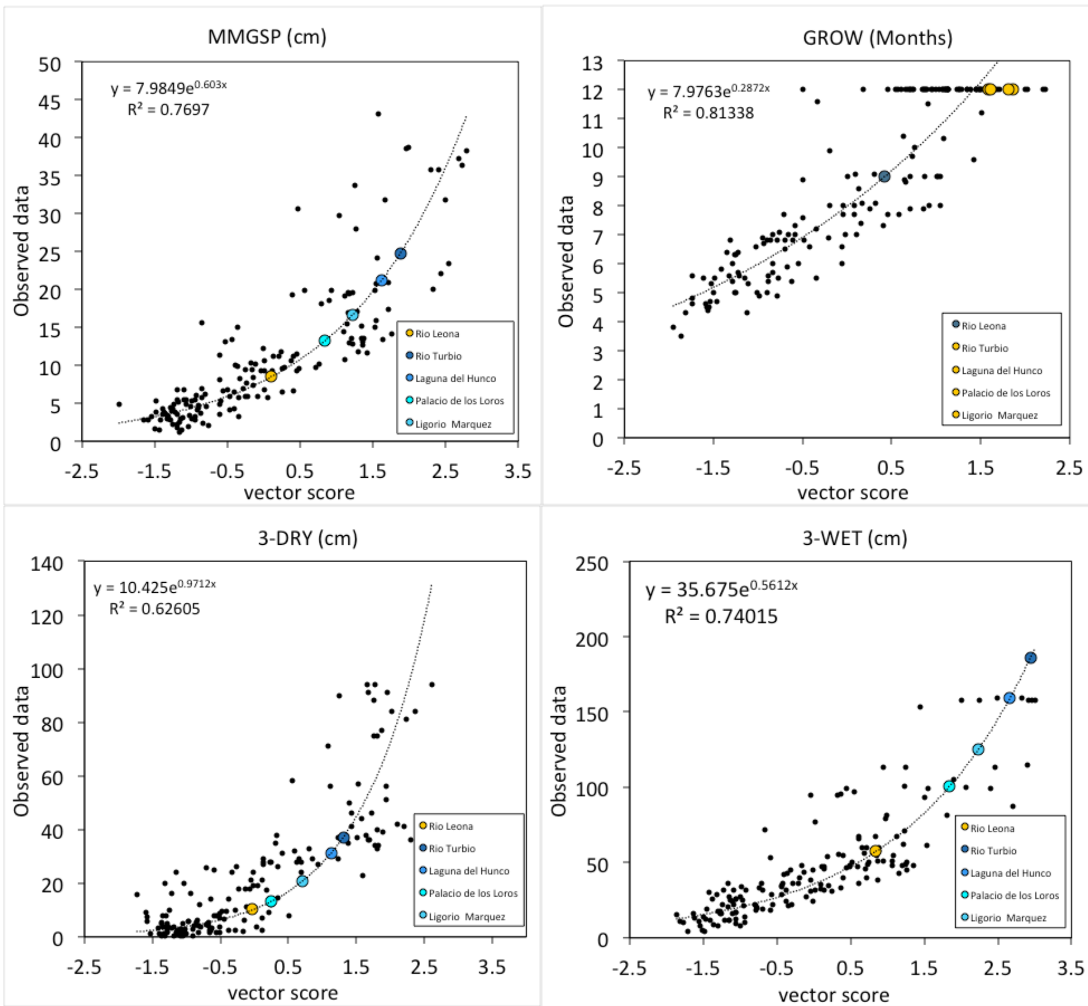

Fig. 8. Precipitation results employing multivariate method for Río Leona, Río Turbio, Laguna del Hunco, Palacio de los Loros, and Ligorio Marquez. Growing Season Precipitation (GSP); Mean Monthly Growing Season Precipitation (MMGSP); Precipitation During Three Wettest Months (3WET); Precipitation During Three Driest Months (3DRY).

5. Discussion

5.1. Diversity and composition

The studied palaeoflora association in the SB is composed of 29 morphotypes, of which 2 are assigned to the family Nothofagaceae. This family is the most abundant at this site, comprising 65% of the total individual paleoflora, while the other 35% belongs to the families Myrtaceae, Fagaceae, Sapindaceae, Poaceae, Berberidaceae, Cunoneaceae, Monimiaceae, Dryopteridaceae, Podocarpaceae, Gesneriaceae, Grossulariaceae, Blechnaceae, Fabaceae, Lauraceae, and Dennstaedtiaceae. Only 11 morphotypes could not be identified to family level (Fig. 3; 4)

The composition of the BFF is dominated by the subgenus *Lophozonia* and *Fuscospora* of the *Nothofagus* genus, both of which are presently microthermal subgenera in the Southern Hemisphere (Hinojosa et al., 2016). Morphologically, as far as their leaves are concerned, there is a strong similarity among the *Nothofagus* morphospecies and those of the subgenus *Lophozonia* in the BFF, in particular between *Nothofagus glauca* and *Nothofagus obliqua*. However, the assignment to any species of Nothofagaceae should ideally be accompanied by a description of reproductive characters such as flowers or fruits, or even cuticle morphological analysis. Thus, the assignation to a specific species within the subgenera of Nothofagaceae without considering reproductive characters and cuticle analysis is very risky considering the high morphological variability in the family (Hill and Read, 1991; Hill, 1992; Hill and Jordan, 1993). For this reason, no attempt was made here to identify individual species.

