

U-Pb zircon constraints on the age of the Cretaceous Mata Amarilla Formation, Southern Patagonia, Argentina: its relationship with the evolution of the Austral Basin

Augusto N. Varela^{1,*}, Daniel G. Poiré¹, Thomas Martin², Axel Gerdes³, Francisco J. Goin⁴, Javier N. Gelfo⁴, Simone Hoffmann²

¹*Centro de Investigaciones Geológicas, Universidad Nacional de La Plata - CONICET, Calle 1 N° 644 (B1900FWA) La Plata, Argentina.*

²*Steinmann-Institut für Geologie, Mineralogie und Paläontologie, Universität Bonn, Nussallee 8, 53115 Bonn, Germany.*

³*Institut für Geowissenschaften, Mineralogie, Universität Frankfurt, Altenhöferallee 1, 60438 Frankfurt am Main, Germany.*

⁴*División Paleontología de Vertebrados, Museo de La Plata, Universidad Nacional de La Plata, Paseo del Bosque s/n (B1900FWA) La Plata, Argentina.*

e-mail: augustovarela@cig.museo.unlp.edu.ar

Tel: +54 221 4215677 / 4258696 Fax: +54 221 4827560.

ABSTRACT. Despite the abundant fossil content of the Mata Amarilla Formation (Southern Patagonia, Santa Cruz Province, Argentina), its age has always generated a considerable number of questions and debates. The chronological data provided by invertebrates, dinosaurs, fish, turtles, plesiosaurs and fossil flora are contradictory. In this

work, twenty U–Pb spot analyses by laser ablation were carried out on the outer parts of the zoned zircon crystals from a tuff layer of the middle section of the Mata Amarilla Formation, yielding a U–Pb concordia age of 96.23 ± 0.71 Ma, which corresponds to the middle Cenomanian. The deposition of the lower section of the Mata Amarilla Formation marks the onset of the foreland stage of the Austral Basin (also known as Magallanes Basin); this transition is characterised by the west–east shift of the depositional systems, which is consistent with the progradation of the Cretaceous fold-and-thrust belt. Thus, the onset of the foreland stage could have occurred between the upper Albian and lower Cenomanian, as the underlying Piedra Clavada Formation is lower Albian in age. On comparing the data obtained with information from the Última Esperanza Province in Chile, it can be suggested that the initiation of the closure of the Rocas Verdes Marginal Basin occurred simultaneously.

Keywords: Mata Amarilla Formation, zircons, laser ablation, Austral Basin (Rocas Verdes Marginal Basin - Magallanes Basin), foreland basin.

RESUMEN. Edades U-Pb en zircones de la Formación Mata Amarilla (Cretácico), Patagonia Austral, Argentina: su relación con la evolución de la Cuenca Austral. A pesar del abundante contenido fosilífero de la Formación Mata Amarilla (Patagonia Austral, Provincia de Santa Cruz, Argentina), siempre se generaron abundantes dudas y debates acerca de cuál es la edad de esta formación. Los datos cronológicos aportados por los invertebrados, los dinosaurios, peces, tortugas, plesiosaurios y flora fósil son dispares. En el presente trabajo se obtuvo una edad U-Pb concordia por la metodología de ablación

laser aplicada a 20 puntos de la parte externa de circones zonados provenientes de un nivel tobáceo hallado en la sección media de la Formación Mata Amarilla, lo cual arrojó una edad de $96,23 \pm 0,71$ Ma, que corresponde al Cenomaniano medio. La depositación de la sección inferior de la Formación Mata Amarilla marca el inicio del estadio de antepaís de la Cuenca Austral (también conocida como Cuenca de Magallanes); este pasaje está signado por el cambio oeste-este de los sistemas depositacionales, los cuales se encuentran en concordancia con la progradación de la faja plegada y corrida cretácica. Así, el comienzo del estadio de antepaís quedaría comprendido entre el Albiano superior y el Cenomaniano inferior, debido a que la subyacente Formación Piedra Clavada posee una edad Albiano inferior. Al comparar estos resultados con los datos de la Provincia de Última Esperanza en Chile, se sugiere que el comienzo del cierre de la cuenca marginal de Rocas Verdes se produjo en forma simultánea.

Palabras clave: Formación Mata Amarilla, circones, ablación laser, Cuenca Austral (Cuenca Marginal de Rocas Verdes - Cuenca de Magallanes), cuenca de antepaís.

1. Introduction

The study area is located in the southwest of the Santa Cruz Province, Argentina, near the locality of Tres Lagos (Fig. 1).

The Mata Amarilla Formation is a key unit in the development of the Austral Basin, as it marks the transition between the thermal subsidence stage and the foreland stage (Varela, 2009, 2011). The exact time of deposition of the Mata Amarilla Formation, however, has always been unclear, and therefore the onset of the compressional phase has

also led to dating speculations on the basis of its fossil content. In this respect, the absence of chronological dating has increased the lack of certainty over the stratigraphy of the Austral Basin. In turn, the presence of both continental and littoral fossil specimens has created confusion as to the stratigraphic nomenclature of the unit, since the fossil content was used to refer to lithostratigraphically identical sediments (*cf.* Goin *et al.*, 2002; Varela, 2011).

In this work, a U–Pb concordia age obtained by laser ablation of primary zircons from a tuff layer of the middle section of the Mata Amarilla Formation is presented. On the basis of such radiometric dating, certain regional considerations regarding the evolution of the Austral Basin (also known as Rocas Verdes Marginal Basin + Magallanes Basin) are introduced.

2. Geological background

The Austral Basin, also known towards the south as Rocas Verdes Marginal Basin — when sea-floor spreading occurs — and Magallanes Basin, is located on the southwestern edge of the South American Plate, and it is bounded to the south by the Scotia Plate (Fig. 1). It covers an area of approximately 230,000 km² which extends over the southernmost end of the Argentine and Chilean territories, and it is surrounded to the east by the Deseado Massif (Macizo del Deseado). With an elongated shape in a north–south direction, and a depositional eastern edge running parallel to the Río Chico (Chico River), it extends to the sea in the Dorsal de Río Chico (Chico River High) or Dorsal de Dungeness (Dungeness High), which separates it from the Malvinas Basin. Its tectonic western edge is constituted by the Patagonian-Fuegian Andes (Andes Patagónico-Fueguinos, Fig. 1).

This basin consists of a thick sedimentary succession which has a maximum thickness of approximately 8,000 m, with the almost exclusive occurrence of siliciclastic rocks. In the study area, it overlies the Bahía de la Lancha Formation (Biddle *et al.*, 1986; Robbiano *et al.*, 1996; Ramos, 2002; Kraemer *et al.*, 2002; Peroni *et al.*, 2002; Rodríguez and Miller, 2005), and towards the south, the Tierra del Fuego igneous and metamorphic basement complex of Hervé *et al.* (2010). Carbonate sediments are only present in certain locations within the basin and they are of limited thickness (Peroni *et al.*, 2002).

As shown in Fig. 1, outcrops of the ophiolite complexes are well south of the study area, which indicates that in the study area the basin was not subject to sea-floor spreading. The evolution of the Austral Basin in this sector differs from the evolution of the Rocas Verdes Marginal Basin - Magallanes Basin. The geological history of the Austral Basin in the study area is characterised by three main tectonic stages (Biddle *et al.*, 1986; Robbiano *et al.*, 1996; Ramos, 2002; Kraemer *et al.*, 2002; Peroni *et al.*, 2002; Rodríguez and Miller, 2005). These are the rift stage, the stage of thermal subsidence and, finally, the foreland stage (Fig. 2). The rift and thermal subsidence stages of the Austral Basin mainly coincide with the deposition of the Rocas Verdes Marginal Basin, whereas the foreland stage of the Austral Basin is simultaneous with the evolution of the Magallanes Basin.

2.1. Rift Stage

This rifting stage is connected to the breakup of Gondwana (Uliana and Biddle, 1988; Pankhurst *et al.*, 2000), which took place during the Middle to Upper Jurassic, approximately 170 Ma ago. It affected mainly the Deseado Massif and it is represented in the Patagonian-Fuegian Andes by the El Quemado Complex, which is known as the

Tobífera Formation in Chile. The El Quemado Complex consists of very thick layers of dacites and andesites controlled by direct faults and intercalated with conglomerates, sandstones and, in certain cases, even mudstones. In this initial stage, grabens and half-grabens developed, which were filled with volcanoclastic and volcanic rocks intercalated with epiclastic sediments (Biddle *et al.*, 1986; Uliana and Biddle, 1988). The sediments become progressively younger towards the east.

To the south of the study area, this stage is characterised by rifting and sea-floor spreading along the western margin (Katz, 1963; Dalziel *et al.*, 1974; Dalziel, 1981; Calderón *et al.*, 2007a), which led to the development of a marginal basin (*i.e.*, the Rocas Verdes Marginal Basin), connected to the opening of the Weddell Sea, in the southwestern section of the basin (Dalziel, 1981; Biddle *et al.*, 1986).

2.2. Thermal Subsidence Stage

Subsequently, once the tectonic activity had ceased the thermal subsidence stage began, the typical transgressive deposits of the Springhill Formation developed, characterised by quartz arenites with bipyramidal quartz clasts. The Springhill Formation broadly overlaps the margins of the initial half-graben, and it was overlaid by a thick deep-marine succession, characterised by the alternating black mudstones and marls of the Río Mayer Formation, which extends to the Barremian. Towards the end of this cycle (early Aptian – Albian), in the northern and eastern sectors of the basin a large passive-margin delta system developed, referred to as the Piedra Clavada Formation, and its equivalent in the Lago San Martín (San Martín Lake) area, the Kachaike Formation.

During this stage, to the south of the study area, the basin acts as a back-arc basin (Calderón *et al.*, 2007a).

2.3. Foreland Stage

A regional change from an extensional to a compressional phase took place in the mid-Cretaceous, as a result of the convergence of an arc and/or a craton, thus causing the obduction of the ophiolites — which constituted the sea floor of the Rocas Verdes Marginal Basin — over the cratonic continental margin (Dalziel, 1981; Ramos, 1989). It has not been possible to determine the exact timing of obduction, but the compression associated with the early stages of the orogeny caused the development of a retroarc fold-and-thrust belt along the Patagonian-Fuegian Andes (Ramos *et al.*, 1982; Biddle *et al.*, 1986; Wilson, 1991; Fildani *et al.*, 2003; Fildani and Hessler, 2005). This fold-and-thrust belt is associated along its eastern margin with a foreland basin (Austral Foreland Basin). This compression process extended from the Upper Cretaceous to the Neogene (Ramos *et al.*, 1982; Biddle *et al.*, 1986; Wilson, 1991; Spalletti and Franzese, 2007; Fosdick *et al.*, 2011).

