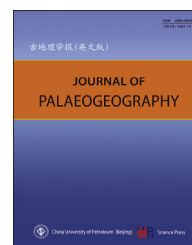




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Tectonopalaogeography and palaeotectonics

# Petrography and tectonic provenance of the Permian Tunas Formation: Implications on the paleotectonic setting during the Claromecó Foreland Basin evolution, southwestern Gondwana margin, Argentina



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**Abstract** The Claromecó Basin is located at the south-western sector of the Buenos Aires province, Argentina. This basin is considered a foreland basin closely related to the evolution of the southwestern Gondwana margin. This contribution focuses on the provenance analysis of the Tunas Formation (Permian, Pillahuincó Group), which represents the last filling stage for the Claromecó Foreland Basin. Petrographic and tectonic provenance analyses were performed in sandstones recovered from subsurface (PANG 0001 and PANG 0003 exploration wells) and outcrops located close to the basin center (Gonzales Chaves locality). In the subsurface, the analyzed succession is composed of medium- to fine-grained sandstones interbedded with tuffs, mudrocks, carbonaceous mudrocks and coal beds. In outcrops, the succession is dominated by medium- to fine-grained sandstones interbedded with siltstones. Modal composition patterns are distributed into the recycled orogen and transitionally recycled to mixed fields. Petrographic analyses, in addition to provenance and sedimentological studies, confirm that sedimentary material was derived from a mixed source, which largely comes from the Sierras Australes fold and thrust belt, located towards the W–SW, where the sedimentary succession is interbedded with volcanic material. The Tunas Formation shows clear differences in its modal composition, paleocurrent direction and paleoenvironmental conditions with respect to the underlying

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units of the Pillahuincó Group (Sauce Grande, Piedra Azul and Bonete formations). Source areas changed from cratonic to mixed fold belt/arc-derived material, suggesting variations in the Claromecó Basin configuration during the Late Paleozoic. Changes in the paleotectonic scenario during the deposition of the Tunas Formation have been interpreted as a consequence of a compressive post-collisional deformation event, the product of adjustment, accommodation and translation of terrains towards the equator during the Permian–Triassic to form Pangea.

**Keywords** Provenance area, Petrography, Tunas Formation, Claromecó Foreland Basin, Southwestern Gondwana margin, Permian, Upper Paleozoic

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## 1. Introduction

Provenance studies in sedimentary rocks of foreland basins have been used to determine the paleogeography and tectonic evolution of adjacent orogenic belts (Dickinson and Suczek, 1979; Dickinson *et al.*, 1983; DeCelles, 1986; DeCelles and Hertel, 1989). The sandstone modal composition is a useful tool to define the source areas and paleotectonic settings throughout basin evolution (Dickinson, 1970; Dickinson and Suczek, 1979; Dickinson *et al.*, 1983; Zuffa *et al.*, 1995). The composition of detrital constituents from sedimentary rocks depends on provenance area, but also is influenced by paleoclimate, weathering, transport agents and mechanisms, distance from source area, depositional environment and diagenesis (Dickinson and Suczek, 1979; McBride, 1985; DeCelles and Hertel, 1989, among others).

The Claromecó Basin is located in southern Buenos Aires province (~37°–39°S Latitude, 61°–63°W Longitude, Fig. 1A), Argentina. This basin was a part of the southwestern margin of the Gondwana supercontinent during the Late Paleozoic (Keidel, 1916, 1921; Du Toit, 1927; Harrington, 1947). This basin extends from the Sierras Australes fold and thrust belt (also known as Sierras de la Ventana o Ventana System) to the northeast, underlying Cenozoic deposits, and towards the Argentinian continental platform, covering a total area of 65,000 km<sup>2</sup>. Pángaro *et al.* (2015) expanded its limits encompassing the Chaco-Paraná Basin (South America) and the Kalahari-Karoo Basin (South Africa), redefining it as the Hesperides Basin. Geophysical data and exploration wells revealed the existence of coal-bearing deposits corresponding to the Piedra Azul and Tunas formations (Lesta and Sylwan, 2005; Arzadún *et al.*, 2016a, 2017; Febbo *et al.*, 2017, 2018a; Zavala *et al.*, 2019). Coal layers recorded in subsurface

can reach thickness of 0.5 m–4.5 m (Arzadún *et al.*, 2016a, 2017; Febbo *et al.*, 2017, 2018a, 2021, 2022; Zavala *et al.*, 2019).

The Claromecó Basin has been interpreted as a foreland basin developed during the Carboniferous–Permian (Ramos, 1984; López-Gamundí and Rossello, 1992; Ramos and Kostadinoff, 2005; Tomezzoli, 2012) in response to flexural loading, due to the deformation and uplift of the Sierras Australes. The basin tectonic evolution is related to the accretion of terranes and microplates to the Gondwana's southwestern margin during the Middle Paleozoic or even the Triassic (Ramos, 1984, 2008; Tomezzoli and Vilas, 1997, 1999; Tomezzoli, 2001, 2012; Ramos and Kostadinoff, 2005; López-Gamundí, 2006; Pángaro and Ramos, 2012; Ramos and Naipauer, 2014). However, the geologic evolution and deformation of the Sierras Australes and the adjacent Claromecó Basin are still under debate.

The Tunas Formation (Early Permian; Harrington, 1947; López-Gamundí *et al.*, 2013; Arzadún *et al.*, 2018) is the youngest unit of the Pillahuincó Group, representing the last stage of the Paleozoic basin filling. The synorogenic Tunas Formation deposits have been considered of great relevance to understanding the Sierras Australes and Claromecó Basin evolution, and represent potential economic resources due to the presence of coal-bearing layers and associated gas (Arzadún *et al.*, 2016a, 2017; Febbo *et al.*, 2017, 2018a, 2022; López-Gamundí and Rossello, 2021). This unit clearly records changes in depositional conditions and paleogeographic and paleotectonic scenarios along the southwestern Gondwana margin during the Late Paleozoic. These changes confirmed the difference in sandstone modal compositions, the reversal of paleocurrent directions and the contemporary volcanic eruptive activity that could be recognized in the geological record (Andreis and Cladera, 1992; López-

Gamundí *et al.*, 1995; López-Gamundí and Rossello, 1998). Provenance studies for the Tunas Formation outcrops from the Sierras Australes fold and thrust belt area were performed by several authors (e.g., Andreis and Cladera, 1992; López-Gamundí *et al.*, 1995; López-Gamundí and Rosello, 1998; Alessandretti *et al.*, 2013; Ramos *et al.*, 2014; Ballivián Justiniano *et al.*, 2020). However, this is the first work in which

the subsurface record of the Claromecó Basin was studied.

This contribution presents petrographic and tectonic provenance studies for the Tunas Formation from the subsurface (PANG 0001 and PANG 0003 exploration wells; Fig. 1) and outcrop data (the Gonzales Chaves locality; Fig. 1) of the Claromecó Foreland Basin area. The obtained data are integrated with previous

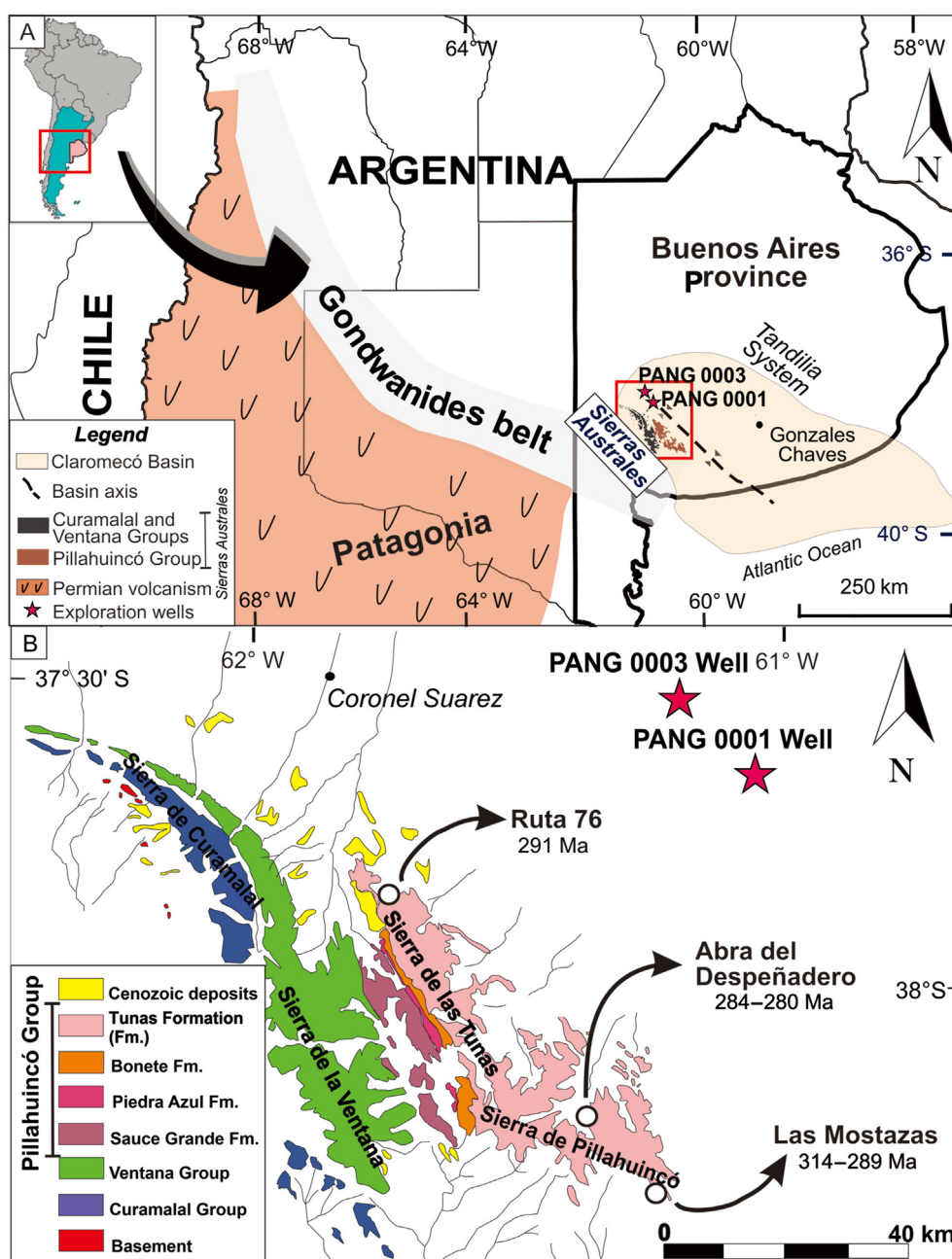


Fig. 1 A) Location map of the Claromecó Basin, PANG 0001 and PANG 0003 exploration wells and the Gonzales Chaves locality. Basin limits were defined by Kostadinoff and Font de Affolter (1982); B) Geological map of the Sierras Australes (modified from Suero, 1972) showing Tunas Formation outcrops, locations of PANG 0001 and PANG 0003 wells, and localities of U–Pb dating obtained by Arzadún *et al.*, (2018; Ruta 76), Tohver *et al.*, (2008; Abra del Despeñadero), Alessandretti *et al.*, (2013; Abra del Despeñadero), López-Gamundí *et al.*, (2013; Abra del Despeñadero), and Ballivián Justiniano *et al.*, (2020; Las Mostazas).

