Tectonic Evolution of Paleozoic and Mesozoic Andean Metamorphic Complexes and the Rocas Verdes Ophiolites in Southern Patagonia

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Abstract The petrology and geochronology of Paleozoic and Mesozoic metamorphic and ophiolitic complexes in southern Patagonia constrain the evolution of magmatic belts, marginal basins, and continental fragments that once formed part of the peripheral realm of the southwestern Gondwanan margin. The upper Paleozoic metasedimentary rocks exposed along the eastern slopes of the Andean ranges contain prominent zircon components of Devonian and earliest Carboniferous age. These strata were deposited in marine basins fed by sediment derived from almost coeval felsic magmatic belts and recycled units with Ordovician and Cambrian components; some of which have been identified to the east, in Argentina. Permian to Triassic metasedimentary complexes, mainly exposed along the western slope of the Southern Patagonian Andes and in the Antarctic Peninsula, show conspicuous peaks of Permian detrital zircons with sparse older age components, supporting their deposition near active magmatic belts in a convergent margin setting. It is proposed that rapid northward migration of Gondwana (between 330 and 270 Ma) promoted crustal extension and the establishment of an arc and back-arc marginal basin configuration during the Permian. Subsequent closure of the marginal basins occurred during the Late Triassic–Early Jurassic Chonide orogeny. Middle Jurassic fragmentation of Gondwana involved continental extension, synrift silicic and bimodal magmatism, and seafloor-spreading, leading to the oceanic-type Late

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M.C. Ghiglione (ed.), *Geodynamic Evolution of the Southernmost Andes*,
Springer Earth System Sciences, DOI 10.1007/978-3-319-39727-6_2

Jurassic to Early Cretaceous Rocas Verdes basin. Once the Antarctic Peninsula microplate migrated southward, subduction was re-established in southern Patagonia in Early Cretaceous time, involving processes of subduction erosion and high-P/T metamorphism in the forearc region. The Rocas Verdes basin started to close in the latest Early Cretaceous involving underthrusting and subduction of its oceanic seafloor. These convergent processes culminated with the Late Cretaceous Patagonian and Fuegian orogeny involving the tectonic emplacement of ophiolitic complexes, collision of drifted crustal slivers against the continent, and development of the Magallanes–Austral foreland basin.

Keywords Metamorphic complexes · Rocas Verdes ophiolites · Patagonian Andes · Fuegian Andes · Antarctic Peninsula · Magallanes–Austral basin

1 Introduction

The southernmost edge of South America, hereafter referred to as southern Patagonia, encompasses igneous and metamorphic complexes that represent one interconnected assemblage of diachronous magmatic belts and accretionary complexes that once formed part of the southwestern margin of Gondwana (Hervé et al. 2003; Pankhurst et al. 2003; Eagles 2016), also known as the Terra Australis Orogen (Cawood 2005). Some of these units composed the continental basement, in which the Upper Jurassic to Lower Cretaceous Rocas Verdes marginal basin was developed (Katz 1964; Dalziel et al. 1974; Suárez and Pettigrew 1976; Dalziel 1981; Stern and de Wit 2003; Calderón et al. 2007a), following the onset of Gondwana fragmentation in Middle Jurassic times (Bruhn et al. 1978; Pankhurst et al. 2000). Today, the rift and oceanic-type seafloor remnants of the Rocas Verdes basin are preserved as discontinuous belts of supracrustal bimodal igneous suites and ophiolitic complexes tectonically juxtaposed onto the cratonic margin of southern Patagonia during the late Mesozoic Andean orogeny (Dott et al. 1977; Dalziel 1981; Cunningham 1994; Stern and de Wit 2003; Calderón et al. 2013) (Fig. 1).

The intricate internal architecture of metamorphic and ophiolitic complexes, coupled with the lack of fossil records in complexly deformed metasedimentary rocks, has fostered the development and application of several analytical techniques (geochemistry, geothermobarometry, igneous and detrital U–Pb zircon geochronology, low-temperature thermochronology) to resolve temporal and genetic relationships among them and provide an improved framework for paleogeographic analysis. The understanding of these complexes has been further established with the combination of U–Pb SHRIMP (Sensitive High-Resolution Ion Microprobe) geochronology and Lu-Hf isotopic data for individual zircon grains, providing timing of formation and sediment deposition and the nature of host magmas and provenance areas (Hervé et al. 2003, 2010a, b; Pankhurst et al. 2003; Augustsson et al. 2006; Augustsson and Bahlburg 2008; Fanning et al. 2011; Castillo et al. 2015). Furthermore, the geological evolution of some of these

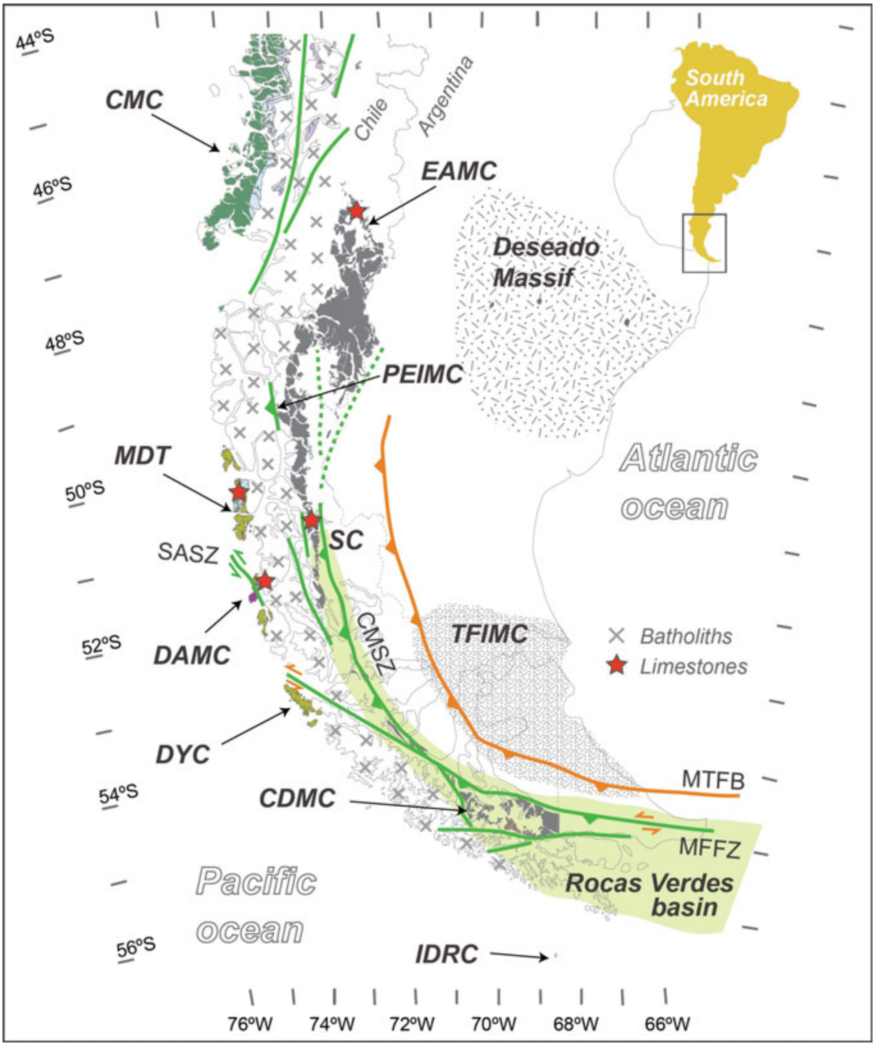

Fig. 1 Geological sketch map of the Paleozoic and Mesozoic igneous and metamorphic complexes in southern South America (after Sernageomin 2003). The contour of the Rocas Verdes basin ophiolites and related volcanic and sedimentary rocks is illustrated. Major fault zones are illustrated. Abbreviations of geological units are: *CDMC* Cordillera Darwin Metamorphic Complex; *CMC* Chonos Metamorphic Complex; *DAMC* Diego de Almagro Metamorphic Complex; *DC* Denaro Complex; *DRMC* Diego Ramirez Metamorphic Complex; *DYC* Duque de York Complex; *EAMC* Eastern Andean Metamorphic Complex; *MDT* Madre de Dios Terrane; *MRMC* Main Range Metamorphic Complex; *PEIMC* Puerto Edén Igneous and Metamorphic Complex; *SC* Staines Complex; *TL* Tarlton Limestones; *TFIMC* Tierra del Fuego Igneous and Metamorphic Complex. Abbreviations of major fault zones are: *CMSZ* Canal de las Montañas Shear Zone, *MFFZ* Magallanes-Fagnano fault zone, *MTFB* Magallanes Thrust and Fold Belt; *SAZS* Seno Arcabuz Shear Zone

complexes has been proposed using determinations of metamorphic pressure (P)–temperature (T) conditions and low-temperature thermochronology (Willner et al. 2000, 2004, 2009; Ramírez-Sánchez et al. 2005; Calderón et al. 2007b, 2012; Sepúlveda et al. 2008; Maloney et al. 2011).

