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# Mesozoic rifting evolution of SW Gondwana: a poly-phased, subduction-related, extensional history responsible for basin formation along the Argentinean Atlantic margin

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## ABSTRACT

The opening of the South Atlantic in the Early Cretaceous was the final stage of the complex rifting history of SW Gondwana. In this contribution we reassess the chronology of Mesozoic basin formation in southern South America and Africa and integrate it in the long-term breakup history of SW Gondwana. Triassic rifting is characterized by intracontinental rifting in Africa (Karoo I phase), and retro-arc extension on the SW-margin of Gondwana. In the Early Jurassic, the impingement of the Karoo plume triggered rifting in Eastern Africa, producing the Karoo II basins (and the Colorado and Salado basins on the Argentinean shelf). East Africa rifting ultimately lead the breakup of Eastern from Western Gondwana in the Middle Jurassic. In Patagonia, the Austral, Malvinas and other related basins formed in association with the synextensional emplacement of the Chon Aike magmatic province in the Patagonian retro-arc. In the Late Jurassic the Rocas Verdes back-arc basin opened in southern Patagonia, while oblique rifting in the core of the Late

Paleozoic Gondwanides orogen produced the Outeniqua and Rawson/Valdés basins. The South Atlantic Rift initiated in the Early Cretaceous associated with present-day E-W extension. Rifting occurred diachronically from south to north, initiating in the previously thinned Rawson/Valdés-Outeniqua segment. A precursor oblique rift system and a larger degree of extension in this segment could explain the lack of Seaward Dipping Reflectors (SDR) south of the Colorado-Cape fracture zones. Rifting and SDR emplacement occurred progressively to the north along different rift segments, producing strongly asymmetric conjugate margins.

**Keywords**: Jurassic, Cretaceous, rifting, Gondwana, South Atlantic, Karoo

**CONTENT**

**1. INTRODUCTION** ..... 3
**2. GEOLOGICAL FRAMEWORK: PRE-RIFTING CONFIGURATION** ..... 6
**3. MATERIALS AND METHODS** ..... 9
**4. MESOZOIC BASINS ACROSS THE SOUTH ATLANTIC** ..... 10
**4.1. Mesozoic basins in southern South America** ..... 10
**4.2. Mesozoic basins in southern Africa** ..... 22
**5. MESOZOIC RIFTING IN SW GONDWANA** ..... 28
**5.1 Triassic-Early Jurassic Rifting** ..... 30
**5.2 Early - Middle Jurassic Rifting** ..... 36
**5.3 Late Jurassic** ..... 40
**5.4 Early Cretaceous** ..... 45
**6. DISCUSSION** ..... 51
**7. CONCLUSIONS** ..... 58
**8. ACKNOLEDGEMENTS** ..... 60
**9. REFERENCES** ..... 60

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## 1. INTRODUCTION

The process triggering supercontinental breakup has frequently been discussed in the last fifty years. Dewey and Burke (1974) suggested that extension was related to hotspots formed by heat concentration produced by insulation under large continental masses. The distribution of oceans and large igneous provinces (LIP) seemed to support this theory. Buiter and Torsvik (2014) reviewed the role of mantle plumes in continental breakup and note that although there is a spatial relationship, in many margins such as the Central or the South Atlantic, rifting had initiated long before the main phase of volcanism the Central Atlantic Magmatic Province (CAMP) and Paraná-Etendeka Large Igneous Province respectively. Rifting and successive breakup of a supercontinent have proved to be a much more complex process, that often occurs in several phases (Moulin et al., 2010, Fig. 1). Recent studies suggest that landmass instability produced by thermal insulation is insufficient to initiate rifting (Heron and Lowman, 2011). Subduction-related slab rollback instability is now presumed by some authors to play a key role in triggering rifting and successive landmass dispersal (Bercovici and Long, 2014; dal Zilio et al., 2018). A recent review of the Pangea breakup by Frizon de Lamotte et al. (2015) propose a combination of *active* (induced by an active upwelling of the asthenosphere) and *passive* rifting (induced by sub-horizontal far-field forces related to subduction) to produce in successive stages the breakup of large continental masses. Active rifting is caused by the impingement of a thermal anomaly (mantle plume), producing doming, volcanism and extension (see Sengör and Burke, 1978). Passive rifting is related to lithospheric far-field forces pulling the lithosphere apart, notably related to subduction zones acting as boundary conditions.

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Supercontinents are intrinsically complex assemblages of cratons and shields bounded by metamorphic orogenic belts (formed during craton amalgamation). The structural grain of these belts introduce heterogeneities which, under extension, can guide fault emplacement and eventually breakup (Buiter and Torsvik, 2014). The supercontinent of Pangea is no exception (Fig. 1), with a complex multi-stage rifting process that lasted more than 100 M.y. This process initiated in the Triassic, with rifting between Laurentia (North America) and Western Gondwana (Fig. 1) and the subsequent opening of the Central Atlantic (Withjack et al., 1999, 2012; Leleu et al., 2016). The emplacement of the CAMP occurred after the main phase of rifting (Frizon de Lamotte et al., 2015) and so breakup would not have been plume-related (McHone, 2000). Triassic basins were not restricted to the Central Atlantic realm, but other rift basins developed across Gondwana (Uliana et al., 1989; Zerfass et al., 2003) and on the paleo-Pacific convergent margin (Ramos and Kay, 1991; Spikings et al., 2016; Espinoza et al., 2018).

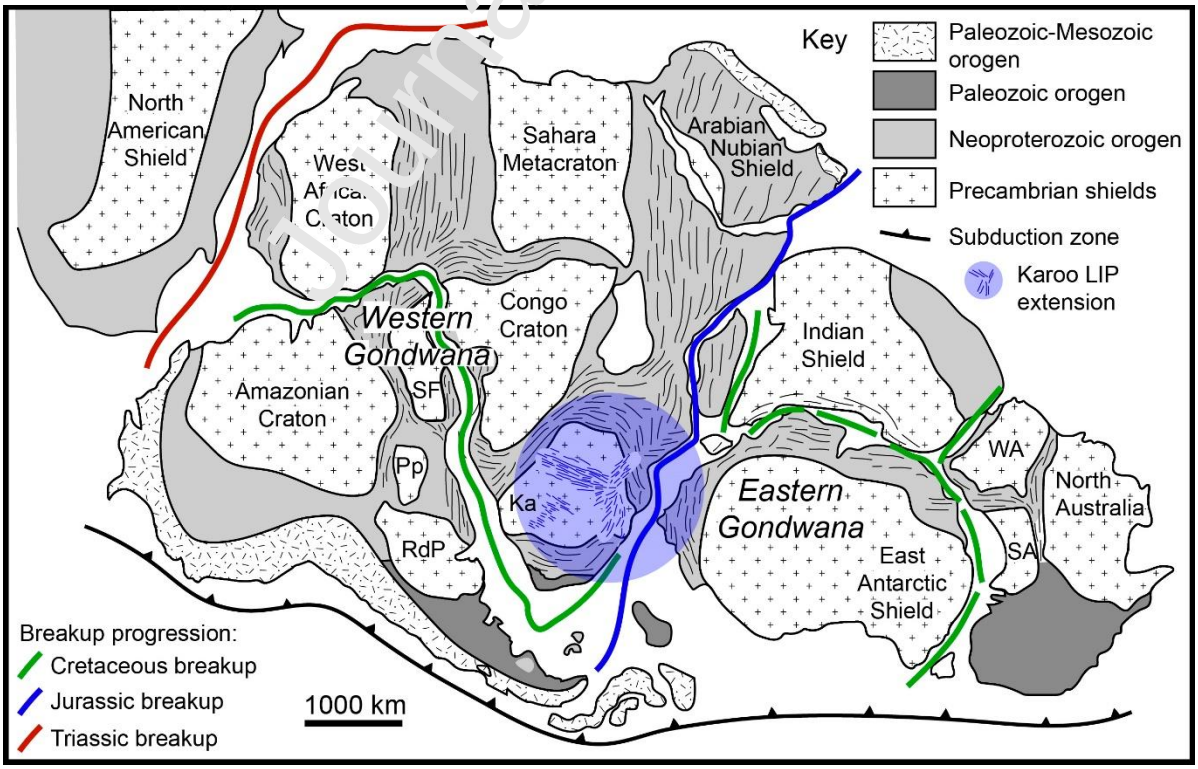


Fig. 1. Progressive Pangea breakup history in a Gondwana view at the end of the Paleozoic after Gray et al. (2008), with main breakup events in the Triassic, Jurassic and Early Cretaceous. Modified from Moulin and Aslanian (2010) and Will and Frimmel (2018). Cratons: RdP: Río de la Plata, Ka: Kalahari, Pp: Paraná-Panema, SF: Sao Francisco, WA: West Australia, SA: South Australia. Note the location of the Karoo LIP relative to the Jurassic breakup of Eastern from Western Gondwana.

On the other hand, the impingement of the Karoo plume on East Africa in the Early Jurassic produced active rifting, characterized by the development of doming, volcanism and eventually caused continental breakup of Western from Eastern Gondwana (Storey et al., 1995; 1997; 2001; Frizon de Lamotte et al., 2015). The continent dispersal process continued in the Early Cretaceous with the opening of the South Atlantic Ocean between South America and Africa and several other oceanic basins produced by the dispersal of the Eastern Gondwana blocks (note the green breakup emplacements in Fig. 1). As recently discussed by Frizon de Lamotte et al. (2015) and Will and Frimmel (2016), the South Atlantic is another case of passive rifting, triggered by far-field forces pulling the lithosphere apart. As in the case of the Central Atlantic, this area was also affected by the massive volcanism: the Paraná-Etendeka LIP. In this scenario the opening seems not to have been triggered by a plume, rather the volcanism came when rifting was already established (Stica et al., 2014). All in all, the South Atlantic opening was only the final stage of the long and complex Gondwana breakup history, where subduction-related processes played a key role (Storey et al., 1992; Peace et al., 2019).

Those separate Mesozoic rifting events played a key role in basin formation along the South American and African Atlantic margins. Argentinean basins' rifting history was previously addressed by the pioneer integrations of Urien et al. (1981) and notably Uliana et al. (1989), later complemented by the contributions of Ramos (1996), Franzese et al. (2003), and Macdonald et al. (2003). Previous work in the Colorado basin (Fig. 3), was crucial to identify at least three super-imposed rifting

stages in the Argentinean margin (Lovecchio et al., 2018). By extrapolating previous results from the Colorado and Malvinas basins (Lovecchio et al., 2018, 2019) and by integrating them in a geodynamic framework updated with the geochronological data produced by different authors in the last 30 years, we review in this contribution the chronology of Mesozoic basin formation in southern South America and Africa and integrate those events in the long-term rifting history of SW Gondwana at a supra-regional scale. We also present here newly generated paleotectonic models that illustrate the different stages of SW Gondwana Mesozoic rifting.

## 2. GEOLOGICAL FRAMEWORK: PRE-RIFTING CONFIGURATION

Southwestern Gondwana is an assemblage of cratons, metamorphic belts and accreted terranes formed because of continuous subduction since at least the beginning of the Phanerozoic (Suárez et al., 2019). In the Neoproterozoic, the Panafrican orogeny welded the Río de la Plata and African shields through the Dom Feliciano belt (Fig. 2, Basei et al. 2018, and references therein).

Since the Cambrian, and throughout the Paleozoic, subduction from the west produced the accretion of different allochthonous terranes: Pampia, Cuyania, Chilenia, Paracas (Ramos, 1999; 2010). Subduction was active throughout the Paleozoic. The terrane of Patagonia was the last to accrete, in this case from the SW, producing the Gondwanides orogen (Ramos, 2008; Ramos and Aleman, 2000), with a Carboniferous-to-Permian volcanic arc in Northern Patagonia and a Permian-to-Early Triassic fold-and-thrust belt (Fig. 2). This fold belt was recognized in South America in the Ventania System (Keidel, 1916; see Pangaro et al., 2016 for further references), that continues in Africa as the Cape fold belt (du Toit, 1927, 1937; Hälbich, 1983) and reaches the Ellsworth-Whitmore Mountains in Antarctica (Curtis,

2001). In the Mesozoic, under an extensional stress regime, negative inversion affected previously compressive structures (for reference see Glennie and Boegner, 1981, and Williams et al., 1989). This process has been described on the Argentinean shelf in the Colorado basin by Lovecchio et al. (2018). On the African conjugate margin, structures at high angles to the margin orientation, and affecting older series have been described by De Wit and Ransome (1992), and more recently by Paton et al. (2016).

At the end of the Paleozoic, with the accretion of Patagonia from the SW (Ramos, 2008), the amalgamation of Pangea was completed. But supercontinents, especially those subjected to continuous subduction, are intrinsically unstable. Soon after the final supercontinent configuration was achieved, different instabilities induced the onset of both intracontinental and retroarc rifting since the early Mesozoic (Fig. 1).

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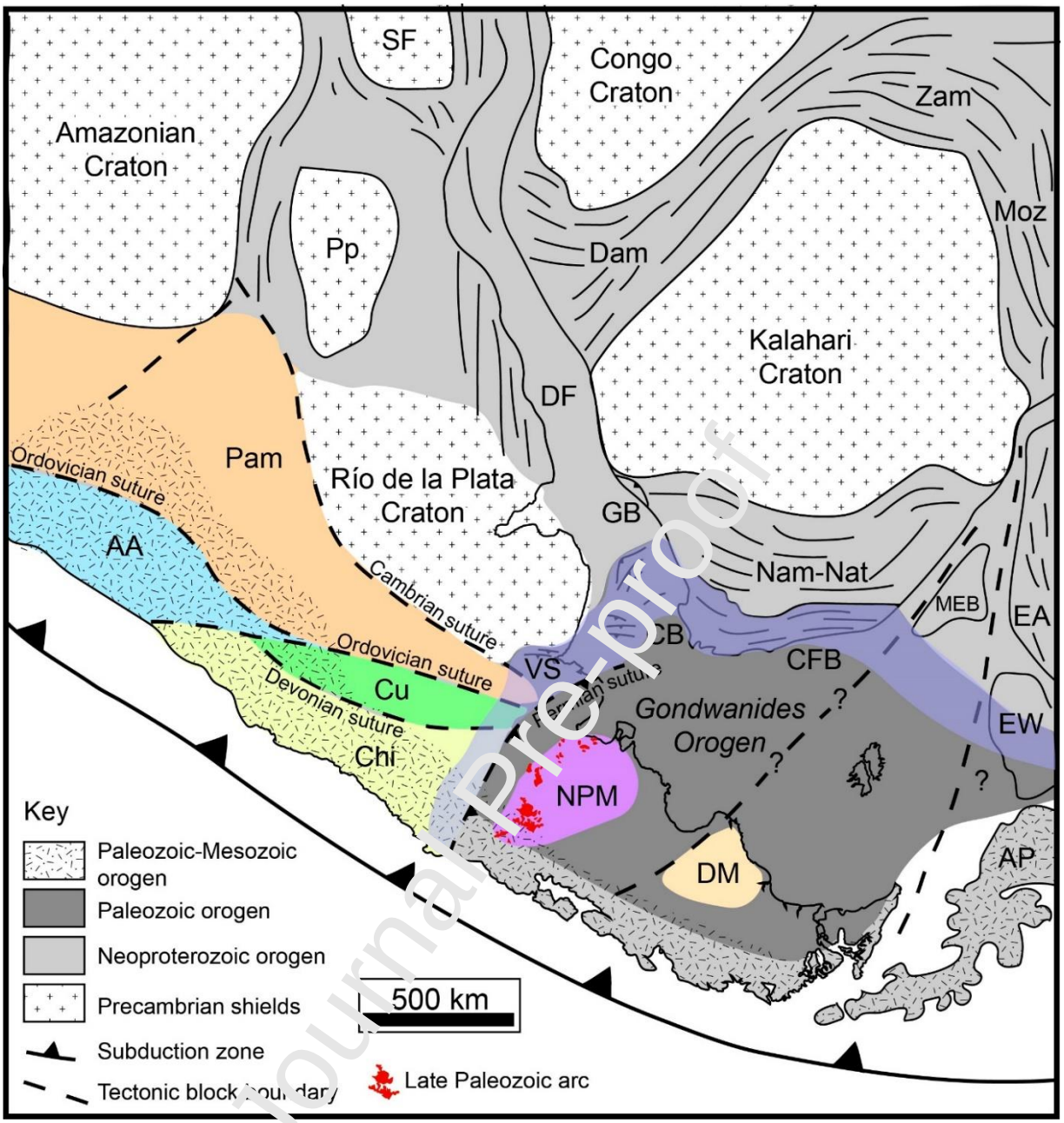



Fig. 2: Simplified structural scheme of SW Gondwana at the end of the Paleozoic, with a detail of cratons, terranes and metamorphic belts, after Gray et al. (2008); Ramos (2010); Pankhurst et al. (2006); Pángaro and Ramos (2012); and Lovecchio et al. (2018). Main Precambrian mobile belts: Dom Feliciano (DF), Gariep (GB), Namaqua-Natal (Nam-Nat), Mozambique (Moz). Main Paleozoic accreted terranes (in different colours): Pampia (Pam), Cuyania (Cu), Arequipa-Antofalla (AA), Chilenia (Chi). Other Tectonic blocks: Paraná-Panema (Pp), Sao Francisco (SF), North Patagonian Massif (NPM), Deseado Massif (DM), Eastern Antarctica (EA), Antarctic Peninsula (AP). Permian-Triassic fold and thrust belt (purple): Ventania system (VS), Prerift of the Colorado basin (CB), Cape Fold Belt (CFB), Ellsworth-Whitmore Mountains (EW). UTM Projection. Undeformed plates, after Ramos (1999, 2008).

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## 3. MATERIALS AND METHODS

After having performed seismic interpretation in the Colorado basin area where three independent Mesozoic rifting events were identified (Lovecchio et al., 2018), in this contribution we correlate and integrate these and other rifting events into a comprehensive scheme of rifting responsible for the formation of the main Mesozoic basins around the South Atlantic realm, with special interest in the evolution of the Argentinean Mesozoic basins. We prepared structural maps, where we compiled published and newly generated data on fault-bounded depocenters, and other structures related to basin formation.