The phytogeographic elements identified in the BFF correspond to Austral-Antarctic, Austral-Asian, Endemic, Pantropical and Neotropical genera, and the association can therefore be described as Mixed Palaeoflora (Romero 1978, 1986; Hinojosa and Villagrán, 1997; Villagrán and Hinojosa 1997, Hinojosa, 2005; Hinojosa & Villagrán 2005; Kooyman et al., 2014). Considering the total of specimens recovered, the climatic classification of the BFF palaeoflora presents morphotypes with variable climatic requirements, in which 68.29% of the morphotypes require conditions varying from cold to temperate or subtropical. Only 7.21% correspond to morphotypes with climatic requirements ranging from temperate to subtropical and tropical. Morphotypes for which no climatic classification could be established make up 24.32% of the total (Table 1). From the Paleocene to middle Eocene (65.5 – 40.4 Ma), the palaeoflora of southern South America registered a change in composition, passing from Tropical Gondwana Palaeoflora to Subtropical Gondwana Palaeoflora. After the Eocene, the Subtropical Gondwana Palaeoflora were replaced by Mixed Palaeoflora, which had been migrating northward from Antarctica since the Paleocene

(Drúsen, 1916; Hinojosa and Villagrán, 1997, 2005b; Hinojosa et al., 2006; Quattrocchio et al., 2013) and were eventually restricted to subtropical latitudes between 30º and 38ºS during the Oligocene (Romero, 1978, 1986; Hinojosa and Villagrán, 1997; Villagrán and Hinojosa, 1997; Troncoso and Romero, 1998; Hinojosa, 2003, 2005; Quattrocchio et al., 2013). In the late Eocene – early Oligocene Rio Guillermo Formation near Santa Cruz (Panti et al., 2011) and the late Oligocene Río Leona Formation of Lago Argentino (Césari et al., 2015), temperate to cold-temperate, humid climatic conditions were inferred from the palaeofloral composition (Panti et al., 2011; Césari et al., 2015). From the viewpoint of forest structure, the Rio Leona forest canopy would have been dominated by the *Nothofagus* genus, as suggested by the high proportion of leaves of the *Nothofagus* genus in samples recovered from Rio Leona (Fig. 3). Currently, species of the *Nothofagus* genus dominate or co-dominate the forests in temperate zones. Indeed, In 10 of the 12 types of forest defined for Chile, *Nothofagus* dominates the forest structure (Donoso, 1998).

The *Nothofagus* species richness during the Oligocene (Rupelian) of Rio Leona is represented by only 2 morphospecies, being the lowest recorded in the middle Eocene (Fig.9). During the Paleogene, the Patagonian record of fossil leaves shows that the Salamanca Formation at 45º58 'S, with a morphotype associated with *Nothofagus* (Iglesias et al., 2007), the diversity of the genus increased progressively to reach a maximum in the middle Eocene, when 7 morphotypes were recorded in Río Turbio Formation (41ºS, Romero, 1977; Gandolfo, 1994; Panti, 2010). Since this maximum, during the Late Eocene, there was a decrease in diversity to only 5 morphotypes in Rio Guillermo Formation (51ºS; Panti, 2010) and 3 morphotypes in the Oligocene of the Rio Leona Formation (49ºS), specifically at the Lago Argentino locality (Césari et al., 2015). A similar pattern can be observed in the pollen record (Fig.9), which shows maximum diversity during the middle Eocene at Río Turbio (Romero, 1977; Gandolfo, 1994), with 9 morphospecies, falling to 5-6 morphospecies during the late Eocene and Oligocene, as evidenced by the Slogget (Olivero et al., 1998; Panti et al., 2008) and Río Leona Formations (Barreda et al., 2009), respectively (Fig. 9).

The analysis of species richness and diversity in the BFF indicates a decrease in both indexes, in which the fossil leaves of the BDH, located stratigraphically at the base of the Río Leona Formation, are more diverse than those of the ARB in the upper middle part of the formation. The rarefaction analysis also demonstrates that there is a decrease in species richness in the BFF. Additionally, a turnover of species was recorded, in which the fossils of the BDH are different from those in the ARB, with the exception of the families Nothofagaceae, Myrtaceae, Grossulariaceae, and Poaceae that occur at both localities. At the BDH, Berberidaceae, Monimiaceae, Lauraceae, and Podocarpaceae were recorded, compared to Cunoneaceae, Sapindaceae, Fabaceae, and Gesneriaceae at the ARB. The development of the BMR flora, showing a decrease in diversity and changes in their composition, can be interpreted as a reaction of the vegetation to global cooling during the Oligocene that caused an increase in the temperature gradient between tropical and austral areas. This process coincided with the initiation of glaciation in Antarctica (Zachos et al., 2001; Hinojosa, 2005).

