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The origin of the San Jorge Gulf Basin in the context of the Mesozoic-Cenozoic evolution of Patagonia

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ABSTRACT

The retroarc region of central Patagonia recorded three contractional stages (Late Triassic, Late Cretaceous, and Miocene) coincident with eastward broadening of arc magmatism. Inboard arc migration may be linked to shallowing of the subducted slab, subduction erosion of forearc regions, or a combination of both. Contractional episodes were followed by slab rollback, producing a series of extensional depocenters and magmatic belts across Patagonia at ~170-130 Ma, ~55-22 Ma and ~5 Ma. These rollback events weakened Patagonian crust through fracturing, mantle upwelling, and magmatic injection, favoring inception and propagation of subsequent contractional episodes. Phases of slab rollback and retroarc extension are reflected in εHf and εNd isotopic trends, with more juvenile trajectories corresponding to mantle upwelling into a broad asthenospheric wedge during slab retreat. Periods of crustal shortening are recorded by evolved εHf and εNd isotopic trajectories, demonstrating modified mantle sources.

Mesozoic-Cenozoic extensional basins of Patagonia, such as the Chubut Basin, Cañadón Asfalto Basin, Río Mayo-Aysén Basin, Pilcaniyeu and Auca Pan-El Maitén magmatic belts/volcanogenic basins, and the Traiguén Basin were generated during episodes of slab rollback. In contrast, the extension-related San Jorge Gulf Basin constitutes an east-west-trending anomaly developed in an interval of the Cretaceous when the rest of western Patagonia experienced shortening. During this time, crustal evolution trends shifted from juvenile to more evolved and the arc expanded toward the continental interior most likely under a flat-slab regime. The San Jorge Gulf Basin is linked to Neocomian extensional structures in an intracratonic basin later influenced by compressional stresses linked to subduction zone in the west and incipient opening of the south Atlantic to east.

1. Introduction

The San Jorge Gulf Basin is situated in the retroarc region of central Patagonia east of the Patagonian fold-thrust belt. Its structural grain comprises a graben-like structure controlled by E-W-striking normal faults perpendicular and structurally disconnected from the Andes and the Atlantic passive margin. These structures controlled the synextensional deposition of the upper Lower Cretaceous-Paleogene sedimentary succession. The structural orientation, limited magmatism (particularly during the initial stages), and the timing of formation of the San Jorge Gulf Basin are anomalous in the context of Patagonian tectonic evolution, which is characterized by discrete periods of extension in Early Jurassic to Early Cretaceous and latest Cretaceous to Oligocene times with NW to N predominantly extensional structures (Fitzgerald et al., 1990; Paredes et al., 2013).

Recent contributions have challenged previously accepted ideas regarding the Jurassic tectonic evolution of the Patagonian and Central Andes. Earlier hypotheses suggested that extensional depocenters formed via mechanical and thermal subsidence at ~200-140 Ma during incipient breakup of Pangea. However, new data have refined these hypotheses, exemplified in the pioneering work of Lock (1980) and Dalziel et al. (2000). The first new controversial premise is that the retroarc region of Patagonia recorded a shortening stage associated with inland migration of a volcanic arc in Late Triassic (Navarrete et al., 2019a), while to the north, in the Southern Central Andes, crustal stretching dominated southwestern Gondwana. This new hypothesis

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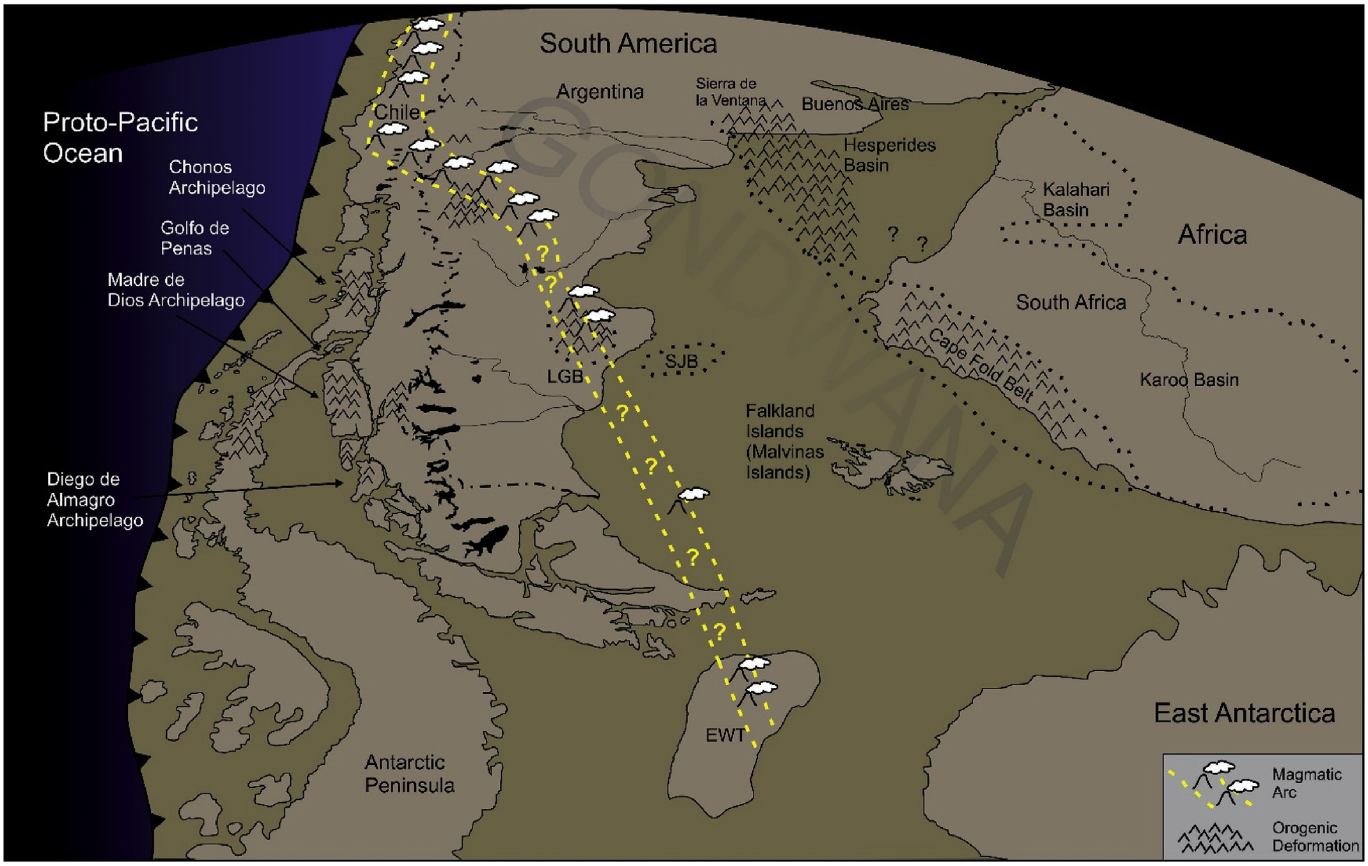

Fig. 1. Plate reconstruction showing a Late Triassic flat-slab hypothesis that considers the Central Patagonian Batholith (CPB) as a magmatic arc that migrated into the Patagonian interior. Flat slab subduction was contemporaneous with the uplift of the Sierra de la Ventana and Cape Fold Belt as part of a broken foreland system associated with flexural basins developed in southern Africa and the present Atlantic passive margin (from Navarrete et al., 2019a).

suggests the Late Triassic Central Batholith constitutes a magmatic arc developed in central Patagonia (Fig. 1) during contemporaneous Late Triassic contraction evidenced in field and seismic data, particularly in the Deseado Massif. The second premise is that Patagonia experienced short pulses of moderate within-plate shortening throughout the Jurassic, interrupting thermal sag conditions within intra-arc and retroarc basins (Navarrete et al., 2016, 2019b). These pulses may be related to strong kinematic changes and southward continental motion registered in Gondwana at ~180 Ma. At this time, opening of the North Atlantic Ocean overlapped with opening of the Weddell Sea at ~164 Ma, trapping the continent, and particularly the Patagonian platform, between these two sea floor spreading centers located at the leading edges of the continent while the Karoo hot spot was emplaced and expanded to the east (Müller et al., 2016). The contemporaneous Liassic and Cañadón Asfalto basins in the retroarc zone of Chubut Province, eastern volcanogenic basins, and North Patagonian and Deseado massifs suffered early contractional inversion and exhumation (Navarrete et al., 2016, 2019b). These Late Triassic to Jurassic pulses of shortening thickened the crust, as indicated by REE elements in Mesozoic magmas of the Patagonian Andes (Echaurren et al., 2017). Exhumation of vast sectors of the North Patagonian massif are indicated by Jurassic Ar/Ar cooling ages (Martínez Dopico et al., 2016), creating topography that fed the Jurassic basins to the north with detritus from the central Patagonian region (Naipauer et al., 2012).

