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Geochronologic evidence of a large magmatic province in northern Patagonia encompassing the Permian-Triassic boundary

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A B S T R A C T

The Los Menucos Complex (northern Patagonia) consists of ~6 km thick succession of acidic and intermediate volcanic and pyroclastic products, which has been traditionally assigned to the Middle/Late Triassic. New U/Pb (SHRIMP) zircon crystallization ages of 257 ± 2 Ma at the base, 252 ± 2 Ma at an intermediate level and 248 ± 2 Ma near the top of the sequence, indicate that this volcanic event took place in about 10 Ma around the Permian-Triassic boundary. This volcanism can now be considered as the effusive terms of the neighboring and coeval La Esperanza Plutono-Volcanic Complex. This indicates that the climax of activity of a large magmatic province in northern Patagonia was coetaneous with the end-Permian mass extinctions. Likely correlation of La Esperanza- Los Menucos magmatic province with similar volcanic and plutonic rocks across other areas of northern Patagonia suggest a much larger extension than previously envisaged for this event. Its age, large volume and explosive nature suggest that the previously ignored potential role that this volcanism might have played in climatic deterioration around the Permian-Triassic boundary should be investigated.

1. Introduction

The Permian-Triassic (P-Tr) boundary corresponds to the most severe and synchronous globally extinction event in the history of life on Earth (Erwin, 1994; Jin et al., 2000; Shen et al., 2011; Song et al., 2012; Burgess et al., 2014, and references therein), with the disappearance of over 85% of marine species and 60% of terrestrial families (Erwin, 1994; Benton, 1995) and in high and low latitudes. Extremely accurate U-Pb zircon dating of tuffs along the Meishan sequence in China, one of the most studied sections for the P-Tr boundary, indicate that the main extinction event occurred in a short period of few tens of thousand years in a single pulse (Shen et al., 2011; Burgess et al., 2014) or as two pulses separated by less than 200 thousand years (Song et al., 2012).

Despite these advances, the triggering causes behind the P-Tr extreme climate change and the severe mass extinction are still matter of high controversy, as well as whether the extinction was a catastrophic event or just the most critic episode of a much longer period in which the biota suffered a steady decline (e.g. Jin et al., 2000; Grasby et al., 2011). Numerous different processes and scenarios inducing climatic changes have been suggested as potential killing mechanisms, including: i) in the oceans, global anoxia (CO_2 poisoning) conditions and acidification (Payne et al., 2007), ii) in the land, increase of CO_2 and reduction of O_2 in the atmosphere (Schneebeli-Hermann et al., 2013), iii) massive release of volcanic sulphate aerosols and metane from clathrate reservoirs (Berner, 2002) and iv) massive wildfires, acid rain, aridity and mass wasting (Benton and Newell, 2014). These causes might all have converged in a global warming process (Joachimski et al., 2012) that caused the mass extinction event, recently dated between 251.941 ± 0.037 and 251.880 ± 0.031 Ma in the Meishan sequence by Burgess et al. (2014).The very hostile environmental conditions associated with the Permian-Triassic boundary are interpreted to be reflected in the very slow recovery of the biota that may have

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taken the whole Early Triassic (Yin et al., 2007 and references therein).

Many, if not most, researchers seem to agree in that increased volcanism around the Permian-Triassic played a role, either leading or subsidiary, in provoking environmental conditions that led to the great extinction. For two or more decades, the Siberian Traps (see Ivanov et al., 2013 and references therein) have been considered as the best candidate for a volcanic event responsible for the P-Tr crisis (Renne and Basu, 1991; Campbell et al., 1992; Bowring et al., 1998, and many others). This is based on the extraordinary extension (around 7×10^6 km^2) and volume (around 4×10^6 km^3) of this flood volcanism as originally computed by Masaitis (1983, in Ivanov, 2007) and confirmed by Ivanov (2007), its explosive character and very short duration, which has been estimated as less than 1 Ma (Kamo et al., 2003). More important, even, is the virtual synchroneity of the Siberian Traps extrusion (251-252 Ma) with the P-Tr boundary 251.902 ± 0.024 Ma, Cohen et al., 2013, updated). However, Ivanov et al. (2013) demonstrated that although a major peak of this huge magmatic event occurred near the P-Tr boundary, a second important peak of activity developed 10 Myr later, in the Middle Triassic, and continued into the Late Triassic (ca. 230 Ma). Another magmatic event that has been linked to the P-Tr crisis is that represented in the basaltic flows of the Emeishan Plateau (Lo et al., 2002), in the western part of the South China Block. However, the size of this magmatic province is significantly smaller than the Siberian traps, and it has been recently dated around 260 Ma and therefore should be associated with the middle-late Permian transition rather than with the P-Tr boundary (He et al., 2007, 2010; Fan et al., 2008; Xu et al., 2010). Evidence for terrestrial or marine Capitanian extinctions related to the Emeshian LIP in the southern hemisphere Gondwana are absent, whereas the responsible mechanisms (volcanism, dramatic sea-level fall) appear to have only affected part of the northern hemisphere (Metcalfe et al., 2015). The Siberian Traps are interpreted as a LIP (large igneous province) which was probably derived from a mantle plume (Campbell and Griffiths, 1990; Chung and Jahn, 1995), although several other possible mechanisms have been postulated (see review by Ivanov et al., 2013). Another very large magmatic province, mainly acidic, developed in the southwestern margin of Gondwana in the Permian, the Choiyoi province (Kleiman and Japas, 2009; Rocha Campos et al., 2011; Sato et al., 2015; Spalletti and Limarino, 2017). This occupied at least half-million km^2 with thicknesses reaching up to 2 km (Strazzere and Gregori, 2005), making it smaller but comparable with the Siberian traps. However, age constraints on this enormous magmatic province, albeit yet scarce, points to a protracted magmatism along the southwestern Gondwana margin of 30–40 Ma, from the early Permian around 285 Ma reaching at least the Early Triassic (Kleiman and Japas, 2009; Spalletti and Limarino, 2017). Henry et al. (2013), Limarino et al. (2014) and, recently, Spalletti and Limarino (2017) proposed that the Choiyoi magmatic province in southwestern South America was a main driving force of climatic amelioration and global warming that led from an icehouse regime in the late Carboniferous-Early Permian to a greenhouse one in the Late Permian-Triassic. This extreme change in climatic conditions and beginning of the greenhouse crises was dated in Eastern Australia -southern hemisphere Gondwana-as Changhsingian- Induan (Metcalfe et al., 2015). In these models, the P-Tr extinction should be considered as a punctuated extreme event of a long magmatic process that started in the early to middle Permian and of which volcanic input into the atmosphere took a significant role in southern Gondwana.

