Geol. Mag. **147** (*2*), *2010, pp. 193–205.* © *Cambridge University Press 2009*
doi:10.1017/S0016756809990355

Cretaceous slab segmentation in southwestern Gondwana

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(*Received* 9 December 2008; *accepted* 7 May 2009; First published online 16 September 2009)

Abstract – The Mesozoic Austral Basin of Patagonia, in southwestern Gondwana, experienced a major tectonic segmentation during Aptian times. Sometime between 121 and 118 Ma (Aptian), the northern part of the Austral Basin, known as the Aisén Basin or Río Mayo Embayment, was inverted, with the sediments overlain by calc-alkaline subaerial volcanic rocks of Aptian to Maastrichtian age. In the southern segment of the Austral Basin, known as the Magallanes Basin, predominantly marine sediments accumulated until Cenozoic times in a back-arc position, relative to a magmatic arc located to the west. The subduction-related N–S-trending volcanic chains of both segments were geographically displaced during Aptian to Late Cretaceous times. In the Aisén segment north of ∼ 49–50° S, the volcanic chain was located further east than the coeval arc in the Magallanes segment. A transform fault connected the trenches of both segments, with the Aisén segment dipping at a shallower angle than the Magallanes segment.

Keywords: slab, segmentation, Cretaceous, Patagonia, Chile, Gondwana.

1. Introduction

The latest Jurassic to Early Cretaceous geology of southernmost South America was dominated by a magmatic arc along the Andean cordillera and a marine back-arc basin, known as the Austral Basin (Fig. 1), to the east, that in its southern part continued into the Cenozoic (Dalziel, De Wit & Palmer, 1974; Suárez, 1979; Winn & Dott, 1979; Biddle *et al.* 1986; Wilson, 1991; Robbiano, Arbe & Gangui, 1996; Bell & Suárez, 1997). The Austral Basin, a well-known oil-producing basin in its southern and central parts, extended from the southernmost tip of the continent (56° S: e.g. Biddle *et al.* 1986) to as far north as the locality of Futaleufú, in Chile (43° S: De la Cruz *et al.* 1996) (Figs 1, 3). In the northern part its deposits diachronously covered volcanic rocks of Late Jurassic and Early Cretaceous age (Covacevich, De la Cruz & Suárez, 1994; Suárez, De la Cruz & Bell, 1996, 2007; De la Cruz *et al.* 2003; Iannizzotto *et al.* 2004). After the early Aptian, the northern part followed a completely different path from that of the southern part, as is presented herein. For this reason, in this work the northern part of the Austral Basin will be referred to as the Aisén Basin (or Río Mayo Embayment: Aguirre-Urreta & Ramos, 1981), and the southern part as the Magallanes Basin, following earlier proposals by Suárez (1976), Ramos (1989) and Kraemer & Riccardi (1997), the boundary being approximately at latitude 49–50° S. The latter includes along its southwestern region the ‘Rocas Verdes Basin’, a sub-basin floored by quasi-oceanic crust composed of ‘ophiolites’ (e.g. Dalziel, De Wit & Palmer, 1974; Suárez & Pettigrew, 1976). The Austral Basin is underlain by volcanic rocks, well exposed along the Patagonian Cordillera, that have been named the Ibáñez or Lago La Plata formations, in Chile and Argentina, respectively, in the north, and the El Quemado Complex or Tobífera Formation (Suárez, 1978) in the south. These rocks represent the youngest volcanic association of the Chon Aike Province, a Lower Jurassic to Upper Jurassic–Lower Cretaceous large igneous province with acid characteristics, emplaced during rifting that preceded the fragmentation of southwestern Gondwana in Patagonia (Gust *et al.* 1985; Pankhurst *et al.* 1998, 2000; Riley *et al.* 2001). They unconformably cover metamorphic rocks of Late Palaeozoic age.

The geological mapping of the Chilean part of the eastern central Patagonian Cordillera, between latitudes 43 and 49° S, aided by fossil guides and U–Pb SHRIMP, K–Ar and $^{40}Ar/^{39}Ar$ dating, has allowed us to build up a stratigraphic and tectonic record of the Aisén segment area (e.g. De la Cruz *et al.* 1996, 2003, 2004; De la Cruz & Suárez, 2006, 2008; Suárez, De la Cruz & Bell, 1996, 2007; Suárez *et al.* 2009; Suárez & De la Cruz, 2000, 2001; Demant, Suárez & De la Cruz, 2007*a*) that could be compared in more detail with published work from the Magallanes segment. Most of the work done on the stratigraphy and sedimentology of the Magallanes segment was published in the period between the late 1950s and 1970s (Cecioni, 1957; Katz, 1963; R. Cortés, unpub. thesis, Univ. Técnica del Estado, 1964; Scott, 1966; J. Stewart *et al.* unpub. report, Instituto de Investigaciones Geológicas, Chile, 1971; Natland *et al.* 1974; Dott, Winn & Smith, 1976; Winn & Dott, 1979; Riccardi & Rolleri, 1980), with more recent contributions (e.g. X. Prieto, unpub. thesis, Univ. Chile, 1993; P. Mella,

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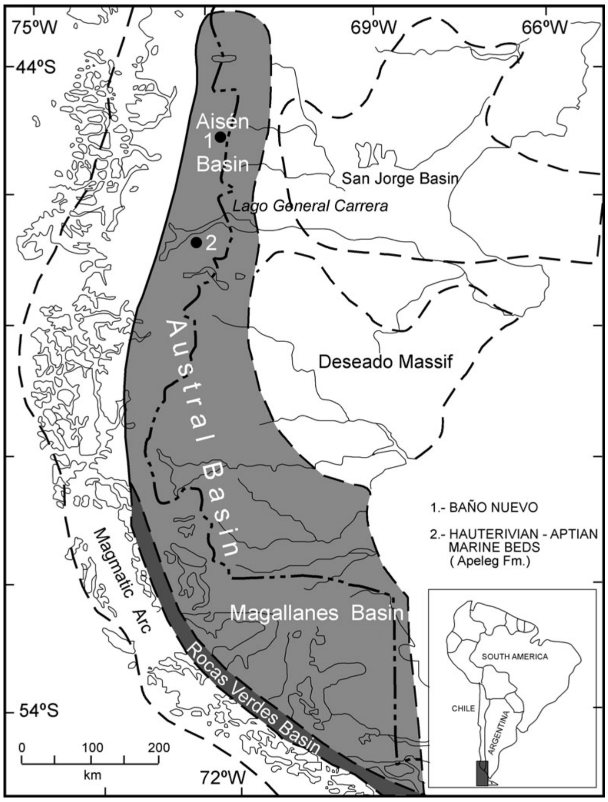

Figure 1. Schematic figure showing the Austral Basin and the magmatic arc for the Late Jurassic–Early Cretaceous of Patagonia (from Suárez *et al.* 2009). The Aisén, Magallanes and Rocas Verdes sub-basins are also indicated. Insert: location map of South America showing the studied area.

unpub. thesis, Univ. Concepción, 2001; Caminos, 1999; Giacosa & Franchi, 2001; Panza, 2001; Panza, Cobos & Zubía, 2001; Beaubouef, 2004; Fildani *et al.* 2003; A. Fildani, unpub. Ph.D. thesis, Stanford Univ. 2004). In this article we will compare the geological evolution of the northern and the southern parts of the Austral Basin during the Cretaceous period, proposing that its segmentation into two parts during the Aptian was related to different subduction processes to the west. In this way we offer an insight into the nature of past subduction processes at the margin of southwestern Gondwana.