5.2. Palaeoclimate

According with our estimation, the BFF grew under a microthermal climate in the sense of Nix (1991), with a mean annual temperature estimate of 6.7 - 8.9 ºC and an mean annual precipitation of 1200 mm. Palaeotemperature estimates for the BFF demonstrate that dramatic cooling occurred in Patagonia during the Oligocene, with temperatures dropping to between 7ºC and 9ºC. The seasonal temperature variation was also high, the difference between the coldest and warmest months being 9.44ºC. This variation suggests that the climate in the BFF was not equable, but had a high seasonal variation.

As far as precipitation is concerned, the BFF registers the lowest values recorded in Patagonia during the Cenozoic, reaching 82 cm during the growing season and 120 cm annually. In addition, the variation range in precipitation during the three wettest months and the three driest months was 47.19 cm, reflecting high seasonality in which nearly 70% (57 cm) of precipitation was concentrated in the wettest months, whereas the three driest months only received 10 cm of precipitation. Our palaeoclimatic data therefore suggest that the BFF experienced cold and dry or sub-humid conditions during the Rupelian.

The temperature decrease recorded in the BFF during the Rupelian coincides with the Oligocene global cooling, which was registered using marine isotope data and in turn coincided with the opening of the Drake Passage and Antarctic glaciation (Zachos et al. 2001). Our data indicate the lowest precipitation recorded to date for the Cenozoic in Patagonia, falling from 200 – 240 cm during the Eocene (Hinojosa 2005; Wilf et al., 2005; Iglesias et al., 2007) to 80 – 120 cm in the BFF during the Oligocene. This drop in precipitation is interpreted as resulting from the development of a rain shadow east of the rising Southern Patagonian Andes that blocked the humid Westerly Winds. Changes in palaeocurrent directions recorded in the BFF from the Late Cretaceous to the Miocene (Gutiérrez et al., 2017) also indicate that until the Eocene, sediments were transported towards the northwest and west, but then changed to the northeast during deposition of the Río Leona Formation. This indicates that a major pulse of uplift in the Southern Patagonian Andes at around 34 Ma initiated the rain shadow, in contrast to the central and northern parts of Chile where this effect only became clearly manifested during the "Quechua Phase" of Andean deformation in the middle Miocene (e.g. Riccardi and Rolleri, 1980; Alpers and Brimhall, 1988; Gregory-Wodziki, 2000; Houston and Hartley, 2003; Gutiérrez et al., 2013). As topographic forcing on climate only begins to take effect at around 1000 m (Browning, 1980), this could represent the minimum amount of uplift at the time.