Obtaining geochronological data to constrain the age of the synrift infill is usually challenging. Samples from the synrift series are scarce (i.e. synrift depocenters are usually deeply buried and hydrocarbon exploration wells have commonly been drilled on structural highs out of the main troughs), or they often consist of red beds (e.g. Barredo et al, 2012; Schmidt et al., 1995) which makes difficult the application of paleontological or biostratigraphic methods. However, volcanic rocks interbedded within the synrift series (e.g. lavas, ash beds), paleontological content and detrital zircon data are often suitable for dating. Chronologic tectonic charts summarizing rifting ages for several Mesozoic basins in southern South America and southern Africa were generated. We put together absolute ages from previous publications that constrain synrift infill. Moreover, thermochronological methods allow the interpretation of exhumation events, which can be linked to rifting events in the appropriate tectonic framework. Besides these limits, we present a synthesis of the main rifting episodes observed in the basins of the study area and surroundings.

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Finally, we produced illustrative paleotectonic maps for the main rifting events, we color-coded faults according to the chronology of rifting and propose a model to explain the formation and evolution of the main basins in the study area throughout the Mesozoic finishing with the opening of the South Atlantic.

## 4. MESOZOIC BASINS ACROSS THE SOUTH ATLANTIC

### 4.1. Mesozoic basins in southern South America

South America is bounded to the west by the active margin resulting from the subduction of the oceanic Pacific plate from the west under the continental South American plate (Fig. 3). Subduction has been continuously active since the Cambrian and is associated with terrane accretion throughout the Paleozoic (Fig. 2; Ramos, 1999). This process is responsible for the largely oriented N-S structural fabric, which explains the abundance of N-S striking-structures in most of the Mesozoic basins in western South America (Fig. 3). The stress regime, related to the subducting slab dynamics, played a key role in structure generation and reactivation under different tectonic regimes. This process observed by Vergani et al. (1995) in the Neuquén basin (Nq in Fig. 3) can be extrapolated to other Subandean basins.

Following the pioneer integration presented by Urien et al. (1981) and Uliana et al. (1989), we present in Fig. 3 a map gathering most of the main Mesozoic basins in southern South America (additional references used: Turner, 1979, 1980; Chebli and Spalletti, 1989; Turic et al., 1996; Caminos, 1999; Chebli et al., 2005; and Kozlowski et al., 2011). To assess the continental-scale geodynamic evolution and its impact in basin formation in SW Gondwana, rifting chronology was summarized in charts (Figs. 4 and 6), that constitute a useful tool for grouping rifting events occurring simultaneously at different locations.

We present hereafter a summary of the main geochronological constraints for the rifting history of the main Mesozoic basins of southern South America in a chronological order. The Cuyo and the Bermejo basins record synrift sedimentation in the Triassic (Fig. 4). These two basins comprehend several depocenters along two axes: the Cuyo basin includes the Río Blanco, Santa Clara, Tupungato, La Esperanza-Divisadero and the General Alvear sub-basins, while the Bermejo basin groups the Ischigualasto, Marayes, Guayagas, Las Salinas and Beazley sub-basins (see Barredo et al., 2012). Vertebrate fossils and radiogenic ages of intruded subvolcanic rocks places rifting in the Early Triassic in the Bermejo and Middle Triassic in the Cuyo basin (Barredo et al., 2012, Stipanicic, 2001). The Triassic stratigraphy of southern South American basins was reviewed by Jenchen and Rosenfeld (2002) and Zerfass et al. (2004). These authors highlight inheritance of the basement fabric, with *en-echelon* depocenters produced by NNW trending faults associated with low-to-moderate angle detachment surfaces. Ramos and Kay (1991) linked the main detachments of the listric faults to the hanging-wall suture between Pampia and Cuyania, two terranes accreted to the SW margin of Gondwana in the Early Paleozoic (Fig. 2).

To the south, the Neuquén basin displays two rifting events (Legarreta and Uliana, 1996; Vergani et al., 1995 and references therein). A series of N-S directed isolated half-grabens restricted to the western border of the basin are filled with Late Triassic volcanic rocks and continental sediments of the Precuyano cycle (Carbone et al., 2011; D'Elia et al., 2015). Towards the basin center and east, depocenters change orientation to SE-NW and become younger (Liassic), with active rifting between the Hettangian and the Pliensbachian. This change has been interpreted as a product of basement inheritance permitting transtension (Becchis et al., 2014).

Outer depocenters are filled with lacustrine successions while depocenters towards the basin center and west are flooded by the paleo-Pacific (Los Molles Fm, see Veiga et al., 2013). A clastic deltaic wedge progrades into that sea during the postrift (Lajas Fm and equivalents). Paleontological and detrital zircon content is abundant in this succession and was used by Naipauer et al. (2018) to calibrate the evolution.

Further south, in the North Patagonian Massif, two retroarc extensional basins develop in the Early Jurassic: the Cañadón Asfalto basin hosts continental successions interbedded with volcanic rocks of Early Jurassic age (Cúneo et al., 2013; Fígari et al., 2015); and the Chubut basin towards the west, with development of the marine systems of the Toarcian Osta Arena Fm (Suárez and Márquez, 2007).

In the San Jorge Gulf basin, Fitzgerald et al. (1990) identified three rifting stages. A first rifting event poorly constrained both in age and areal distribution, and was assigned to the Triassic-Mid Jurassic by extrapolation from deposits in the Deseado Massif (to the south). These deposits are difficult to distinguish from the Mid Jurassic Volcano-Sedimentary Complex (Clavijo, 1986), part of the Chon Aike Magmatic Province (Kay et al., 1989; Pankhurst et al., 2000). In the Early Cretaceous, the Neocomian rifting stage is responsible for the development of half-grabens, mostly under continental conditions (Fígari et al., 1997). To the west, several NW-striking depocenters developed in the Rio Mayo embayment (Iannizzotto et al., 2004) and were filled with marine series rich in paleontological content (Olivero, 1987; Olivero and Aguirre-Urreta, 2002). Finally, a third rifting stage in the Late Cretaceous is recorded by E-W trending faults on the eastern part of the basin. These faults either reactivate previous normal faults (basement-rooted) or detach within the sedimentary cover (Fitzgerald et al., 1990).

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Offshore Patagonia, the San Julián basin rifting chronology is yet poorly constrained, and its evolution is interpreted to be similar to the Deseado Massif basins (Homovc and Constantini, 2001). However these sequences were not reached by hydrocarbon exploration wells in the San Julián basin (Micucci et al., 2011).

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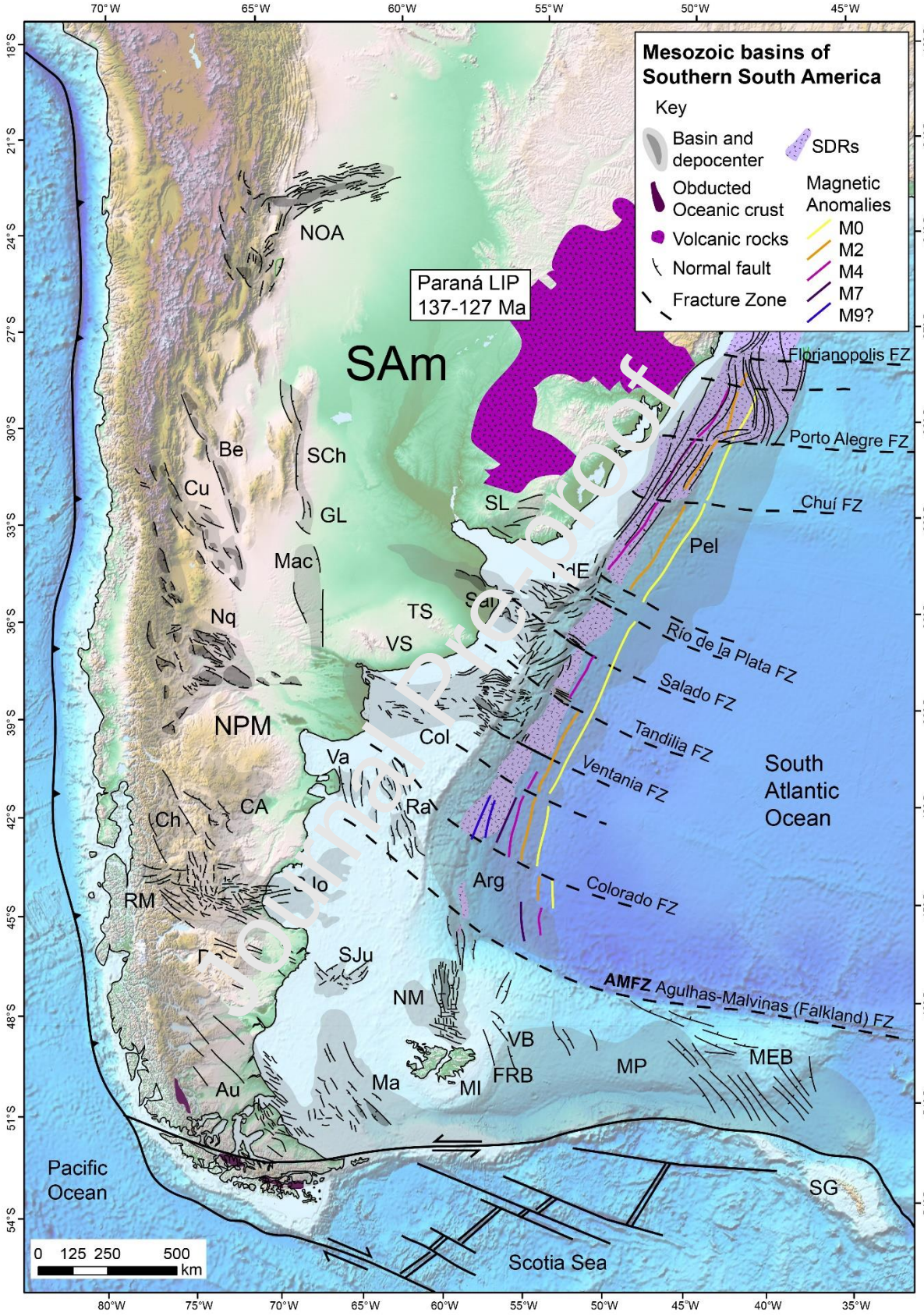



Fig. 3: Map of the main Mesozoic basins of SE South America (SAm). NOA: Northwest Argentina Cretaceous basin, SCh: Sierras Chicas, GL: General Levalle, Mac: Macachín, Be: Bermejo, Cu: Cuyo basin, Nq: Neuquén, NPM: North Patagonian Massif, CA: Cañadón

Asfalto, Ch: Liassic Chubut basin, RM: Río Mayo, SJo: San Jorge Gulf basin, De: Deseado Massif basin, Au: Austral/Magallanes basin, Ma: Malvinas basin, NM: North Malvinas (North Falkland), Arg: Argentina basin, SJu: San Julián, Va: Valdés, Ra: Rawson, Col: Colorado, Sal: Salado, PdE: Punta del Este basin, SL: Santa Lucía, Pel: Pelotas. Other features: MI: Malvinas (Falkland) islands, VB: Volunteer basin, FRB: Fitz Roy basin, MP: Malvinas (Falkland) Plateau, MEB: Maurice Ewing Bank, SG: South Georgia, VS: Ventania system, TS: Tandilia system. FZ: Fracture Zone. Faults and depocenters after Uliana et al. (1995, 1989); Veroslavsky (1999); Franke et al. (2007); Micucci et al. (2011); Starck (2011); Becker et al. (2012); Bechis et al. (2014); Stica et al. (2014); Figari et al. (2015); Folguera and Ianizzotto (2004), Lohr and Underhill (2015); Gianni et al. (2015), Lovecchio et al. (2018, 2019) and Rodriguez Raising et al. (2019). Background topography from Etopo 1 (Amante & Eakins, 2009).

The Deseado Massif was affected by the profuse volcanism of the Chon Aike Magmatic Province in the Jurassic (Pankhurst et al., 2000). However, remnants of two older sedimentary basins crop out among the volcanic cover: the Permian La Golondrina and the Triassic El Tranquilo series (that we gather here in the Deseado Massif basin). Various tectonic settings have been assigned for these extensional basins. Bellosi and Jalfin (1989) support an intra-arc basin interpretation, while Ramos and Palma (1996) interpret an intracratonic setting. An Early-to-Middle Jurassic rifting event is confirmed across the Deseado Massif area, with volcanic rocks and continental deposits rich in volcaniclastic content (Gust et al., 1985; Figueiredo et al., 1996).

Further south, the Austral (Magallanes) and the Malvinas basins record a main phase of rifting in the Early-to-Middle Jurassic, with half-grabens largely oriented NNW (Fig. 3). The presence of a Triassic synrift below the Malvinas basin was proposed by Uliana et al. (1989) and recently confirmed by Lovecchio et al. (2019). In the Tierra del Fuego island, the main synrift stage for the Austral (Magallanes) basin was dated Early Jurassic in an exploration well (Pankhurst et al., 2000). This age is consistent with the Early Jurassic ages for NW-striking igneous dykes in the Malvinas (Falkland) islands (Musset and Taylor, 2004; Stone et al., 2008) and

thermochronological data interpreted as rift-shoulder uplift at this time (Thomson et al., 2002). The central graben of the Malvinas basin remains undrilled, however recent U-Pb zircon geochronology from an ignimbrite layer at the top of Serie Tobífera (synrift) yielded a Mid Jurassic age (Lovecchio et al., 2019). A new pulse of extension in the Late Jurassic produced retroarc rift basins (filled with the bimodal volcanism of the El Quemado complex, Pankhurst et al., 2000) and the opening of the Rocas Verdes marginal basin towards the west. Oceanic crust accretion is evidenced by the presence of ophiolite complexes (Fig. 3; Dalziel et al., 1974; Stern, 1979; Stern et al., 1992; Alabaster and Storey, 1990, Mukasa and Dalziel, 1996). Reader is referred to the recent reviews published by Calderón et al. (2013) and Malkowski et al. (2015).

To the east, in the North Malvinas (North Falkland) basin (Fig. 3), two intersecting rift systems are observed (Brandsen et al., 1999). The Neocomian, N-S striking faults forming the northern branch, intersect the NW-striking faults forming the older southern rift system. The southern rift system remains underexplored. A Late Jurassic rifting age was assigned by Lohr and Underhill (2015). However, an Early to Middle Jurassic age seems more consistent with regional data, as suggested by Ramos et al. (2017). The presence of two transecting rift basins has been used to support a rotation of the Malvinas (Falkland) microplate during the Jurassic (*sensu* Marshall, 1994, Adie, 1952). More recently, this observation has been reinterpreted as a record of the change in the orientation of the stress field between the Jurassic and the Early Cretaceous (Brandsen et al., 1999; Lohr and Underhill, 2015; Ramos et al., 2017).

The Malvinas (Falkland) Plateau is a projection to the east of the Argentinean continental shelf that extends between the Malvinas (Falkland) Islands and the

Maurice Ewing Bank (Ewing et al., 1971; Chemale et al., 2018). The plateau limits to the south with the Scotia oceanic plate (via a transpressive margin) and is bounded to the north by the Agulhas-Malvinas (Falkland) Fracture Zone (AMFZ). The geology of the Malvinas (Falkland) Plateau is poorly constrained due to the lack of public seismic data. Biddle et al. (1996) published a map with the main interpreted faults and suggest a Jurassic rifting stage. Marine sedimentation since at least the Mid-to-Late Jurassic boundary is recorded in DSDP-511 well on the Maurice Ewing Bank (Price and Gröcke, 2002). Barker (1999) and recently Schimschal and Jokat (2019) proved the presence of oceanic crust under the plateau, although other authors suggest highly-extended continental crust (Chemale et al., 2018; Kimbell and Richards, 2008). Fraticelli et al. (2016) mention the development of two main sedimentary troughs east from the islands: the Fitz Roy and Volunteer basins (Fig. 3).

North of the AMFZ develops the Southern segment of the South Atlantic Ocean, that extends between the AMFZ and the Río Grande FZ north of the Pelotas basin (Moulin et al., 2010). This segment is characterized by the overall presence of seaward dipping reflectors (SDRs) on the continent-ocean transition (COT, also referred to as transitional domain as in Blaich et al., 2011). SDRs are volcanic wedges with interbedded continental sediments deposited in subaerial environments, emplaced during breakup on both conjugate margins (Hinz, 1981). SDR development characterizes volcanic or magma-rich passive margins such as the Southern South Atlantic. A general review of the Argentinean volcanic margin was presented by Hinz et al. (1999) and Franke et al. (2007; 2010).

The Argentinean shelf is one of the widest platforms in the world. It extends for up to 500 km east from the coastline and is characterized by the presence of several

sedimentary basins perched on continental crust, notably San Julián (already discussed), and the Rawson/Valdés, Colorado and Salado/Punta del Este basins (Fig. 3). The Rawson/Valdés basins are two rift basins oriented NNW composed of several half-grabens formed mainly by west-dipping faults. The main depocenters remain undrilled. Otis and Schneidermann (2000) inferred a Mid-Jurassic age for the rifting, while Continanzia et al. (2011) suggest a Late Jurassic-Neocomian age. No absolute ages are available to precisely constrain rifting chronology in the Rawson/Valdés basins.

Further north, the Colorado and Salado/Punta del Este basins display a general E-W to NW strike at high angles with the NNE-oriented COT (the area with development of SDRs in Fig. 3). Several hypotheses were proposed to explain this obliquity through: aulacogenic origin (Yrigoyen, 1975; Introcaso and Ramos, 1984), transtensional origin associated with NW–SE dextral shear systems (Keeley and Light, 1993; Tankard et al., 1995; Franke et al., 2006), structural inheritance (Urien et al., 1995; Gebhard, 2005; Domínguez et al., 2011), and two superimposed rifting stages (Franzese et al., 2003; Gerster et al., 2011; Pángaro and Ramos, 2012; Autin et al., 2013; Koopmann et al., 2014). Recently Lovecchio et al. (2018) interpreted the existence of three superimposed rifting events in the Colorado basin area. Firstly, Late Paleozoic thrusts of the Ventania/Cape foldbelt were extensionally reactivated in the Late Triassic-Early Jurassic. These faults were then intersected by Early-to-Mid Jurassic normal faults forming the main depocenters of the Colorado and Salado basins. Finally, in the Early Cretaceous, extension associated with the opening of the South Atlantic generated normal faults in the outermost 100-km strip of continental crust, and characterized by normal faults dipping inboard, as the surfaces limiting SDR wedges. Observations in the Colorado basin were extrapolated to the Salado

and Punta del Este basins, which are two depocenters separated by the Martín García High and form part of the same rift system (see Raggio et al., 2011 and references therein).

