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Miocene block uplift and basin formation in the Patagonian foreland: The Gastre Basin, Argentina

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A B S T R A C T

The intraplate fault-block mountains and intermontane deposits of the Gastre Basin, which are recorded more than 550 km east of the Andean trench in central Patagonia, Argentina, are analyzed. The Gastre Basin is one of the largest Patagonian intermontane basins, limited by uplifted blocks strongly oblique to the Andean chain. It was originated by reverse faulting and inversion of pre-existing normal faults associated with a Mesozoic rift basin and defined by older crustal heterogeneities. The deformational event occurred during the middle Miocene, related to a short contractional episode (16.1–14.86 Ma), probably in response to an eastward migration of the Andean fold and thrust belt. During Pliocene to Quaternary times, neither younger fault-block uplifts nor reconfigurations of the basin occurred. Similarities between the study area and other parts of the Patagonian foreland – such as the presence of Miocene reverse or inversion tectonics, as well as the accommodation of the Miocene sedimentary successions – suggest that the Gastre Basin is part of a major late early to middle Miocene broken foreland system (i.e. the Patagonian broken foreland) that exhumed discrete fault-block mountains and generated contemporary basins along more than 950 km parallel to the Andean trench (i.e. between 40°00′ and 48°00′ south latitude). Based on recent studies on the southern Andean Margin, this continental-scale contractional episode may be the result of a flat-slab subduction segment. Nevertheless, such a hypothesis is very difficult to support when analyzing such a large flat subduction segment along the entire Patagonian trench. This suggests the need to consider alternative flat-slab trigger mechanisms or other factors in the generation of broken foreland systems.

1. Introduction

Several segments of the Central and Southern Andes show evidence of deformation relatively far away from the orogenic front. As a result, a landscape constituted by fault-blocks mountains and intermontane basins was developed in the Andean foreland, several hundred kilometers away from the trench (Cobbold et al., 2007; Cogné et al., 2013; Hain et al., 2011; Jordan and Allmendinger, 1986; Mon and Gutiérrez, 2009; Strecker et al., 2011). Usually, these segments of foreland deformation have been associated with a flat-slab subduction regime (e.g. the Sierras Pampeanas [Pampean Ranges] with a Pampean flat-slab subduction segment; Ramos and Folguera, 2009) that reactivated and/or inverted the pre-existing structures (Franzese et al., 2011; García Morabito et al., 2011; Ramos et al., 2002; Sempere et al., 2008).

The North Patagonian foreland exhibits mountains up to 1800 m a.s.l. located more than 550 km east of the Andean trench, in the intraplate region of Patagonia. Several of these mountains define topographic lows filled with Neogene–Quaternary clastic and volcanic deposits (Fig. 1). One of these intraplate depressions, called the Gastre Basin (Bilmes, 2012; Coira et al., 1975; Dalla Salda and Franzese, 1987), has received special attention due to its large dimensions and obliquity with respect to the Andean chain. The northeast and southwest boundaries of this basin correspond to NW–SE-trending fault-blocks that follow regional NW-trending and NNE-trending lineaments (i.e. the Gastre and Comallo domains, respectively; Coira et al., 1975; Fig. 2). The kinematic significance of these structures during the Neogene is controversial, as they have been interpreted as the result of extensional tectonics (Volkheimer, 1965); strike-slip tectonics (Coira et al., 1975; Dalla Salda and Franzese, 1987; Rapela et al., 1991) and contractional tectonics (Dessanti, 1956; Figari et al., 1996; Giacosa and Heredia, 2004). All of these morphostructural features have led some authors to consider the Gastre Basin as a rift basin (Massaferro et al., 2006; Regairaz and Suivres, 1984; Volkheimer, 1965), a transtensional basin associated with intracontinental strike-slip faults (Coira et al., 1975; Dalla Salda and Franzese, 1987; Proserpio, 1978) or a contractional basin (Figari et al., 1996).

This paper examines the Neogene tectonic evolution of the North Patagonian area around the Gastre Basin in an attempt to fill a critical gap in the knowledge of the foreland deformation in Patagonia. Based on a multidisciplinary approach, which includes new structural, stratigraphic, geomorphological and geochronological data, together with

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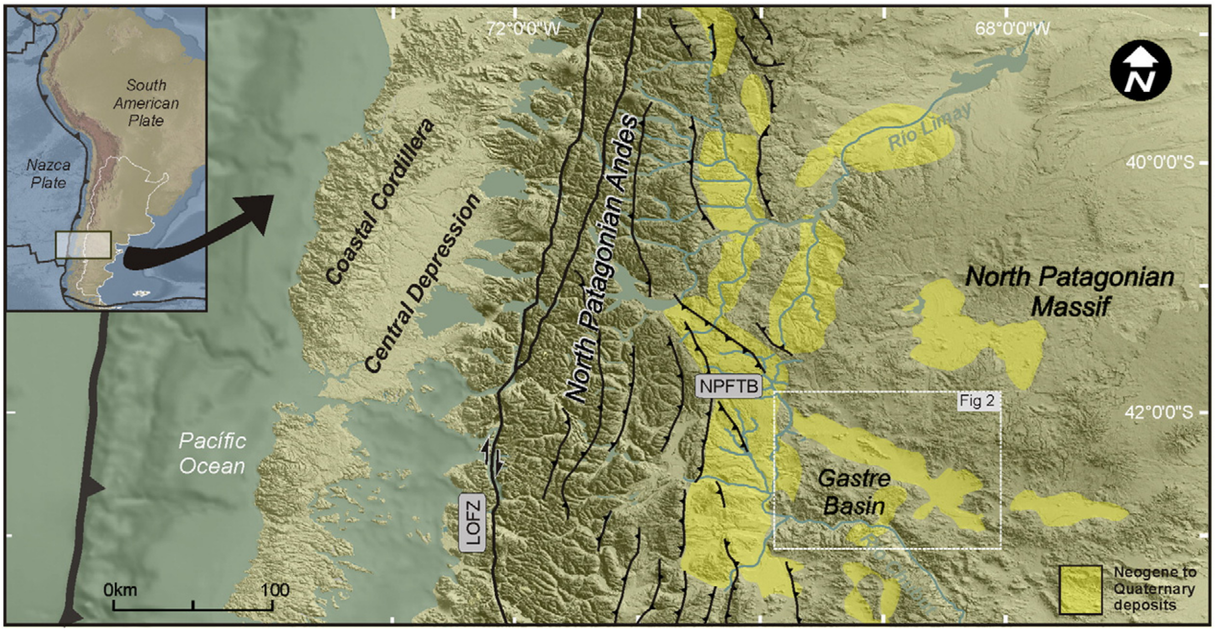

Fig. 1. Simplified map of the North Patagonian Andes and the adjacent foreland where the Gastre Basin is located, showing main structures and distribution of Neogene to Quaternary deposits (yellow areas). Modified after Cingolani et al. (2006), D'Elia, (2010), Giacosa and Heredia, (2004), Franzese et al. (2011), García Morabito et al. (2011), Orts et al. (2012), SEGEMAR, 1995, 1998. Location of Fig. 2 is highlighted with a white dashed line. Base hillshade map constructed from an SRTM30 PLUS dataset at 30 arc-second resolution. Global bathymetry data and SRTM elevation data at 3 arc-second resolution. LOFZ: Liquiñi-Ofqui Fault Zone; NPFTB: North Patagonian fold and thrust belt.

