

# Neogene sedimentation and tectonics in the Collón Curá basin (Patagonian Andes of Argentina)

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#### 1 Neogene Sedimentation and Tectonics in the Collón Curá Basin (Patagonian Andes

#### 2 of Argentina)

3

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14	kinematics; subduction.

15

#### 16 **ABSTRACT**

17 We recall here recent developments concerning the filling and paleogeography of the Neogene Collón Curá 18 basin in the foothill of the North Patagonian Andes. To better constrain its evolution, we bring two new 19  $^{40}$ Ar/ $^{39}$ Ar on biotite datings of two ignimbrites that allow bracketing of the filling between 19.04 ± 0.72 20 and 5.06 ± 0.69 Ma. Like the other intramontane basins of the North Patagonian foothill, the Collón Curá 21 basin initiated around 18 Ma at the time of the Quéchua phase. This corresponds in the area neither to an 22 increase of the convergence rate of the Nazca and South America plates, nor to a significant change in the 23 angle of convergence. We propose to look at this profound alteration of the regional stress regime in the 24 light of the recent results of analog and numerical modeling of subduction. Folding of the slab above the 25 mantle discontinuity at 660 km depth leads to the development of geometries that we retrieve in seismic 26 tomography images in the region. Modeling shows that the overriding plate is coupled to this folding in 27 depth. It suffers from changes in stress (from extensive to compressive stress regime) and topography. It 28 is assumed that a more compressive stress regime will favor the reactivation of border faults of the basin 29 and a regional uplift, hence agradation in basins. On the contrary, subsidence associated with a decrease in shortening will favor the backward erosion that will cannibalize these basins. The life duration of basins will be modulated by efficiency of earth surface processes proper to each watershed (catchment area, river slopes, lithology...). This internal cyclicity of subduction due to slab folding is freed from the kinematics of convergence. It is now necessary to look for the expression of this process in the sequential filling of the basins.

35

#### 36 Introduction

37 As for the Neuquén Andes to the north (e.g. Branellec et al, 2015; Branellec et al, 2016), the Neogene 38 reactivation of basement heterogeneities resulted in the North Patagonian Andes to the generation of an 39 array of partitioned basins surrounded by basement highs (Figure 1; Mosquera and Ramos, 2006; García 40 Morabito et al., 2011; García Morabito and Ramos, 2012; Huyghes et al., 2015a). Some of these basins have 41 an Oligocene extensional history and they have been subsequently inverted during the Miocene (e.g. 42 Ñirihuau basin, Paredes et al., 2009; Cura Mallín Basin, Folguera et al., 2006; Kilca-Aluminé Basin, 43 Franzese et al., 2011; Auca Pan Basin, Ramos et al., 2015). The Collón Curá basin is one of these Miocene 44 basins. It is a small basin (<5000 km<sup>2</sup>) that currently contains no more than 350 m of Neogene sediments 45 and these sediments are being excavated. It does not present the economic resources of its huge neighbor, 46 the Neuquén basin. It is a fault-bounded intramontane basin integrated in the thrust belt (García Morabito 47 et al., 2011) and formed behind an actively growing topography. Here is one of its geological interest, it is 48 an important recorder of the Miocene deformation, erosion, and syntectonic deposition.

The stratigraphic framework is now laid out in broad outline as well as the main stages of its paleogeographic evolution (e.g. Huyghes et al., 2015a). We recall the main lines at the beginning of the paper. But recent discussions show that the chronological framework remains to be consolidated (Franzese et al., 2018). This is why we present here two new absolute dating of ignimbrites at the top and at the base of the outcropping Miocene sedimentary filling in order to better constrain the period of activity of the basin.

The Collón Curá basin is an intra-mountain basin above an active margin and tectonics has potentially played a determining role in its evolution. Significant progress has been made in recent years in understanding the dynamics of subduction when the slab is encountering the mantle discontinuity at 660 km in depth. Analog modeling first and then numerical approaches specified the folding of the slab above this discontinuity. They characterized the durations of the process and evaluated how it forced shallow uplift and stress (e.g. Guillaume et al., 2009, Gibert et al., 2012, Cerpa et al., 2014, 2015). In parallel, seismic tomography imagery returned in the area geometries that resemble the modeled geometries (Pesicek et al., 2012). Slab break-off had already been invoked to comment the evolution of the basin (e.g. Ramos et al., 2014b). We propose to include it as an element of a broader scheme of analysis that could open (or not) a new way of interpretation of the regional dynamic.

We will therefore pursue three main goals here. Given the expectations of this issue, we will first focus on the Neogene infill and stratigraphic framework of the basin. We then consolidate the timing of the basin with two new dating of ignimbrites. At least, the final discussion is speculative. It proposes to extend interpretations already advanced on the link between subduction and the dynamics of the basin. One may wonder if this evolution is not partially decoupled in time from the global kinematics.

70

### 71 Regional Setting

We focus on an area located south of the Huincul Ridge that is a east-west inverted fault zone corresponding to a structural high formed after the Jurassic in the south of the Neuquén basin (Mosquera and Ramos, 2006; Grimaldi and Dorobek, 2011; Naipauer et al., 2012; Figure 1). This part can be divided into four main morpho-structural domains corresponding from west to east to (1) the Main Cordillera, (2) a series of several NNW-SSE oriented depocenters on the borders of the relief, (3) a nearly north-south continuous topographic high and (4) the Picun Leufu basin that corresponds to the main foreland.

78 The depocentres individualized east of the main cordillera correspond from north to south to the Kilca-79 Aluminé depocenter, the Auca Pan and Catán Lil depocenters and the Collón Curá basin, which is the most 80 important one in the study area (Figure 1). The Kilca-Aluminé and Collón Curá depocenters have been 81 interpreted as extensive depocenters during the Oligocene and lower Miocene and were filled at that time 82 by volcanic and volcano-sedimentary deposits corresponding to the Auca Pan Formation in the Collón 83 Curá Basin (Vergani et al., 1995; Franzese et al., 2011; García Morabito and Ramos, 2012). These basins 84 have been inverted since the middle Miocene in response to the establishment of the Quechua 85 compressive phase (Pardo-Casas & Molnar, 1987; Cobbold & Rossello, 2003; García Morabito et al., 2011; 86 Huyghe et al., 2015a). Thus, due to this shift toward a compressive regime, these depocenters were 87 isolated from the rest of the foreland by the inversion of Triassic normal faults (D'Elia et al., 2012) and the

88 uplift of basement blocks corresponding to the Sañico Massif, prolongated to the north by the Catán Lil 89 anticline (Ramos et al., 2014b). Thus, the Collón Curá, KIlka and Catán Lil basins became – at least partially 90 - endorheic during most of the Neogene and were filled by the erosional products of the main cordillera 91 and by volcanic and volcano-sedimentary deposits (García Morabito et al., 2011; Huyghe et al., 2015a). In 92 particular, the Collón Curá basin was partially isolated from the Picun Leufu basin from  $\sim 11$  to 8 Ma due 93 to the onset of the uplift of the Sañico massif and was probably fully endorheic until the Late Pliocene (~3 94 Ma) when the drainage network reconnected to the Picun Leufu basin (Huyghe et al., 2015a). After that, 95 erosion predominated in the Collón Curá Basin and Huyghe et al. (2015b) suggested that compression was 96 pushed to the east of the Sañico Massif near the Pampa Curacó Plateau during the Pliocene. Although Plio-97 Quaternary deformation processes have been documented in the Chihuidos and Anelo area farther north 98 (Messager et al. 2010), a continuation of shortening up to the present day is still a matter of debate, 99 particularly across the foreland of the North Patagonian Andes, where evidence of continuing shortening 100 during the Quaternary is scarce and ambiguous.

101 The Neogene sedimentary filling is then unequally distributed in the study area. The Collón Curá basin
102 with a maximum thickness of 500 m (García Morabito et al., 2011) is the main depocenter. The Picun
103 Leufu area only preserves small relicts of Neogene syn-compressive deposits on topographic highs
104 (Huyghe et al., 2015a).

North (the Cura Mallin and Agua Amarga basins) and south of the study area (the Nirihuau and Gastre
basins) are the largest Neogene intermontane basins of the foothill and of the mountain interior (Figure
1). The Cura Mallin and the Nirihuau basins preserve above Oligocene extensional deposits, several
kilometers of syn-synorogenic Neogene deposits (Bechis & Cristallini, 2005; Bechis et al., 2014; Paredes
et al., 2009; Orts et al., 2012).

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#### 111 Miocene Depositional History of the Collón Curá Basin

At the bottom of the basin filling, the Auca Pan Formation is made up of andesitic rocks related to a magmatic event from 36 to 43°S that took place between 33 and 20 Ma in the retroarc zone of the foreland system (Figures 2 and 3; Turner, 1965, 1973; Rapela et al., 1983; Lagorio et al., 1998; Franzese et al., 2011; Ramos et al., 2014b). It was deposited in extensive depocenters at the feet of the main cordillera.

117 The Collón Curá Formation. The Collón Curá Fm is exposed along rivers of the eastern margin of the 118 basin at the border of the Sañico Massif and along the Rio Limay in the southern part of the basin (Figure 119 2). The pioneering work by Roth (1899) identified the formation later named by Yrigoyen (1969). Based 120 on its mammal fauna, Roth (1899) attributed it to Middle Miocene and Pascual and Odreman Rivas (1971) 121 re-evaluated this attribution as Middle to Late Miocene.

Absolute ages came with K/Ar radiometric dating of pyroclastic deposits that yielded ages of 15.4±0.3 Myr
and 14±0.3 Myr (Marshall et al., 1977) and 11±1 Myr (González Díaz & Nullo, 1980). At the base of the
formation, the Pilcaniyeu Ignimbritic Member was dated at 15 Myr by Rabassa (1975) and 13.8±0.9 Myr
by Mazzoni & Benvenuto (1990). Above it, Cazau et al. (1989) obtained an age between 11.5 and 10.7 Myr

126 of Mazzoni & Schröhlich (1996), Moore R, Gazad et al. (1969) (Scalled an age Scencen 116 and 13126 at the base of the clastic deposits.

In the Collón Curá basin, Giacosa et al. (2001) attributed to the Langhian and Serravalian the Collón Curá
Fm. but the upper boundary is not consistently defined.