published results to better understand the paleogeographic and paleotectonic context during the deposition of the Tunas Formation and the evolution of the Claromecó Basin in the southwestern Gondwana margin during the Late Paleozoic.

## 2. Geologic and stratigraphic setting

The study area is located in the northwestern area of the Claromecó Basin in southern Buenos Aires province, Argentina (Fig. 1A). The origin of the Claromecó Basin was defined based on gravimetric studies, which revealed a sedimentary infill with a maximum thickness of 9 km–10.5 km (Kostadinoff and Font de Affolter, 1982; Introcaso, 1982). Its main axis is oriented NW–SE, parallel to the Tandilia System and the Sierras Australes trend (Kostadinoff and Font de Affolter, 1982; Ramos and Kostadinoff, 2005; Álvarez, 2007, Fig. 1A). The Paleozoic sedimentary infill of the Claromecó Basin is exposed along the Sierras Australes and underlies the Cenozoic sedimentary cover to the east–northeast, limiting with the Tandilia System, with some isolated outcrops near Gonzales Chaves locality (Fig. 1A). Seismic data and offshore exploration wells confirm the basin extension toward the Argentinian continental platform (Lesta *et al.*, 1978; Lesta and Sylwan, 2005; Pángaro and Ramos, 2012), constituting the pre-rift basement of the Colorado Basin (Fryklund *et al.*, 1996).

The tectonic evolution of the Sierras Australes and the adjacent Claromecó Basin is complex and recorded multiple compressional and extensional tectonic events throughout the Paleozoic–Mesozoic (Arzadún *et al.*, 2020). Ramos and Kostadinoff (2005) proposed that the basin developed in three stages, from the Early to the Late Paleozoic: a rifting phase during the Early Paleozoic followed by a passive margin period from the Ordovician to the Devonian, and finally, the development stage of a foreland basin from the Carboniferous up to the Early Permian. Some authors interpreted the establishment of an active margin as resulting from the Patagonia terrane collision with the southwestern Gondwana margin during the Late Paleozoic (Ramos, 1984, 2008; Lesta and Sylwan, 2005; Pángaro and Ramos, 2012; Ramos and Naipauer, 2014). However, other authors considered that collision events began in the Cháñica Orogenic phase during the Middle Devonian (Azcuay and Caminos, 1987) and continued up to the Permian (Tomezzoli, 1999, 2001, 2012; Arzadún *et al.*, 2021). The compressive regime ended at the Late Paleozoic–Early Mesozoic boundary as the continents moved towards the equator to finally

configure Pangea during the Triassic (Tomezzoli, 2009; Gallo *et al.*, 2017). During the Mesozoic, several rifting events affected the southern part of this area due to the formation of the Colorado Basin on the Argentinian continental platform (Lovecchio *et al.*, 2018, 2020; Arzadún *et al.*, 2020).

Deformation and uplift of the Sierras Australes were related to the Gondwanides Orogeny of Late Paleozoic age (Keidel, 1916; Du Toit, 1927; Milani and De Wit, 2008). Ramos (1984, 2008) proposed that the deformation of the Sierras Australes was linked to the accretion of the Patagonia terrane between Carboniferous and even late Early Triassic (Pángaro and Ramos, 2012). In contrast to the collisional model, other authors suggested an intracontinental deformation resulting from continental blocks which moved producing crustal fragmentation through strike-slip faults (Japas, 1989; Cobbold *et al.*, 1991; Kostadinoff, 1993, 2007; Álvarez, 2004; Gregori *et al.*, 2008; Vizán *et al.*, 2015). According to Tomezzoli (2001, 2012), the deformation might have been a combination of these mentioned processes, with a collisional phase occurring during the Devonian–Carboniferous and a later post-collisional spasmodic deformation (Arzadún *et al.*, 2021). These deformation events were associated with latitudinal movements due to the adjustment and coupling of terrains during the Permian–Triassic, to form Pangea, with a climax of the deformation during the Early Permian (~290 Ma) (Tomezzoli, 2012; Arzadún *et al.*, 2021).

The Paleozoic sequence outcropped at the Sierras Australes displays a decreasing deformation from west to east (Harrington, 1947; von Gosen *et al.*, 1991; Tomezzoli, 1999). The Lower Paleozoic successions (Curamalal and Ventana Groups; Fig. 1B) display a lower greenschist metamorphism (Cobbold *et al.*, 1986; Buggisch, 1987), while the Upper Paleozoic sequences (Pillahuincó Group; Figs. 1B and 2A) present a very low-grade metamorphism to high diagenesis (Buggisch, 1987; von Gosen *et al.*, 1991). Anisotropy of magnetic susceptibility (AMS) studies of the Tunas Formation from the Sierras Australes area (Tomezzoli, 2001; Arzadún *et al.*, 2016b, 2021) and in the Claromecó Basin subsurface (Febbo *et al.*, 2021) confirm a decrease in the magnitude of deformation towards the foreland basin during the Permian.

The Curamalal Group (Late Cambrian–Ordovician; Fig. 1B; Harrington, 1947) is a 1200 m-thick succession deposited in a stable marine platform, starting with a basal conglomerate (La Lola Formation), and it is mostly composed of quartzite with mudrock intercalations toward the top (Mascota, Trocadero and Hinojo Formations). The Ventana Group (Silurian–Middle

Devonian; Fig. 1B; Harrington, 1947) is a 1200–1400 m-thick succession deposited under stable marine conditions. This unit consists of sandstones with conglomerate lenses (Bravard Formation), quartzites (Napostá Formation), quartzites interbedded with sandstones and mudrocks (Providencia Formation), and mica-rich sandstones with slates and schist layers (Lolén Formation) (Harrington, 1947, 1972).

The Upper Paleozoic succession of the Claromecó Basin comprises the Pillahuincó Group, which is subdivided into four formations: Sauce Grande Formation, Piedra Azul Formation, Bonete Formation and Tunas Formation (Fig. 2A; Harrington, 1947). These units outcropped in the eastern portion of the Sierras Australes (Fig. 1) and reach a maximum thickness of approximately 2800 m (Harrington, 1970; López-Gamundí *et al.*, 1995). The Pillahuincó Group is composed of glaciomarine deposits of the Sauce Grande Formation (Harrington, 1970), equivalent to the Dwyka Group in the Karoo Basin (López-Gamundí and Rossello, 1998), of a Late Carboniferous age (Pennsylvanian–Cisuralian; di Pasquo *et al.*, 2008). This unit

consists of diamictites, sandstones and mudrocks and has a maximum thickness of 1100 m (Andreis *et al.*, 1987). Glacial conditions ceased during the Early Permian (Gallo *et al.*, 2020, and references therein), when shallow marine mudstones and sandstones, corresponding to the Piedra Azul and Bonete formations, progressively replaced diamictite deposits (Harrington, 1947). The presence of *Eurydesma* fauna and *Glossopteris* flora indicates an Early Permian age for these units (Archangelsky and Cúneo, 1984, Fig. 2A).

The Tunas Formation was deposited in deltaic to fluvial environments, representing the regressive culmination characterized with shallow marine conditions (Andreis *et al.*, 1989; López-Gamundí *et al.*, 1995, 2013; Andreis and Japas, 1996; Zorzano *et al.*, 2011; Arzadún *et al.*, 2017; Zavala *et al.*, 2019; Ballivián Justiniano *et al.*, 2020). This unit is exposed north of Sierras de las Tunas and south of Sierra de Pillahuincó (Fig. 1B), with small isolated outcrops near Gonzales Chaves locality (S38°03'18", W60°03'57"; Fig. 1A) (Monteverde, 1937; Furque, 1965; Harrington, 1970; Llambías and Prozzi, 1975; Tomezzoli and Vilas, 1997;