In light of already-published data from heterochronous petrotectonic assemblages, the paleogeographic evolution of the continental margin of southern Patagonia is discussed in terms of shared geodynamic scenarios, such as the emplacement of magmatic belts (arc and/or rifts) and related sedimentary basins on older basement complexes, and development of oceanic-type marginal basins above subduction zones. The possibility that the Antarctic Peninsula was located west of the present margin of southern Patagonia (cf. Jokat et al. 2003; Hervé et al. 2006) is also addressed.

2 Igneous and Metamorphic Complexes of Patagonia and Tierra del Fuego

The Southern Patagonian and Fuegian Andes are a relatively low-elevation mountain belt made up in part by the upper Paleozoic to Mesozoic metamorphic complexes and by Jurassic to Cretaceous supra-subduction zone ophiolitic complexes of the Rocas Verdes basin. Most of the metamorphic and ophiolitic complexes crop out west and east of the continuous Mesozoic to Cenozoic Patagonian Batholith (Hervé et al. 1984, 2007a; Pankhurst et al. 1999; Guillot 2016) with portions of continental basement rocks buried beneath the Jurassic volcaniclastic deposits of the Chon Aike Silicic Large Igneous Province and younger sedimentary infill of the Magallanes–Austral basin (Pankhurst et al. 2003; Hervé et al. 2008) (Fig. 1). The older continental rocks in southern Patagonia are in the Deseado Massif area (Pankhurst et al. 2003) and below the Jurassic to Cenozoic strata in southern Patagonia and Tierra del Fuego (Söllner et al. 2000; Hervé et al. 2010a). In this section, we present a summarized description of metamorphic and ophiolitic complexes, detailing lithologies, U–Pb zircon geochronology, metamorphic characteristics, and geodynamic significance.

Two main divisions are recognized and employed to arrange the descriptions: Upper Paleozoic to Mesozoic **Andean metamorphic complexes** (Sect. 2.1) and **Ophiolitic complexes of the Rocas Verdes basin** from Jurassic to Cretaceous supra-subduction zone (Sect. 2.2). The **Mesozoic Mylonitic Belts** of the Seno Arcabuz (SASZ) and Canal de las Montañas (CMSZ) shear zones acting as main tectonic boundaries (Figs. 1 and 2) are described separately (Sect. 2.3).

2.1 Andean Metamorphic Complexes

The Andean metamorphic complexes are mainly composed by polydeformed metasedimentary rocks, local bodies of limestone, and metamorphosed mafic rocks. Deformation and metamorphism precludes conventional stratigraphic logging and preservation of biostratigraphic records. However, U–Pb SHRIMP geochronology of detrital zircon grains in different metasedimentary rocks provides constraints on the timing of sediment deposition of their protoliths and their possible

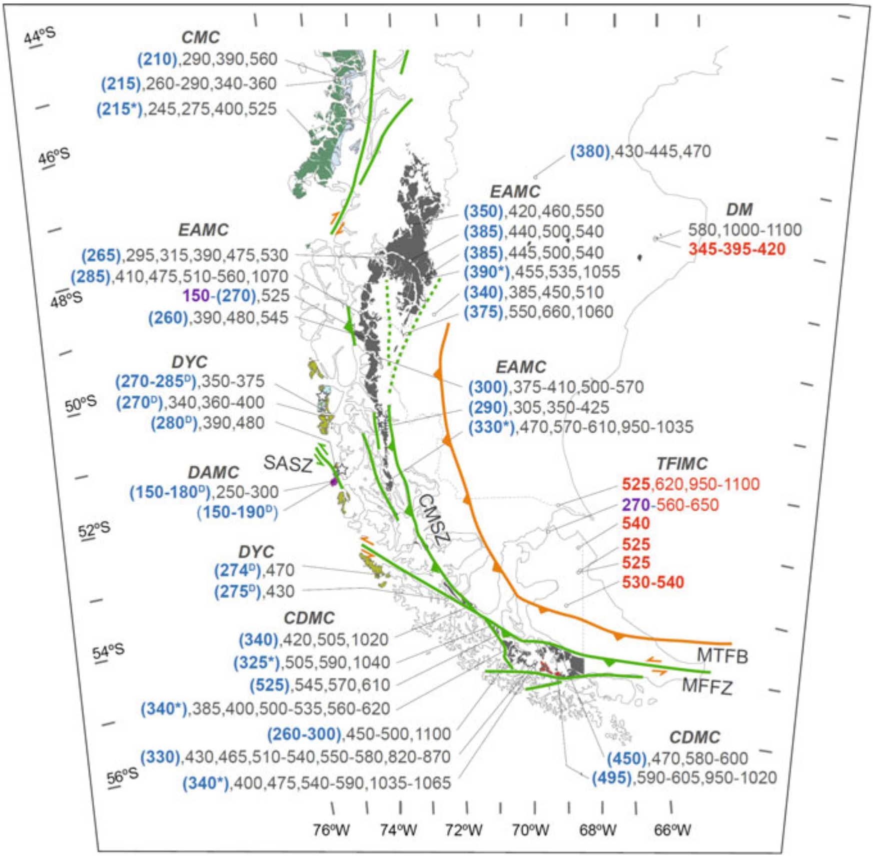

Fig. 2 Geological sketch map with published SHRIMP U–Pb zircon ages (Ma). In metamorphic rocks, the detrital zircon ages in parenthesis (*blue*) are the youngest obtained detrital age calculated with 3 zircon grains that can be interpreted as maximum sedimentation ages (*asterisks* indicate the age of 1 or 2 grains); older ages indicate principal provenance grouping of zircons. In situ crystallization ages in plutonic and gneissic rocks are indicated in *red*; older ages indicate inherited crustal components involved during their formation. Ages in *purple* correspond to the metamorphic age obtained in zircon overgrowths from migmatitic gneisses. For a detailed analysis of the data, reference should be made to the original papers (Hervé et al. 2003, 2010a, b; Pankhurst et al. 2003; Augustsson et al. 2006; Augustsson and Bahlburg 2008; Permuy Vidal et al. 2014; Malkowski et al. 2015; Castillo et al. 2015). Abbreviations are the same than those in Fig. 1

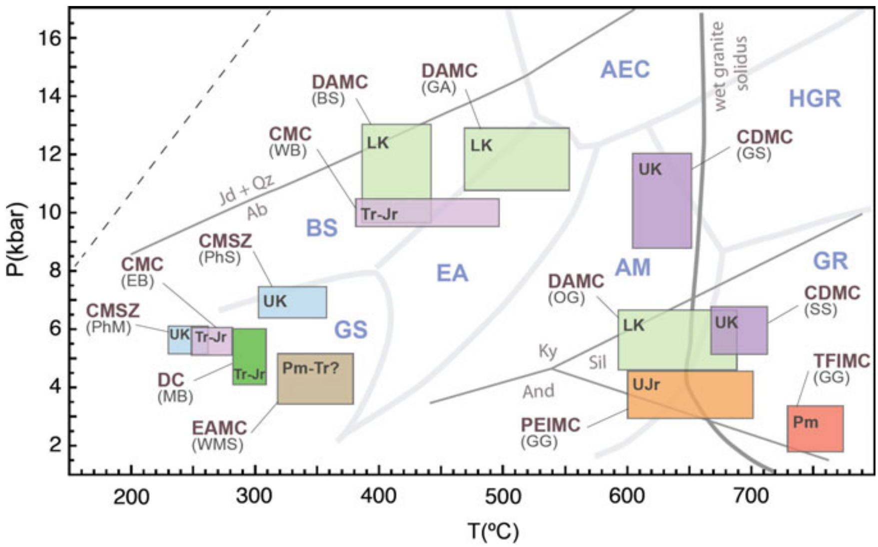

Fig. 3 Pressure–temperature diagram showing metamorphic conditions calculated in metamorphic rocks and the age of metamorphism. The overview of general metamorphic facies, stability field of andalusite-sillimanite-kyanite and wet granite solidus are also shown (Spear et al. 1999; Ernst 2009). For a detailed analysis of the data, reference should be made to the original papers (Ramírez-Sánchez et al. 2005; Calderón et al. 2007b, 2012; Willner et al. 2000, 2004, 2009; Sepúlveda et al. 2008; Hervé et al. 2010a; Maloney et al. 2011). Metamorphic facies abbreviations are: *GS* greenschist; *BS* blueschist; *EA* epidote amphibolite; *AM* amphibolite; *GR* sillimanite-granulite; *HGR* kyanite-granulite; *AEC* amphibolite-eclogite. Abbreviations are the same than those in Fig. 1

paleogeographic settings. The compilation of U–Pb detrital and igneous zircon ages of igneous and metamorphic complexes is shown in Fig. 2. A P–T diagram indicating the P–T conditions and age of metamorphism rocks belonging to different metamorphic complexes is illustrated in Fig. 3. Here, we describe the igneous and metamorphic complexes from the oldest to the youngest.