The Collón Curá Fm. is rarely exposed in the Collón Curá basin. To the north of the basin, it exhibits an angular unconformity with the underlying Paleogene Auca Pan Fm. The formation is thin, its basal part consists of a 20 m thick ignimbrite. This pyroclastic flow grades vertically into 5 m of sandstones with igneous rock pebbles. Sedimentary facies correspond to tuffaceous deposits, mostly reworked by fluvial processes, showing channels larger than 5 m, alternating with primary volcanosedimentary deposits (Figure 3, section C).

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129

137 Caleufú Formation. The middle and upper Neogene Caleufú Formation consists of the Limay Chico and
138 Alicura members (González Díaz et al., 1986) that comprises the vast majority of Neogene strata in the
139 basin.

González Díaz et al. (1986) shed new light on the stratigraphic framework of the Collón Curá basin. They named Caleufú Fm the sediments overlying the tuffaceous material of the Collón Curá Fm that were formerly known as the Rio Negro Fm and the Alicura Fm (Dessanti, 1972; Nullo, 1979; González Díaz & Nullo, 1980). The Chimehuin Fm of Turner (1973) included the Collón Curá Fm and the grey sandstones (Galli, 1954) of the present Limay Chico Mb of González Díaz et al. (1986). The question was about the number of aggradational cycles recorded by these series. Invoking a single aggradational sequence from sedimentologic arguments, González Díaz et al. (1986) regrouped the Río Negro and Alicura Fm into a 147 single unit, the Caleufú Fm, which they divided into two members.

148 If Nullo (1979) ascribed the formation to the Middle Pliocene by analogy with the Río Negro Fm in its type 149 locality, Nullo (1979) and González Díaz & Nullo (1980) nevertheless placed in the Pleistocene the Alicura 150 Member. A partial chronologic framework is given by K/Ar dating of ignimbrites and basalt flows. Basalts 151 at the base of the Limay Chico Mb yield an age of 20±4 Myr and two ignimbrites in the middle of the 152 formation, ages of 14±1 Myr (González Díaz et al., 1990). The top of the Limay Chico Mb is given by 153 another ignimbrite dated at 8±2 Myr (González Díaz et al., 1990). The 3±0.5 Myr Tipilihuqué basalt flow 154 that covers the Alicura Member, gives the upper bound of the Caleufu Fm (González Díaz et al., 1990). But 155 this framework remains to be consolidated especially for its basal part where these ages overlap those 156 obtained for the Collón Curá Fm (e.g. Rabassa, 1975; Mazzoni & Benvenuto, 1990; or Cazau et al., 1989). 157 Another question is whether or not the ignimbrite at the top of the Limay Chico Mb (8±2 Myr; González 158 Díaz et al.,1990) corresponds to the Chimehuin Ignimbrite dated by Mazzoni & Rapela (1991). Moreover 159 the age of 3±0.5 Myr obtained by González Díaz et al. (1990) does not strictly date the end of the 160 agradation of the Alicura member. In the Las Coloradas basin which is located northeast of the Collón Curá 161 basin, Franzese et al. (2018) dated to 8.5 Myr (<sup>39</sup>Ar/<sup>40</sup>Ar age) the Tipilihuque basalt that toplaps the 162 Miocene infill of this basin. In the field the lava flow does not overlap the Alicura member but its 163 southernmost remnants are very close to the basin closure. So this arrangement raises questions about 164 the actual age of the end of agradation in the Collón Curá basin. We will come back to this point later on in 165 the paper.

166

The Caleufú Fm consists of siliciclastic and volcanosedimentary material. Dominant lithologies correspond
to clay, sand and coarse sands in the lower part of the formation and grades up in the upper part where
coarse conglomerates become more prevalent (Figure 3).

The Limay Chico Mb usually shows grey sandstones, tuffaceous deposits, conglomerates and claystones. Centimetre- to decimetre-sized clasts derived from Cenozoic and Mesozoic volcanic sources and from Paleozoic plutonic rocks. Pumice fragments with a greyish colour are abundant and frequent crossbedding indicates a fluvial depositional environment. Laterally, the Limay Chico Mb. is made up of grey sandy pumice-rich fluvial deposits with the occurrence of red pebbles of igneous rocks, frequently at the base of fining-upward sequences.

176 Above the Limay Chico Mb in the middle of the basin, the Alicura Mb is composed of conglomerates with

177 sandstones and tuffaceous intercalations. Nature of clasts remains unchanged as well as lithologies. The 178 transition with the Limay Chico Mb is difficult to locate (González Díaz et al., 1986). Red pebbles of 179 igneous rocks are locally observed along the western border of the basin, frequently at the base of fining-180 upward sequences (Huyghe et al., 2015a). 181 A spectacular 130 m thick white ignimbrite is intercalated within the Caleufú Fm at the north east of the 182 basin (Figure 3, section A). This unit is completely homogeneous and shows abundant quartz and pumice 183 content. Another thinner ignimbrites (only a few meter thick) have been preserved in the basin 184 particularly at the top of the series.

185

186 Pampa Curacó Formation

187 These facies are interpreted to have been deposited in fluvial environments, with some lacustrine events 188 (Escosteguy & Franchi, 2010) and several paleogeographic settings have been proposed. It would record 189 the growth of the orogenic front (González Díaz et al., 1986) or could have a fluvio- glacial origin (Gracia, 190 1958; Galli, 1969; González Díaz & Nullo, 1980). Alternatively, Flint & Fidalgo (1968) postulated that it 191 corresponds to a pediment.

192

### 193 Time Bracketing of the Collón Curá Infill

The sedimentary filling of the basin where it can be observed, rests on different formations which extend from the Triassic in the south to the Oligocene elsewhere and even on the crystalline basement. This lack of stratigraphic concordance does not allow an easy assignment of the age of the basin. The authors have therefore endeavored to characterize their faunistic content (see above). Dating of tephra in conjunction with stratigraphic relations had been performed to better constrain the ages of geomorphic units.

199 These dates did not contradict the first assignments but they nevertheless raise in the current context 200 some difficulties. The first is documentary. Most often published in symposium proceedings, they are 201 hardly accessible for the time being to the international community. In addition, these often old datings do 202 not always allow the reader to locate accurately the dated samples geographically and stratigraphically. 203 Authors implemented two methods, K-Ar ou <sup>40</sup>Ar/<sup>39</sup>Ar, most often (it seems to us) on whole-rock samples

204 (e.g. Marshall et al., 1977; Mazzoni & Benvenuto, 1990). The current reader cannot evaluate if former

205 workers neglected or not uncertainty in nucleogenic interference corrections in defining a plateau. This is

strictly valid only when a sample is compositionally homogenous (Renne, 2000). This is frequently untrue in the case of whole rock basalts and therefore interference corrections should be included in the definition of the plateau. Pyroclastic rocks too should be always suspected of containing xenocrystic contaminents and should never be analyzed as a whole-rock sample. Highly vesicular lavas, scorias, and pumices are problematic because their high surface to volume ratio causes excessive adsorption of atmospheric Ar which may overhelm <sup>40</sup>Ar\*. So whole-rock K-Ar dates are increasingly suspected of being systematically too young (e.g. Mc Dougall et al., 1992; Renne et al., 1993).

213

We chose to date individual crystals of biotite sampled in ignimbrites of the Collón Curá and Caleufú formations. One of the most profound advantages of this approach is that pyroclastic material such as crystal-bearing tuffs can be dated without danger of biais from xenocrystaic contamination (e.g. Curtis, 1966; Lo Bello et al., 1987; Deino et al, 1990). Moreover <sup>40</sup>Ar/<sup>39</sup>Ar incremental heating analysis of biotite presents significant advantages because the proportion of atmospheric 40Ar is typically reduced in higher temperature steps. For volcanic biotites, a <sup>40</sup>Ar/<sup>39</sup>Ar plateau is generally a sufficient criterion for reliability.

So, we sampled two thick ignimbrites located at the base of the Collón Curá Formation (Figure 3; base of section C of Huyghe et al., 2015a; S 40°10.27', W 70°39.39') and at the top of the Alicura Member of the Caleufú Formation (top of section B of Huyghe et al., 2015a; S 40°07.121', W 70°55.212' location in Figure 2). We sampled 5 kg of these ignimbrites riches in pumices and biotites. Samples were taken at ~ 1 m depth to avoid potential surface alteration of the biotites. The plateau date has been calculated as the inverse variance weighted mean of individual plateau step ages. The uncertainty derived from error propagation (e.g. Renne et al, 1996).

228

The basal ignimbrite in the Collón Curá Formation yields an age of 19.04 ±0.72 Ma and the top one in the Caleufú Formation, an age of 5.06 ±0.69 Ma (Figures 4 and 5 and Table 1). Compared to the stratigraphic synthesis these ages provide new direct constraints of the history of the CCB. First, it moves the base of the Collón Curá Formation and the top of the Auca Pan Formation from 16 to 19 Ma compared to the stratigraphic framework proposed by Huyghe et al. (2015a) (Figure 4). The age boundary between these two formations was not accurately dated and this new age brings strong constrains about its age.

- 236 The age of the top of the sedimentary filling of the basin is subject to several controversies (see the
- synthesis of Huyghe et al., 2015a) and ranges between 8 and 3 Ma according to the authors and the dating
- 238 method (Nullo, 1979; González Díaz and Nullo, 1980; González Díaz et al., 1990; Mazzoni & Rapela, 1991).
- Here, the absolute dating of the ignimbrite allows a time constrain of 5 Ma for the end of the filling of the
- basin (Figures 3 and 6).
- 241 These ages remain consistent with stratigraphic contains.
- 242

#### 243 **Tectonic and Stratigraphic Evolution**

Huyghe et al. (2015a) considered four stages of paleogeographic evolution during the Neogene in this area
where shortening is supposed to be low (<10 km, Ramos et al., 2014a).</li>

Prior to the Neogene filling of the basin, Eocene and Oligocene intervals are interpreted as a phase of
major erosion since Neogene deposits preserved to the east of the Sanico Massif often lie over Cretaceous
or Jurassic sediments with a reduced angular discordance (<5°) and seem to fill ancient paleovalleys</li>
(Leanza et al., 1997; Hugo & Leanza, 2001). This evolution is characteristic of retro-arc foreland basins
(Jordan, 1995).