This review describes the Triassic to the Neogene tectonic evolution of Patagonia in light of these new ideas, with particular focus in the anomalous formation of the San Jorge Gulf Basin, following the hypothesis of Gianni et al. (2015) who interpreted a within-plate synorogenic extensional basin contemporaneous with the inception of the early Patagonian fold-thrust belt.

2. Geological setting

2.1. Late Triassic arc magmatism

Late Triassic magmatism of central to southern Patagonia is represented by the NNW- Central Patagonian Batholith (CPB) (Rapela et al., 1991) which crosses the region from the southwest (Rio Negro Province) to the northeast (Santa Cruz Province) and has an age range spanning from the late Upper Triassic (Norian to Rhaetian) to early Lower Jurassic (~220–198 Ma) (e.g., Rapela et al., 1991; Rapela and Pankhurst, 1992; Varela et al., 1992; Zaffarana et al., 2014; Lagorio et al., 2015; Navarrete et al., 2019a). This composite batholith had been assigned to intraplate extensional to transtensional magmatism (e.g., Rapela et al., 1991; Rapela and Pankhurst, 1992), but later was interpreted as a magmatic arc (e.g., Rapela and Pankhurst, 1996). More recently, it was linked to a flat subduction setting because of its inland position and composition (the South Gondwanian flat-slab of Navarrete et al., 2019a). Geochemically, the CPB shows a clear relationship with a subduction environment based on calc-alkaline to high-K calc-alkaline compositions, I-type magmatism (alumina saturation index < 1.1), enrichments of Th and U, negative Nb and Ta anomalies, and zircon saturation temperatures below 800 °C (see Navarrete et al., 2019a for more details). Likewise, an adakitic geochemical signature was suggested for the most of CPB by Navarrete et al. (2019a) based on the high $La/Yb_{(N)}$ and Sr/Y ratios, which reinforces its link to a flat-subduction environment (e.g., Gutscher et al., 2000).

These plutonic rocks have been grouped into the Gastre and Lipetrén super units, representing magmatic pulses of mostly granitic composition between ~220 and ~200 Ma (Rapela et al., 1991; Zaffarana et al., 2014). The syntectonic emplacement of these plutons is evidenced in the magmatic lineations identified through AMS (anisotropy of magnetic susceptibility) data and structural analyses of mylonitic shear zones, indicating a sinistral transpressive regime (Zaffarana et al., 2017).

Therefore, the emplacement of the CPB occurred during and after Late Triassic contraction that involved much of southwestern Gondwana, provoking intense deformation that affected regions from the Antarctic Peninsula to southern Africa (Navarrete et al., 2019a and references therein). Late Triassic contraction was partitioned within a strike-slip regime along internal-ductile arc axis zones, corresponding to a transpressive tectonic regime that affected the center-north Patagonian region (Zaffarana et al., 2017) and external fold-thrust belts within the Deseado Massif, Sierra de la Ventana, and Cape Fold Belt systems (Fig. 1) (Navarrete et al., 2019a, and references therein).

This Late Triassic contractional event of southwestern Gondwana interrupted a generalized extensional tectonic regime in this region developed from Late Paleozoic to early Upper Triassic. This Late Paleozoic to Triassic extensional regime through which multiple depocenters developed (e.g., La Golondrina, El Tranquilo, Paso Flores, Los Menucos) (e.g., Ramos, 1994) and the intrusion of syn-extensional/syn-transtensional plutons occurred (e.g., Martínez Dopico et al., 2016) was related to both the Gondwanide orogen collapse and the anti-clockwise rotation of Pangea (Riel et al., 2018).

2.2. Early to Late Jurassic-Early Cretaceous within-plate and arc magmatism

Jurassic magmatism in the extra-Andean sector of Patagonia, as represented by Chon Aike SLIP magmatism (Kay et al., 1989; Pankhurst et al., 1998), was produced by an intense crustal melting event (Riley et al., 2001; Seitz et al., 2018) due to the thermal effects of the Karoo Mantle Plume (KMP) (e.g., Riley et al., 2001; Storey et al., 2013; Tassara et al., 2017). This magmatism (predominantly rhyolitic) occurred in an intraplate environment under an extensional regime during initial Gondwana breakup. Geochemically, the Chon Aike record exhibits numerous features of subduction-related magmatism such as calc-alkaline to high-K calc-alkaline compositions, Th and U enrichment, and negative Nb and Ta anomalies; however, associated isotopic data ($^{87}Sr/^{86}Sr$ = ~0.706–1.03; εNdt = ~-1.8–7.9; high $\delta^{18}O$ values = 10.9–12.5‰; Pankhurst and Rapela, 1995; Seitz et al., 2018) instead suggest crustal melting processes linked to a mantle thermal anomaly. Zircon saturation temperatures above 800 °C reinforce this interpretation (Liu et al., 2014; Navarrete et al., 2019a). This contradiction in geochemical results can be explained by the presence of hydrated relicts of previous subducted oceanic remnants beneath the continental lithosphere, which would have been melted and mixed with the mantle plume asthenospheric melts, resulting in a partial magmatic arc geochemical signature (e.g., Riley et al., 2001).

According to Féraud et al. (1999) and Pankhurst et al. (2000), Chon Aike SLIP magmatism migrated westward from eastern Patagonia (V1, V2, and V3 event of Pankhurst et al., 2000), later explained as westward suction of the KMP induced by the slab rollback during Early Jurassic re-establishment of subduction (Navarrete et al., 2019a). This geodynamic context could have favored the thermo-mechanical removal of the lithospheric mantle of Patagonia, promoting crustal melting.

During migration of SLIP magmatism to the southwest, the Subcordilleran plutonic belt (Gordon and Ort, 1993; Haller et al., 1999) (~185-180 Ma, according to Rapela et al., 2005, Fig. 2), a subduction-related plutonic association, was emplaced near the present volcanic arc axis with an NNW orientation (see Echaurren et al., 2019). This plutonic belt partly coincided with intermediate volcanic rocks of the Lonco Trapial Formation that span from ~188 to ~179 Ma (Cúneo et al., 2013; Echaurren et al., 2016; Hauser et al., 2017), and with thick silicic ignimbrites of the Marifil Formation to the east. Both regions were characterized by regional subsidence and basin formation, with the Las Leoneras depocenter to the east in the Cañadón Asfalto Basin and the Piltriquitrón-Osta Arena depocenters to the west in the Chubut Liassic Basin, hosting fluvial, deltaic and shallow marine deposits (Lizuaín et al., 1995; Suárez and Márquez, 2007; Fígari et al., 2015).

During the Middle-Late Jurassic, the Cañadón Asfalto Basin accumulated thick deltaic, fluvial and lacustrine sequences represented by the Cañadón Asfalto and Cañadón Calcáreo formations (e.g., Volkheimer et al., 2009; Cabaleri et al., 2010), with reduced volcanic activity represented by poorly differentiated basaltic members emplaced at ~176–170 and ~160 Ma (Hauser et al., 2017). Contemporaneously, in the proto-Andean zone, westward retreat of the magmatic arc led to the initial activity of the long-lived North Patagonian Batholith (Fig. 3), whose early plutonic suites are represented by ~170 Ma granitoids near Bariloche (Castro et al., 2011). Based on a compilation of radiometric data and previous descriptions of the regional distribution of Jurassic volcanism, Echaurren et al. (2017) proposed that ~180-170 Ma mafic volcanism (Ghiara et al., 1999; Blesa, 2004) was a precursor of the main Late Jurassic volcanic episode in the Cordillera (part of the "V3" event of Pankhurst et al., 2000). This latter event is well represented by > 1000 km thick volcanic and volcanoclastic rocks of mainly acidic composition associated with the Ibáñez Formation in Chile and the Lago la Plata Formation in Argentina (e.g., Haller and Lapido, 1982). They have been attributed to a subduction environment at ~152-136 Ma (Pankhurst et al., 2000; Suárez et al., 1999) distributed throughout the present hinterland and toward the eastern Andean slope. The top of this volcanic succession is intercalated with the basal member of the Coyhaique Group, a marine sequence deposited in an intra-arc to retroarc setting of the Aysén basin or Río Mayo embayment (Aguirre-Urreta and Ramos, 1981). Westward migration of magmatic activity is interpreted to last until the Early Cretaceous (Berriasian-Barremian), as represented by ~138-120 Ma granitoids in the eastern Chonos Archipelago and scattered through the Andean western slope (Fig. 3) (Pankhurst et al., 1998).

2.3. Late Early Cretaceous inland arc migration and contemporaneous shortening in Patagonia

The North Patagonian Batholith (Fig. 3) corresponds to the Cretaceous to Neogene arc front and comprises two main pulses (173–75 Ma and 21–9 Ma), which correlate with periods of rapid orthogonal convergence (Pankhurst et al., 1998). The first and more voluminous pulse took place in the Cretaceous (173–75 Ma), together with its volcanic counterparts (120–100 Ma: Divisadero Group) that exhibit an eastward expansion at ~118 Ma, from the North Patagonian Andes axis to its eastern foothills (Echaurren et al., 2016; Pankhurst et al., 1998).