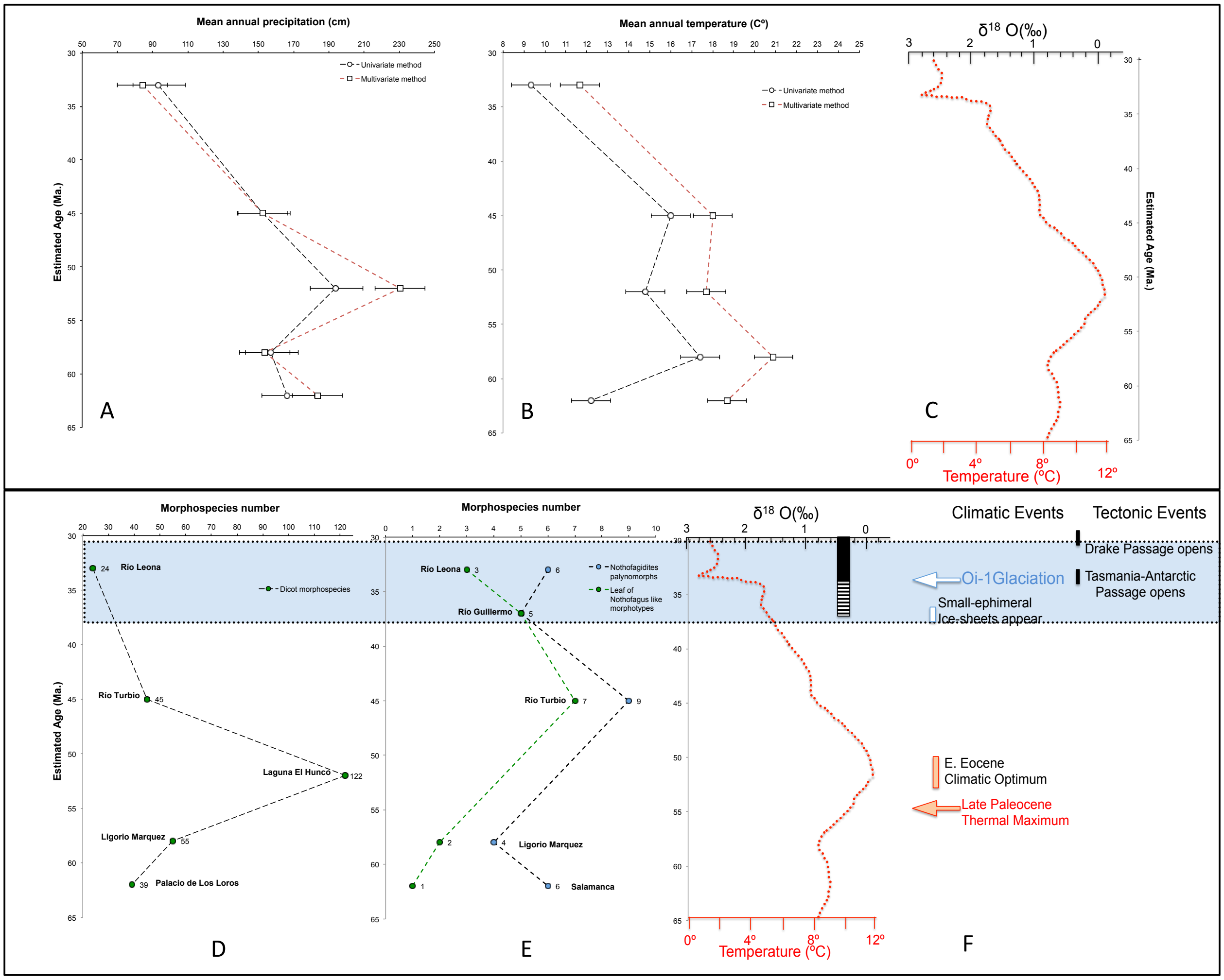

Fig. 9. Synthesis of climatic results and diversity of Patagonia during the Cenozoic. A) Mean annual precipitation for the Cenozoic using univariate and multivariate method in fossil leaves; B) Mean annual temperature for the Cenozoic using univariate and multivariate method in fossil leaves C) and F) Global oxygen isotope curve for the Cenozoic (Zacho et al. 2001); D) Number of dicot for the Cenozoic in patagonia; E) Number of Nothofagidites and leaf Nothofagus like morphospecies for the Cenozoic in Patagonia.

Our paleoclimatic reconstruction is the first estimate for a microthermal climate during the Rupelian, temperate conditions that dominate forest areas until today in Patagonia. In South America, according to pollen coexistence analysis, Nothofagaceae represented an ancestral, mesothermal climate with temperatures between 14°C and 22°C and a mean annual precipitation of 108 – 151 cm during the Eocene (Hinojosa et al., 2016). Independent evidence suggests that during the Oligocene, there was a marked decrease in temperature that coincided with the initiation of glaciation in the Antarctic (Barker, 2001; Zachos et al., 2001; Liu et al., 2009). Recent niche climate models also indicate that *Nothofagus* species currently occur under microthermal conditions in South America and under mesothermal conditions in tropical latitudes (Hinojosa et al., 2016). The presence of the *Nothofagus* genus in the BFF therefore suggests that it adapted to low temperature conditions between 6.6ºC and 11ºC during the Rupelian, constituting the first evidence that this genus supported microterminal conditions during the Oligocene in Southern Patagonia.

6. Conclusions

The composition, palaeofloral diversity and palaeoclimate of the plant fossil-rich Río Leona Formation (Rupelian) was studied in the Baguales Mountain Range of the Magallanes-Austral Basin in the Última Esperanza Province of Chilean Patagonia. Statistical diversity analysis of 3,746 fossil leaves, identified as the Baguales Fossil Flora (BFF), presents a phytogeographic composition associated with the Mixed Palaeoflora association, but in this case dominated by the Nothofagaceae family of Austral-Antarctic origin. The climatic requirements of the BFF taxa indicate cold-temperate conditions. From the base to the upper middle part of the Río Leona Formation, a decrease in diversity is indicated by an impoverishing of species richness and a species overturn, in which the Nothofagaceae family became the dominant taxon comprising 65% of the total taxa. The response of the BFF to global temperature changes caused an increase in the proportion of dicotyledon morphospecies with toothed margins, whereas the decrease in precipitation resulted in smaller leaves. Both climatic conditions generated a high-stress environment, in which Nothofagaceae adapted to microthermal conditions (Hinojosa et al. 2016). This constitutes the first recorded forest dominated by Nothofagaceae under microthermal conditions in Patagonia during the Cenozoic.

The registered low temperatures coincide with a period of global marine cooling at the time, linked to the opening of the Drake Passage and the initiation of glaciation in Antarctica (Zachos et al., 2001). On the other hand, the decrease in precipitation can be correlated with an important pulse of uplift in the Southern Patagonian Andes (Ramos, 2008), which is also recorded by a change in palaeocurrent directions from northwest to northeast during the early Oligocene (Gutiérrez et al., 2017). This decrease in precipitation reflects the development of a rain shadow to the east of the Andes at around 34 Ma, which indicates that the Arid Diagonal developed earlier here than at lower latitudes.