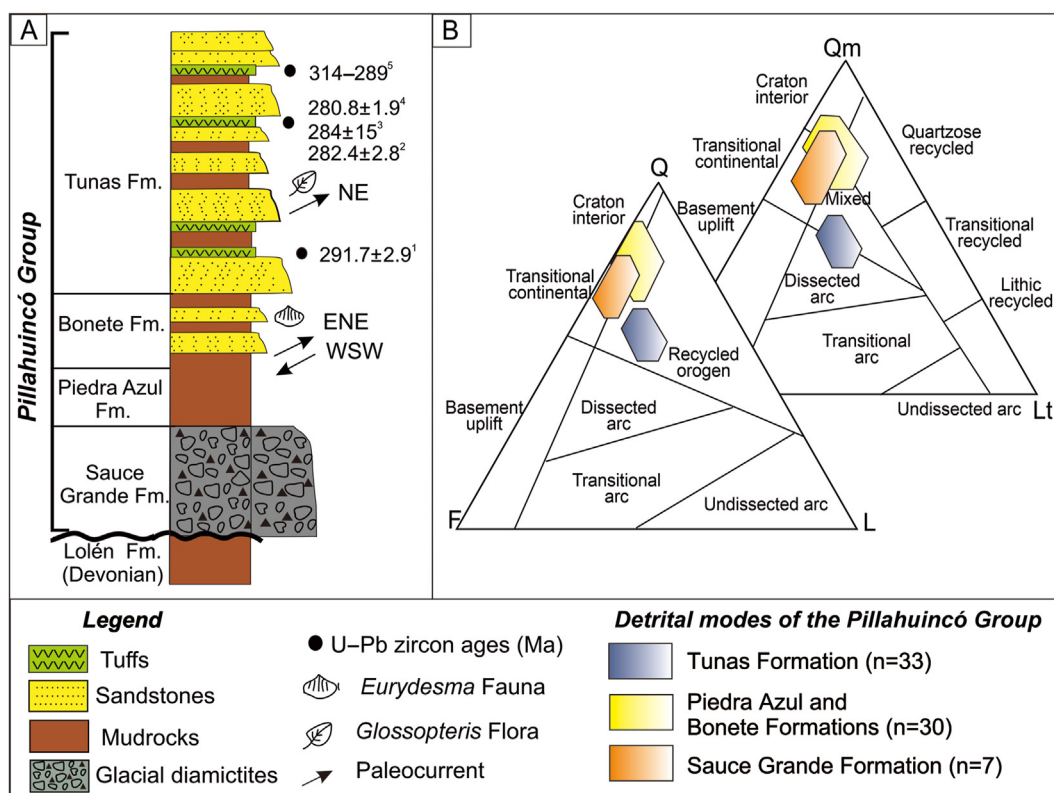


Fig. 2 A) Stratigraphic column of the Upper Paleozoic Pillahuincó Group (based on Harrington, 1947; Suero, 1972). Paleocurrents from Andreis and Japas (1991) and López-Gamundí *et al.* (1994). U–Pb zircon ages from tuff levels of Tunas Formation reported by Arzadún *et al.* (2018)<sup>1</sup>, Tohver *et al.* (2008)<sup>2</sup>, Alessandretti *et al.* (2013)<sup>3</sup>, López-Gamundí *et al.* (2013)<sup>4</sup> and Ballivián Justiniano *et al.* (2020)<sup>5</sup>, located at different levels of the sequence; B) Detrital modes of the Pillahuincó Group plotted in the Dickinson *et al.* (1983) provenance diagrams, modified from López-Gamundí *et al.* (1995). Notice differences in the provenance areas among the lower units (Sauce Grande, Piedra Azul and Bonete formations), with a cratonic source and the Tunas Formation, with recycled orogeny/mixed-dissected arc source.

Febbo *et al.*, 2018b). Sedimentary deposits are composed of fine- to medium-grained greenish and yellowish sandstones, with cross stratification, interbedded with finely laminated purple and green mudrocks and thin pyroclastic levels (Harrington, 1947, 1970; Andreis *et al.*, 1979; Andreis and Cladera, 1992; Zavala *et al.*, 1993, 2019; López-Gamundí *et al.*, 1995; Arzadún *et al.*, 2018). There are many uncertainties regarding its thickness due to the lithological homogeneity and tectonic complexity, and the absence of marker horizons. The exposed thickness ranges from 600 m to 2400 m (Harrington, 1970; Suero, 1972; Andreis and Japas, 1991; Vazquez Lucero *et al.*, 2020). In the subsurface of the Claromecó Basin, this unit reaches 700 m in thickness (Lesta and Sylwan, 2005; Zorzano *et al.*, 2011; Arzadún *et al.*, 2017). The *Glossopteris* flora indicates an Early Permian age (Sakmarian–Artinskian; Archangelsky and Cúneo, 1984), which is consistent with the U–Pb zircon ages ( $284 \pm 15$  Ma, Alessandretti *et al.*, 2013;  $282.4 \pm 2.8$  Ma, Tohver *et al.*, 2008;  $280.8 \pm 1.9$  Ma, López-Gamundí *et al.*, 2013) obtained from pyroclastic layers located at Abra del Despeñadero (top of the sequence; Figs. 1B and 2A). Recently, Ballivián Justiniano *et al.* (2020) proceeded LA–ICP–MS U–Pb zircon dating from tuff layers, obtaining ages between 314 Ma and 289 Ma at Las Mostazas locality (top of the sequence; Figs. 1B and 2A). Arzadún *et al.* (2018) obtained SHRIMP U–Pb zircon ages of  $291.7 \pm 2.9$  Ma from tuff layers located at Ruta 76 (base of the sequence; Figs. 1B, 2A) and  $295.5 \pm 8.0$  Ma from the PANG 0001 well (Fig. 3). These ages are consistent with available palynological data from core samples of the Tunas Formation (di Pasquo *et al.*, 2018).

Cores of the Tunas Formation were recovered from wells PANG 0001 ( $S37^{\circ}40.8'17''$ ,  $W61^{\circ}11'30.06''$ ) and PANG 0003 ( $S37^{\circ}34'44.24''$ ,  $W61^{\circ}22'12.56''$ ) located in the northwest of the Claromecó Basin (Fig. 1), which are preserved and stored at Universidad Nacional del Sur, Bahía Blanca, Argentina. Sediments are composed of medium- to fine-grained sandstones, with black organic-rich mudrocks, heterolites, greenish mudrocks, tuff levels, carbonaceous mudrocks and coal levels (Zorzano *et al.*, 2011; Arzadún *et al.*, 2016a, 2017; Febbo *et al.*, 2017, 2018a; Zavala *et al.*, 2019; this work).

### 3. Provenance and tectonic evolution of the Pillahuincó Group

The Upper Paleozoic deposits of the Pillahuincó Group represent the onset of the foreland stage in

the evolution of the Claromecó Basin (Ramos, 1984; López-Gamundí and Rossello, 1992; López-Gamundí *et al.*, 1995). The paleotectonic scenario changed between the deposition of the lower units (Sauce Grande, Piedra Azul and Bonete formations) and the uppermost unit (Tunas Formation). The oldest units are characterized by quartz-rich petrofacies, with bimodal paleocurrents from ENE–WSW, which indicate a cratonic source area (Fig. 2B; Andreis and Cladera, 1992; López-Gamundí *et al.*, 1995). On the other hand, lithic-rich petrofacies and inversion in the paleocurrent directions, coming from SW, denote a recycled orogen/magmatic arc source area for the Tunas Formation (Fig. 2B; Andreis and Cladera, 1992; López-Gamundí *et al.*, 1995; López-Gamundí and Rossello, 1998; Alessandretti *et al.*, 2013; Ramos and Naipauer, 2014; Ballivián Justiniano *et al.*, 2020).

The Tunas Formation was interpreted as a synorogenic unit, based on the occurrence of growth strata (López-Gamundí *et al.*, 1995, 2013) and paleomagnetic data that show syntectonic magnetizations acquired during or very soon after its deposition (Tomezzoli, 1999, 2001; Tomezzoli and Vilas, 1999). The sedimentation was contemporary with the explosive volcanic activity evidenced by tuffs interbedded with clastic material (Fig. 2), which confirms an Early Permian volcanism in the southwestern Gondwana margin (Alessandretti *et al.*, 2013; López-Gamundí *et al.*, 2013; Arzadún *et al.*, 2018; Ballivián Justiniano *et al.*, 2020). These events are interpreted as the distal equivalent of the earliest Choiyoi volcanic episodes in western Argentina (López-Gamundí, 2006; López-Gamundí *et al.*, 2013; Sato *et al.*, 2015).

### 4. Methodology

Petrographic and modal composition analyses were performed on 30 sandstone samples from the Tunas Formation: 22 samples from the subsurface (PANG 0001 and PANG 0003 wells; Fig. 3) and 8 samples from the outcrop (Gonzales Chaves locality; Fig. 4) at the Claromecó Basin center. The sedimentary sequences for PANG 0001 and PANG 0003 boreholes can reach depths of ~900 meters below wellhead (mbw), and are overlaid by Cenozoic deposits with a thickness of ~180 m.

Petrographic studies were performed with a Nikon Eclipse 50i POL microscope. The modal composition was determined according to the Gazzi-Dickinson method, counting 300–350 grains per