2. The Aisén segment

The Aisén segment is here defined as the area initially covered, during Tithonian to early Aptian times, by a marine basin known as the Aisén Basin (Bell & Suárez, 1997) or Río Mayo Embayment (Aguirre-Urreta & Ramos, 1981), which represents the northern part of the Austral Basin (Fig. 1). This segment was subsequently covered by Aptian to Albian (Divisadero Group) and Upper Cretaceous calc-alkaline volcanic rocks (El Toro Formation, Casa de Piedra Volcanic Complex: De la Cruz *et al.* 2003; Demant, Suárez & De la Cruz, 2007*a*; Suárez, De la Cruz & Bell, 2007). It extended from approximately latitude 43° S (De la Cruz *et al.* 1996) to approximately latitude 49° S, where the southernmost equivalent to the Aptian volcanic rocks (Kachaike Formation) crops out as indicated in the geological map of Panza, Cobos & Ragona (1994).

2.a. The magmatic arc

The most conspicuous Meso-Cenozoic magmatic arc in Patagonia is represented by the north-trending Patagonian Batholith, consisting of I-type calc-alkaline plutons, which approximately marks the western border of the present-day exposures of the Austral Basin beds (Fig. 1). Emplacement of the Patagonian Batholith appears to have occurred episodically, with the oldest episode dated at *c.* 159 Ma and subsequent episodes at *c.* 120–90 Ma and in the Cenozoic (Parada, Lahsen & Palacios, 1997; Martin *et al.* 2001; Suárez & De la Cruz, 2001; De la Cruz *et al.* 2003, 2004; De la Cruz & Suárez, 2006; Pankhurst *et al.* 2003).

Although the batholith has been interpreted as the roots of volcanic chains, both the Ibáñez and Divisadero volcanoes, at least in part, were distributed covering a much wider area extending further to the east, where isolated coeval plutons have been identified (Suárez & De la Cruz, 2000; Rolando *et al.* 2002).

The emplacement of the batholith along the western part of the continent followed a major Middle Jurassic southwestwards magmatic shift of an Early Jurassic arc from a northwestward oblique position in the centre of Patagonia (Suárez & Márquez, 2007).

2.b. The Aisén Basin

For the first 11 Ma, during Tithonian to early Hauterivian times, sedimentation in the Aisén Basin was synchronous with volcanism of the Ibáñez Formation (Suárez *et al.* 2009; Suárez, De la Cruz & Bell, 2007). As a whole, the basin was a back-arc basin, locally with intra-arc sub-basins. Geochemical analyses of rocks of the Ibáñez Formation have given a calc-alkaline trend (Baker *et al.* 1981; Suárez, Demant & De la Cruz, 1999; D. Quiroz, unpub. thesis, Univ. Concepción, 2000; Z. Bruce, unpub. Ph.D. thesis, Univ. Canterbury, 2001). This, complemented by the presence of I-type late Jurassic coeval granitoids west of the known exposures of the Coihaique Group (Suárez & De la Cruz, 2001), suggests subduction processes already operating during this period of time. The subsidence of this basin was at first due to back-arc extension related to the previous rifting stage, and later to post-rift thermal cooling. The sedimentary and volcanic deposits accumulated in the Aisén Basin are grouped in the Coihaique Group, which in Chile is formed, from base to top, by the Toqui, Katterfeld and Apeleg formations (see De la Cruz *et al.* 2003; Fig. 2) and in Argentina includes equivalent formations (e.g. Ramos, 1981; Iannizzotto *et al.* 2004). A new unit of basaltic and andesitic volcanic rocks typically exposed in the area of Baño Nuevo, 75 km to the northeast of the city of Coihaique (Figs 1, 3) and known as the Baño Nuevo Volcanic Complex (Suárez

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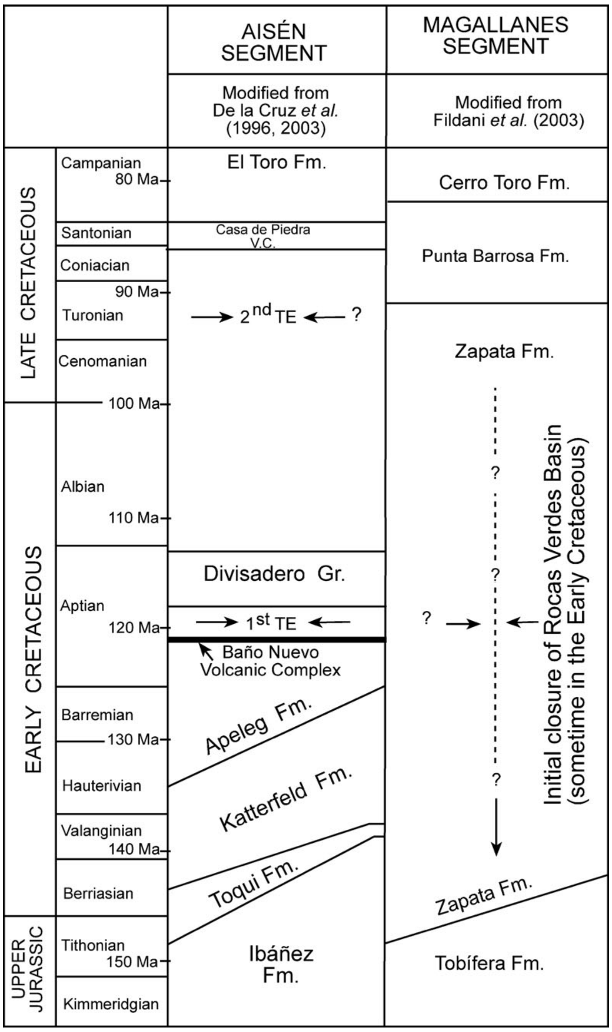

Figure 2. Late Jurassic–early Late Cretaceous lithostratigraphy of the Aisén and Magallanes basins (TE – tectonic event). Time scale from Gradstein, Ogg & Smith (2005). The hypothesis of an initial closure of the Rocas Verdes Basin during deposition of the upper Zapata Formation is from Fildani & Hessler (2005).

et al. 2005; Suárez, De la Cruz & Bell, 2007; Demant, Suárez & De la Cruz, 2007*b*), marked the final deposits of the Aisén Basin.