At the end of the Oligocene or at the beginning of the Miocene, sedimentation began along a nearly N–Soriented axis of maximum thickness deposition parallel to the Sañico Massif. The Collón Curá basin is supposed to have been individualized since the end of the Early Oligocene (Ramos et al., 2014a) but in the field, the oldest deposits are Early Miocene in age and are localized alteration products resulting from erosion of the Oligocene volcanic Auca Pan Fm. (Figure 6A; Huyghe et al., 2015a). The North Patagonian Massif (NPM) was probably not yet a prominent structure at that time.

In the Middle Miocene, a major volcanic phase supplied a large volume of volcaniclastic material to the
Collón Curá Fm. (Galli, 1969) that extended in the basin and in a wide surrounding area to the south, to
the east and up to the north of the NPM (Figure 6B). In the Picun Leufu basin, the same sedimentary
material displays channelized structures characteristic of a single fluvial system showing that the Sañico
Massif was probably not yet exhumed (Huyghe et al., 2015a).

Major change occurred during the Late Miocene and Early Pliocene. Progressive unconformities, with a
maximum dip of 13°, are observed within the Caleufú Fm. along the western margin of the Sañico Massif
in the central part of the Collón Curá basin (García Morabito et al., 2011). Many liquefaction structures,

interpreted as seismically induced and synsedimentary normal faults in the Limay Chico Mb. also show an
intensification of tectonic activity (Huyghe et al., 2015a). In the same time, the Picun Leufu basin to the
east is rather in non-deposition and possible erosion. This segmentation of the deposits is a consequence
of the uplift of the Sañico Massif (García Morabito et al., 2011; Ramos et al., 2014a).

269 Thus, the Late Miocene Early Pliocene deposition is confined to an area of ca. 150 km by ca. 30 km in the 270 Collón Curá basin with a thickness of tens of meters east of the Sañico Massif while sedimentary thickness 271 reaches only few meters in the Renteria Plateau area to the east (Figure 2). Its connection with the rest of 272 the foreland remains questionable at this time; the Collón Curá basin might have been isolated from the 273 rest of the foreland basin. The deposition of the Limay Chico Member of the Caleufú Fm. in the Picun Leufu 274 basin along the eastern border of the Sañico Massif suggests that it was rising and was eroded by rivers 275 flowing to the east. Nevertheless, given the reduced volume of relicts of the formation in the Picun Leufu 276 basin, if gateways existed during the filling of the Collón Curá basin, they were probably not active during 277 long periods. This observation shows that the uplift of the Sañico Massif was faster than the filling of the 278 Collón Curá basin, at least until the end of the deposition of the Caleufú Fm.

The deposition of the Alicura Mb. of the Caleufú Fm. during the Early Pliocene exhibits a coarsening
compared to the Limay Chico Mb. This may reflect the end of the major filling of the Collón Curá basin
(González Díaz et al., 1986) that was endoreic at this time (Huyghe et al., 2015a).

The Collón Curá basin underwent erosion during Late Pliocene and Early Pleistocene and the main depositional area moved to the east. It is questionable whether regressive erosion began to affect the Sañico Massif at this time and subsequently the Collón Curá basin, or if the activity of the surface processes in the basin allowed its overflowing towards the Picun Leufu basin. There is a lack of any sedimentological or morphological evidence to favor one or the other of these scenarios.

287

### 288 Discussion

#### **289** Timing of the basin in the foreland setting

How the aggradational scheme of the basin highlights the mountain building processes in the area? The question spans the temporal space when considering whether shortening prevails over a single prolonged interval (~50–100 Myr) or over a series of punctuated events of shorter duration (<5–10 Myr) alternating with episodes of neutral or extensional modes (e.g. Steinmann, 1929). It spans the spatial space when questioning if individual pulses are restricted or not to particular segments of the Andean margin (e.g. Groeber, 1951). It is why we choose to discuss the evolution of the Collón Curá basin compared to that of its close neighbors, the Catán Lil and Agua Amarga to the north and the Ñirihuau-Collón Curá basin to the south. These basins are the outermost Miocene intramountaine basins of the considered area.

298 Between 39°28'-39°48' S and 70°29'-70°44' W, the Catán Lil basin is a small intermontane basin (40x20 299 km) that accumulated 400 m of sediments during the Miocene (García Morabito et al., 2011; Figure 1). 300 Developed between two thick-skinned anticlines, it nests above a Paleozoic crystalline basement where a 301 Mesozoic continental-marine sedimentary succession forms the southermost part of the Neuquén Basin 302 (Figure 2). Farther to the north, the Agua Amarga basin also developed above the Mesozoic infill of the 303 Neuquén basin but to the north of the Huincul ridge, a strong inherited transverse structure that delimits 304 the southern limit of the Neuquén basin (Figure 1). The Agua Amarga basin is larger (80x20 km) but not 305 thicker than the Collón Curá basin and is located at the toe of the thin-skinned domain of the Agrio fold-306 and-thrust-belt and west of the thick-skinned Chihuidos anticlines. Compared to the northernmost basins, 307 the Ñirihuau–Collón Curá basin at south of the Collón Curá basin, is larger (200 x 40 km; Figure 1). With 308 more than 2000 m of Late Oligocene to Middle Miocene sediments deposited on top of the Oligocene 309 volcanic rocks of the Ventana Formation (Rapela et al., 1988) and the igneous-metamorphic rocks of the 310 Cushamen Formation (Volkheimer, 1964), it is also thicker (Spalletti, 1981; González Bonorino & González 311 Bonorino, 1978). It has been alternately interpreted as a pull-apart basin (Spalletti & Dalla Salda, 1996), as 312 an extensional basin in a back-arc setting (Mancini & Serna, 1989; Cazau et al., 1989) and as a foreland 313 basin (Ramos & Cortés, 1984; Giacosa & Heredia, 1999; Bechis et al., 2014).

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315 Did shortening prevail over a single prolonged interval or over a series of punctuated events of shorter 316 duration? This makes necessary to set the chronological framework of these basins with the reserve 317 imposed by the partial knowledge that we have of these basins. We dated two ignimbrites at the base and 318 top of the sedimentary filling of the Collón Curá basin. At the bottom of the infill outcropping to the heart 319 of the basin at the base of the Collón Curá Formation, we obtained an age of  $19.4 \pm 0.72$  Ma (Figure 5). This 320 dating allows revising the former ages by Rabassa (1975), Marshall et al. (1977) and Mazzoni & 321 Benvenuto (1990) that yielded younger ages comprised between 13 and 16 Ma. So subsidence of the basin 322 occurred a little bit earlier than the age given by Huyghe et al. (2015a). But this age does not correspond 323 to the onset of sedimentation in the basin because the base of the basin is still buried.

324 The bottom of the Catan Lil basin is comprised between 16.1 and 13.8 Ma (Figure 7; Marshall et al., 1977; 325 Rabassa, 1978; Rapela et al., 1988; Mazzoni & Benvenuto, 1990; Orts et al., 2012; Bilmes et al., 2013, 2014; 326 Ramos et al., 2014a, 2015). The bottom of the sedimentary infill outcrops in the Agua Amarga basin. It is 327 the Puesto Burgos Formation (Hugo & Leanza, 2001) late Oligocene-early Miocene in age (Figure 7). The 328 sedimentary history began in the Ñirihuau basin at the same time with deposition of the marine Ñirihuau 329 Formation (Roth, 1922; González Bonorino, 1973) that opened towards the Pacific (Figure 7). Cazau et al. 330 (2005) and Paredes et al. (2009) revised the stratigraphic frame of the formation. More important here is 331 the transition from lacustrine to fluvial deposition that occurred at the top of the Nirihuau formation 332 around 17 Ma and signed the onset of tectonic inversion (Paredes et al., 2009). So the onset of these 333 basins as intra-mountainous basins occurred in a relatively narrow time bracket centered around 18 Ma 334 (± 1 Ma).

335 Sampled at the top of the Collón Curá Formation, the upper ignimbrite gives us the end of aggradation at 336 about  $\sim$ 5 Ma (Figure 5). On the basis of the bibliographic data, Huyghe et al. (2015a) previously assigned 337 it to a little over 3 Ma. In the close Catán Lil basin, Franzese et al. (2018) dated plagioclases (<sup>39</sup>Ar/<sup>40</sup>Ar) of 338 a lava flow of the basaltic plateau at top of the sedimentary infill that was assigned to the Plio-Quaternary 339 (Cucchi & Leanza, 2005; Rojas Vera et al., 2014). They obtained an older age of  $\sim$ 9 Ma, in agreement with 340 the <sup>39</sup>Ar/<sup>40</sup>Ar age of the upper basaltic unit in the Kilca-Aluminé basin (Franzese et al., 2011, Figure 7). So 341 aggradation in the basin ended earlier than expected and this allows these authors to postulate that 342 shortening did not continue in the area after the end of the Miocene. Nevertheless our dating in the Collón 343 Curá basin shows that volcanic activity continued until the Pliocene what supports the interpretations by 344 Ramos et al. (2014a) and Huyghe et al. (2014, 2015). Franzese et al. (2018) did not sample the youngest 345 flow of the basaltic plateau. Farther north in the Agua Amarga basin, the Pampa Encima Formation 346 constitutes the last interval of aggradation before a drop of the base level of the Rio Neuquén and Rio 347 Agrio (Hugo & Leanza , 2001; Messager et al., 2010). It was deposited during the Pliocene (Leanza and 348 Hugo, 2001). Similarly to the Collón Curá basin, the final stage of the Ñirihuau basin contains pyroclastic 349 and volcanoclastic materials reworked by fluvial and aeolian processes until Early-Late Miocene 350 (Langhiane–Tortoniane; Giacosa et al., 2001). Comprised between  $\sim 10$  and  $\sim 5$  Ma, the time window 351 spanning the onset of the excavation of these basins is larger.

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353 The Miocene history of these basins is that of intra-mountainous basins. On the basis of bibliographic data,

the aggradation in these basins located between 37 and 40 ° S over more than 300 km began on a rather narrow window of time centered around 18 Ma. It coincides to the west with the closure of the Traigen oceanic basin between 20 and 15 Ma (Folguera et al., 2018). These features (timing and geographic distribution) suggest that we entered at this time under dynamic conditions that allowed the segmentation of the foreland by localized uplifts, it is the Quechua phase of the authors (e.g. Steinmann et al., 1929).