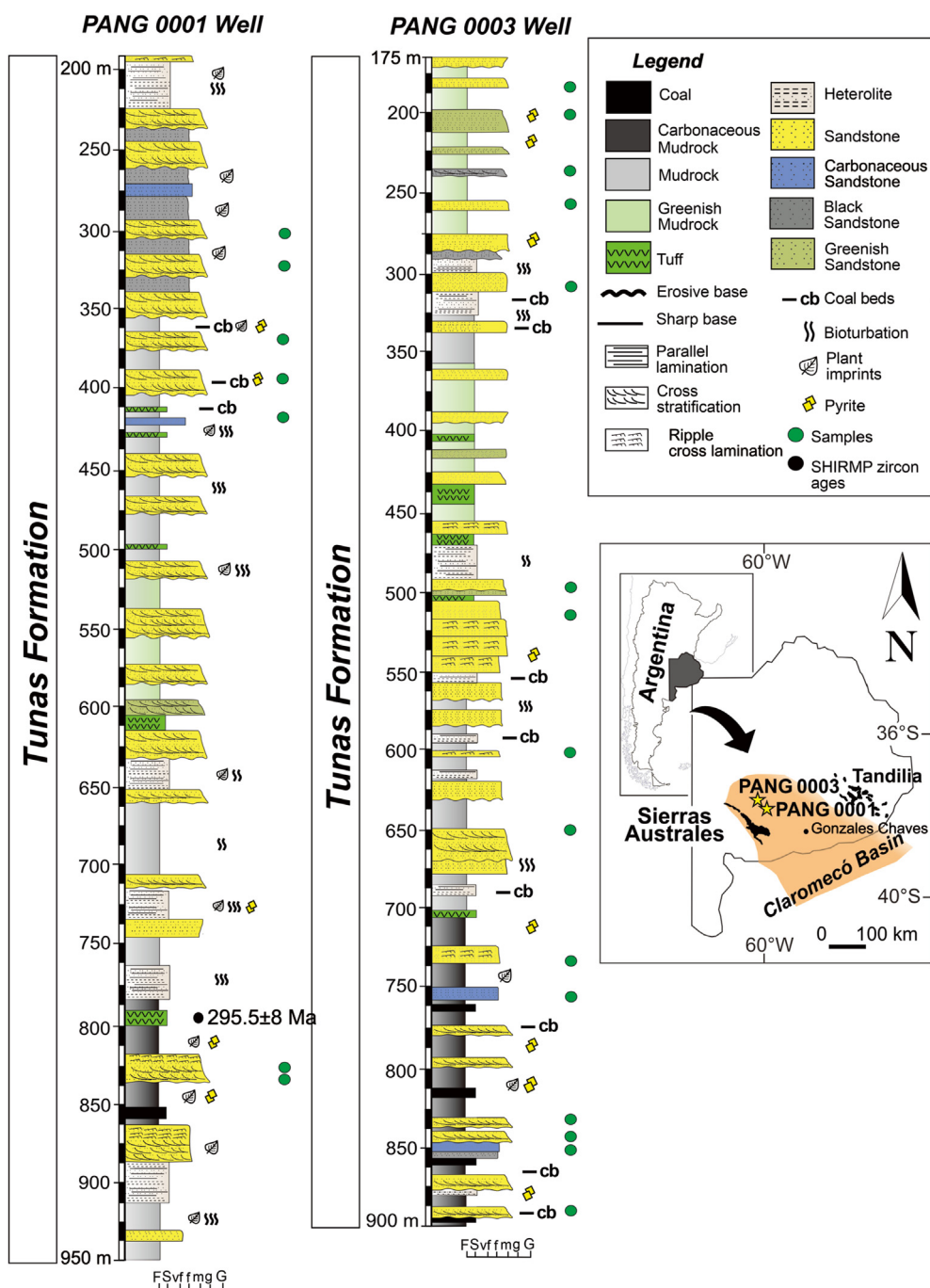


Fig. 3 Sedimentary logs of the Tunas Formation in PANG 0001 and PANG 0003 wells, showing the location of analyzed sandstones samples, SHIRMP zircon ages obtained by Arzadún et al. (2018) and studied wells.

sample. This method minimizes the compositional variability due to the influence of grain size (Dickinson, 1970; Ingersoll et al., 1984; Zuffa et al., 1995). Sandstone constituents were classified into monocrystalline quartz (Qm), polycrystalline quartz (Qp), potassium feldspars (Fk), plagioclase (Pl) and lithic fragments that include volcanic (Lv) and sedimentary and metasedimentary (Ls-m) ones. They

were differentiated based on optical mineralogical characteristics, such as extinction, twinning and relict textures. Sandstones were classified according to Folk et al. (1970) based on their quartz, feldspar and lithic content, recalculated to 100% (Table 1). Detrital constituents in the framework, percentage of matrix, porosity and cement were visually estimated by microscopic analysis.

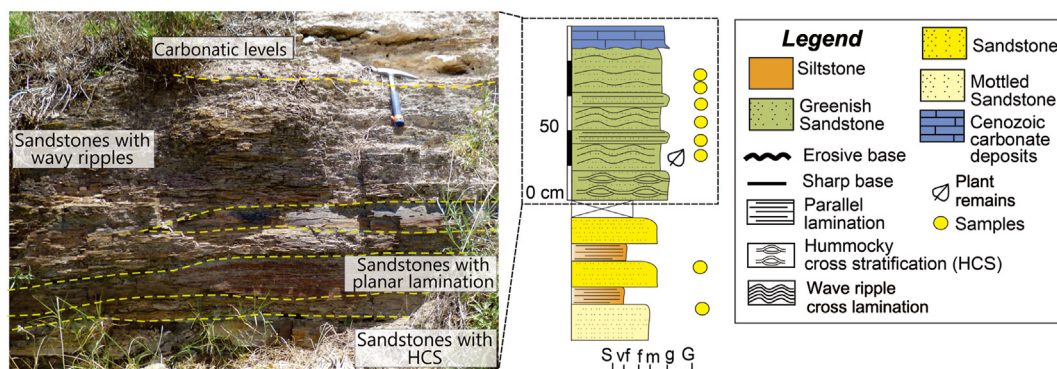


Fig. 4 Outcrops and sedimentary log of the Tunas Formation at the Gonzales Chaves locality, showing the location of analyzed sandstones samples.

Ternary diagrams QFL (total quartz–feldspars–lithic fragments) and QmFLt (monocrystalline quartz–feldspars–total lithic fragments + polycrystalline quartz), proposed by Dickinson et al. (1983), were used to determine provenance sources (Table 2). QmPLK

complementary diagrams were employed to differentiate the crystalline basement supply from that of the volcanic arc (Table 2). In addition, results were compared with the Tunas Formation outcrop data from the Sierras Australes area obtained by other authors

Table 1 Main features of the Tunas Formation sandstones and their classification based on Folk et al. (1970). The summary of the major detrital components was recalculated to 100%.

	Sample	Depth	QFL (%)			Folk et al. (1970)'s classification
			Q	F	L	
PANG 0001 Well	509	304.6	48.7	15.3	36.0	Feldspathic litharenite
	495	323.2	44.6	14.5	40.9	Feldspathic litharenite
	458	365.6	47.7	7.4	44.9	Litharenite
	442	382.5	38.0	14.3	47.7	Litharenite
	414	419.3	43.5	7.0	49.5	Litharenite
	103a	822.8	46.9	9.4	43.7	Litharenite
	103b	821.5	44.5	10.5	45.0	Litharenite
PANG 0003 Well	M377	182.4	55.0	15.0	30.0	Feldspathic litharenite
	M368	198.9	54.5	15.4	30.1	Feldspathic litharenite
	M351	239.6	51.3	16.5	32.2	Feldspathic litharenite
	M343	251.5	48.2	13.6	38.2	Feldspathic litharenite
	M315	311.5	40.9	21.5	37.6	Feldspathic litharenite
	M261	492.6	42.5	15.5	42.0	Feldspathic litharenite
	M248	516.3	51.0	17.0	32.0	Feldspathic litharenite
	M212	601.0	53.5	20.5	26.0	Feldspathic litharenite
	M186	648.9	57.8	13.3	28.9	Feldspathic litharenite
	M136	732.0	41.0	10.9	48.1	Litharenite
	M117	757.2	50.0	9.4	40.6	Litharenite
	M54	838.3	43.6	16.4	40.0	Feldspathic litharenite
	M47	846.3	44.6	7.0	48.4	Litharenite
	M38	854.8	54.2	10.8	35.0	Litharenite
M22	879.9	43.0	12.5	44.5	Litharenite	
Gonzales Chaves	G Ch1	Outcrop	54.0	8.8	37.2	Litharenite
	G Ch2	Outcrop	57.2	8.8	34.0	Litharenite
	G Ch3	Outcrop	47.0	16.4	36.6	Litharenite
	P2	Outcrop	51.5	14.0	34.5	Feldspathic litharenite
	P4	Outcrop	51.4	9.8	38.8	Litharenite
	Gh 00	Outcrop	42.8	16.0	41.2	Feldspathic litharenite
	Gh 01	Outcrop	48.0	18.6	33.4	Feldspathic litharenite
	Gh 02	Outcrop	47.1	18.3	34.6	Feldspathic litharenite

F: Feldspars; L: Lithic fragments; Q: Quartz.