The beds of the Toqui Formation conformably overlie and interfinger with those of the Ibáñez Formation (Suárez, De la Cruz & Bell, 1996; Suárez *et al.* 2009). Silicic peperites emplaced along the contact between the Ibáñez and Toqui formations were observed at two localities (8 km south of the town of Coihaique and 10 km south of the town of Chile Chico: De la Cruz *et al.* 2003 and De la Cruz & Suárez, 2008, respectively), indicating that the volcanic activity of the Ibáñez Formation persisted after deposition of the basal beds of the Toqui Formation. The Toqui Formation is composed of sandstones, tuffites, tuffs (including submarine ignimbrites and ash fall tuffs: De la Cruz *et al.* 1996), calcareous beds (mainly formed by oyster beds, in places up to 10 m thick and beds with coral and echinoderm fragments), local intercalations of thin layers of coal (less than 0.6 m thick), volcaniclastic

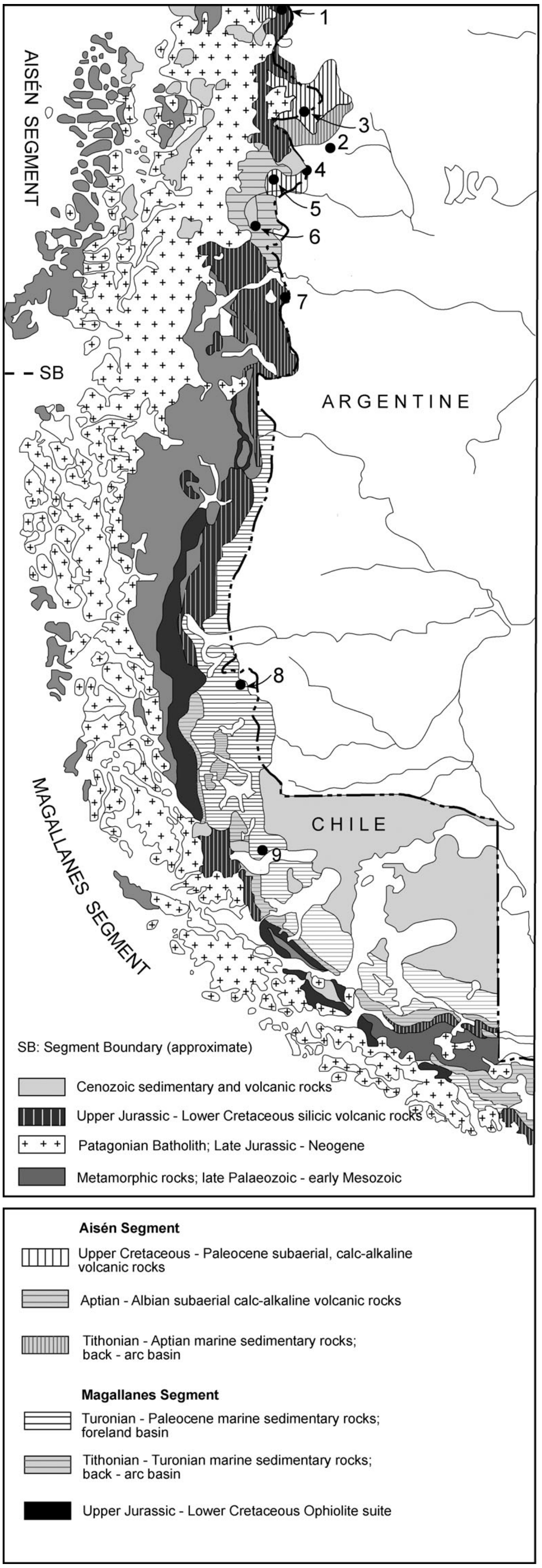

Figure 3. Geological map with geographic names mentioned in the text: (1) Futaleufú, (2) Alto Río Senguerr; (3) Lago La Plata; (4) Cerro Bayo; (5) Baño Nuevo; (6) Coihaique; (7) Chile Chico; (8) Torres del Paine National Park; (9) Bahía La Pera.

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turbidites and horizons with abundant crustacean trace fossils. These beds represent shallow marine synvolcanic deposits (De La Cruz *et al.* 2003). The age of this formation determined by ammonites and zircon U–Pb SHRIMP dating of underlying and interfingering volcanic rocks is highly diachronous, from Tithonian to early Hauterivian (Covacevich, De la Cruz & Suárez, 1994; De la Cruz *et al.* 1996; Suárez, De la Cruz & Bell, 1996; Suárez *et al.* 2009; Suárez, De la Cruz & Bell, 2007; Pankhurst *et al.* 2003). In Argentina, fossils in equivalent rock units (Tres Lagunas Formation) indicate a Tithonian to early late Valanginian age (Olivero, 1987; Olivero & Aguirre-Urreta, 2002).

Black shales of the Katterfeld Formation were deposited in a shelf environment. They overlie the Toqui Formation and occasionally are directly on the Ibáñez Formation. These beds were deposited in the still-water anoxic conditions of a sheltered and partly enclosed marine embayment (Bell & Suárez, 1997; De la Cruz *et al.* 2003), while to the east, in Argentina, they interfinger with prodelta turbidites (Iannizzotto *et al.* 2004). The Katterfeld Formation includes Valanginian and Hauterivian ammonites (Ramos, 1976; Bell & Suárez, 1997; Olivero & Aguirre-Urreta, 2002; De la Cruz *et al.* 2003), and in places may have been as old as Berriasian, considering that it conformably overlies the Toqui Formation with Berriasian ammonites (Suárez, De la Cruz & Bell, 2007). Marine sandstones and shales of the Apeleg Formation conformably overlie and interfinger with the Katterfeld Formation (Fig. 2; Ploszkiewicz & Ramos, 1977; González-Bonorino & Suárez, 1995; Bell & Suárez, 1997; Suárez *et al.* 2009). This formation is the youngest sedimentary marine unit accumulated in the Aisén Basin and the outcrops exposed in Chile represent mainly tidal sandbars and muddy flats of an epicontinental shelf (Bell & Suárez, 1997). Easterly-derived deltaic deposits have been recognized further east (Cerro Bayo: González-Bonorino & Suárez 1995). To the east of Lago La Plata, in Argentina, only continental facies have been described (Ploszkiewicz, 1987), however, the presence of trace fossils comparable to those in the marine beds of this formation exposed to the west (Bell, 2004), including *Gyrochorte* sp. in some of these rocks, indicate marine deposition for those beds. In most exposures of this formation the marine fossils are mainly Hauterivian (*Favrella* sp.), but in the mountains south of Lago General Carrera ($\sim 46^{\circ}$ S), the upper beds of the Apeleg Formation have been dated as early Aptian, based on the presence of the ammonite *Tropaeum* or *Australiceras* sp. (V. Covacevich, pers. comm. 1995; De la Cruz & Suárez, 2008).