Acknowledgements

This research was financially supported by Project ANILLOS ATC-105 and Projects FONDECYT 1130006 and 1150690, being carried out under the auspices of Project CONICYT/FONDAP 15090013. N.M.G. is grateful for a doctoral grant from CONICYT.

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4. DISCUSIÓN.

Las diferentes líneas de evidencia presentadas en los capítulos I y II, incluyen los cambios registrados en los ambientes deposicionales, las direcciones paleocorrientes, zonas de proveniencia de circones y paleoclima, resultados que coinciden con la siguiente secuencia de eventos tectónicos:

Durante el Cretácico Superior los ambientes deposicionales pasaron de un sistema de talud continental con turbiditas en la Formación Tres Pasos a condiciones someras deltaicas en la Formación Dorotea. Esta somerización sugiere que el levantamiento tectónico habría iniciado durante el Campaniano tardío. Las paleocorrientes fueron bastante variables, con una amplia gama de zonas de proveniencia, pasando de zonas al noreste a zonas al sudeste, pero principalmente con fuentes de aporte ubicadas al oriente de la Cuenca de Magallanes. La zona de proveniencia más probable habría sido los Arcos Magmático Occidental y Arco Río Chico-Punta Dúngenes (según lo propuesto previamente por Ramos, 2008), así como también la provincia riolítica Chon-Aike.

El levantamiento tectónico continuó después de la deposición de la Formación Dorotea, provocando un largo período de erosión de 30 Ma que abarcó todo el Paleoceno y la mayor parte del Eoceno (~ 70-40 Ma), terminando con la deposición de la Formación Man Aike. Esta última sucesión recibió detritos provenientes del este y del sudeste, sugiriendo que la erosión fue causada por el levantamiento tectónico enfocado en esta área. Aunque la procedencia oriental puede atribuirse al arco de Río Chico-Punta Dúngenes, las fuentes ubicadas al sureste necesita otra explicación. Se propone que un fragmento de placa continental local habría estado unida al extremo oriental de la Patagonia Fueguina e inmediatamente al sur de la cuenca plateau Falkland-Malvinas. Nuestros datos de circón sugieren que puede haber formado parte de la Península Antártica y / o una prolongación de la península hacia el noreste.

Se han registrado edades de circón entre 120 Ma y 80 Ma desde el extremo norte de la Península Antártica (Pankhurst, 1990). Esta área también podría haber contribuido con algunos circones del grupo IIe, así como el basamento cristalino que aflora en Target Hill y en otras partes de Graham Land (Fig. 16 Capítulo I), donde se han obtenido edades de roca total de 410 ± 15 y 426 ± 12 Ma (Milne y Millar, 1989).

La posición relativa de la Península Antártica con respecto al sur de Sudamérica durante el Mesozoico y el Cenozoico sigue siendo problemática (Miller, 2007), aunque muchos aceptan que estaba situada al oeste de Sudamérica desde el Jurásico Medio hasta el Tardío (por ejemplo Grunow et al 1987 y 1987), y de allí se desplazó hacia el sur a lo largo del limite de la Placa Sudamericana.

Un problema con esta interpretación es que las fallas de rumbo de edad Cretácico Tardío y Cenozoico en los Andes Patagónicos Meridionales, así como en el lado oriental de la Península Antártica, son predominantemente fallas laterales dextrales (Storey y Nell, 1988; Diraison et al., 2000), Lo que contradice esta noción. Por otra parte, Seton et al. (2012) muestra que la posición de la Península Antártica se mantuvo al sur-suroeste de la Patagonia entre 200 y 120 Ma, desde donde se desplazó hacia el norte y al este, convirtiéndose casi en una prolongación hacia el sur de la Patagonia Fueguina durante 60 Ma. Diraison et al. (2000, figura 3b y c Capítulo I) indican que esta posición se alcanzó entre 90 y 50 Ma, y que para esta última fecha, South Georgia estaba situada a lo largo del límite norte de la Placa Scotia. Varios otros autores también han indicado que la posición de la Península Antártica está inmediatamente al sur de la Patagonia Fueguina durante el Cretácico Superior (Barker y Lawver, 1988; Lagabrielle et al., 2009; Eagles, 2016a).

También se ha sugerido que la Península Antártica fue una continuación de la Patagonia Fueguina y la Cordillera Darwin (Veevers et al., 1984; Pankhurst, 1990; Reguero et al., 2013) extendiéndose al sureste de la Cuenca de Magallanes - Cuenca Falkland-Malvinas incluso durante el Jurásico. Sin embargo, Eagles (2016b) cuestionó la proximidad de South Georgia a Tierra del Fuego durante el Cretácico Temprano.

Una extensión alternativa al noreste de la Península Antártica es la pequeña subsidencia de bancos en el Mar Scotia, incluyendo Terror Rise, Pirie Rise, y el banco Bruce, los cuales Eagles y Jokat (2014) designaron como Omond Land. Dada su actual proximidad a la Península Antártica y al microcontinente South Orcadas, éstas podrían quizás ser más fácilmente conciliadas con la fuente del sudeste postulada, que habrían sido removida por extensión, ruptura y hundimiento durante el Eoceno.