**Table 2** Detrital modes from Tunas Formation sandstones (recalculated 100%).

	Sample	Qm	Qp	K	Pl	Lv	Ls	Dickinson <i>et al.</i> (1983)						Dickinson and Suczek (1979)		
								QFL (%)			QmFLt (%)			QmPIK (%)		
								Q	F	L	Qm	F	Lt	Qm	Pl	K
PANG 0001 Well	509	40.1	8.6	5.3	10.0	27.2	8.8	48.7	15.3	36.0	40.1	15.3	44.6	72.5	18.0	9.5
	495	36.6	8.0	4.0	10.5	30.0	10.9	44.6	14.5	40.9	36.6	14.5	48.9	71.6	20.6	7.8
	458	46.6	1.1	1.7	5.7	10.9	34.0	47.7	7.4	44.9	46.6	7.4	46.0	86.2	10.6	3.2
	442	36.0	2.0	9.5	4.8	22.7	25.0	38.0	14.3	47.7	36.0	14.3	49.7	71.5	9.6	18.9
	414	41.8	1.7	2.2	4.8	11.9	37.6	43.5	7.0	49.5	41.8	7.0	51.2	85.6	9.8	4.6
	103a	42.5	4.4	1.9	7.5	18.0	25.7	46.9	9.4	43.7	42.5	9.4	48.1	81.7	14.5	3.8
PANG 0003 Well	103b	43.4	1.1	2.7	7.8	10.9	34.1	44.5	10.5	45.0	43.4	10.5	46.1	80.5	14.5	5.0
	M377	50.0	5.0	3.8	11.2	18.5	11.5	55.0	15.0	30.0	50.0	15.0	35.0	77.0	17.1	5.9
	M368	43.1	11.4	6.8	8.6	19.0	11.1	54.5	15.4	30.1	43.1	15.4	41.5	73.6	14.8	11.6
	M351	43.7	7.6	3.5	13.0	23.5	8.7	51.3	16.5	32.2	43.7	16.5	39.8	72.5	21.7	5.8
	M343	44.8	3.4	3.4	10.2	23.2	15.0	48.2	13.6	38.2	44.8	13.6	41.6	76.7	17.5	5.8
	M315	37.2	3.7	8.7	12.8	22.2	15.4	40.9	21.5	37.6	37.2	21.5	41.3	63.9	21.3	14.8
	M261	32.8	9.7	2.2	13.3	25.2	16.8	42.5	15.5	42.0	32.8	15.5	51.7	68.1	27.9	4.0
	M248	42.3	8.7	4.5	12.5	19.4	12.6	51.0	17.0	32.0	42.3	17.0	40.7	71.3	21.1	7.6
	M212	43.7	9.8	6.9	13.6	14.5	11.5	53.5	20.5	26.0	43.7	20.5	35.8	68.0	21.2	10.8
	M186	50.3	7.5	4.8	8.5	13.0	15.9	57.8	13.3	28.9	50.3	13.3	36.4	79.1	13.4	7.5
	M136	40.2	0.8	2.9	8.0	17.6	30.5	41.0	10.9	48.1	40.2	10.9	48.9	78.7	15.6	5.7
	M117	46.8	3.2	1.9	7.5	15.1	25.5	50.0	9.4	40.6	46.8	9.4	43.8	83.3	13.3	3.4
	M54	42.6	1.0	2.4	14.0	9.6	30.4	43.6	16.4	40.0	42.6	16.4	41.0	72.2	23.8	4.0
	M47	37.6	7.0	1.1	5.9	13.4	35.0	44.6	7.0	48.4	37.6	7.0	55.4	84.3	13.2	2.5
	M38	54.0	0.2	3.3	7.5	5.0	30.0	54.2	10.8	35.0	54.0	10.8	35.2	83.3	11.6	5.1
	M22	37.0	6.0	5.5	7.0	11.4	33.1	43.0	12.5	44.5	37.0	12.5	50.5	74.9	14.1	11.0
Gonzales Chaves	GChi1	51.0	3.0	2.0	6.8	10.2	27.0	54.0	8.8	37.2	51.0	8.8	40.2	85.3	11.4	3.3
	GChi2	42.2	15.0	3.3	5.5	15.5	18.5	57.2	8.8	34.0	42.2	8.8	49.0	82.7	10.7	6.6
	GChi3	37.6	9.4	2.4	14.0	15.5	21.1	47.0	16.4	36.6	37.6	16.4	46.0	69.6	26.0	4.4
	P2	46.0	5.5	2.3	11.7	9.7	24.8	51.5	14.0	34.5	46.0	14.0	40.0	76.7	19.5	3.8
	P4	48.0	3.4	2.8	7.0	10.5	28.3	51.4	9.8	38.8	48.0	9.8	42.2	82.0	12.1	5.9
	Gh 00	38.4	4.4	3.1	12.9	2.7	38.5	42.8	16.0	41.2	38.4	16.0	45.6	70.5	23.7	5.8
	Gh 01	41.8	6.2	3.9	14.7	6.4	27.0	48.0	18.6	33.4	41.8	18.6	39.6	69.2	24.3	6.5
	Gh 02	38.9	8.2	2.0	16.3	5.0	29.6	47.1	18.3	34.6	38.9	18.3	42.8	68	28.4	3.6

F: Feldspars (K + Pl); K: Potassium feldspar; L: Total lithic fragments (Ls + Lv); Ls: Sedimentary/metasedimentary lithic fragments; Lt: Total lithic fragments + polycrystalline quartz (L + Qp); Lv: Volcanic lithic fragments; Pl: Plagioclase; Q: Total quartz; Qm: Monocrystalline quartz; Qp: Polycrystalline quartz.

(Andreis and Cladera, 1992; López-Gamundí *et al.*, 1995; Alessandretti *et al.*, 2013; Ballivián Justiniano *et al.*, 2020).

## 5. Results

### 5.1. Sandstone petrography

Petrographic and modal analyses were performed on the Tunas Formation samples from subsurface (Fig. 3; PANG 0001 and PANG 0003 wells) and outcrops (at the Gonzales Chaves locality; Fig. 4). The subsurface sequences are composed of carbonaceous mudrocks and coal beds with abundant pyrite nodules, plant remains and *Glossopteris* imprints, which are interbedded with medium- to fine-grained grayish sandstones. Coal beds have a thickness of 0.5 m–4 m. Towards the top, the sequences are dominated by

medium- to fine-grained greyish to greenish sandstones, greenish mudrocks and heterolites interbedded with thin tuffs and coal beds (Fig. 3).

The sedimentary succession outcropping in Gonzales Chaves locality (Fig. 1A) is characterized by small outcrops (<2 m in thickness) composed of fine-grained brownish mottled sandstones interbedded with laminated mudrocks (Fig. 4). Towards the top, the succession is dominated by medium- to fine-grained greenish sandstones with planar lamination, interbedded with fine- to very fine-grained sandstones with wave ripples cross lamination (Fig. 4). Upwards, the succession is overlain by Cenozoic carbonate deposits (Fig. 4).

Sandstones were classified as feldspathic litharenites (53%) and litharenites (47%) according to Folk *et al.* (1970) (Table 1; Fig. 5). The average modal composition is Q49 F13 L38, showing scarce variations along the analyzed sequence. Grain size varies from

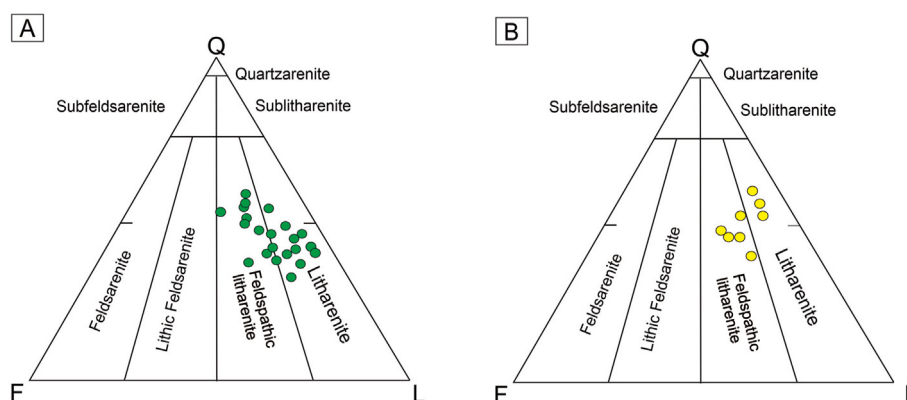


Fig. 5 Classification diagram according to Folk *et al.* (1970) for the Tunas Formation sandstones from A) Subsurface samples (PANG 0001 and PANG 0003 wells); B) Outcrop samples (Gonzales Chaves locality). Q: Quartz, F: Feldspar, L: Lithic fragments.

medium (1 mm) to very fine (0.062 mm), predominating medium to fine grain sizes. Sandstones are clast-supported, with sub-rounded to sub-angular grains, long to concavo-convex contacts and moderate-to-well sorting.

Quartz, feldspar and lithic fragments dominate sandstone framework components. Quartz occurs as monocrystalline or polycrystalline grains, constituting from 38% to 57.8% of the total main components (Tables 1 and 2). Monocrystalline quartz predominates, with an average of 43.25% (Table 2). Grains have sub-rounded to sub-angular shapes with straight and occasionally undulatory extinction (Fig. 6A and B). Polycrystalline quartz is scarce, with an average of 5.5% (Table 2). Grains show sub-angular shapes (Fig. 6C).

Feldspars include potassium feldspar and plagioclase, comprising from 7% to 21.5% of the total main components (Tables 1 and 2). Plagioclase predominates, with an average of 9.2% (Table 2). Grains usually exhibit polysynthetic twinning and sub-tabular shapes (Fig. 6D and E). Potassium feldspar is represented by orthoclase and microcline, with an average of 3.7% (Table 2). The orthoclase is usually untwined, with sub-tabular shapes (Fig. 6D). Microcline exhibits tartan twinning, with sub-tabular shapes (Fig. 6F). The plagioclase to total feldspar (Pl/Ft) ratio ranges from 0.85 to 0.60 with an average of 0.70.

Lithic fragments include metamorphic, sedimentary and volcanic rock fragments, constituting from 26% to 49.7% of the total main components (Tables 1 and 2), with an average of 35.8%. Metamorphic and sedimentary rock fragments are dominant at the basal and middle portion of the succession, while volcanic ones increase in content toward the uppermost part (Table 2). Metamorphic lithic fragments have a low to medium metamorphic grade, comprising shales,