Between the middle Cenomanian and the lower Coniacian (96–84 Ma), a deformation event occurred which could be related to the closure of the Rocas Verdes Marginal Basin (Ramos *et al.*, 1982; Biddle *et al.*, 1986). The onset of the compressional phase in the northern sector of the Austral Basin is characterised by the west to east progradation of the fluvial-estuarine facies of the Mata Amarilla Formation (Varela, 2009, 2011). This change towards a compressional phase was also interpreted in the northern sector of the Lago Viedma (Lake Viedma), on the basis of paleocurrent data and facies changes in the Lago Viedma Formation, which is upper Albian to upper Cenomanian in age

(Canessa *et al.*, 2005). In Chile, on the other hand, in the region of the Torres del Paine National Park and in the Última Esperanza Province, the compressional phase occurs in the transition from the Zapata Formation to the Punta Barrosa Formation, the former being a shelf marine environment, and the latter a deep-marine environment (Wilson, 1991; Fildani *et al.*, 2003; Fildani and Hessler, 2005). The transition was dated by means of detrital zircons, and the age was estimated as being no older than 92 ± 1 Ma (Fildani *et al.*, 2003). Recently, Fosdick *et al.* (2011) obtained new zircon U-Pb ages from an interbedded volcanic ash in the Zapata-Punta Barrosa transition, suggesting an age of 101 ± 1 Ma. They indicated that the deformation at $51^{\circ} 30' S$ began ~ 100 Ma and progressed during six main stages (Fosdick *et al.*, 2011).

3. Background to the Mata Amarilla Formation

This succession has been referred to as Estratos de Mata Amarilla (Mata Amarilla Strata; Feruglio, in Fossa Mancini *et al.*, 1938) or Mata Amarilla Formation (Leanza, 1972; Russo and Flores, 1972), and it coincides with the succession that Ameghino (1906) called *Sehuenense* [sic] (Cione *et al.*, 2007; Varela *et al.*, 2008; Varela, 2009; O’Gorman and Varela, 2010). It is one of the units that best exemplifies the early Late Cretaceous in the Austral Basin, which could be connected to the closure of the Rocas Verdes Marginal Basin (Biddle *et al.*, 1986; Varela, 2009, 2011).

This formation has a maximum thickness of approximately 350 m in outcrops, and it is composed of gray and blackish siltstone and claystone, alternating with banks measuring between 1 and 10 m constituted by whitish and yellowish-grey fine- to medium-grained sandstone, deposited in littoral and continental environments (Arbe, 1989, 2002;

Poiré *et al.*, 2004; Russo and Flores, 1972; Russo and Di Benedetto, 1980; Varela and Poiré, 2008; Varela *et al.*, 2008; Varela, 2009, 2011). According to the classification of Folk *et al.* (1970), the sandstones of the Mata Amarilla Formation are feldspathic litharenites, except for three samples which were labelled as lithic feldarenites (Varela, 2011). The petrographic study of 48 thin sections concluded that the main provenance of the sandstones of the Mata Amarilla Formation derives from a magmatic arc and, to a lesser extent, from an orogenic area (Varela, 2011). The type section is located on the southern margin of the Río Shehuen or Chalia (Shehuen or Chalia River), approximately 23 km east of the locality of Tres Lagos, in the area surrounding the Estancia Mata Amarilla (Mata Amarilla Farm), also known as Estancia La Soriana (La Soriana Farm), (locality 3, Fig. 3). It overlies the Piedra Clavada Formation, which is lower Albian in age, with transitional contact and it is unconformably covered by the Campanian sediments of the La Anita Formation (Varela and Poiré, 2008; Varela, 2009, 2011) (Fig. 4). This formation (see Fig. 4) was deposited during the early Upper Cretaceous, extending from the Cenomanian to the Santonian (Poiré *et al.*, 2007; Varela and Poiré 2008; Varela, 2009).

On the basis of facies analysis, Varela (2009, 2011) recently divided the Mata Amarilla Formation into three sections, according to the different conditions of accommodation space creation with respect to sediment supply (Fig. 4).

The lower section of the Mata Amarilla Formation consists of fine-grained sediments with palaeosol development interbedded with laminated shale and coquinas. In the eastern part of the study area, eight littoral facies associations or sedimentary units were recognised: sabulithic bars, large-scale bars, bioclastic lobes, sand bars with herringbone cross-stratification, sand bars with hummocky cross-stratification, small-scale gravelly channels and diamictites, fine-grained sediments with shells, and heterolithic deposits with

marine fossils. These facies associations correspond to littoral marine, lagoon, estuary, and bayhead delta palaeoenvironments (Varela, 2011). In turn, in the western sector of the study area, the facies associations identified were large-scale simple ribbons and fine-grained sedimentation, which is consistent with a distal fluvial system, with palaeocurrents coming from the west (Varela, 2011).

The middle section of the Mata Amarilla Formation is characterised by conglomerates, sandstones, siltstones and mudstones. In the western part of the study area, four facies associations or sedimentary units were defined: gravelly sheets, sandy sheets, small-scale bars and fine-grained sedimentation. These correspond, from west to east, to a gravel-bed braided fluvial system and a sandy high-sinuosity meandering fluvial system (Varela, 2011). The palaeocurrents run from west to east, flowing into the main fluvial system located to the east. In the eastern part of the study area six facies associations were recognised: complex ribbons, small-scale simple ribbons, small-scale bars, lobes, fine-grained sedimentation, and heterolithic deposits with continental fossils. These are associated with a low-sinuosity meandering fluvial system with aggradation, which is the main drainage system, and the palaeocurrents flow from the northeast to the southwest (Varela, 2011).

As regards the upper section of the Mata Amarilla Formation, it is similar to the lower section, as it consists of fine-grained sediments with palaeosol development interbedded with laminated shale and coquinas (Varela, 2011). In the eastern part of the study area, the littoral facies associations or sedimentary units identified — *i.e.*, bioclastic lobes, sand bars with herringbone cross-stratification, fine-grained sedimentation with shells, and heterolithic deposits with marine fossils — correspond to littoral marine, lagoon, and estuary palaeoenvironments (Varela, 2011). The western sector of the study area is

characterised by two facies associations or sedimentary units: large-scale simple ribbons and fine-grained sedimentation, which can be assigned to a distal fluvial system, with palaeocurrents coming from the west (Varela, 2011).

The lower and upper sections show conditions with high rates of accommodation / sediment supply, whereas the middle section shows low rates of accommodation / sediment supply (Varela, 2009, 2011). These changes are inferred to be promoted by relative sea-level oscillations in response to the tectonic evolution of the Austral fold-and-thrust belt (Varela, 2009, 2011).

4. Problems of dating on the basis of fossil content

Despite the abundant fossil content of the Mata Amarilla Formation, a considerable number of doubts and debates have arisen concerning the age of this formation. On the one hand, the presence of invertebrates such as *Exogyra guaranitica*, *Pterotrigonia aliformis*, *Corbula sehuena*, and the gastropod *Potamides (Pirenella) patagoniensis* (Ihering, 1907; Wilckens, 1907; Feruglio, 1936, 1937, 1938; Piatnizky, 1938; Griffin and Varela, *in press*) are not index fossils which could be used to determine ages and/or limit options. Yet, this association suggests a Coniacian age (*e.g.*, Riccardi and Rolleri, 1980).

The most reliable chronological information is given by the presence of ammonites at Cerro Índice (Índice Hill, locality 9, Fig. 3), which are assigned to the “Estratos” de Mata Amarilla and were placed in a new species of the genus *Peroniceras* (*P. santacrucense*) (Leanza, 1970). Subsequently, Blasco *et al.* (1980) and Nullo *et al.* (1981) described specimens of *Placenticeras* sp. in the Mata Amarilla Formation at Cerro Índice, and regarded them as Santonian in age. On the basis of the few specimens found by Leanza

(1970) in the locality mentioned above, Riccardi (1984a; 1984b) described the faunule of *Peroniceras santacrucense*, assigning it a Coniacian age. Riccardi *et al.* (1987) relocated the species to the genus *Gauthiericeras*, adding that it occurs approximately 75 m above levels with *Placenticeras* and approximately 20 m below the point of contact with the Pari Aike Formation (currently regarded as the middle section of the Mata Amarilla Formation; Varela, 2011). In turn, they found ammonites in the Bajo del Cerro Índice (Cerro Índice Depression) which belong to the same species (*Gauthiericeras santacrucense*), and located this faunule to the upper Coniacian, according to the stratigraphic distribution of the genus *Gauthiericeras* (Riccardi *et al.*, 1987). Finally, Riccardi (2002) established the *Gauthiericeras santacrucense* zone and dated it as late Coniacian, in agreement with the stratigraphic range of the genus *Gauthiericeras* suggested by Grossouvre (Riccardi, 2002). Regardless of the exact stratigraphic location of the ammonite-bearing level or levels, it is difficult to locate them in any of the three sections of the Mata Amarilla Formation, as they have not been found yet.

On the other hand, vertebrates provide inconsistent and partially contradictory data (Goin *et al.*, 2002; Varela, 2011); such is the case for dinosaurs, among which the most prominent are the Ornithischia *Talenkauen santacrucensis* Novas, Cambiaso, and Ambrosio 2004; the theropod *Orkoraptor burkei* Novas, Ezcurra and Lecuona 2008; and the sauropod *Puertasaurus reuili* Novas, Salgado, Calvo and Agnolín 2005 (Lacovara *et al.*, 2004; Novas *et al.*, 2004a, 2004b, 2005, 2008). They were assigned to the Maastrichtian following the stratigraphic criteria of Kraemer and Riccardi (1997). What caused persistent doubts was the presence of large sauropods such as *Puertasaurus reuili*, which were extinct worldwide towards the end of the Santonian (Novas, pers. com.). The occurrence of *Carcharodontosaurus* teeth (Novas *et al.*, 1999), which were found in Cenomanian units in

Argentina and Africa, suggests similar ages. In this regard, Ameghino (1899) described at the Cerro Pari Aike (Pari Aike Hill, locality 7, Fig. 3) — currently referred to as the Mata Amarilla Formation, following Varela, 2011 — a *Loncosaurus argentinus*, a primitive ornithopod similar to *Talenkauen santacrucensis* discovered at Cerro Hornos (Hornos Hill, locality 13, Fig. 3). These ornithopods from the Santa Cruz Province, in turn, bear similarities with those found in Cenomanian to Santonian units in other Patagonian regions (Novas *et al.*, 2002).