The Salado/Punta del Este and the Santa Lucía basins (located onshore Uruguay) developed on the Rio de la Plata Craton. The Santa Lucía basin has been interpreted as a pull-apart basin, initiated in the Late Jurassic (Veroslavsky, 1999), but the lack of absolute ages impedes confirmation of this interpretation.

The Pelotas basin spans offshore Uruguay and southern Brazil (Fig. 3). Rifting in this basin is intimately related to the South Atlantic opening (Abreu, 1998), with faults oriented largely parallelly to the COT and dipping inboard, similarly to the Early Cretaceous faults in the Colorado-Salado segment (Lovecchio et al., 2018). Rifting chronology was constrained by Stica et al. (2014) between a maximum age given by the basalts of the Paraná-Etendeka LIP (137-127 Ma, Fig. 3) in the Pelotas basin's prerift and the magnetic anomalies on SDRs and oceanic crust (Rabinowitz and LaBreque, 1979; Moulin et al., 2010).

The southernmost Atlantic segments is characterized by an absence of SDRs (Franke et al., 2007; Becker et al., 2010) and the development of a very deep basin, known as the Argentina basin (Fig. 3, Ludwig et al., 1968).

Onshore in central Argentina, a N-S directed branch of Early Cretaceous rift basins is present along the western margin of the Rio de la Plata craton (Fig. 3). From south to north, the Macachín basin (undrilled and only known from gravimetric and refraction seismic data, de Elorriaga, 2010; Kostadinoff and Llambías, 2002) displays a strong NNW direction. Immediately north, the General Levalle basin (Webster et al., 2004) is bounded by a N-S directed high-angle master fault to the west associated with reactivated basement structures. The Sierras Chicas basin in

Córdoba is formed of different depocenters along the Córdoba ranges. Similarly, to the General Levalle basin, is formed by the extensional reactivation of an east-dipping basement fault. The Sierras Chicas basin was then inverted in the Miocene with the Andean orogeny exposing its whole stratigraphy, characterized by red beds typical of continental settings (Schmidt et al., 1995). Volcanic and subvolcanic rocks interbedded in the synrift succession yield Early Cretaceous ages (Lagorio et al., 2016).

In northern Argentina, the Northwestern Argentina Cretaceous basin also known as the Salta basin (NOA in Fig. 3 and 4) is formed of three depocenters: Metán-Alemanía and Tres Cruces depocenters form a N-S directed branch, while the Lomas de Olmedo depocenter is oriented E-W (for general reference see Starck, 2011, and references therein). Synrift is composed of red beds interbedded volcanic rocks. Galliski and Viramonte (1988) report Early Cretaceous ages for the synrift Pirgua Group.

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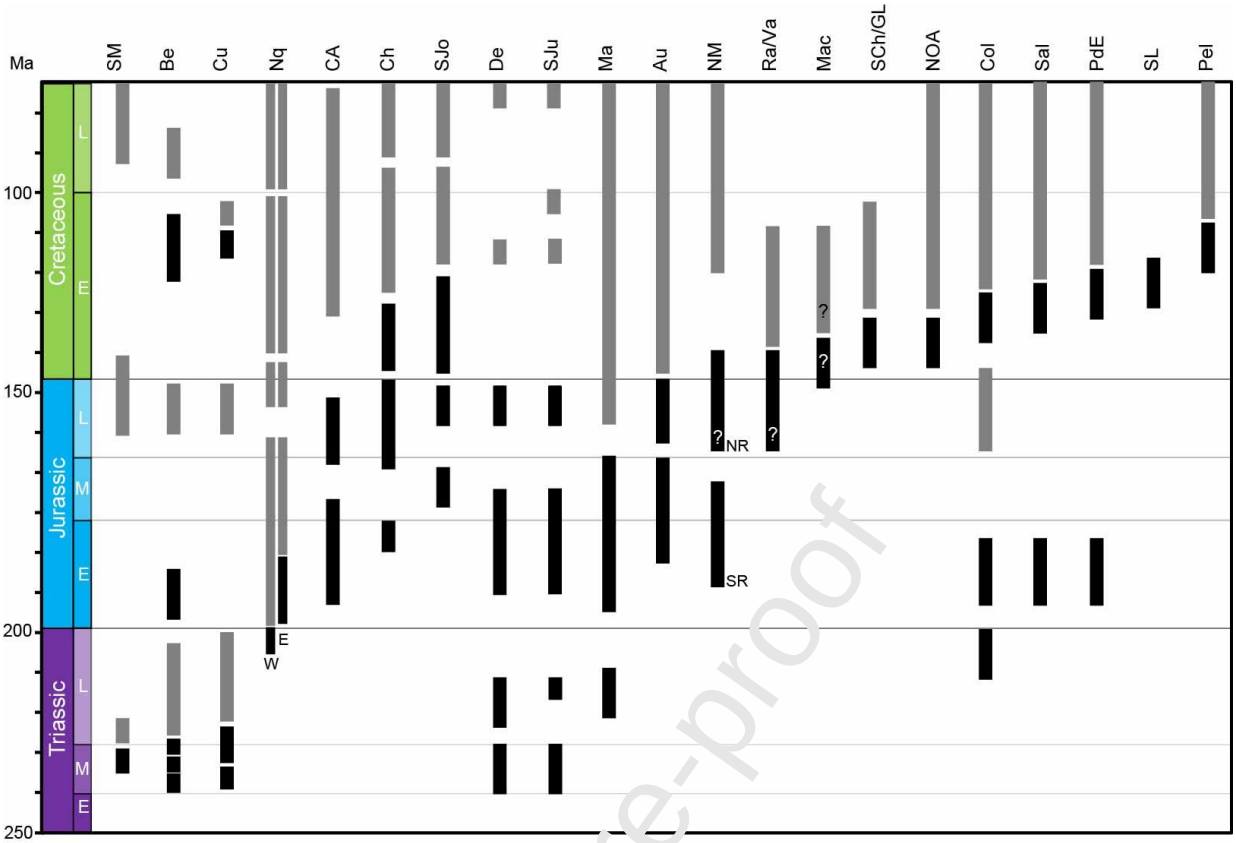



Fig. 4: Rifting chronology chart for the main Mesozoic basins of SE South America. Black bars represent active rifting, while grey bars represent sag or other tectonic scenarios (e.g. drift, foreland). Santa María (SM), Bermejo (Be), and Cuyo basin (Cu) after Kokogian and Mancilla (1989); Zerfass et al. (2004); Barredo et al. (2012) and Colombi et al. (2015). Neuquén basin (Nq) after D'Elia et al. (2015), references therein and authors' interpretation. Cañadón Asfalto (CA) after Cúneo et al. (2013) and Figari et al. (2015). Chubut Liassic basin after Suárez and Márquez (2007) and references therein, San Jorge Gulf basin (SJo) after Fitzgerald et al. (1990), and Lanizzotto et al. (2004). Deseado (De) and San Julián (SJu) basins after Figueiredo et al. (1996). Austral/Magallanes (Au) includes the Late Jurassic Rocas Verdes basin, ages after Pankhurst et al. (2000) and Calderón et al. (2013). Malvinas (Ma) after Galeazzi (1998) and Lovecchio et al. (2019); North Malvinas (North Falkland) basin after Ramos et al. (2017); and Lohr and Underhill (2015). Rawson/Valdés basin (Ra/Va) after Continanzia et al. (2011). Macachín basin (Mac) is undrilled, thus rifting age is poorly constrained. Sierras Chicas and General Levalle basins in Córdoba (SCh/GL) after Lagorio et al. (2016); Schmidt et al. (1995); and Webster et al. (2004). Northwestern Argentina Cretaceous basin (NOA) after Starck (2011) and references therein, age after Galliski and Viramonte (1988). Colorado (Col), Salado (Sal), and Punta del Este (PdE) basins after Lovecchio et al. (2018); Gerster et al. (2011); and Loegering et al. (2013). Santa Lucía basin (SL) after Veroslavsky, (1999). Pelotas (Pel) after Stica et al. (2014) and references therein.

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### 4.2. Mesozoic basins in southern Africa

Although the African basins are not the focus of this study, we summarize their rifting chronology to better illustrate the regional framework in the study of the South American basins.

The collision of Patagonia against the SW margin of Gondwana in the Late Paleozoic produced the Ventania-Cape fold belt and changed the subsidence regime of the neighboring Main Karoo basin of South Africa from intracratonic sag to a foreland setting (Fig. 5, see Veevers et al., 1994; Catuneanu et al., 2005; Miller et al, 2016; Linol and de Wit, 2016). 'Karoo' is a term also used for a large number of extensional basins that developed across Africa since the Late Carboniferous regardless of the tectonic regime (see the discussion of Guillocheau et al., 2018). These basins record continental deposits interbedded with volcanic rocks and lack datable marine fossils. Thus the chronostratigraphic framework for these basins remains poorly understood. Frizon de Lamotte et al. (2015) suggest a two-step scenario, by splitting all the Karoo basins in two groups. The first group of Karoo basins (Karoo I) gathers all the Late Carboniferous to Triassic poly-phased depocenters, overall NE- trending; and the Karoo II basins the Jurassic depocenters interpreted to be related to extension associated with impingement of the Karoo plume (Bouvet hotspot) and breakup of East Africa from Madagascar and East Antarctica. In this study, to characterize the chronology of the Karoo rifting, we follow the *rationale* of Frizon de Lamotte et al. (2015) and complement it with the work of Nairn et al. (1991), Smith et al. (1993), Zerfass et al. (2005), Mahanjane (2012), Mueller and Jokat (2017), Guillocheau et al. (2018), and the recent reviews for the East Africa region by Macgregor (2017) and Davison and Steel (2018).

We present in Fig. 5 a map of the Mesozoic basins in southern Africa. Onshore, besides the Main Karoo Basin (MKB) the other Karoo depocenters are distributed along two axes oriented ENE: 1) the Waterberg-Zambezi axis (Karoo I *sensu* Frizon De Lamotte et al., 2015); and 2) the Kalahari- Botswana-Limpopo axis (Karoo II). In East Africa, a group of N-S oriented grabens are observed, but they are consequence of two different origins: 1) the Lebombo monocline (Klausen, 2009) and its eastern extension in the Zululand basin (Broad et al., 2012), of Early Jurassic age (Karoo II); and 2) a group of grabens to the east of Early Cretaceous age in the area of Beira (Mozambique, see Senkans et al., 2019).

The southeast coast of Africa is an abrupt margin largely characterized by the dextral movement of Africa along the AMFZ. However, the synrift of the Durban basin (Fig. 5) was drilled offshore and produced Late Jurassic to Late Valanginian ages that were correlated to the red beds described in the Zululand basin by Visser (1998).

In southern South Africa, extensional reactivation of the Cape fold belt throughout the Mesozoic has been described by de Wit and Ransome (1992); Paton (2006) and Paton et al. (2016). These reactivations are interpreted to have taken place intermittently during the different extensional events experienced by Africa in the Mesozoic, but so far, they are poorly constrained in age as many other Karoo basins.

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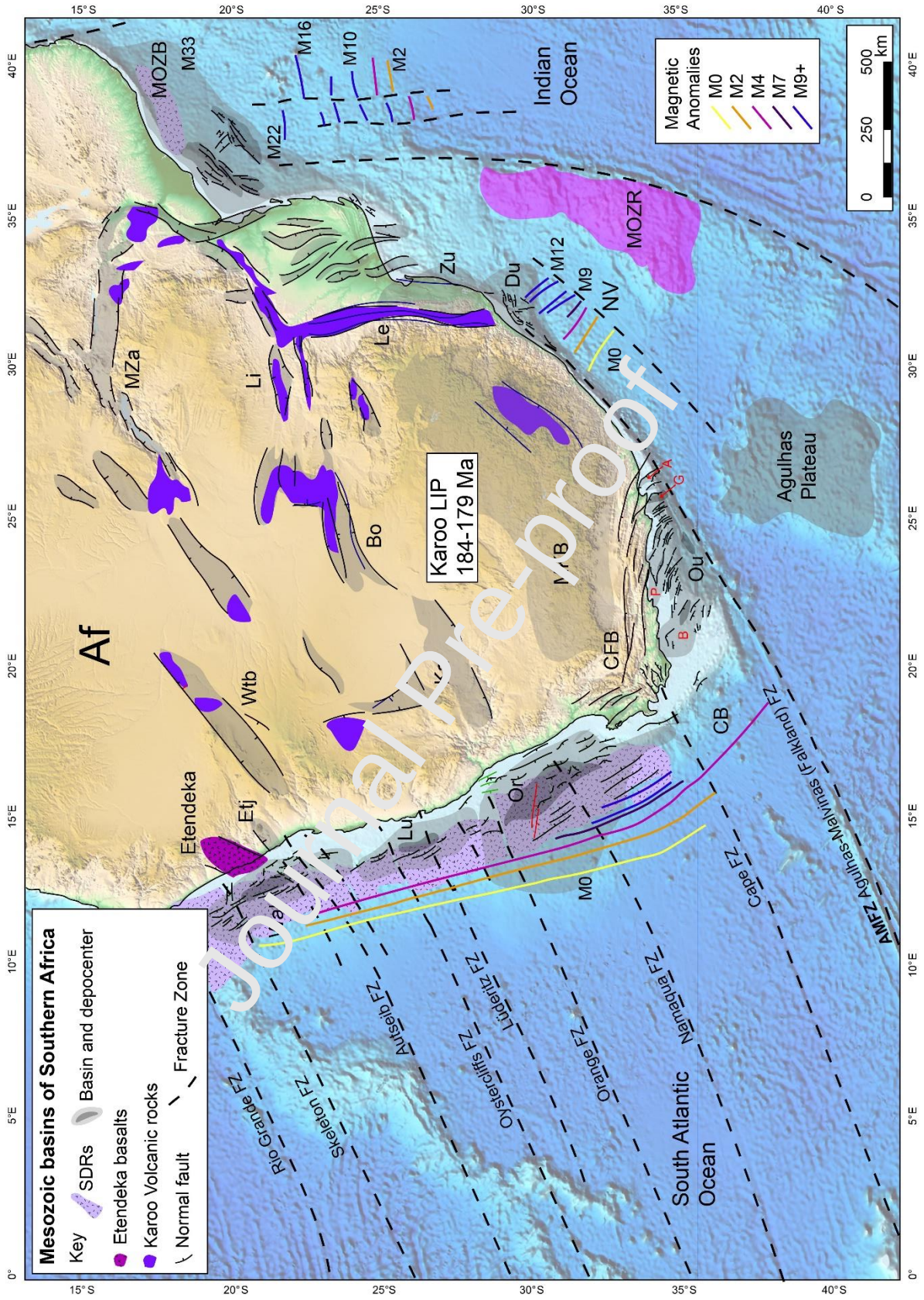



Fig. 5: Map of the main Mesozoic basins of southern Africa (Af). MKB: Main Karoo basin, Etj: Etjó, Wtb: Waterberg, MZa: Mid-Zambezi, Li: Limpopo, Bo: Botswana, Ka: Kalahari, Le: Lebombo, Zu: Zululand, MOZB: Mozambique basin, MOZR: Mozambique Ridge ,Du: Durban, NV: Natal Valley, Wal: Walvis, Lu: Luderitz, Or: Orange, CB: Cape basin, Ou:

Outeniqua basin (sub-basins: B: Bredasdorp, P: Pletmos, G: Gamtoos, A: Algoa). After Goodlad et al. (1982), Smith et al. (1993), Frizon de Lamotte et al. (2015), Nairn et al. (1991), Mahanjane (2012), Mueller and Jokat (2017), König and Jokat (2006), Stollhofen et al. (1998), Davison and Steel (2018), Broad et al. (2012), Clemson et al. (1999), Koopmann et al. (2014), and Paton et al. (2016). Background topography from Etopo 1 (Amante & Eakins, 2009).

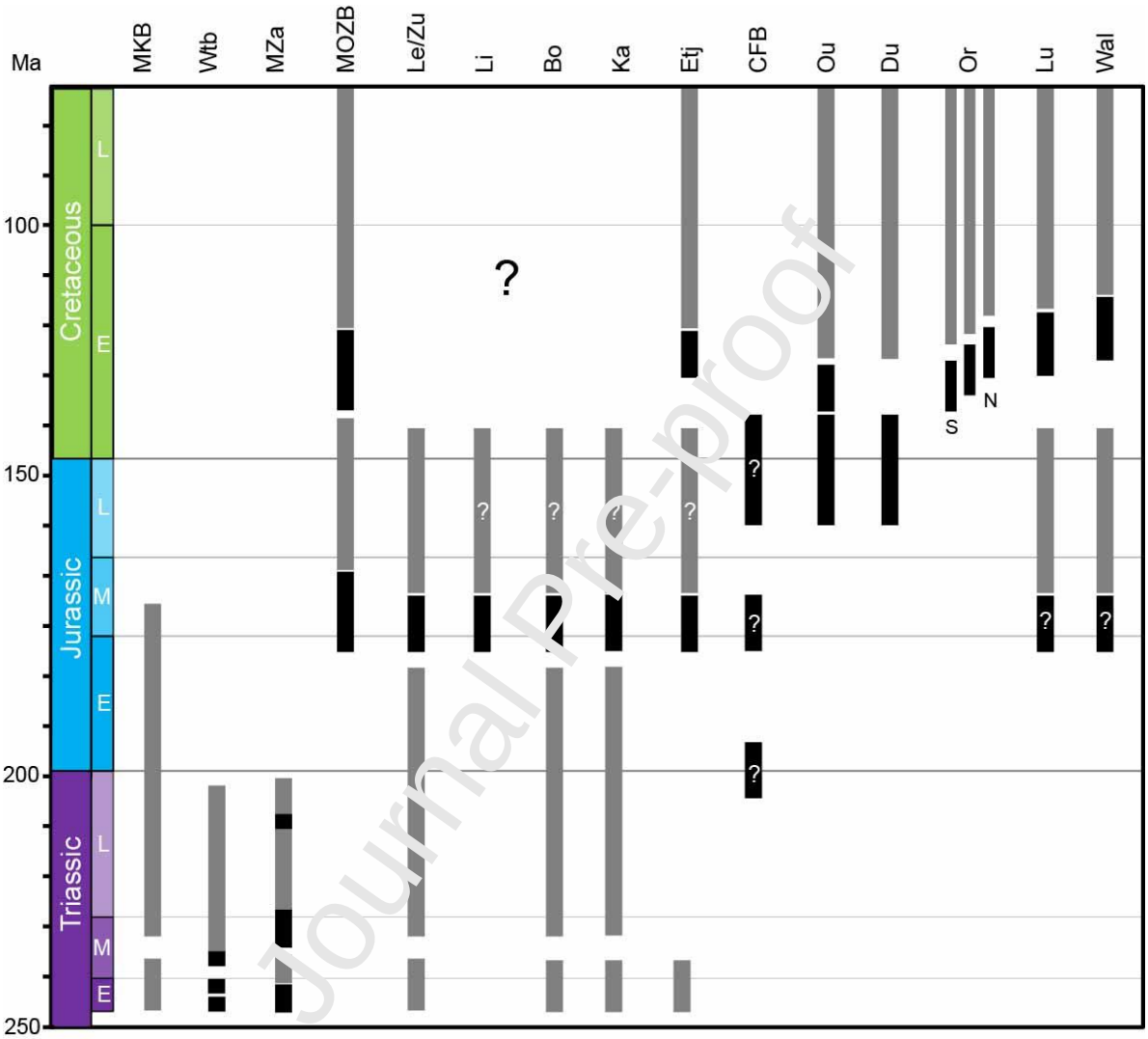



Fig. 6: Rifting chronology chart for the main Mesozoic basins of southern Africa. Black bars represent active rifting, while grey bars represent sag or other tectonic scenarios (e.g. drift, foreland). Main Karoo basin (MKB) after Catuneanu et al. (2005), and Duncan et al. (1997). Waterberg (Wtb) and Mid-Zambezi (MZa) after Zerfass et al. (2005) and references therein. Mozambique basin (MOZB) after Mueller and Jokat (2017). Limpopo (Li) and Lebombo (Le) monocline ages after Jourdan et al. (2007), and Klausen (2009). Botswana (Bo), Kalahari (Ka) and Etjó (Etj) basins after Catuneanu et al. (2005) and Smith et al. (1993). Etjó also records the Etendeca Zululand (Zu) and Durban (Du) after Broad et al. (2012). Etjó basin (Etj) after Renne et al. (1996).