As briefly mentioned above, geochronologic studies of important magmatic provinces of likely Permian to Triassic age are still needed for better understanding and modelling the lithospheric, environmental and biological processes that surrounded the critical P-Tr transition. In this paper, we present new geochronologic data (U-Pb SHRIMP in magmatic zircon grains) on the large volcanic Los Menucos Complex, exposed in NW Patagonia. Up to now, this complex had been exclusively attributed to the Middle or Late Triassic on the basis of a whole-rock Rb-Sr isochron (Rapela et al., 1996) for a dacite ignimbrite deposited in the uppermost levels of the sequences, and weak biostratigraphic correlations. Our results show that this complex was erupted in about 10 million years around the P-Tr boundary and it is likely associated with the La Esperanza Plutono-Volcanic Complex exposed some tens of km to the north (Llambías and Rapela, 1984; Rapela and Llambías, 1985; Martínez Dopico et al., 2017a; Luppo et al., 2017a). Their likely correlations with other volcanic and plutonic products across northern Patagonia suggest that a much more important explosive volcanic activity than previously considered was taken place in northern Patagonia during the P-Tr mass extinction.

1.1. *Geologic framework*

The North Patagonian Massif (NPM) extends from the foothills of the Patagonian Andes to the Atlantic Ocean in southern Argentina (Fig. 1, inset) and is characterized by poorly exposed Early Paleozoic igneous and metamorphic rocks, a restricted Silurian-Devonian sedimentary cover and extensive Permian-Triassic magmatism that crops out along its margins.

Los Menucos Complex (LMC), exposed in northern NPM (Fig. 1), is mainly made up by pyroclastic deposits that cover an area of at least 40,000 km^2 (Labudía and Bjerg, 2001). Thickness of the succession has been under debate (Labudía and Bjerg, 2001; Lema et al., 2008), but a minimum of 2000 m as suggested by the latter authors, likely underestimates its real thickness. Widely distributed ignimbrite sequences vary from dacitic to rhyolitic compositions with interlayered mesosilicic lava flows and volcano-sedimentary beds. Rhyolitic dykes and small, dioritic to monzonitic subvolcanic plutons has been associated with the complex (Lema et al., 2008). This complex was first named as Los Menucos Group (Labudía and Bjerg, 2001, 2005) and subdivided into the lower Vera Fm., made up of thin dacitic ignimbrites and sedimentary layers, and the upper Sierra Colorada Fm. composed of thick rhyolitic ignimbrites. On the other hand, Lema et al. (2008) considered it a complex, and the different rock types as facies. A solid chronostratigraphic framework is lacking for the LMC. First age constraints come from findings of *Dicroidium* paleo flora in several levels of the Vera Fm., which have generally been interpreted as indicative of middle to late Triassic age, although Permian and Jurassic taxa have also been described (Artabe et al., 2007 and references therein). Rapela et al. (1996) presented a Rb-Sr whole rock isochron of 222 ± 2 Ma from dacitic ignimbrites overlaying the Vera Fm., while Lema et al. (2008) published an Ar-Ar isochron age of 207 ± 1 Ma (biotite) from a quartz-monzonite porphyry subvolcanic pluton that they assigned to the LMC but with no clear field relationships with the volcanic and pyroclastic levels.

The extension of the complex, the scarcity of reliable crystallization ages, problems with the biostratigraphic record and the proximity to the Permian-Early Triassic epizonal La Esperanza Plutono-Volcanic Complex (Llambías and Rapela, 1984; Martínez Dopico et al., 2017a) highlight the importance of reliable geochronologic studies on this important volcanic manifestation.

Our study was carried out in a 500 km^2 area located between La Esperanza ranch and Los Menucos town (Fig. 1) where LMC (Lema et al., 2008) displays one of the best preserved and thickest volcanic accumulations. A geologic survey and paleomagnetic systematic sampling (work in progress) was carried out along W-E and N-S sections, respectively located along the western and eastern flanks

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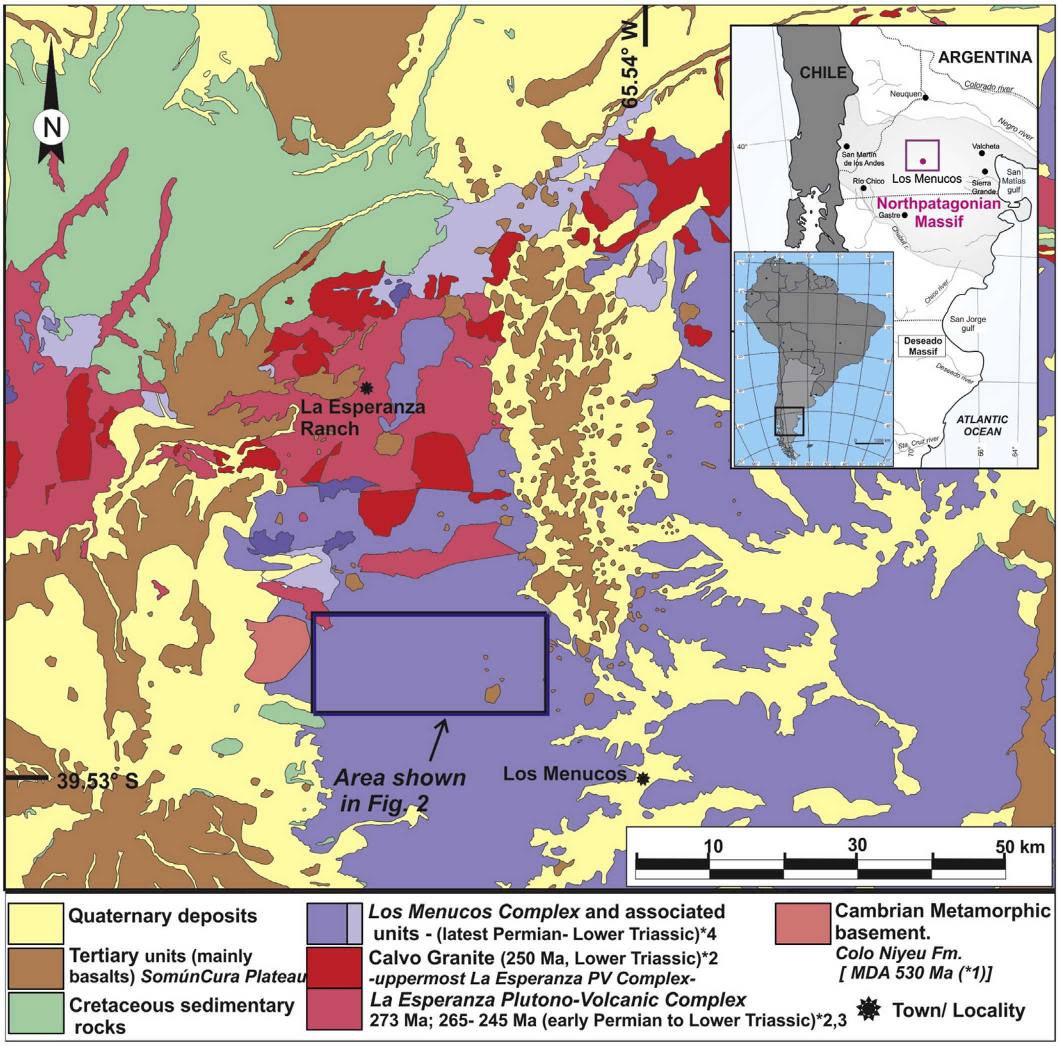