Si nuestra propuesta es correcta, la punta norte de la Península Antártica y / o su extensión hacia el noreste habría estado situada inmediatamente al sureste de la Cuenca de Magallanes durante el Lutetiano, esto podría haber proporcionado detritos a la Formación Man Aike a lo largo del eje de la cuenca hacia el noroeste. La elevación podría haber sido causada por el desarrollo de una falla de transformación acompañada de un levantamiento del hombro, que pudo haber llegado fácilmente a más de 1 kilómetro de altura (Buck, 1986; Basile y Allemand, 2002). El candidato más probable es el North Scotia Ridge, el cual es un límite de transformación con desplazamiento lateral-izquierda que hace parte de la extensión hacia el este del Sistema de Fallas Magallanes-Fagnano en la Patagonia Fueguina y que se extiende al este hasta South Georgia, con una serie bancos someros entre medio (Eagles y Jokat, 2014).

Las prospecciones geofísicas indican que este ridge está conformado principalmente por bloques continentales, lo que sugiere una fragmentación post-cretácea de una antigua zona continental continua (Barker y Griffiths, 1972). Todavía no está claro si las Islas South Georgia, actualmente ubicadas en el lado sudamericano del límite de la placa, forman parte de la Placa Scotia o han sido recientemente acrecionadas a la Placa Sudamericana (Thomas et al., 2003), pero podrían presentar vestigios de dicho levantamiento del hombro. La posición original del microcontinente de South Georgia se encontraba al sur del banco Burdwood y al sur de las Islas Malvinas-Falkland, desde donde se desplazó hacia el este durante el curso de alargamiento del Ridge North Scotia (Dalziel et al., 2013). Teniendo en cuenta el movimiento lateral izquierdo a lo largo del ridge, podría implicar que el ridge originalmente fue parte de la Placa Antártica

/Scotia y podría haber formado, junto con los bancos sumergidos anteriormente mencionados, la extensión nororiental de la Península Antártica. La Placa Scotia se formó principalmente a partir de un cambio en el movimiento relativo entre las Placas Sudamérica y la Placa Antártica durante el Ypresiano (~ 50 Ma) según Pelayo y Wiens (1989). Los datos geofísicos marinos indican que el movimiento entre las Placas Sudamericana y Antártica en ese momento cambió de N-S a WNW-ESE, lo cual fue acompañado por un aumento de ocho veces en la tasa de separación (Livermore et al., 2005).

Existen muchas similitudes paleontológicas entre la Península Antártica y la Cuenca de Magallanes. Por ejemplo, Aristonectinae (Plesiosauria) encontrada en la Sierra Baguales también se encuentra en la isla Seymour (Gasparini et al., 1984, Chatterjee y Small, 1989, Fostowicz-Frelik y Gaździcki, 2001), James Ross Island (Otero et al. 2014) y Vega Island (O'Gorman et al., 2010) de la Península Antártica.

Los registros del Pacífico Sur están hasta ahora restringidos a la Cuenca Quiriquina de Chile Central, que según Cecione (1970) y Le Roux (2012) estuvo conectada a la Cuenca de Magallanes durante el Cretácico Superior. Sin embargo, los elasmosauridos plesiomorficos estaban presentes tanto en la última cuenca como en la Península Antártica durante el Campanio temprano, pero sólo aparecieron en la Cuenca de Quiriquina durante el Maastrichtiano temprano (Otero et al., 2015). Además, la paleoichtyofauna con afinidad Atlántico Norte presente tanto en la Cuenca de Magallanes como en Isla Seymour incluyen los géneros de *chondrichtyan Squatina*, *Pristiophorus* y *Carcharocles* (Otero et al., 2013; Kriwet et al., 2016).

Los condrictianos eran elementos dominantes en la fauna de peces antárticos durante el Paleógeno, pero disminuyeron en abundancia desde el Eoceno medio hasta tardío, durante el cual los osteícties aumentaron. Esta disminución de chondrichthyans registrada en la Formación Eocena La Meseta en Isla Seymour se relacionó con el enfriamiento repentino del agua de mar, la reducción en el área de plataforma y el aumento en la profundidad de la plataforma de acuerdo con Kriwet et al. (2016). Aunque estos autores atribuyeron su desaparición durante el Eoceno tardío a las condiciones climáticas en lugar de la tectónica de placas, también podría deberse al desarrollo de fallas de transformación y un ridge entre el sur de América del Sur y la punta septentrional de la Península Antártica. Lagabrielle et al. (2009) muestran de hecho este último sector inmediatamente al sur de la Patagonia a los 43 Ma, desde donde se desplazó hacia el este hasta 32 Ma, acompañado por el fortalecimiento de la Corriente Circumpolar Antártica. Hasta los 25 Ma, todavía se desplazaba hacia el este a lo largo de la falla de transformación Magallanes-Fagnano, que se extiende desde la Patagonia Fueguina hasta la frontera sur de la Meseta de las Malvinas, desde donde comenzó a desplazarse hacia el sur con el desarrollo de un ridge oceánico en el Paso Drake.