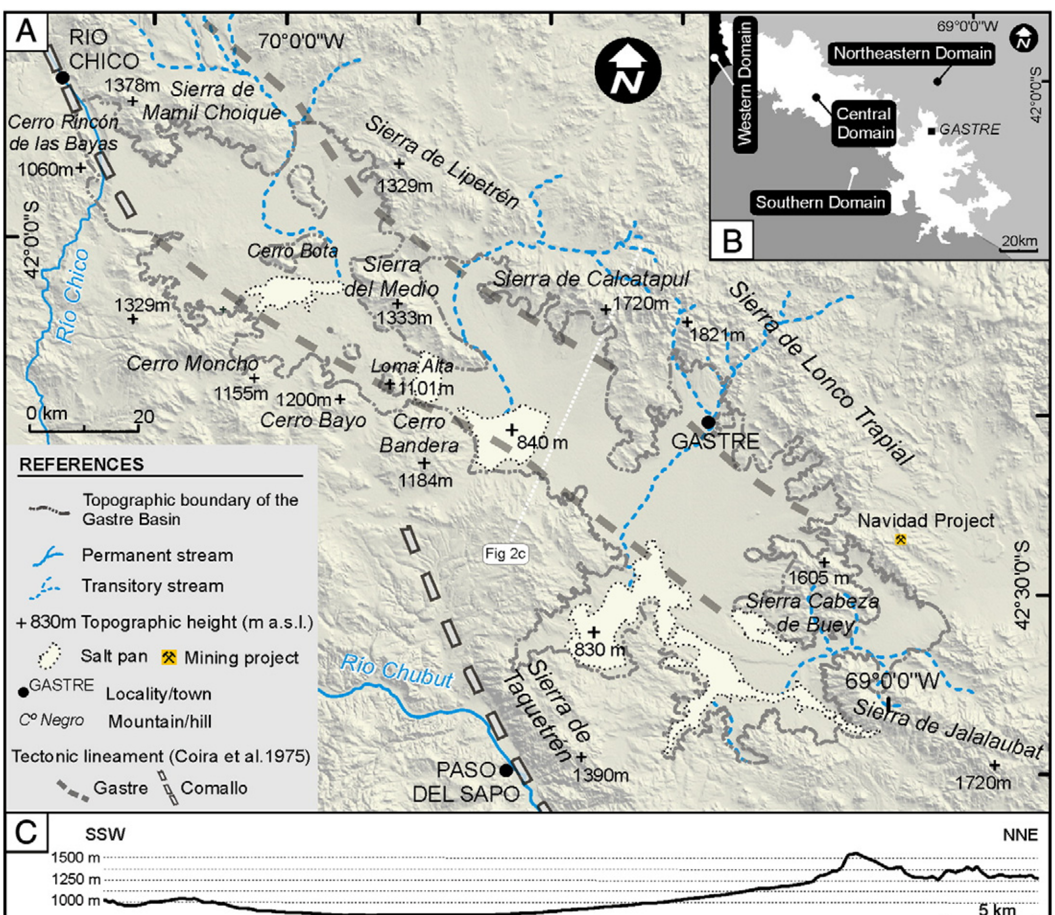

Fig. 2. (A) Hillshade map of the Gastre Basin showing tectonic lineaments (the Comallo and Gastre lineaments, sensu Coira et al., 1975), major rivers, topographic heights and geographical locations referred to in the text. Base hillshade map constructed from SRTM elevation data, 3 arc-second resolution (90 m). (B) Morphostructural domains established in the Gastre Basin. (C) Topographic profile across the Gastre Basin.

previous surface and subsurface regional surveys, the main goals of this study are (1) to analyze the structural framework of the basin and the nature of its infill, (2) to establish the timing of basin configuration, and (3) to correlate the results with the surrounding Patagonian foreland areas, in order to understand the processes of mountain building and basin generation in the intraplate Patagonian Andes.

2. Tectonic setting and stratigraphic framework

The Gastre Basin (Dalla Salda and Franzese, 1987) constitutes a 150 km long and 20 km wide trough, situated in the North Patagonian foreland between 41°50′ S and 42° 50′ S (Fig. 1), up to 550 km east of the Andean trench. To the west, it is bounded by the North Patagonian Andes and the North Patagonian fold and thrust belt (Fig. 1), formed during the last contractional phase that generated the present-day structural relief of the Andean chain at this latitude (Folguera et al., 2011; Giacosa and Heredia, 2004). Towards the east and northeast, it is limited by the North Patagonian Massif (Fig. 1), defined by uplifted blocks constituted by Paleozoic and Mesozoic rocks (Ramos, 1999). The Gastre Basin has a NW–SE elongated shape strongly oblique to the Andean chain. The endorheic central depression – at ~1000 m a.s.l. – is broken by internal basement highs (e.g. the Sierra del Medio, Cerro Bota and Loma Alta hills; Fig. 2) that separate different depressed areas in which a Quaternary basaltic lava field, together with alluvial and playa-lake environments developed.

The pre-Neogene stratigraphic record in the Gastre area, which is well-known since the pioneering work of Feruglio (1949), records a pre-Jurassic igneous–metamorphic basement, the Jurassic–Lower Cretaceous infill of an extensional or transtensional basin (the Cañadón Asfalto Basin; Figari and Courtade, 1993), an Upper Cretaceous–Paleocene shallow marine to continental succession, and Eocene volcanic complexes (Fig. 3). The pre-Jurassic basement is composed of granitoids and metamorphites of Carboniferous to Triassic age (Duhart et al., 2002; Pankhurst et al., 2006; von Gosen, 2009) grouped into several lithostratigraphic units. The Cushamen Formation (Volkheimer, 1964) and the Calcatapul Formation (Proserpio, 1978) are part of a metamorphic basement that was intruded by plutonic bodies of the El Platero Formation (Volkheimer, 1964), the Mamil Choique Formation (Ravazzoli and Sesana, 1977) and the Lipetrén Formation (Ravazzoli and Sesana, 1977). During the Early Jurassic, an extensional basin was formed: the Cañadón Asfalto Basin (Cortiñas, 1996; Figari and Courtade, 1993). Its Jurassic–Lower Cretaceous infill was accumulated in isolated depocentres, bounded by normal faults that were partially inverted during the Cretaceous (Allard et al., 2011; Folguera and Ramos, 2011). In the study area (Fig. 3), the infill of the Cañadón Asfalto Basin is constituted by the Leoneras Formation (Nakayama,

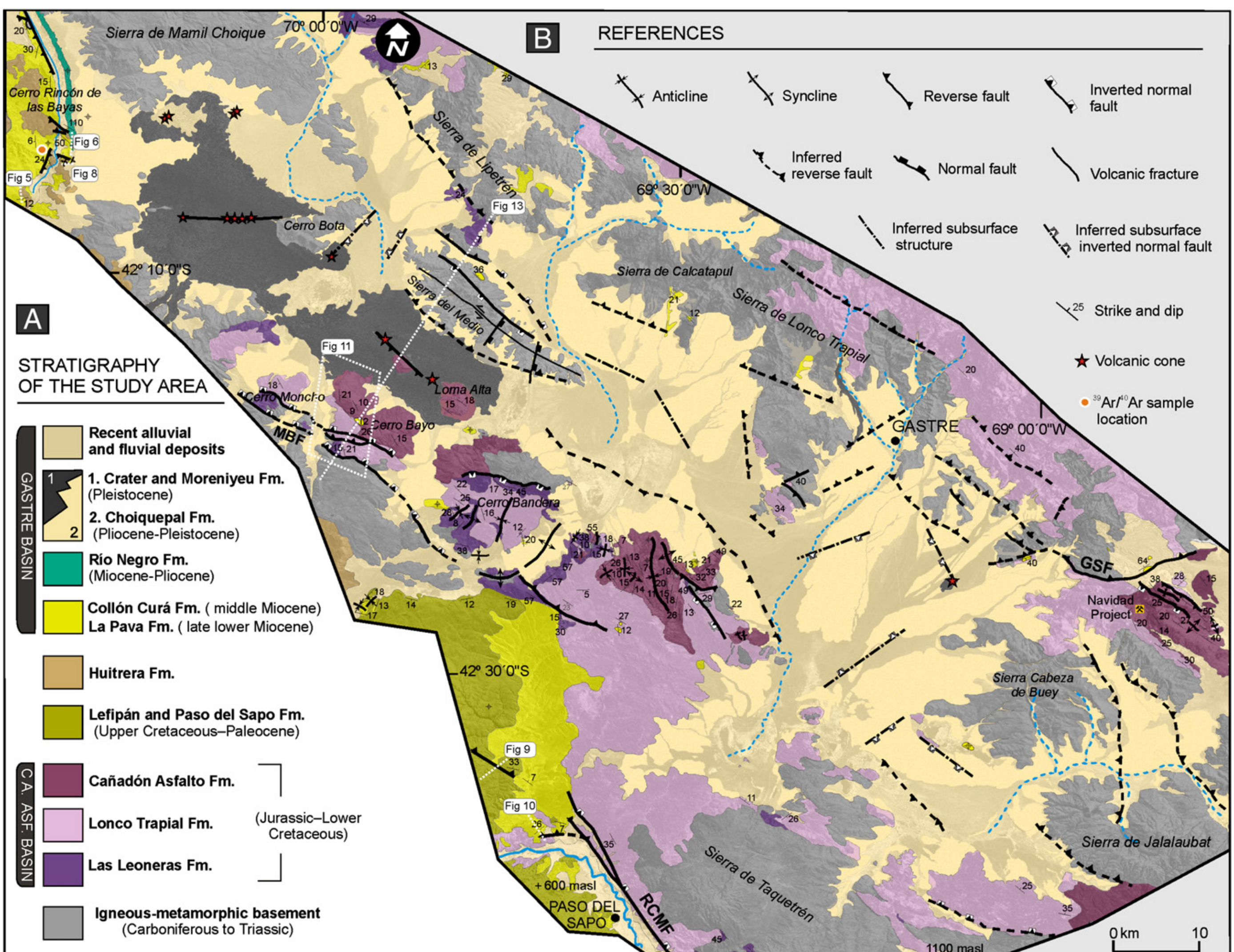

Fig. 3. (A) Schematic stratigraphic column of the study area. The colors of the units are the legend of Fig. 3B. (B) Geological map of the study area. Locations of the outcrop-scale photographs (Figs. 5, 6, 8, 9, and 10), cross section (Fig. 13), and 3D hybrid model near the Cerro Bayo (Fig. 11) are indicated by white dotted lines. MBF: Moncho-Bandera Fault; RCMF: Río Chubut Medio Fault; GSF: Gastre-Sacanana Fault.

1972), the Lonco Trapial Formation (Lesta and Ferello, 1972) and the Cañadón Asfalto Formation (Stipanicic et al., 1968). The Jurassic–Lower Cretaceous record was unconformably followed by Upper Cretaceous–Paleocene mixed marine to continental deposits described as the Paso del Sapo and Lefipán Formations (Lesta and Ferello, 1972), which represent the record of the Campanian–Danian transgression in the southeastern section of the study area (Spalletti, 1996). These units were covered by an Eocene volcanic succession (Cazau et al., 1989; Rapela et al., 1984) composed of andesites, dacites and rhyolites of the Huitrera Formation (Ravazzoli and Sesana, 1977). The Neogene to Quaternary record of the study area is constituted by continental deposits preserved within the Gastre depression and, to a lesser extent, on top of the boundary blocks (Fig. 3). These Neogene units are important for understanding the structural evolution of the basin, since they preserve evidence of the Andean tectonic events.