2.1.1 Tierra del Fuego Igneous and Metamorphic Complex (TFIMC)

The TFIMC corresponds to the Fuegian basement of the Magallanes–Austral basin (Söllner et al. 2000; Pankhurst et al. 2003; Hervé et al. 2010a), buried beneath km-thick successions of Jurassic volcaniclastic and younger sedimentary strata. This complex is dominated by foliated peraluminous biotite granitoids, and some containing cordierite and garnet, variably transformed to orthogneisses. Gneisses are predominately composed by coarse-grained aggregates of quartz, plagioclase, and K-feldspar, separated by finer bands of deformed and partly chloritized green biotite. The attitude of the foliation is difficult to determine, but is usually at high angles to the core length, suggesting that a low-dipping foliation is predominant. Some of the gneisses contain the mineral assemblage cordierite-sillimanite-garnet-biotite-plagioclase-orthoclase-quartz.

The plutonic zircon age spectra in samples of this complex (Hervé et al. 2010a) display: (1) a Cambrian igneous component (525–540 Ma); (2) a Cambrian migmatitic gneiss with peaks of inherited zircons at ~950–1100 and 560–650 Ma; and (3) a Permian high-grade anatectic event (of ~270 Ma) recorded in metamorphic zircon overgrowths on precursor rocks with noticeable Cambrian zircon components. The P–T metamorphic conditions calculated in the Permian cordierite-sillimanite-garnet migmatitic gneisses varies between 2–3 kbar and 730–770 °C, respectively (Fig. 3).

The oldest rocks in the TFIMC can be related to the sedimentary source of phyllitic metasedimentary rocks at Dos Hermanos locality (Deseado Massif, Fig. 1) characterized by a younger peak of ~565 Ma in detrital zircons (Pankhurst et al. 2003). Meanwhile, the Permian age for the upper crustal anatexis in the TFIMC is comparable with the age of high-grade metamorphism (~260 Ma) in gneisses located at Adie inlet (eastern margin of Antarctic Peninsula), formed from precursor metasedimentary rocks with Cambrian ages (Millar et al. 2002). These indicate similar and contemporaneous crustal anatectic processes in southern Patagonia and western Antarctic Peninsula (Hervé et al. 2010a).

2.1.2 Eastern Andean Metamorphic Complex (EAMC)

The EAMC includes the previously defined Cochrane and Lago General Carrera units (Lagally 1975) as well as the Staines Complex at the latitude of Puerto Natales (Forsythe and Allen 1980). Metamorphic complexes located in the Andean range consist mainly of polydeformed turbiditic successions, with minor limestone bodies and metabasites. The EAMC has been correlated with other units in Argentina such as the Devonian to lower Carboniferous Bahía de la Lancha and Río Lácteo Formations, and the Cerro-Negro mica schists (Permuy Vidal et al. 2014).

On the basis of detrital zircon U–Pb analyses (Hervé et al. 2003; Augustsson et al. 2006; Augustsson and Bahlburg 2008), the EAMC includes sedimentary components deposited between the late Devonian and the early Carboniferous (eastern domain), as well as younger turbidites deposited during the Permian and Triassic (western domain) (Fig. 2). Metamorphosed turbidites from the eastern domain shows Ordovician, Devonian, and early Carboniferous peaks of detrital zircons, and the western domain shows peaks of Permian zircons with variable proportions of Carboniferous, Devonian, Ordovician, and Cambrian grains.

Provenance studies based on petrographic and geochemical data (Hervé et al. 1998; Faúndez et al. 2002; Ramírez-Sánchez 2002; Augustsson and Bahlburg 2003; Lacassie 2003) suggest that turbidites of the eastern domain record deposition in a passive continental margin and were derived from a cratonic source, which possibly had undergone a complex and extended sedimentary recycling history. However, Augustsson and Bahlburg (2008) suggested that the eastern domain was fed from metasedimentary country rocks of an evolving magmatic arc. In contrast, detrital zircon U–Pb ages in the sedimentary protoliths of the Cerro Negro schists yield a statistically well-defined Devonian maximum depositional age (of ~380 Ma), supporting a forearc setting for its deposition (Permuy Vidal et al. 2014). The detrital zircon spectra, occurrence of metaplutonic lithic fragments, detrital biotite, and the major element composition of the metasedimentary strata of the western domain indicate that the basin probably was fed from the arc proper and their country rocks (Augustsson and Bahlburg 2008). Potential sedimentary source areas for the Ordovician, Devonian, and early Carboniferous detrital zircons in the eastern domain are located to the east, in the Deseado Massif, and in northern Patagonia (Figs. 1 and 2) (Pankhurst et al. 2003, 2006; Moreira et al. 2013).

Potential sources of Permian detritus for the western domain are the plutonic complexes in the northern Patagonia interpreted as the result of voluminous and widespread silicic plutonism and volcanism linked to break-off of the subducted plate between the Deseado Massif and northern Patagonia (Fig. 1) (Pankhurst et al. 2006). Magmatic belts of Permian and Triassic age are not known at present in southern Patagonia, with the exception of punctual Permian migmatites and granites described in the TFIMC (Hervé et al. 2010a). Similarly, Permian and Triassic granitoids crop out sporadically along the Antarctic Peninsula, and many of them are peraluminous (Millar et al. 2002).

The metamorphic grade of the EAMC is in the greenschist facies or lower, and higher-grade rocks occur only in the contact aureoles of Mesozoic to Cenozoic intrusions (Ramírez-Sánchez 2002; Calderón 2000; Valdés 2005). P–T calculations in low-grade metapelites of the EAMC (Cochrane unit), consisting of quartz, albite, and white mica, yielded P–T conditions of 4 ± 1.2 kbar and 300–390 °C (Fig. 3). The rocks of this complex were affected by a Permian metamorphic event (Thomson and Hervé 2002; Augustsson et al. 2006) under lower P/T metamorphic conditions than those that are typical of subduction accretionary complexes (Hervé et al. 1998; Ramírez-Sánchez et al. 2005). At the Puerto Edén area, the EAMC underwent Late Jurassic low P/T amphibolite facies metamorphism and anatexis (Watters 1964; Calderón 2000; Hervé et al. 2003).

2.1.3 Cordillera Darwin Metamorphic Complex (CDMC)

The CDMC consists of metasedimentary, metaplutonic and metavolcanic units, of supposed late Paleozoic to early Mesozoic age, which have a unique late Mesozoic metamorphic imprint among the metamorphic basement complexes of the Southern Patagonian and Fuegian Andes, which is characterized by the generation of biotite, staurolite, kyanite, and sillimanite zones (Nelson et al. 1980; Hervé et al. 1981a; Kohn et al. 1995; Klepeis et al. 2010). The main lithologies of this complex are: (1) pelitic schists with quartz, plagioclase, muscovite, biotite, chlorite, garnet, staurolite, ilmenite, kyanite, and sillimanite (fibrolite); (2) metabasites with garnet, plagioclase, hornblende, biotite, chlorite, quartz, epidote, titanite, and ilmenite; (3) garnet-bearing orthogneisses; and (4) quartz-mica schists generated by dynamic metamorphism of precursor Jurassic silicic volcaniclastic rocks (cf. Hervé et al. 2010b; Klepeis et al. 2010; Maloney et al. 2011).

The detrital zircon U–Pb age spectra in most metasedimentary rocks of the CDMC are characterized by Mississippian peaks (~330–340 Ma) with variable proportions of Devonian, Ordovician, Cambrian, and Neo- to Meso-proterozoic components (Fig. 2) (Hervé et al. 2010b). These age peak signatures are comparable with detrital zircon patterns from the eastern domain of the EAMC. The paucity of Cambrian detrital zircons indicates that the TFIMC was not the main source of detritus for the protolith of the CDMC, suggesting the existence of a pre-Jurassic suture zone between both metamorphic complexes (Hervé et al. 2010b).

Metamorphic P–T conditions determined by Maloney et al. (2011) in garnet-bearing schists constrain a P–T path dominated by decompression from 12 to 9 kbar at ~620 °C (Fig. 3), culminating with staurolite and kyanite growth at 75 Ma (U–Th–Pb in situ dating of monazite). Additionally, these authors indicate that late contact aureoles developed adjacent to granite intrusions include sillimanite-bearing migmatites formed at P of 6 kbar and at T higher than 670 °C. The metamorphic petrology and field relationships are consistent with processes of continent-ward underthrusting, imbrications, and crustal thickening during the closure of the Rocas Verdes basin (Klepeis et al. 2010) with later exhumation controlled by thrusting (Maloney et al. 2011) that is an alternative to the model that considers the CDMC as an extensionally exhumed metamorphic core complex (Dalziel and Brown 1989; Kohn et al. 1993).

2.1.4 Madre de Dios Terrane (MDT)

The MDT is composed of three tectonically interleaved lithostratigraphic units: the Tarlton Limestone, the Denaro, and the Duque de York complexes (Forsythe and Mpodozis 1979, 1983). The Tarlton Limestone (TL) is a massive pelagic limestone body that was deposited in an oceanic carbonate platform during late Carboniferous–early Permian times (Douglass and Nestell 1976) overlying a broadly contemporaneous (Ling et al. 1985) oceanic substrate (the Denaro Complex). The Denaro Complex (DC) represents the oceanic floor composed of pillow basalts with enriched (E) and normal (N) mid-oceanic ridge basalts (MORB) geochemical signatures, radiolarian and Mn- and Fe-bearing cherts probably representing an oceanic ridge environment distal from the continental influence of Gondwanaland. This exotic terrane was later accreted to the continental margin during the early Mesozoic. The metabasalts of the DC preserve relic igneous phases, augite, and chromite and comprise metamorphic mineral assemblages of the pumpellyite-actinolite facies consisting of albite, chlorite, epidote, pumpellyite, stilpnomelane, titanite, garnet (grandite), white mica (phengite), actinolite, titano-magnetite, and quartz (Sepúlveda 2004; Sepúlveda et al. 2008). Peak metamorphic conditions of ~290–310 °C and 4–6 kbar (Fig. 3) were estimated by Willner et al. (2009). These authors suggest that the Madre de Dios Accretionary Complex was frontally accreted in a subduction zone environment.