The record of the turtle family Chelidae in South America ranges from the Albian until today (Broin and de la Fuente, 1993; de la Fuente *et al.*, 2001; Lapparent de Broin and de la Fuente, 2001). The turtles collected in the lower section of the Mata Amarilla Formation, at the Estancia Bajada de los Orientales (Bajada de los Orientales Farm, locality 8) and the Estancia Mata Amarilla (locality 3, Fig. 3) have much in common with various taxa that constitute the Campanian–Maastrichtian chelonifauna (Goin *et al.*, 2002).

Lungfish (Dipnoi) were described by Cione *et al.* (2007) based on 200 complete and partial tooth plates. These authors described two “*Ceratodus*” *iheringi* species and a new genus, *Atlantoceratodus iheringi* Cione, Gouric, Goin and Poiré 2007, which is similar to the “*Ceratodus*” *madagascariensis* Priem 1924 of the Upper Cretaceous (Campanian) from Madagascar, to the extent that they are regarded as belonging to the same genus.

Recently found plesiosaur remains have been studied by O’Gorman and Varela (2010), who compared them with the remains of *Polyptychodon patagonicus* described by Ameghino (1893). The remains found in the lower section of the Mata Amarilla Formation at the Estancia Mata Amarilla (locality 3) and Estancia La Blanca (locality 15, Fig. 3) include some vertebrae, a propodium and over 300 teeth which could be assigned to

Plesiosauria indet. and *Elasmosauridae* indet., and can be compared to the plesiosaurs of the Cenomanian from Antarctica and Australia (O’Gorman and Varela, 2010).

Regarding the flora, Berry (1928) described several leaf impressions of species such as “*Adiantum*” *patagonicum* (erroneously classified as a fern as it belongs to the “*Ginkgoites*”; Iglesias, pers. com.), the conifer *Fitzroya tertiaris*, and eight species of angiosperms (*Rollinia patagonica*, *Hydrangea incerta*, *Sterculia washburnii*, *Peumus clarki*, *Laurelia amarillana*, *Laurophyllum chalianum*, *Apocynophyllum chalianum*, *Bignonites chalianus*, *Phyllites* sp.). On the basis of this relatively high diversity of Cretaceous angiosperms, Berry (1928) erroneously dated it as Cenozoic (Oligocene–Miocene; *fide* Frenguelli, 1953). In turn, Iglesias *et al.* (2007, 2009) described an abundant angiosperm taphoflora in the lower and middle sections of the Mata Amarilla Formation, at the Estancia Mata Amarilla (locality 3) and Mafer (locality 4, Fig. 3), which was attributed to the adaptive radiation of that group of plants during the Cenomanian.

The trunks of the María Elena Petrified Forest are almost exclusively gymnosperms of the Podocarpaceae family and, to a lesser extent, Araucariaceae (Zamuner *et al.*, 2004, 2006, 2008), they do not have biostratigraphic value.

In short, the chronological information provided by invertebrates, theropod dinosaurs and sauropods, fish, turtles, plesiosaurs, and fossil flora does not coincide. Owing to this, and to the lack of radiometric data, the need to have a reliable age which would dispel all doubts on the age of the Mata Amarilla Formation has become of the utmost importance.

5. Methodology

In order to obtain a reliable radiometric age which would solve the problem concerning the age of the formation, a sample was collected from a primary tuff located 29 m above the point of contact between the lower and middle sections of the Mata Amarilla Formation, at the Estancia Mata Amarilla (locality 3, Figs. 3 and 4).

Zircon crystals from the primary tuff sample were recovered from a heavy mineral concentrate by hand-picking under a binocular microscope. Once extracted, they were mounted and polished to approximately half their thickness. The crystals were observed and imaged by cathodoluminescence (CL) using a Jeol JSM-6490 scanning electron microscope (SEM) equipped with a Gatan MiniCL detector at the Goethe-Universität Frankfurt am Main (GUF), in Germany. The U–Th–Pb analyses were performed at the GUF using a sector field inductively coupled plasma mass spectrometer (SF-ICP-MS) coupled with a new ultraviolet (UV) laser ablation system, the New Wave Research UP-213, with a teardrop-shaped, low-volume ($< 2.3 \text{ cm}^3$) laser cell. The instrument setup and the analytical method used in this study were described in detail by Gerdes and Zeh (2006, 2009), and Frei and Gerdes (2009). Analytical spots (30 μm in diameter) were chosen on the basis of the internal structure of the grains, as observed in the CL images. Raw data were corrected for background signal. Common Pb, laser-induced elemental fractionation, instrumental mass bias, and time-dependent elemental fractionation of Pb/U were calculated using an Excel[®] spreadsheet (Gerdes and Zeh, 2006). Drift-correction was performed by fitting a linear regression through all measured ratios, excluding the outliers (± 2 standard deviation, 2σ), and using the intercept with the y-axis as the initial ratio. The laser-induced elemental fractionation and instrumental mass bias were corrected by normalization to the reference zircon GJ-1 (at GUF, ID-TIMS U–Pb age $608 \pm 1 \text{ Ma}$). Reported uncertainties (2σ) of the $^{206}\text{Pb}/^{238}\text{U}$ were propagated by quadratic addition of the

external reproducibility (2SD, standard deviation) obtained from the GJ-1 zircon during each analytical session and the within-run precision of each analysis (2SE, standard error). In the case of the $^{207}\text{Pb}/^{206}\text{Pb}$ ratio, a ^{207}Pb signal-dependent uncertainty propagation was used (Gerdes and Zeh, 2009). The accuracy of the method was verified by means of the analysis of reference zircons 91500 (1064.8 ± 4.3 Ma, MSWD of concordance and equivalence = 0.86), Plešovice (337.7 ± 1.6 Ma, $\text{MSWD}_{\text{C} + \text{E}} = 0.84$), and Temora (416.6 ± 2.5 Ma, $\text{MSWD}_{\text{C} + \text{E}} = 0.9$). Plots and age calculations were made using the ISOPLOT software (Ludwig, 2003).

6. Tuff level

The tuff level is located 29 m above the contact between the lower and middle sections of the Mata Amarilla Formation, at the Estancia Mata Amarilla (locality 3, Figs. 3 and 4). This tuffaceous level is 60 cm thick, massive and white coloured, and it is interbedded with fine-grained floodplain deposits with abundant palaeosol development (Fig. 5a). The tuff has no overimposed pedogenesis, its grain size is very fine to fine (Fig. 5b), and based on its fragmental composition it could be classified as a vitric tuff with minor crystal content (Fig. 5c). Even though this level has lateral continuity in locality 3 (Estancia Mata Amarilla) and other tuff levels which display no pedogenesis were found in other localities, the nature of the fluvial palaeoenvironment prevents its direct correlation. Added to this, all palaeosols of the Mata Amarilla are composed almost entirely of smectite clays, which have a genesis associated with the alteration of volcanic glass (Varela, 2010; 2011).

7. Radiometric data

The prismatic zircon crystals from the tuff studied by cathodoluminescence revealed that their growth is characterised by oscillatory zoning, which is typical for primary volcanic crystals. It could be observed that certain crystals were fractured at right angles, which could be connected to eruptive violence, that is, clast collision during the eruptive event (Fig. 5). On occasion, rounded inherited cores could be distinguished, characterised by a darker luminescence (Fig. 5). Xenocrystic zircon typically shows signs of resorption and original oscillatory zoning is blurred or obliterated (Fig. 5). In this manner, twenty U–Pb spot analyses by laser ablation were carried out on the outer parts of the zoned zircon crystals (Table 1), which yielded a concordia age of 96.23 ± 0.71 Ma (Fig. 6A). This age is interpreted as dating the crystallisation of zircons from the tuff layer and, as it constitutes a primary deposit, it coincides with the time of deposition of the middle section of the Mata Amarilla Formation.

Fourteen ages older than 100 Ma were obtained: 6 spot analyses by laser ablation were carried out on zircon cores with younger overgrowth rims and 8 spot analyses were obtained on xenocrystic zircon (Table 1). The datings of the inherited zircon cores and xenocrystic zircon suggest crustal involvement, and three magmatic and/or metamorphic events prior to the eruption that deposited the tuff were registered. These are, in increasing order of age, a lower Permian event (280–300 Ma), a Lower Jurassic event (180–200 Ma) and finally a younger group of ages indicating an Upper Jurassic event (~ 157 Ma, Fig. 6B).

7. Discussion

The new dating of the Mata Amarilla Formation indicates the occurrence of magmatism at 96.2 ± 0.7 Ma, which would be located to the west of the study area. This

magmatic arc may have been active both during the thermal subsidence stage and the foreland stage (Fig. 2). However, on the basis of the sedimentological data — which indicate a marked west–east shift in the proximal-to-distal sedimentological facies — and the paleocurrent data, Varela (2009, 2011) suggests that such a change reflects the onset of the foreland stage at the Austral Basin. The lower section of the Mata Amarilla Formation shows distal fluvial facies to the west, whereas to the east the deposits occur in a prograding sequence coarsening and thickening upwards from an estuary towards a bayhead delta. The middle section of the Mata Amarilla Formation shows, from west to east, a clear transition from gravel-bed braided systems to sandy high-sinuosity meandering fluvial systems; finally, in the eastern section the fluvial systems are of the anastomosing type (low-sinuosity meandering fluvial systems with aggradation). The upper section of the Mata Amarilla Formation shows a transition from distal fluvial deposits to the west — wherein the floodplain has been preserved to a great extent — to purely littoral facies to the east of the study area. The marked west–east change in the evolution of the fluvial systems, as well as the west–east transition from distal continental facies to estuarine facies, is coherent with the propagation direction of the Cretaceous fold-and-thrust belt of the Austral Basin. Therefore, the relative sea level changes of the Mata Amarilla Formation are related to tectonic control more than to purely eustatic fluctuations (Varela, 2009, 2011).

The onset of the foreland basin is regarded as coinciding clearly with the onset of deposition of the lower section of the Mata Amarilla Formation (Varela, 2009, 2011), as the increase in the rate of accommodation / sediment supply represents the flexural response of the lithosphere due to the increase in weight of the fold-and-thrust belt. Therefore, according to this study, the age of compression is older than 96.2 ± 0.7 Ma and is located within the range between the lower Cenomanian and the upper Albian (~ 100 Ma), since

the Piedra Clavada Formation, underlying the Mata Amarilla Formation, is lower Albian (Fig. 7), as indicated by *Mohria*-like spores (Archangelsky, 2009).