The Neogene sedimentation in the study area (Figs. 3, 4) started during the lower Miocene with the deposits of the La Pava Formation (Nullo, 1978). This is a thin unit (2 to 8 m thick), constituted by brownish tuffaceous sandstones. The La Pava Formation shows evidence of tectonic deformation, such as tilted or folded strata on the flanks of folds or in fault blocks (Figs. 5, 8). Based on geochronological data from the underlying and overlying units (Mazzoni and Benvenuto, 1990; Nullo, 1979), the age of the La Pava Formation was constraint between 21 and 16.1 Ma. The Collón Curá Formation (Yrigoyen, 1969) overlies the La Pava Formation conformably or unconformably (Figs. 5, 8). It has a variable thickness, from at least 80 m within the Gastre depression (Fig. 6) to less than 10 m over

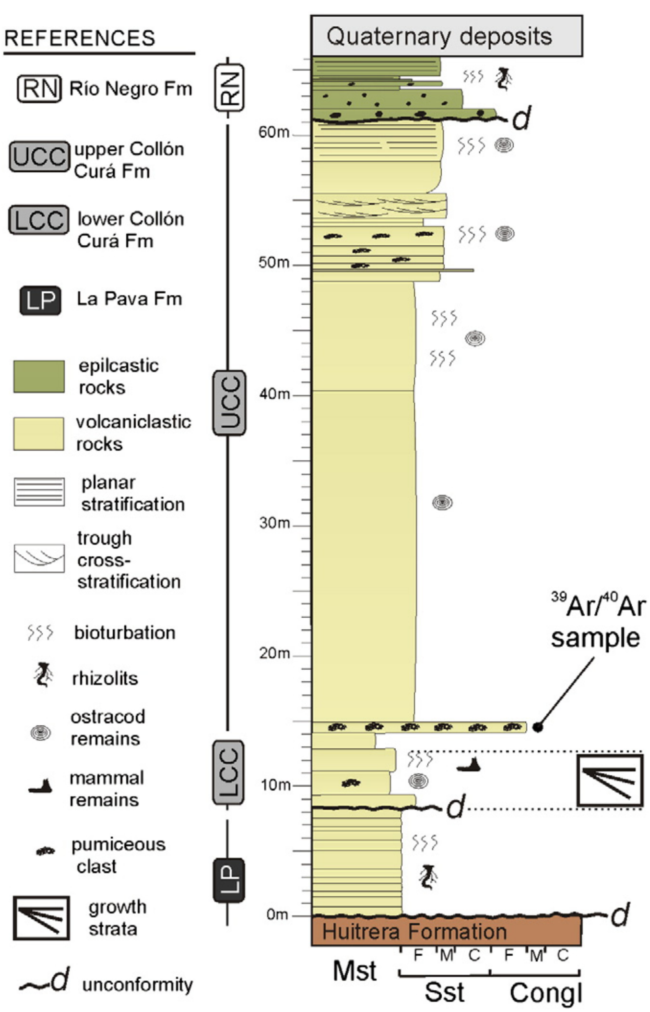

Fig. 4. Neogene Stratigraphy of the Gastre Basin.

the margins of the Gastre Basin (Fig. 5). The lower part of this unit (less than 5 m) shows evidence of tectonic deformation, such us growth-strata, whereas the upper part appears as horizontal beds with no evidence of tectonic deformation (Fig. 4). The Collón Curá Formation is composed of whitish, tuffaceous sandstones and tuffs with mammal and ostracod remains (Volkheimer and Lage, 1981). According to the mammal fossil content, it was constrained to the middle Miocene (Pascual et al., 1984; Pérez and Vucetich, 2011).

A new geochronological analysis was carried out during this study to establish an accurate age for the Collón Curá Formation and the deformation episode registered in the lower part of the unit (Fig. 4). $^{40}Ar/^{39}Ar$ analysis in amphibole crystals collected from fresh pumice clasts revealed an age of 14.86 ± 0.13 Ma (middle Miocene; Fig. 7). This new data is consistent with previous ages obtained for the Collón Curá Formation in neighboring areas that constrains this formation to the middle Miocene (Cazau et al., 1989; González Díaz and Nullo, 1980; Marshall et al., 1977; Mazzoni and Benvenuto, 1990; Nullo, 1979; Rabassa, 1978).

The Collón Curá Formation is uncomformably overlain in the western part of the Gastre depression by the Río Negro Formation (Figs. 4, 6), which is composed of epiclastic continental siltstones, sandstones and conglomerates (Dessanti, 1972; Volkheimer, 1973). Based on stratigraphic relationships, this formation was constrained to a Miocene–Pliocene age (González Díaz, 1990; Pascual et al., 1984). The Quaternary record of the Gastre depression is composed of a 10 to 150 m thick succession of clastic and chemical deposits of the Choiquepal Formation (Volkheimer, 1964), developed in piedmont and playa environments. This unit is interbedded with alkaline basaltic lavas (Fig. 3), grouped in the Moreniyeu and Cráter Formations (Proserpio, 1978; Ravazzoli and Sesana, 1977). The stratigraphic relationships between the sedimentary and volcanic units, as well as the isotopic ages of the basaltic lavas (1.9 to 0.23 Ma; Haller et al., 2009; Mena et al., 2006; Pécskay et al., 2007), constrain the Quaternary formations to the lower–Middle Pleistocene. Holocene and recent alluvial and fluvial deposits (Fig. 3) cover all of the previous units and represent the present-day infill of the Gastre Basin.

3. Structure of the Gastre depression

Based on new field observations, together with previous stratigraphic studies, vertical electrical sounding (VES) and regional surveys, four main morphostructural domains are defined to describe the structural configuration of the Gastre Basin and its bounding areas (Fig. 2B). A geographic information system (ArcGIS® 9.3) was used to manage and analyze spatial data, such as digital elevation models (NASA SRTM), ALOS AVNIR remote sensing images and derived spatial information. Available subsurface data from the Comisión Nacional de Energía Atómica (CNEA, 1990) and the Navidad silver mining project (SEDAR, 2010) were also used.

3.1. Western domain

The western domain is characterized by small mountain blocks (less than 10 km in length) composed by pre-Jurassic igneous–metamorphic and Oligocene volcanic rocks partially covered by Neogene and minor Quaternary deposits in the proximities of the Río Chico (Chico River; Figs. 2A, B). These mountain blocks, which show heights up to 1060 m a.s.l. (e.g. the Cerro Rincón de las Bayas hill; Fig. 3), are bounded by high-angle reverse faults of variable trends and vergences. The most remarkable structure of this domain is a NNW-trending fault located along the trace of the Río Chico (Fig. 3) that coincides with the Comallo regional lineament (Coira et al., 1975). It is a reverse fault of more than 10 km long, with NE vergence (Fig. 3) that exhumed pre-Neogene rocks. The Miocene record of this domain (La Pava and Collón Curá Formations) crops out mainly in the western margin of the river. The deposits of La Pava Formation

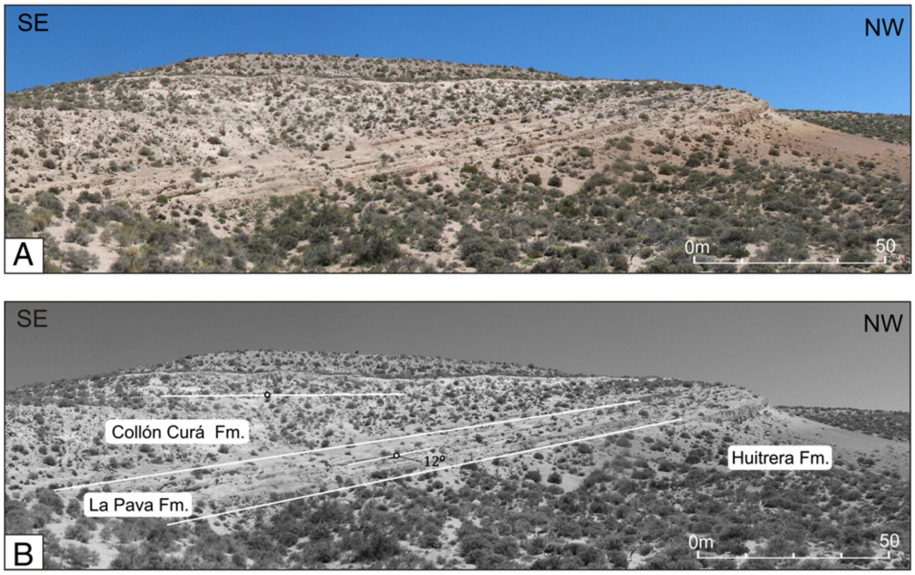

Fig. 5. (A) Outcrop-scale photograph at the west margin of the Río Chico. (B) Deformed strata of the La Pava Formation uncomfortably overlain by horizontal beds of the Collón Curá Formation. Locations (white circles) and values of measured bed dip data are shown. See Fig. 3B for location.

are folded as gentle anticlines and synclines with beds tilted 15° in average, showing fold axes up to 1 km long (Figs. 3, 8). Near the main faults, steeply tilted to overturned beds are also observed (Fig. 3). On the contrary, no evidence of tectonic deformation is registered in the Collón Curá Formation. It is important to note that close to the topographic heights, the middle Miocene Collón Curá Formation does not exceed 10 m in thickness (Figs. 5, 8) and pinches out towards the basement blocks, whereas in other areas of the basin, the stratigraphic record of this unit may be more than 80 m thick (Fig. 6). This suggests that a previous structural relief controlled its distribution and thickness towards the south and southwest. The upper Miocene to Quaternary deposits that cover the Collón Curá Formation are well exposed in the eastern margin of the Río Chico River and crop out in a topographic depression caused by the same structural relief (Fig. 6). This indicates that this relief remains until the present, providing accommodation for the Holocene deposits.