The end of the aggradation in these basins spreads over a longer period of 5 Ma. Field observations show active crustal folding of the Chihuidos and Sauzal folds east of Agua Amarga basin (Messager et al., 2010) and along the eastern border of the San Rafael block (northern Neuquén Basin) which is inverting since the Late Miocene (Costa et al., 2006, Folguera et al., 2018; Branellec et al, 2016). On the basis of these observations, the Quechua phase would continue untill the late Pleistocene at north of the Collón Curá basin.

The development along the Neuquén River of an alluvial fan at the outlet of the Agua Amarga basin shows that reconnection of the basin with its foreland has been achieved by backward erosion which then initiated the excavation of the basin. If backward erosion is of course controlled by the activity of the tectonic dam, it is also modulated by the intensity of surface processes determined by external forcing (climate, lithology, watershed geometry; e.g. Hilley and Strecker, 2005). These factors could therefore spread the timing of the basin excavation over time according to local characteristics.

However, Huyghe et al. (2015a) showed that the Collón Curá basin was still subsiding when the foreland,
behind the tectonic dam, was already excavating. The vergence of the structure that initially isolated the
basin from its foreland is directed towards the basin. Its lithostatic load could drive a flexural subsidence
allowing for a time the activity of the basin.

The timing of initiation of these basins suggests that shortening controlled it at first order. The end of
aggradation spreads on a broader time window probably as the result of a stack of regional and local
forcings.

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#### 380 Kinematic forcing on basin evolution

Although the basins are distant from each other by several hundred kilometers, aggradation began in a narrow time window (18+/-1 Ma). This suggests that a lithospheric forcing probably controlled it and we examine here if the Atlantic spreading or if the conditions of the Pacific subduction can be linked to 384 shortening.

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The growth of mid-oceanic ridges makes gravitational forces that could force the young and raised oceanic lithosphere to slide down the weaker asthenosphere and push on lithospheric material farther from the ridges (Meijer and Wortel, 1992). That is why the mid-Atlantic oceanic spreading could be a potential tectonic forcing.

390 The geological marker does not show a lot of demonstrative evidence of the Peruvian phase of shortening 391 in the Collón Curá area because Cretaceous deposits are now eroded. But in the southern Neuquén basin, 392 the older macroscopic record of inversion we observed in the field is the discordance of the Huitrìn 393 Formation above the folded Avilé sandstones west of Chos Malal. This shows that the onset of inversion 394 was Aptian in age. This is confirmed elsewhere in the basin by other observation or by seismic data (e.g. 395 Cobbold and Rosello, 2003; Grimaldi and Dorobek, 2011) and now by thermochronology (e.g. Sánchez et 396 al., 2017). This discontinuity follows shortly the onset of South Atlantic spreading at this latitude. Basing 397 on the age of the oldest magnetic record along the Atlantic margin of South America (e.g. 133 Ma at 39°S 398 and 120 Ma at 20°S; Meyer et al., 2017), kinematics models show that the Atlantic opening propagated 399 northward (Setton et al., 2012; Müller et al., 2018). It is especially interesting to note that the onset of 400 shortening in the Andes follows too this trend during the Cretaceous times: it begun at 125 Ma in the 401 southern Neuquén basin and only at 113 Ma in Peru (10°S; Margirier et al., 2017). So the mid-Atlantic 402 opening could play an operating forcing. The late Cretaceous inversion in Neuquén basin would be 403 unrelated for Chen et al. (2019) to the westward motion of South America because the magnitude of 404 displacement would be too low. But oceanic-opening and tectonic-shortening coincide in time and in 405 space.

The correlation does not work in the Miocene time. Indeed aggradation in the basins (i.e. shortening, 18 Ma) occurred when the mid-Atlantic spreading rate was steady at 37 and 40°S (Figure 8). For the Pacific Ocean, the spreading rate decreased during this interval. It is not so surprising because ridge push is mostly active in lithosphere younger than 90 Ma, after which it has cooled enough to reach thermal equilibrium with older material and the slope of the lithosphere-asthenosphere boundary becomes effectively zero.

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413 The tectonic regime changes may be associated with other parameters as plates velocities, plates

directions, the absolute movement of the trench, the age of the oceanic plate, the presence of sediments or
the geometry of the oceanic plate (e.g., Ruff and Kanamori, 1983; Heuret et al., 2007; Schellart, 2008) that
is to say to the dynamics of subduction.

417 The westward shift of South America could have forced the inversion of the basin. Plate-tectonic 418 reconstructions show that South America did not stop migrating westward at the first order since the 419 opening of the South Atlantic Ocean (Setton et al., 2012; Müller et al., 2018; Gurnis et al., 2018). For the 420 period of time covered by the Collón Curá basin (0-18 Ma), is a change in the conditions of convergence 421 likely to initiate the onset of the Quechua phase? For the considered time window, the South America 422 plate continuously moved to the northwest and convergence angle between the Nazca and South America 423 plates did not change more than 25° (Figure 9 and 10). The onset of aggradation in the basins is coeval 424 with a decrease of the convergence rate between plates (Figure 10). It seems more "physical" to link the 425 onset of shortening with an increase of the convergence rate. Also it could be more reasonable to interpret 426 this inflexion in the convergence rate not as the cause of the occurrence of the Quechua episode but only 427 as an evidence of the increase of the coupling between both plates.

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429 The inversion that occurred at 40°S without strong kinematic change, leads to look for another 430 explanations. The effect of the slab anchoring on the lower mantle interface and more generally the 431 modality of the penetration of the slab into the mantle above it, remains an under-explored way of 432 interpretation. The mantle retains a memory of subducted slabs, which body-wave tomography images in 433 situ as domains of faster-than-average seismic wave velocities. The rupture with at least 5 m of slip of the 434 M8.8 Maule earthquake in Chile in 2010 spreaded from 34 to 38°S (Lorito et al., 2011) and made it 435 possible to image it for the latitudes we are interested in (Figure 11; Pesicek et al., 2012). The first order 436 change in the slab geometry is located around 35°S with the transition from a horizontal Pampean flat 437 slab (at north) to a southern slab with a moderate dip of  $\sim 30^{\circ}$ . At the latitudes of our study area, this 438 image does not show at the first order major differences between the north (section at 37°S) and south 439 (section at 39°S; Figure 11A). The slab normally dips up to 200 km. The anomaly then bends towards the 440 east and comes to horizontalization at a depth of 650 km. The slab, however, appears less continuous at 441 39°S and Pesicek et al. (2012) and Ramos et al. (2014) interpreted it as a result of slab tearing and 442 detachment at ~200 km in depth.

443 Another fast anomaly stands almost vertically below the subduction trench and reaches depths greater 444 than 1000 km (Figure 11A). This anomaly could also be interpreted as the remnant of a former slab diving 445 in the mantle as observed along the Pacific margin of North (e.g. Sigloch & Mihalynuk, 2013; Sigloch & 446 Mihalynuk, 2017) and South America (e.g. Pesicek et al., 2012; Chen et al., 2019). But its position may 447 surprise. Since the South American plate shifted continuously westwards since 125 Ma (Figure 9; e.g. 448 Seton et al., 2012), the trench shifted westwards too. So, we would be inclined to find the relics of the 449 ancient slabs further to the east below the American plate as observed farther to the north by Chen et al. 450 (2019). And the MITP08 tomography model too shows anomalies of seismic rates farter to the east that 451 could be interpreted as remnants of former slab segments (Li et al., 2008; Hosseini et al., 2018).

452 In detail, the image of Pesicek et al. (2012) at 37 ° S is emblematic (Figure 11A). The Wadati-Benioff plane 453 is associated with an anomaly of fast speeds which continues in depth up to 400 km. More than 200 km 454 away from the trench, the slab then stumbles on a thick anomaly of 350 km which continues until a depth 455 of 650 km. This one could correspond to a pile made by a slab folding on itself above the rheological 456 discontinuity of the mantle (Figure 11B and 13; e.g. Guillaume et al., 2009; Gibert et al., 2012; Sigloch & 457 Mihalynuk, 2013). The deep anomaly below the current slab shows an upward concave shape that must 458 be included in this pattern (Figure 11A). We propose at 39°S a scheme that involves first the shallow 459 rupture of the slab above 200 km in depth as invoked by Pesicek et al. (2012) and by Ramos et al. 460 (2014b)(Figure 12B). The tomographic image shows another deeper anomaly in the lower mantle that 461 requires a second rupture at the top of the pile in response to the pull of the slab diving into the lower 462 mantle (Figure 12C). At 39 ° S, the image of Pesicek et al. (2012) does not necessarily show this second 463 break up.

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465 Numerical modeling shows that the way the slab deforms in depth depends strongly on the far-field 466 boundary conditions i.e. on the individual values of the subducting and overriding plate velocities (Gibert 467 et al., 2012; Cerpa et al., 2015). Two different styles of subduction are obtained once the subducting plate 468 reaches the 660 km discontinuity. If the overriding plate moves toward the trench or not, the slab 469 respectively lies forwards (case 1) or backwards (case 2) on the 660 km discontinuity (Figure 13). At the 470 first order, the South America plate always shifted to the west (i.e. to the trench) since the Atlantic 471 opening (e.g. Setton et al., 2012). But the absolute subduction velocity of the Nazca plate had always been 472 greater (e.g. Pardo-Casas & Molnar, 1987; Müller et al., 2018). This ratio of subducting and overriding plate velocities is compatible with a folding of the slab above the 650 km mantle discontinuity as exploredby Gibert et al. (2012). And when folding occurs, the dip of the shallow slab changes.

475 Transient shallowing and steepening of the subducting slab has exerted an important influence on 476 orogenic patterns (e.g. Ramos et al., 2002, 2014; Haschke et al., 2002, 2006; Kay et al., 2006; Kay & Coira, 477 2009; Ramos & Folguera, 2009; Chen et al., 2019) and might force the evolution of basins. Indeed, 478 numerical modeling studies showed that the state of stress of the overriding plate is directly linked to the 479 absolute velocity of the upper plate and the dynamic of the lithospheric mantle but also to the dip of the 480 slab: upper plate shortening when the angle of the slab shallows, and extension when it steepens (Gibert 481 et al., 2012; Cerpa et al, 2014). Thus a cyclic stress regime in the overriding plate due to slab folding in 482 depth can be achieved with constant boundary conditions. Topography is also linked to the slab dip angle: 483 when the slab has a shallow dip angle, the upper plate shortens and the topography is positive. In turn, 484 when the slab dip angle steepens, the upper plate undergoes extension or less shortening and the 485 topography becomes negative. Numerical modeling predicts for the far-field plate kinematics setting of 486 the study area that these cycles will span about 20 Ma, depending of the mantle viscosity (Gibert et al., 487 2012; Cerpa et al., 2014; 2015) with alternating pulses of compression, of lesser compression or tension 488 and episodes of regional uplift.