The Duque de York Complex (DYC) is a turbiditic succession, which was deposited unconformably over the TL and the DC when they reached the vicinity of the continental margin (Forsythe and Mpodozis 1979, 1983). The DYC includes palynomorphs of Permian age (Sepúlveda et al. 2010), as well as radiolarian cherts which indicate an early Permian deposition age (Quezada 2010). Metapelites exhibit porphyroblasts of cordierite and biotite in contact with the batholith (Parra 2015).

Detrital zircon U–Pb age data from rocks of the DYC show a dominant peak of Permian zircons (~270–290 Ma) (Hervé et al. 2003; Sepúlveda et al. 2010; Castillo et al. 2015), consistent with the biostratigraphic age. These rocks also comprise subordinate Carboniferous and Ordovician zircon populations, the latter becoming an important contribution in the southernmost outcrops of this unit (e.g., Desolation Island, Castillo et al. 2015). Combination of petrographic and geochemical analyses in rocks of the DYC (Lacassie 2003) indicates that this unit was derived from a geochemically intermediate igneous source, interpreted to have originated on a deeply dissected continental magmatic arc. The DYC basin was probably adjacent to the continental crust of Gondwanaland, in an active margin tectonic setting (Faúndez et al. 2002; Lacassie et al. 2006). Zircon fission track data indicate that the DYC (and probably the TL and DC units) was metamorphosed before or during the earliest Jurassic under low-grade metamorphic conditions (Thomson and Hervé 2002).

2.1.5 Chonos Metamorphic Complex (CMC)

The CMC consists predominantly of metaturbidites (Pimpirev et al. 1999), with more restricted occurrences of metabasites and metacherts. The CMC has a Late Triassic depositional age, as indicated by fossil fauna (Fang et al. 1998) and by detrital zircon SHRIMP U–Pb age determinations (Hervé and Fanning 2000). The complex was differentiated into two north–south-trending belts by Hervé et al. (1981b). The eastern belt has well-preserved primary sedimentary and volcanic structures, which are progressively obliterated when passing into the more pervasively deformed and recrystallized western belt rocks. Detrital zircons show characteristic peaks of the Upper Triassic detrital zircons with variable proportions of Permian, Carboniferous, Devonian, and Cambrian components (Hervé et al. 2003)

The lithologies of this complex correspond to psammopelitic rocks in the eastern belt with detrital quartz, plagioclase, K-feldspar, and muscovite in a very fine matrix consisting of quartz, albite, illite, chlorite (clinochlore), and white mica (muscovite and phengite). Accessory phases are titanite, rutile, zircon, tourmaline, apatite, and epidote. Metabasites with relict pillow structures and subophitic textures display mineral assemblages of quartz, albite, amphibole (actinolite), pumpellyite, chlorite, stilpnomelane, titanite, epidote, and veinlets of phengitic white mica. Meta-ironstones, usually interleaved with tectonic lenses of metachert, are dark finely banded carbonate rocks consisting of siderite, chlorite, and graphite. The metamorphic mineral assemblage of metapsammopelitic schists in the western belt consists of quartz, albite, white mica (generally phengite), chlorite, titanite, graphite with epidote, calcite, tourmaline, and Fe–Ti oxides as common accessory phases. Foliated metabasites or greenschists are made up by amphibole (magnesium-hornblende), epidote, quartz, albite, titanite, ilmenite, and rare apatite. Exceptional garnet-bearing metabasites also occur. Meta-ironstone in the western belt consists of rocks formed by quartz-rich bands with abundant stilpnomelane and subordinate chlorite, amphibole, calcite, and white mica. Willner et al. (2000) resolved that maximum P–T conditions are 4.5–6 kbar and 250–280 °C for the eastern belt and 8–10 kbar and 380–550 °C for the western belt (EB and WB, respectively, in Fig. 3).

2.1.6 Puerto Edén Igneous and Metamorphic Complex (PEIMC)

The PEIMC consists of medium- to high-grade metamorphic rocks, migmatites, and plutonic rocks. Schists are composed of quartz, muscovite, plagioclase, biotite, pinnitized cordierite, andalusite (some with inclusions of staurolite), sillimanite, and K-feldspar. Accessory minerals are tourmaline, zircon, apatite, corundum, graphite, and Fe–Ti oxides. Also occur medium- to coarse-grained leucocratic gneisses, sillimanite gneisses, and stromatitic migmatites. Metamorphic assemblages, textural relations, and geothermobarometry suggest a low P/T and nearly isobaric metamorphic and partial melting event (~600–700 °C and 3–4.5 kbar) superimposed on the greenschist facies metamorphic rocks of the EAMC (Calderón 2006; Calderón et al. 2007b).

Metamorphic overgrowths on zircons in sillimanite paragneisses record a Late Jurassic (~150 Ma) age taken as evidence of local gneiss formation under in situ anatectic conditions during the emplacement of the Jurassic components of the South Patagonian Batholith (Hervé et al. 2003) formed during continental rifting in a supra-subduction setting (Calderón et al. 2007b).

2.1.7 Diego de Almagro Metamorphic Complex (DAMC)

The DAMC is composed of two subunits of differing metamorphic imprints, one composed of garnet amphibolites and blueschists, and the other of quartz-mica schists and an orthogneiss. The contact between them has not been observed in the field. SHRIMP U–Pb ages in zircons from the orthogneiss and a quartz-rich spessartine-bearing schist interleaved in the blueschists (Hervé and Fanning 2003) have yielded Middle Jurassic ages that are interpreted as the crystallization age of their igneous forerunners, a muscovite-garnet-bearing granite and a rhyolitic rock. This complex is in tectonic contact (Forsythe 1981, 1982) with the DYC along the mid-crustal sinistral strike-slip Seno Arcabuz shear zone (Olivares et al. 2003; Willner et al. 2004).

Quartz-rich mica schist and a mylonitized granite contain Late Jurassic zircons of ~166 and 170 Ma, respectively (Hervé and Fanning 2003). According to these authors, these rocks were metamorphosed during the Cretaceous in a subduction zone environment, which developed blueschist assemblages in metabasalts interleaved with the mica schist.

The mineralogy of the DAMC metamorphic rocks is well described by Willner et al. (2004) and Hyppolito (2010). The amphibolites consist of Ca-amphibole (hornblende and actinolite), epidote, chlorite, albite, quartz, phengite, titanite, and subordinate garnet (partially altered to chlorite), calcite, ilmenite, apatite, and pyrite. Orthogneisses and schists within the Seno Arcabuz shear zone consist of quartz, plagioclase, muscovite, biotite, apatite, and tourmaline. Hypidioblastic garnet with helicitic inclusion trails of graphite, biotite, and white mica occur in the schists. These rocks were overprinted by discrete shear band cleavage with newly grown quartz, phengite, chlorite, stilpnomelane, epidote, and albite. Amphibolites in the shear zone consist of hornblende, quartz, plagioclase, epidote, and titanite. Willner et al. (2004) established a converging P–T path followed by blueschists (initially crystallized at 9.5–13.5 kbar and 380–450 °C) and amphibolites (first crystallized at 11.2–13.2 kbar and 460–565 °C) into the P–T space defined between 6.3–9.6 kbar and 320–385 °C, respectively (Fig. 3). Orthogneisses crystallized first at 4.9–6.5 kbar and 580–690 °C and their retrograde phengite, chlorite, and stilpnomelane assemblage crystallized at a minimum pressure of ~5.7 kbar at 300 °C. The high P/T metamorphism in the rocks of the DAMC developed in a subduction zone during the Cretaceous (Hervé et al. 1999; Willner et al. 2004).

2.1.8 Diego Ramírez Metamorphic Complex (DRMC)

The DRMC is located in the Diego Ramirez Island, in the southern extreme of South America, and consists of pillow basalts and metasedimentary rocks that form a crush mélange (Wilson et al. 1989) with glaucophane-bearing metamorphic assemblages. A Middle Jurassic Rb–Sr whole-rock errorchron in the metasedimentary rocks (Davidson et al. 1989) suggests that these rocks can be correlated with those of the DAMC. Both complexes are envisaged as the remnants of mafic oceanic floor developed in a Jurassic marginal basin located between southern Patagonia and Antarctic Peninsula (Hervé and Fanning 2003).