3.2. Northeastern domain

The northeastern border of the Gastre Basin (Fig. 2B) is characterized by the presence of pre-Jurassic igneous–metamorphic rocks and Jurassic deposits of the Cañadón Asfalto Basin (Fig. 3). This region shows a relatively high mean height (1226 m a.s.l.), including some of the highest peaks in the Central Patagonian foreland (up to 1820 m a.s.l.; Sierra de Lonco Trapial; Fig. 2). Thin localized outcrops of the La Pava and Collón Curá Formations are also present in this area (Fig. 3).

The blocks that define the northern limit of the Gastre Basin are bounded by NW–SE-trending reverse faults, partially interrupted by oblique accommodation zones (Fig. 3B). The Gastre-Sacanana Fault is the most conspicuous element in this sector (Fig. 3B). It is a subvertical reverse fault more than 35 km long, with an ENE strike in the eastern sector that shifts to a SE strike towards the northwestern margin of the basin (Fig. 3B). This structure thrusts the pre-Jurassic igneous

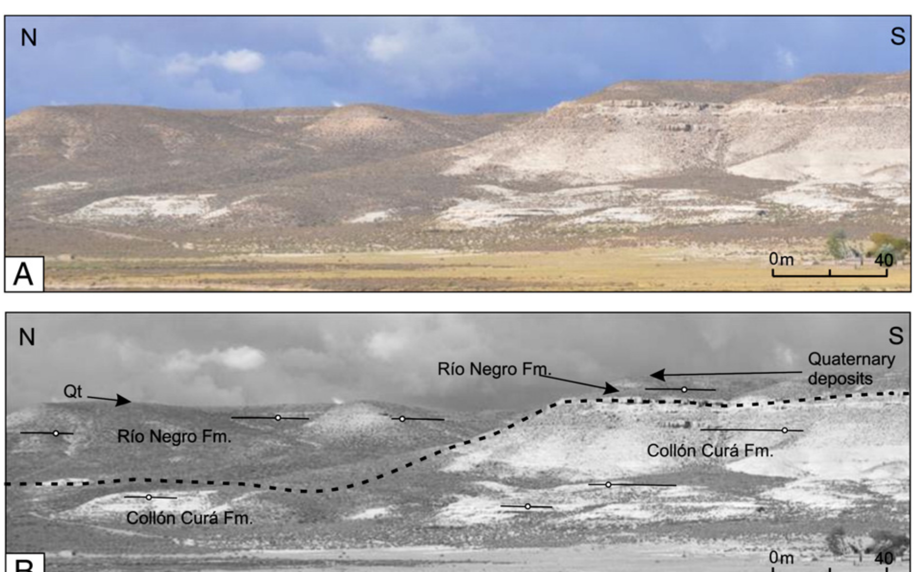

Fig. 6. (A) Outcrop-scale photograph at the eastern margin of the Río Chico. (B) Erosive unconformity (black dashed line) between the Collón Curá and the Río Negro Formations. White circles represent horizontal strata locations in the Collón Curá Formation, the Río Negro Formation and Quaternary deposits. See Fig. 3B for location.

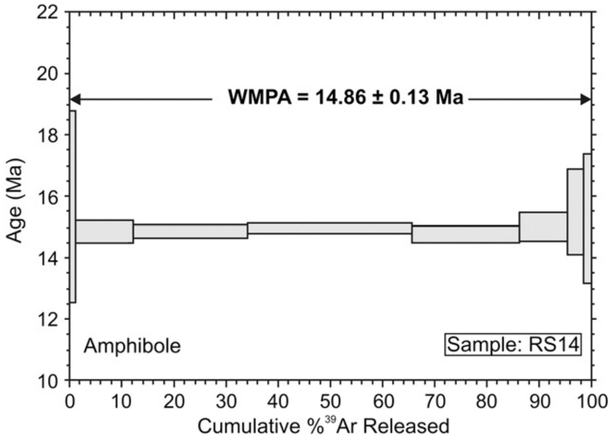

Fig. 7. $^{40}Ar/^{39}Ar$ age spectra of sample RS 14 calculated by weighted mean plateau age (WMPA) for amphibole crystals, handpicked from fresh pumiceous clasts of non-deformed strata of the Collón Curá Formation. Data sample location at 41°56′54.18″ S, 70°23′20.41″ W, at 906 m a.s.l. See Fig. 3B for location.

rocks over the Middle Jurassic deposits of the Lonco Trapial Formation, also tilting the thin deposits of the La Pava Formation up to 65° to the northeast (Fig. 3B). Based on subsurface surveys of the Navidad silver mining project (SEDAR, 2010; Figs. 2A, 3B), the vertical displacement of this fault is over 300 m. To the northwest, NW–SE- and SW–NE-trending fractures define the mountain fronts (Coira et al., 1975; Rapela et al., 1992; von Gosen and Loske, 2004). Despite the predominance of igneous–metamorphic rocks without any tectonic marker, the asymmetric topographic profiles of the mountain blocks (e.g. the Sierra de Calcatapul and Sierra de Lipetrén hills; Fig. 2A, C), associated with the steeply tilted beds of Mesozoic and Neogene deposits, suggest the presence of reverse faults with predominantly SW to WSW vergence (Fig. 3). It is important to note that the eastern limit of the Gastre Basin is characterized by mountain blocks (e.g. the Sierra de Jalalaubat and Sierra de Cabeza de Buey hills) partially covered by horizontal beds of the middle Miocene Collón Curá Formation and Quaternary deposits (Fig. 3). A subvertical NW-trending fault, which is 10 km in length, was observed on the southwestern border of the Sierra de Jalalaubat (Figari et al., 1996), whereas the central and northeastern steep borders are related to NNW-trending antithetic reverse faults that extend towards the Sierra de Cabeza de Buey (Fig. 3).

3.3. Southern domain

This domain includes the mountain blocks that define the southern limit of the Gastre Basin (Fig. 2A, B). It is characterized by a lower mean height than the northeastern sector (960 m a.s.l.), with isolated peaks just below 1400 m (Fig. 2A). The stratigraphic units in this sector include the pre-Jurassic basement, the early deposits of the Cañadón Asfalto Basin and the Campanian–Danian deposits of the Paso del Sapo and Lefipán Formations (Fig. 3). Minor Neogene deposits (i.e. the La Pava and Collón Curá Formations) and Quaternary deposits are also recorded (Fig. 3). Two NW- to NNW-oriented fault systems characterize the southern border of the Gastre Basin: the Río Chubut Medio Fault and the Moncho-Bandera Fault (Fig. 3B). Both show evidence of tectonic inversion of the Mesozoic extensional faults of the Cañadón Asfalto Basin and superimposed contractional faults (Fig. 3B).

The NNW-striking Río Chubut Medio Fault is a high-angle fault related to the inversion of a Mesozoic active border of one of the grabens of the Cañadón Asfalto Basin (Figari et al., 1996). It is associated with an emergent anticline that uplifted the basement (up to 1390 m a.s.l.) and part of the early rift deposits of the Cañadón Asfalto megasequence. These Paleozoic and Mesozoic units are unconformably overlain by Campanian–Danian rocks of the Paso del Sapo and Lefipán Formations (Fig. 3). The frontal limb of the emergent anticline steepens towards the main fault, while the back limb shows a gentle inclination to the northeast, suggesting an asymmetric fold with vergence to the southwest. West of the Río Chubut Medio Fault, the base of the Paso del Sapo Formation is recorded at 600 m a.s.l., whereas to the east, it is recorded as high as 1100 m a.s.l. This topographic contrast of around 500 m indicates the magnitude of the maximum post-Danian displacement (Fig. 3). In the footwall of the Río Chubut Medio Fault, NW-trending synthetic reverse faults interpreted as footwall shortcuts and thin-skinned thrust faults (Fig. 9) are also registered. These faults affect pre-Neogene rocks (Fig. 9), the Neogene deposits of the La Pava Formation and the basal deposits of the Collón Curá Formation. The deposits of the La Pava Formation are tilted, whereas the basal part of the Collón Curá Formation shows growth-strata geometry (Fig. 10).