The study area within this sector of the Austral Basin coincides with the edge of the Rocas Verdes Marginal Basin, which according to several contributions opened by ‘unzipping’ from south to north (de Wit and Stern, 1981; Biddle *et al.*, 1986; Alabaster and Storey, 1990; Hervé *et al.*, 2007a; Fildani and Hessler, 2005). Nevertheless, this ‘unzipping’ model was questioned by Calderón *et al.* (2007a) on the basis of new zircon ages. The Rocas Verdes Marginal Basin widens to the south and is much narrower to the north, where the study area for this work is located (Fildani and Hessler, 2005; Romans *et al.*, 2010, 2011). Therefore, when the basin is under compression — *i.e.*, during the foreland stage — it is logical for the onset of the deformation to become more evident from north to south, as if the ‘zipper’ were closing. The depocentre of the basin is located in the Última Esperanza Province in Chile, to the southwest of the study area. In this region, the presence of the deep-marine sediments of the Punta Barrosa Formation over the shelf-marine sediments of the Zapata Formation indicates the occurrence of a well-developed subaerial fold-and-thrust belt (Wilson, 1991; Fildani *et al.*, 2003; Fildani and Hessler, 2005; Romans *et al.*, 2010; 2011; Fosdick *et al.*, 2011). The Punta Barrosa Formation was dated on the basis of detrital zircon analysis, suggesting an age no older than 92 ± 1 Ma (Fildani *et al.*, 2003). Fildani and Hessler (2005) suggest the occurrence of thrusting during the deposition of the Zapata-Punta Barrosa transition on the basis of provenance data. Recently, this incipient thrust belt formation was dated as being in progress at 101 Ma (Fosdick *et al.*, 2011), but it has not caused significant changes in the sedimentary sequences (Fildani and Hessler, 2005; Romans *et al.*, 2010). Yet, on the northern edge of the basin the crust is more rigid, as it is less thinned (Romans *et al.*, 2010; Varela, 2011). That is why small

uplifts in the arc and in the fold-and-thrust belt may have caused major changes in the sedimentary environments. In this regard, these uplifts have modified the general direction of the drainage network (north-to-south), which in this case has shifted towards a marked west-to-east direction of flow.

In addition the age obtained for the middle section of the Mata Amarilla Formation coincides with the peak age of the histogram for detrital zircons of the Punta Barrosa Formation, which is between 95 and 100 Ma (see Fildani *et al.*, 2003; Fig. 3B) and recently Fosdick *et al.* (2011) constrains the age of Punta Barrosa at 101 ± 1 Ma (Fig. 7).

On the basis of the previously discussed data, it may be concluded that the compression and the ensuing development of the foreland basin occurred simultaneously throughout the basin. In this sense, the onset of the compressional phase at 49.5° south latitude in the lower section of the Mata Amarilla Formation must be older than 96.2 ± 0.7 Ma, whereas this compression becomes evident at 51.5° south latitude in the Punta Barrosa Formation ~ 100 Ma (Fosdick *et al.*, 2011). These ages coincide with the beginning of the Andean uplift at the 34° – 35° S latitude (98.6 Ma–88 Ma) suggested by Tunik *et al.* (2010). However, Suárez *et al.* (2009a, 2009b, 2010 and references therein) argue that the uplift of the Aisén Basin (43° – 48° S latitude) must have taken place some time between 121 and 118 Ma.

Finally, regarding the ages of the inherited zircon cores, an older group was found, which was located in the lower Permian (280–300 Ma, Fig. 6B); these ages are coherent with the age of the metamorphic rocks of the Austral Basin (see Hervé *et al.*, 2003; 2010). In Argentina, it is known as the Bahía de la Lancha Formation and the Río Lácteo Formation; whereas in Chile it is represented in the metamorphic complexes of Aysén and

Magallanes. These two were dated at the same latitude as the study area by Hervé *et al.* (2003, 2007b) and Augustsson *et al.* (2006).

In the graph of the inherited zircon cores (Fig. 6B) there is an absence of ages in the range between the lower Permian and the Jurassic, which could be related to the collision of the allochthonous Madre de Dios terrane (Thomson and Hervé, 2002). Likewise, Hervé *et al.* (2007a) pointed out the absence of plutonic rocks in the South Patagonian Batholith in the same time interval.

The second group of zircon cores with inherited ages lies between 180 and 200 Ma (Lower Jurassic), which probably corresponds to another metamorphic event in the Chonos Metamorphic Complex and, less probably, in the Eastern Metamorphic Complex (Hervé *et al.*, 2007a; 2007b), or else to the Subcordilleran Batholith (Rapela *et al.*, 2005). The youngest inherited age event is approximately 157 Ma (Upper Jurassic), which is contemporary with the final stage of V3 volcanism (157–153 Ma) in Pankhurst *et al.* (2000). This extensive rhyolitic volcanism comprises the El Quemado Complex in Argentina and the Ibáñez and Tobífera Formations in Chile (Pankhurst *et al.*, 2000; Suárez *et al.*, 2009b). This magmatism is associated with a process of extensional continental rifting which caused the breakup of Gondwana (Pankhurst *et al.*, 2000). On the other hand, the 157 to 145 Ma ages group could be more precisely related to a granitic magma emplacement in the South Patagonian Batholith (Hervé *et al.*, 2007a). Therefore, Hervé *et al.* (2007a) assigned ages to the first constructional phase of the South Patagonian Batholith ranging from 157 to 145 Ma (Late Jurassic), which is in part coeval with the rhyolitic ignimbrites of the Tobífera Formation (Pankhurst *et al.*, 2000; Calderón *et al.*, 2007a; Suárez *et al.*, 2009b).

8. Conclusion

The time of deposition of the middle section of the Mata Amarilla Formation was U–Pb dated by means of zircons collected from a tuff layer at 96.2 ± 0.7 Ma, which corresponds to the middle Cenomanian (Walker and Geissman, 2009). The onset of the foreland stage is considered to coincide clearly with the deposition of the lower section of the Mata Amarilla Formation (upper Albian – lower Cenomanian, ~ 100 Ma).

Dating the middle section of the formation allowed us to suggest a more specific time frame for the Austral Basin, as well as being of the utmost importance to understand the paleontological implications of the flora and fauna under study collected in the area.

The presence of Cenomanian deposits in continental facies is of considerable relevance as the Cenomanian is an extremely important period in the biological evolution of the Earth.

On the basis of this new data, it may be concluded that the compression and ensuing development of the Austral Foreland Basin occurred simultaneously, being the onset of compression older than 96.2 ± 0.7 Ma (upper Albian – lower Cenomanian, ~ 100 Ma) at 49.5° south latitude in the lower section of the Mata Amarilla Formation, which coincide with the compression at 51.5° south latitude in the Punta Barrosa Formation ~ 100 Ma (Fosdick *et al.*, 2011).

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Figure captions

FIG. 1: Geological setting of the Austral Basin and location of the study area. Location map of the southwestern Patagonian geological units (modified from Hervé *et al.*, 2007a, b; Calderón *et al.*, 2007a, c; Fildani y Hessler, 2005)

FIG. 2: Schematic stages of geological evolution of the Austral Basin from Middle Jurassic to the Cenozoic. **(a)** Rift Stage (Middle to Upper Jurassic), characterised by rifting in a series of narrow grabens. **(b)** Thermal Subsidence Stage (Upper Jurassic to Lower Cretaceous), once the tectonic activity ceased thermal subsidence began with a transgression that broadly overlapped the margins of the initial half-grabens. **(c)** Foreland Stage (mid-Cretaceous to Cenozoic), occurrence of the Andean uplift, development of a foreland thrust belt and basin.

FIG. 3: Geological map of the study area showing the Cretaceous units of the Austral Basin (after Varela, 2011).

FIG. 4: Schematic cross-section of the three Mata Amarilla Formation sections and their relationship to the over- and underlying units. Location of the tuff layer dated is indicated in the cross-section.

FIG. 5: **(a)** Photograph of the tuff layer of the middle section of the Mata Amarilla Formation at Estancia Mata Amarilla (black arrow), interbedded with fine-grained floodplain deposits with palaeosol development (white arrows). **(b)** Detail of the tuff level, where the massive structure and very fine to fine grain size can be observed (hammer for scale is 33 cm long). **(c)** Microphotographs of the tuff, without polarised light (left), showing ash glass and crystals; and with polarised light (right), only crystals can be distinguished due to the isotropic nature of volcanic glass.