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Offshore, the Outeniqua basin is formed of several WNW-trending half-grabens, named from east to west: Algoa, Gamtoos, Pletmos and Bredasdorp sub-basins (Fig. 5). These half-grabens are bounded by SW-dipping, *en echelon* listric faults, coherent with the extensively-reactivated thrusts of the Cape foldbelt further north (Fourché et al., 1992; Paton and Underhill, 2004). These faults display an arcuate shape, changing strike from WNW to NNW towards the east as they approach the AMFZ (Fig. 5). It had been suggested that the arcuate shape could be inherited from the Cape foldbelt (de Swardt and McLachlan, 1982), however, it seems more probably an effect of strike-slip along the AMFZ (Broad et al., 2012). For the chronology of rifting, we follow here the review of Broad et al. (2012) and the references therein. Two synrift units are identified across the different Outeniqua sub-basins. The first synrift package starts with fluvial sediments, overlaid by a shallow marine succession (dated Kimmeridgian/Tithonian), topped by a fluvial section. The unconformity between synrift I and II is a regional unconformity of intra-Valanginian age, named 1At1 offshore South Africa (Broad et al., 2012; Jungslager, 1996), that was interpreted to mark the onset of strike-slip movement along the AMFZ (du Toit, 1979). The synrift II varies considerably across the Outeniqua basin: shallow marine Valanginian-Hauterivian beds deposited in the Algoa sub-basin (Valicenti and Stephens, 1984), while deep-water Hauterivian shales are present in the Bredasdorp sub-basin (Broad et al., 2012).

The structure of the Atlantic margin of southern Africa, is marked by development of Early Cretaceous basins oriented NNW, parallel to the present-day coastline that evolved to a volcanic margin with abundant SDRs (Fig. 5), conjugate to the Argentinean margin. The Orange basin is the most prominent basin of the margin, occupying the western coast of South Africa and southern Namibia. Several

half-grabens developed on continental crust, three of which have been drilled. The oldest dated sediments are Hauterivian lacustrine shales (Broad et al., 2012). Several SDR wedges develop to the west, on the continent-ocean transition. Absolute ages have not been published, but SDRS were interpreted to have emplaced in the Hauterivian (Broad et al., 2012). A Barremian biostratigraphic age is reported for some sedimentary packages interbedded with volcanic rocks in the Kudu well (McMillan, 2003). The breakup unconformity (named 6At1) is dated late Hauterivian and deeply erodes the more proximal eastern depocenters (Broad et al., 2012). A complete review of the Atlantic volcanic margin was presented by Gladczenko et al. (1998) and Jungslager (1999) and more recently by Koopmann et al. (2014). The margin is transected by several WSW-ENE oriented fracture zones (FZ, Fig. 5) which, similarly to what is observed on the Argentinean shelf, affect the COT and the outer continental crust domain. In volcanic segmented margins, the formation of FZ is a process interpreted to be deeply related to breakup and SDR emplacement (Franke et al., 2013).

The distribution of SDRs, however, is not continuous along the margin. Similarly to what is observed on the conjugate Argentinean margin, the southernmost segment of the African Atlantic margin, between the AMFZ and the Cape FZ seems to be lacking SDRs (Koopmann et al., 2014). The sedimentary basin on the slope and oceanic crust is referred to as the Cape basin (Fig. 5). On the shelf, the Outeniqua basin developed on continental crust but the crustal structure of the COT remains poorly constrained. To the north, the different FZ segmenting the margin present a dextral component. The oldest magnetic anomalies (M9 to M7, according to Koopmann et al., 2014) were determined in the southernmost segment with SDRs (just north of the Cape FZ) and disappear to the north, illustrating diachronism in the

South Atlantic opening as originally postulated by Rabinowitz and LaBreque (1979) and also observed in the Pelotas basin by Stica et al. (2014).

To the north of the Orange basin, two other basins are described on the Namibian margin south of the Walvis Ridge, these are the Luderitz and Walvis basins (Fig. 5), which are also characterized by faults largely oriented parallel to the COT and to the present-day coastline (Clemson et al. , 1997). These basins are also interpreted to be of Neocomian age and conjugate with the Pelotas basin (see Cartwright et al., 2012). A thick pre-rift unit is interpreted on seismic data and correlated with Karoo-age sediments of the Namib rift and flood basalts of the Etendeka Group (Clemson et al., 1999). The Etendeka basalts are equivalent to the Serra Geral basalts of the Paraná basin (Fig. 3) and form part of the Paraná-Etendeka LIP (Milner et al., 1995). A 132 Ma age, close to the Valanginian-Hauterivian boundary, was established by Renne et al. (1996).

## 5. MESOZOIC RIFTING IN SW GONDWANA

The amalgamation in the analyzed sector of the supercontinent of Pangea was completed in the Late Paleozoic (Fig. 7). The geodynamic scenario for the Permian-Triassic is characterized by subduction along the Panthalassic margin (Laurentia-Gondwana), the opening of the Neotethys ocean in the Permian (280 - 260 Ma, Fig. 7), followed by rifting along the Central Atlantic with closure of the Paleotethys in the Triassic (230 - 220 Ma, see Riel et al. 2018 and references therein).

In SW Gondwana, the Early Permian San Rafael tectonic phase produced eastward expansion of the volcanic arc and intense deformation and orogenic building (*circa* 290 Ma). This event has been interpreted by Ramos and Folguera (2009) as a case of flat slab subduction in the Late Paleozoic. The term “Gondwanide

orogeny" was introduced by Keidel (1921) and also used by Du Toit (1927, 1937) to gather all late Paleozoic deformation events (in the SW Gondwana margin) and to explain deformation along the Ventania-Cape thrust system (VCS in Fig. 7). Deformation along this system is diachronous, Late Permian in the Ventania system of central Argentina (Dimeri et al., 2005) spanning until the Early Triassic in South Africa (Hansma et al., 2016).

Absolute counterclockwise rotation of Pangea since the Middle Permian (Marcano et al., 1999) with a rotation pole in northern South America (Torsvik et al., 2012, Fig. 7) caused a decrease in the convergence velocity at the SW Gondwana margin (inducing retroarc extension) and, on the contrary, compression along the Laurentian margin (Riel et al., 2018). In this context, normal andesitic arc volcanism along the Gondwana margin in the Early Permian experienced arc expansion to the south and east, and an increase in rhyolite abundance. Silicic volcanism is gathered in the Choiyoi Magmatic Province (Kay et al., 1989; Sato et al., 2015), emplaced in a subduction-related extensional arc setting, and produced by slab roll-back after the Gondwanide orogeny (Rocher et al., 2015; del Rey, 2019).

The Mesozoic was an era of overall continental dispersion, with continuous subduction of the paleo-Pacific plate (Panthalassa) below SW Gondwana. In the following sections we present four paleo-tectonic maps depicting the rifting evolution of the different Mesozoic basins in the area of study (AOI in Fig. 7). Besides the Early Cretaceous South Atlantic breakup, we intend to illustrate the different rifting stages that occurred since the Early Mesozoic. We refer to Frizon de Lamotte et al. (2015) for a review of the initial Pangea breakup in other regions which remain out of the scope of this study.

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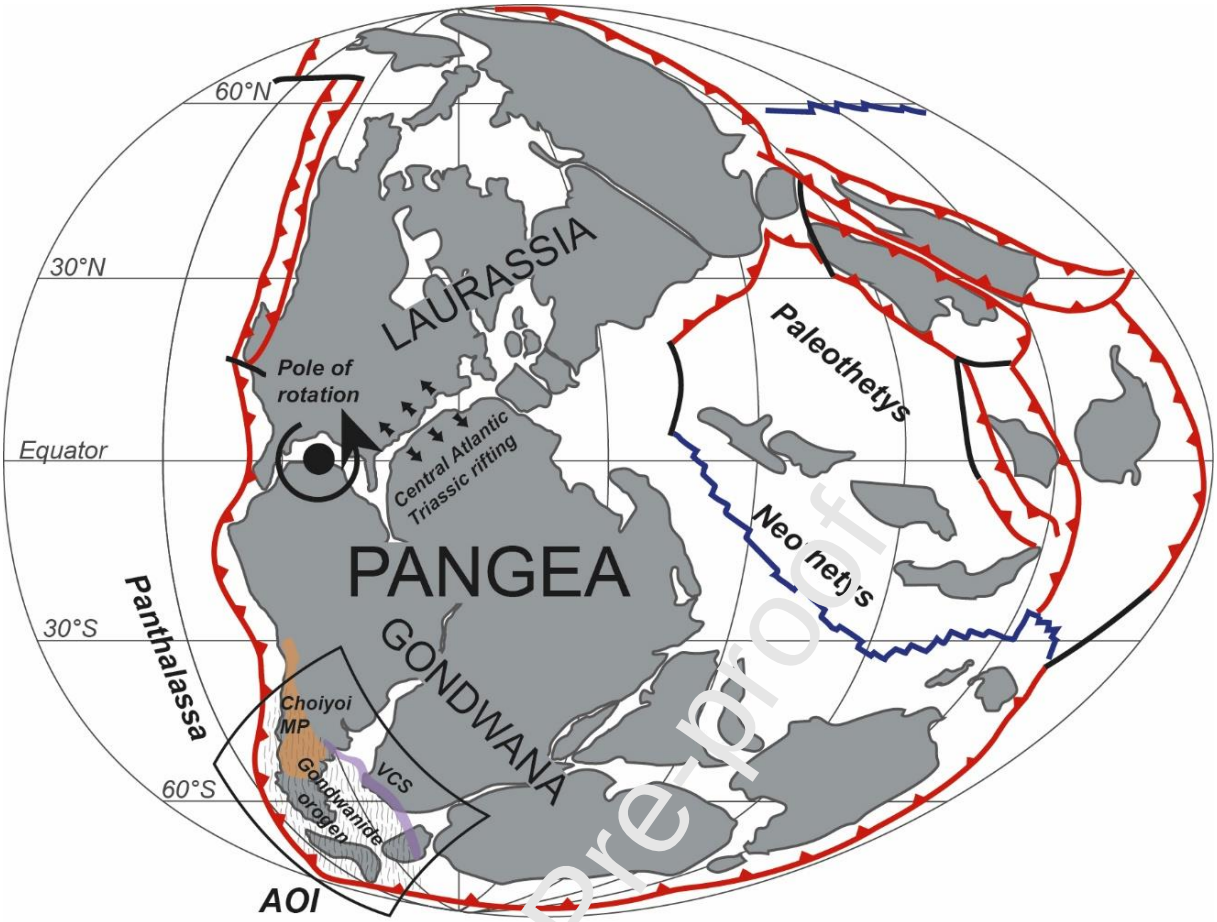



Fig. 7: Paleo-tectonic map of the Pangea supercontinent at the end of the Paleozoic (circa 250 Ma) after Riel et al. (2018). Euler rotation pole of Pangea from Torsvik et al. (2012). Note the location of the Area of Interest (AOI), the Gondwanide orogen, the Choiyoi Magmatic Province and the Ventania-Cape foldbelt (VCS).

### 5.1 Triassic-Early Jurassic Rifting

In this first rifting phase we gather all rifting events taking place throughout the Triassic, with Early-to-Late Triassic rifting (*sensu lato*) indicated by faults mapped in purple in Fig. 8 and differentiated from faults active since the Late Triassic rifting (mapped in red in Fig. 8). Three groups of depocenters are indicated: a series of depocenters in SW Gondwana retroarc aligned sub-parallel to the margin, and two sets of depocenters orthogonal to the margin. The retroarc depocenters (1 in Fig. 8) include the Cuyo, Bermejo, Neuquén, and Deseado basins and some recently identified Late Triassic depocenters in the Malvinas basin area. The other two extensional features, oriented at high angles with the margin, are: the axis formed by

the Santa María (Brazil) and the Waterberg and Mid-Zambezi basins extending into East Africa as part of the Karoo I system (2 in Fig. 8) *sensu* Frizon De Lamotte et al. (2015); and the Permian-Early Triassic Cape fold-and-thrust belt, and its extension into South America known as the Ventania system, reactivated throughout the Mesozoic (3 in Fig. 8).

Following a period of flat slab subduction that lasted between the Late Carboniferous and the Early Permian (Ramos and Folguera, 2009), slab steepening associated with lower crust delamination produced the rhyolitic flare of the Choiyoi Magmatic Province (Fig. 7), widely distributed in Central Chile and Argentina (see Kay et al., 1989; and Sato et al., 2015 for further reference). In northern Chile, the Triassic arc is present in the Coastal Cordillera (Maksaev et al., 2014). In central Chile, the volcanic arc was established since the Early-Middle Triassic in the Domeyko Range (Fig. 8), and migrated westward in the trench direction, towards the Coastal Cordillera in the Early Jurassic (Oliveros et al., 2018; Fig. 8). The presence of a Triassic arc and its trench-ward migration until the Early Jurassic was also observed in the Antarctic Peninsula by Storey et al. (1992, 1996) and recently reassessed by Bastias et al. (2020), who linked these observations to a steepening of the subducting plate and highlighted the importance of subduction-plate boundary forces in the initial stages of Gondwana breakup.

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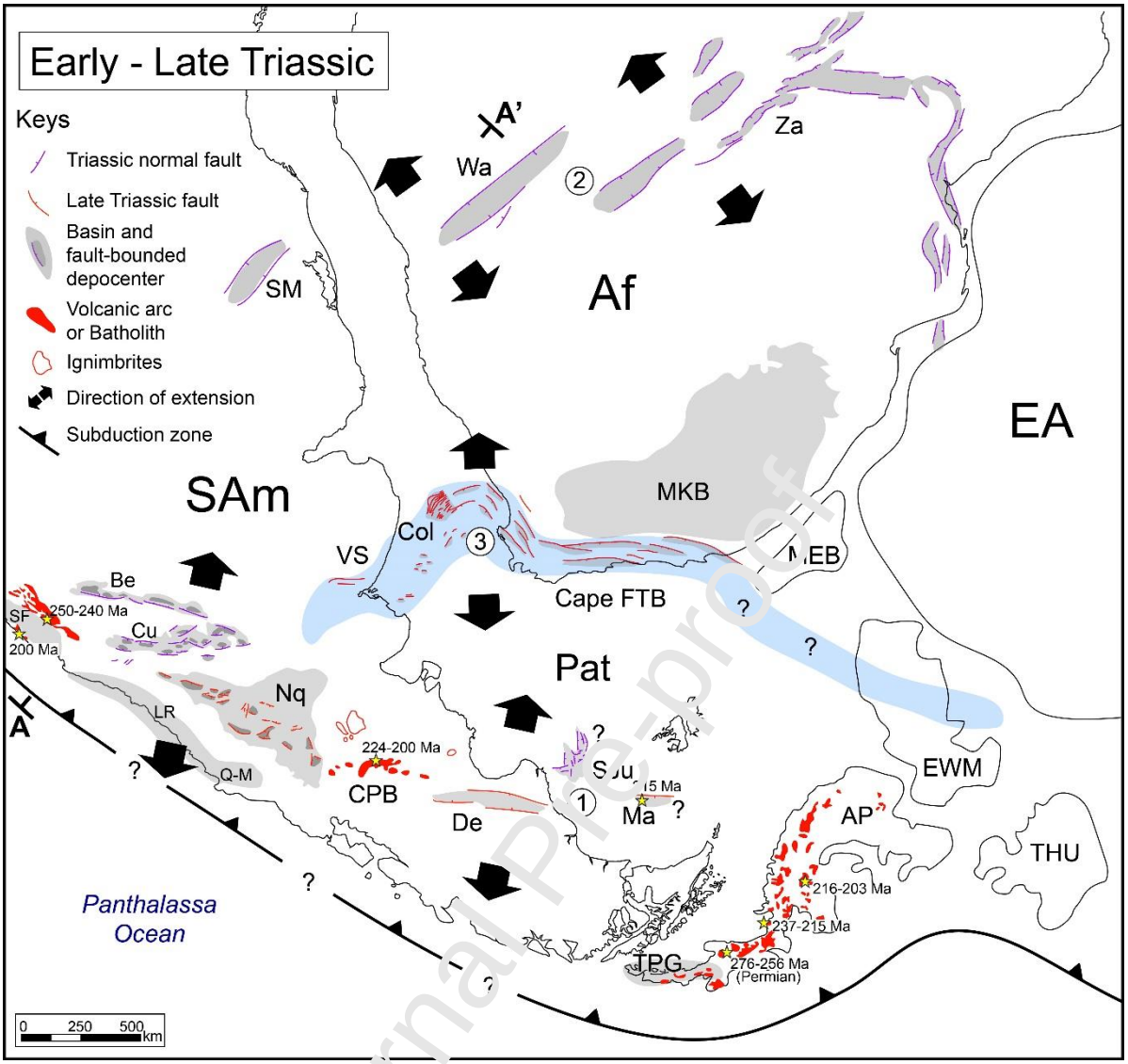



Fig. 8: Paleo-tectonic reconstruction of SW Gondwana at 200 Ma. Africa in its present-day position. Gondwana fit after Daziel et al. (2013). Triassic volcanic arc in Central Chile after Oliveros et al. (2018), Central Patagonian Batholith (CPB, age after Rapela et al., 2005). Fore and intra-arc basins in Chile: SF: San Felix-Rivadavia basin, LR: La Ramada, Q-M: El Quereo-Los Molles basin (after Charrier et al., 2014). Volcanic arc in the Antarctic Peninsula (AP) and extension of the Trinity Peninsula Group (TPG) basin the after Bastias et al. (2020), Storey et al. (1992), Millar et al. (2002), Flowerdew et al. (2006), and Riley et al. (2012). Basins develop in a back-arc: Cuyo (Cu), Bermejo (Be), faults after Uliana et al. (1995); or intracratonic setting: Santa Maria (SM), Waterberg (Wa), Zambezi (Za), after Zerfass et al. (2004), San Julián (SJ, after Micucci et al., 2011). Late Triassic-Early Jurassic basins: Neuquén (NQ, Precuyano cycle, faults after Bechis et al., 2014), Deseado (De) and Malvinas (Ma) basins after Uliana et al. (1989). The previously compressive faults of the Ventania (VS) - Cape Permian-Early Triassic fold and thrust belt (FTB, in blue) have been extensionally reactivated in the Colorado (Col) and Cape area (Lovecchio et al., 2018; Paton, 2006). MKB: Main Karoo basin. Tectonic blocks: South America (Sam), Patagonia (Pat), Africa (Af), Maurice Ewing Bank (MEB), Eastern Antarctica (EA), Ellsworth-Whitmore Mountains (EWM), Antarctic Peninsula (AP), Thurston Island–Eights Coast (THU). 1, 2 and 3 are different groups of basins referred in the text.