489 The seismic tomography shows also a vertical offset of about 200 km between both segments of the slab 490 where the first rupture of our scheme occurred (Figure 11 and 12; Pesicek et al., 2012). This break-off 491 might cause the basins to invert throughout an upward rebound of the remaining slab (Haschke et al., 492 2006; Ramos et al; 2014). The authors do not yet agree on values of sinking rate of slabs in the mantle. 493 But the interval of proposed values is narrow, comprised between 10 +/- 2 mm/yr (Sigloch & Mihalynuk, 494 2017) and 13 +/- 3 mm/yr (Butterworth et al., 2014). The distance between the two segments of the slab 495 (i.e. 200 km) could yield a proxy of the onset of the slab break-off. We obtain here a value of 20 Ma 496 compatible with the timing of basin aggradation.

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Focal-mechanism solutions of intermediate depth and deep earthquakes under the Japan Sea and the East Asian margin (Zhao et al., 2009) show that the Pacific slab is under a compressional-stress regime in the depth range of 200 to 600 km. Such a stress regime in the slab might be caused by the slab meeting strong resistance at the 660-km discontinuity. In the same way, the asthenosphere under East China would be both hot and wet, being associated with the deep dehydration of a stagnant Pacific slab (Ichiki et al.,

503 2006). The velocity field in the fluid also changes during fold development (Cerpa et al., 2014). The 504 convective circulation process in the upper mantle above the stagnant slab and the deep dehydration 505 process of the slab would cause upwellings of hot and wet asthenospheric materials, leading to the 506 formation of lithospheric attenuation as well as intraplate volcanoes (Zhao, 2012). This fits in the study 507 area observations by Folguera et al. (2018) who modeled the elastic thickness (Te) of the study area. 508 Showing the coincidence between lowest values of Te and emplacements of Plio-Quaternary magmatism, 509 they speculated that heating would have weakened crustal rigidity. However, Te quickly increases toward 510 the foreland and reaches its maximum in the North Patagonian massif and its continuation to the north in 511 the Neuquén platform area where the lithosphere thickens (Tašárová, 2007).

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### 513 Conclusion

514 The Collón Curá basin is one of these intramountainous basins of the Mio-Pliocene foothills of the 515 Patagonian Andes. Growing within the wedgetop depozone of a wider Andean foreland basin, sediments 516 accumulate above the active orogenic thrust wedge. Contrarily to other basins where accommodation is 517 achieved by their subsidence, that of these intramontane basins is by the dynamics of the tectonic barrier 518 which limits them (e.g. Hilley and Strecker, 2005). So the tectonic control is crucial for their development. 519 Former studies focused on the surface mapping and logging of the formations in order to obtain a 520 satisfactory stratigraphic frame. This must now be anchored on an absolute timing by multiplying 521 absolute dating of the filling. This effort must be made in order to overcome apparent contradictions rose 522 by the extrapolation of local data (e.g. Franzese et al., 2018).

Another important shortcoming concerns the subsurface data due to its lack of industrial potential. Sounderstanding of its articulation with the Paleogene history of the area remains unclear.

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If tectonics plays a determining role in the evolution of these basins, it seemed important to us to apprehend it in parallel with that of its neighbors. And it is striking to note that filling of these basins occurred around 18 Ma. This filling answered to a regional event that authors called the Quechua phase. However this episode did not correspond in the study area to a kinematic reorganization in terms of rates or orientation of the South America and Nazca plates (Figures 9 and 10). The kinematics would not explain to the first order this compressive episode.

532 In parallel to this, seismic tomography recently imaged anomalies of rapid velocities in the mantle that we 533 interpret as the relics of ancient slabs (Pesicek et al., 2012). It shows slab segments laying above the 660 534 km-depth mantle discontinuity and slab folding as those obtained in analogic and numerical models (e.g. 535 Guillaume et al., 2009; Gibert et al, 2012; Cerpa et al., 2014; Cerpa et al., 2015). This observation seems 536 important to us because mechanically, the slab controls the transfer of stress and strain between this 537 mantle discontinuity and the surface. Thus the state of stress of the overriding plate and topography too 538 link directly with the dip of the slab. An important result of this interpretation is that a cyclic stress regime 539 in the overriding plate can be achieved with constant boundary conditions. Thus the dynamics of 540 subduction, independently of its boundary conditions, imposes on the surface a cyclicity which will be 541 potentially inscribed in the sedimentary record.

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543 If these basins are initiated at the same time, their excavation spreads itself over time. As a first 544 approximation, this results from the efficiency of the surface processes which, by reconnecting the basin 545 to its foreland, condemn it to excavation. This efficiency is determined by many parameters such as the 546 size of catchments, the slope of the flows, the lithology of the grounds which are specific to a given basin 547 and explains this spreading. But the development of slab folding, as it deposits on the 660 km depth 548 boundary, periodically flatten the slab with a strong impact on the state of stress and topography. Upper 549 plate shortening and uplift when the angle of the slab shallows, extension or lesser shortening and 550 subsidence when it steepens (e.g. Gibert et al., 2012; Cerpa et al, 2014). The balance between local uplift 551 (fault reactivation along the tectonic dam) and regional uplift (dynamic topography) through episodes of 552 higher shortening, will also interfere with surface processes. The evolution of these basins should also be 553 apprehended by the link to their close foreland that will generate or not space to accommodation. So a 554 quantification of the regional vertical displacements is required to constrain well the dynamics of these 555 basins.

Located in the hinterland of a volcanic arc, the combination of preserved landforms and abundant intercalated volcanic ashes may resolve the timing of filling and excavation, tectonic activity, and geomorphic evolution necessary to indentify a forcing of the internal dynamics of subduction on these depozones.

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- 561 562 Barrio, C., Carlini,
- Barrio, C., Carlini, A.A. and Goin, F.J., 1989. Litogenesis y antiguedad de la F. Chichinales de Paso Cordova
  (Rio Negro, Argentina), Actas 4° Congreso Argentino de Paleontologia y Bioestratigrafia, 4, 149–156.
- Bechis, F. and Cristallini, E. O., 2005. Tectonic evolution of northern Nirihuau basin, northwestern Patagonia,
   Argentina, 6th International Symposium on Andean Geodynamics (ISAG), Barcelona, 103-106.
  - Bechis, F., Encinas, A., Concheyro, A., Litvak, V., Aguirre-Urreta, B. and Ramos, V. 2014. New age constraints for the Cenozoic marine transgressions of northwestern Patagonia, Argentina (41-43 S): Paleogeographic and tectonics implications. Journal of South American Earth Sciences, 52, 72-93, doi: 10.1016/j.jsames.2014.02.003.
  - Bilmes, A., D'Elia, L., Franzese, J., Veiga, G., Hernández, M., 2013. Miocene block uplift and basin formation in the Patagonian foreland: The Gastre Basin, Argentina. *Tectonophysics*, 601, 98–111
  - Bilmes, A., D'Elia, L., Veiga, G.D., Franzese, J.R., 2014. Intermontane infill in the patagonian broken foreland: Neogene evolution of the gastre Basin. Revista de la Asociación Geologica Argentina, 71- 3, 311-330.
  - Branellec, M., Callot, J.P., Nivière, B., Ringenbach, J.C., 2015. The fracture network, a proxy for mesoscale deformation: Constraints on layer parallel shortening history from the Malargüe fold and thrust belt, Argentina. Tectonics, 34- 4, 623-647.
  - Branellec, M., Nivière, B., Callot, J. P., Ringenbach, J. C., 2016. Mechanisms of basin contraction and reactivation in the basement-involved Malargue fold-and-thrust belt, Central Andes (34–36° S). Geological Magazine, 153 (5-6), 926-944, doi: 10.1017/S0016756816000315.
- Butterworth, N.P., Talsma, A.S., Müller, R.D., Seton, M., Bunge, H.P., Schuberth, B.S.A., Shephard, G.E.,
  Heine, C., 2014. Geological, tomographic, kinematic and geodynamic constraints on the dynamics of sinking slabs. *Journal of Geodynamics*, 73, 1–13, doi: 10.1016 /j.jog.2013.10.006.
  - Cazau, L., Mancini, D., Cangini, J., Spalletti, L., 1989. Cuenca de Ñirihuau. In: Chebli, G., Spalletti, L. (Eds.), Cuencas Sedimentarias Argentinas, Serie Correlación Geológica, vol. 6. Universidad Nacional de Tucumán, pp. 299–318.
  - Cazau, L., Cortiñas, J., Reinante, S., Asensio, M., Bechis, F., Apreda, D., 2005. Cuenca de Ñirihuau. In: Chebli, G., Cortiñs, J.S., Spalletti, L., Legarreta, L., Vallejo, E.L. (Eds.), Frontera Exploratoria de la Argentina, IV Congreso de Exploración y Desarrollo de Hidrocarburos, pp. 251–273.
- Cerpa, N.G., Hassani, R., Gerbault, M., Prévost, J.-H., 2014. A fictitious domain method for lithosphereasthenosphere interaction: Application to periodic slab folding in the upper mantle. *Geochem. Geophys. Geosyst.*, 15, 1852–1877, doi:10.1002/2014GC005241.
  - Cerpa, N.G., Araya, R., Gerbault, M., Hassani R., 2015. Relationship between slab dip and topography segmentation in an oblique subduction zone: Insights from numerical modelling. *Geophys. Res. Lett.*, 42, 5786–5795, doi:10.1002/2015GL064047.
- 607 Chen, Y.-W., Wu, J. and Suppe, J., 2019. Southward propagation of Nazca subduction along the Andes, Nature, 565, 441–447.
  609
- 610 Cobbold, P.R., Rossello, E.A., 2003. Aptian to recent compressional deformation, foothills of the Neuquén
  611 Basin, Argentina. *Mar. Petrol. Geol.*, 20, 429–443.
- 613 Costa, C., Cisneros, H., Salvarredi, J., Gallucci, A., 2006. La neotectónica del margen oriental del bloque de San
  614 Rafael: Nuevas consideraciones. Asociación Geológica Argentina, Serie D: Publicación Especial, 6, 33–
  616
- 617 Cucchi, R., Leanza, H., 2005. Hoja Geológica 3972-IV Junín de los Andes, provincia del Neuquén. Servicio
   618 Geológico Minero Nacional. Boletín 357, 1-102.