In the eastern Patagonian Andes, volcanic rocks of the Divisadero Group unconformably overlay Neocomian successions. This angular unconformity developed between 41° and 48°S implies an Early Cretaceous orogenic event that affected the present Main Cordillera and western foreland zone (e.g. Folguera and Iannizzotto, 2004).

In the foreland zone, the San Bernardo fold-thrust belt presents extensive outcrops of the late Early Cretaceous to Late Cretaceous continental deposits of the Chubut Group characterized by ash-fall deposits reworked in lacustrine and fluvial settings (Fitzgerald et al., 1990). The high pyroclastic component of this unit is associated with a coeval eastward migration of the magmatic arc during deposition (Tunik et al., 2004; Paredes et al., 2007). The Chubut Group is formed by the Pozo D-129/Matasiete, Castillo, Bajo Barreal, Laguna Palacios and Colhué Huapi formations, ranging in age from the Aptian to the Maastrichtian based on fossil records and U/Pb zircon data (Fitzgerald et al., 1990; Césari et al., 2011; Pérez Loinaze et al., 2013; Casal et al., 2015; Vallati et al., 2016).

Early uplift of the San Bernardo fold-thrust belt is supported by seismic surveys and surface detection of growth-strata in the Chubut Group. However, this synorogenic character is presently discussed.

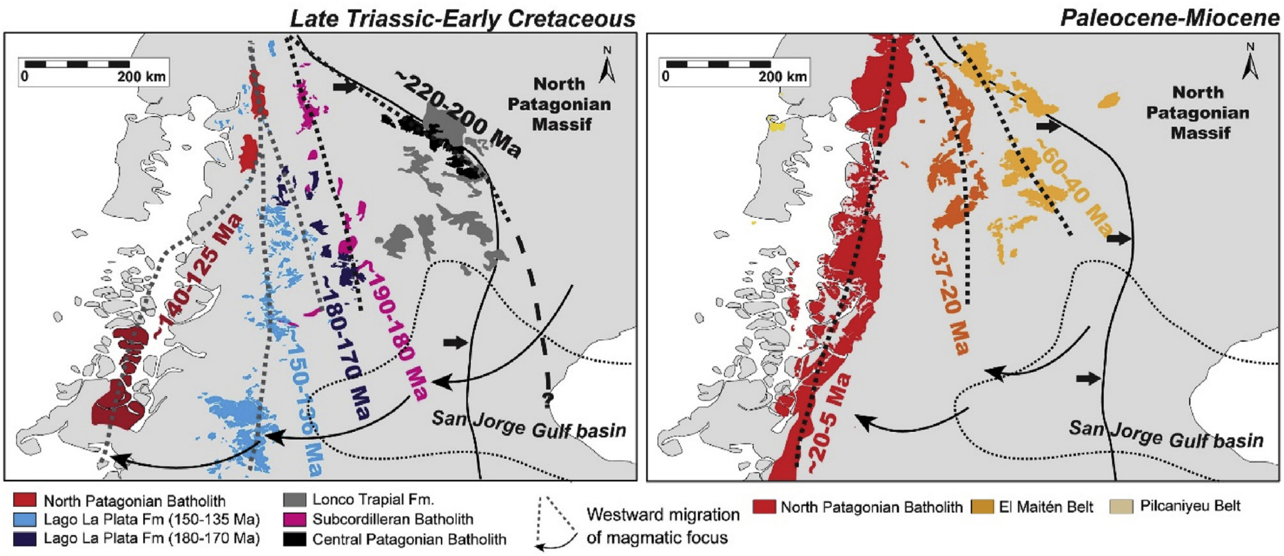

Fig. 2. Map of Mesozoic-Cenozoic magmatic belts showing the retreat of arc magmatism during subduction rollback in central Patagonia following inland arc migration events in the Late Triassic (left) and Late Cretaceous (right) (from Echaurren et al., 2019).

Based on certain hypotheses a synorogenic character is assigned for the entire sequence of the Chubut Group or at least from the Castillo Formation upward (Navarrete et al., 2015; Gianni et al., 2015) (Fig. 4), while in others using comparable datasets in the subsurface (see Allard et al., 2019) a synorogenic character is only described for the Laguna Palacios Formation (late Upper Cretaceous).

2.4. Paleocene to early Miocene magmatism and extension in Patagonia

Two Cenozoic magmatic belts were formed related to extensional tectonics (see Giacosa and Heredia, 2004; Giacosa et al., 2005): i) the eastern Pilcaniyeu belt (60-42 Ma, Huitrera Formation) and ii) the western El Maitén belt (37-23 Ma, Ventana Formation) (Fig. 2). The Paleocene to early Eocene Pilcaniyeu magmatic belt is characterized by a bimodal composition with rhyolitic ignimbrite facies and subordinate andesites and basalts, interpreted as an intraplate magmatic activity (Aragón et al., 2011a,b; Iannelli et al., 2017). To the west, the late Eocene-early Miocene El Maitén magmatic belt is characterized by arc-related andesitic to dacitic lava flows with subordinated basalts and rhyolitic ignimbrites (see Fernández Paz et al., 2018). These successions are characterized by synextensional deformation, wedge-like geometries, and tilted blocks (Echaurren et al., 2017). Volcanic depocenters show wedge-like geometries from field and seismic data associated with normal faults (Orts et al., 2012).

The late Oligocene extensional Traiguén Basin developed between the partially submerged Coastal Cordillera represented by Los Chonos Archipelago and the North Patagonian Andes (43°45′-47°S) (Fig. 2) (Hervé et al., 1995). Isolated and sparse outcrops of alkali to tholeiitic-subduction-related pillow basalts, interbedded with sandstones, shales, and breccias with facies and benthic foraminifers indicative of a deep-marine environment are spread through numerous small islands (Hervé et al., 1995; Encinas et al., 2015). Detrital zircon U-Pb geochronology yielded a maximum depositional age of 26–23 Ma (late Oligocene-early Miocene) (Encinas et al., 2015). The Traiguén basin infill is affected by meter-size syndepositional normal faults (Encinas et al., 2015).

2.5. Early to late Miocene inland arc development and last phase of contractional deformation in northern Patagonia

Rapela et al. (1988) and Rapela and Kay (1988) interpreted an eastward expansion of Miocene magmatism over the western Andean slope, represented by isolated plutons intruding the Mesozoic batholiths and the Paleozoic basement. Radiometric data indicate that this eastward arc expansion occurred at 19-14 Ma from the Main Andes to the eastern Andean foothills. After this, magmatism was reinstalled along the western Andean slope by 13 Ma (Orts et al., 2015). Based on this behavior, Orts et al. (2015) interpreted a shallow subduction regime from 19 to 14 Ma affecting the northern Patagonian Andes at the latitudes of the North Patagonian Massif.

At the latitudes of the Chile triple junction and San Jorge Gulf Basin (45–47°S), synorogenic successions yielded 18.7–16.4 Ma U-Pb ages in the western Patagonian Cordillera corresponding to Meseta Guadal, Jeinemeni and Alto de Río Cisnes sections (Folguera et al., 2018). This uplift was contemporaneous with broken foreland deformation associated with the final deformational phase of the San Bernardo fold-thrust belt to the east at 17.7–15 Ma (Ramos et al., 2015; Gianni et al., 2015). Younger synorogenic successions of 13.5–12.3 Ma are intercalated with proximal ignimbritic sheets along the eastern Andean front in the Chalía and Guenguel sections, implying diminished orogenic activity and out-of-sequence growth of the Patagonian Cordillera. Contractional deformation ended sometime after ~12 Ma, sealed by the extrusion of extensive alkali flood basalts indicating that Neogene shortening lasted until ~6 Myr (Folguera et al., 2018). During ~19-12 Ma, the migration of the magmatic arc and the closure of the Traiguén basin occurred. Shortened 26-23 Ma deposits of the Traiguén Basin are intruded by syndeformational granitoids with ages between 20 and 15 Ma (Hervé et al., 1995).

3. εHf and εNd isotopic trends of Late Triassic- Cenozoic magmatism

Late Triassic–earliest Early Jurassic magmatism (~227–190 Ma) comprises the Central Patagonian Batholith adakitic magmatic arc, located in a distal retroarc position compared to the former trench configuration (Navarrete et al., 2019a; Rapela et al., 1991; Rapela and Pankhurst, 1996). This magmatism includes calc-alkaline I-type granites and high-K calc-alkaline monzonites with εNd values between −3.1 and 0.3 (Fig. 5). This magmatic signature was linked to the partial melting of an enriched mantle wedge in a distal sector of the subduction zone (Rapela et al., 1991).