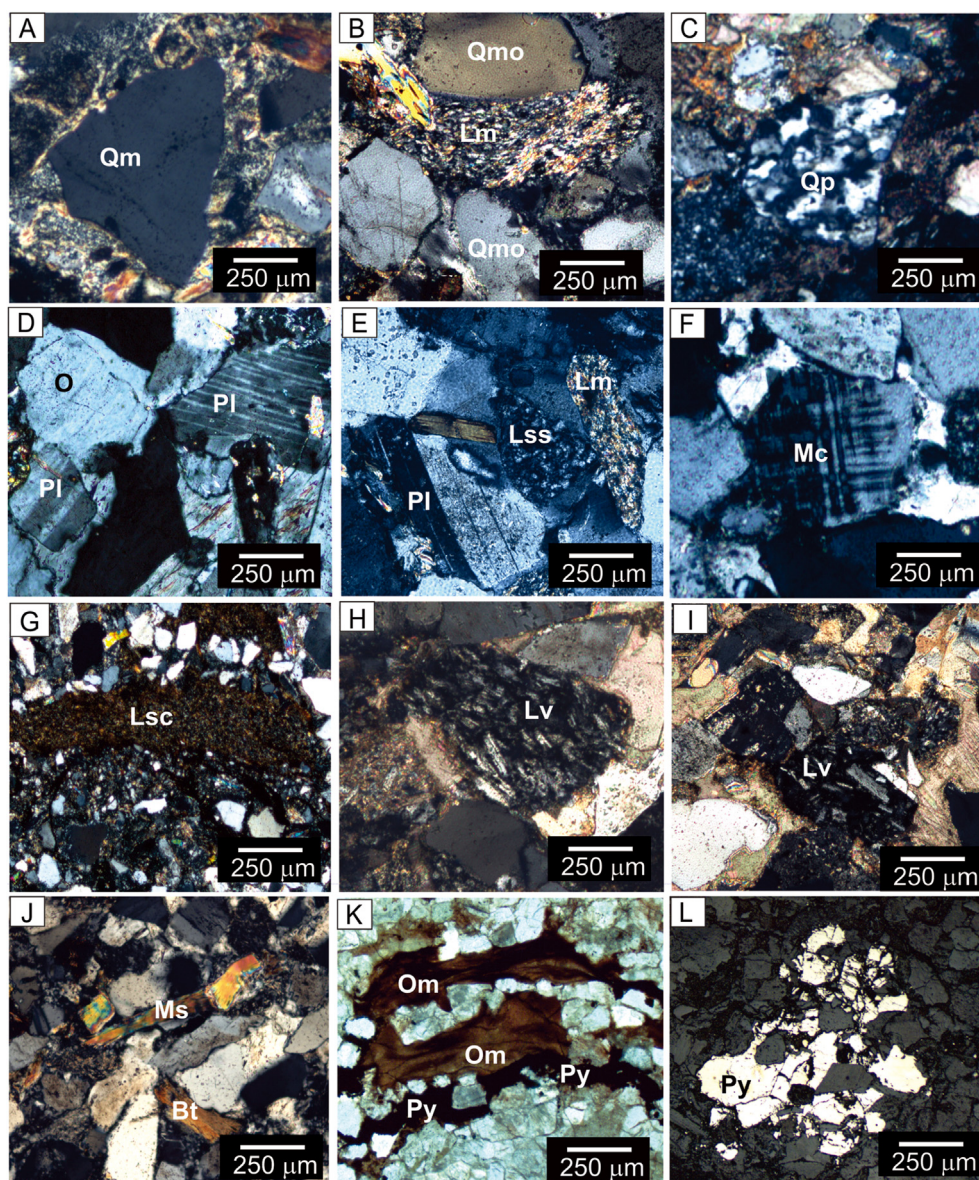
slates, schists and quartzites (Fig. 6B and E). Grains show sub-angular shapes. Sedimentary rock fragments include claystones, siltstones and very-fine sandstones, with sub-angular to sub-rounded shapes (Fig. 6E and G). Volcanic fragments present microlithic and vitrophyric textures (Fig. 6H and I) of sub-rounded shapes.

Accessory minerals comprising from 0.1% to 3% of the total main components, consist of micas (muscovite, biotite, and chlorite; Fig. 6J), sulfurs (commonly pyrite; Fig. 6K and L), epidote and undetermined opaque minerals. Samples also present dispersed organic matter (Fig. 6K).

Sandstones have low matrix content (<5%), composed of quartz, lithic rock fragments and clay minerals. The presence of pseudomatrix is common, formed by unstable detrital grains. Cement constitutes 5%–15% of the total rock volume, composed of carbonate, zeolite (laumontite), quartz and feldspar. Authigenic minerals, such as calcite, zeolite, and clay minerals, often replaced framework grains, especially feldspar and lithic fragments. It should be noted that diagenetic processes affected the unstable components of the framework (especially feldspar and lithic fragments), making it difficult to differentiate them.

## 5.2. Provenance analysis

Sandstone modal composition of the Tunas Formation from the subsurface (PANG 0001 and PANG 0003 wells) and outcrops was plotted on the QFL and QmFLt ternary diagrams of Dickinson *et al.* (1983) and on the QmPLIK complementary diagram of Dickinson and Suczek (1979) (Table 2; Fig. 7) to determine tectonic provenance. In the QFL diagram, samples from subsurface and outcrops are located in the recycled orogen field (Fig. 7A). In the QmFLt diagram, samples



**Fig. 6** Thin-section photomicrographs of modal components for Tunas Formation sandstones. **A**) Monocrystalline quartz with straight extinction (Qm); **B**) Monocrystalline quartz with undulatory extinction (Qmo) and metamorphic lithic fragment (Lm); **C**) Polycrystalline quartz (Qp); **D**) Orthoclase (O) and plagioclase (Pl); **E**) Plagioclase (Pl), sandstone lithic fragment (Lss) and metamorphic lithic fragment (Lm); **F**) Microcline (Mc) with tartan twinning; **G**) Mudrock lithic fragment (Lsc); **H**) Volcanic lithic fragment (Lv) with microlitic texture; **I**) Volcanic lithic fragment (Lv) with vitrophyric texture; **J**) Muscovite (Ms) and biotite (Bt); **K**) Organic matter (Om) and associated pyrite (Py); **L**) Pyrite (Py). Photomicrographs are taken under transmitted light with crossed Nicols (A–K) and under reflected light (L).

from subsurface correspond to the basal and middle portion of the sequence lay in the transitional recycled field, while those from the top of the sequence fall in the mixed field (Fig. 7B). This difference is due to a slight increase in feldspar content towards the upper portion of the succession (see Table 2). Similarly, samples from outcrops are located in the transitional recycled to mixed fields (Fig. 7B).

In the QmPlK complementary diagram, most of samples fall in the upper part, which reveals a high

content of quartz and a minor proportion of plagioclase (Fig. 7C), representing a recycled orogen source (or provenance from continental blocks) according to Dickinson and Suczek (1979). However, samples from subsurface belonging to the top of the sequence are slightly enriched in plagioclase, probably associated with a volcanic source (Fig. 7C). The content of K-feldspar is low; only a few subsurface samples show a similar range of K-feldspar and plagioclase (Fig. 7C).

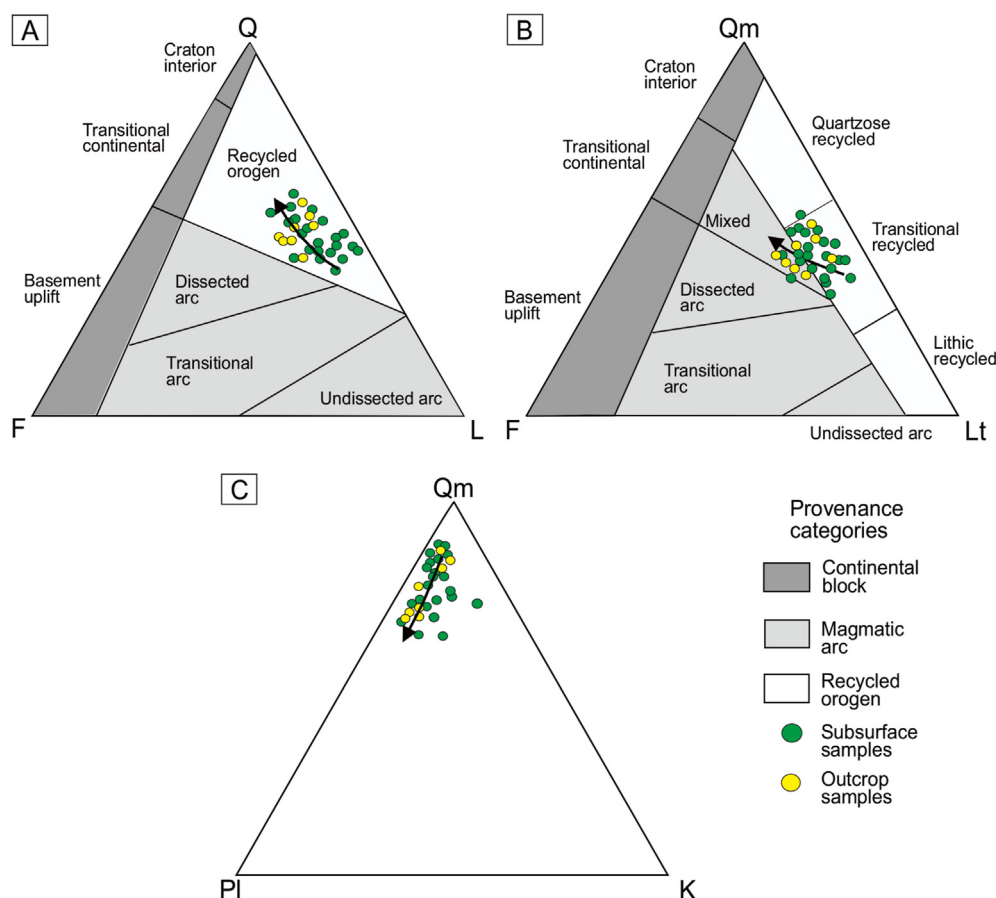


Fig. 7 QFL, QmFLt and QmPIK diagrams with provenance areas according to Dickinson *et al.* (1983) for Tunas Formation sandstones from subsurface (PANG 0001 and PANG 0003 wells, green circles) and outcrops (Gonzales Chaves locality, yellow circles). A) QFL discrimination diagram, B) QmFLt discrimination diagram with provenance areas according to Dickinson *et al.* (1983), and C) QmPIK discrimination diagram of Dickinson and Suczek (1979). Arrows show the evolution from the lower towards the upper part of the analyzed succession. Q: Total quartz grains; F: Feldspars (K + Pl); L: Total lithic fragments (Ls + Lv); Qm: Monocrystalline quartz; Pl: Plagioclase; K: Potassium feldspar.