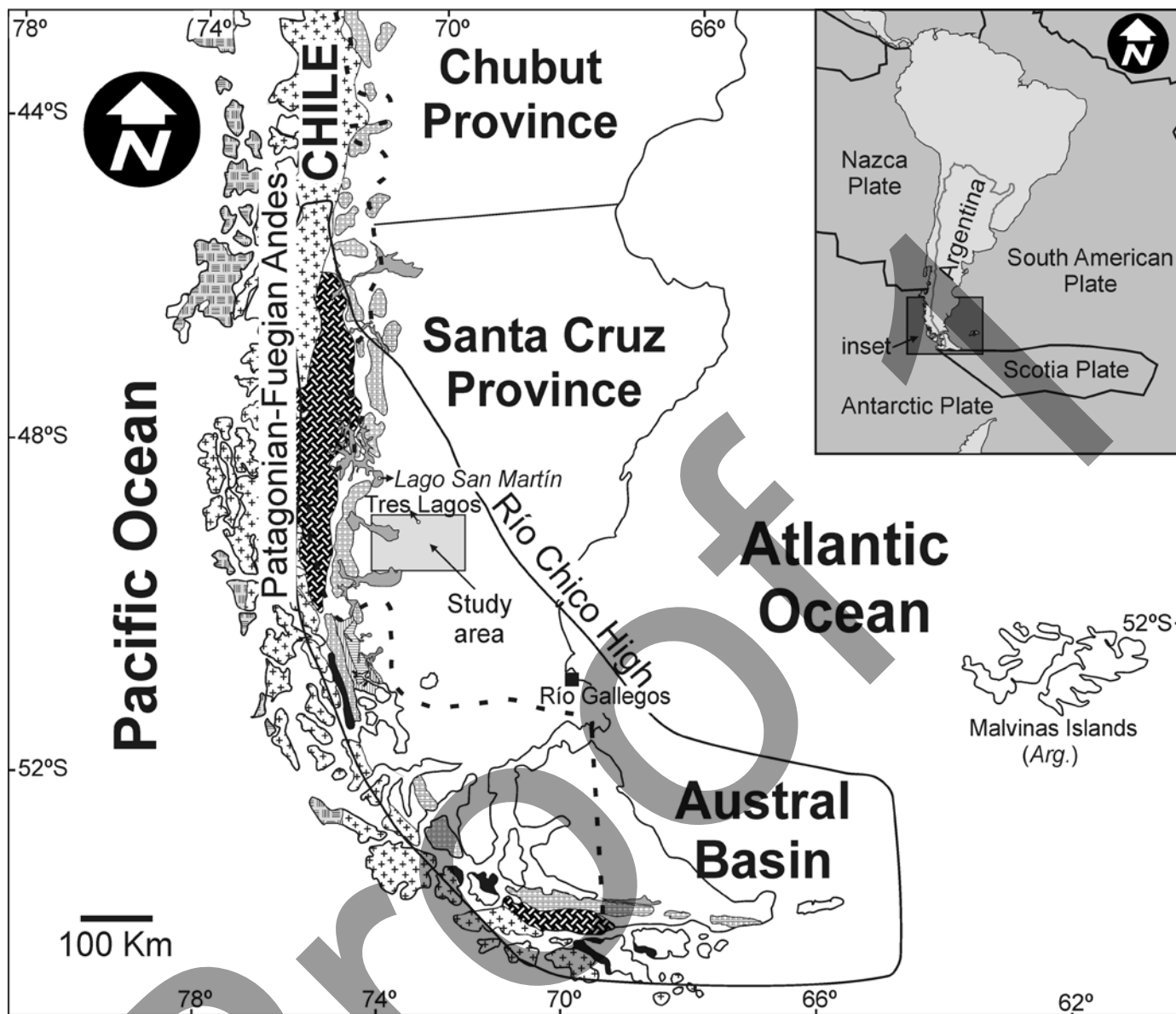
FIG. 6: Photographs of zircon crystals zoned under cathodoluminescence; note their prismatic shape and fractured edges.

FIG. 7: **(a)** U–Pb concordia diagram of the 20 spot analyses on 9 grains from the tuff layer of the middle section of the Mata Amarilla Formation. **(b)** U–Pb concordia diagram of all data from the tuff layer of the middle section of the Mata Amarilla Formation, including the inherited cores of zircons (6 spot analyses) and xenocrystic zircon (8 spot analyses). **(c)** Age vs. relative probability diagrams from the tuff layer of the middle section of the Mata Amarilla Formation.

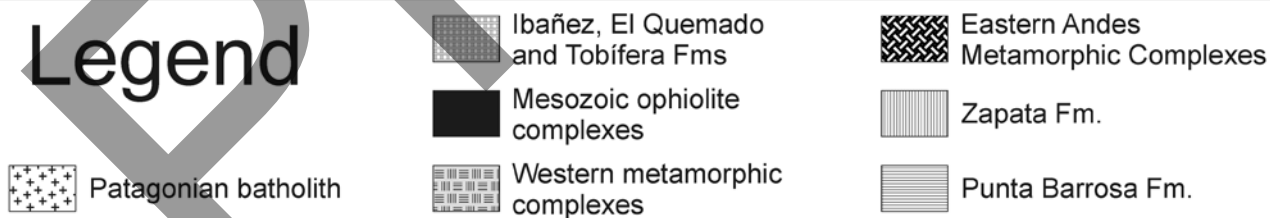
FIG. 8: Stratigraphic summary and geological history of the Austral Basin compared to the Rocas Verdes Marginal Basin - Magallanes Basin. Stratigraphy and data on the Rocas

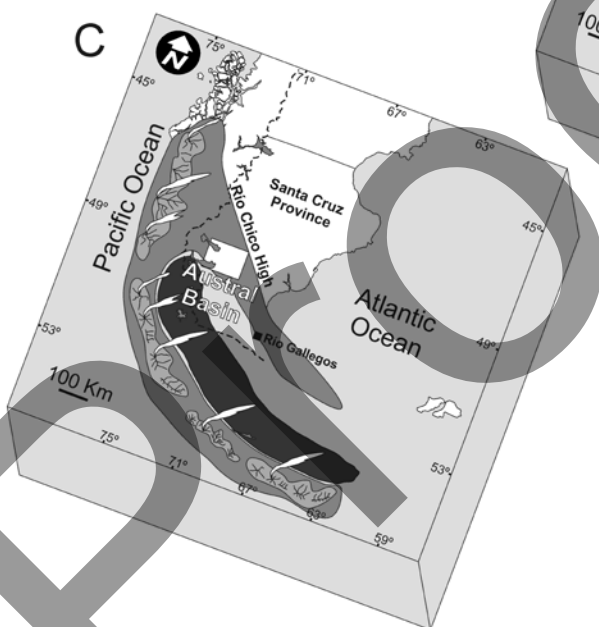
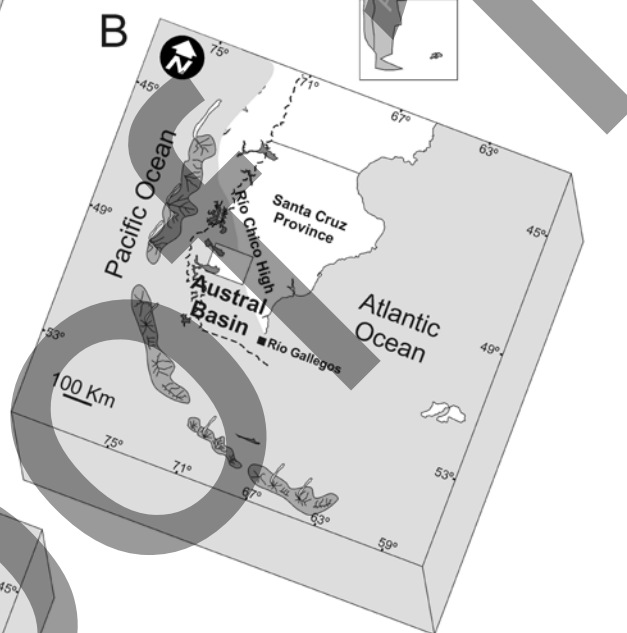
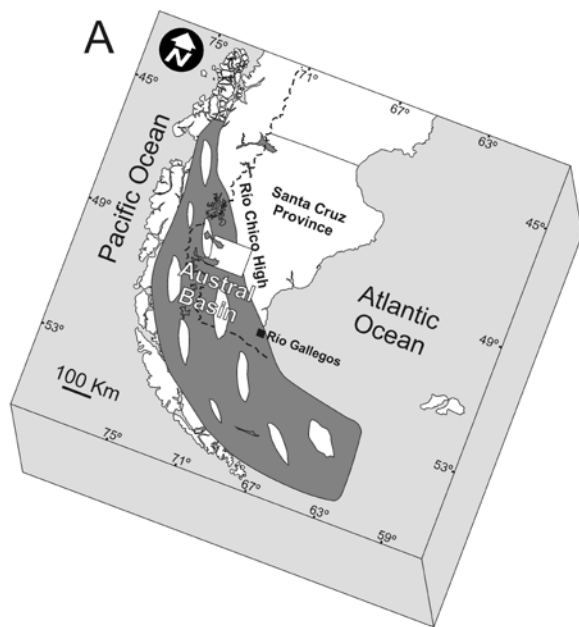
Verdes Marginal Basin - Magallanes Basin taken from Fildani *et al.* (2003) and Fosdick *et al.* (2011).

TABLE 1: DATA FROM ISOTOPIC ANALYSIS BY LASER ABLATION OF 35 SPOT ANALYSES FROM TUFF LAYER (MIDDLE SECTION, MATA AMARILLA FORMATION). References: c, spot analysis on zircon core; x, spot analysis on xenocrystic zircon; r, spot analysis on outer overgrowth rim of zircon; gr, zircon grain number.



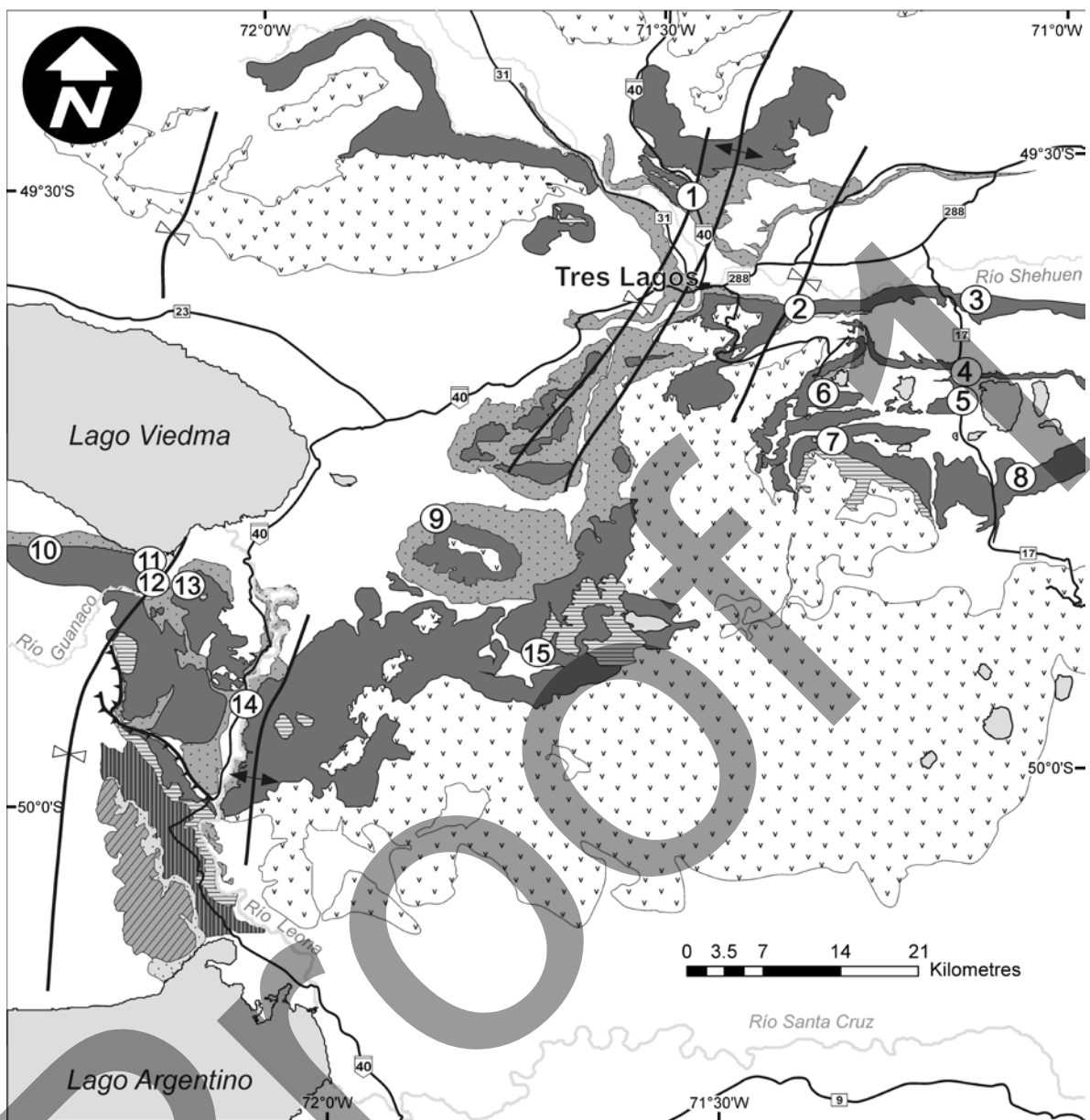
Legend





REFERENCES

- Volcanic arc
- Volcaniclastic deposits
- Continental deposits
- Shallow-marine deposits
- Deep-marine deposits