During the Early Jurassic, discontinuous arc-related calc-alkaline I-type granites and coeval mafic rocks of the Subcordilleran Batholith (185–181 Ma) developed in western position respect to the Late Triassic volcanic front (e.g., Mpodozis and Ramos, 2008). Isotopic composition

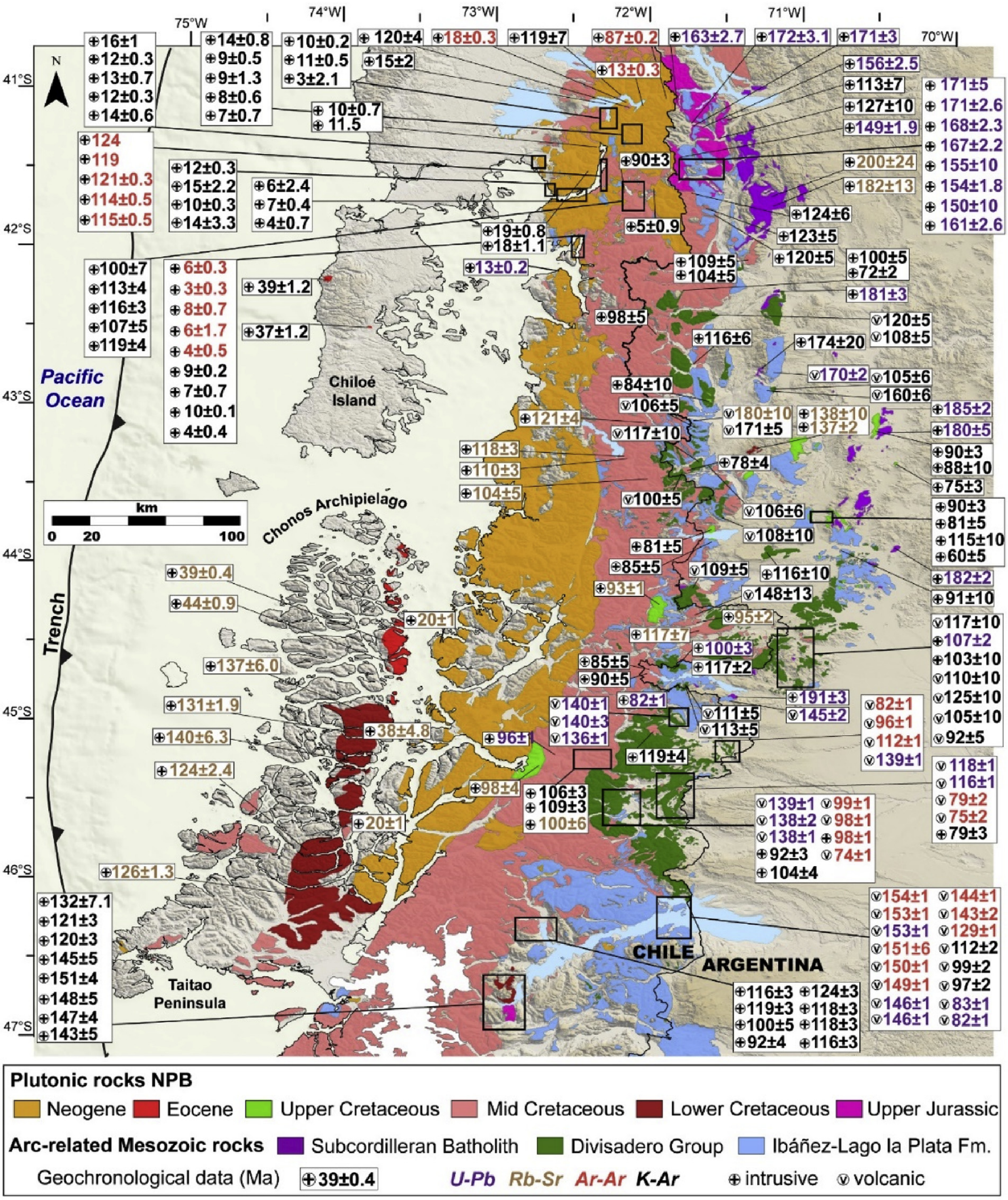

Fig. 3. Map of compiled radiometric ages of arc-related rocks in the North Patagonian Andes and Patagonian extra-Andean region (from Echaurren et al., 2019). The eastward younging of ages implies an eastward shift of the arc at 107-80 Ma, roughly corresponding to the age of the synorogenic extra-Andean Chubut Group. Radiometric ages from Haller and Lapido (1982), Pankhurst et al. (1998, 2000), Ghiara et al. (1999), Castro et al. (2011), Aragón et al. (2011a,b), Hervé et al. (2017) (see Echaurren et al., 2019 for additional sources).

of Early Jurassic arc magmatism is geochemically similar to younger units of the Central Patagonian Batholith, showing slightly more positive Nd values (εNd = −1.6–1.3; Fig. 5). Synchronously with the development of this magmatic arc, the initial phase of the intraplate rhyolite volcanism took place in the extra-Andean region (Chon Aike large igneous province: ~188-178 Ma: Marifil Formation; ~190-157 Ma Lonco Trapial Formation in the Cañadon Asfalto Basin), ascribed to the thermal effects of the Karoo mantle plume that led to the rifting of the Gondwana (Pankhurst et al., 2000; Zaffarana et al., 2014). Nd and Hf isotopes of this silicic extra-Andean volcanism show a clear trend from moderately negative to positive epsilon signatures (εHf (t) = -17–-8; εNd = −8–-2) (Fig. 5). Rapela and Pankhurst (1996) proposed a different source for this volcanism, ruling out a genetic relationship with Late Triassic–early Jurassic arc magmatism, and associated the negative εHf and εNd values with partial melting of the basaltic lower crust. More juvenile magmatic contributions identified in

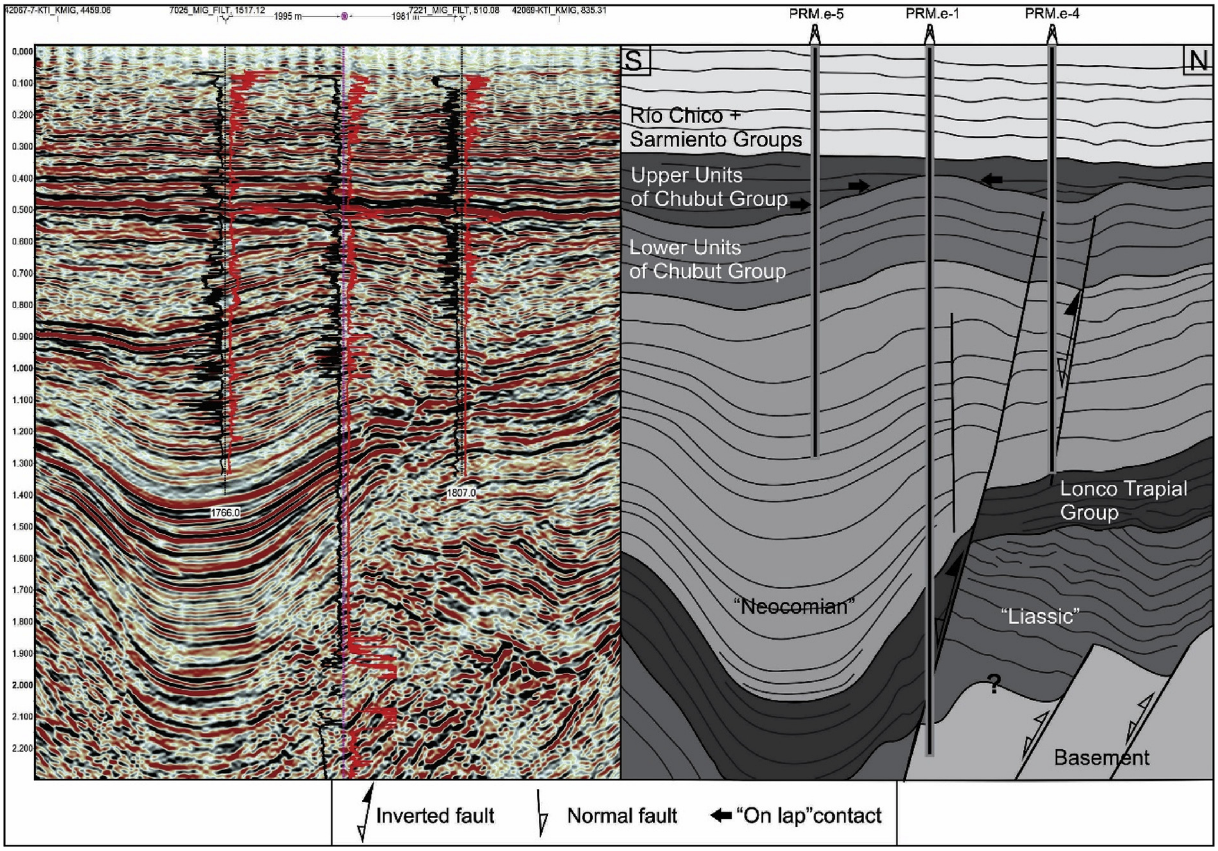

Fig. 4. Seismic line across a section of the Río Mayo embayment that displays the Lower Jurassic unconformity between the Liassic and Middle Jurassic sections, and the parallel arrangement of the lower Chubut Group followed by the upper Chubut Group, which shows a clear synorogenic character with onlap terminations against folds (modified from Navarrete et al., 2016), showing the inception of synorogenic basin sedimentation in central Patagonia.