Basaltic and andesitic surtseyan tuff cones of the Baño Nuevo Volcanic Complex represent the emerging stage of volcanic islands developed in the upper part of the Apeleg Formation (Demant, Suárez & De la Cruz, 2007*b*; Suárez *et al.* 2005; Suárez, De la Cruz & Bell, 2007). In the area of Baño Nuevo, Chile, these tuff cones form a succession of mounds corresponding to remnants of the original volcanic structures, formed by well-stratified and quenched pyroclastic ejecta that resulted from successive explosions of varying strength (Demant, Suárez & De la Cruz, 2007*b*). The quenched lithic clasts are included in a fine grey to yellowish matrix. The vesicularity of the juvenile pyroclasts, the absence of accidental basement fragments and the presence of pellets of muddy sediments from the Apeleg Formation within the deposits, indicate that fragmentation was mainly driven by magma–water interaction at shallow depth in a marine environment (Demant, Suárez & De la Cruz, 2007*b*). Most of the volcanic material is fragmented; however, dykes or central plugs are preserved in some edifices. The best-preserved cones have a diameter of approximately 1 km and heights of 100 m. The development of the surtseyan cones indicates the progressive retreat of the Early Cretaceous sea, and their chemistry indicates a subduction-related origin (Demant, Suárez & De la Cruz, 2007*b*). Three amphibole Ar/Ar ages and one U–Pb SHRIMP zircon age from samples of this complex gave concordant ages of 122 and 121 Ma (Suárez, De la Cruz & Bell, 2007). These ages are also concordant with the younger palaeontological age given to the Apeleg Formation in the region that represents the youngest age for the Aisén Basin (De la Cruz & Suárez, 2008).

2.c. The first Cretaceous tectonism: Aptian disappearance of the Aisén Basin, segmentation of the Austral Basin and subaerial volcanism

Calc-alkaline Aptian subaerial volcanism, mainly silicic in character and included in the Divisadero Group, followed the disappearance of the Aisén Basin (Fig. 4a). The Divisadero Group is well represented in the central Patagonian Cordillera, both in Chile and Argentina, having been identified from at least latitude 42° S in Argentina (Haller & Lapido, 1980) and latitude 43° S in Chile (e.g. De la Cruz *et al.* 1996) in the north, and latitude 49° S in the south, where the Kachaike Formation, which we interpret as equivalent to the Divisadero Group, is exposed (Panza, Cobos & Ragona, 1994). Thick ignimbrites are an important part of this unit and can form volcanic associations characteristic of plinian eruptions and caldera development (De la Cruz *et al.* 2003). Contact metamorphism and hydrothermal alteration has been locally recognized in these rocks (see De La Cruz & Suárez, 2008).

Most radiometric dates from samples assigned to this unit in Chile are K–Ar and Ar–Ar ages, with a range from *c.* 118 to 113 Ma (Suárez, De la Cruz & Bell, 1996; De la Cruz *et al.* 2003) to 74–99 Ma (Parada, Lahsen & Palacios, 2001). Both the relative ease with which Ar is lost or gained during thermal and hydrothermal alteration, and the possibility of erroneously assigning to the Divisadero Group rocks belonging to the Late Cretaceous volcanism well identified in the region (De la Cruz *et al.* 2003; Demant, Suárez & De la Cruz, 2007*a*), may explain this large

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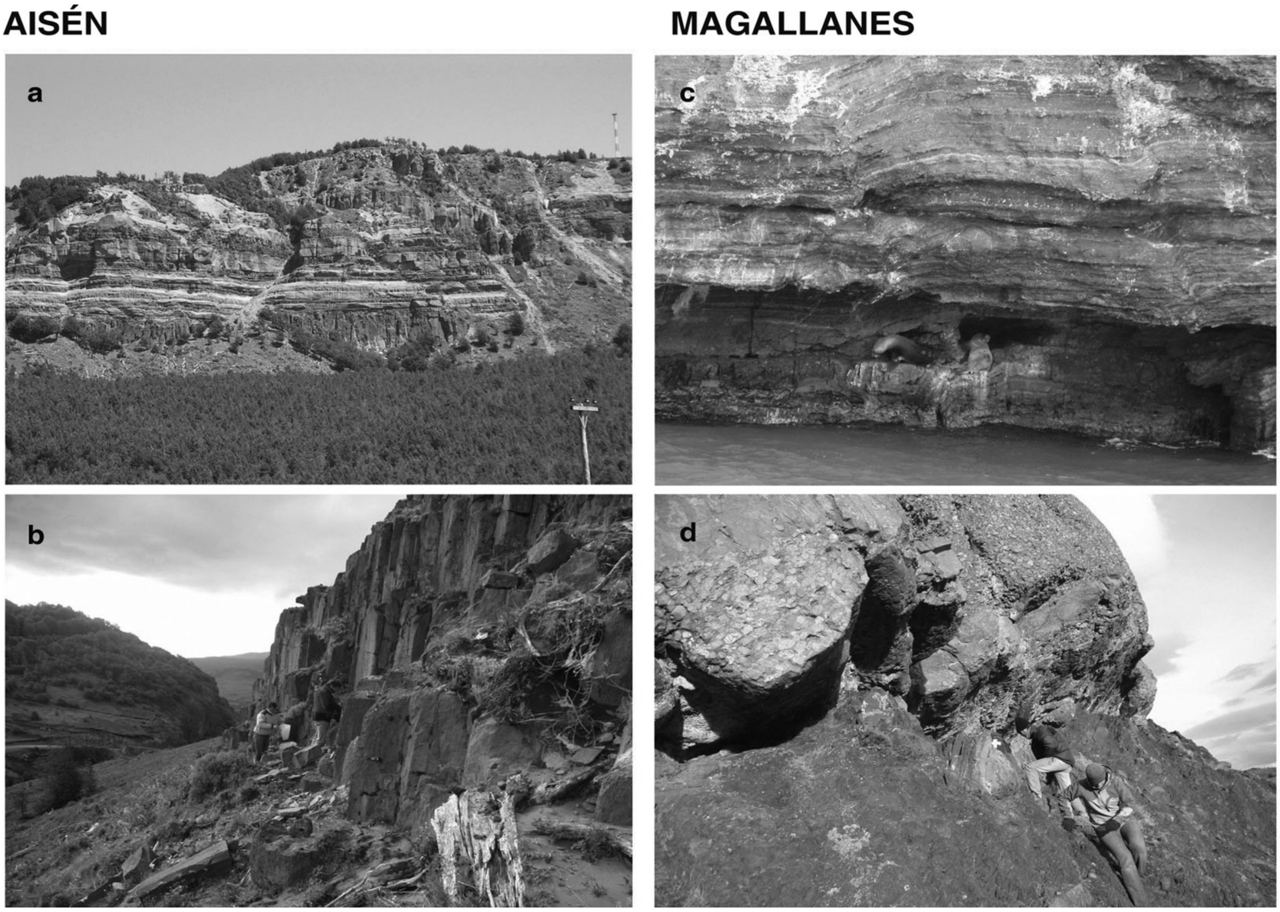