REFERENCES

Planimetry

- ③ Study locality
- 40 Highway/Road
- Tres Lagos
- River
- Lake

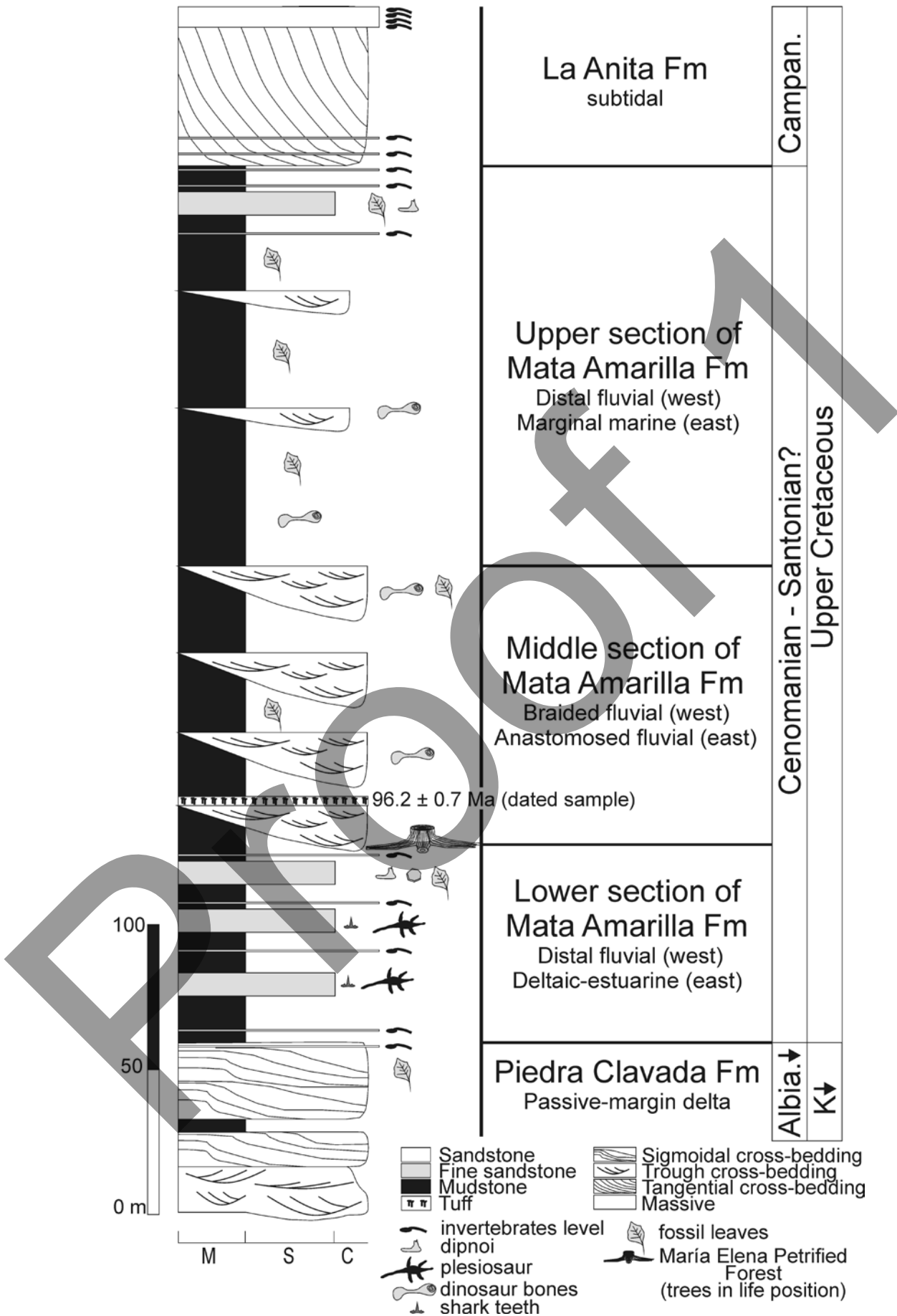
Structures

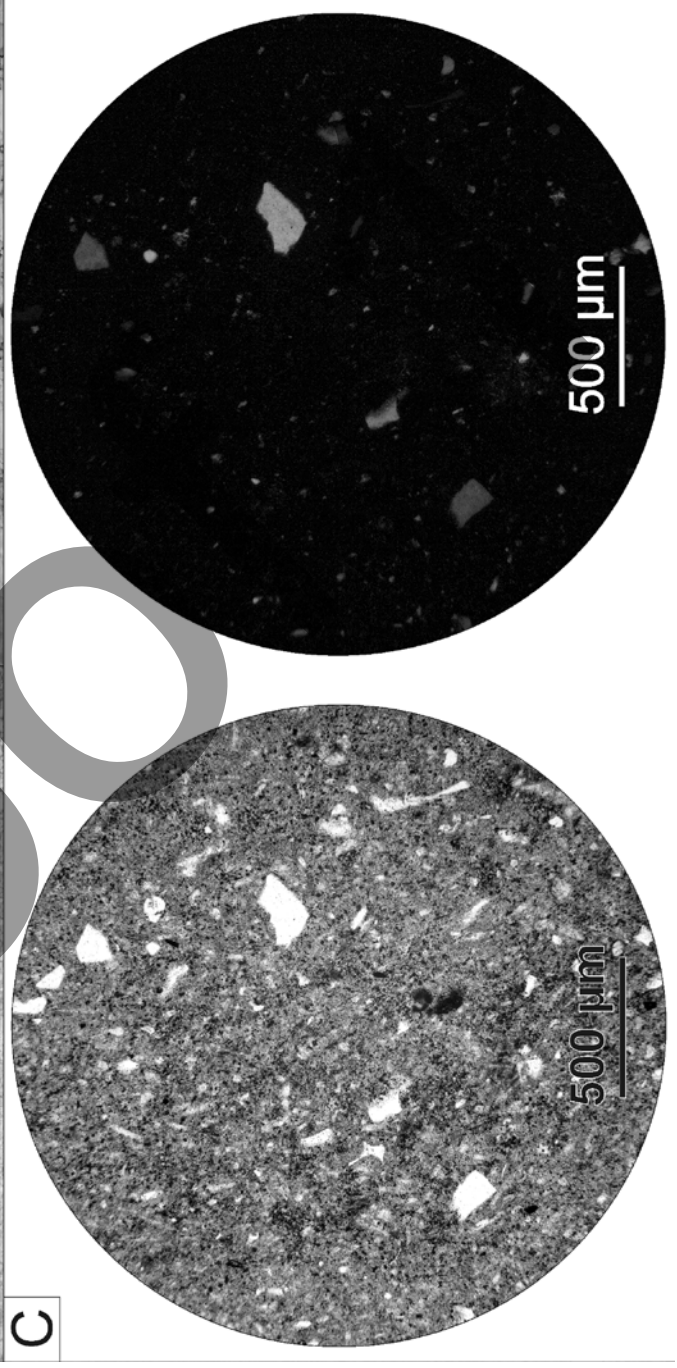
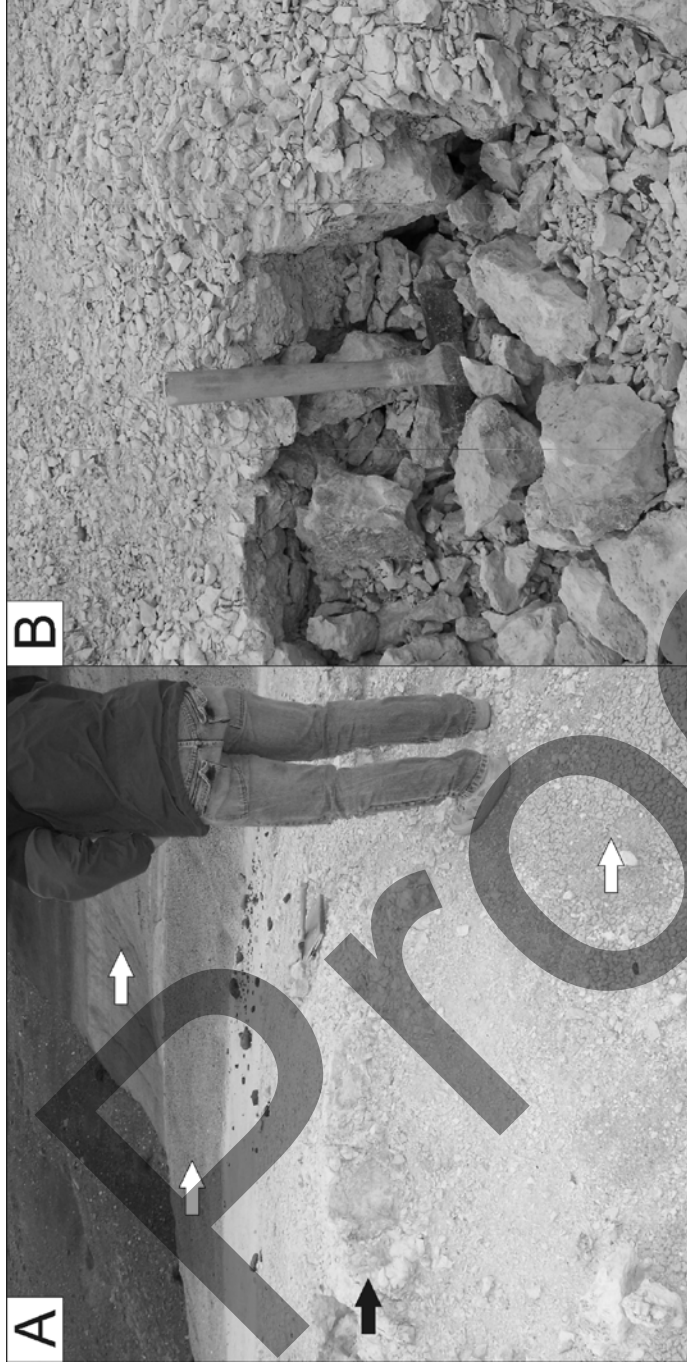
- Anticline
- Syncline
- Inverse fault