Los estudios paleomagnéticos indican que el bloque de la Península Antártica se localizó en o cerca de su posición actual con respecto a la Antártida Oriental por ~ 130 Ma, mientras que los polos de la Península Antártica ~ 110 y ~ 85 Ma son similares a los polos equivalentes de edad del bloque Oriente de la Antártida, indicando que poco o ningún movimiento relativo ocurrió entre estos dos bloques (Grunow, 1993). Poblete et al. (2011) también concluyó de sus estudios paleomagnéticos en la Península Antártica que el pequeño desplazamiento entre este último y el bloque Antártico Este durante el Terciario probablemente no sea discernible a partir de paleomagnetismo. Además, los polos del Cretácico Medio en las partes norte y sur de la Península Antártica son similares, sugiriendo que la forma "S" de la península no se debió a flexión oroclinal desde 110 Ma (Grunow, 1993). El ajuste de la Península Antártica a lo largo del margen occidental de la Placa Sudamericana durante el Cretácico Superior requeriría una considerable rotación en sentido anti horario de la Península Antártica, la Placa Sudamericana y la Antártida Oriental para llevarlos a su posición y orientación actual. Esto también se debe manifestar con la presencia de fallas con desplazamientos lateral-izquierdo en lugar de observar fallas con desplazamiento lateral-derecha a lo largo del flanco occidental de América del Sur y el lado oriental de la Península Antártica. Sin embargo, si la Península Antártica se localizó inicialmente al sur-suroeste de América del Sur y luego se desplazó hacia el norte-noreste para unirse a la punta

sureste de la Patagonia, explicaría la dirección de deslizamiento lateral-izquierdo a lo largo del Sistema de Fallas Magallanes-Fagnano North Scotia Ridge. La falla de deslizamiento lateral derecha observada en el lado oriental de la Península Antártica podría deberse a su desviación hacia el suroeste a lo largo del South Scotia Ridge después de la separación del fragmento continental del sur de Georgia-Falkland-Malvinas. Todo este proceso requeriría muy poca rotación para llevarlo a su orientación actual, lo que estaría de acuerdo con los 10 ° postulado por Poblete et al. (2011).
La Formación Man Aike fue depositada en un ambiente costero (estuarino), lo que indica que la elevación del hombro del ridge postulado entre las placas de Scotia y Sudamérica había llegado a su fin a los 40 Ma y la denudación o menor subsidencia acercó la región al nivel base.

Durante la deposición de la Formación Río Leona, se mantuvo un entorno continental cercano al nivel de base hasta el Rupeliano (Oligoceno temprano). Las zonas de proveniencia ya se habían desplazado hacia el suroeste, lo que refleja la elevación inicial de los Andes Patagónicos Australes alrededor de los 34 Ma. Este levantamiento llevó al desarrollo de una sombra de lluvia al este de los Andes Patagónicos, causando una disminución marcada en la precipitación. Proceso acompañado por una caída en la temperatura y una disminución en la diversidad de morfoespecies, que también se reflejó globalmente durante el Oligoceno. Esto se puede atribuir a la completa separación de la Península Antártica de América del Sur, con la apertura final del Paso de Drake que permitió la generación de la Corriente Circumpolar Antártica y el período Bartoniano-Rupeliano que conduce a la glaciación de la Antártida (Zachos et al., 2001; Le Roux, 2012).

Un período de subsidencia de la corteza ocurrió alrededor de los 19 Ma el cual causó la Transgresión Patagónica, como se refleja en la Formación Estancia 25 de Mayo. Esto fue seguido por un período de aceleración de la convergencia placas junto con el desprendimiento de la losa alrededor de 17 Ma, causando otro período de levantamiento rápido en los Andes meridionales de la Patagonia. Las edades de trazas de fisión en apatito en el flanco occidental del segmento andino sugieren que en esta región se produjeron 3-4 km de denudación desde 17 Ma (Blisniuk et al., 2006). Este alzamiento elevó el área de Sierra Baguales por encima del nivel de base y condujo al establecimiento del ambiente deposicional continental de la Formación Santa Cruz. Los circones probablemente retrabajados de formaciones subyacentes más antiguas estaban ahora expuestos al oeste, lo que sugiere que el plegamiento acompañó a este levantamiento de los Andes Patagónicos.