- - Curtis, G.H., 1966. The problem of contamination in obtaining accurates dates of young geologic rocks, In Shaeffer, O. A., & Zahringer, J., eds., Potassium-Argon dating, Springer-Verlag, New York, p.151-162.
    - Deino, A. L., Tauxe, L., Monaghan, M. And Drake, R., 1990. Single-crystal <sup>40</sup>Ar/<sup>39</sup>Ar ages and the litho- and paleomagnetic stratigraphies of the Negorora Formation, Kenya Rift, Journal of Geology, 98, 567-587.
    - D'Elia, L., Muravchik, M., Franzese, J.R., Lopez, L., 2012. Tectonostratigraphic analysis of the Late Triassic-Early Jurassic syn-rift sequence of the Neuquén Basin in the Sanico depocentre, Neuquén Province, Argentina. *Andean Geol.*, 39, 133–157.
  - Dessanti, R.N., 1972. Andes Patagonicos Septentrionales. In: Geologia Regional Argentina (Ed. by A.F. Leanza), pp. 655–688. Academia Nacional de Ciencias, Cordoba.
  - Escosteguy, L., Franchi, M., 2010. Estratigrafia de la región de Chapelco, Provincia del Neuquén. *Revista de la Asociación Geológica Argentina*, 66, 418–429.
  - Flint, R.F., Fidalgo, F., 1968. Drift glacial al este de los Andes entre Bariloche y Esquel. *Inst. Nac. Geol. y Min Bol.*, 119, 1–14.
  - Folguera, A., Zapata, T., Ramos, V.A., 2006. Late Cenozoic Extension and the evolution of the Neuquén Andes.
     In: Kay, S.M., Ramos, V.A. (Eds.), Late Cretaceous to Recent Magmatism and Tectonism of the Southern Andean Margin at the Latitude of the Neuquen Basin (36–39°S). Geological Society of America, Special Paper, vol. 407, pp. 267–285.
  - Folguera, A., Gianni, G., Encinas, A., Alvarez, O., Orts, D., Echaurren, A., Litvak, V. D., Navarrete, C., Sellés, D., Tobal, J., Ramos, M., Fennell, L., Giménez, M., Martínez, P., Ruiz, F. and Iannelli, S., 2018. Neogene Growth of the Patagonian Andes. In: Folguera A. et al. (eds) The Evolution of the Chilean-Argentinean Andes. Springer Earth System Sciences. Springer, Cham
  - Franzese, J.R., D'Elia, L., Bilmes, A., Muravchik, M. & Hernández, M., 2011. Superimposition of Oligo-Miocene extensional and contractional basins in the North Patagonian Andean retroarc: The Aluminé basin, Neuquén, Argentina. *Andean Geology*, 38- 2, 319-334.
  - Franzese, J.R., D'Elia, L., Bilmes, A., Bucher, J., García, M., López, M., Muravchik, M. & Hernández, M., 2018.
     Evolution of a patagonian Miocene intermontane basin and its relationship with the Andean foreland:
     Tectono-stratigraphic evidences from the Catán Lil Basin, Argentina. *Journal of South American Earth Sciences*, 86, 162-175.
  - Galli, C.A., 1954. Acerca de una nueva interpretacion de las Formaciones Rético-liasicas de la Patagonia septentrional. *Revista de la Asociacion Geologica Argentina*, 8, 220–235.
  - Galli, C.A., 1969. Descripcion geológica de la Hoja 38c, Piedra del Aguila, Province Del Neuquén y Rio Negro. *Dir. Nac. Geol. Min. Bol.*, 111, 1–65.
  - García Morabito, E., Ramos, V.A., 2012. Andean evolution of the aluminé fold and thrust belt, northern patagonian Andes (38°30′-40°30′S). J. South Am. Earth Sci. 38, 13-30.
  - García Morabito, E.G., Götze, H.J., Ramos, V.A., 2011. Tertiary tectonics of the Patagonian Andes retro-arc area between 38°150 and 40°S latitude. *Tectonophysics*, 499, 1–21.
  - Giacosa, R., Heredia, N., 1999. La cuenca de antepaís terciaria asociada a la faja plegada y corrida de los Andes
     Patagónicos entre los 41° y 42° SO de Argentina. In: Busquets, P., Colombo, F., Perez-Estaun, A.,
     Rodriguez Fernández, R., (Eds.), Geología de los Andes Centrales Argentino-Chilenos. Acta Geológica
     Hispánica 32 (1–2), 103–111.
  - Giacosa, R., Heredia, N., Cesari, O., Zubia, M., 2001. Hoja geológica 4172-IV, San Carlos de Bariloche (provincias de Río Negro y Neuquén). Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino. Boletín 279, 67p.

- 679 Gibert, G., Gerbault, M., Hassani, R., Tric, E., 2012. Dependency of slab geometry on absolute velocities and
  680 conditions for cyclicity: Insights from numerical modelling. *Geophys. J. Int.*, 189-2, 747–760,
  681 doi:10.1111/j.1365-246X.2012.05426.x.
  - González Bonorino, F., 1973. Geología del área entre San Carlos de Bariloche y Llao-Llao, vol. 16. Fundación Bariloche, Publicación, 53p.
  - González Bonorino, F., González Bonorino, G., 1978. Geología de la región de San Carlos de Bariloche. Asociación Geológica Argentina, Revista 33-3, 175–210.
  - González Díaz, E.F., Nullo, F., 1980. Cordillera Neuquina. Segundo Simposio de Geologia Regional Argentina,
     *Acad. Nac. Cienc.*, 2, 1099–1147.
  - González Díaz, E.F., Riggi, J.C., Fauqué, L., 1986. Formación Caleufu (Nov. Nom): reinterpretación de las Formaciones Rio Negro y Alicura, en el área de Collón Cura, sur del Neuquén. Asociación Geológica Argentina, Revista XLI, 1–2, 81–105.
  - González Díaz, E.F., Ostera, H.A., Riggi, J.C., Fauqué, L., 1990. Una propuesta temporal acerca del Miembro Limay Chico (ex "Rionegrense") de la Formación Caleufu, en el valle del rio Collón Cura y adyacencias (SE del Neuquén). 11° Congreso Geológico Argentino (San Juan), 2, 243–246.
  - Gracia, R., 1958. Informe geológico de las Cartas Paso Flores y Traful. Secret. Ejerc. Direc. Gral. Ing., Buenos Aires.
  - Grimaldi, G. O. and Dorobek, S. L., 2011. Fault framework and kinematic evolution of inversion structures: Natural examples from the Neuquén Basin, Argentina. AAPG Bulletin, 95, 1, 27–60.
  - Groeber, P., 1951. La Alta Cordillera entre las latitudes 34° y 29°30', Revista del Instituto Nacional de Investigaciones de las Ciencias Naturales, Museo Argentino de Ciencias Naturales "Bernardino Rivadavia", Buenos Aires, Argentina, 1-5, 235–352.
  - Guillaume, B., Martinod, J., Espurt, N., 2009. Variations of slab dip and overriding plate tectonics during subduction: Insights from analogue modelling, *Tectonophysics*, 463(14), 167-174, doi:10.1016/j.tecto.2008.09.043.
  - Gurnis, M., Yang, T., Cannon, J., Turner, M., Williams, S., Flament, N., Müller, R. D., 2018. Global tectonic reconstructions with continuously deforming and evolving rigid plates, in: Computers & Geosciences, 116, 32-41. doi:10.1016/j.cageo.2018.04.007.
  - Haschke, M., Scheuber, E., Gunther, A., Reutter, K.-J., 2002. Evolutionary cycles during the Andean orogeny: repeated slab breakoff and flat subduction? *Terra Nova*, 14, 49–55.
  - Haschke, M., Günther, A., Melnick, D., Echtler, H., Reutter, K.-J., Scheuber, E., Oncken, O., 2006. Central and Southern Andean tectonic evolution inferred from arc magmatism, in The Andes, Springer, Berlin, pp. 337–353.
  - Heuret, A., Funiciello, F., Faccenna, C., Lallemand, S., 2007. Plate kinematics, slab shape and back-arc stress: a comparison between laboratory models and current subduction zones. Earth Planet. Sci. Lett. 256 (3), 473e483.
  - Hilley, G.E. and Strecker, M.R., 2005. Processes of oscillatory basin filling and excavation in a tectonically active orogen: Quebrada del Toro Basin, NW Argentina, Geol. Soc. Am. Bull., 117, 887–901.
  - Hosseini, K., Matthews, K. J., Sigloch, K., Shephard, G. E., Domeier, M. and Tsekhmistrenko, M., 2018. Submachine: Web-Based tools for exploring seismic tomography and other models of Earth's deep interior. Geochemistry, Geophysics, Geosystems, 19, doi:10.1029/2018GC007431.
  - Hugo, C.A., Leanza, H.A., 2001. Hoja Geológica 3669-IV, General Roca. Provincia del Neuquén. Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino 308, 70.