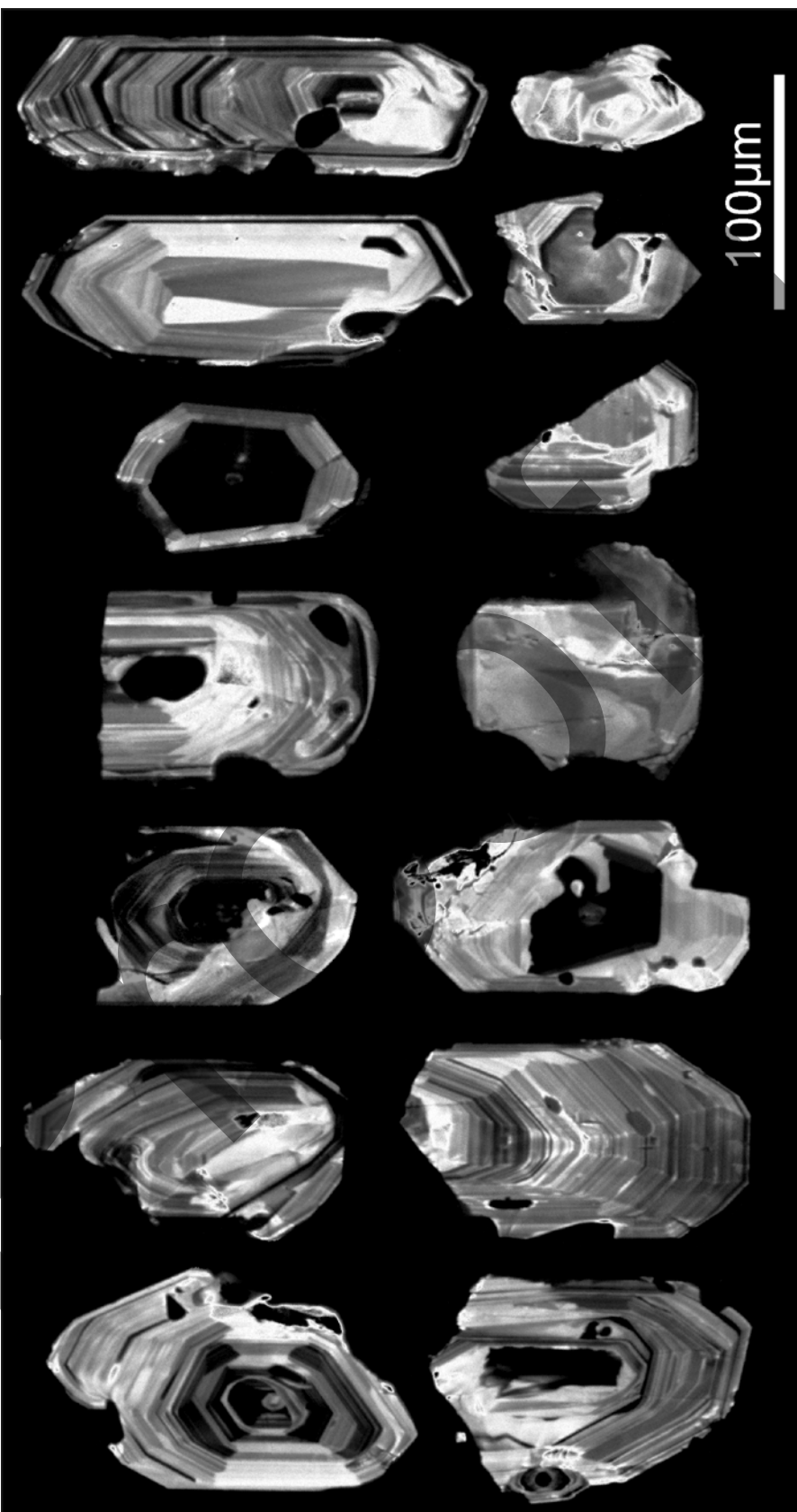
Lithostratigraphic Units

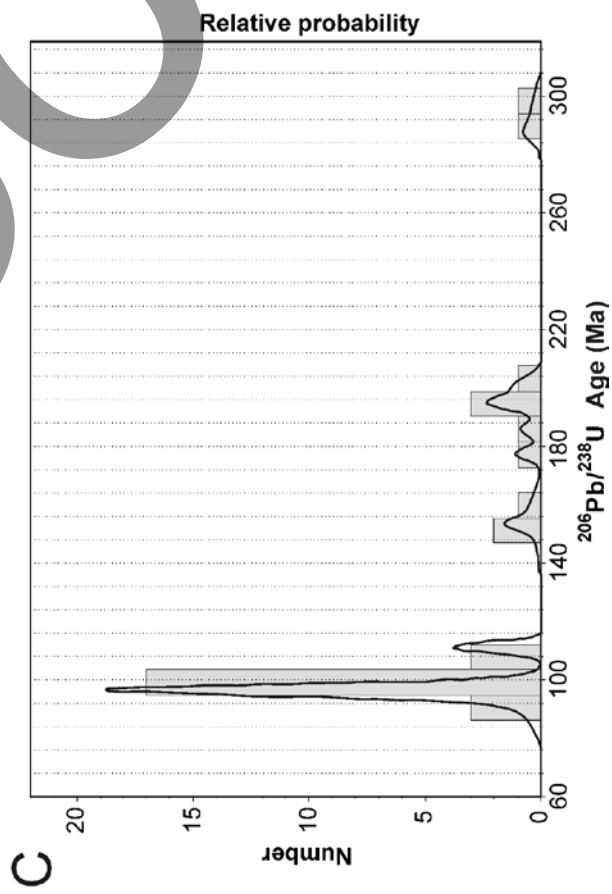
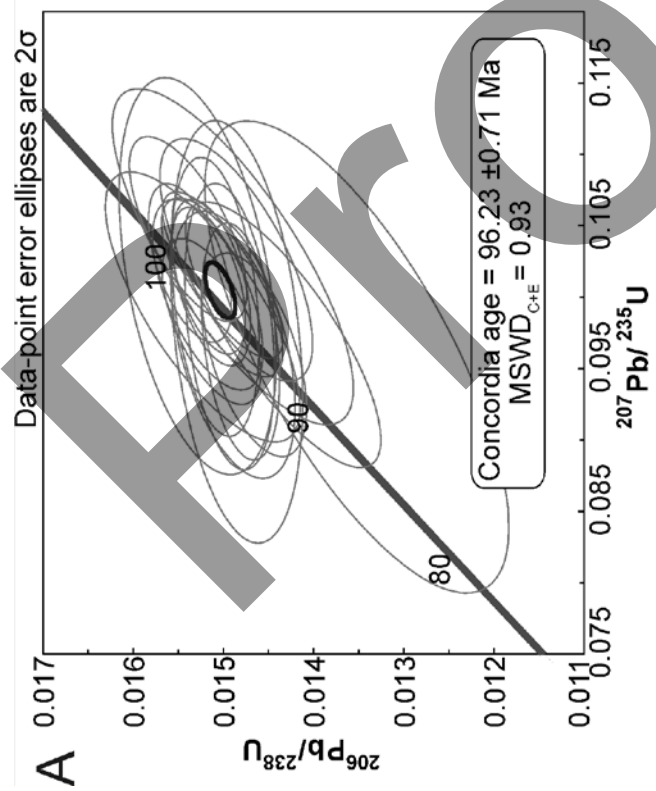
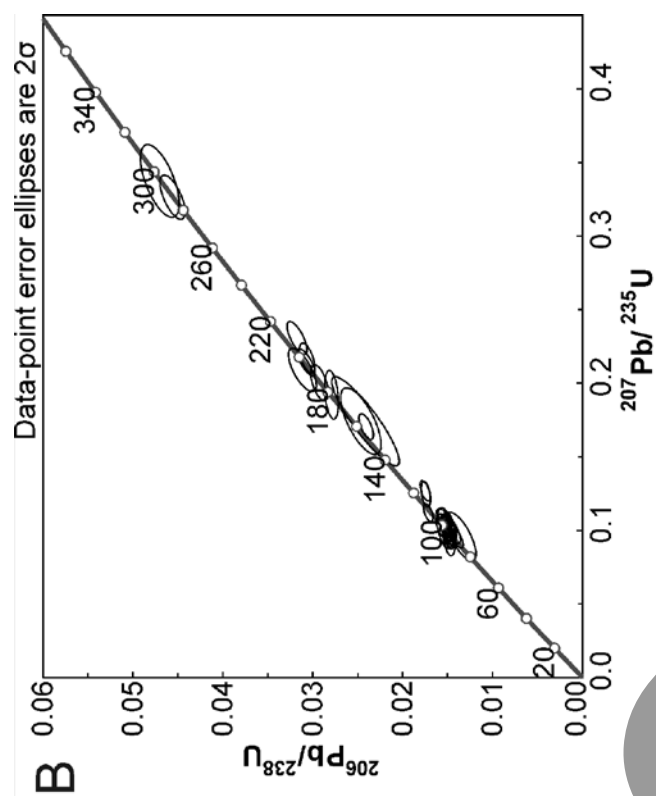
- | | |
|--------------------------|----------------------------------|
| Cachorro Formation | Undifferentiated Quaternary |
| La Anita Formation | Undifferentiated Neogene basalts |
| Mata Amarilla Formation | Calafate Formation |
| Piedra Clavada Formation | La Irene Formation |