2.2 Rocas Verdes Ophiolitic Complexes

The Rocas Verdes ophiolitic complexes preserve an incomplete "ophiolite pseudostratigraphy" (lacking the ultramafic rocks) and are particularly well suited for examining the tectonic and petrological transition from rift to back-arc basin evolution and subsequent closure and orogeny in the Southern Patagonian Andes. The rocks are foliated and metamorphosed in a discontinuous way; most parts of the large complexes preserve original textures and structures with characteristic secondary mineralogy of non-deformative seafloor hydrothermal metamorphism (Stern et al. 1976; Elthon and Stern 1978; Allen 1982; Calderón 2006; Avendaño 2008; Prades 2008; Calderón et al. 2013). In this section, the lithological, geochronological, geochemical, and isotopic information of the main ophiolitic complexes is presented. The location and geochronological data of ophiolitic complexes and

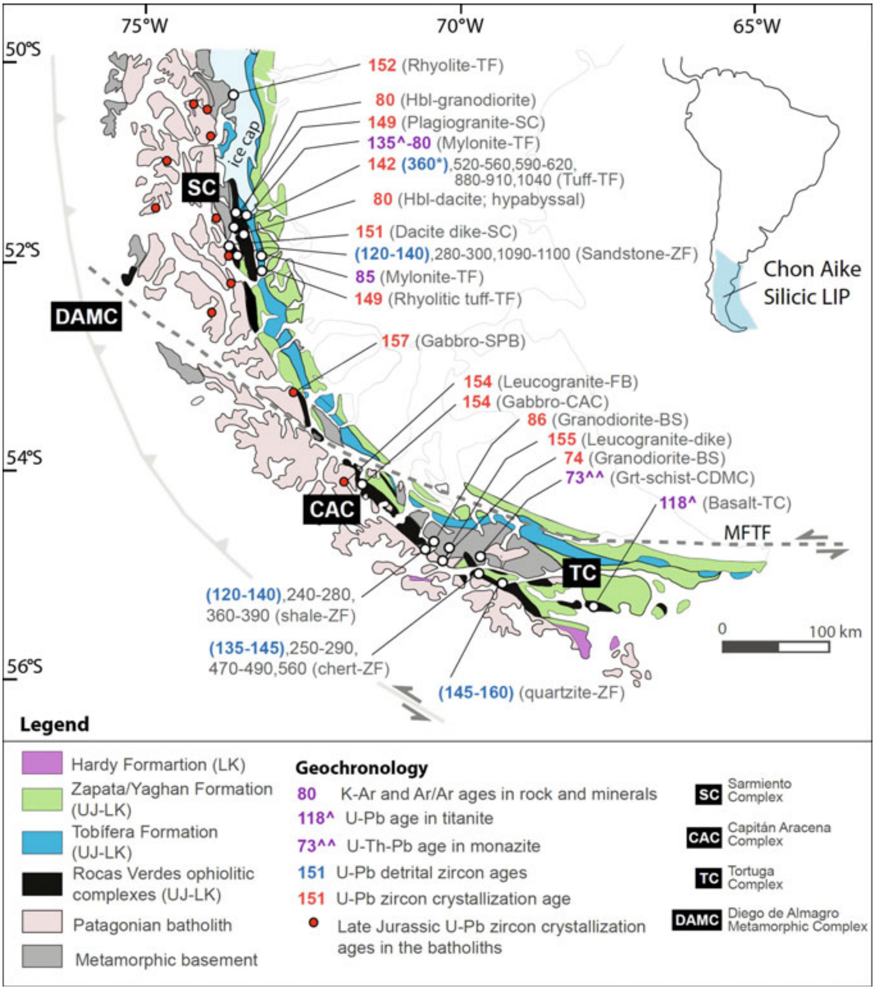

Fig. 4 Geological sketch map of Paleozoic and Mesozoic lithostratigraphic units in the Southernmost Andes of South America, including the Rocas Verdes ophiolites, folded and sheared volcanic and sedimentary successions of the Tobífera, Zapata, Yahgán Formations, the Patagonian and Fuegian batholiths, and metamorphic complexes. In sedimentary rocks, detrital zircon ages in parenthesis (*blue*) are the youngest obtained detrital age grains (*asterisks* indicate the age of 1 or 2 grains); older ages indicate principal provenance grouping of zircons. In situ crystallization ages in volcanic and plutonic rocks are indicated in *red*. Ages in *purple* correspond to the metamorphic age obtained by several methods as indicated in the figure. For a detailed analysis of the data, reference should be made to the original papers (Hervé et al. 2007a; Klepeis et al. 2010; Maloney et al. 2011; Calderón et al. 2007a, 2012, 2013). Abbreviations are: *CAC* Capitán Aracena Complex; *DAMC* Diego de Almagro Metamorphic Complex; *SC* Sarmiento Complex; *TC* Tortuga Complex

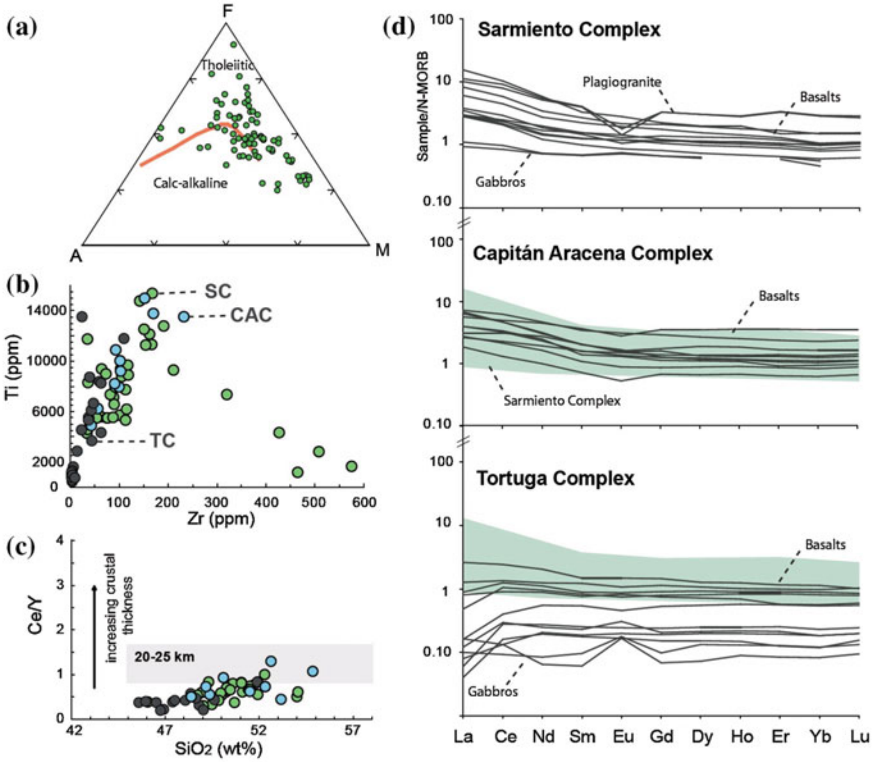

Fig. 5 Geochemical and petrological features of pillow basalts, basaltic dikes, diabases, and gabbroic rocks of the different Rocas Verdes ophiolitic complexes shown in diagrams. **a** AFM, **b** Ti versus Zr, **c** Ce/Y versus SiO_2 [values of crustal thickness are from Mantle and Collins (2008)]. **d** Normal mid-ocean ridge basalt (N-MORB) normalized Rare Earth Element diagram of the ophiolitic complexes of the Rocas Verdes basin, using Sun and McDonough (1989) normalization values. For a detailed analysis of the geochemical data, reference should be made to the original papers (Stern 1979, 1980; Saunders et al. 1979; Fildani and Hessler 2005; Calderón et al. 2013)

related granitic rocks are presented in Fig. 4. The available major and trace element geochemical composition and Nd-isotopic data for the ophiolitic rocks and other geological units in the region are illustrated in Figs. 5 and 6.

2.2.1 Sarmiento Complex (SC)

The Sarmiento Complex occurs in a north–south-trending 10- to 20-km-wide belt bound by the Canal de las Montañas Shear Zone in the east. Three main lithological units are distinguished (Calderón et al. 2007c): a thick mafic extrusive layer of pillow basalts and breccias with intercalations of radiolarian chert; a mafic–felsic