A series of extensional basins developed in the retroarc during this stage (Franzese et al., 2003). The Bermejo and the Cuyo basins in western Argentina have been related to the evolution of the Gondwanide active margin (Fig. 9; Zerfass et al., 2004). U-Pb zircon ages for the Cuyo basin indicate several pulses of rifting throughout the Middle Triassic (Spalletti et al., 2008; Barredo et al., 2012). An Early Triassic age is suggested for rift initiation in the Bermejo basin (Stipanicic and Bonaparte, 1979). Recent U-Pb zircon ages from tuffs interbedded in the late synrift units (*sensu* Milana and Alcober, 1994) indicate Middle to Late Triassic ages of 236-234 Ma (Marsicano et al., 2016). The location and the orientation of these basins is a consequence of crustal heterogeneities as they were emplaced along the hanging-wall sutures between Paleozoic terranes (Ramos and Kay, 1991). Triassic depocenters develop as well in central and northern Chile (see Charrier 1979; Mpodozis and Ramos, 2008; and Espinoza et al., 2018).

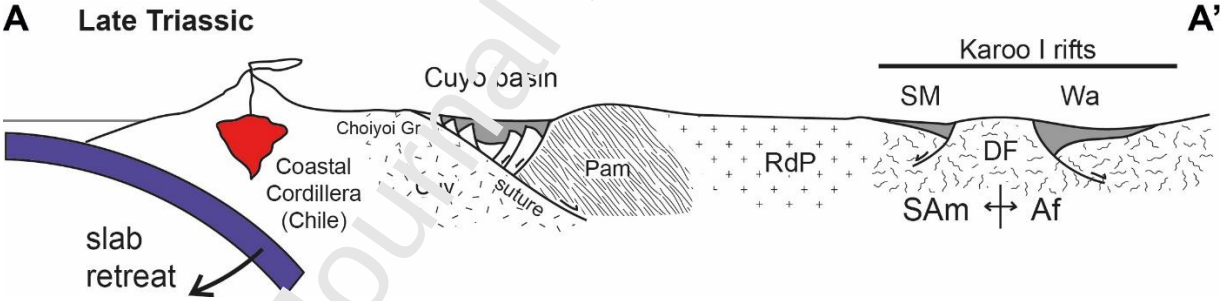



Fig. 9: Schematic cross section of the SW Gondwana margin for the Late Triassic (not to scale). See location in Fig. 8. The magmatic arc is represented by the Coastal Cordillera Batholith (Chile); extension took advantage of the Early Paleozoic Cuyania suture to form the Cuyo basin; Intracontinental rifting in Africa produced the Karoo I rifts. After Ramos and Kay (1991), Oliveros et al. (2018) and Zerfass et al., (2004). See keys on cratones and tectonic blocks in Fig. 2.

In Patagonia, there is still discussion regarding subduction being active during this period. The granitoids of the Central Patagonia Batholith (Stipanicic and Methol, 1972; Rapela and Kay, 1988), were emplaced in the Late Triassic (200-224 Ma, Rapela et al., 2005) in the North Patagonian Massif and form a NW-directed batholith

that has been associated with either an intraplate extensional setting (Rapela et al., 1992; Kay, 1993), or with a subduction-related setting (Rapela et al., 1991; Zaffarana et al., 2014). Navarrete et al. (2019) have recently proposed that this batholith formed in a flat-slab setting. However, a flat-slab subduction would preclude any arc magmatism at more than 700 km from the trench, where the subducted slab would be completely dehydrated, and so cease to interact with the asthenospheric wedge, as shown in several Cenozoic flat-slabs (Ramos et al., 2002; Ramos and Folguera, 2009). The slab partial melting proposed by Navarrete et al. (2019) is unrealistic, since only very young slabs should melt, as shown by Kay et al. (1993). Besides, contraction as proposed does not seem probable for the Late Triassic given the overall extensional setting in the Gondwana's margin retroarc at this time (Fig. 7), and in particular the Late Triassic rifting in the Malvinas basin (Lovecchio et al., 2019).

In the Deseado massif (De la Fig. 8), the Mid-Late Triassic El Tranquilo rifting event formed a NNW-oriented rift filled with fossil-rich continental deposits interbedded with volcanic rocks (Haller, 2002). El Tranquilo probably developed as a late stage of the Permian extension recorded in the Deseado massif by the La Golondrina rifting (Homovc and Constantini, 2001). Offshore, the San Julián basin might record a similar stratigraphy but its depocenters remain unexplored. Late Triassic synrift volcanic rocks were recently reported by Lovecchio et al. (2019) in the Malvinas basin, who interpreted a retroarc extensional setting.

Moving to the intracratonic area, Zerfass et al. (2005) proposed the correlation of the Triassic Santa Maria basin with the Waterberg and Mid-Zambezi Karoo I basins in Africa. Guillocheau et al. (2018) extended this correlation for other basins in Eastern Africa, India and Australia. Considering spatial orientation and synchronicity,

there seems to be a relationship between the formation of Karoo I depocenters and rifting and breakup along the Central Atlantic (between NW Africa and eastern North America, see Fig. 1).

Following the end of compression in the Cape fold belt in the Early Triassic, negative inversion of the compressive structures has been identified in Africa by De Wit and Ransome (1992) both onshore on the Cape fold belt itself, and offshore towards the south, in the Outeniqua basin. The chronology of this extensional reactivation is poorly constrained. Offshore in Outeniqua, the oldest datable marine sediments are of Late Jurassic age, but onshore the sedimentary infill indicates more proximal environments: the Enon Fm. conglomerates of Late Triassic-Jurassic age (Dingle, 1973). Reactivation probably took place in several pulses (Fig. 6). Extensional reactivation of previously compressive structures has also been identified offshore Argentina, in the Colorado basin, by Pángaro and Ramos (2012), Pángaro et al. (2016) and Lovecchio et al. (2018) and below the Orange basin by Paton et al. (2016).

In the Neuquén basin, Late Triassic to Early Jurassic rifting is recorded by the Precuyano cycle. D'Elia et al. (2015) suggested rifting diachronism since the Late Triassic until the Early Jurassic from north to south. However, the occurrence of Triassic depocenters also in the south (Sañicó-Piedra del Águila, see Carbone et al., 2011) challenges this interpretation. We depict all Triassic depocenters restricted to a strip in the west and oriented subparallel to the subduction zone (Fig. 8). In the Huincul ridge area, along the southern edge of the Neuquén basin, some NW-SE oriented Late Paleozoic structures associated with the Patagonia collision (Mosquera and Ramos, 2006) were reactivated in an extensional setting (Pángaro et al., 2009). This Late Triassic rifting event was correlated with the extensional reactivation of the

offshore portion of the Ventania-Cape fold belt in the Colorado basin by Lovecchio et al. (2018).

### 5.2 Early - Middle Jurassic Rifting

In the Early Jurassic, two different but regionally important events were taking place in Gondwana: Africa was affected by the Karoo II rifting (*sensu* Frizon de Lamotte et al., 2015) as a consequence of the impingement of the Karoo mantle plume, while extension was also affecting the SW Gondwana retroarc with emplacement of the Chon Aike silicic magmatic province (*sensu* Kay et al., 1989; Pankhurst et al., 1998) as demonstrated by Gust et al. (1985) and Uliana et al. (1985).

We have mapped the maximum extent of the Karoo volcanic rocks (Fig. 10) and obtained a diameter of influence of the mantle plume of about 2,000 km, consistent with estimations of White and McKenzie (1989). According to Frizon de Lamotte et al. (2015), various observations such as regional doming and volcanism preceding rifting, are evidence of an active rifting process, with plume impingement being the triggering mechanism for the Karoo II event. The detection of a three-way junction of dyke swarms in East Africa that could be interpreted as a triple junction (Elliot and Fleming, 2000, Figs. 1 and 10) has increased the debate. Jourdan et al. (2004) suggest that the Jurassic Karoo igneous dyke swarms were emplaced along reactivated Proterozoic mobile belts between cratons, and thus the variety of dykes' orientations would not be due to a triple junction but conditioned by the basement fabric. The Limpopo area remains however the geographic center of volcanic activity and the predominant orientation of rifts seems to be ENE (Fig. 10). Storey et al. (1992) relate the Karoo rifting to subduction processes, a rifting that would have been accentuated, but not triggered by the Karoo plume.

In the Mozambique basin area (Fig. 10), rifting evolved and succeeded throughout the Early - Middle Jurassic, with SDR emplacement in the Bathonian and normal oceanic crust accretion since the Callovian (Mueller and Jokat, 2017).

On the southwestern margin of Gondwana, a new phase of extension is recorded in the Neuquén basin during the Early Jurassic: the Cuyano cycle. This extension is associated with larger depocenters formed by reactivation of some Precuyano structures (Vergani et al., 1995). The Neuquén basin and the Liassic Chubut basin, further south, developed behind the same Early Jurassic magmatic arc, represented by the Patagonian Subcordilleran Batholith (Fig. 10 and 11).

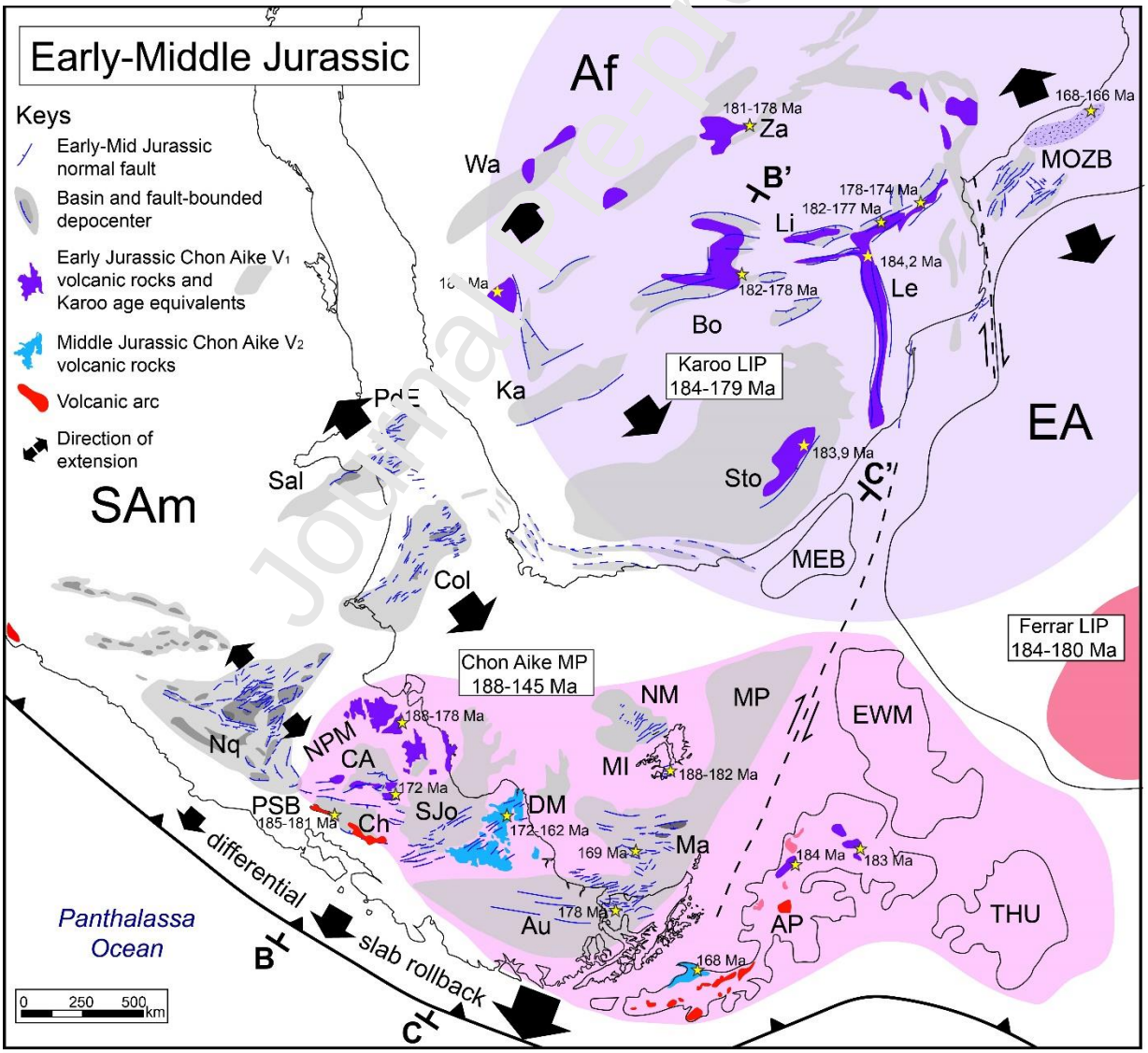



Fig. 10: Paleo-tectonic reconstruction of SW Gondwana in the Early-Mid Jurassic. Gondwana fit after Dalziel et al. (2013). Eastern Africa and Eastern Antarctica are impacted by the Karoo

mantle plume (purple), coeval with the Ferrar LIP and Chon Aike Magmatic Province (in dark and light pink respectively, Pankhurst et al., 2000). Karoo rifts: Kalahari (Ka), Botswana (Bo), Limpopo (Li), Lebombo (Le), Stormberg (Sto), Mozambique (MOZB), ages from Jourdan et al. (2005), and Mueller and Jokat (2017). In South America, this is a period of intense rifting in the Colorado (Col), Salado (Sal) and Neuquén basins (Nq, Cuyano cycle). Also in the Cañadón Asfalto (CA) and San Jorge (SJ) basins. The Liassic Chubut basin (Ch) is a back-arc basin for the arc-related Patagonian Subcordilleran Batholith (PSB, age after Rapela et al. (2005). Dykes of this age reported in the Malvinas (Falkland) Islands (MI; Ramos et al., 2017). The Tobífera Series in the Malvinas (Ma) and Austral (Au) basins also developed at this time (Pankhurst et al., 2000; Uliana et al., 1989).

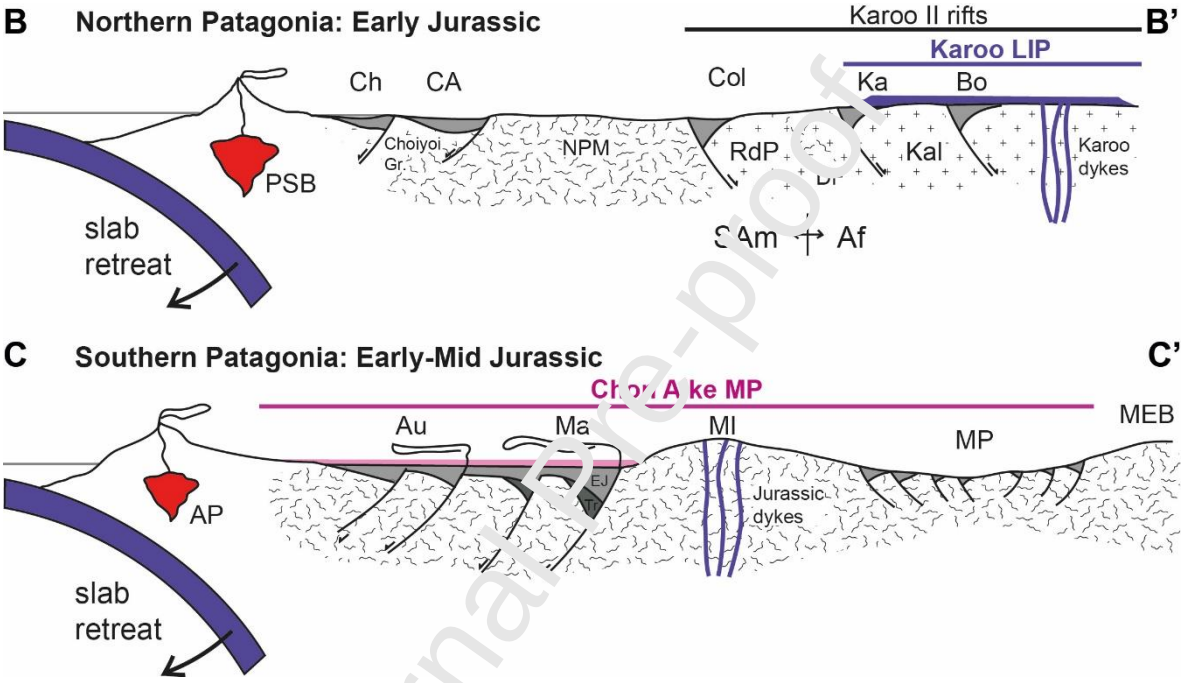



Fig. 11: Schematic cross sections of the SW Gondwana margin for the Early-Mid Jurassic at two different latitudes. See location in Fig. 10. B-B' is a transect across northern Patagonia, with a magmatic arc represented by the Patagonian Subcordilleran Batholith, the retroarc Chubut and Cañadón Asfalto basins and the Karoo II basins in Africa (Kalahari, Botswana) associated with the Karoo plume and the Colorado basin (offshore Argentina). C-C' is a transect across southern Patagonia, with a magmatic arc in the Antarctic Peninsula and retroarc extension associated with emplacement of the Chon Aike Magmatic Province. Early Jurassic dykes are reported in the Malvinas (Falkland) Islands. Extension between the islands and the Maurice Ewing Bank (Malvinas -Falkland- Plateau) occurs at this time induced by a slab-tear between Patagonia and the Antarctic blocks. Keys for basins and tectonic blocks as in Fig. 2, 3, 5 and 10.