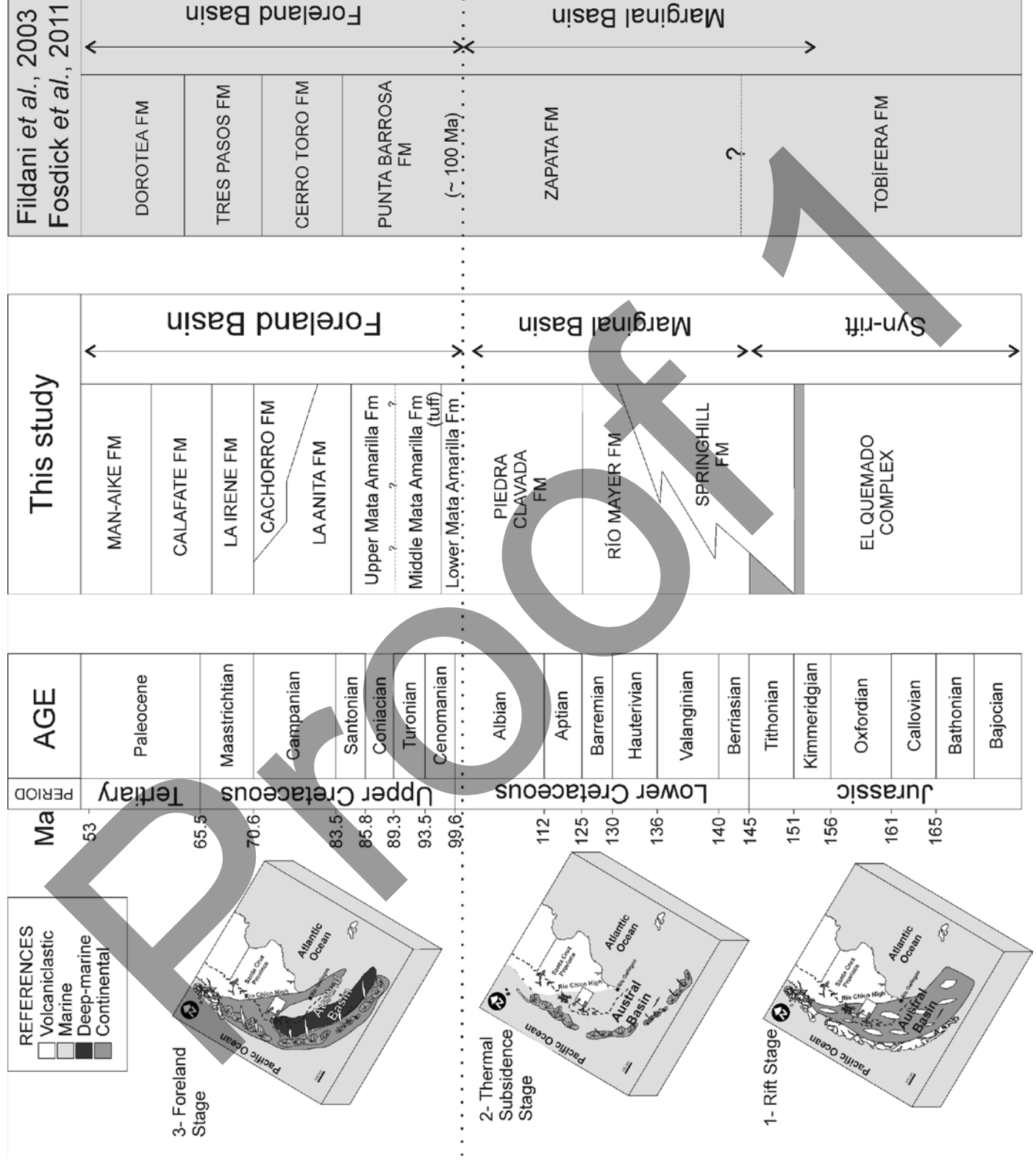
- ① C° Waring ② Ea. La Regina ③ Ea. Mata Amarilla ④ MAFer ⑤ CME ⑥ Ea. La Urbana
- ⑦ Ea. Pari Aike ⑧ Ea. Bajada de los Orientales ⑨ C° Índice ⑩ Pto. La Marina
- ⑪ South of Lago Viedma ⑫ Mouth of Río Guanaco ⑬ C° Hornos ⑭ C° Fortaleza ⑮ Ea. La Blanca











Spot	grain	$^{207}\text{Pb}^a$ (cps)	U^b (ppm)	Pb^b (ppm)	Th^b U	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{206}\text{Pb}^c}{^{238}\text{U}}$	$\pm 2\sigma$ (%)	$\frac{^{207}\text{Pb}^c}{^{235}\text{U}}$	$\pm 2\sigma$ (%)	$\frac{^{207}\text{Pb}^c}{^{206}\text{Pb}}$	$\pm 2\sigma$ (%)	rho^e	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\pm 2\sigma$ (Ma)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\pm 2\sigma$ (Ma)
1	c, gr3	1898	212	6.6	0.46	8809	0.02925	2.7	0.2003	5.0	0.0497	4.2	0.55	186	5.0	185	8
2	c, gr4	5254	374	18	1.49	44063	0.04559	2.5	0.3265	3.8	0.0519	2.8	0.66	287	7.0	287	9
3	gr1	685	153	2.3	0.47	3602	0.01466	3.2	0.0960	6.1	0.0475	5.1	0.53	93.8	3.0	93.0	5.4
4	gr1	847	187	2.8	0.30	2734	0.01489	3.8	0.0967	7.9	0.0471	7.0	0.48	95.3	3.6	93.7	7.1
5	gr2	973	229	4.1	0.34	4266	0.01352	10	0.0958	14	0.0514	9.8	0.72	86.6	8.8	92.9	13
6	c, gr5	1874	210	6.3	1.98	16535	0.03063	2.2	0.2170	3.8	0.0514	3.1	0.58	194	4.3	199	7.0
7	x, gr6	1262	243	4.6	0.58	2340	0.01716	2.5	0.1121	4.4	0.0474	3.6	0.57	110	2.7	108	4.5
8	gr1	1118	246	3.9	0.50	2233	0.01513	2.9	0.0983	4.8	0.0471	3.8	0.61	96.8	2.8	95.2	4.4
9	r, gr5	1894	432	7.7	0.76	3319	0.01517	3.3	0.1002	5.4	0.0479	4.3	0.60	97.1	3.2	96.9	5.0
10	x, gr7	3867	289	13	0.59	33624	0.04700	3.7	0.3375	6.0	0.0521	4.7	0.63	296	11	295	15
11	gr8	1008	238	5.0	0.55	5618	0.01486	4.7	0.1026	7	0.0501	4.9	0.69	95.1	4.4	99	6
12	gr8	675	162	2.5	0.38	2734	0.01493	2.7	0.0979	8.4	0.0476	7.9	0.32	95.5	2.6	94.9	7.6
13	gr8	1706	443	7.2	0.51	15756	0.01513	2.3	0.1010	4.7	0.0484	4.1	0.50	96.8	2.3	97.7	4.4
14	c, gr9	1612	226	6.3	0.29	14630	0.02791	2.3	0.1921	7.0	0.0499	6.7	0.32	177	4.0	178	12
15	gr10	1326	361	5.5	0.44	9597	0.01481	2.4	0.0969	7.0	0.0475	6.6	0.34	94.8	2.2	93.9	6.3
16	x, gr11	2078	324	8.8	0.29	18184	0.02465	7.4	0.1742	10.6	0.0513	7.6	0.70	157	12	163	16
17	gr10	1613	404	8.2	1.51	3254	0.01516	2.2	0.1012	4.2	0.0484	3.5	0.53	97.0	2.1	97.8	3.9
18	gr10	1581	424	8.4	1.37	12004	0.01537	2.4	0.1024	4.4	0.0483	3.7	0.55	98.3	2.4	99.0	4.2
19	gr12	1163	332	6.3	0.47	11123	0.01523	5.8	0.0993	7.8	0.0473	5.2	0.74	97.4	5.6	96.1	7.2
20	gr13	1302	376	6.0	0.61	11725	0.01434	6.2	0.0974	7.8	0.0493	4.8	0.79	91.8	5.6	94.3	7.1
21	gr13	2103	592	9.8	0.41	18936	0.01490	7.3	0.1028	9.3	0.0501	5.8	0.78	95.3	6.9	99.4	8.9
22	gr14	906	252	3.7	0.30	3650	0.01485	4.0	0.0976	12.4	0.0476	11.7	0.33	95.1	3.8	95	11
23	x, gr15	4814	840	20	0.56	10137	0.02406	2.7	0.1705	4.2	0.0514	3.2	0.65	153	4.1	160	6
24	gr16	680	158	2.4	0.36	985	0.01509	2.6	0.1000	8.0	0.0481	7.5	0.33	96.5	2.5	96.8	7.4
25	r, gr17	1788	533	10	1.11	16389	0.01539	3.5	0.1048	5.0	0.0494	3.7	0.69	98.5	3.4	101	5
26	c, gr18	1374	234	7.3	0.80	4000	0.02413	13	0.1741	14	0.0523	6.3	0.90	154	19	163	22
28	gr16	1274	382	5.6	0.18	4396	0.01528	4.7	0.1015	11.2	0.0482	10.2	0.42	97.8	4.5	98	11
29	x, gr19	5063	711	21	0.79	13997	0.03175	2.8	0.2307	4.0	0.0527	2.8	0.72	201	5.6	211	7.6
30	gr20	1036	307	4.5	0.13	2733	0.01501	3.6	0.1015	4.7	0.0491	3.0	0.77	96.0	3.5	98.2	4.4
31	c, gr21	3794	1005	17	1.93	25841	0.01750	2.7	0.1268	4.5	0.0526	3.6	0.60	112	3.0	121	5.1
32	r, gr15	2137	684	11	0.43	4624	0.01501	3.7	0.1007	5.1	0.0486	3.5	0.72	96.1	3.5	97.4	4.7
33	x, gr21	2841	461	14	0.98	10551	0.03115	4.1	0.2090	5.8	0.0487	4.1	0.70	198	7.9	193	10
34	x, gr22	5072	845	25	1.46	13144	0.03073	2.6	0.2142	3.5	0.0506	2.3	0.75	195	5.0	197	6.2
35	x, gr23	869	384	8.9	1.76	7537	0.01742	2.4	0.1246	5.7	0.0519	5.2	0.42	111	2.7	119	6.5