The NW-trending, steeply dipping Moncho-Bandera Fault is also an inverted structure related to the inversion of Mesozoic grabens of the Cañadón Asfalto basin. It separates a peneplain of pre-Jurassic basement to the southwest from a thick succession of largely inverted syn-rift deposits of the Cañadón Asfalto Basin to the northeast (Figs. 3, 11). Localized outcrops of the La Pava and Collón Curá Formations lie unconformably above the Cañadón Asfalto Basin units (i.e. the Lonco Trapial and Cañadón Asfalto Formations) near the Cerro Bayo and Cerro Bandera hills (Fig. 3B). The La Pava Formation is arranged as gently tilted strata, whereas the Collón Cura rocks appear as horizontal thin layers less than 5 m thick (Fig. 3B). Therefore, such data show that the Moncho-Bandera Fault is an inverted normal fault that was previously a depocentre boundary of the Cañadón Asfalto Basin. To the northeast of this major structure, antithetic and synthetic inverted normal faults also reveal graben (e.g. the Cerro Bandera hill) and

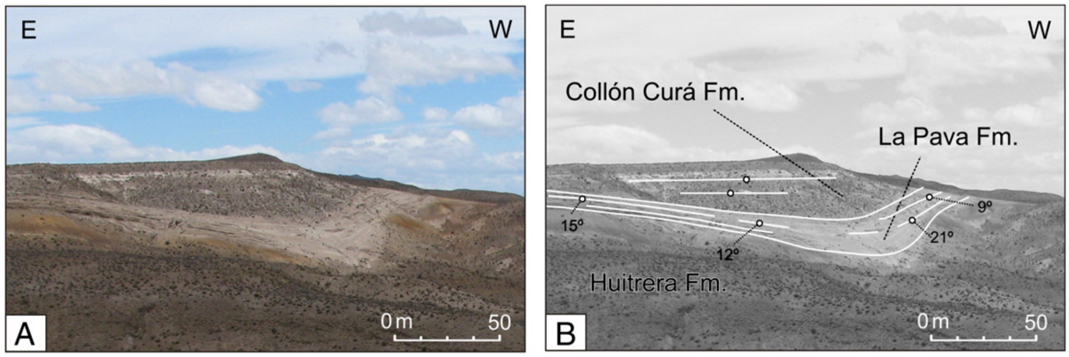

Fig. 8. (A) Outcrop-scale photograph at the eastern margin of the Río Chico. (B) Folded La Pava Formation, unconformably overlain by the Collón Curá Formation. Locations (white circles) and values of measured bed dip data are shown. See Fig. 3B for location.

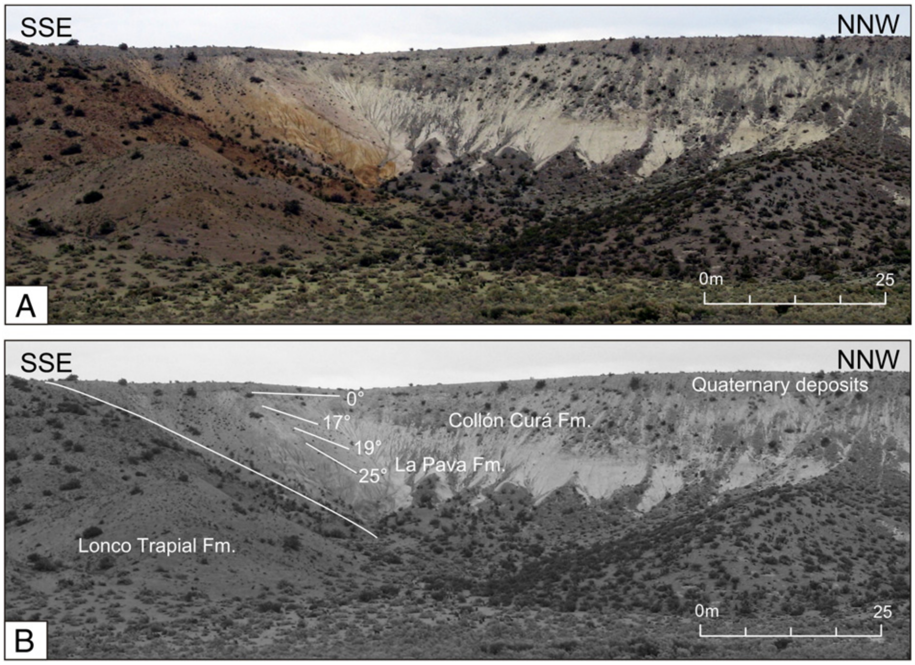

Fig. 9. (A) Outcrop-scale photograph of the Paso del Sapo Formation in the Southern Domain. (B) Thin-skinned thrust in the Paleocene deposits. White lines indicate trace and values of measured bed dip data. Black lines highlight fault domains. See Fig. 3B for location.

half-graben (e.g. the Cerro Moncho and Cerro Bayo hills) depocentres of the Cañadón Asfalto Basin in the study area (Fig. 3B, 11). Further southeast, the Moncho-Bandera Fault has no surface expression, but it generated a fold-and-fault interference pattern (Fig. 3B). NW–SE to NNE–SSW inverted normal faults, reverse faults and folds include pre-Neogene and lower Miocene deposits of the La Pava Formation that are unconformably overlain by horizontal beds of the middle Miocene Collón Curá Formation (Fig. 3).

3.4. Central domain

This domain corresponds to the present-day depocentre of the Gastre Basin (Fig. 2A, B), which has the lowest heights in the area, with base levels that range between 830 and 850 m a.s.l. The Quaternary cover is constituted by sedimentary and volcanic deposits (more than 80% of the basin surface) partially interrupted by internal highs that range from 1000 to 1333 m a.s.l. (e.g. the Sierra del Medio and Loma Alta hills; Fig. 3). These interior mountain blocks represent fault-blocks that uplifted the lower Miocene La Pava Formation (Fig. 3). One of these internal highs shows subvertical NW-striking faults (Fig. 3) with evidence of small strike-slip displacements (i.e. the Sierra del Medio hill; Llambías et al., 1986).

A Quaternary volcanic field (i.e. the Cráter and Moreniyeu Formations) occupies the central-western part of the basin around the interior fault-block mountains. Based on the vent shape and space distribution of the volcanic cones (Paulsen and Wilson, 2010), two

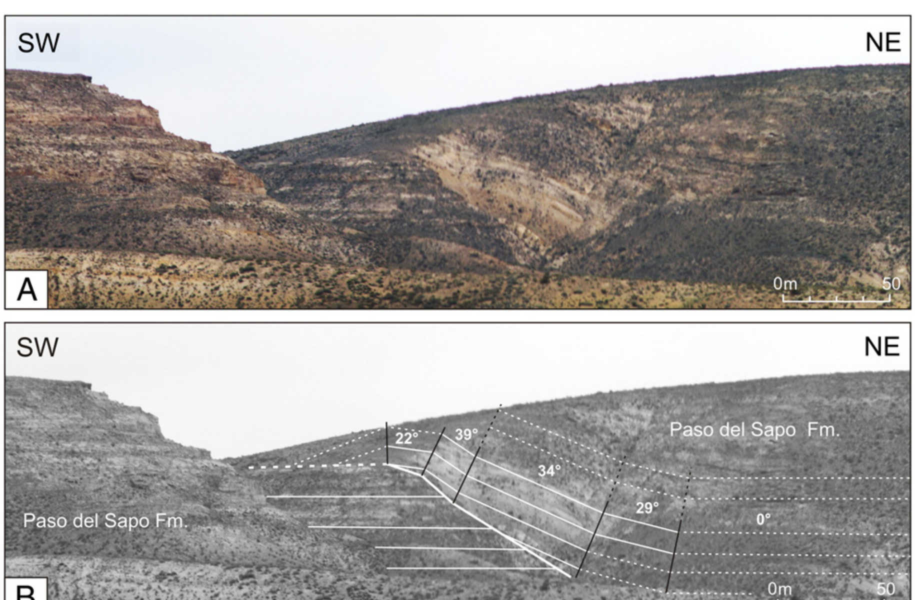

Fig. 10. (A) Outcrop-scale photograph at the north margin of the Río Chubut (Chubut River). (B) Growth-strata towards the base of the Collón Curá Formation. Locations (white circles) and values of measured bed dip data are shown. See Fig. 3B for location.

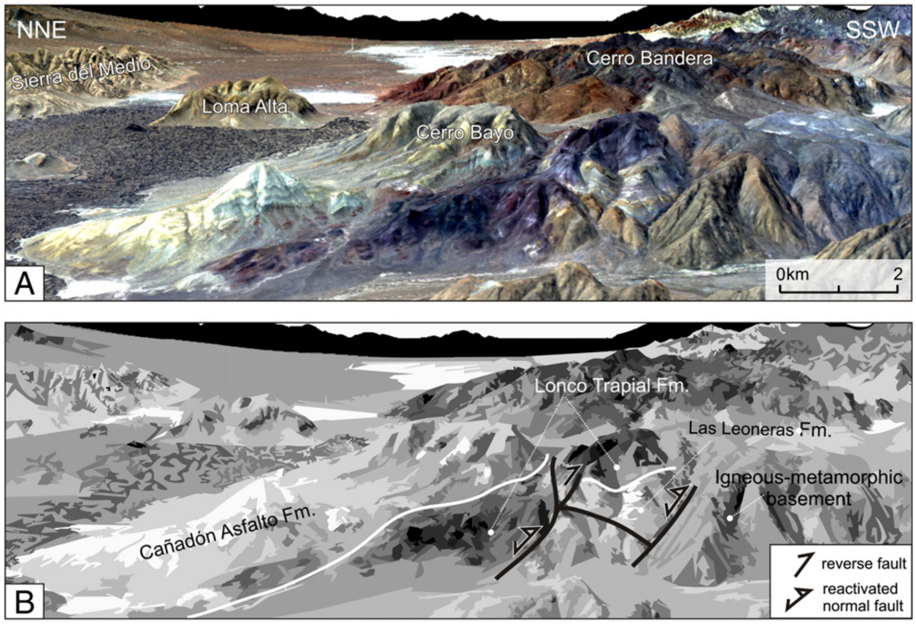

Fig. 11. (A) 3D hybrid model near the Cerro Bayo. (B) Inverted half-graben geometries of the Cañadón Asfalto Basin. 3D model constructed with a digital elevation model (SRTM at 3 arc-second resolution) with overlay ALOS AVNIR images. See Fig. 3B for location.

main monogenetic volcanic alignments may be established (Fig. 3). They indicate the existence of subsurface fractures that determined the orientation of the feeder dykes. This evidence was previously mentioned by other authors (Massaferro et al., 2006). No evidence of fault scarps or deformed Quaternary deposits is recorded around the vent alignments, which is indicative of little or no shear displacement.