Figure 4. Contrasting Cretaceous rocks from the Aisén and Magallanes segments. (a) Aptian–Albian tuffs, mainly ignimbrites, of the Divisadero Formation; cliff approximately 80 m high. (b) Upper Cretaceous andesitic lava (El Toro Formation). (c) Shales of the Lower to lower Upper Cretaceous Zapata Formation; cliff approximately 8 m high (note sea-lions in the foreground). (d) Deep-sea resedimented conglomerates overlying debris flow deposits (slump) of the Upper Cretaceous Cerro Toro Formation. For a colour version of this figure see the online Appendix at http://journals.cambridge.org/geo.

range. Four U–Pb SHRIMP zircon ages range between *c.* 118 and 116 Ma (Pankhurst *et al.* 2003; De la Cruz *et al.* 2003). Pankhurst *et al.* (2003) proposed that the Divisadero Group was erupted during a short period of time between approximately 118 and 116 Ma (Aptian). However, recent U–Pb SHRIMP ages of *c.* 102 and 105 Ma (unpub. data of the authors), obtained from stratigraphically equivalent tuffs exposed in the area of Lago La Plata and Sierra San Bernardo, Argentina, respectively, indicate that silicic volcanism that could be correlated with that of the Divisadero Group continued during Albian times.

The final stages of marine conditions in the Aisén Basin, represented by the surtseyan tuff cones of the Baño Nuevo Volcanic Complex, have been dated by ^{40}Ar–^{39}Ar and U–Pb SHRIMP methods at *c.* 120 Ma, concordant with the early Aptian ammonite chronology given to the youngest Apeleg sediments. On the other hand, the Aisén Basin disappeared by 118 Ma, the age of the basal subaerial ignimbrites of the Divisadero Formation, that is, approximately 2.0 Ma later. Accordingly, during the early Aptian, the final shallowing of the marine Aisén Basin took place synchronously with volcanism of basaltic and andesitic tuff cones of the Baño Nuevo Volcanic Complex, which marked the reinitiation of a westward advance of subduction-related volcanic centres, covering areas formerly occupied by the volcanic edifices of the Ibáñez Formation approximately 16 Ma before. Volcanism, but this time mainly silicic, was subsequently well established by 118 Ma in a subaerial environment, with the emplacement of the Divisadero Group.

An unconformity, not always present, separating the Divisadero Group from the folded underlying Lower Cretaceous volcanic and sedimentary rocks (Suárez & De la Cruz, 2000; Iannizzotto *et al.* 2004), suggests that the disappearance of the Aisén Basin was related to a compressional tectonic event prior to the emplacement of the Divisadero Group. Although the volcanic beds of the Divisadero Group usually overlie the Apeleg Formation in a parallel manner, this contact has been interpreted as a paraconformity. Southeast of Cerro Estatuas, in Chile, the Divisadero Group paraconformably overlies the Ibánez Formation with a probable hiatus of 18 Ma (see Suárez *et al.* 2009). In the area of Lago La Plata, in Argentina near the border with Chile, the Apeleg Formation is weakly folded, whereas the Divisadero Group shows less deformation (see geological maps of Ramos, 1981; Ploszkiewicz, 1987; also M. Márquez, 2009, pers. comm.), which

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may reflect pre-Divisadero folding. In the area north of Lago General Carrera, in Chile, the Divisadero Group directly overlies the Ibáñez Formation, which may either indicate that the Coihaique Group rocks were eroded prior to the deposition of the Divisadero Group or that some rocks of the Ibáñez Formation remained emergent during deposition of the marine beds of the Coihaique Group (Z. Bruce, unpub. Ph.D. thesis, Univ. Canterbury, 2001). Further east, in Argentinean extra-Andean Patagonia, an unconformity exists between Neocomian rocks and overlying Albian (unpub. U–Pb SHRIMP age from the authors)–Upper Cretaceous beds of the Chubut Group (Fitzgerald *et al.* 1990; Strelkov, De la Paz & Baldi, 1994).

One characteristic of this tectonism is that deformation appears to have been concentrated in specific areas. Other areas with subhorizontal bedding indicate that it did not represent significant shortening. The presence of local unconformities and the concentration of deformation in specific areas may suggest tectonic inversion of pre-existing normal faults associated with the development of the previous back-arc basin. This is important to consider when making a comparison with the Magallanes segment, where folding and faulting was more intense, indicative of greater shortening. Whether the Aptian tectonism, related to the disappearance of the Aisén Basin, created an important orogenic belt is not clear.

2.d. The second Cretaceous tectonism and Late Cretaceous volcanism

Campanian–Maastrichtian (77–75 Ma; K–Ar) subaerial calc-alkaline volcanic rocks of the El Toro Formation overlie the Divisadero Group with a gentle unconformity and a hiatus of approximately 39 Ma (Fig. 2; De la Cruz *et al.* 2003; Demant, Suárez & De la Cruz, 2007*a*). This suggests a tectonic event sometime between Albian and early Campanian times. The El Toro Formation forms part of three subaerial calc-alkaline volcanic sequences identified in the area of Coihaique Alto, 20 to 40 km northeast of the town of Coihaique (Suárez, De la Cruz & Bell, 1996, 2007; De la Cruz *et al.* 2003; Demant, Suárez & De la Cruz, 2007*a*). The oldest sequence corresponds to the rhyolitic and rhyodacitic domes of the Casa de Piedra Volcanic Complex. Eight K–Ar dates give ages ranging from 84 ± 2 to 78 ± 2 Ma and one $^{40}Ar/^{39}Ar$ biotite an age of 77.23 ± 0.76 Ma (De la Cruz *et al.* 2003; Demant, Suárez & De la Cruz, 2007*a*), equivalent to a Santonian–Campanian age (Gradstein, Ogg & Smith, 2005). The second volcanic succession, the El Toro Formation (De la Cruz *et al.* 2003), consists of a complex association of andesitic to dacitic lava flows (Fig. 4b) and breccias, reaching up to 450 m in maximum thickness. K–Ar analyses give two distinct groups of ages, which may indicate either that the youngest are reset ages (De la Cruz *et al.* 2003) or that they represent two different volcanic episodes (Demant, Suárez & De la Cruz, 2007*a*), one at 77–75 Ma (Campanian age), the other ranging from 66 Ma to 63 Ma (Maastrichtian to Danian age). The Casa de Piedra volcanic rocks and the andesitic to dacitic lavas of the El Toro Formation have the mineralogy and geochemical signature of subduction-related magmas: strong enrichment in light rare earth elements (LREE) and highly incompatible elements (Rb, Th, U and K), and depletion in Nb–Ta (Demant, Suárez & De la Cruz, 2007*a*). The third volcanic sequence corresponds to a basaltic succession observed at Morro Negro, just at the border between Chile and Argentina. The K–Ar dates from the basaltic lava flows exposed in this small meseta range from 75.5 ± 2.4 to 64.2 ± 2.6 Ma (Butler *et al.* 1991), representing a Campanian–Danian range, although these authors suggest that the latter age is younger than the crystallization age. The basalts from Morro Negro have been correlated with basaltic mesas that crop out in the region of Alto Río Senguerr in Argentina; these lavas gave the same discrepancies in ages (from 79 to 63 Ma) and large errors in the dates (Butler *et al.* 1991). A whole-rock K–Ar age of 60 ± 2 Ma, on a basaltic lava flow overlying the Apeleg Formation in angular unconformity, in the area of Alto Río Senguerr, suggests that the basaltic activity extended into the earliest Cenozoic (Danian) (Demant, Suárez & De la Cruz, 2007*a*). Major hypabyssal bodies of dacites with spectacular columns intruding the Divisadero Group, such as Cerro Mac Kay (adjacent to Coihaique) and Cerro Coihaique (9 km east of Coihaique), can be also associated with this episode, as a sample from Cerro Mac Kay gave a whole-rock K–Ar date of 63 ± 2 Ma, interpreted as a reset age (De la Cruz *et al.* 2003).