- Huyghe, D., Bonnel, C., Nivière, B., Fasentieux, B., Hervouët, Y., 2015a. Neogene tectonostratigraphic history of the southern Neuquén basin (39°-40°300S, Argentina): implications for foreland basin evolution. *Basin Res.*, 27 (5), 613-635. doi: 10.1111/bre.12091
  - Huyghe, D., Nivière, B., Bonnel, C., 2015b. Geomorphologic evidence for Plio-Quaternary shortening in the southern Neuquén basin (40°S, Argentina). *Terra Nova*, 27-6, 426-432.
  - Ichiki, M., Baba, K., Obayashi, M., Utada H., 2006. Water content and geotherm in the upper mantle above the stagnant slab: Interpretation of electrical conductivity and seismic P-wave velocity models. *Phys. Earth Planet. Inter.*, 155, 1-15.
  - Jordan, T.E., 1995. Retroarc Foreland and Related Basins. In: Tectonics of Sedimentary Basins (Ed. by C.J. Busby, R.V. Ingersoll), Blackwell Science, Oxford., pp. 331-362.
  - Kay, S.M., Burns, M., Copeland, P., 2006. Upper Cretaceous to Holocene Magmatism over the Neuquén basin: Evidence for transient shallowing of the subduction zone under the Neuquén Andes (36° S to 38° S latitude). In: Kay SM, Ramos VA (eds) Late Cretaceous to Recent magmatism and tectonism of the Southern Andean margin at the latitude of the Neuquen basin (36–39° S). *Geological Society of America, Special Paper*, 407, 19-60
  - Kay, S.M., Coira, B.L., 2009. Shallowing and steepening subduction zones, continental lithospheric loss, magmatism, and crustal flow under the Central Andean Altiplano-Puna Plateau. In: Kay S.M., Ramos V.A., Dickinson W.R. (eds) Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision. *Geol. Soc. Am. Memoirs*, Boulder, 204, 229-259
  - Lagorio, S., Montenegro, T., Massaferro, G., Vattuone, M.E., 1998. Edad y geoquimica de las ignimbritas de Aluminé, provincia del Neuquén, Argentina. In Congreso Latinoamericano de Geologia, Buenos Aires, 10-2, 321-325.
  - Leanza, H.A., Hugo, C.A., Herrero, J.C., Donnari, E., Pucci, J.C., 1997. Hoja Geológica 3969-III, Picun Leufu. Instituto de Geología y Recursos Minerales, *Servicio Geológico Minero Argentino: Boletín* 218, 135.
  - Leanza, H.A., Hugo, C.A. (2001) Hoja Geologica 3969-I, Zapala. Instituto de Geologia y Recursos Minerales, Servicio Geologico Minero Argentino: Boletin 275, 135pp.
  - Li, C., van der Hilst, R. D., Engdahl, E. R. and Burdick, S., 2008. A new global model for P wave speed variations in Earth's mantle, Geochem. Geophys. Geosyst., 9, Q05018, doi:10.1029/2007GC001806.
  - Lo Bello, P., Féraud, G., Hall, C. M., York, D., Lavina, P., andBernat, M., 1987. <sup>40</sup>Ar/<sup>39</sup>Ar step-heating and laser fusion dating of a Quaternary pumice from Neschert, Massif Central, France: The defeat of xenocrystic contamination, Chemical Geology, 66, p. 61-71.
  - Lorito, S., Romano, F., Atzori, S., Tong, X., Avallone, A., McCloskey, J., Cocco, M., Boschi, E., Piatanesi, A., 2011. Limited overlap between the seismic gap and coseismic slip of the great 2010 Chile earthquake, Nature Geosci., 4(3), 173–177.
  - Mancini, D., Serna, M., 1989. Evaluación petrolera de la Cuenca de Ñirihuau. Sudoeste de Argentina. 1 Congreso Nacional de Exploración de Hidrocarburos (Argentina). Actas 2, 739-762.
  - Margirier, A., Audin, L., Robert, X., Pêcher, A. and Schwartz, S., 2017. Stress field evolution above the Peruvian flat-slab (cordillera Blanca, northern Peru). Journal of South American Earth Sciences, 77, 58-69.
  - Marshall, L.G., Pascual, R., Curtis, G.H., Drake, R.E., 1977. South american geochronology: radiometric time scale for middle to late tertiary mammal-bearing horizons in patagonia. *Science*, 195, 1325-8. <u>https://doi.org/10.1126/science.195.4284.1325</u>
  - Mazzoni, M., Benvenuto, A., 1990. Radiometric ages of Tertiary ignimbrites and the Collón Curá Formation northwestern Patagonia. In: XI Congreso Geológico Argentino, San Juan, pp 87–90.

- 799 Mazzoni, M.M., Rapela, C.W., 1991. Caracteristicas químicas e isotopicas de ignimbritas Miocenas. Andes 800 Patagonicos septentrionales (SVZ), Argentina. Congreso Geologico Chileno, 6, 125-128. 801
- 802 McDougall, I., Brown, F.H., Cerling, T.E. and Hillhouse, J.W., 1992. A reappraisal of the geomagnetic polarity 803 time scale to 4 MA using data from the Turkana Basin, East Africa, Geophisical Research Letters, 19, 23, 804 2349-2352, doi: 10.1029/92GL02714. 805
- Messager, G., Niviére, B., Martinod, J., Lacan, P., Xavier, J.-P., 2010. Geomorphic evidence for Pio-Quaternary 806 807 compression in the Andean foothills of the southern Neuquén Basin, Argentina. Tectonics, 29, 1-18. 808 doi:10.1029/2009TC002609. 809
- 810 Meijer, P.Th. and Wortel, M.J.R., 1992. The dynamics of motion of the South American 811 Plate. Journal of Geophysical Research: Solid Earth, 97(B8), 11915–1193.

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- 813 Meyer, B., Saltus, R. and Chulliat, A., 2017. EMAG2: Earth Magnetic Anomaly Grid (2-arc-814 minute resolution) Version 3. National Centers for Environmental Information, NOAA. Model. doi:10.7289/V5H70CVX
  - Mosquera, A., Ramos, V.A., 2006. Intraplate deformation in the Neuquén Embayment. In: Evolution of an Andean margin: A Tectonic and Magmatic View from the Andes to the Neuquén Basin (35°-39°S lat) (Ed. by S.M. Kay & V.A. Ramos), Geol. S. Am. S., 407, 97–123.
  - Müller, R.D., Cannon, J., Qin, X., Watson, R.J., Gurnis, M., Williams, S., et al. 2018. GPlates: Building a virtual Earth through deep time, in: Geochemistry, Geophysics, Geosystems, 19, 2243-2261. doi:10.1029/2018GC007584.
  - Naipauer M, García Morabito E, Marques JC, Tunik V, Rojas Vera E, Vujovich GI, Pimentel MP and Ramos VA, 2012. Intraplate Late Jurassic deformation and exhumation in western central Argentina: Constraints from surface data and U-Pb detrital zircon ages. Tectonophysics, 524-525 (1), 59-75.
  - Nullo, F., 1979. Descripción geológica de la Hoja 39c, Paso Flores, provincias de Rio Negro y Neuquén. Servicio Geológico Nacional, Boletín, 167, 73p.
  - Orts, D., Folguera, A., Encinas, A., Ramos, M., Tobal, J., Ramos, V.A., 2012. Tectonic development of the North Patagonian Andes and their related Miocene foreland basin (41°30′–43° S). *Tectonics* 31- TC3012. https://doi.org/10.1029/2011TC003084
- 836 Pardo-Casas, F., Molnar, P., 1987. Relative motion of the Nazca (Farallón) and South American plates since Late Cretaceous time. Tectonics, 6, 233-248 838
  - Paredes, J.M., Giacosa, R.E., Heredia, N., 2009. Sedimentary evolution of Neogene continental deposits (Nirihuau Formation) along the Nirihuau River, North Patagonian Andes of Argentina. Journal of South American Earth Sciences, 28-1, 74-88. DOI: 10.1016/j.jsames.2009.01.002
- 843 Pascual, R., Odreman Rivas, O., 1971. Evolucion de las comunidades de los vertebrados del Terciario 844 Argentino. Los aspectos paleozoogeograficos y paleoclimaticos relacionados. Ameghiniana, 8, 372-412. 845
- 846 Pascual, R.P., Bondesio, M.G., Vucetich, G., Scillato Ya~Ne, G., Bond, M. & Tonni, E.P., 1984. Vertebrados 847 fosiles cenozoicos. Relatorio 9° Congreso Geologico Argentino, 2, 439-461. 848
- 849 Pesicek, J.D., Engdahl, E.R., Thurber, C.H., Deshon, H.R., Lange, D., 2012. Mantle subducting slab structure in 850 the region of the 2010 M8.8 Maule earthquake (30-40°S), Chile. Geophysical Journal International, 851 191-1, 317-324. 852
- 853 Rabassa, J., 1975. Geología de la región de Pilcaniveu-Comallo, Provincia de Río Negro, Argentina, Publicación 854 Fundación Bariloche, Departamento Recursos Naturales y Energéticos, San Carlos de Bariloche. Vol. 17, 855 129 pp. 856
- 857 Rabassa, J., 1978. Estratigrafía de la región de Pilcaniyeu-Comallo, Provincia de Río Negro. In: 7 Congreso

Geológico Argentino, Buenos Aires, Actas 1: 731-746.