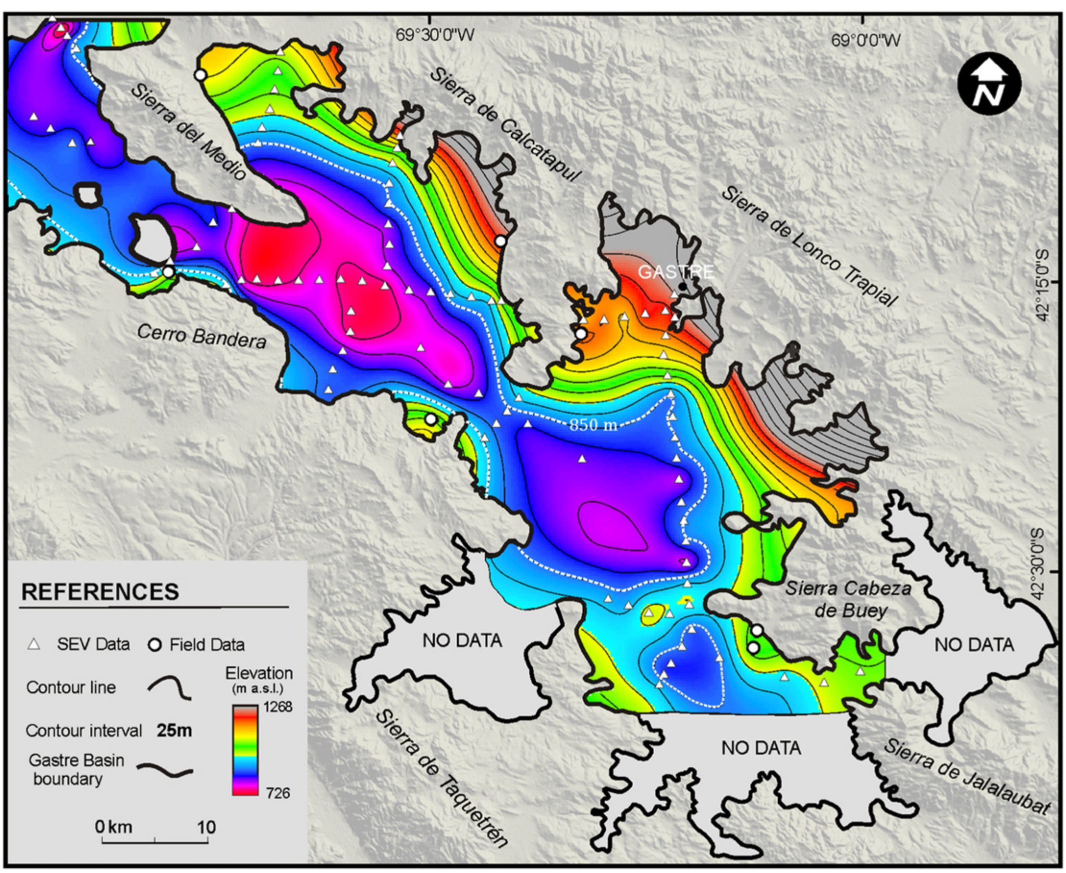

Fig. 12. Structural map of the top of the Collón Curá Formation constructed from direct and indirect data. Nine direct data obtained from water wells and layers exposed by fluvial incisions. Ninety-one indirect data obtained from pre-existing vertical electrical soundings (VES; CNEA, 1990). Sharp electrical resistivities registered in these VES are linked with differences in the lithological characteristics between the Neogene deposits (fine-grained volcaniclastic deposits with high conductive properties), and the overlying Río Negro Formation and Quaternary deposits (predominantly coarse-grained epiclastic deposits with high resistive properties).

At depth, below the Quaternary cover, the Collón Curá and La Pava Formations can be observed (Fig. 12). However, it is important to highlight that on the basis of subsurface studies the existence of pre-Neogene rocks has been inferred (i.e. the pre-Jurassic igneous–metamorphic basement and Jurassic–Lower Cretaceous infill of the Cañadón Asfalto Basin; CNEA, 1990; Figari and Courtade, 1993; Lince Klinger et al., 2011). A structural map of the top of the Collón Curá Formation (Fig. 12) shows the existence of sub-basins and internal highs within the Gastre Basin. These highs are bounded by steep slope borders (above the 850 m a.s.l. contour line), without surface expression, that coincide with the orientation of the structural configuration of the basin. Thus, these may be interpreted as subsurface faults (Fig. 12) which affect the pre-Neogene stratigraphy but not the distribution of the Quaternary deposits. This evidence together with the lack of tectonic evidence in the upper Collón Curá Formation (Fig. 4) indicates that younger deposits than the lower Collón Curá Formation were accommodated in a space previously developed. Surface and subsurface evidence made it possible to define the tectonic nature of many previously identified lineaments, including the main NW-trending Gastre Sur lineament (Coira et al., 1975; Dalla Salda and Franzese, 1987; Rapela and Pankhurst, 1992; von Gosen and Loske, 2004). This lineament is interpreted to represent a reverse fault with NE vergence (Fig. 3b). The topographic height range of the early Miocene La Pava Formation (at 1050 m a.s.l. above the fault-block mountains and at 900 m a.s.l. in the subsurface) defined a minimum post-early Miocene vertical displacement of 150 m.

4. Discussion

4.1. Uplift in the Central Patagonian Foreland: origin and evolution of the Gastre Basin

The Gastre Basin represents an endorheic basin oblique to the Andean chain, located more than 550 km east of the trench. It is surrounded by fault-block mountains constituted by a Paleozoic–Triassic crystalline basement, uplifted Jurassic–Cretaceous sedimentary and volcanic deposits, volcanic Oligocene rocks and volcaniclastic lower Miocene rocks. The infill of the Gastre Basin is composed by middle Miocene to Quaternary continental rocks: (1) volcaniclastic Collón Curá Formation, (2) the epiclastic Río Negro and Choiquepal Formations, and (3) the volcanic Cráter and Moreniyeu Formations. Below the Miocene record, the existence of a thick sequence of Jurassic continental sediments and volcanic rocks was interpreted by geophysical data (Lince Klinger et al., 2011), as previously mentioned by other authors (Figari et al., 1996).

The basin was generated during a middle Miocene contractional tectonic episode through reverse faulting and by the inversion of pre-existing normal faults. The new reverse faults are mainly high-angle faults that involve the crystalline basement, although minor thin-skinned thrusts are developed in the Upper Cretaceous and Paleogene successions (i.e. the Paso del Sapo Formation) with the development of fault-related folds (Fig. 9). The inversion of pre-existing normal faults associated with the extensional depocentres of the Cañadón Asfalto Basin generated basement-cored anticlines covered by the Jurassic stratigraphy and, in several cases, minor reverse faults as footwall shortcuts. No important strike-slip displacement was involved in the uplift of the mountain ranges that bound the Gastre depression. The structure and tectonic styles of the Gastre Basin indicate that it represents an intermontane basin.

The evidence presented in this contribution indicates that the lower part of the Collón Curá Formation was involved in the contractional deformation (Fig. 4). Tilted beds and growth-strata below horizontal beds of the same formation were observed near the main border reverse faults (Fig. 10). The geochronological $^{40}Ar/^{39}Ar$ age of 14.86 ± 0.13 Ma obtained (middle Miocene) from the non-deformed strata of the upper part of the Collón Curá Formation (Fig. 4) is indicative of the time when the contractional tectonic episode ceased.

The main northern, northeastern and southern border faults of the basin show top- to-the-southwest vergence (Fig. 3B). The western border fault may be interpreted as part of the eastern border of the North Patagonian fold and thrust belt (Giacosa and Heredia, 2004) with a main northeast vergence. In the central part of the Gastre Basin, an alignment of antithetical top-to-the-north reverse faults was observed (Fig. 3B). This structural morphology generated internal highs (e.g. the Sierra del Medio and Cerro Bota hills; Fig. 3B) and characterizes the main part of the Gastre Basin as a triangular zone between antithetic reverse faults (Figs. 3B, 13).

The structure of the Gastre Basin is strongly influenced by the pre-Neogene tectonic history of the study area, defined by crustal heterogeneities developed from the upper Paleozoic to the Paleogene. This history was related to the continental amalgamation of magmatic belts from Carboniferous to Triassic times (Pankhurst et al., 2006; von Gosen, 2009; Zaffarana et al., 2010), rifting and basin formation during the Jurassic–Lower Cretaceous (Figari et al., 1996), the Cretaceous contraction (Allard et al., 2011; Folguera and Ramos, 2011; Orts et al., 2012; Proserpio, 1978) and Paleogene extension and volcanism (Rapela et al., 1984).