3. The Magallanes segment

Mainly sedimentary deposits, up to 6000 m thick, accumulated in the Magallanes Basin from Tithonian to Cenozoic times (e.g. Biddle *et al.* 1986). The review presented herein is mainly based on the better-known stratigraphic record exposed in the area of the Torres del Paine National Park (51° S). An eastward area with a continental basin floor was bounded along its western side by the so-called Rocas Verdes Basin, characterized by a quasi-oceanic basin floor formed by Late Jurassic ophiolites (Dalziel, De Wit & Palmer, 1974; Suárez & Pettigrew, 1976; M. Calderón, unpub. Ph.D. thesis, Univ. Chile, 2006).

The Magallanes Basin had two distinct stages, according to its tectonic setting. An early stage of back-arc environment during Tithonian to Turonian times was characterized by an extensional, followed by a sag tectonic phase. The Magallanes Basin shared a comparable tectonic history with the Aisén basin until the Aptian, although the sedimentary facies were different (Fig. 2). During this phase, the black shales of the Zapata Formation, deposited in a shelf environment (Fig. 4c), accumulated over the volcanic rocks of the Tobífera Formation, with a transitional contact in the cordilleran area. A second phase of development

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of the foreland basin started with the deposition of thin-bedded turbidites and the presence of abundant slumped intervals in the uppermost section of the Zapata Formation, possibly indicative of increased seismic activity. This is the first sedimentological record in the Magallanes segment reflecting a change in the source area (Wilson, 1991). The appearance of the conformably overlying Punta Barrosa Formation was marked by the occurrence of thicker (40–150 cm) turbidites (e.g. Cecioni, 1957; Katz, 1963; R. Cortés, unpub. thesis, Univ. Técnica del Estado, 1964; Scott, 1966; A. Fildani, unpub. Ph.D. thesis, Stanford Univ. 2004). The transition from the Zapata to the Punta Barrosa formations (Fig. 2) has been interpreted as the transition from back-arc to foreland basin deposition related to tectonic uplift of an orogen to the west of the basin (Biddle *et al.* 1986; Wilson, 1991; Fildani *et al.* 2008). The Punta Barrosa turbidites are interpreted to have been fed from a rising orogen to the west into a north–south-oriented foreland trough, where the sediment direction turned southward, parallel to the basin axis (R. Cortés, unpub. thesis, Univ. Técnica del Estado, 1964; Scott, 1966). West to east palaeocurrents have been reported in some of these rocks (Choe *et al.* 2004). The Punta Barrosa Formation is overlain by the Cerro Toro Formation, a 2000 m thick unit of deep-water clastic sedimentary rocks representing channel–levee systems (e.g. Winn & Dott, 1978; DeVries & Lindholm, 1994; Beaubouef, 2004), which has been identified to the east and north in Argentina (Riccardi & Rolleri, 1980). This formation includes an exceptionally well-exposed conglomeratic interval that crops out in the Torres del Paine National Park (Fig. 4d), known as the Lago Sofía Conglomerates or Lago Sofía Member (Cecioni, 1957; Katz, 1963; R. Cortés, unpub. thesis, Univ. Técnica del Estado, 1964; Scott, 1966; Riccardi & Rolleri, 1980; Dott, Winn & Smith, 1976, 1982; Winn & Dott, 1979). Clasts in the conglomerates are volcanic, plutonic and metamorphic in origin, indicating derivation from the inferred proto-Andean cordillera (Scott, 1966; Winn & Dott, 1979; Fildani *et al.* 2008; A. Sánchez, unpub. M.Sc. thesis, Univ. Chile, 2007). These conglomeratic facies are surrounded and encased by thin-bedded, fine-grained sandstones and mudstones. The Cerro Toro Formation is overlain by a shallowing-upward clastic succession of the Tres Pasos Formation (Santonian–Maastrichtian: Katz, 1963; Scott, 1966; Winn & Dott, 1979; Shultz, 2002).

New radiometric data (Fildani *et al.* 2003) puts in doubt part of the ages assigned to these formations on the basis of palaeontological studies done in the 1950s and early 1970s (Cecioni, 1957; Katz, 1963; R. Cortés, unpub. thesis, Univ. Técnica del Estado, 1964; Scott, 1966; Natland *et al.* 1974). The Punta Barrosa Formation has been assigned to the Albian–Cenomanian (R. Cortés, unpub. thesis, Univ. Técnica del Estado, 1964) or Albian–Turonian (Skarmeta & Castelli, 1997) on account of its fossils, but recently a Turonian maximum age of *c.* 92 ± 1 Ma has been indicated, based on the U–Pb SHRIMP dating of detrital zircons from sandstones from near the base of the Punta Barrosa Formation (Fildani *et al.* 2003). Therefore, the transition from the back-arc to foreland basin occurred at or after 92 ± 1 Ma (Turonian; Fildani *et al.* 2003), probably within Turonian times if we accept the minimum age proposed by Skarmeta & Castelli (1997) for this formation. According to new radiometric data for the Punta Barrosa Formation (Fildani *et al.* 2003), the Zapata Formation, conformably underlying it and previously dated as Tithonian to Albian, may be as young as Turonian in its upper levels and the Cerro Toro Formation, overlying the Punta Barrosa Formation and previously assigned to the Cenomanian–Campanian (R. Cortés, unpub. thesis, Univ. Técnica del Estado, 1964) must have a Turonian or younger age at its base.