Fig. 1. Geologic map of the Los Menucos area, simplified from Cucchi et al. (2001). Inset: location of the study area in the North Patagonian Massif in South America and Argentina. Area represented in Fig. 2 is also shown. In the references, U-Pb SHRIMP zircón ages belong to *1 Martínez Dopico et al. (2017b) and is interpreted as a maximum depositional age; *2 Pankhurst et al. (2006); *3 Martínez Dopico et al. (2017a); *4 *This paper.*

of a major structure referred as the "Piche Synform" by Giacosa et al. (2007). This is characterized by a NW-SE axis smoothly plunging to the SE (Fig. 2). The W-E section is a homoclinal succession (mean strike 035°/mean dip 22SE) of tabular units, reaching up to ~6 km thick, although lateral thinning is observed at a bigger scale (Fig. 2). The basal levels are dominated by few metres thick (exceptionally few tens of metres) rhyolitic ignimbrites with low crystal/matrix ratio, and subordinate volcaniclastic/epiclastic deposits. The lowermost rhyolitic ignimbrites lay unconformably on top of the early Paleozoic basement exposed nearby. In the central part of the W-E section, two levels of mesosilicic non-vesicular lava flows, previously mapped as "andesitic lavic and pyroclastic facies" and "lavic to subvolcanic mesosilicic to basic facies" by Lema et al. (2008), are observed. A succession of rhyolitic ignimbrites and tuffs are interleaved between these two effusive levels. The upper part of the section is mainly constituted by thick (tens of metres) dacitic ignimbrites with higher crystal/matrix ratio than the lowermost ignimbrites. Mesosilicic to basic units and sedimentary/volcaniclastic levels are also present.

The N-S section (Fig. 2) exhibits a smoothly south dipping stratification (mean strike 103°/mean dip 17°), with an estimated accumulated thickness of 3.6 km. The lateral continuity of the levels is sometimes masked by second order faults and irregular topography along the strike. The most abundant units are high crystal/matrix ratio dacitic ignimbrites intercalated with sedimentary/volcaniclastic levels. A good correlation between the successions along both limbs of the "Piche Synform" is observed, with the eastern flank (N-S section) being equivalent to the upper part of the successions exposed along the western limb, specifically those located stratigraphicaly above the mesosilicic intermediate levels (Fig. 2).

1.2. U–Pb SHRIMP geochronology

U–Pb SHRIMP zircon ages were obtained from three samples. M265 corresponds to the basal levels, M82 to a central section and M252 close to the highest exposed levels (Fig. 2). Analyses were performed at the Research School of Earth Sciences of the Australian National University, Canberra. The bulk of zircons extracted from each sample were largely euhedral and predominantly translucent, with length ratios between 2:1 and 7:1 (Fig. 2). Standard zircon separation procedure was performed in the Instituto de Geociencias Básicas, Aplicadas y Ambientales de Buenos Aires (IGEBA) at the University of Buenos Aires. SHRIMP U-Th-Pb

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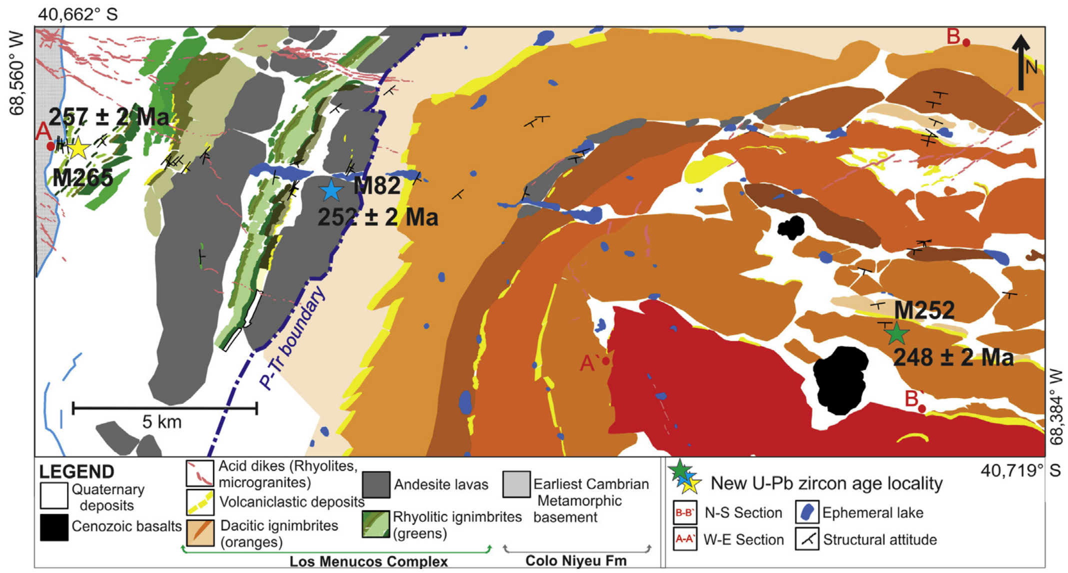

Fig. 2. Geologic sketch of the study area with sampling locations of Los Menucos Complex and the corresponding SHRIMP U-Pb zircon ages indicated with stars. The complex unconformably lays on the early Cambrian Colo Niyeu Formation (Martínez Dopico et al., 2017b) and is cross-cut by a *ca* 245 Ma acid dike swarm dated further north, in La Esperanza area (Pankhurst et al., 2006).

analyses were performed at the Research School of Earth Sciences at the Australian National University, Canberra. Collection and reduction of the data followed methods described by Williams (1998). Data were reduced using Excel toolkit (Ludwig, 2008). Uncertainties given for individual analyses are at the 1σ level. All the uncertainties in the calculated intercept or Concordia ages are reported at 2σ confidence limits. A summary of results of the spot analyses are presented in the Electronic Appendix A.