5. CONCLUSIONES FINALES.

El presente estudio muestra el efecto del levantamiento de los Andes Patagónicos, apertura del Paso Drake y la posición de la Península Antártica en la evolución de la Cuenca de Magallanes durante el Cenozoico en Sierra Baguales. La pregunta planteada en este estudio es ¿Cuál es el vínculo entre los procesos tectónicos y la evolución de la Cuenca de Magallanes en términos sedimentológicos, paleoclimáticos, paleoambientales y paleogeográficos durante el Cenozoico en Sierra Baguales bajo un escenario de cambio climático global? Para contestar esta pregunta se postularon 3 predicciones:

1.- Dados los cambios tectónicos (i.e levantamiento andino, apertura del Paso Drake) ocurridos durante el Cenozoico, en Sierra Baguales se espera que las fuentes de aporte de la Cuenca de Magallanes estén localizadas al norte y occidente y las edades de las poblaciones de circones detríticos identificados en las unidades cenozoicas sean similares con las edades de los plutones datados en los Andes Patagónicos.

Las mediciones de paleocorrientes en esta sucesión Mesozoico-Cenozoico indican cambios en las zonas de origen de los sedimentos, pasando de fuentes de aporte situadas al nororiente (Arco Magmático Occidental, Arco Río Chico-Punta Dúngenes y Provincia Chon-Aike) y suroriente (Península Antártica/Islas South Georgia) durante el Cretácico superior y Eoceno Medio a zonas de origen localizadas al occidente y suroccidente (Andes Patagónicos) a partir del Oligoceno temprano. Este cambio en las direcciones de paleocorrientes coincide con un importante impulso de elevación en los Andes Patagónicos Meridionales registrado por Ramos, (2008).

Este cambio es confirmado por poblaciones de edades de circón detrítico en las diferentes unidades, que pueden estar vinculados a las probables fuentes con edades similares en esta área. La procedencia del sudeste se identifica aquí como la Península Antártica, mientras que las fuentes del suroeste y oeste posteriores fueron exhumados durante la elevación gradual de los Andes Patagónicos del Sur.

Durante el Mioceno inferior, un período de subsidencia de la corteza ocurrió alrededor de los 19 Ma el cual causó la Transgresión Patagónica, como se refleja en la Formación Estancia 25 de Mayo. Esto fue seguido por un período de aceleración de la convergencia placas junto con el desprendimiento de la losa alrededor de 17 Ma, causando otro período de levantamiento rápido en los Andes meridionales de la Patagonia. Este alzamiento elevó el área de Sierra Baguales por encima del nivel de base y condujo al establecimiento del ambiente deposicional continental de la Formación Santa Cruz durante el Mioceno Medio. Los circones probablemente retrabajados de formaciones subyacentes más antiguas estaban ahora expuestos al oeste, lo que sugiere que el plegamiento acompañó a este levantamiento de los Andes Patagónicos. Este proceso coincidió con el cambio de condiciones marinas a condiciones continentales en la Cuenca de Magallanes.

2.- Dado el levantamiento de la Cordillera de los Andes Patagónicos y el bloqueo de los westerlies, y el correspondiente efecto de sombra de lluvia a los vientos del oeste, se espera en la flora fósil de Sierra Baguales una disminución en términos de diversidad de morfoespecies junto con una disminución del área foliar de las floras fósiles en concordancia con el descenso de las precipitaciones.

El análisis de la diversidad estadística de 3.746 hojas fósiles, identificado como la Flora Fósil Baguales presenta una composición fitogeográfica asociada a la asociación de Palaeoflora Mixta, pero en este caso dominada por la familia Nothofagaceae de origen Austral-Antártico. Desde la base hasta la parte media superior de la Formación Río Leona, la disminución de la diversidad se refleja en un empobrecimiento de la riqueza de especies y un recambio de especies. A nivel de morfología foliar se identifica disminución del área foliar de las floras fósiles en concordancia con el descenso de las precipitaciones. La disminución de la precipitación puede correlacionarse con un importante impulso de elevación en los Andes Patagónicos Meridionales (Ramos, 2008). Esta disminución de las precipitaciones refleja el desarrollo de una sombra de lluvia al este de los Andes alrededor de los 34 Ma, lo que indica que la Diagonal Árida se desarrolló antes, en Andes Patagónico que en las latitudes más bajas.

3.- Dado el proceso de enfriamiento global ocurrido desde el Optimo Climático del Eoceno, se espera en la flora de Sierra Baguales encontrar una mayor proporción de hojas de dicotiledóneas con borde dentado en comparación al Eoceno.

Se registra una mayor proporción de hojas de dicotiledóneas con borde dentado, morfología a partir de la cual se estima una temperatura media anual entre 8-10 ºC, temperatura que refleja un clima microtermal. Esta evidencia se asocia con las bajas temperaturas registradas durante el Oligoceno en el período de enfriamiento global de las aguas marinas superficiales, proceso que a su vez coincide con la apertura del Paso de Drake y a la iniciación de la glaciación en la Antártida (Zachos et al., 2001).

La disminución de precipitación junto con la disminución de la temperatura habrían generado condiciones de alto estrés para la vegetación durante el Oligoceno, en el que Nothofagaceae se adaptó a condiciones microtermales. Éste constituye el primer registro de un bosque dominado por Nothofagaceae en condiciones microtermales en la Patagonia durante el Cenozoico.

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