Huge magmatic volumes where extruded during the Early to Middle Jurassic in Patagonia as part of the Chon Aike magmatic province (Fig. 10 and 11; Pankhurst et al., 2000). Early Jurassic acidic volcanism in the North Patagonian Massif is coeval with the arc volcanism of the Patagonian Subcordilleran Batholith (Rapela et al.,

2005). Suárez and Márquez (2007) proposed that the Liassic Chubut basin developed in the retroarc region of the coetaneous Patagonian Subcordilleran Batholith. According to these authors, the closure of the Chubut basin in the Middle Jurassic coincides with a westward migration of the magmatic arc, from a position in the extra-Andean region towards the Patagonian Cordillera, and a rotation from a NNW strike to a nearly N-S direction.

Slab retreat is also coherent with the retroarc extensional regime observed in other coetaneous basins developed further south. If we interpret the orientation of the NW-directed mafic dykes in the Malvinas (Falkland) Islands (Musset and Taylor, 2004; Stone et al., 2008) as indicators of the paleo-stress field (sigma 3) for the Early Jurassic, a diachronism can be interpreted between these structures and the Early to Middle Jurassic synrift infill, of the Austral (Magallanes) and Malvinas basins (Lovecchio et al., 2019). Thermochronological data from the Malvinas (Falkland) islands (Thomson et al., 2002) indicate exhumation in the Early-Middle Jurassic, consistent with shoulder uplift, with respect to the Malvinas basin. Further west, in the Austral (Magallanes) basin, Malkowski et al. (2015) and Zerfass et al. (2017) highlight diachronism of rifting initiation and bimodal volcanism towards the northwest, as well as diachronism of oceanic crust accretion in the Late Jurassic for the Rocas Verdes back-arc basin, which also becomes younger towards the north (see Fig. 12). In this framework, Lovecchio et a. (2019) interpret the overall diachronism of rifting initiation from east to west as a product of differential rollback below Patagonia (Echaúrren et al., 2017) triggered by a slab tear that would have been located between Patagonia and the Antarctic territories. The proposed slab tear would have been represented at the overriding plate's surface by a regional strike-slip fault zone, which is also necessary to accommodate lateral displacement between Eastern and Western

Gondwana that break apart at this time (König and Jokat, 2006) during the opening of the Mozambique basin (Fig. 12).

For the Antarctic Peninsula, Storey et al. (1992) also observe a westward migration of the Jurassic arc compared to the Triassic arc location (see Fig. 8 and 10 for comparison) and development of back-arc extension and magmatism. The Early Jurassic magmatism in the Antarctic Peninsula has been also correlated with the subduction-related Patagonian Subcordilleran Batholith in Patagonia by Riley et al. (2016).

The Colorado and Salado basins are located between, but presumably outside, the areas affected by magmatism of the Karoo LIP and the Chon Aike Magmatic Province (MP, Fig. 10). This Early-Middle Jurassic rifting stage has been interpreted as responsible for the formation of the main depocenters of the Colorado and Salado rifts (Lovecchio et al., 2018). This event is associated with SW-NE to N-S extension in the present-day South American reference frame. In a paleo-tectonic perspective (Fig.10), these basins are aligned with the ENE-oriented Karoo II Kalahari, Botswana, Limpopo and Mozambique rifts in Africa. Following this rationale and considering their synchrony and spatial relationships, the Colorado and Salado rifts could be the westernmost extension of the Karoo II rift system (Fig. 10).

### 5.3 Late Jurassic

In the Late Jurassic, oceanic crust accretion was already occurring in the Mozambique channel in East Africa (see Mueller and Jokat, 2017, and references therein). The dextral strike-slip fault zone that accommodated relative displacement between East and West Gondwana changed from strike slip to spreading and formed the Weddell Sea (Fig. 12, see Livermore and Hunter, 1996; König and Jokat, 2006;

Eagles and Vaughan, 2009). According to the slab-tear model recently published by Lovecchio et al. (2019), oceanic spreading of the Weddell Sea would have been triggered by the thermal anomaly produced by the asthenospheric window introduced by the vertical slab tear. There are still many uncertainties regarding the opening of the Weddell sea. Most of the conjugate passive margin on southern South America was consumed by subduction under the Scotia plate during the Cenozoic, while the other conjugate margin in Antarctica is covered by ice most of the year making it difficult to access and study. Magnetic data from the present-day Weddell Sea were documented by Livermore and Hunter (1996), Ghidella et al. (2002) and Jokat et al. (2003). A possible SDR wedge associated with the Gondwana breakup is also illustrated in Fig. 12 (Explora wedge, Hinz, 1981; Kristoffersen et al., 2014).

On the Pacific margin, arc migration to the west continued in central Patagonia, with the establishment of the Andean Patagonian Batholith in the Late Jurassic (PB in Fig. 12). Again westerly arc migration and clockwise rotation is observed, suggesting differential rollback of the subducted slab (Rapela et al., 2005; Echaúrren et al., 2017).

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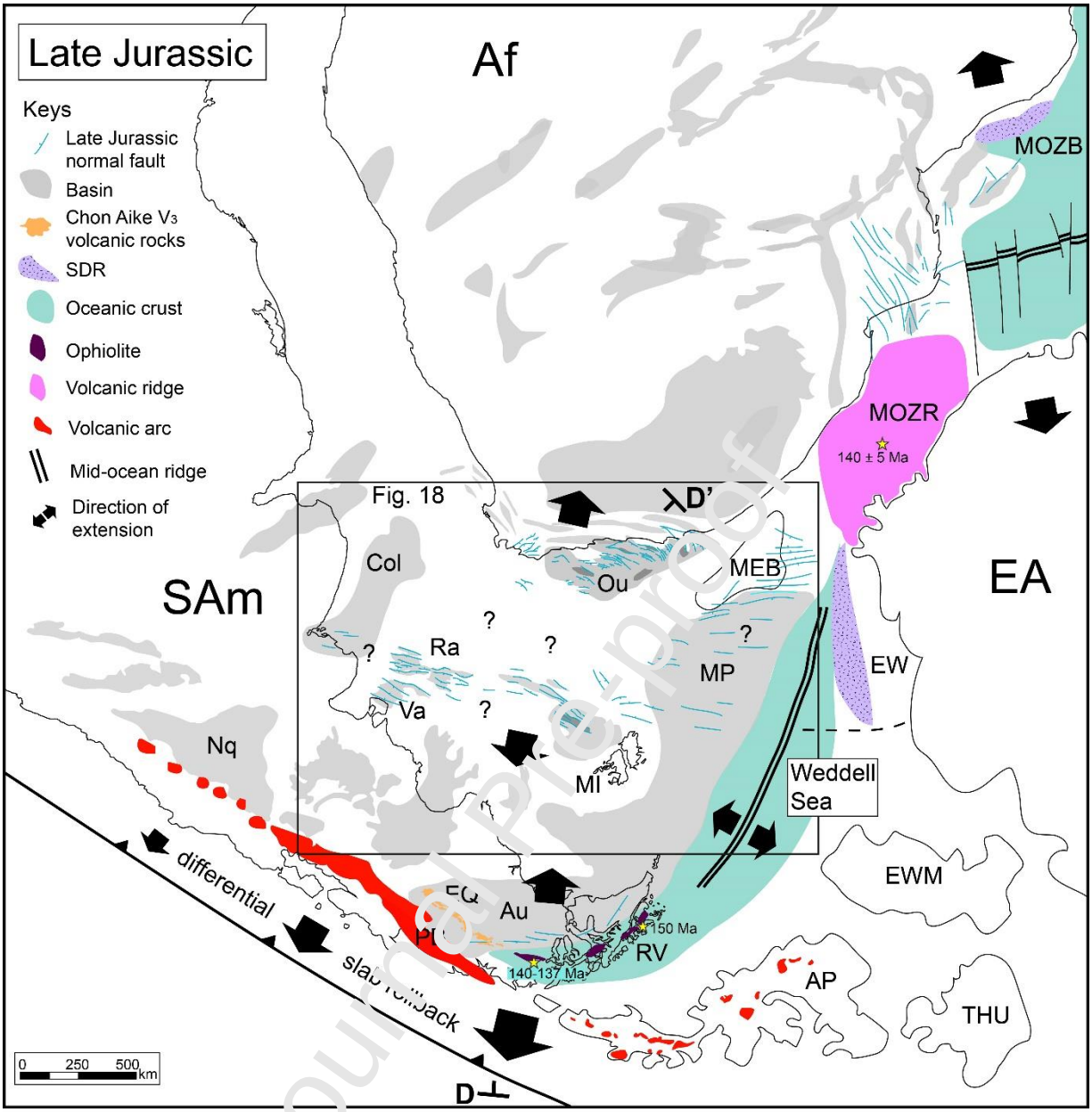



Fig. 12: Paleo-tectonic reconstruction of SW Gondwana in the Late Jurassic. Gondwana fit after König and Jokat (2006). The Mozambique channel opens as Antarctica moves south. Wrenching along the South America-Antarctica limit ends with seafloor spreading and the origin of the Weddell sea. Faults in the Mozambique area after Macgregor (2017) Mozambique Ridge (MOZR) age after Mueller and Jokat (2017). The Rocas Verdes (RV) back-arc basin develops to the west of the Austral basin. Schematic Patagonian Batholith (PB) after Rapela et al. (2005). Oceanic crust ages after Mukasa and Dalziel (1996) and Stern et al. (1992). Oblique rifting produced the formation of the Rawson/Valdés (Ra/Va) and Outeniqua (Ou) basins in the core of the Late Paleozoic Gondwanides orogen. Wrenching along the future Agulhas-Malvinas (Falkland) fracture zone (AMFZ) will release South America from Africa and produce the breakup along the Neoproterozoic mobile belt. The black rectangle shows the location of the zoom presented in Fig. 18.

Rifting associated with opening of the Rocas Verdes back-arc basin in the Late Jurassic (*circa* 160 Ma) is represented by the bi-modal magmatism observed in the El Quemado complex and its equivalents: the Lago La Plata Fm (Ramos, 1981) further north and the Ibañez Fm in Chile (Pankhurst et al., 2000). Rifting succeeded with the onset of oceanic crust accretion in the Rocas Verdes marginal basin since 150 Ma (Fig. 12, 13, Calderon et al., 2016). Although the Rocas Verdes basin displays a curved shape in its present day configuration (Fig. 12), it was probably a N-S elongated basin (see Vérard et al., 2012). The continuity of a single mid-ocean ridge between this back-arc basin and the Weddell Sea seems possible, as suggested by Diraison et al. (2000), and Eagles (2016). However, these basins are related to two tectonically independent mechanisms: the Rocas Verdes back-arc basin produced by rollover of the subducting plate, and the Weddell Sea generated by spreading of an active oceanic ridge between Eastern and Western Gondwana (Fig. 1). The solution proposed by Vérard et al. (2012), depicts these two independent oceanic basins, however the amount of extension (final width) and shape they infer for the Rocas Verdes basin (they favor a N-S elongated back-arc basin all along the margin) seems unlikely. The Rocas Verdes basin was an asymmetric basin, where rifting and oceanic spreading started earlier in the south (see Malkowski et al., 2015), producing more cumulative extension than in the north, thus generating a triangular shaped basin (also consistent with the clockwise rotation of the arc in northern Patagonia between the Early and Late Jurassic; Echaúrren et al. 2017; Lovecchio et al., 2019). The northernmost obducted oceanic crust outcrops south of 51°S (Sarmiento Complex), suggesting that the back-arc basin could not have reached further north than 48°S latitude (see Fig. 3 and 12) while Vérard et al. (2012) suggest the back-arc basin reached north of 20°S latitude. The impact of the

Patagonian orocline in curving the remnants of the Rocas Verdes basin in the south, plays an important role and remains a matter of discussion out of the scope of this study (Ghiglione and Cristallini, 2007; Torres Carbonell et al., 2016; Eagles, 2016). In our reconstruction (Fig. 12) we present the Patagonian orocline and the Fuegian Andes with their present-day shape.

In Africa, Late Jurassic marine sediments are recorded in the Outeniqua basin. In a paleo-tectonic perspective (Fig. 12), regardless of the continental fit used, fault orientations in the Outeniqua and in the Rawson/Valdés basins in South America seem parallel, consistent with largely present-day N-S extension for African (ENE extension for present-day South American) reference frame. As suggested by Continanzia et al. (2011), we associate both basins with a single oblique rifting event initiated in the Late Jurassic (Fig. 12 and 13). The extensional faults interpreted by Biddle et al. (1996) around the Maurice Ewing Bank (MEB in Fig. 12) and in the Malvinas (Falkland) Plateau could have started earlier or belong to this same rifting event. Also the North Rift of the North Malvinas (North Falkland) basin develops at this stage (Lohr and Underhill, 2015; Richards and Hillier, 2000). A northern connection between this basin and the Atlantic rift has been suggested by Becker et al. (2012).

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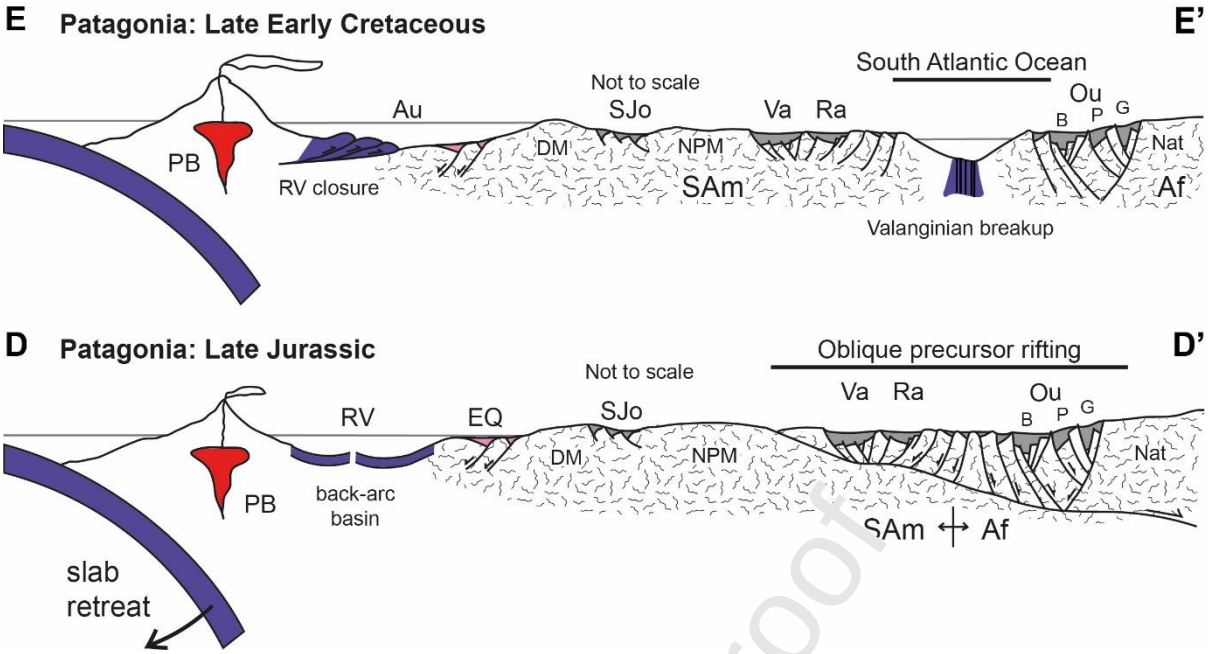



Fig. 13: Schematic cross sections of the SW Gondwana margin (not to scale). D-D' is a transect across SW Patagonia in the Late Jurassic with a magmatic arc represented by the Patagonian Batholith, retroarc extension marked by the emplacement of El Quemado complex and equivalents and spreading in the Rocas Verdes back-arc basin. Oblique rifting in the Rawson/Valdés and Outeniqua basin was precursor of the South Atlantic opening. See location in Fig. 12. Modified after Ramos (1996), Continanzia et al. (2011) and Broad et al. (2012). E-E' is a generalized transect across SW Patagonia in the Early Cretaceous (*sensu lato*), compression in the SW Gondwana margin is evidenced by the closure of the Rocas Verdes basin and onset of a foreland setting in the Austral-Magallanes basin in the Late Early Cretaceous. Spreading in the southern South Atlantic Ocean initiated in the Valanginian. See partial location in Fig. 15. Keys for basins and tectonic blocks as in Fig. 2, 3, 5 and 15.

### 5.4 Early Cretaceous

The main tectonic event taking place in the Early Cretaceous is the opening of the South Atlantic Ocean between Africa and South America. This process has been interpreted to be diachronous, initiating in the south and progressively propagating northwards (Rabinowitz and LaBreque, 1979). The southern South Atlantic is a typical magma-rich margin (or volcanic margin, see Tugend et al., 2018, and references therein), characterized by the presence of SDRs on the continental-oceanic transition domain (COT, Fig. 14). Volcanic margins have been related to high extension rates (spreading half rates in the order of 25-30 mm/yr, Lundin et al.,

2014). In the case of the South Atlantic, the northwards migration of rifting and ocean spreading took place in segments. Both conjugate margins, South American and African, present a strong segmentation as illustrated in Figs. 3 and 5 (Franke et al., 2007; Koopmann et al., 2014). Fracture zones (FZ) limit the different segments and are interpreted to be active at least since SDR emplacement (Franke et al., 2007; Franke, 2013). For reference on the segmentation of the South Atlantic margin, refer to Clemson et al. (1997), Franke et al. (2007), and Blaich et al. (2009). The origin and emplacement mechanisms of SDRs are out of the scope of this study. Hereafter, in this study of the Southern South Atlantic Argentinean margin, we follow the *rationale* presented by Geoffroy et al. (2005) and McDermott et al. (2018) who differentiate between inner fault-bounded SDRs, and outer flexured SDRs, that develop as part of the breakup process in a *continuum* from rifting to oceanic spreading.