1.3. Sample M265

It is a strongly welded rhyolitic ignimbrite with pink, green, or

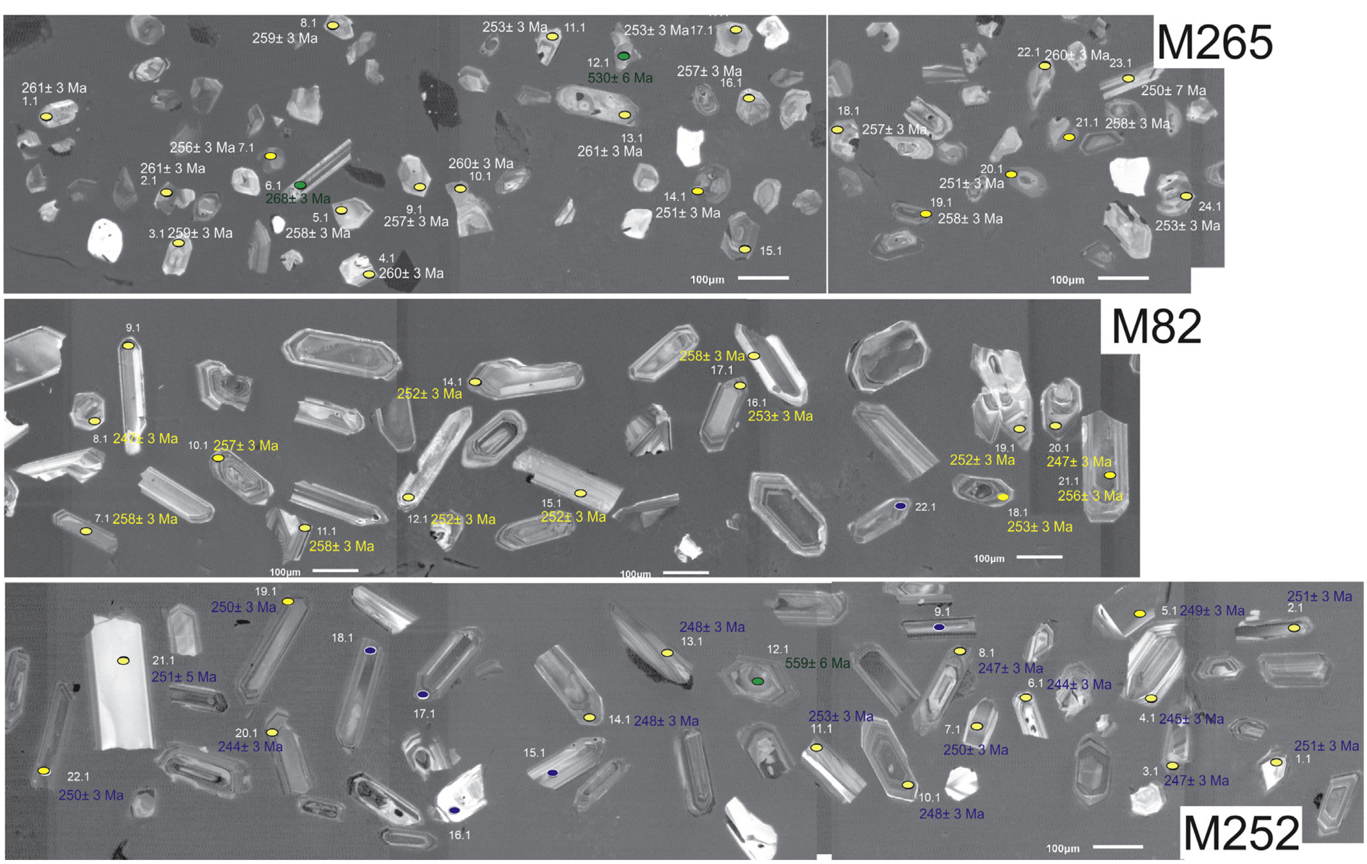

Fig. 3. CL image of zircon grains dated by SHRIMP technique from samples M265, M82 and M252 (upper, central and lower rows, respectively).

white groundmass; 5-14% of up to 2 mm phenocrysts of sanidine, plagioclase, biotite and minor quartz with traces to 25% yellow-white (up to 15 mm) pumice fragments and <5 mm (gray intermediate volcanic) lithic fragments. Accessory minerals include zircon, as well as apatite and magnetite.

The zircons are dominated by relatively small, equant to subequant, subhedral to euhedral grains, some with bipyramidal terminations. Coarser, elongate euhedral grains are also present, as are some irregularly shaped grains. Slender prismatic grains are a minor component. CL images (Fig. 3) show a mostly subdued internal response. Some grains have sector, and/or oscillatory zoning, but the majority either shows little or no zoning, or irregular internal CL features. From the 25 grains analysed, only one yielded an older $^{206}Pb/^{238}U$ age of ~530 Ma. The others are dominated by radiogenic Pb and form a single grouping within uncertainty of the Tera-Wasserburg Concordia (Fig. 4). The areas analysed on grains 6 and 23 however are slightly enriched in common Pb. The enlarged probability density plot of radiogenic $^{206}Pb/^{238}U$ ages shows a simple bell-shaped distribution, with the analysis of grain 6 slightly older at ~267 Ma. A weighted mean for the 23 analyses forming that dominant age grouping (Fig. 4) gives a $^{206}Pb/^{238}U$ age of 257 ± 2 Ma (MSWD = 1.2) constraining the time of igneous zircon crystallization.