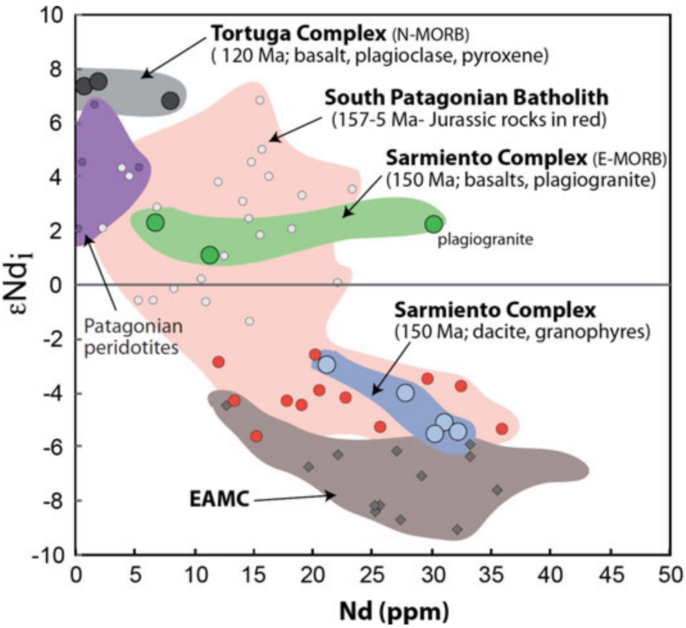

Fig. 6 Comparison of εNd_i versus Nd values of: igneous rocks from the Sarmiento and Tortuga ophiolitic complexes, and the South Patagonian Batholith; metasedimentary rocks, schists, and gneisses of the Eastern Andean Metamorphic Complex (EAMC); and peridotite xenoliths in extra Andean Patagonia (Stern 1991; Augustsson and Bahlburg 2003; Schilling et al. 2005; Hervé et al. 2007a; Calderón et al. 2007c). Noticeable are the similarities between felsic rocks of bimodal association in the Sarmiento Complex and Jurassic granites of the batholith, indicating the involvement of crustal components during their formation. It is also obvious the cogenetic origin between the basalts and plagiogranites, the last as product of extreme fractional crystallization

extrusive layer consisting predominantly of layers of pillow basalts, including intercalations of rhyolitic tuffs, hyaloclastites, and rhyolitic and dacitic dikes, which is in turn cut by mafic intrusive bodies; and a mafic–felsic intrusive layer consisting mainly of medium-grained granophyre cut by fine-grained gabbro and late sub-horizontal plagiogranite dikes. The base of this unit is composed of metagabbro and amphibolite. These rocks are exposed in two north–south-trending steeply dipping thrust sheets located in the central and western portions of the Sarmiento Cordillera (Allen 1982; Calderón et al. 2007a; Rapalini et al. 2008).

A dacite dyke crosscutting pillow-basalt successions and a plagiogranite dyke in sheeted dikes of the basal Sarmiento Complex contain ~150 Ma zircon crystals, indicating that mafic submarine volcanism had started prior to or during the Late Jurassic (Calderón et al. 2007a). The neighbor silicic pyroclastic rocks of the Tobífera Formation, intercalated with synrift deposits along fault-bounded grabens within Paleozoic metasedimentary rocks, were dated at 148 and 142 Ma, and thus coeval with ophiolitic magmatism. A fine-grained sandstone layer between the hemipelagic shales of the Zapata Formation located at c. 1000 m above its depositional contact over pillow basalts reveals 12 ages between 132 and 143 Ma (a prominent peak that constrains an apparent maximum depositional age) and a Permian population (260–300 Ma) defined by four grains. Pre-tectonic grains of titanite from phyllonites of the basal and low-grade metamorphic sole of the Sarmiento Complex yielded a SHRIMP U–Pb mean crystallization age of roughly 135 Ma that probably constrain the age of seafloor-like metamorphism in the back-arc setting (Calderón et al. 2013).

2.2.2 Capitán Aracena Complex (CAC)

To the south of and in the middle portion of the main trace of the Magallanes–Fagnano Fault Zone, the CAC crops out in a northwest–southeast-trending 20-km-wide belt located at the northeast of Cordillera Darwin (Prades 2008). It forms a body elongated in a southeast–northwest direction that is thrust northward over metasedimentary rocks of the Yahgán Formation (Otzen 1987). The rocks are associated with diverse granitoid bodies that intrude them and with rhyolitic rocks of the Tobífera Formation.

Basaltic pillow lavas are occasionally cut by mafic dikes and preserve primary variolitic, amygdaloidal, porphyritic, and glomerophyric textures. The fine-grained seriate, intersertal, microgranular, and ophitic textures are characteristic in mafic dikes. There are also short tracts of green aphanitic foliated rocks, as their occasional intense foliation appears in the field to be mafic dike complexes. Coarse-grained gabbros were observed at several localities and, at some of these, were close to pillow basalts with no apparent discontinuity between them.

A medium-grained gabbro collected 100 m below pillow basalts having no discontinuity with the underlying rocks yielded a weighted mean age of ~154 Ma (Calderón et al. 2013). A similar age of ~155 Ma was obtained in a leucogranite intruded by ophiolitic mafic dikes. Both indicate that the early rifting stage of the Rocas Verdes basin development at the latitudes of the CAC was accompanied by bimodal magmatism.

2.2.3 Tortuga Complex

The Tortuga ophiolite is exposed in an east–west-trending 20-km-wide belt extending from the southwestern part of the Isla Navarino to the region south of the Canal Beagle. The southern border of the ophiolite is in fault contact with a tightly folded and weakly foliated package of turbiditic rocks. To the north, the possible depositional contact between the Tortuga ophiolite and the sedimentary rocks is obscured by subsequent thrust-fold deformation and earliest Late Cretaceous magmatism (Hervé et al. 1984). The Tortuga Complex is remarkable for its exceptional exposures of mafic oceanic-like crustal pseudostratigraphy, which grades upward from cumulate gabbros to pillow and sheet-flow basalts (Godoy 1978; Stern 1979).

The extrusive unit of the Tortuga ophiolite consists of a more than 2000-m-thick succession of submarine volcanic rocks, including massive and pillowed basalts, volcanic breccias, hyaloclastites, and intercalated horizons of chert and siltstones. The basalts bear plagioclase and clinopyroxene, and some contain subordinate pseudomorphs after discernible primary orthopyroxene and olivine. Pillow basalts preserve a fine-grained variolitic texture, with skeletal plagioclase laths and fans of dendritic clinopyroxene. Massive lava flows, or diabase sills, with characteristic columnar structures have medium-grained ophitic and variolitic textures of plagioclase intergrown with pyroxene granules. Massive diabase screens within a 1-km-thick level of sheeted dikes consist of medium-grained plagioclase and clinopyroxene and orthopyroxene and have ophitic, subophitic, and intergranular textures. The exposed base of the Tortuga ophiolite consists of an igneous complex made up of slightly altered massive and layered gabbros, most of which are two pyroxene and olivine gabbros, leucogabbros, and clinopyroxene troctolites intruded by dikes of basalt and fine diabase with chilled margins.

A cherty layer directly overlying pillow basalts yielded two dominant groups of zircon ages, about 136 and 143 Ma (that constrains an apparent maximum depositional age), with subordinate zircon grains of Permian, Cambrian, and latest Neoproterozoic ages (Calderón et al. 2013).

U–Pb LA-MC-ICP-MS in situ analyses in titanite, which is in association with amphibole, epidote, chlorite, plagioclase, and quartz in veins within the margins of pillow basalts yielded and Aptian mean crystallization age of ~ 118 Ma (Calderón et al. 2013). This can be interpreted as the age of greenschist facies seafloor metamorphism in the back-arc basin.

2.2.4 Geochemistry and Nd-Isotope Compositions

The mafic rocks of the Rocas Verdes basin ophiolites crystallized from tholeiitic magmas that are characterized by increasing Ti contents during the early stages of differentiation followed by decreasing contents in the later stages because of fractionation of magnetite (Fig. 5) (Stern 1979, 1980; Miller et al. 1994; Calderón et al. 2013). Geochemistry is also compatible with the concept of a thinned crust resulting from extension in a rift or back-arc environment.

Rare Earth Elements (REE) diagrams normalized to the composition of normal mid-oceanic ridge basalts show the similarity between the Sarmiento and the Capitán Aracena complexes; these are more enriched in large-ion lithophile elements than is the Tortuga Complex, which suggests that the former have a greater affinity with E-MORB magma. In the Tortuga Complex, mafic rocks crystallized from N-MORB magma probably generated by decompression melting of the sub-back-arc mantle and record the most advanced evolutionary stage of the Rocas Verdes basin opening to a mid-ocean ridge-type setting (cf., Saunders et al. 1979; Stern 1979; Calderón et al. 2013). The contrasting affinities of E- and N-type MORB compositions are also suggested by the Nd-isotopic compositions of mafic rocks of the Sarmiento and Tortuga complexes (Fig. 6) (Stern 1991; Calderón et al.

2007c). These features reflect that mantle-derived tholeiitic magmas were generated by melting of progressively more depleted sources during the interplay between back-arc mantle convection and the release of stress across the continental plate boundary (Stern and de Wit 2003).

2.3 Mesozoic Mylonitic Belts

2.3.1 Seno Arcabuz Shear Zone (SASZ)

The SASZ is a NNW-trending low-grade mylonitic belt that juxtaposes different structural levels at Isla Diego de Almagro (DAMC and DYC) and record two deformation events (Olivares et al. 2003): an early mylonitic foliation, and a late low-strain foliation originated by folding of the older fabric. Ductile deformation and sinistral-reverse kinematic indicators are typical of transpressional shear zones. According to the syntectonic mineralogy, deformation occurred at greenschist metamorphic grade. Zircon fission track ages from rocks of the SASZ are of ~65 Ma and record the end of shearing that juxtaposed all rocks in the middle crust (Willner et al. 2004).