## 6. Discussion

Sandstone modal composition from different basins is a function of diverse provenance areas governed by plate tectonics (Dickinson and Suczek, 1979). In addition, the composition of detrital constituents from sedimentary rocks is also influenced by paleoclimate, weathering, transport agents and mechanism, distance from source area, depositional environment, and diagenesis (Dickinson and Suczek, 1979; McBride, 1985; DeCelles and Hertel, 1989). In foreland basins, the sedimentary supply is linked to the adjacent orogenic belt evolution (Dickinson and Suczek, 1979; Dickinson *et al.*, 1983; DeCelles, 1986; DeCelles and Hertel, 1989). In the case of the Sierras Australes fold and thrust belt and the adjacent Claromecó Basin, the tectonic evolution is complex and recorded multiple compressional (Arzadún *et al.*, 2021) and extensional events throughout the Paleozoic–Mesozoic

(Lovecchio *et al.*, 2018, 2020; Arzadún *et al.*, 2020). Provenance studies of the synorogenic deposits of the Tunas Formation constitute a key piece to understand the paleotectonic context during the last filling stage of the Claromecó Foreland Basin and to reconstruct the uplift history of the Sierras Australes fold and thrust belt.

### 6.1. Provenance areas for the Tunas Formation

The results obtained from petrography analyses of Tunas Formation sandstones reveal a high proportion of metamorphic and volcanic components, which suggest mixed provenance areas. Monocrystalline quartz and lithic fragments (mainly metamorphic and volcanic) dominate the main proportion of the framework clasts, while feldspar content is subordinate (Table 2). The presence of sub-angular to sub-rounded clasts, products of low to moderate sediment transport, could

indicate source areas located close to the basin. Monocrystalline quartz with undulatory extinction, polycrystalline quartz grains and metamorphic and sedimentary lithics could be derived from the weathering of metamorphic and/or sedimentary rocks, related to the fold-thrust belt erosion. Detrital feldspar grains could be supplied by metamorphic and volcanic rocks (Datta, 2005). The relatively high values of the plagioclase to total feldspar ratio ( $>0.60$ ) indicate a mixture of volcanic and metamorphic sources (Dickinson, 1970). Volcanic lithic fragments of acid and intermediate composition, with characteristic features of neo-volcanic fragments (Critelli and Ingersoll, 1995) and tuff layers interbedded with the siliciclastic sequence (Fig. 3), indicate volcanic explosive events coetaneous with sedimentation. Moreover, zeolites, occurred as cement or detrital grains, could be related to alteration and replacement of volcanic materials (De Ros *et al.*, 1997; Morad *et al.*, 2010).

Tectonic provenance analysis for the Tunas Formation sandstones defines a sedimentary material supplied from a mixed provenance source, contributed by the recycled orogen and magmatic arc (Fig. 7). These results, in addition to paleocurrent dataset, coming from the southwest (Andreis and Japas, 1991; López-Gamundí *et al.*, 1995), suggest a sedimentary material contribution potentially linked to the Sierras Australes fold and thrust belt, located to the W/SW, adjacent to the Claromecó Basin (Fig. 1). Polycrystalline quartz grains and abundant metamorphic lithics in sandstone constituents (Andreis and Cladera, 1992; López-Gamundí *et al.*, 1995; this study), propose an adjacent uplifted orogenic belt (Sierras Australes), which supplied material to the basin from the recycled orogen. Metamorphic and sedimentary components could be derived from quartzites of the Mascota, Trocadero, Napostá or Providencia formations (Curamalal and Ventana Groups; Fig. 1B) and slates and schists corresponding to the Lotén Formation (Ventana Group; Fig. 1B).

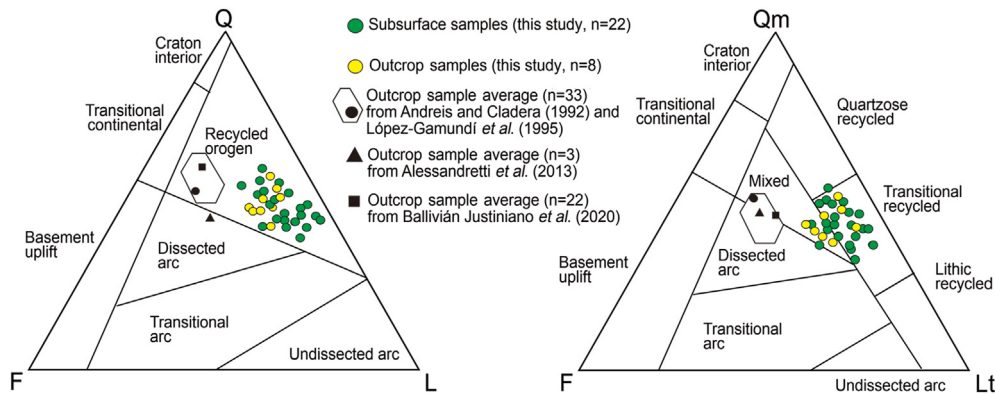
The sedimentation was coeval with volcanic activity, recorded by the intercalation of pyroclastic material (tuff beds) and sandstones with significant amounts of volcanic lithics. The increase in volcanic components upwards in the sequence suggests that volcanic material contribution was relevant towards the final stages of the Tunas Formation deposition (Table 2). Tuff layers are present in Tunas Formation outcrops (Figs. 1B and 2A; e.g., Ruta 76: Arzadún *et al.*, 2018; Abra del Despeñadero: Iñiguez *et al.*, 1988; López-Gamundí *et al.*, 1995, 2013; Alessandretti *et al.*, 2013; and Las Mostazas: Ballivián Justiniano *et al.*, 2020) and in the subsurface (PANG 0001 and 0003 wells, Fig. 3; Arzadún *et al.*, 2018,

2020). These pyroclastic levels with an Artinskian age (average of  $285.5 \pm 2.4$  Ma; Ballivián Justiniano *et al.*, 2020 and references therein) confirm the existence of an active Early Permian pyroclastic activity along southwestern Gondwana margin. Volcanic events have been interpreted as the earliest episodes of the Choiyoi volcanism in western Argentina (Rocha-Campos *et al.*, 2011; Alessandretti *et al.*, 2013; López-Gamundí *et al.*, 2013; Sato *et al.*, 2015) and have been reported in other Permian Gondwana basins as the Paraná (Brazil) and Karoo (South Africa) basins (Bangert *et al.*, 1999; Stolhofen *et al.*, 2000; Guerra-Sommer *et al.*, 2005; Rocha-Campos *et al.*, 2006, 2008). Based on magmatic detrital zircon ages, Ramos and Naipauer (2014) interpreted the volcanic material as derived from a Lower Paleozoic magmatic arc, located to the south, in the North Patagonian Massif. Other authors (e.g., Sato *et al.*, 2015; Ballivián Justiniano *et al.*, 2020) argued that the pyroclastic material could have been supplied from the Chilean Precordillera, Frontal Cordillera and Las Matras and Chadileuvú blocks, related to the Choiyoi magmatic province, located to the W–SW–S.

The results of this work are slightly different from those obtained by other authors for the Tunas Formation outcrops of the Sierras Australes fold and thrust belt area (Fig. 8). In the QmFLT diagram, subsurface and outcrop samples (Claromecó Foreland Basin area, this study) are distributed into transitional recycled to mixed fields, while outcrop samples (Sierra Australes area; Andreis and Cladera, 1992; López-Gamundí *et al.*, 1995; Alessandretti *et al.*, 2013; Ballivián Justiniano *et al.*, 2020) show more feldspar-rich, falling into the mixed to dissected arc fields (Fig. 8). These differences are mainly due to feldspar content. Variations in sandstone composition could be attributed to different transport distances from the provenance area (Sierras Australes) to the basin center (PANG 0001 and 0003 wells and Gonzales Chaves locality), during which feldspars could be eroded by mechanical transportation. Furthermore, diagenetic processes, such as alteration, dissolution, and replacement, affected unstable framework components like feldspar and lithic fragments, and could influence detrital mode determinations.

## 6.2. Paleotectonic implications

Differences in provenance areas between the lower (Sauce Grande, Piedra Azul and Bonete formations; Fig. 2) and the uppermost (Tunas Formation; Fig. 2) units of the Pillahuincó Group were the consequence of variations in basin configuration during the Late Carboniferous–Early Permian. Quartz-rich petrofacies



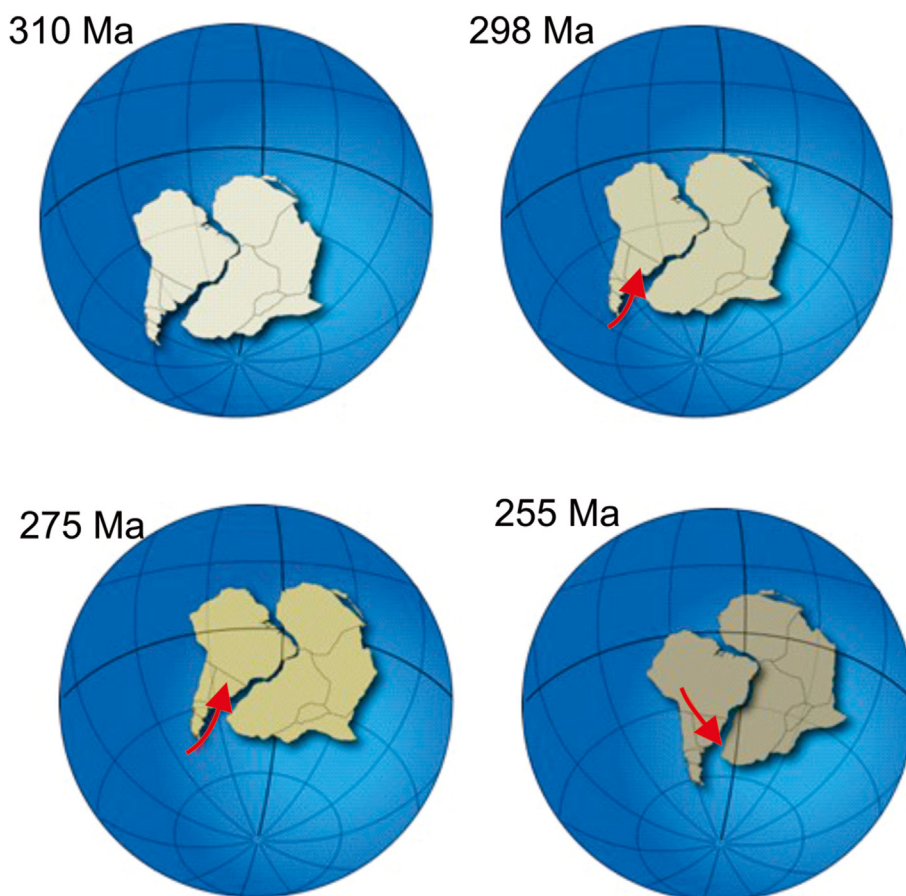
**Fig. 8** QFL and QmFLt diagrams with provenance areas according to Dickinson *et al.* (1983) for Tunas Formation sandstones from Claromecó Basin area (this study; green and yellow circles) and from outcrops (black circles, triangles and squares) in the Sierras Australes fold and thrust belt obtained by Andreis and Cladera (1992), López-Gamundí *et al.* (1995), Alessandretti *et al.* (2013) and Ballivián Justiniano *et al.* (2020). Results from the Claromecó Basin area are distributed into recycled orogen and transitional recycled/mixed fields, while data from the Sierras Australes fold and thrust belt fall in the recycled orogen and mixed to dissected arc fields.