In the seismic line presented in Fig. 14, the SDR wedges observed in the Argentinean margin are emplaced along the COT. Further inboard, on continental crust, several half-grabens bounded by inboard-dipping faults are depicted. These depocenters are located along the outermost 200 km wide fringe of the continental crust domain along the Colorado, Salado and Punta del Este basins, and have been associated with the Early Cretaceous South Atlantic Rift (Lovecchio et al., 2018; see Fig. 15a).

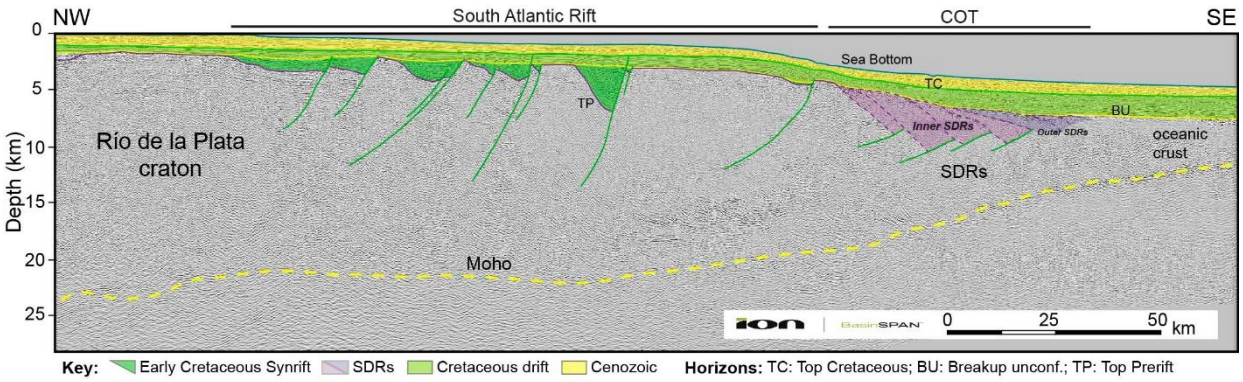



Fig. 14: Depth-converted dip seismic section of the northern Argentinean margin (southern Salado basin), between the Tandilia and Salado FZs. Location in Fig. 16.

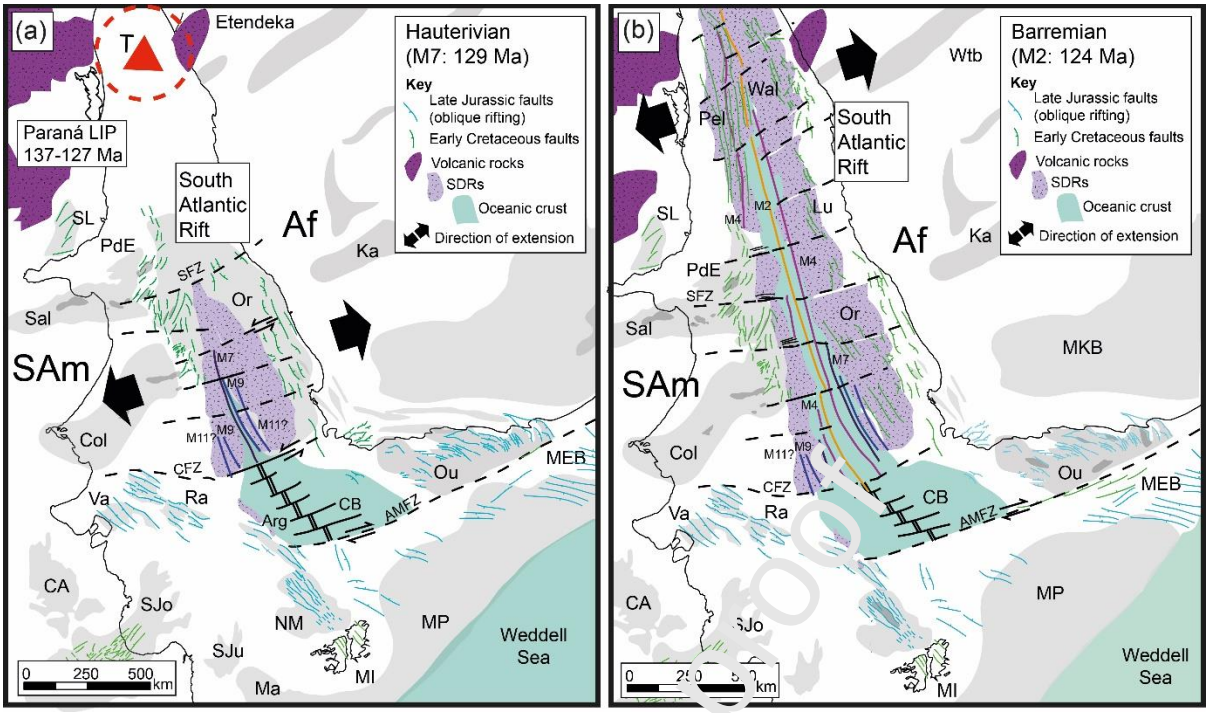



Fig. 15: Paleo-tectonic reconstructions of the South Atlantic Rift in the Early Cretaceous: a) Hauterivian: the southernmost Rawson/Valdes – Outeniqua segment where breakup occurred in the Valanginian is in the drift phase; north of the Colorado fracture zone (CFZ), SDRs are being emplaced along different segments during the breakup process. The South Atlantic rift has an approximate width of 500 km. Further North in the Pelotas/Walvis segment, the Paraná-Etendeka basalts are produced by the Tristan da Cunha (T) hotspot before onset of rifting; b) Barremian: active rifting in the Pelotas/Walvis segment, while south the Salado fracture zone (SFZ) the conjugate margins are in the drift phase.

In the southernmost segment of the southern South Atlantic however, it is interesting to note the apparent absence of SDRs, below the Argentina and Cape conjugate basins (Fig. 3 and 5 respectively). This area with apparent absence (or proportionally less) SDRs is bracketed between the Agulhas-Malvinas (Falkland) FZ and the Colorado-Cape FZ (Fig. 15 and 16).The lack of SDRs in the southernmost segment of the South American margin has been interpreted, considering the vicinity of the AMFZ, as due to transform margin dynamics (Becker et al., 2012). Another characteristic to analyze is the difference in length (N-S) of the magma-poor segment on both sides of the South Atlantic (see Fig. 16): 380 km north of the AMFZ offshore South America (Franke et al., 2010) and approximately 460 km between the AMFZ

and the first occurrence of SDRs offshore South Africa. This difference was interpreted by Koopmann et al. (2014) as a product of a pre-breakup extensional regime. Following Heine et al. (2013), they suggest that extension initiated in the Late Jurassic, with N-S extension that formed the Outeniqua and Rawson/Valdés basins and successively turned clockwise towards an E-W direction. Besides the SDRs, directly related to continental breakup, we present in Fig. 16 the Atlantic basins on the African margin and the main depocenter-bounding faults. Most of these structures are oriented parallel to the African present-day coastline and the outer limit of the SDRs. In the Orange basin, some half-grabens developed on continental crust, most of them bounded by seaward-dipping faults (like the AJ depocenter, Fig. 16; see Broad et al., 2012). On the South American conjugate margin, Stica et al. (2014) presented a series of continentward-dipping faults as bounding both synrift depocenters and SDR wedges. The nature of the SDRs bounding surfaces, either SDR-bounding faults (*sensu* Stica et al., 2014) or feeder dykes for the SDR volcanic layers (Quirk et al., 2014), remains under debate. We propose that even if these SDRs bounding surfaces might not behave as standard normal faults, their orientation is directly associated with the stress regime at the time of SDR emplacement and thus parallel to other normal faults on continental crust (Figs. 14 and 15a).

The COT in the segments between the Colorado/Cape FZ and the Salado/Orange FZ is characterized by along-strike asymmetry in width of the SDR wedges (transect G-G' in Fig. 17). The COT on the Argentinean margin is narrower and decreases in width northward towards the Salado FZ, while on the African margin the COT is wider and underwent significant thinning (Blaich et al., 2011).

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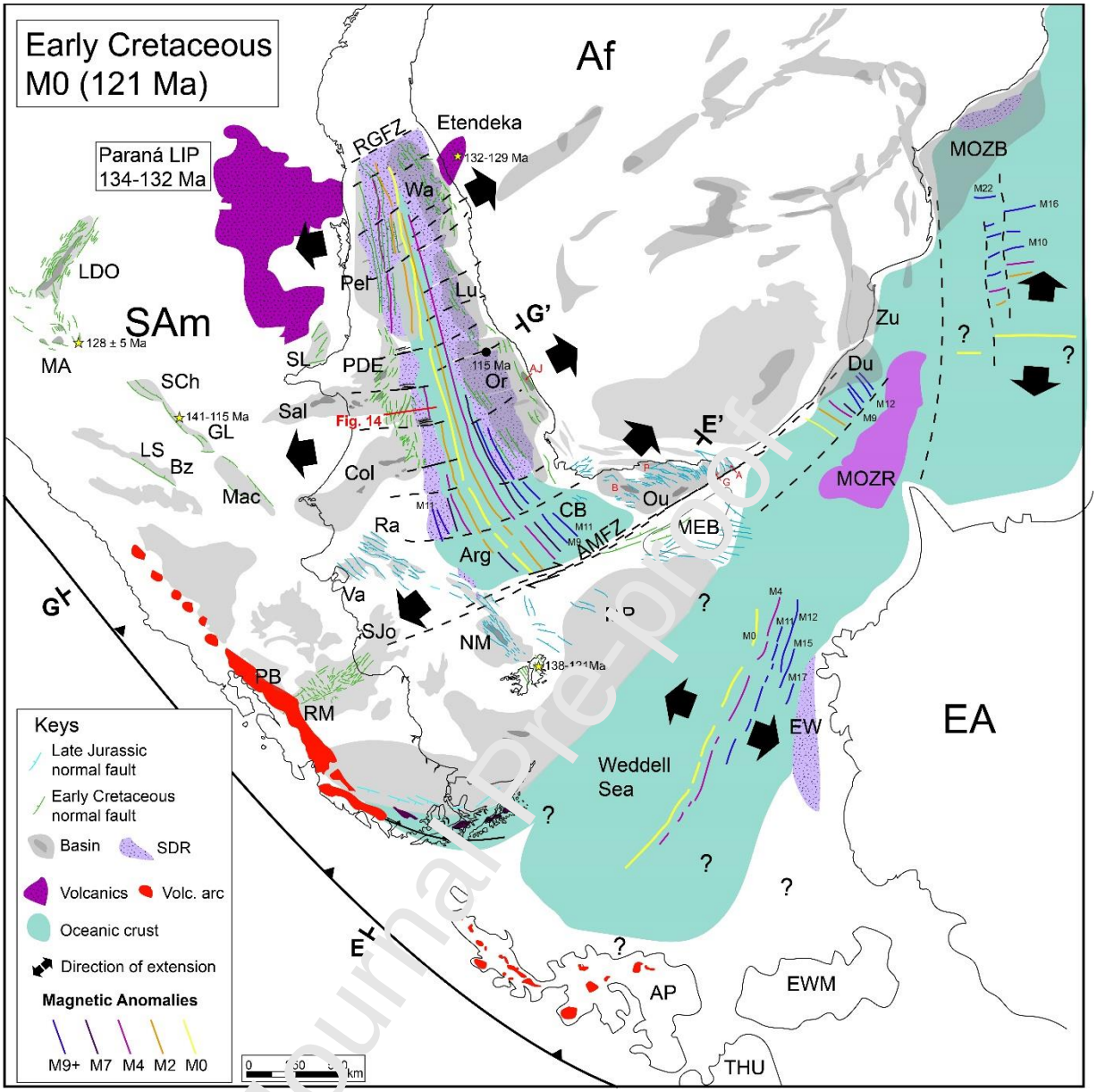



Fig. 16: Paleo-tectonic reconstruction of SW Gondwana in the Early Cretaceous (at 121 Ma). The South Atlantic opening is presented at an evolved stage. South America-Africa fit after Blaich et al. (2011), Antarctica blocks and magnetic anomalies in the Weddell Sea area and Mozambique basin after König and Jokat (2006). Magnetic anomalies in the and Natal Valley after Goodlad et al. (1982). Antarctica continues to drift south. Wrenching along the AMFZ allows the opening of the South Atlantic Ocean since the Mid-Valanginian. SDRs are absent in the southernmost segment. Southwards, the North Malvinas (North Falkland) graben is an extension of the Atlantic rift (Becker et al., 2012). Faults in the North Malvinas (North Falkland) area after Lohr and Underhill (2015). Dykes in the Malvinas (Falkland) Islands yielded an Early Cretaceous age (Stone et al., 2008). Extension is recorded on both margins in a narrow rift on both sides of the present-day COTs. SDRs develop on the other segments norths of Rawson. South American basins: Punta del Este (PDE); Santa Lucía (SL), Pelotas (Pel). African basins: Outeniqua (Ou), Orange (Or, age from biostratigraphy in the Kudu well, Erlank et al., 1990), Luderitz (Lu) and Walvis (Wa). Ancient basement structures are extensionally reactivated producing the Macachín (Mac), Sierras Chicas (SCh, ages from

Lagorio, 2008), Las Salinas (LS) and Beazley basins of San Luis, Metán-Alemanía (MA) and Lomas de Olmedo basins (LDO, age after Galliski and Viramonte, 1988). The Paraná-Etendeka LIP extrudes during this period (Pinto et al., 2011). Structures and depocenters after Uliana et al. (1989), Ramos and Turic (1996), Gladczenko et al. (1997), Jungslager (1999), Franke et al. (2007), Starck (2011), Broad et al. (2012), Stica et al. (2014), Koopmann et al. (2014), Figari et al. (2015), Lohr and Underhill (2015), and Lovecchio et al. (2018).

Although the age of rifting onset in the southernmost South Atlantic segment is yet poorly constrained (as both conjugate margins remain underexplored with limited magnetic data, see Franke, 2007; Becker et al., 2012; Koopmann et al., 2014), we presume that E-W oriented rifting might have started in the Berriasian-Valanginian. Breakup (onset of oceanic spreading) initiated in the south possibly in the Valanginian. The unconformity between synrift I and II in the Outeniqua basin is dated mid-Valanginian (Jungslager, 1996) and has been related to strike-slip movement along the Agulhas-Malvinas (Falkland) FZ due to E-W extension (Broad et al., 2012). Breakup progressively advanced north (Rabinowitz and LaBreque, 1979; Nürnberg and Müller, 1991). Heine et al.'s, 2013) plate kinematic model indicates a top Hauterivian age for the initiation of normal oceanic crust accretion at the Colorado/South Orange segment, and Aptian in the northern Pelotas/Walvis segment (Fig. 11;. Rifting and successive breakup were thus strongly diachronous and evolved in individual segments bounded by fracture zones, possibly inherited form the rifting stage.

Onshore Argentina, a series of aligned Cretaceous basins developed on the western edge of the Rio de la Plata craton (Fig. 16; e.g. Macachín, General Levalle, Sierras Chicas, etc.) and another trend to the west of that one (e.g. Las Salinas, Beazley, etc., Uliana et al., 1989). The Santa Lucia basin develops within the Rio de la Plata craton, possibly associated with strike-slip as suggested by Veroslavsky (1999). In the San Jorge Gulf basin, a Neocomian phase of extension is responsible

for a series of depocenters across the basin and extending to the west into the Rio Senguerr, Rio Mayo, and Rio Guenguel sub-basins (RM in Fig. 16, Iannizzotto et al., 2004; Mpodozis and Ramos, 2008). In northern Argentina, the three-branched NW Argentina basin opened at this stage (Fig. 16), with the N-S oriented Metán/Alemanía and Tres Cruces sub-basins, and the E-W directed Lomas de Olmedo sub-basin.

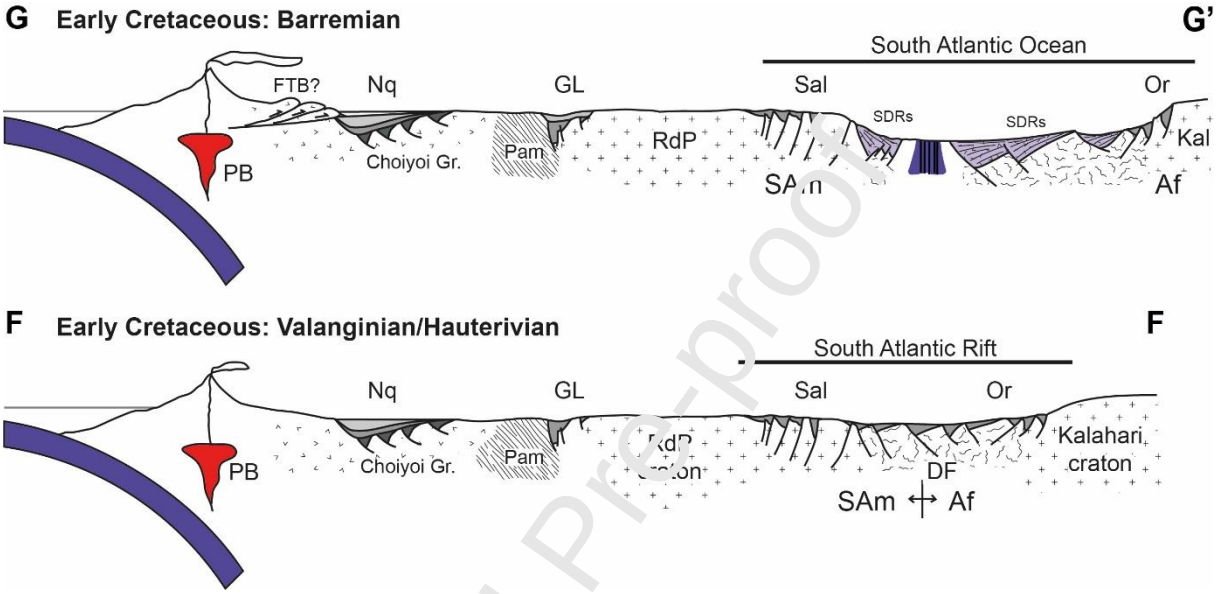



Fig. 17: Schematic cross sections of the SW Gondwana margin. F-F' is a transect for the Valanginian, with a magmatic arc represented by the Patagonian Batholith. The General Levalle graben (GL) is depicted (after Webster et al., 2004). Rifting in the South Atlantic Rift area (Fig. 15a) across the southern Salado basin (Fig. 14) and the Orange basin. Transect G-G' represents the same section in the Barremian, with SDRs emplacement along this segment in the Hauterivian, and breakup near the Hauterivian/Barremian boundary. Compression is interpreted for the Neuquén basin retroarc (Nq), possibly with development of a fold and thrust belt (FTB). See approximate location in the map in Fig. 15 and 16.