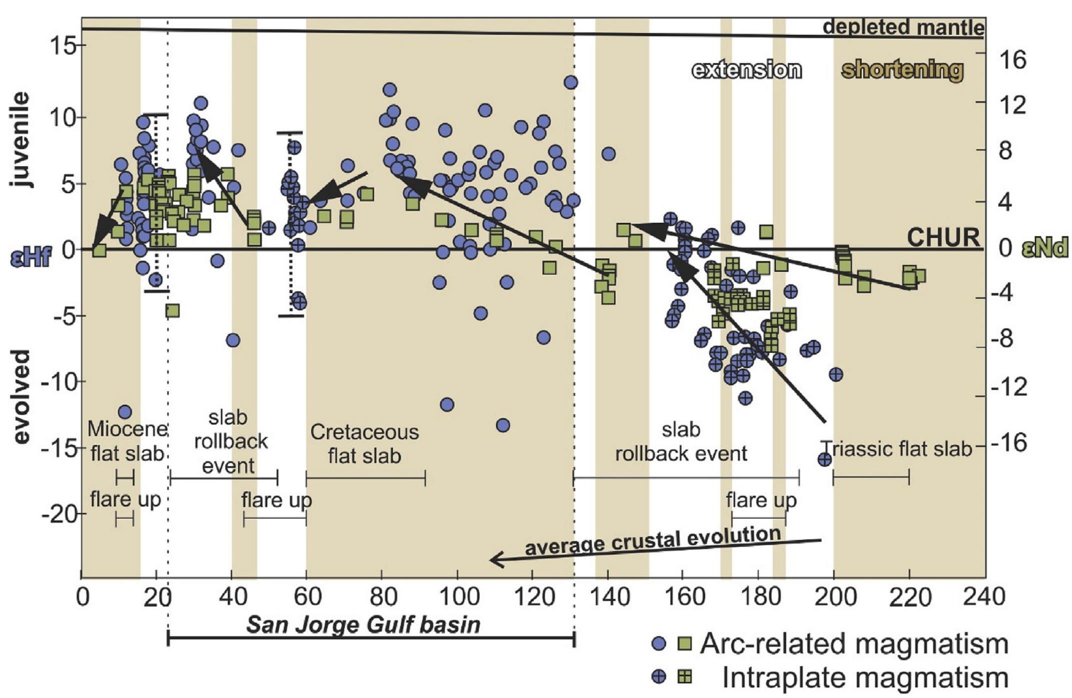

Fig. 5. (A) εHf and εNd evolution diagram showing the 240–0 Ma record in Patagonia. Black arrows identify general temporal trends in Hf and Nd isotope values. CHUR = chondritic bulk reservoir (modified from Butler et al., 2019). Shaded vertical bars correspond to contractional regimes whereas white bars denote extensional regimes in Patagonia (see text for details). Isotopic data taken from: Mesozoic intrusions (Dopico et al., 2011; Lucassen et al., 2004; Rapela and Pankhurst, 1996; Rapela et al., 2005; Pankhurst and Rapela, 1995; Pankhurst et al., 1999). Mesozoic volcanic rocks: Cañadon Asfalto and Lago la Plata Formations and Divisadero Group (Bouhier et al., 2017; Echaurren et al., 2017). Cenozoic volcanic rocks: Traiguén Formation, Coastal Magmatic Belt and El Maitén Belt (Encinas et al., 2015; Munoz et al., 2000; Kay et al., 2007). Cenozoic North Patagonian Batholith (Aragón et al., 2011a,b; Pankhurst et al., 1999).

both arc and intraplate associations suggest progressively greater degrees of mantle derivation, which may have been promoted by prolonged extensional conditions from the latest Triassic to earliest Cretaceous (~210-140 Ma; Butler et al., 2019; Folguera and Iannizzotto, 2004; Pankhurst and Rapela, 1995; Rapela and Pankhurst, 1992).

Arc magmatism continued to migrate in a southwesterly direction from the Subcordilleran Batholith to the North Patagonian Batholith and the Ibáñez- Lago La Plata formations during the Upper Jurassic, in conjunction with synextensional deformation (Echaurren et al., 2016, 2017). Andesitic–basaltic associations of the Lago La Plata Formation (170-153 Ma) represent the older and more primitive pulse of volcanism linked to initial Andean subduction magmatism. These lava flows have εNd values of 3.1 to 1.0 (Echaurren et al., 2017) (Fig. 5), which point to a mantle-derived juvenile origin. These arc-related rocks reinforce the different origin of the Chon Aike large igneous province event, whose isotopic signatures suggest higher lower crustal contributions.

Isotopic compositions of the Cretaceous North Patagonian Batholith (173–75 Ma) and its volcanic counterparts (120–100 Ma: Divisadero Group), show a clear trend from negative isotopic values concentrated in the Early Cretaceous, to positive ones in the Late Cretaceous (εHf (t) = -22–14; εNd(t) = -4–4; Fig. 5). As stated before, the negative εHf and εNd values registered in Patagonian magmatism were associated with anatexis of the older mafic lower crust, reflecting larger degrees of crustal contributions in large, long-lived magma chambers (Hervé et al., 2007). These negative isotopic values coincide with the onset of shortening in northern Patagonia, with south Atlantic opening, and a period of seafloor global spreading acceleration (Echaurren et al., 2019; Gianni et al., 2019). In contrast, the trend toward more positive epsilon values in the Late Cretaceous seems to be controlled by source heterogeneity and/or could reflect the incorporation of depleted mantle melts and/or reduction of the crustal component (Hervé et al., 2007; Pankhurst et al., 1998).

After ~80 Ma, isotopic compositions show relatively more negative values (εHf(t) ~ 5; εNd = 2–2.5) (Fig. 5), coeval with a Late Cretaceous phase of eastward migration of the magmatic arc front toward the foreland as a result of a slab flattening (Pankhurst et al., 1998; Echaurren et al., 2016, 2017). Immediately after this period, a gap in arc magmatism is registered (~75–50 Ma) coeval to the development of the Paleocene–Eocene bimodal intraplate magmatism of the Pilcaniyeu Belt (~60-42 Ma; Aragón et al., 2013; Iannelli et al., 2017) (Fig. 2). Hf isotopes for this unit show a variable signature with positive and negative εHf values that were interpreted as evolved signatures due to greater crustal contributions in the context of a thickened crust generated during Late Cretaceous shortening (εHf(t) = -5–7; Butler et al., 2019) (Fig. 5).

Arc activity resumed in the western slope of the North Patagonian Andes, forming part of the late Eocene–early Miocene El Maitén Belt (~37–20 Ma; Fernández Paz et al., 2018; Bechis et al., 2014), and in the Coastal Cordillera as the Oligocene–early Miocene Coastal Magmatic Belt (~29–18 Ma) and the sparse activity of the North Patagonian Batholith (Fig. 2). These arc-related units show a highly variable isotopic composition, with εHf and εNd values slightly more positives than in the previous period (εHf(t) = -7–12; εNd(t) = 0.5–6; Fig. 5). Late Eocene–early Miocene volcanism was associated with extensional conditions, that became maximum at the early Miocene, reflected in the opening of the intra-arc Traiguén Basin and the development of marine transgressions both in the forearc and retroarc zone (Bechis et al., 2014; Encinas et al., 2015) (Fig. 2). In this sense, the variable isotopic compositions recorded at this time are best explained by the lack of a homogeneous mantle source, probably because of widespread extensional conditions (Aragón et al., 2013). On the other hand, the shift towards more juvenile isotopic compositions could be explained by replenishment of the mantle wedge during enhanced mantle convection triggered by slab rollback (Fernández Paz et al., 2019).

During the Miocene, renewed arc magmatism is expressed as the voluminous Neogene tonalities and granodiorites of the North Patagonian Batholith (~20–9 Ma), synchronous with the main phase of Andean shortening at ~20 Ma (Ramos et al., 2015; Echaurren et al., 2016). Nd and Hf isotopic values display a pronounced shift to lower isotopic values (εHf(t) = -13–10 range; εNd(t) = 3, 5–0; Fig. 5). The more evolved signatures are consistent with Neogene crustal thickening and greater crustal interactions, although by this stage such sources would also have included the previously crystallized batholithic rocks (Butler et al., 2019; Hervé et al., 2007), which show more juvenile compositions.