Subduction-related magmatism, which started during the Late Jurassic, continued during the development of the foreland basin. This magmatism is exposed in the Patagonian Batholith to the west of the back-arc assemblages and along the western exhumed margin of the continent (Hervé, Suárez & Puig, 1984; Hervé *et al.* 2007; Suárez, Hervé & Puig, 1985; Bruce *et al.* 1991; Weaver *et al.* 1990). With the exception of localized Lower/mid-Cretaceous volcanic beds of the Barros Arana Formation (Stern, 1991) and those exposed in Bahía La Pera (P. Mella, unpub. thesis, Univ. Concepción, 2001), there is no evidence of volcanic rocks intercalated in the Cretaceous back-arc or foreland deposits. This represents a major difference relative to the Aisén segment. The presence of rare volcanic shards in rocks of the Zapata and Cerro Toro formations (authors' unpub. data) indicates a distal deposition from contemporaneously active volcanic centres, either from the western arc and/or from the volcanism from the Aisén segment.

4. Discussion

The main tectonic segmentation of the Austral Basin occurred in Aptian times, sometime between 121 and 118 Ma, when the northern part of the Austral Basin (Aisén Basin) was uplifted and the environmental setting drastically changed from marine deposition of sands (Apeleg Formation) and minor shallow marine volcanism (Baño Nuevo Volcanic Complex) to subaerial geographically widespread volcanism (Divisadero Group and Upper Cretaceous volcanic rocks). Differences between the Aisén and Magallanes basin deposits started even earlier, during the Hauterivian, with the deposition of the Apeleg Formation, mainly tidal sandstones of Hauterivian to Aptian age, deposited in the Aisén Basin but non-existent in the Magallanes Basin, where black shales accumulated in a shelf environment. Even earlier, during the latest Jurassic rifting, ophiolite emplacement and the development of a wide back-arc basin was restricted to western Magallanes.

An angular unconformity between the Divisadero Group and usually gently folded Late Jurassic to

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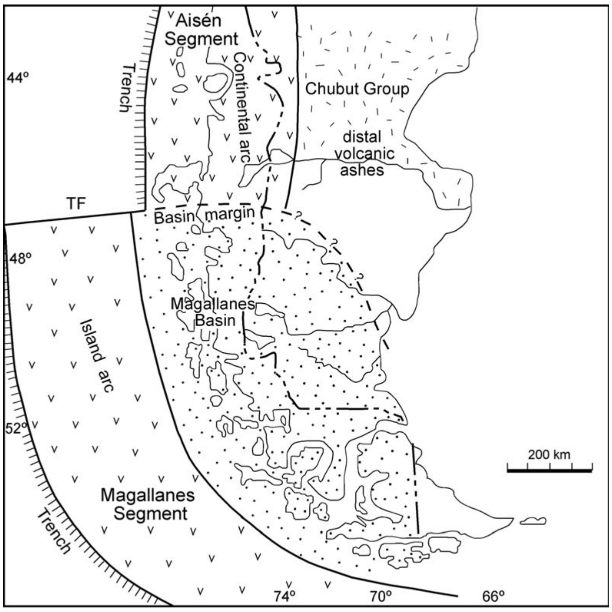
early Aptian volcanic and sedimentary rocks, observed in Chile and Argentina (e.g. Suárez & De la Cruz, 2000; Iannizzotto *et al.* 2004), indicates localized compressional tectonism sometime during the Aptian in the Aisén segment. Therefore, the disappearance of the Aisén Basin, the eastwards advance of calc-alkaline volcanism and localized compressional tectonism were approximately synchronous and probably causally related.

A remarkable aspect of this segmentation is the lack of evidence for the Aptian uplift and subaerial volcanism of the Aisén segment, in the marine sedimentation of the Magallanes Basin. The Divisadero Group has been identified as far south as latitude 49°, only 200 km north of the Punta Barrosa Formation exposures in the Torres del Paine National Park. The latter is surprising when one considers that during late Aptian times (118–116 Ma), the Austral Basin in the Magallanes segment, where the black shales of the Zapata Formation were deposited, was bounded to the north by the highly explosive volcanoes of the Divisadero Group built up on continental crust formed by Palaeozoic metamorphic rocks and Middle Jurassic–Lower Cretaceous volcanic and sedimentary rocks (Fig. 5). One possibility is that the existence of sub-basins, generated previously during the Middle Jurassic–earliest Cretaceous rifting episode, may have trapped sediments from a northern source. Another possibility is to consider that the present-day adjacent areas were in very different geographic locations in the past.

The first major change in the source area of the sediments that accumulated in the Magallanes segment has been dated as not older than Turonian (Fildani *et al.* 2003); this was 26 Ma later than the closure and uplift of the Aisén segment. The change in the source area is represented by the arrival of the turbidites of the Punta Barrosa Formation, which according to Wilson (1991) and Fildani (A. Fildani, unpub. Ph.D. thesis, Stanford Univ. 2004) marks the beginning of foreland basin accumulation associated with the build-up of an orogen to the west. Although these beds have north-to-south palaeocurrents, this hypothetical western orogen has been taken as the source area for the clasts in the Punta Barrosa and Cerro Toro formations. It has been proposed that the currents from this hypothetical westerly source changed direction towards the south on arrival in the north–south trough (R. Cortés, unpub. thesis, Univ. Técnica del Estado, 1964; Scott, 1966; Winn & Dott, 1978, 1979). This means that the sediments currently exposed at latitude 51° S were transported from the north after having been fed from the inferred source in the west. An alternative hypothesis is that the sediments were derived from an elevated terrain some 200 km to the north in the Aisén segment where outcrops of Palaeozoic metamorphic and Upper Jurassic to Lower Cretaceous volcanic and sedimentary rocks have similar lithological characteristics to those of the clasts in the turbidites (see Fildani *et al.* 2008).



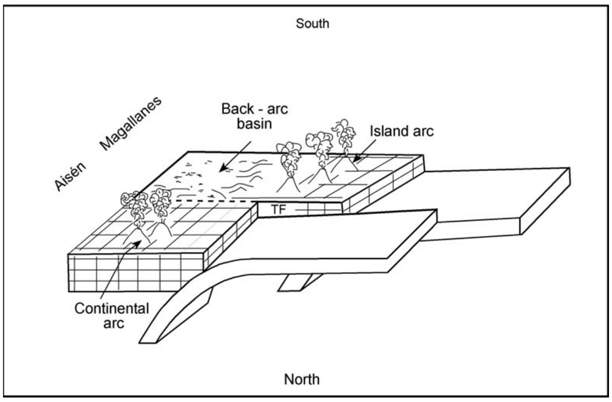


Figure 5. Schematic palaeogeographic reconstruction during Aptian times. TF – trench to trench transform fault.

Therefore, it is possible that at least part of the turbidite detritus of the Punta Barrosa and Cerro Toro formations was derived from this northern block. The Turonian (*c.* 92 Ma) tectonic event may be represented in the Aisén segment where compressive tectonism occurred sometime between 102 (late Albian, the youngest age assigned to the Divisadero Group) and 84 Ma (Santonian: e.g. De la Cruz *et al.* 2003).