1.4. Sample M82

It is a gray to dark gray andesite made up by 20–25% phenocrysts, mostly of plagioclase, amphibole and minor clinopyroxene in recrystallized glassy groundmass. The zircons are mostly elongate euhedral grains with pyramidal terminations. Some subequant to equant grains are also present. The more elongate grains have central cavities indicating rapid crystallization. CL images (Fig. 3) show both oscillatory and length parallel zoning. Some older "cores" may also be present. The twenty-two grains analysed are dominated by radiogenic Pb and plot within uncertainty of the Tera-Wasserburg Concordia curve (Fig. 4). Grain 4 is slightly

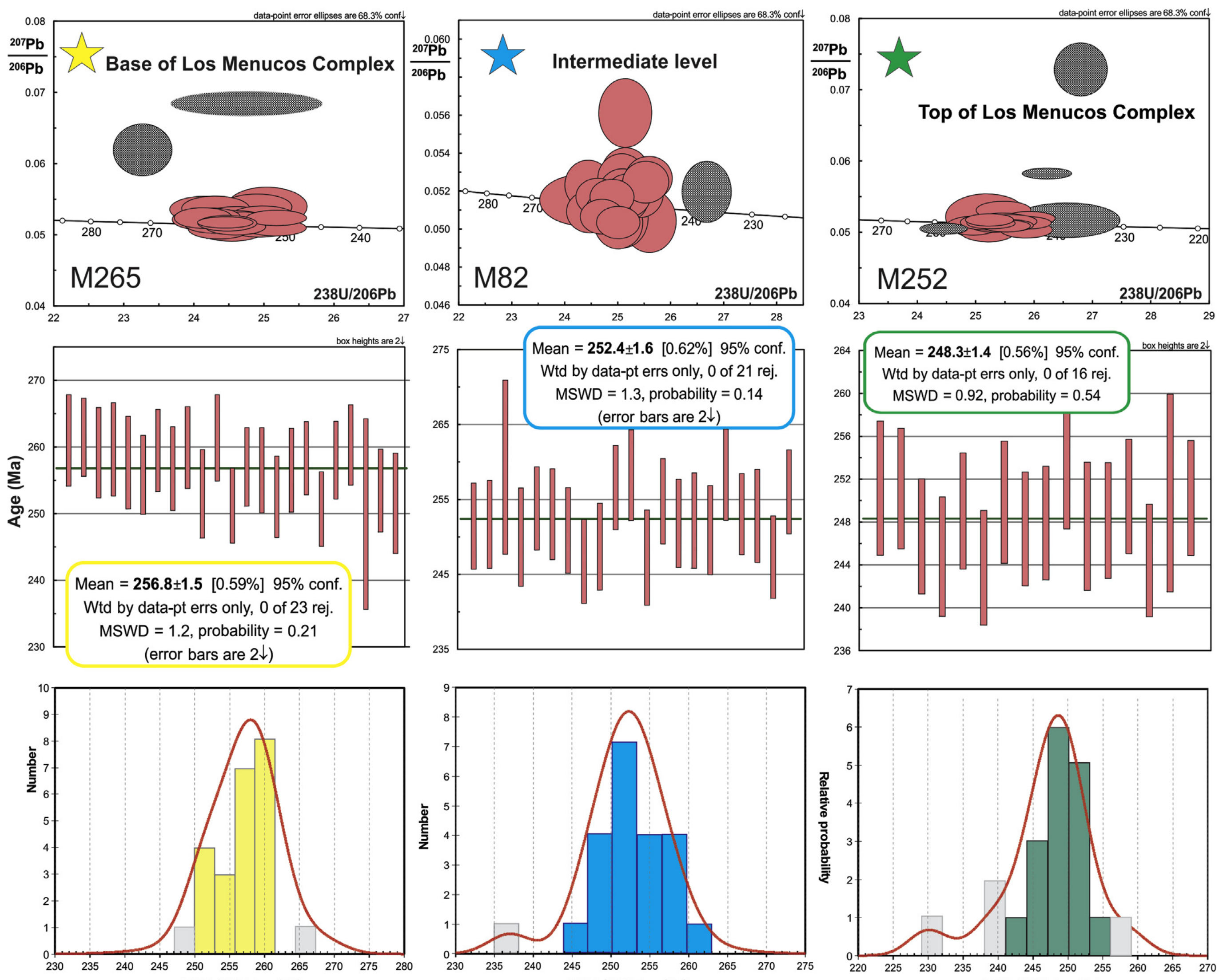

Fig. 4. Geochronologic results from the Los Menucos Complex reported in this paper. Graphs in the left column corresponds to sample M265 collected near the base of the succession; those in the center, to sample M82 collected from intermediate levels and those in the right to sample M252 belonging to top levels of the succession. Up: Tera-Wasserburg plots with plots of individual zircon data; gray ellipses correspond to data excluded for computing the mean. Center: Weighted averages plot for all SHRIMP zircon analyses and calculated mean age. Low: Probability distribution and histogram showing the age distribution of magmatic zircons for each sample. Data is presented in the electronic appendix A and Figs. 3 and 4 and discussed in the text.

enriched in common Pb, whilst grain 22 is an outlier and has a younger $^{206}Pb/^{238}U$ age of ~237 Ma. The latter is highlighted on the probability density plot of radiogenic $^{206}Pb/^{238}U$ ages. Twenty-one of the areas analysed form a simple bell-shaped distribution and a weighted mean with little excess scatter (MSWD = 1.3) giving a $^{206}Pb/^{238}U$ age of 252 ± 2 Ma (Fig. 4) that constrains the time of igneous zircon crystallization.

1.5. Sample M252

Sample M252 represents a group of dacitic ignimbrites that are generally crystal-rich (35%) to crystal-moderate (<20%) with a phenocryst–microphenocryst/crystaloclast mineral assemblage dominated by plagioclase (~20 vol.%), amphibole and biotite (~6 vol.%.), Fe–Ti oxides (~1 vol.%), apatite and quartz in a glassy, densely welded brownish red groundmass with 20% gray fiamme and 5-10% lithic fragments. The zircons are elongated to subequant grains, many with pyramidal terminations. Prismatic grains and those that are broken fragments of presumed euhedral crystals are also common. Central cavities are present in the more elongate forms. CL images (Fig. 3) show a variety of internal features ranging from oscillatory zoning, to length parallel and wispy zoning, to those that are un-zoned within the predominant central part of the grain. Older inherited components are likely in a few grains. For the 22 grains analysed, the low U central part of grain 16 yielded an age of ~1105 Ma whilst the core of grain 12 has an age of ~560 Ma. The other grains analysed form a rather dispersed cluster on the Tera-Wasserburg plot; some areas are enriched in common Pb. The probability density plot of radiogenic $^{206}Pb/^{238}U$ ages shows a dominant simple bell-shaped peak at about 250 Ma, with significant tailing on the younger age side, and slight tailing on the older age side. The younger analyses are considered to be areas that have lost radiogenic Pb. A weighted mean for 16 analyses (Fig. 4) has no excess scatter (MSWD = 0.92) giving a $^{206}Pb/^{238}U$ age of 248 ± 2 Ma, which is interpreted as the dominant period of igneous zircon crystallization.