- Ramos, V., Cortés, J., 1984. Estructura e interpretación tectónica. In: Ramos, V. (Ed.), Geología y Recursos Naturales de la Provincia de Río Negro, 1- 12, 317–346.
- Ramos, V.A., Folguera, A., 2009. Andean flat-slab subduction through time. *Geol. Soc. Lond. Special Publ.*, 327-1, 31-54, doi:10.1144/SP327.3.
- Ramos, V.A., Cristallini, E., Pérez, D.J., 2002. The Pampean flat-slab of the Central Andes. J. S. Am. Earth Sci., 15, 59-78.
- Ramos, V.A., Litvak, V., Folguera, A., Spagnuolo, M., 2014a. An Andean tectonic cycle: from crustal thickening to extension in a thin crust (34°-37°SL). *Geosci. Front.*, 5, 351–367.
- Ramos, M.E., Folguera, A., Fennel, L., Giménez, M., Litvak, V.D., Dzierma, Y., Ramos, V.A., 2014b. Tectonic evolution of the North Patagonian Andes from field and gravity data (39-40°S). J. S. Am. Earth Sci., 51, 59–75.
- Ramos, M., Tobal, J., Sagripanti, L., Folguera, A., Orts, D., Giménez, M., Ramos, V., 2015. The North Patagonian orogenic front and foreland evolution: Nirihuau-Norquinco Depocenter (-42° S). J. South Am. Earth. Sci., 64, 467–485.
- Rapela, C.W., Spalletti, L.A., Merodio, J., 1983. Evolucion magmatica y geotectonica de la "Serie Andesitica" andina en la Cordillera Norpatagonica. *Rev. Asoc. Geol. Argent.*, 38, 469-484.
- Rapela, C., Spalletti, L.A., Merodio, J., Aragón, E., 1988. Temporal evolution and spatial variations of early Tertiary volcanism in the Patagonian Andes. (40 S–42° 30' S). J. South Am. Earth. Sci., 1-1, 75–88.
- Renne, P., R., 2000. K-Ar and <sup>40</sup>Ar/<sup>39</sup>Ar Dating, In J., S. Noller, J., M. Sowers & W. R. Lettis (Eds.), Quaternary Geochronology: Methods and Applications, Volume 4, (pp. 77-100), Washington DC, American Geophysical Union.
  - Renne, P.R., Deckart, K., Ernesto, M., Féraud, G., Piccirillo, E.M., 1996. Age of the Ponta Grossa dike swarm (Brazil), and implications to Paraná flood volcanism, Earth and Planetary Science Letters, 144 (1-2), 199-211.
- Renne, P.R., Walter, R., Verosub, K., Sweitzer, M.,and Aronson, J., 1993. New data from Hadar (Ethiopia) support orbitally tuned time scale to 3.3 MA, Geophysical Research Letters, 20 (11), 1067-1070.
- Rojas Vera, E.A., Selles, D., Folguera, A., Gímenez, M., Ruíz, F., Orts, D., Zamora Valcarce, G., Martínez, P., Bechis, F., Ramos, V.A., 2014. The origin of the Loncopué trough in the retroarc of the Southern Central Andes from field, geophysical and geochemical data. *Tectonophysics*, 637, 1–19
- Rolleri, E., Dellap\_E, D.A. & Mance~Nido, M.O., 1984. Relaciones estratigraphicas y correlación de las Formaciones Pichi Picún Leufú y Collón Cura (Miembro Naupa Huen) aflorantes en el curso inferior y medio del cañadón Michihuau, provincia de Río Negro. 9° Congreso Geológico, 1, 257–265.
- Roth, S., 1899. Reconocimiento de la region andina de la Republica Argentina. Apuntes sobre la geologia y paleontología de Rio Negro y Neuquén. Revista Museo de La Plata, 9, 141–197.
- Roth, S., 1922. Investigaciones geológicas en la región norte de la Patagonia durante los años 1897 a 1899.
   *Revista del Museo de La Plata*, 26, 333–392.
- Ruff, L.J. and Kanamori, H., 1983. Seismic coupling and uncoupling at subduction zones, Tectonophysics, 99 (2-4), 9-117.
- Sánchez, N., Coutand, I., Turienzo, M., Lebinson, F., Araujo, V. and Dimier, L., 2017. Middle Miocene to Early
  Pliocene Contraction in the ChosMalal Fold-and-Thrust Belt (Neuquén Basin, Argentina): Insights From
  Structural Analysis and ApatiteFission-Tracks Thermochronology, Tectonics, 36, 10, 1966-1987,
  doi.org/10.1002/2017TC004516.

- Schellart, W.P., 2008. Overriding plate shortening and extension above subduction zones: a parametric study to explain formation of the Andes Mountains, Geol. Soc. Am. Bull., 120 (11-12), 1441-1454.
- Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., and Chandler, M., 2012. Global continental and ocean basin reconstructions since 200 Ma: Earth- Science Reviews, 113, 212-270, doi: 10.1016/j earscirev.2012.03.002.
- Sigloch, K., Mihalynuk, M.G., 2013. Intra-oceanic subduction shaped the assembly of Cordilleran North America, Nature, 496-7443, 50-56.
- Sigloch, K., Mihalynuk, M.G., 2017. Mantle and geological evidence for a Late Jurassic-Cretaceous suture spanning North America, Geological Society of America Bulletin, 129 (11-12), 1489-1520, doi: 10.1130/B31529.1
- Spalletti, L.A., 1981. Facies sedimentarias de la Formación Ñirihuau en la región de San Carlos de Bariloche, provincia de Río Negro. Asociación Geológica Argentina Revista, 36-3, 286–311.
- Spalletti, L.A., Dalla Salda, L., 1996. A pull-apart volcanic related Tertiary Basin, an example from the Patagonian Andes. Journal of South American Earth Sciences, 9 (1-4), 197-206.
- Steinmann, G., Lissón, C.I., Sieberg, A., Stappenbeck, R., 1929. Geologie von Peru, Winter, Heidelberg, Germany.
- Tašárová, Z.A., 2007. Towards understanding the lithospheric structure of the southern Chilean subduction zone (36° S-42° S) and its role in the gravity field. Geophys. J. Int., 170, 995-1014. doi: https://doi.org/10.1111/j.1365-246X.2007.03466.x
- Turner, J.C.M., 1965. Estratigrafía de Aluminé y adyacencias, provincia de Neuquén. Asociación Geológica Argentina, Revista 20-2, 153-184.
- Turner, J.C.M., 1965. Estratigrafia de Aluminé y adyacencias. Rev. Asoc. Geol. Argent. 20, 153-164.
- Turner, J.C.M., 1973. Descripcion geologica de la Hoja 37 a-b, Junin de los Andes, provincia del Neuquén. Servicio Nacional Minero Geologico, Boletin, Buenos Aires, 138, 86pp.
- Vergani, G.D., Tankard, A.J., Belotti, H.J. and Welsink, H.J., 1995. Tectonic evolution and paleogeography of the Neuquén Basin, Argentina. In: Petroleum Basins of South America (A.J. Tankard, R. Su arez, R. Soruco and H.J. Welskink, eds). AAPG Mem., 62, 383-402.
- Volkheimer, W., 1964. Estratigrafía de la zona extraandina del Departamento de Cushamen (Chubut) entre los paralelos de 42° y 42°30' y los meridianos 70° y 71°. Asociación Geológica Argentina, Revista 19-2, 85-107.
- Yrigoyen, M.R., 1969. Problemas estratigráficos del terciario de Argentina. Ameghiniana, 6, 315-329.
- Zhao, D., Tian, Y., Lei, J., Liu, L., Zheng, S., 2009. Seismic image and origin of the Changbai intraplate volcano in East Asia: Role of big mantle wedge above the stagnant Pacific slab, Phys. Earth Planet. Inter., 173, 197-206.
- Zhao, D., 2012. Tomography and Dynamics of Western-Pacific Subduction Zones, Monogr. Environ. Earth Planets, 1-1, 1-70.

973	FIGURE CAPTIONS
974	
975	Figure 1: Neogene intra mountaine basins (yellow patches) of the North Patragonian foothill with main
976	structures above the shaded topography. Inset with location of Figure 1 in South America.
977	
978	Figure 2: Geological map of the southern Neuquén basin with location of the Collón Curá basin (location
979	in Figure 1). Red dots are the sedimentary sections in Figure 3.
980	
981	Figure 3: Sedimentary sections in the Collón Curá basin (from Huyghe et al., 2015a). Stars are the sampled
982	ignimbrites for dating (40Ar/39Ar on biotite).
983	
984	Figure 4: Synthesis of the ages of Cenozoic sedimentary formations in the southern part of the Neuquén
985	basin. Dating results are from: 1: Barrio et al. (1989), 2: Pascual et al. (1984), 3: Rolleri et al. (1984), 4:
986	Pascual and Odreman Rivas (1971), 5: Marshall et al. (1977), 6: Gonzalez Diaz and Nullo (1980), 7:
987	Rabassa (1975), 8: Mazzoni and Buenvenuto (1990), 9: Cazau et al. (1989), 10: Gonzalez Diaz et al. (1990),
988	11: Ramos et al. (2014b) and 12: this study. Biostratigraphic ages are in blue and radiometric ages are in
989	red.
990	
991	Figure 5: 40Ar/39Ar age spectra for the two sampled ignimbrites at the outcropping base and at the top
992	of the Collón Curá Basin. Ar-11-15 (top) is concordant, Ar-11-30 (bottom) is discordant.
993	
994	Figure 6: Paleogeographic sketch map of the Collón Curá Basin and foreland from early Miocene (bottom)
995	to Present (top).
996	
997	Figure 7: Compilation of the ages of the sedimentary filling of the main intra montane basins between 38
998	and 41°S. Ages are from Roth (1922); González Bonorino (1973); Giacosa et al. (2001); Cazau et al. (2005)
999	and Paredes et al. (2009) for the Ñirihuau Basin; from Marshall et al. (1977); Rabassa (1978); Rapela et al.
1000	(1983); Mazzoni and Benvenuto (1990); Cucchi y Leanza (2005); Orts et al. (2012); Bilmes et al. (2013,
1001	2014); Ramos et al. (2014b, 2015); Rojas Vera et al. (2014) and Franzese et al. (2018) for the Catan Lil
1002	basin; Leanza & Hugo (2001) and Messager et al. (2010) for the Agua Amarga Basin, and this study for the

1003	Collón Curá Basin. The bottom of the sedimentary infill does not outcrop in the Collón Curá Basin, so
1004	agradation began before the dated ignimbrite Ar-11-30 (around 19 Ma). The light grey triangles show the
1005	uncertainty on onset of agradation.

Figure 8: Oceanic spreading rates above the South Atlantic (dashed lines) and South Pacific (dotted lines)
ridges at 37 and 40°S from Oligocene to Present (from Meyer et al., 2017).

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Figure 9: Location of the South America plate with respect to the current geographical frame through time
from Oligocene to Present. South America continuously moved to the northwest during this time interval
(from Müller et al., 2018).

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Figure 10: Convergence rates (red) and angle of convergence (violet) between the Nazca and South
America plates from Oligocene to Present at the latitude of the Collón Curá basin (40°S; from Müller et al.,
2018).

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Figure 11: A) Seismic tomographic image of lithosphere and lower mantle at 37 and 39°S (from Pesicek
et al., 2012). B) Analogical modeling of slab folding above the 660 km-depth mantle discontinuity (from
Guillaume et al., 2009).

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Figure 12: An interpretation of the seismic tomographic image by Pesicek et al. (2012). A) Stacking of slab
folds above the 660 km-depth mantle discontinuity and its stagnation could force convective circulation
process in the upper mantle and a deep dehydration process of the slab. The resulting upwellings of hot
and wet asthenospheric materials could lead to lithospheric attenuation and intraplate volcanoes (Zhao,
2012). B) First shallow slab break-off with upward rebound of the remaining slab (Haschke et al., 2006).
This break-off might cause the basins to invert. C) Second deep slab break-off at the top of the slab fold
stack with sinking in the lower mantel.

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Figure 13: Four characteristic modes of subduction toward the ocean (mode 2b) or the continent (other
modes) and implying folding of the oceanic slab (mode 1a and 2a) or not (mode 1b and 2b). The arrows
show far-field absolute plates velocities (black arrows indicate trenchward motion). The symbol ⊗

- 1033 indicates that the velocity is zéro (from Gibert et al., 2012).







39°S

# 69°W

# 68°W























## Setsyle 1



## Steyle 2