The Aptian event was a major tectonic episode with a reorganization of the slab geometry as evidenced by the abrupt segmentation of the volcanic belts during Aptian and Late Cretaceous times (Fig. 5). Subduction-related volcanic centres of the Divisadero Group and the Late Cretaceous–Danian volcanic units covered the former site of the marine Aisén Basin and other areas to the east. This volcanism occupied a similar location to that of the Ibáñez Formation; hence, it can be envisaged that for approximately 16 Ma, from the Early Hauterivian, the youngest age of the Ibáñez Formation, to the early Aptian, the time of disappearance of the basin, the width of the magmatic arc in the Aisén segment was reduced and concentrated along an approximately N–S belt to the west. This could be explained by changes

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in the angle of the subduction slab, lower during the Late Jurassic to early Hauterivian (Ibáñez volcanism) and late Aptian to latest Cretaceous (Divisadero and Late Cretaceous volcanism), and greater during the Hauterivian to early Aptian (Katterfeld and Apeleg sedimentation), when the arc retracted to the west.

The generalized absence of interbedded tuffs within the Zapata, Punta Barrosa and Cerro Toro formations indicates that these beds accumulated far away from any coeval volcanic centres. Petrographic data indicate that the mean composition of the Punta Barrosa Formation sandstone is within the recycled orogen field with few samples located in the dissected arc field (Fildani *et al.* 2008). Modal sandstone composition determinations place the Cerro Toro Formation within the recycled orogen domain of Dickinson (1985; Fildani *et al.* 2008). Sandstones of the Tres Pasos and Dorotea formations are within the transitional arc field (Fildani *et al.* 2008). Therefore, and although Cretaceous plutons crop out within the Patagonian Batholith exposures, relatively near the Upper Cretaceous marine sedimentary rocks of the Paine area, one interpretation would be that the volcanic arc of that age in the Magallanes segment existed further to the west and, consequently, not above the coeval plutons. If this is correct, then a volcanic arc terrane west of the Magallanes segment, and missing today, may have existed during the Late Cretaceous and possibly during Early Cretaceous and Late Jurassic times (Fig. 5). Alternatively, if the Upper Cretaceous plutons were the roots of volcanoes, then a major fault system with a compressional component must exist between the magmatic and the coeval marine sedimentary rocks, which, however, has not been reported in the literature. This fault system, if present, may represent a type of suture belt marking the disappearance of the ophiolitic back-arc basin floor during the closure of this basin.

Therefore, the Aptian and Upper Cretaceous volcanic domain in the Aisén segment reached further to the east than the synchronous magmatic arc that bounded the Magallanes basin to the west, and the southward continuation of the Aptian and Upper Cretaceous volcanic belt in the Aisén segment was drastically terminated at the Magallanes basin. This agrees with the greater Late Jurassic–earliest Cretaceous crustal extension that took place in the Magallanes segment associated with the Rocas Verdes ophiolite emplacement. It may be inferred that there was a segmentation of the subducting slab, with a transform fault connecting the Aisén and Magallanes trenches, as previously suggested by Suárez (1976) (Fig. 5).

Current reconstructions of Gondwana during this time encounter a space problem with the Antarctic Peninsula and, following the palaeomagnetic data of Grunow (1993), the peninsula has been located precisely west of the Magallanes segment (see Hervé, Miller & Pimpirev, 2006). It may be inferred that the missing arc terrane west of the Magallanes segment was the Antarctic Peninsula (Fig. 5). Hence, it is considered that the above reasoning represents the first proposal of the presence of the Antarctic Peninsula west of Magallanes at least during Aptian and Late Cretaceous times, and probably since the Late Jurassic, based on geological grounds.

The palaeogeographic setting inferred for the Magallanes arc during Aptian and Late Cretaceous times was comparable to that during the early stages of the Austral Basin. The Magallanes and Rocas Verdes basins were together much wider than the Aisén Basin. This implies that the palaeogeographical position of the Late Jurassic to Early Cretaceous Aisén magmatic arc may have been displaced to the east relative to the Magallanes magmatic arc.

Although the mainly magmatic history of the Patagonian Cordillera has led to considering subduction processes as the leading mechanism controlling the geological history of the Patagonian Cordillera during the Jurassic and Cretaceous periods, the opening of the South Atlantic may have also influenced geological processes taking place there. Modelling of relative motions between the South American and African plates indicates a diachronous opening lasting approximately 40 Ma, during which time the relative motions of these plates must have been accommodated by significant intracontinental deformation (Eagles, 2007). Changes in spreading direction and spreading rate within the Atlantic Ocean have been associated with compressional events occurring within the African plate (Bumby & Giraud, 2005), and a comparable situation may have occurred in the South American plate, where tectonism probably was controlled both by subduction processes occurring along the Pacific margin and by processes associated with the opening of the South Atlantic. Previous authors have proposed that the start of what was called the Andean Orogeny was related to the westward drift of South America after its complete detachment from Africa *c.* 90 Ma ago, with ridge-push by mid-Atlantic spreading exceeding trench-pull along the western margin of South America (see Jacques, 2003). This may have been the cause of the Turonian and Late Cretaceous tectonism in the Magallanes and Aisén segments, respectively. It may be possible that before this drift stage there were periods when the western displacement of the South American plate was faster, and that during the opening of the South Atlantic plate, bursts of rapid opening of a segment of the South Atlantic did occur during the Aptian, which could have had a causal impact on the Aisén tectonism.

5. Conclusions

(1) Southwestern Gondwana was segmented during the Aptian and probably had been segmented since Late Jurassic–Early Cretaceous times, with a magmatic arc along the southern segment (Magallanes) in a much more westward position than that in the northern segment (Aisén), north of approximately latitude 49° S. This also reflected a segmented subduction slab.

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(2) The Aptian segmentation resulted in an elevated terrane in the Aisén segment, with subaerial volcanism (Divisadero Group, restricted to this segment) and the continuation of a marine basin in the Magallanes segment to the south. However, no sedimentological evidence of this elevated terrane in Aisén has been registered in the Magallanes Basin during this period. One interpretation is that the present-day geographic location of the involved outcrops was different at that time, implying that the more deformed Magallanes exposures are allochtonous. Alternatively, there could have been a deep tectonic sub-basin that could have concentrated the erosional products of the uplifted Aisén terrane.

(3) Different changes in the angle of subduction in adjacent subducting slabs occurred during Late Jurassic to Late Cretaceous times.

(4) At least part of the clasts of the Upper Cretaceous Cerro Toro Formation may have been derived from the elevated Aisén segment. This raises some doubts about the magnitude of the western orogen bounding the western margin of the Magallanes basin and inferred to have been the only source of those sediments.

(5) The tectonic history of the Patagonian Cordillera, in large part controlled by subduction processes, could have also experienced the complementary effects of the processes related to the opening of the South Atlantic.

Acknowledgements. This work was partially funded by Fondecyt projects No. 1030162 and No. 1080516 and the Servicio Nacional de Geología y Minería. We thank the field assistance and friendship given by Mr Leonardo Zuñiga. This manuscript has been improved by the constructive comments of R. Charrier and an anonymous referee.

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