4. Discussion

4.1. Flare up and extensional basins development in Patagonia as a consequence of changes in subduction angle through time

Three periods of flat subduction are recognized in central Patagonia based on episodes of eastward arc migration at ~220-200 Ma, ~90-60 Ma and ~15-10 Ma (Fig. 5). In general, phases of magmatism tend to pass from isotopically less evolved to more evolved values (Fig. 5). After flat-slab subduction, highly voluminous acid volcanic units were erupted, first the V1 association in the earliest Jurassic (~188-178 Ma) following Late Triassic shallow subduction, then the Paleocene to early Eocene (~60-42 Ma) Pilcaniyeu magmatic belt, and finally the Collón Cura and Guenguel-Chalía formations in the middle Miocene (15-11 Ma) (Ramos et al., 2015; Echaurren et al., 2016, 2017; Horton, 2018; Butler et al., 2019). These silicic volcanic associations have been linked to extensional conditions that can be associated with incipient destabilization of the orogen in the final stages of flat-slab subduction or heat advection by uprising magmas that could elevate the lithospheric thermal base and promote local extension. These units can be interpreted as magmatic flare-up events following shallow subduction in Patagonia, associated with the removal of forearc crustal material into the asthenospheric wedge and underthrusting of the foreland during crustal shortening (Figs. 5 and 6).

On the other hand, after voluminous silicic magmatism, mantle-derived arc magmatism defines two periods of trench retreat, one in the Early Jurassic to Early Cretaceous and a younger since the late Eocene to Oligocene or early Miocene (Figs. 6 and 7). These magmatic records have been interpreted as associated with the steepening of the subducted slab and contemporaneous development of extensional basins (Fig. 7). Besides, both cases of trench retreat are characterized by variable magmatic signatures with a progressive change from isotopically modified or more evolved values to more juvenile compositions, which can be interpreted as a consequence of the broadening of the asthenospheric wedge during rollback while new and more depleted/juvenile-eastern mantle material emplaces (Figs. 6 and 7).

4.2. The development of the San Jorge Gulf Basin as a synorogenic intracratonic basin

Retroarc magmatism in Patagonia is associated with extensional conditions during trenchward retreat of the magmatic arc, coinciding with re-steepening of the subducting slab (Folguera and Ramos, 2011; Horton, 2018). However, the San Jorge Gulf Basin constitutes an anomaly in (1) its orogen-perpendicular orientation, (2) paucity of magmatism, and (3) timing. The first two elements imply different mechanisms than the other extensional basins of Patagonia, as most of those volcano-sedimentary basins associated with incipient or accelerated rollback have a NW to N strike (Fig. 2) and all of them contain a voluminous magmatic component associated with mantle decompression melting. The third characteristic implies that the main phase of extension in the San Jorge Gulf Basin occurred in mid to Late Cretaceous time, when the Andes developed in the west. In fact, the San Bernardo fold-thrust belt, which is usually considered as part of the San Jorge Gulf Basin because it deforms materials that are buried in the

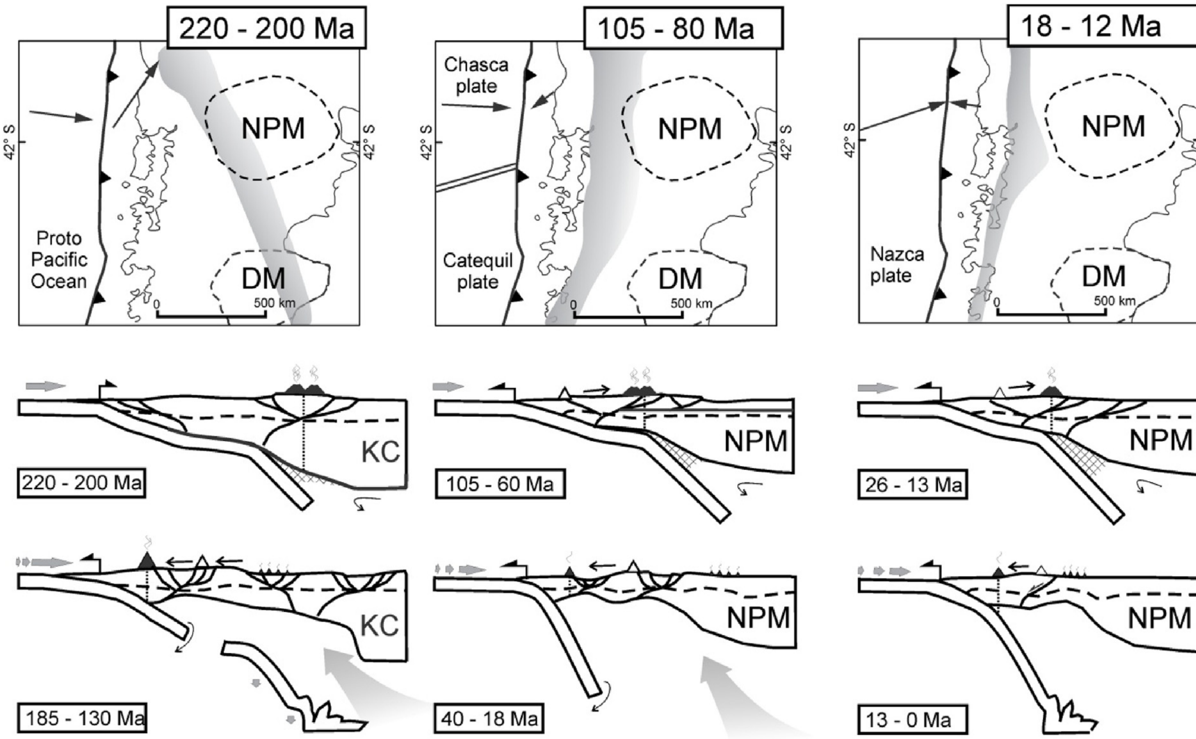

Fig. 6. Reconstruction of arc migration associated with three episodes of slab shallowing, in relationship to the North Patagonian and Deseado massifs. Each episode — a) Late Triassic (after Navarrete et al., 2019a,b); b) Late Cretaceous (after Folguera and Ramos, 2011; Gianni et al., 2015); c) middle to late Miocene (after Orts et al., 2015) — was followed by magmatic flare-up events registered in extra-Andean Patagonia (~188-178 Ma: Marifil Formation, Rapela and Pankhurst, 1996; ~60-42 Ma; Aragón et al., 2013; Iannelli et al., 2017; 15-11 Ma, Folguera et al., 2018).

east, grew during these stages and absorbed contraction (Gianni et al., 2015). This contrasting behavior within a single sedimentary unit (the Chubut Group), from synorogenic shortening in the San Bernardo fold-thrust belt to synextensional processes in the San Jorge Gulf Basin (Fig. 8), has been attributed by Gianni et al. (2015) to reactivation of a crustal heterogeneity due to mid to Late Cretaceous indentation of the fold-thrust belt (Fig. 9). The advance of the frontal structures of the San Bernardo fold-thrust belt into the northern Deseado Massif is localized and accounts for the scarceness of mantle-derived decompression melting materials through this reactivated basement anisotropy.

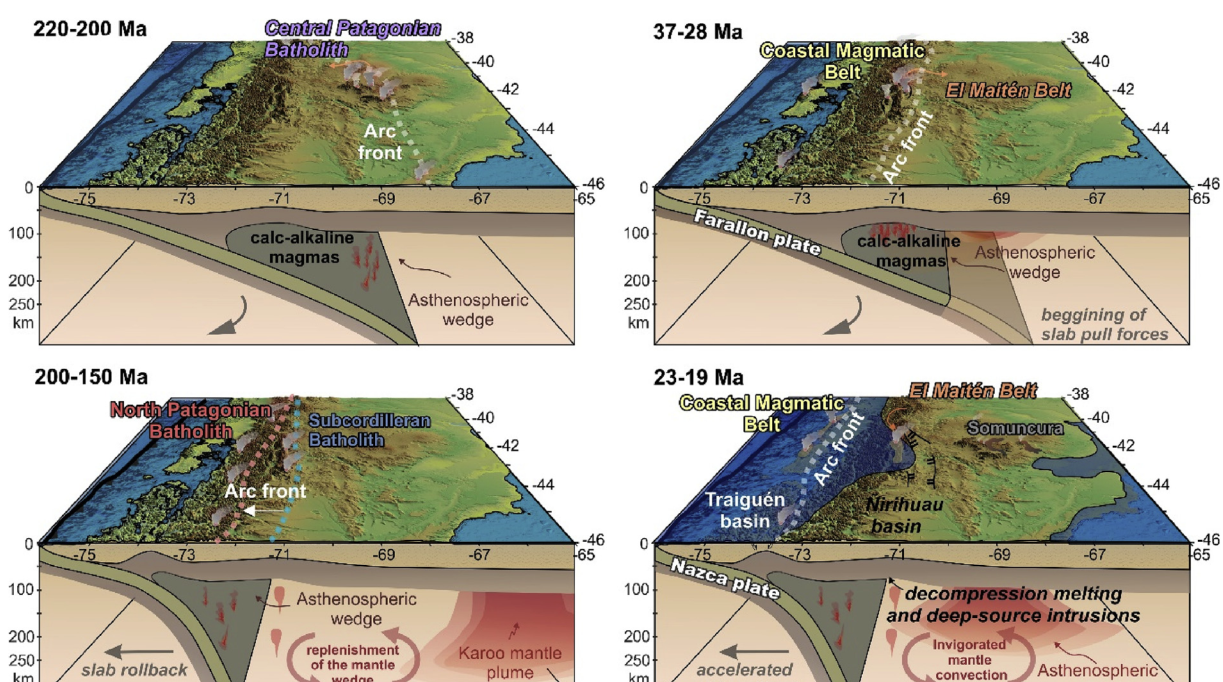

Fig. 7. Cartoons showing spatial development of mantle-derived arc magmatism defining two periods of trench retreat, one in the Early Jurassic to Early Cretaceous and a younger since the late Eocene to early Miocene, interpreted as associated with the steepening of the subducted slab.