2. Discussion and interpretation

The new radiometric ages change the traditional Middle to Late Triassic accepted age for LMC, placing it in the latest Permian – Early Triassic interval and suggesting that most if not all of the volcanic products were erupted between 257 ± 2 (at the base) and 248 ± 2 Ma (at the top). Moreover, a change in the magmatic composition (from Rhyolite Ignimbrites to Dacite Ignimbrites to the top) was detected close to an intermediate level dated *ca* 252±2 Ma (Fig. 2). Previous Late Triassic (222 ± 2 Ma) age obtained for a dacitic ignimbrite from a Rb-Sr whole rock isochron (MSWD = 1.1 and initial $^{87}Sr/^{86}Sr$ ratio of 0.7079 ± 0.0001; Rapela et al., 1996) could be explained by either altered K bearing minerals within the rocks from which Rb-Sr age was calculated or a local partial resetting of the Rb-Sr isotopic system due to the intrusion of yet

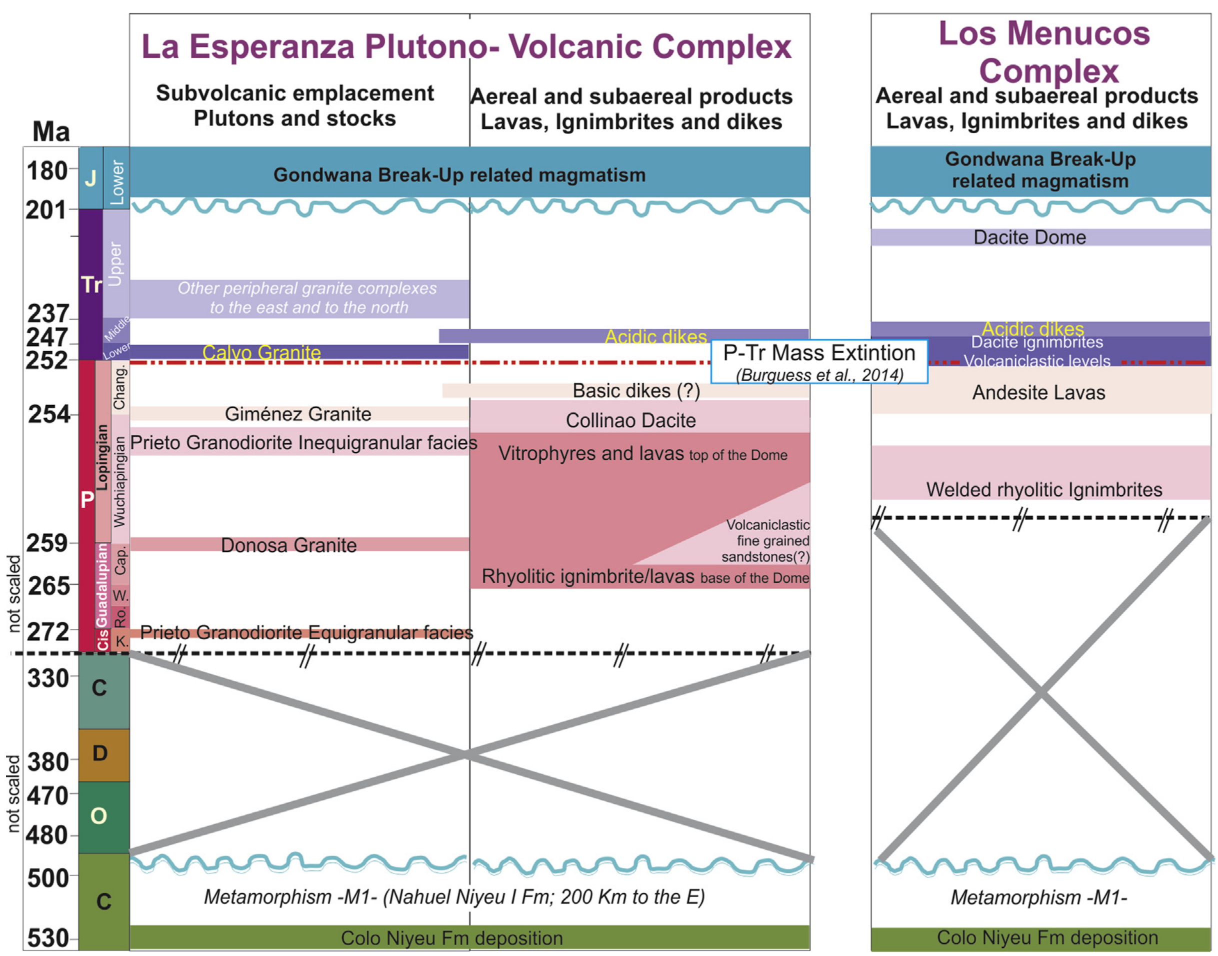

Fig. 5. Chronological columns for comparison of the plutonic and volcanic events of the La Esperanza Complex (Llambías and Rapela, 1984; Martínez Dopico et al., 2017a; Luppo et al., 2017a, b) with the volcanic units of the Los Menucos Complex (*this paper*). Note the similar age constraints that support the hypothesis of a single "La Esperanza-Los Menucos magmatic province".

undated porphyritic acidic dikes in that sampling area. Our new results also imply that the 207± 1Ma quartz monzonite porphyry (Lema et al., 2008) must belong to a different and probably unrelated latest Triassic magmatic event.

With respect to the paleontological content reported for the LMC, for which a Middle to Late Triassic age has been attributed, several localities with the assigned "*Dicroidium*-type Flora" (Miranda, 1966; Stipanicic et al., 1968; Artabe, 1985a, b; Labudía et al., 1992) are stratigraphically intercalated between samples M82 (252 ± 2 Ma) and M252 (248 ± 2 Ma) arguing for an Early Triassic age for those remains. A large part of the previously studied *Dicroidium* specimens considered as Middle to Late Triassic (Artabe et al., 2007 and references therein), however, were collected from the Tchering and La Laja quarries (east of Los Menucos Town, Fig. 1), whose stratigraphic position in the LMC is not completely clear yet. In these quarries, Domnanovich (2003) and Domnanovich and Marsicano (2006) analysed ichnofossils, that suggest a peculiar tetrapod fauna for northern Patagonia significantly different from that found in other South American and Gondwana Late Triassic localities. An older age for these footprints might explain their "anomalous" character and should be considered in the light of our new data.