The marked WNW orientation of the basin coincides with the "Gastre Fault System" (sensu Coira et al., 1975) which was interpreted as a Triassic–Jurassic intercontinental dextral strike-slip zone of tens of kilometers wide and hundred kilometers long (Rapela and Pankhurst, 1992; Rapela et al., 1991, 1992). Even though this fault system was considered for some Gondwana break up reconstructions (e.g. MacDonald et al., 2003; Marshall, 1994; Martin, 2007), other studies (von Gosen and Loske, 2004; Zaffarana and Somoza, 2012; Zaffarana et al., 2010) have demonstrated that the geological record in the Gastre region do not show the evidence required (intensity, kinematics and timing of deformation) in previous Gondwana break-up models. Whichever, the similar trend and location of discrete pre-Neogene faults with the location and orientation of the Miocene faults of the Gastre basin demonstrate a major influence of the previous Palaeozoic and Mesozoic basement structures in the configuration of the Gastre Basin.

The influence of the Jurassic Cañadón Asfalto Basin faults in the configuration of the Gastre Basin can be clearly appreciated in the inversion of the extensional structures that affected the stratigraphic record of the Cañadón Asfalto Basin (Figs. 3B, 11). Nevertheless, the control of the later Cretaceous inversion is more difficult to determine and can be addressed by analyzing the amount of Cenozoic uplift from the mountain borders of the Gastre Basin. Thus, the estimation of the absolute late Cenozoic uplift can be calculated from the displacement of Maastrichtian beds, at around 0.5 km. The magnitude of this uplift does not explain the presence of outcrops of the initial deposits of the Cañadón Asfalto Basin uplifted more than 1.6 km on top of the border blocks. Outcrops of the Cañadón Asfalto Formation were observed at 1300 m a.s.l. to the northeast of the Sierra de Cabeza de Buey and at 1200 m a.s.l. on top of the Cerro Bayo (Fig. 3B), while they are registered in the subsurface of the Gastre Basin at heights lower than 500 m a.s.l. (Fig. 13). Thus, the difference in the amount of uplift can be related to a Cretaceous pre-Maastrichtian inversion that uplifted and deformed the Jurassic to Lower Cretaceous sequence. Finally, no evidence of an influence of the Paleogene extension that generated the volcanic Huitrera Formation to the west was registered in the Neogene configuration of the Gastre Basin.

The contractional character of the Gastre Basin described in this paper agrees with, and expands, the findings of Figari et al. (1996). These results argue against both an extensional regime (Volkheimer, 1965, 1972) and a transcurrent regime (Coira et al., 1975; Dalla Salda and Franzese, 1987; Rapela et al., 1991, 1992) previously attributed to the formation of the border mountain ranges. Extensional faults were only recorded as ancient faults associated with the Jurassic

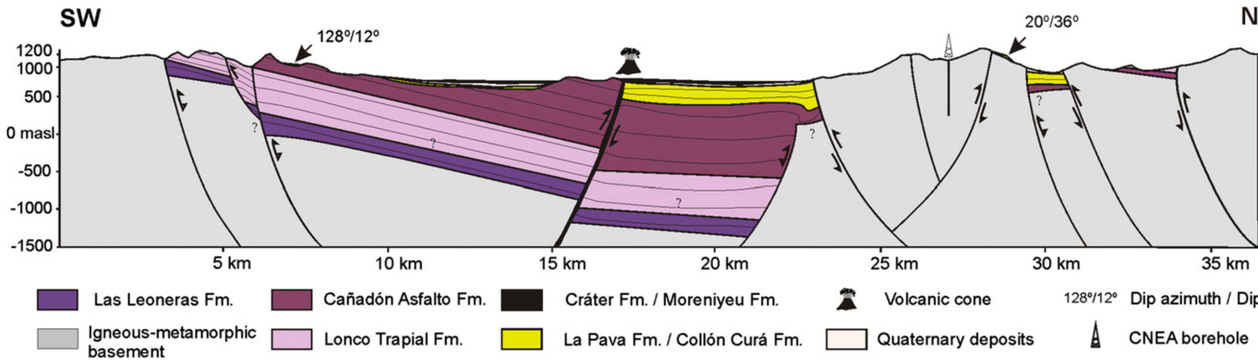

Fig. 13. Geological cross section of the Gastre Basin. The trace of the cross section is indicated in Fig. 3B.

Cañadón Asfalto Basin, some of them with important evidence of inversion (Figs. 3, 11, 13), whereas the observed minor strike-slip faults (Fig. 3B) are interpreted as local structures related to the complex contractional basement uplift.

Neogene wrench faulting was proposed in the magmatic arc (Hervé, 1994; Rosenau et al., 2006) as a response to an oblique convergence between the oceanic Nazca plate and the continental South American plate (Dewey and Lamb, 1992). This tectonic regime was also described in the fold and thrust belt zone (Diraison et al., 1998) through northwest reverse faults, north-trending, right-lateral, strike-slip faults and east-trending, left-lateral, strike-slip faults. Nevertheless, other authors have recently described exclusively reverse faults in the fold and thrust belt zone, denoting that wrench tectonics is negligible to the east of the magmatic arc (Giacosa and Heredia, 2004; Orts et al., 2012).

In the study area, even if strike-slip movements cannot be dismissed, they are clearly subordinated to vertical movements. Stratigraphic offsets of pre-Neogene and Neogene units do not show evidence of important horizontal displacement, comparable with the vertical displacement (up to 500 m) registered in the margins of the basin. The presence of large-scale and small-scale folds parallel to observed reverse fault systems and the absence of en echelon and oblique related structures points out in the same direction. Overall observations considered in this work, widely suggest a relevance of the reverse component of the faults with respect to the strike-slip component during the configuration of the Gastre Basin. Finally, the contractional style of the major NW-SE trending reverse faults of the Gastre region agrees with the main conclusions of Diraison et al. (1998), who despite emphasize strike slip faults in the North Patagonian fold and thrust belt zone also describes major reverse faults and thrusts trending northwest.

No structural indication of reactivation of the basin was observed in the post-middle Miocene stratigraphy or in the present configuration of the basin, even during the development of the Quaternary volcanic field (Fig. 3B). This does not agree with other authors that proposed a Quaternary fault-block uplift based on aerial photographs and satellite image interpretation (Coira et al., 1975; Proserpio, 1978; Volkheimer, 1965). The presence of vent alignments related to the lava fields indicates the existence of deep fractures (Massaferro et al., 2006) that controlled the ascent of magma without a significant shear component. This suggests that the fractures were developed earlier, as in the so-called "low magma flow fields" (Cebriá et al., 2011), in which magma ascent is prone to being captured by faults and eruptive fissures, with an orientation mainly determined by the structural grain (Cebriá et al., 2011; Valentine and Gregg, 2008). The lack of deformational structures younger than middle Miocene implies a tectonic quiescence during most of the evolution of the Gastre Basin.

4.2. The middle Miocene Patagonian broken foreland system

The middle Miocene Andean contraction inverted or reactivated pre-existent anisotropies, producing discrete fault-block mountains and basin formation in the study area. This morphostructural scenario, in which isolated or partially connected basement uplifts segmented the foreland basin, can be defined as a broken foreland system (sensu Jordan, 1995; Jordan and Allmendinger, 1986). Therefore, we propose that the Gastre Basin is part of a broken foreland system located to the west of the North Patagonian fold and thrust belt (Fig. 14).

To the north and south of the Gastre Basin in the Patagonian foreland, key elements of broken foreland systems, such as Miocene basement uplifts that partially disconnect the arrangement of synchronic foreland deposits, were described (e.g. the San Bernardo fold and thrust belt, Peroni et al., 1995; the Deseado fold and thrust belt, Giacosa et al., 2010, 2012; Fig. 15). Towards the north of the study area, deformed strata of the La Pava Formation have been described around the localities of Ingeniero Jacobacci and Piedra del Águila (Coira, 1979; Cucchi, 1998; Uliana and Robbiano, 1974). These deposits can be interpreted as evidence that the middle Miocene tectonic deformation phase also affected the foreland area north of the Gastre Basin (Fig. 15).

According to the data presented in this paper, the uplift in the Gastre Basin and surrounding areas is constrained to the early middle Miocene (16.1–14.8 Ma). To the south, the structural building of the Sierra de San Bernardo (Fig. 15) was dated as early middle Miocene (Guillaume et al., 2009), marked by the presence of deformed strata of the Santa Cruz Formation (19–14 Ma; Cobos and Panza, 2003; Perkins et al., 2012; Peroni et al., 1995). Close to the Sierra de San Bernardo, several Miocene reverse faults were described in subsurface as part of the San Jorge fold and thrust belt (Figari et al., 1998; Fig. 16). In addition, the Deseado fold and thrust belt (Fig. 16) was constrained to the Miocene (Giacosa et al., 2010). These authors also suggest a link between this belt and the San Bernardo fold and thrust belt to the north. All these data show a significant similarity in the age of the mountain uplift throughout the Patagonian foreland. Thus, we propose that similar processes of mountain uplift and foreland segmentation occurred during the late early–middle Miocene in the Patagonian Andean foreland between 40°00′ and 48°00′ south latitude (i.e. the Patagonian broken foreland; Figs. 14, 15). This continental interior broken foreland scenario, caused by contractional tectonics, supports the recent idea that Andean compression has affected the entire South America plate, hundreds of kilometers west from the trench (Cobbold et al., 2007). The configuration of the "Patagonian broken foreland" (late early–middle Miocene) is in agreement with the middle Miocene age proposed for the development of the North Patagonian fold and thrust belt, west of the study area (Orts et al., 2012; Paredes et al., 2009), but it is not coincident with previous studies that indicated that the main deformation of the Patagonian foreland was constrained to the late Miocene (Folguera and Ramos, 2011). The lapse between the age of deformation of the Andean fold and thrust belt (18.3 Ma; Orts et al., 2012) and the age of formation of the Gastre Basin could reflect the migration of the active deformation front from west to east during the middle Miocene. Well-preserved