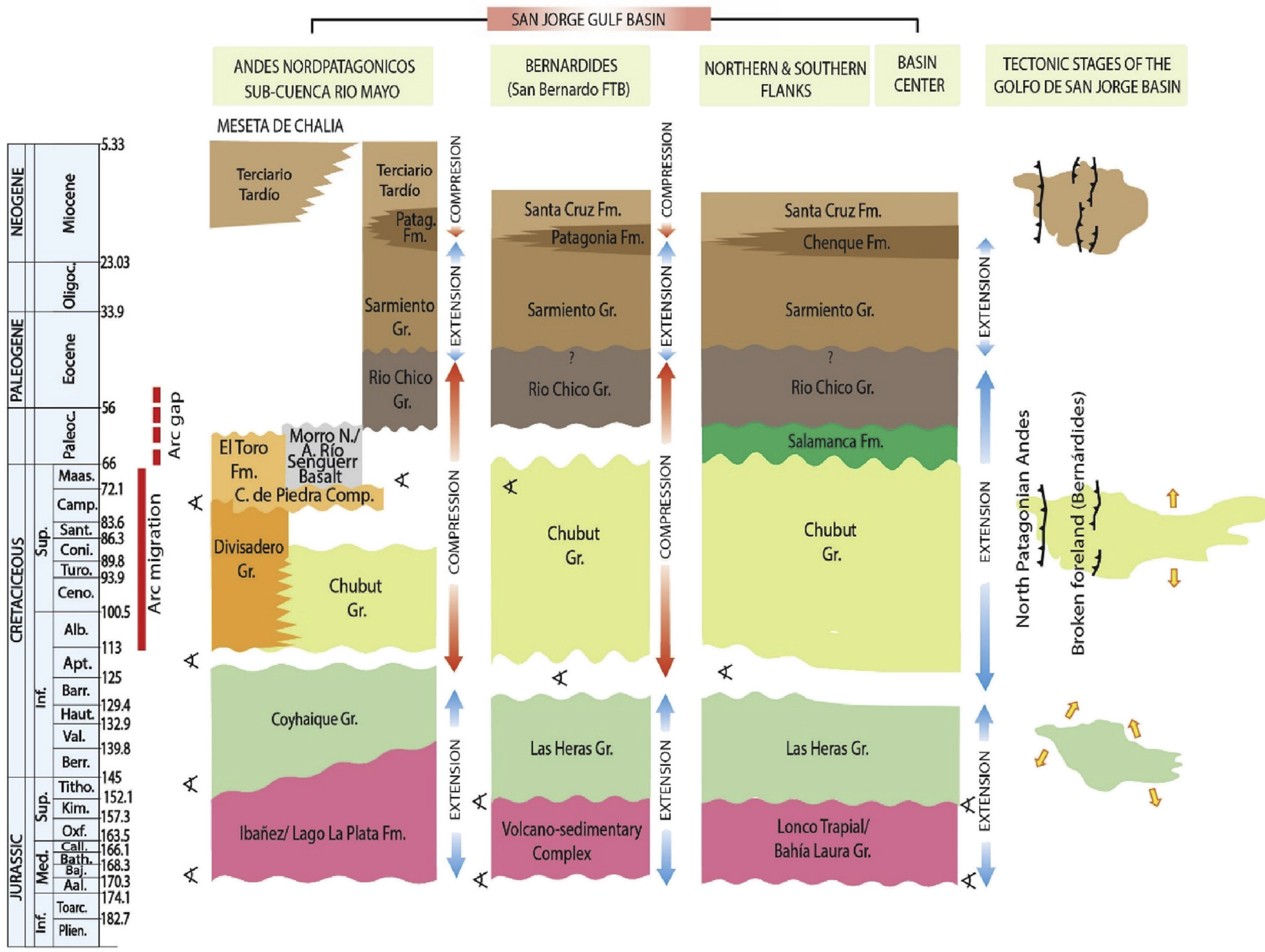

Fig. 8. Comparison of the contrasting stratigraphic framework for Upper Cretaceous to Paleogene strata across the Patagonian platform region, from synorogenic Cretaceous to Eocene sections of the San Bernardo fold-thrust belt to synextensional deposits of the San Jorge Gulf Basin (modified from Gianni et al., 2015).

4.3. Reactivation of within-plate heterogeneities in Patagonia as a function of absolute plate movement and seafloor spreading

The opening of the San Jorge Gulf Basin is anomalous considering the absolute motion of the South American plate (Fig. 10) (Müller et al., 2016). A major change in absolute motion occurred at ∼165 Ma. Before that time, South America motion involved a strong northward component and a minor eastward component away from the Pacific trench. These processes, and the strong rollback of the subducted slab at this time would have favored retroarc extensional conditions. The Cañadón Asfalto Basin, the Liassic depocenters of the Chubut Basin, and possibly Neocomian depocenters of the Aysén-Río Mayo Basin are the result of continental motion roughly parallel to the trench with coeval rollback of the Pacific subducted slab. The respective orientations of these basins seem to be a function of reactivated local crustal heterogeneities: including the northern edge of the Deseado Massif for the Neocomian depocenters (Paredes et al., 2018); the southern edge of the North Patagonian Massif for the Cañadón Asfalto Basin and a mid-Paleozoic suture that crosses Patagonia for the Liassic depocenters (Figs. 9 and 10). After ∼165 Ma, South America changed to south-directed motion, coupled with opening of the North Atlantic Ocean (Labails et al., 2010) and incipient spreading of the Weddell Sea in the south (Fig. 10) (Mueller and Jokat, 2019). This situation trapped Patagonia, producing N-S stresses that explain the within-plate contraction described by Navarrete et al. (2016) that interrupted extensional conditions associated with an ongoing rollback of the subducted plate. Finally, after 128-120 Ma, opening of the South Atlantic Ocean pushed South America against the Pacific trench and provoked initial contractional development of the Patagonian Andes (Fig. 10). This process accelerated after 95 Ma, associated with the structural development of the San Bernardo fold-thrust belt and its interaction on the northern edge of the Deseado Massif and opening of the San Jorge Gulf Basin (Gianni et al., 2015). Due to the proximity of the proto-Atlantic spreading ridge axis at that time, we cannot discard the action of this ridge-push force in the evolution of the early passive margin.

5. Conclusions

The tectonic evolution of the Northern Patagonian Andes and adjacent extra-Andean zone comprise three shallow slab subduction events and three associated slab-rollback and flare-up events. Shallow slab subduction provoked the eastward migration of arc volcanism and triggered the propagation of the fold-thrust belt against the North Patagonian and Deseado massifs. The first eastward arc shifting corresponded to the Late Triassic Central Patagonian Batholith (220-200 Ma), the second to the Divisadero Group in late Early to Late Cretaceous times (105-80 Ma), and the third to isolated early to late Miocene plutons distributed in the eastern foothills of the Patagonian Andes. The three cratonward arc migrations were followed by voluminous acidic volcanic provinces most likely related to flare-up events: the V1 corresponding to the Marifil Formation (180-170 Ma), the Pilcaniyeu magmatic belt (60-50 Ma) and finally The Guenguel-Chalía and Collón Cura units (15-11 Ma). Eastward arc broadening and subsequent flare-ups coincided with progressive modification of the