2.3.2 Canal de las Montañas Shear Zone (CMSZ)

The CMSZ is a low-grade mylonite belt generated from felsic ignimbritic, pelitic and basaltic protoliths of the Upper Jurassic–Lower Cretaceous Rocas Verdes basin, interpreted as the metamorphic sole thrust of the Sarmiento Complex (Calderón et al. 2012). Highly strained rocks of the CMSZ display a reverse, continent-ward tectonic transport, with a minor dextral component of shearing. Transitional pumpellyite–actinolite and the upper greenschist facies metamorphic conditions at ~5–6 kbar and 230–260 °C indicate that the primary shearing event occurred in a subduction zone setting. In situ 40Ar/39Ar laserprobe chronology yielded ages of ~85 Ma on syntectonic phengite.

3 Discussion

In this section, we summarize the Paleozoic and Mesozoic tectonic and magmatic evolution of Southern Patagonian Andes based on the combined petrological, geochemical, and geochronological datasets described herein. Our tectonic synthesis is considered within the paleogeographic context provided by the PLATES program (The University of Texas Institute for Geophysics) in which the southwestern continental margin of Gondwana was nearly WNW-trending until Triassic time.

In these models, three discrete episodes of rapid drifting of the Gondwanan margin occurred between 420–390 Ma (to the south), 390–360 Ma (to the west), and 330–300 Ma (to the north). These changes, attributed to underlying mantle dynamics and changes in the configuration of tectonic plates, were likely a major control on the tectonic evolution of the continental margin and sediment routing of clastic detritus shed into marginal basins, as reflected by detrital zircon provenance data discussed below (Fig. 2). Additionally, we revisit the tectonic evolution of the Rocas Verdes basin in light of new geochronology and petrology of different supracrustal units (ophiolites, metamorphic complexes, mylonite belts) metamorphosed under different P–T conditions, at different times.

3.1 Devonian-Carboniferous

The occurrence of lower Devonian and Mississippian plutonic rocks in the Deseado Massif and the southward migration of Gondwana (420–390 Ma) suggest that subduction processes operated along the continental margin before the accretion of the Antarctic Peninsula to southern Patagonia (Fig. 7). However, given the persisting lack of information about the tectonic setting in which these magmatic rocks have formed, we prefer to conservatively refer to them as magmatic belts associated with either to subduction-related magmatic arcs or to volcanic rift zones.

Detrital zircon U–Pb geochronology of turbidite protoliths to the upper Paleozoic metamorphic rocks of the eastern domain of the EAMC and the CDMC points to the existence of Cambrian, Ordovician, Devonian, and Carboniferous magmatic belts in southern Patagonia and/or neighboring continental areas that have since been removed or buried (cf. Hervé et al. 2003, 2010a; Augustsson et al. 2006; Augustsson and Bahlburg 2008). Most of the Cambrian, Devonian, and Carboniferous igneous and metamorphic rocks are found in the Deseado Massif and in the TFIMC. However, detrital zircons of Ordovician age are recovered from some of these rocks and no evidence of plutonic/volcanic complexes of this age is known in southern Patagonia (Fig. 2). Plutonic complexes of Ordovician age crop out in the North Patagonian Massif (Pankhurst et al. 2006) and the evidence of a similar belt possibly concealed in southern Patagonia is indirectly provided by Middle Ordovician granitic cobbles in basal clastic successions of the Jurassic Tobífera Formation (to the north of the CDMC; Hervé et al. 2010b) and within conglomerates of the Permian Golondrina Basin, east of the Deseado Massif (Fig. 1) (Pankhurst et al. 2003).

According to paleogeographic models, the Antarctic Peninsula microplate transited from east to west, parallel to the westward drift of Gondwana (390–360 Ma) until the microplate became attached to the south part of southern Patagonia in the Mid-Carboniferous (Fig. 7) (cf. Ramos 2010). Bell and Suarez (2000) suggested that the main deformation and metamorphic events in the eastern belt of the EAMC occurred in pre-late Carboniferous times probably resulting from microplate interactions, rather than forearc accretion. A reasonable scenario that we consider is that, during the middle–late Devonian, a transform boundary was established along the continental margin with episodic magmatism and transpressional deformation in precursor basins.

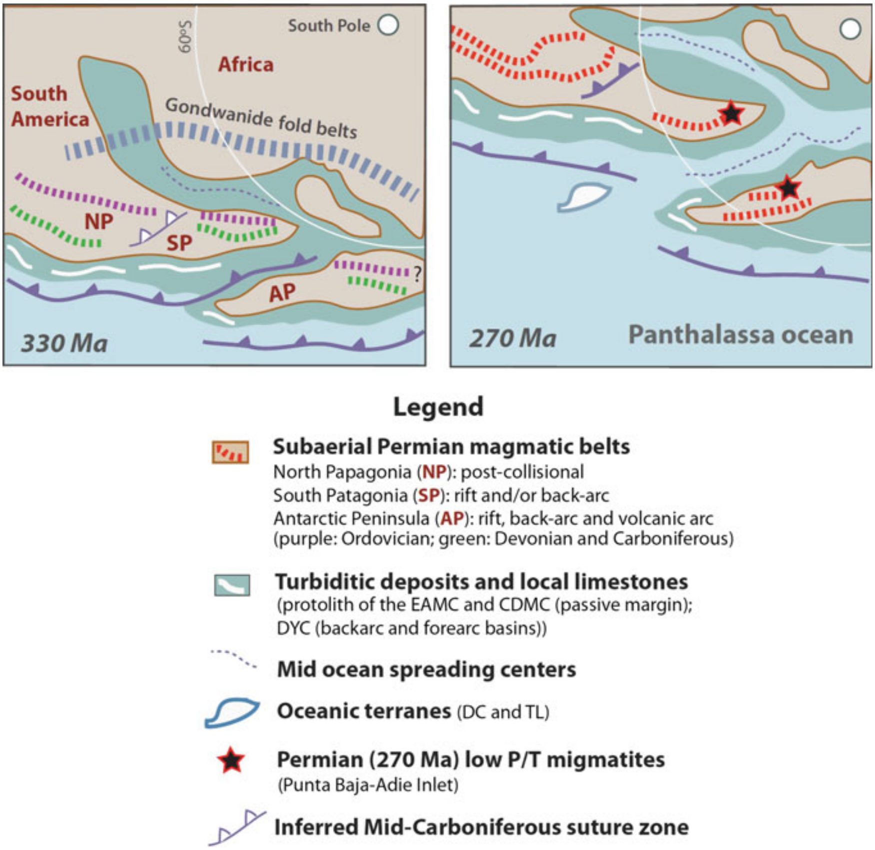

Fig. 7 Schematic reconstructions of the late Mississippian to early Permian paleogeographic and tectonic evolution of Gondwana margin at southern South America based on the geodynamic significance of Paleozoic metamorphic and igneous complexes in southern Patagonian and Antarctic Peninsula. The location of Antarctic Peninsula is based on paleogeographic maps of the Institute for Geophysics, The University of Texas at Austin

3.2 Permian-Triassic

Detrital zircon U–Pb geochronology of metasedimentary rocks of the western belt of the EAMC and the DYC indicates that their sedimentary protoliths contain predominantly Permian zircons and subordinate older grains. A wide variety of detrital components are recognized in the western belt of the EAMC, with zircons of Cambrian, Ordovician, Devonian, and Pennsylvanian ages. In contrast, the Duque de York Complex (DYC) yields a dominant peak of Permian zircons (~270–280 Ma; Hervé et al. 2003; Fanning et al. 2011; Castillo et al. 2015) with minor but discernable peaks of zircons with Devonian age and few Ordovician grains (Fig. 2). Cambrian components, such as those igneous rocks in the TFIMC and detrital components in the EAMC and CDMC, are absent. This detrital signature is consistent with a depositional setting of the DYC far from the influence of Cambrian basement rocks and tectonic evolution and recycling of Patagonian Andes metasedimentary complexes.

The Trinity Peninsula Group (TPG) in the northern Antarctic Peninsula yields a similar detrital zircon U–Pb age distribution compared to the DYC, but with the addition of pronounced Ordovician zircon populations (Hervé et al. 2006; Barbeau et al. 2010; Bradshaw et al. 2012; Castillo et al. 2015). Cobbles of Ordovician and Devonian igneous rocks are also found in Permo-Carboniferous conglomerates of the TPG (Bradshaw et al. 2012) suggesting that hidden magmatic belts, such as those identified in Patagonia, were proximal to the TPG (Fig. 7). Amphibolite-grade metamorphic rocks in Antarctic Peninsula were formed during episodic events of Ordovician, Permian, and Triassic metamorphism linked to tectono-magmatic activity in this block (cf. Pankhurst et al. 2003; Wendt et al. 2008; Riley et al. 2012).

Provenance analyses in turbidites of the DYC and TPG suggest deposition in forearc basins of the Gondwana convergent margin (Faúndez et al. 2002; Lacassie et al. 2006; Castillo et al. 2015), despite lack of known bedrock exposures of Permian igneous sources. In contrast, previous workers postulate that Permo-Triassic turbidites in Antarctic Peninsula were also deposited in a passive margin environment and/or within back-arc basins (cf. Burton-Johnson and Riley 2015). Taking this into consideration, we propose that the apparent southward jump of the magmatic activity in the region was related to the fast northward drift of the supercontinent at ~330 Ma that promoted the relative retreat of the continental margin and crustal extension in the supra-subduction setting with the consequent establishment of an arc and back-arc basin configuration during the Permian and Early Triassic (Fig. 7). Such as in retreating convergent margins (e.g., the modern western Pacific), contemporaneous development of passive margins, back-arc, and forearc basins are present, and this complex setting may help elucidate the variety of sedimentary environments interpreted for the western belt of the EAMC, the DYC, and the TPG. Afterward, the marginal basins were closed during the Late Triassic–Early Jurassic Chonide orogeny. Dalziel et al. (2000) proposed that this orogenic event was related to subduction of buoyant oceanic lithosphere that induced shallow flat subduction of the downgoing lithosphere.