The new ages indicate that the magmatic event represented by LMC encompasses the Permian-Triassic boundary which corresponds to the most severe extinction episode in the history of life (Jin et al., 2000; Shen et al., 2011; Song et al., 2012; Burgess et al., 2014, and references therein). The exposed area of LMC suggests a minimum volume of erupted material of around 1 to 2 × 10^5 km^3, considering a mean thickness of 2–4 km for the whole volcanic pile. This could increase significantly if its extension is extrapolated

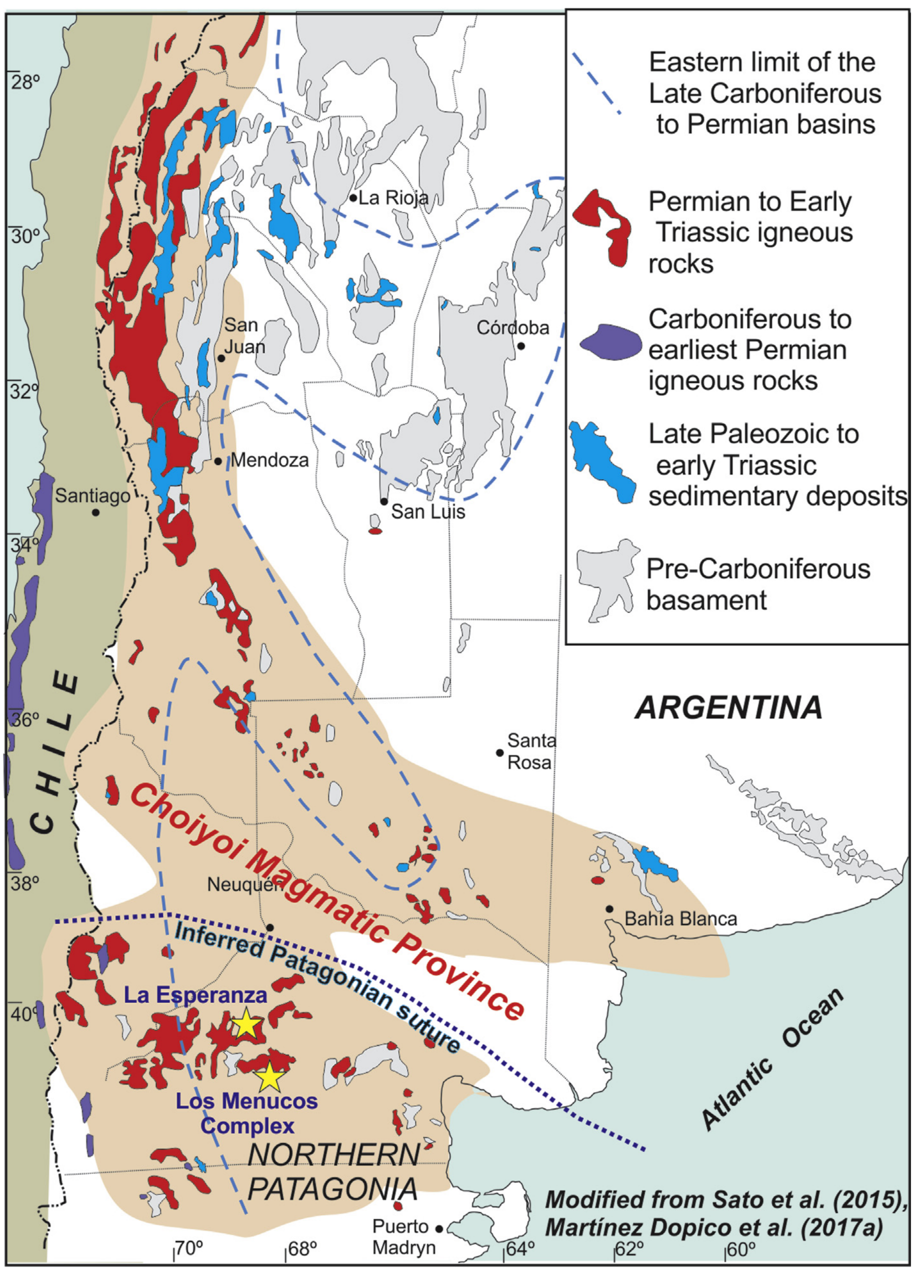

Fig. 6. Extension of the Choiyoi Magmatic Province in Argentina and the Permian-Triassic magmatism in northern Patagonia (modified from Sato et al., 2015; Martínez Dopico et al., 2017a). Location of the study area is indicated. See discussion in the text.

to areas covered by younger rocks. Although these volumes are a small fraction of that computed for the Siberian traps (Reichow et al., 2009) and also smaller than the early Permian Emeishan volcanics (He et al., 2007), the dominant acidic composition of LMC implies explosive events which are more prone to produce large gas inputs and therefore to affect more dramatically the atmosphere and climate. In particular, it is noteworthy that the near 2000 m of low density rhyolitic ignimbrites of the lower part of our study section accumulated in less than 5 Ma just before the P-Tr boundary. New radiometric ages by Martínez Dopico et al. (2017a) on the La Esperanza Plutono-Volcanic Complex (LEC), located 60 km north of the LMC main outcrops, indicate a Late Permian-earliest Triassic magmatic event with the more abundant plutonic and volcanic units between 260 and 250 Ma (Fig. 5). In the same area, Luppo et al. (2017a, b) obtained an age of 253 Ma for a group of dacites indicating that LEC and LMC are coeval and can be considered part of the same magmatic province ("The La Esperanza-Los Menucos magmatic province").

The tectonic setting of this magmatism is not fully understood yet (Pankhurst et al., 2006; Ramos, 2008; Martínez Dopico et al., 2016, 2017a; among others) and models involving a magmatic arc, slab break-off and extensional processes have been proposed. This magmatism may represent, as well, the southernmost part and youngest expressions of the Choiyoi magmatic province (Fig. 6), which took place over more than 30 Ma., during the Permian (Rocha-Campos et al., 2011; Sato et al., 2015). Whether or not LMC is part of the larger Choiyoi province is not clear. In fact, comparing with the age compilation made by Sato et al. (2015) for the whole Choiyoi magmatism, crystallization ages from both plutonic and volcanic rocks in northern Patagonia tend to be shifted towards younger ages, closer to the Permian-Triassic boundary. In any case, it is important to consider that many volcanic units of the NPM still remain undated, and large areas are buried below the modern basaltic plateaux, suggesting that the La Esperanza-Los Menucos magmatic province may be just a fraction of a much larger Permian-Triassic volcanic province in northern Patagonia. Fig. 7 illustrates the distribution of U-Pb ages from zircons of magmatic rocks in the northern areas of the North Patagonian Massif, compiled from various authors (in the caption). With the only exceptions of the Navarrete pluton (281 ± 3 Ma, Pankhurst et al., 2006) and one facies of the Prieto Granodiorite (273 ± 2 Ma, Pankhurst et al., 2006), all remaining dated units belong to the latest Permian or Lower to early Middle Triassic.