and bimodal paleocurrents, from ENE–WSW, suggest a cratonic source area for Sauce Grande, Piedra Azul and Bonete formations (Fig. 2B; Andreis and Cladera, 1992). Sediment supply may be attributed to quartzites from the Ventana Group (e.g., Naposta and Providencia Formations), exposed along the western portion of the Sierras Australes fold and thrust belt (Fig. 1). Oppositely, lithic-rich petrofacies and inversion in paleocurrent direction from SW denote mixed source for the Tunas Formation (Figs. 7 and 8). These changes in the paleotectonic setting were the result of a compressive post-collisional deformation occurred along the southwestern Gondwana margin, the product of the adjustment and accommodation of previously collided terrains, and the translation of landmasses towards the equator to form Pangea during the Late Permian–Triassic (Fig. 9; Tomezzoli, 2001, 2012).

Changes in paleotectonic and paleogeographic settings are also evidenced by paleoenvironmental and paleoclimatic conditions during the deposition of the Pillahuincó Group. As a consequence, there is a clear transition from the shallow marine conditions during the depositional period of the Piedra Azul and Bonete formations (Harrington, 1970; Andreis *et al.*, 1989) to deltaic and fluvial conditions represented by the Tunas Formation deposits (Andreis *et al.*, 1989; Zavala *et al.*, 1993, 2019; López-Gamundí *et al.*, 1995; Andreis and Japas, 1996). A continentalization of the basin occurred as a result of the deformation and uplift of the Sierras Australes fold and thrust belt, with development of continental to mixed environments. Towards the foreland basin area, the presence of floodplains and interdistributary swamps (Arzadún

*et al.*, 2016a, 2017; Zavala *et al.*, 2019) promoted the accumulation and preservation of organic matter in coal-bearing deposits (PANG 0001 and PANG 0003 wells; Fig. 3). The development of carbonaceous deposits reveals an improvement in climate conditions during the Late Paleozoic, characterized by cold and humid weather (Limarino *et al.*, 2014; Arzadún *et al.*, 2017; Gallo *et al.*, 2020), resulting from the Gondwana supercontinent drift across the South Pole towards high paleolatitudes (Tomezzoli *et al.*, 2018; Gallo *et al.*, 2020, Fig. 9).

The deformation and uplift of the Sierras Australes fold and thrust belt were linked to different tectonic events. For some authors, the Early Paleozoic Gondwanides Orogeny (Permian–Triassic; Keidel, 1916; Du Toit, 1927; Milani and De Wit, 2008), known as San Rafaelic orogenic phase in Argentina (SROPh; Azcuy and Caminos, 1987) and Hercinian phase in the rest of Gondwana, was responsible for the construction and configuration of fold and thrust belts in South America (Sierras Australes; Ramos, 1984, 2008; Pángaro and Ramos, 2012) and South Africa (Cape Fold System; De Wit *et al.*, 1988; Catuneanu *et al.*, 1998). These compression events were not exclusive to the southwest Gondwana margin, by contrary, they were recorded along all the southern margin of Gondwana during the Permian (e.g., Catuneanu *et al.*, 1998). For other authors, the tectonic deformation began in the Late Devonian–Early Carboniferous (Chañica orogenic phase in Argentina, ChOPh; Azcuy and Caminos, 1987) as a consequence of terrane collision against Gondwana from the west and the south (Chilena terrane and Patagonia terrane respectively, i.e., CHI–PA; Tomezzoli *et al.*, 2019), and continued until the



**Fig. 9** Paleogeographic reconstruction of the Gondwana supercontinent during the Late Paleozoic showing latitudinal movements of continents toward the equator during the Permian (red arrows), based on paleomagnetic poles of [Tomezzoli \(2009\)](#) and [Gallo \*et al.\* \(2017\)](#). Modified from [Arzadún \*et al.\* \(2017\)](#).

Permian ([Tomezzoli, 2001, 2012](#)). This Permian deformation was recorded in the Tunas Formation by the occurrence of synorogenic deposits ([López-Gamundí \*et al.\*, 1995, 2013](#)) and changes in provenance areas ([Andreis and Cladera 1992](#); [López-Gamundí \*et al.\*, 1995](#); [Alessandretti \*et al.\*, 2013](#); [Ramos and Naipauer, 2014](#); [Ballivián Justiniano \*et al.\*, 2020](#); this work). In addition, Permian deformation was also recorded by different types of paleomagnetization ([Tomezzoli and Vilas, 1999](#); [Tomezzoli, 2001](#)), anisotropy of magnetic susceptibility ([Arzadún \*et al.\*, 2017, 2021](#); [Febbo \*et al.\*, 2021](#)), and structural data ([Tomezzoli and Cristallini, 1998](#)). Recent anisotropy of magnetic susceptibility results ([Arzadún \*et al.\*, 2021](#)) obtained all along the Pillahuincó Group show that during the Late Paleozoic the tectonic deformation had a spasmodic behavior, with cycles of higher and lower intensity. The high deformation cycles correspond to the interval during the deposition of the Sauce Grande Formation, decreasing in intensity towards the deposition period of the Bonete Formation

(nearly 300–290 Ma; [Arzadún \*et al.\*, 2021](#)). The second peak of deformation occurred during the early stage of deposition of the Tunas Formation (290–276 Ma), with lower intensity than the previous interval ([Arzadún \*et al.\*, 2021](#)). This spasmodic deformation is also reflected in the sharp cusp of the apparent polar wander path of Gondwana during the Early Paleozoic ([Tomezzoli, 2009](#); [Gallo \*et al.\*, 2017, Fig. 9](#)). Further, the Permian deformation was again attenuated towards the foreland until the end of the Permian, during the last stage of deposition of the Tunas Formation ([Tomezzoli, 1999, 2001, 2012](#); [Arzadún \*et al.\*, 2016b, 2021](#); [Febbo \*et al.\*, 2021](#)).

## 7. Conclusions

The Tunas Formation represents the last depositional stage of the Claromecó Foreland Basin and constitutes a key piece to understand the evolution of the southwestern Gondwana margin, since it records

the paleogeographic and paleotectonic changes occurred during the Permian. Petrography and tectonic provenance studies were performed for the Tunas Formation sandstones, on subsurface (PANG 0001 and PANG 0003 wells) and outcrop samples (Gonzales Chavez locality) to determinate the paleotectonic scenario during its deposition.

Sandstones were classified as feldspathic litharenites and litharenites, with an average modal composition of Q49 F13 L38. Sandstone components are characterized by moderate to high content of quartz, high percentage of lithic fragments (predominantly metamorphic and volcanic rock fragments) and subordinate feldspars. Modal composition of sandstones from the Claromecó Basin area is distributed into the recycled orogen and transitional recycled to mixed fields. The provenance analysis result of this work is slightly different from those obtained by other authors (e.g., Andreis and Cladera 1992; López-Gamundí *et al.*, 1995; Alessandretti *et al.*, 2013; Ballivián Justiniano *et al.*, 2020) for outcrops in the Sierras Australes fold and thrust belt, which fall into the mixed to dissected arc fields. Differences could be attributed to different transport distances from the provenance area (Sierras Australes itself: Curamalal and Ventana groups) to the center of the basin, where feldspars could have been eroded by mechanical transportation.

Petrographic analyses, in addition to previous provenance and sedimentological studies, determine that sedimentary material was derived from a mixed source, which largely comes from the recycled orogen, with contributions of a volcanic source. This suggests that the Sierras Australes (located to the W–SW of the Claromecó Basin) was already uplifted as a fold and thrust belt, subjected to erosion and capable of supplying sedimentary material, particularly supplying metamorphic constituents, to the Claromecó Basin as a recycled orogeny. Sedimentation in the basin was coeval with volcanic activity, recorded by the intercalation of pyroclastic materials (tuff levels; Arzadún *et al.*, 2018) and sandstones with significant amounts of volcanic lithic grains interbedded in the siliciclastic sequence.

The synorogenic deposits of the Tunas Formation recorded a typical sedimentation of a foreland basin, developed along an active margin, characterized by the paleocurrent reversal and the dominance of fold belt/arc-derived material. The Tunas Formation shows clear differences in its modal composition, paleocurrent direction and paleoenvironmental condition with respect to the underlying units of the Pillahuincó Group. Source areas changed from

cratonic (Sauce Grande, Piedra Azul and Bonete formations) to mixed (Tunas Formation) fields, indicating the variations of the Claromecó Basin configuration during the Late Paleozoic. Changes on the paleotectonic scenario during the sedimentation period of Tunas Formation have been interpreted as the consequence of compressive post-collisional deformation, and, the product of adjustment, accommodation and translation of terranes and plates towards the equator during the Permian–Triassic, which forms the Pangea.

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## Availability of data and materials

The data that support the findings of this study are available on request from the corresponding author.

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## Authors' contributions

All the authors have actively participated in the preparation of the manuscript.

All authors read and approved the final proof.

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## Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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