3.3 Jurassic-Cretaceous

During the initial stage of Gondwana breakup, continental extension was accompanied by synrift silicic and bimodal magmatism and oceanic-type spreading in the overriding and attenuated continental crust (cf. Bruhn et al. 1978; Pankhurst et al. 2000; Stern and de Wit 2003). Paleogeographic models show that at the end of the Triassic, the southwestern Gondwana margin was NW-trending at that at 180 Ma Antarctic Peninsula was detached from southern Patagonia resulting in the development of marginal basins separating both continental blocks, and the emplacement of the Upper Jurassic—Lower Cretaceous Rocas Verdes basin in southern Patagonia (Dalziel 1981).

During the incipient stages of the Rocas Verdes basin evolution (Fig. 8), repetitive injection of mantle-derived mafic magmas triggered high-grade metamorphism, anatexis, and granite magma generation at mid- to upper crustal levels, resulting in the generation of bimodal magmatic associations and granites (Calderón et al. 2007a, b, c). Granophyres and dacitic dikes in the Sarmiento Complex are isotopically similar to the Upper Jurassic granitoids in the South Patagonian Batholith (Fig. 6) and thus probably represent the earliest components of the composite batholith that formed during the early rifting phase of the Rocas Verdes basin evolution, in a supra-subduction setting.

The back-arc stage of the Rocas Verdes basin started once the Antarctic Peninsula microplate was translated southward in Early Cretaceous time, and subduction was re-established along the margin of southern Patagonia. Subduction activity is recorded in blueschist and epidote-amphibolite facies metamorphic rocks of the DAMC (Fig. 5), involving processes of subduction erosion and high-P/T metamorphism of the forearc segment (Willner et al. 2004). These processes were coeval with the greater extension and ocean ridge-type magmatism in the back-arc basin suggesting that both domains, the forearc and back-arc, were tectonically decoupled.

The Rocas Verdes basin started to close at the end of the Early Cretaceous (Aptian–Albian), involving underthrusting and subduction of its oceanic seafloor until Late Cretaceous time (Calderón et al. 2013), coeval with the early development of the Magallanes–Austral foreland basin signaled by distal turbiditic deposits in the sedimentary record (Fildani et al. 2003; Fosdick et al. 2011). A subduction environment for the closure of the Rocas Verdes basin has been determined in felsic schists and mylonites of the CMSZ (Hervé et al. 2007b; Calderón et al. 2012). These processes culminated with collision or accretion of the drifted magmatic arc and/or peripheral crustal blocks against the continent (Cunningham 1995; Kohn et al. 1995; Klepeis et al. 2010; Fosdick et al. 2011; Maloney et al. 2011; Calderón et al. 2012, 2013; Betka et al. 2015; Guillot 2016), in part recorded in high-P and high-T metamorphic rocks of the CDMC.

Lithospheric shortening, thickening, and resulting thrust-loading of the retroarc Patagonian fold and thrust belt caused deepening of the Magallanes–Austral foreland basin during the Late Cretaceous. The sedimentary infill of the Magallanes–Austral basin records additional detrital geochronological evidence of lower Paleozoic magmatic arc activity (Fildani and Hessler 2005; Barbeau et al. 2009; Romans et al. 2010; Fosdick et al. 2015), although variable deformation and exhumation across the magmatic arc and hinterland have obscured much of the Paleozoic outcrop record.

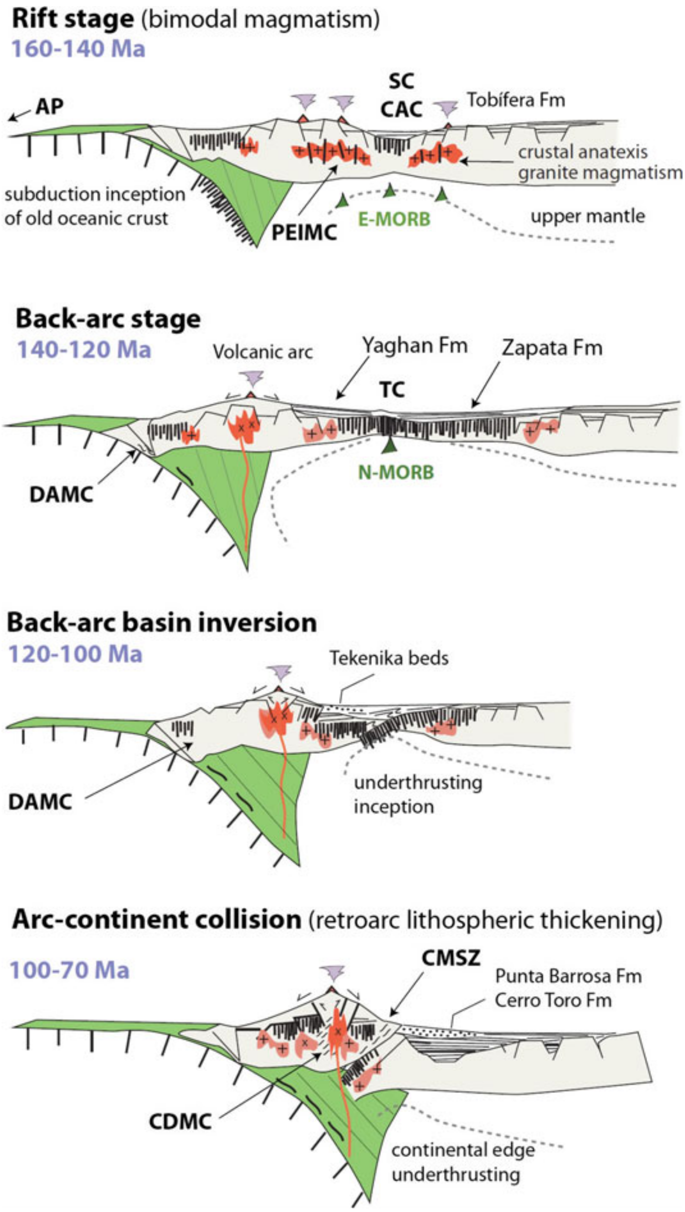

Fig. 8 Schematic reconstructions of the Jurassic to Cretaceous tectonic evolution of the Rocas Verdes basin after Calderón et al. (2013). The time span coincides with the relative separation of Antarctic Peninsula from South America. Abbreviations of metamorphic and ophiolitic complexes are presented in the caption of Figs. 1 and 4

4 Conclusions

The southern edge of South America records a complex Phanerozoic geological history related to global changes in plate configuration, including several episodes of magmatism related to crustal extension or contraction in a supra-subduction setting. Because older basins and sedimentary successions are overprinted by younger tectonic events, much of the history must be deduced from combined petrological and geochronological studies and the application of actualistic plate tectonic models and paleotectonic reconstruction models. We propose that extensional fault zones and spreading ridges, developed during breakup and/or dispersion of peripheral microplates, can evolve to transform zones, and vice versa. The closure of basins, formed within such zones of crustal weakness, causes internal deformation of the basin in-fill and formation of low- or medium-grade metamorphic complexes, with well-defined, frequently tectonically reactivated margins. Whether these zones host voluminous injections of mantle-derived magmas during continental extension, processes will contribute to the lateral growth of the continental crust and reworking via anatexis and generation of granitic magmas. An integrated four-dimensional analysis of igneous and metamorphic complexes, including ophiolites and batholiths, is necessary for more complete understanding of the entire geological evolution of the Patagonian and Antarctic regions.

Acknowledgements This contribution was supported by the CONICYT Anillo Antártico Projects (ARTG-04 and ACT-105) and by the FONDECYT projects to FH (1980741, 1010412, 7010412, 1050431) and to MC (11075000, 1161818), which allowed the study of the Patagonian Andes in recent years. Captains Conrado Alvarez, Gilles Rigaud, and Hugo Cárdenas in their boats Penguin, Foam, Explorador, Morgane, Chonos, and Marypaz II took us safely to remote areas. C. Mark Fanning has guided the SHRIMP U–Pb zircon age determinations and participated in most field campaigns. Valuable discussions and fieldwork with Elisa Ramirez, Cecilia Herrera, Augusto Rapalini, Umberto Cordani, Hans Massonne, Cristóbal Ramirez de Arellano, Bob Pankhurst, Andrea Fildani, and Brian Romans are greatly acknowledged.

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Geodynamic Evolution of the Southernmost Andes
Connections with the Scotia Arc
Ghiglione, M. (Ed.)
2016, X, 206 p. 74 illus., 66 illus. in color., Hardcover
ISBN: 978-3-319-39725-2