Although the most conspicuous volcanic unit yet dated is the Los Menucos Complex reported here, similar ages for acidic dykes, a rhyolite dome and dacitic flows in La Esperanza district (Pankhurst et al., 2006; Luppo et al., 2017a) strongly suggest the contemporaneity of most of these magmatic units. Pankhurst et al. (2014) showed that Carboniferous magmatic rocks in northern Patagonia are absent or unexposed. Recent datings confirm a Late Permian-Early Triassic dominant age for several plutonic units in northern Patagonia, to the East of the study area. Between Valcheta and Ramos Mexia towns (Chernicoff et al., 2013; Martínez Dopico et al., 2016) most of the plutonic units (Fig. 7), have crystallized between *ca.* 260 and 245 Ma. Further east, 250 km to the ESE of our study area near Sierra Grande town, in the eastern border of the exposed North Patagonian Massif, González et al. (2014) recently reported an Early Triassic age for trachyandesite lavas and dikes. Lavas and pyroclastic flows of the Treneta Formation (Caminos, 1983), exposed near the towns of Ramos Mexia and Nahuel Niyeu (Fig. 7), about 100 km East from the study area, have been correlated to LMC, but radiometric dating is lacking. If this correlation is confirmed with precise dating, the area covered by this magmatic event could probably double.

This suggests that LMC may represent a localized record of a much larger magmatic event that took place in northern Patagonia

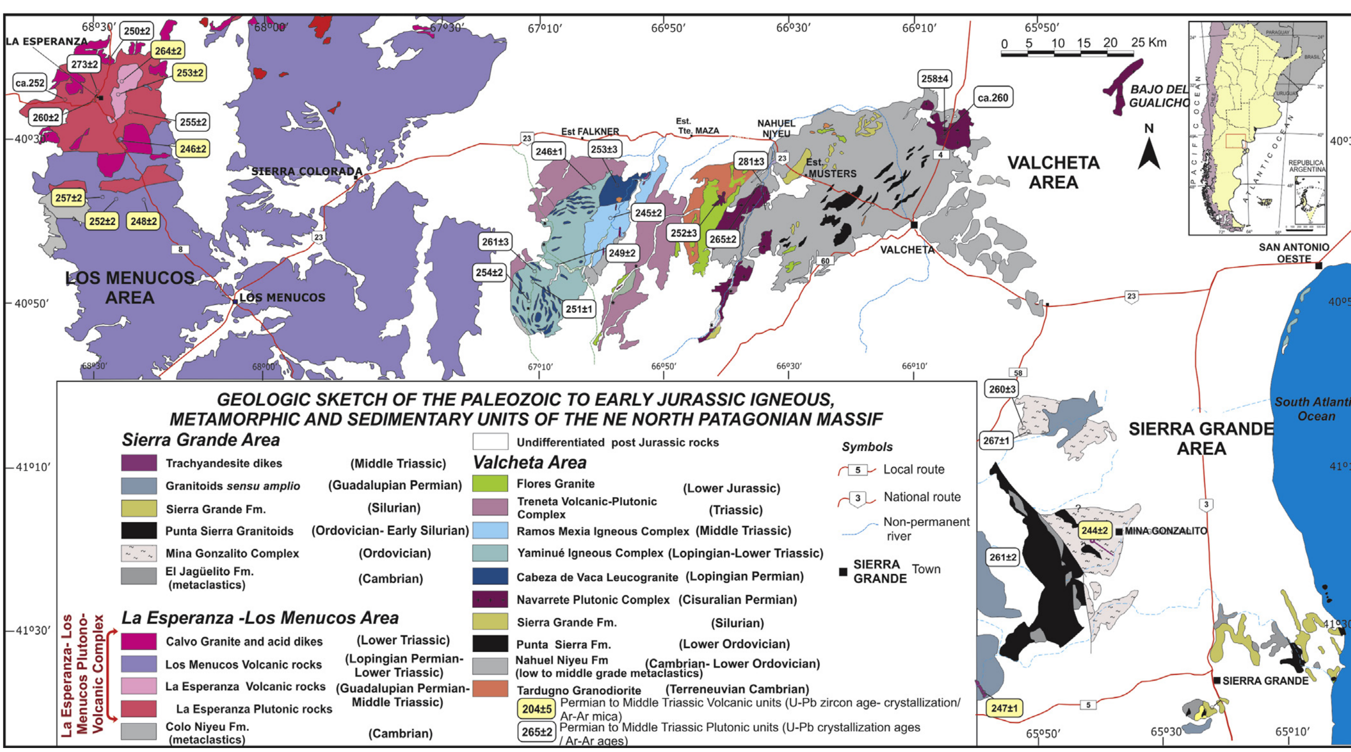

Fig. 7. Geologic sketch of Paleozoic to Early Jurassic units exposed in the northern and eastern North Patagonian Massif. U-Pb zircon crystallization ages obtained from Late Paleozoic-Early Mesozoic plutonic (white) and volcanic (yellow) rocks are indicated (Pankhurst et al., 2006, 2014, Chernicoff et al., 2013, González et al., 2014, Martínez Dopico et al., 2016, 2017a, Luppo et al., 2017a and this paper. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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(Luppo et al., 2017a). Many more precise radiometric ages on this magmatism must be obtained and a detailed reconstruction of its extension and volume accomplished in order to define the potential significance of this event in the climatic disturbance that was likely associated with the Permian-Triassic extinctions.

3. Conclusions

Geochronologic studies of important magmatic provinces of Permian to Triassic age are crucial for better understanding and modelling the lithospheric, environmental and biological processes that surrounded the Permian-Triassic transition. We present three new geochronologic data on the large volcanic Los Menucos Complex, exposed in northern Patagonia that has been, up to now, attributed to the Middle to Late Triassic. Our results show that this complex was erupted in a few million years around the Permian-Triassic boundary and it is likely part of a larger magmatic province, the La Esperanza- Los Menucos Plutono-Volcanic Complex, with its protracted activity around the same time. It is also likely that this important magmatism took place across much larger areas of northern Patagonia. Although the precise extension and volume of this magmatism remain to be firmly established, its potential in disturbing global climatic conditions before and after the P-Tr massive extinctions in southwest Gondwana should be investigated.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jsames.2018.01.003.

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