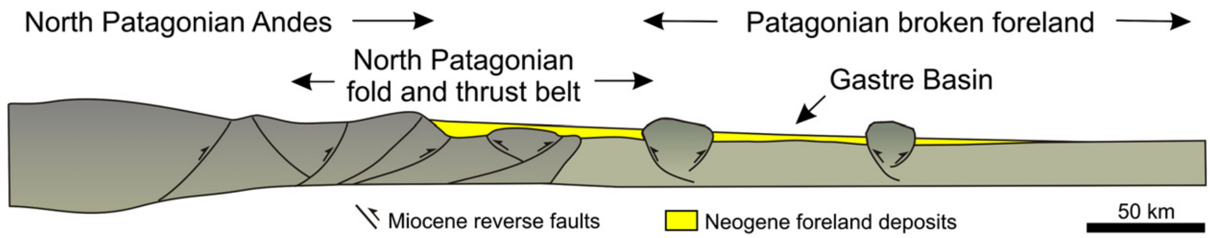

Fig. 14. Schematic cross section of the Gastre Basin in its regional context, in a WE direction (perpendicular to the Andean chain).

strata of the La Pava Formation (pre-16.1 Ma) below the Collón Curá Formation in different parts of the North Patagonian foreland (Coira, 1979; Cucchi, 1998; Nullo, 1978, 1979; Volkheimer, 1973) may indicate the onset of flexural subsidence in response to the early tectonic activity in the North Patagonian fold and thrust belt (lower to middle Miocene).

Hypotheses concerning the Neogene configuration of the Patagonian Foreland should incorporate mechanisms that explain basement uplifting at several hundred kilometers from the trench, in a period when convergence velocity in the Andean margin was decreasing (Somoza and Ghidella, 2012). Recent broken foreland systems are commonly associated with the interaction between crustal heterogeneities and flat-slab subduction in the intraplate (Barazangi and Isacks, 1979; Jordan et al., 1983; Mora et al., 2006; Pilger, 1981; Ramos et al., 2002; Siame et al., 2005). These conditions have also been cited as triggering mechanisms of ancient broken foreland systems (Ramos and Folguera, 2009). Large Palaeozoic and Mesozoic penetrative crustal heterogeneities susceptible of inversion or reactivation were described in the Patagonia foreland, (e.g. Cobbold et al., 2007; Giacosa et al., 2012; Pankhurst et al., 2006; Ramos, 2008; Zaffarana et al., 2010). In the Gastre region, many Paleozoic and Mesozoic crustal anisotropies were reactivated or inverted during the Neogene block uplift and configuration of the Gastre Basin (e.g. inversion of Cañadón Asfalto Basin faults). To the north and south of the Gastre Basin in the Patagonian foreland, a similar scenario was also recognized in which pre-existing anisotropies were activated during Neogene Andean orogeny (D'Elia, 2010; Figari et al., 1996; Giacosa et al., 2010).

The existence of shallow subduction segments in the Andean chain was proposed to explain the deformation in the Patagonian foreland (Espinoza et al., 2010; Folguera and Ramos, 2011; Orts et al., 2012). The late Miocene age proposed by Folguera and Ramos (2011) for this process is not consistent with the timing of deformation presented in this paper and other studies (Giacosa and Heredia,

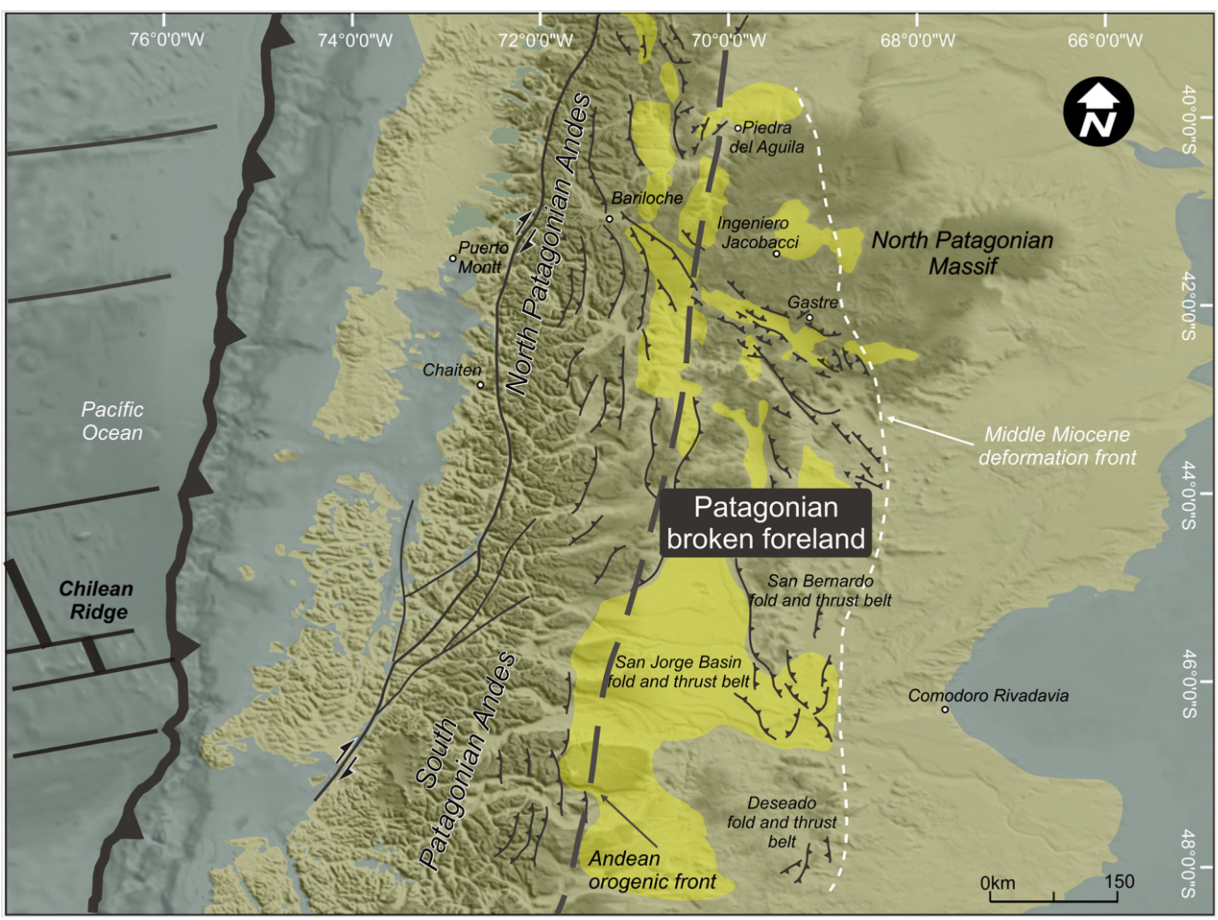

Fig. 15. Tectonic setting of the late early–middle Miocene Patagonian broken foreland. Faults and Neogene foreland deposits were modified from Cingolani et al. (2006), Cobos and Panza (2003), D'Elia (2010), Figari et al. (1998), Figari (2005), Folguera and Ramos (2011), Franzese et al. (2011), Giacosa and Heredia (2004), Giacosa et al. (2010), Kraemer et al. (2002), García Morabito et al. (2011), Orts et al. (2012), Peroni et al. (1995), SEGEMAR (1995), SEGEMAR (2003), Thomson (2002).

2004; Orts et al., 2012). The intraplate deformation processes presented in this paper could be a response to a late early–middle Miocene flat-slab subduction, as proposed by other authors to explain the composition and distribution of arc and retroarc volcanism in Patagonia (Espinoza et al., 2010; Folguera and Ramos, 2011). The similarities in style (i.e. fault-block mountain building), distance from the trench (mainly between 550 and 580 km) and timing of deformation (19–14.8 Ma) along more than 950 km in the central-southern Patagonian Andes would imply the existence of a relatively continuous, large shallow subduction segment, at least as big as the longest flat-slab segment observed at present (i.e. the Peruvian flat slab, Skinner and Clayton, 2011). Such a large flat subduction segment would need a remarkable uniformity in plate velocity and/or age of the subducted slab, and the subduction of local roughnesses that could change the geometry of the subduction margin. These flat-slab trigger conditions frequently mentioned in small Andean segments (Espinoza et al., 2010; Folguera and Ramos, 2011; García Morabito and Ramos, 2012) seem unlikely to be maintained along the entire Patagonian trench and, therefore, suggest the need to find alternative flat-slab trigger mechanisms or the possibility that other factors contributed to the generation of broken foreland systems.

5. Conclusion

The Gastre Basin is an intermontane basin located in the North Patagonian foreland. It was generated by reverse faulting and inversion of pre-existing normal faults strongly influenced by the pre-Neogene structure. The onset of the Gastre Basin occurred during a short contractional tectonic episode (16.1–14.86 Ma) with no younger fault-block uplifts. It is part of a major broken foreland system (i.e. the Patagonian Broken Foreland), that exhumed discrete fault-block mountains and generated contemporary basins more than 550 km from the trench. Mountain uplift and foreland segmentation occurred during the late early–middle Miocene along more than 950 km from north to central-southern Patagonia (i.e. between 40°00′ and 48°00′ south latitude). This remnant landscape represents one of the largest preserved broken forelands of the Andean chain.

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