## 6. DISCUSSION

We have presented in our reconstructions a new model that portrays the occurrence and timing of Mesozoic rifting in SW Gondwana. Basement structural inheritance has played a key role in conditioning faults and development of depocenters throughout the Mesozoic. In the Triassic, for instance, the Cuyo basin developed on a suture between terranes accreted to the SW margin of Gondwana during the Paleozoic (Fig. 9; Ramos and Kay, 1991) that was extensionally

reactivated in a retroarc setting when subjected to extension. In the Early Cretaceous, with E-W extension and the opening of the South Atlantic Ocean, a series of N-S oriented basins developed along the boundary between the Río de la Plata craton and the Pampia cratonic block (Fig. 17; e.g. Macachín, General Levalle, Sierras Chicas basins).

Regarding the mechanisms triggering rifting, we follow the rationale of Frizon de Lamotte et al. (2015) for Central Gondwana. Besides active rifting produced by plume impingement (Dewey and Burke, 1974), recent studies suggest that in most cases rifting precedes volcanism (Buiter and Torsvik, 2014; Peace et al., 2019) and subduction-related slab rollback instability is presumed to be a major trigger of continent dispersal (Bercovici and Long, 2014). We have highlighted this effect for the Mesozoic evolution of SW Gondwana (Fig. 8; e.g. Cuyo, Bermejo, Neuquén basins). In a global scale perspective, Riel et al. (2018) suggest a counter-clockwise rotation of Pangea between 260 and 230 Ma as the cause for initiation of extension in the SW Gondwana margin. This is also evident in the Antarctic Peninsula, with the trench-ward migration of the volcanic arc (Storey et al., 1992, 1996; Bastias et al., 2020). The presence of intracratonic rifts associated with the Karoo I event in central Gondwana (e.g. Santa Maria, Waterberg) could also be related to far-field stresses associated with rifting in the Central Atlantic area occurring at that time (Figs. 1 and 7).

The Early Jurassic Karoo event (Karoo II) is an exception. Regional doming and volcanic activity prior to rifting confirm an active rifting mechanism (Frizon de Lamotte et al., 2015 and references therein) responsible for the opening of the Mozambique channel and breakup between Eastern and Western Gondwana (Storey, 1995; Fig. 1). We associate the Karoo event with the main phase of

extension in the Colorado and Salado basins, offshore Argentina. Even if these basins would remain outside the area with plume-related volcanic activity, in their paleo-tectonic position (Fig. 10) they are aligned with the Karoo II depocenters in Africa and could be coeval with the Cuyo Group rifting in the Neuquén basin, largely associated with N-S extension in the Early Jurassic. The Colorado and Salado basins developed prior to the South Atlantic Rift (see Lovecchio et al., 2018 and references therein) and should be considered separately, especially when carrying out thermo-mechanical modelling of the South Atlantic breakup.

Out of the area of influence of the Karoo plume, towards the SW Gondwana margin, the Chon Aike magmatic province, one of the largest silicic igneous provinces known in the world (Kay et al., 1989) played a major role, as it is intrinsically related to diachronous extension in Patagonia, the Antarctic Peninsula and other Antarctic territories (Pankhurst et al., 2000). Rapela et al. (2005) propose the development of the Patagonian Subcordilleran Batholith volcanic arc, coeval with the Chon Aike MP, emplaced under crustal extension. The southwestward migration and clockwise rotation of the arc between the Early Jurassic Patagonian Subcordilleran Batholith position and the Late Jurassic-to-recent (N-S oriented) position along the Andes has been associated with differential slab rollback (Echaurren et al., 2017). Extension related to the Chon Aike MP has also been linked to the formation of the Cañadón Asfalto, Malvinas and Austral basins (Uliana et al., 1985; Lovecchio et al., 2019), to which we add, following Ramos et al. (2017), the South Rift of the North Malvinas (North Falkland) basin (Fig. 10).

Rifting in the Mozambique basin since the Early-Mid Jurassic (Karoo II rifting), and the successive opening of the Mozambique channel, could not have been accomplished without lateral slip along the proto-Weddell fracture zone that

mechanically released Eastern from Western Gondwana (König and Jokat, 2006). This Jurassic deformation zone has been interpreted as the surface response to a slab-tear in the paleo-Pacific subduction zone, located between Patagonia and Antarctica (Lovecchio et al., 2019). The separation of Eastern from Western Gondwana both continents was a key milestone in the Gondwana dispersal process. Moreover, it allowed the acceleration of retro-arc extension in Western Gondwana, with rifting in the Malvinas and Austral basins, a process that culminated in the Late Jurassic with the opening the Rocas Verdes back-arc basin (Lovecchio et al., 2019).

In the core of Western Gondwana, in a more intra-continental setting, Late Jurassic rifting in the Outeniqua and Rawson/Valdés basins is presumed to have been oblique to the strike of the future South Atlantic COT, but rather parallel to the paleo-tectonic orientation of the northern Rocas Verdes basin (Fig. 12). The area affected by the Outeniqua-Rawson/Valdés rifting is presumably the core of the Gondwanides orogen (Fig. 2 and 7), an area subjected to compression in the Late Paleozoic with the collision of Patagonia. A possible analog to better understand the Rawson/Valdés – Outeniqua segment could be the Gulf of Aden (see Leroy et al., 2010, 2012; Mohriak and Leroy, 2013). Both systems seem to be related to oblique rifting and evolve through a lateral third branch at almost 90° (the South Atlantic Ocean, and the Red Sea respectively, Fig. 18). There are differences, however, between these two case studies. Regarding the rift-to-drift transition, in the Gulf of Aden, the system evolved to an oceanic basin as the stress regime remained oblique to the structural grain, and if extension persists in the Main Ethiopian Rift between Africa and Somalia, the system will end up split in three plates. In the case of the South Atlantic, the oblique rifting related to the Rawson-Valdés and Outeniqua basins was aborted, as the stress regime presumably changed from near N-S to almost E-W

in a short period of time (Heine et al., 2013). The Agulhas-Malvinas (Falkland) lineation evolved, under the new stress regime, as a dextral shear zone at least since the Valanginian (Baby et al., 2018). The AMFZ could be another case of structural inheritance, as it could be the eastern extension of the suture related to the collision of a terrane comprising the Deseado Massif (see Fig. 2) against the Northern Patagonian Massif suggested by Pankhurst et al. (2006). Although there are differences regarding plume impingement in the Afar region, in our understanding the Gulf of Aden and the Afar triple junction could work as a good analog for the early evolution of the Malvinas elbow (Fig. 18a), originating the Argentina and Cape basins.

As has recently been suggested from numerical modeling, oblique rifting seems to facilitate continental breakup, as it requires less force to reach the plastic yield limit when compared to rift-perpendicular extension (Brune et al., 2012). In our study case, we propose that a first phase of oblique rifting in the Rawson/Valdés – Outeniqua segment, might have been effective in thinning the lithosphere starting in the Late Jurassic (Fig. 13, transect D-D'), where we interpret a single east-dipping detachment (following Ramos, 1996). In the Early Cretaceous, lithosphere would have already been thinned in the southernmost segment of the South Atlantic and when subjected to E-W extension, was the first segment to break up, without large magmatic volumes forming SDRs (Fig. 13, transect E-E'). The southernmost segment behaves, in our opinion and until new data are available, as a magma-poor, abrupt margin (Fig. 15a).

Breakup along the South Atlantic Rift occurred in segments delimited by fracture zones (FZ). Mechanics of rift propagation across the different segments have been postulated by several authors, notably Franke et al. (2007), Franke (2013),

Blaich et al. (2013), and Koopmann et al. (2014). Regarding the E-W oriented extension since at least the Mid-Valanginian, we agree with the model presented by Blaich et al. (2011) who introduced a two-phase breakup process, with first a continental rifting phase (crustal thinning) forming a 500-km wide Atlantic rift system (Fig. 15 and 17) followed by the breakup phase with SDR emplacement and successive oceanic spreading (Lovecchio et al., 2018). Both phases could have taken place as part of a continuous process. The origin of that E-W extension could also be related to retroarc dynamics produced by changes in the subduction regime (notably the depth reached by the subducting plate and the size of the convection cell) as recently postulated by dal Zilio et al. (2018), and the occurrence of SDRs would then be produced by interactions of an already installed rift system (the South Atlantic Rift) with a mantle plume (Tristán da Cunha, Fig. 15a).

In the Hauterivian, oceanic spreading had already started in the southernmost Rawson/Valdés – Outeniqua segment (probably since the mid Valanginian, Fig. 15a). The Colorado FZ is a major feature at this stage, accommodating oceanic crust accretion to the south, and continental rifting and SDR emplacement to the north. In the Colorado-Orange segment, rifting is restricted to a 500 km wide rift system, while the areas affected by older fossilized rifting stages (Late Triassic to Early-Mid Jurassic) remain in a thermal sag phase (Lovecchio et al., 2018). We believe this is an important observation to be considered in future thermo-mechanical modeling of the South Atlantic breakup at the Colorado segment: the older rifts forming the Central and Eastern Colorado depocenters should not be modelled as part of the same Early Cretaceous South Atlantic rifting.

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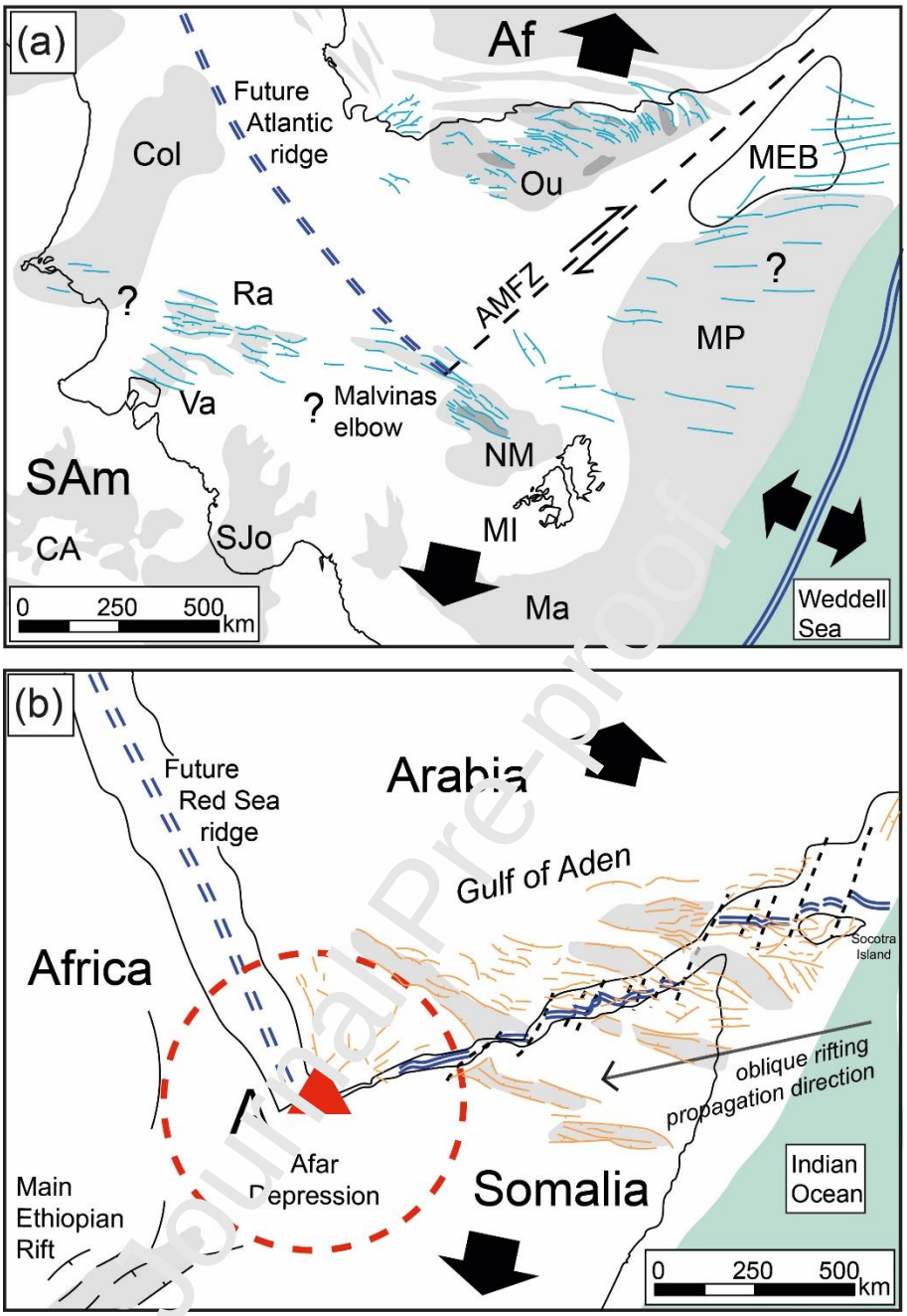



Fig. 18: Comparison of a) Late Jurassic oblique rifting in the southern South Atlantic area; and b) Cenozoic oblique rifting in the Gulf of Aden (after Leroy et al., 2012 and Mohriak and Leroy, 2013).

The South Atlantic Rift followed basement weakness zones, formed in the Neoproterozoic Brasiliano-Panafrican Orogeny. These weakness zones could have been either sutures (Hartnady et al., 1985) or, as recently suggested by Will and Frimmel (2018), the long axes of Neoproterozoic back-arc basins (the Marmora basin, Namibia). We believe that basement inheritance certainly played an important

role, but what was key for the orientation of the South Atlantic rift was the rotation of the stress regime in the Early Cretaceous to a more orthogonal position with respect to this basement structural fabric. This configuration would have allowed the rapid propagation of rifting following precursor weakness zones, north of the already rifted Rawson-Valdés/Outeniqua segment. Wrenching along the AMFZ was necessary to accommodate extension to the north of it and allow continent separation. Early Cretaceous rifting is present, however, south of the AMFZ. The North Branch of the North Malvinas (North Falkland) basin and some minor rifts could have formed during the Late Jurassic, but they also seem to connect to the South Atlantic Rift to the north (Becker et al., 2012; Lohr and Underhill, 2015). Probably due to plate's relative rotations and the presence of a lithospheric discontinuity, breakup favored wrenching along the AMFZ instead of continuing propagation to the south (through the nowadays aborted North Malvinas -North Falkland- graben).

## 7. CONCLUSIONS

The opening of the South Atlantic in the Early Cretaceous was only the final stage of the complex rifting history of SW Gondwana. Evidence for intracontinental rifts is present in Africa and South America in the Triassic (Karoo I), synchronous with retroarc depocenters in SW Gondwana margin (Cuyo, Bermejo, Precuyano of Neuquén, Deseado and Malvinas basins) that are clearly related to subduction dynamics (passive rifting).

In the Early Jurassic, rifting in Eastern Africa was triggered by the impact of the Karoo plume, which produced the formation of a network of Karoo II depocenters in Africa (active rifting). The Colorado and Salado basins in the Argentinean shelf formed at this stage, together with the Cuyano cycle of the Neuquén basin. Rifting in

East Africa ultimately produced the breakup of Eastern from Western Gondwana in the Middle Jurassic. In Patagonia, the Chon Aike silicic magmatic province was emplaced at this time, in a retroarc setting behind the Subcordilleran Batholith arc. Retroarc extension, due to differential slab rollback is responsible for the formation of the Cañadón Asfalto, Austral and Malvinas basins, and possibly the southern rift of the North Malvinas (Falkland) basin and was possibly triggered by a slab tear between Patagonia and Antarctica (Lovecchio et al., 2019).

Retro-arc extension continued and, subsequent slab steepening produced in the Late Jurassic the opening of the Rocas Verdes back-arc basin. Rifting in the Outeniqua and Rawson/Valdés basins took place at this stage, in an oblique setting to the future South Atlantic COT. The Late Jurassic rifting affected the orogenic core of the Gondwanides orogen and is precursor to South Atlantic opening. Subduction dynamics is the main process controlling extension in the SW Gondwana region during the Mesozoic.

The South Atlantic Rift possibly took advantage of crustal weakness zones (Precambrian mobile belts) but is related to a rotation of the stress field to a present-day near E-W direction. Rifting occurred diachronically from south to north and started during or before the Valanginian. The southernmost segment, between the Agulhas-Malvinas (Falkland) fracture zone and the Colorado-Cape, had already been affected by crustal thinning during the Late Jurassic oblique rifting. This could explain the lack of SDRs in this segment, which was the core of the Late Paleozoic Gondwnides orogen later on subjected to multiple phases of extension. North of the Colorado-Cape fracture zones, rifting and SDR emplacement took place in segments bounded by fracture zones. SDR emplacement was asymmetrical on both margins and eventually oceanic crust inception propagated diachronically along the margin,

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between Hauterivian and Aptian times. The opening of the South Atlantic is another case of passive rifting and recent models suggest that subduction-related mechanisms linked to deep subduction could trigger extension as far as 3,500 km away from the trench (dal Zilio et al. 2018).

The nucleus where the South Atlantic Ocean was initiated, corresponds to the place where the main extensional phases identified were locally superimposed throughout the Mesozoic. Thus, maximum crustal extension present in the area, favored breakup and the development of the magma-poor southernmost segment of the southern South Atlantic.

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Highlights:

- Gondwana experienced poly-phased rifting, related to Mesozoic subduction dynamics.
- The Colorado and Salado basins, offshore Argentina, are part of the Karoo system.
- Late Jurassic oblique rifting was precursor of spreading in the South Atlantic.
- The South Atlantic Rift was a highly-segmented, 500 km-wide, diachronous rift system.
- North of Colorado-Cape Fracture Zone (CFZ), magma-rich margins formed product of interaction with the Paraná LIP.

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