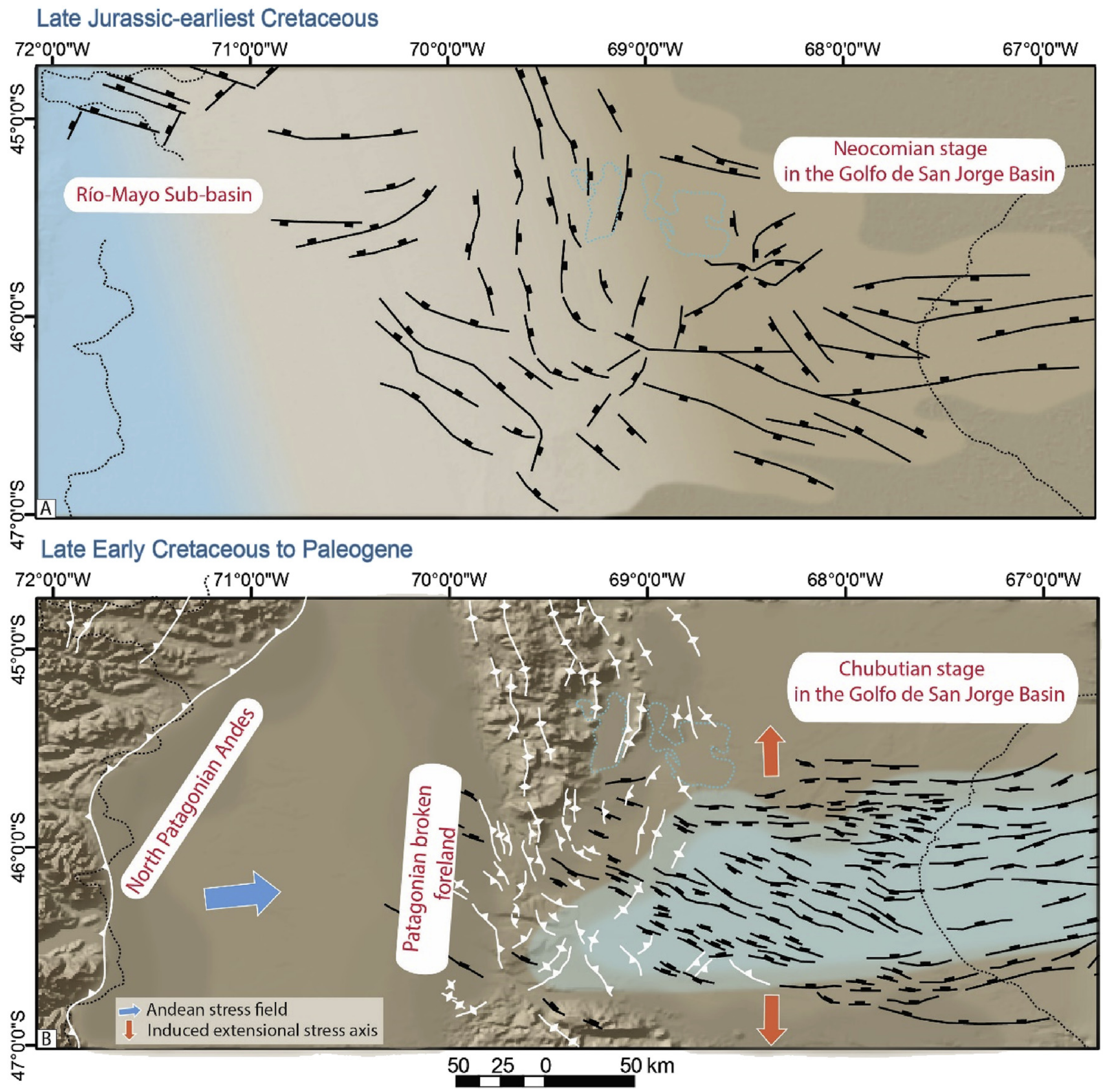

Fig. 9. Map-view reconstructions showing (above) Late Jurassic-earliest Cretaceous development of Neocomian extensional depocenters in the Patagonian foreland zone, and (below) late Early Cretaceous to Paleogene contraction in the San Bernardo fold-thrust belt and coeval extension in the San Jorge Gulf Basin (from Gianni et al., 2015).

asthenospheric source likely induced by crustal erosion during slab shallowing and penetration of the cratonic foreland sector beneath the fold-thrust belt during shortening phases. Between eastward shifts in arc magmatism and subsequent flare-ups, westward retreat of the magmatic arc coincided with periods of progressive asthenospheric rejuvenation as indicated by more juvenile isotopic composition trajectories which imply the progressive replacement of previous metasomatized mantle by the shallowly emplaced mantle in a broadening asthenospheric wedge. These periods are associated with the rollback of the subducted oceanic slab and the formation of extensional basins from the foreland to the Andean axial zone. Thus, the Liassic basins, the Late Jurassic basins, and the Early Cretaceous Río Mayo-Aysén basins and later the Pilcaniyeu and Maitén magmatic belts and Traiguén basin are formed during both rollback periods. The San Jorge Gulf Basin is anomalous as the only extensional basin in Patagonia that is not associated with extension during slab resteepening. Its origin, as previously proposed, could be related to the indentation of the San Bernardo fold-thrust belt between the North Patagonian and Deseado massifs at the early opening of the south Atlantic Ocean.

Declaration of competing interest

We declare no conflict of interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsames.2019.102422.

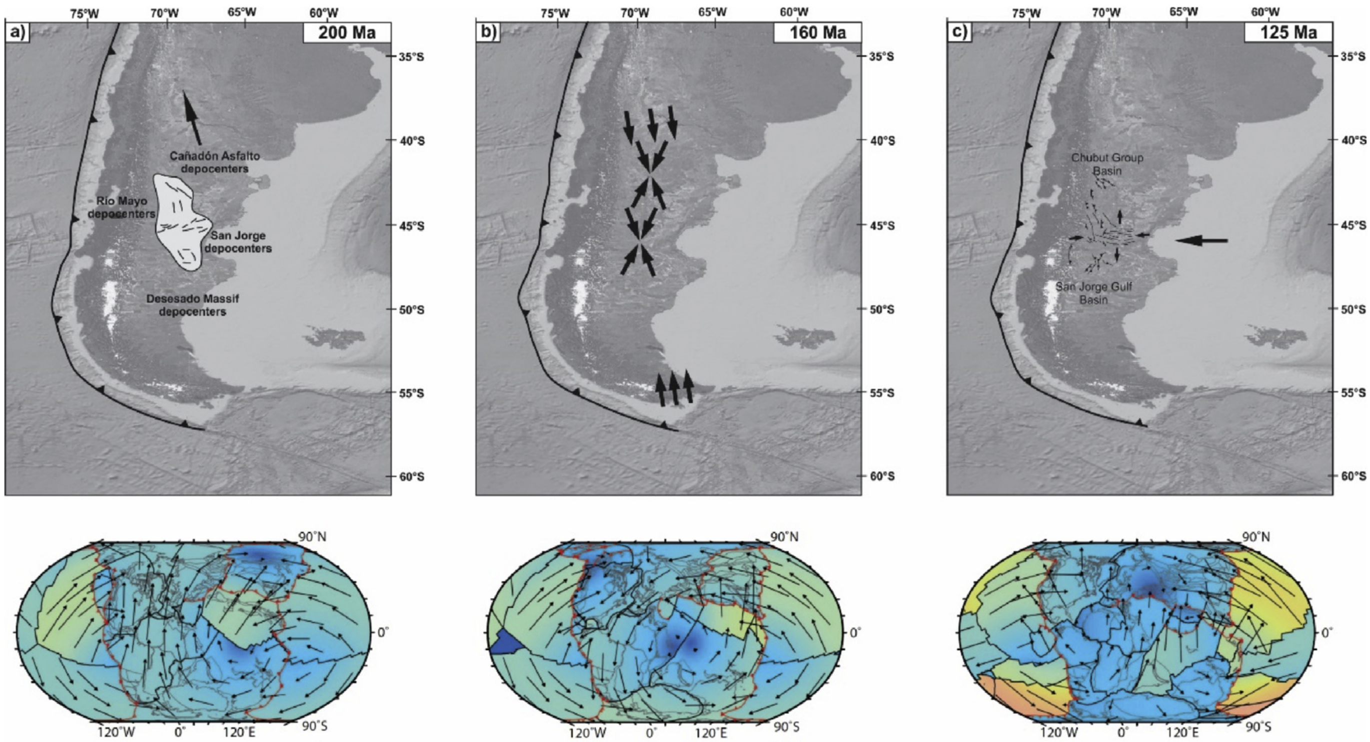

Fig. 10. Reactivation of within-plate heterogeneities in Patagonia due to the absolute motion of South America and opening of ocean basins. a) Latest Triassic to earliest Jurassic northward motion of South America and formation of extensional depocenters. b) Jurassic southward displacement of South America, opening of the Weddell sea, and within-plate contraction in Patagonia. c) Mid-Cretaceous opening of the South Atlantic, east-west contraction in Patagonia, and opening of the synorogenic San Jorge Gulf Basin. Modified from Navarrete et al. (2019a), Gianni et al. (2015, 2019), Müller et al. (2016).

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