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The metamorphic complexes of the Patagonian and Fuegian Andes

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ABSTRACT

The Patagonian and Fuegian Andes are made up in part by late Paleozoic to Mesozoic metamorphic complexes. The mostly low grade late Paleozoic Eastern Andes Metamorphic Complex (EAMC) crops out to the East of the Meso-Cenozoic South Patagonian batholith (SPB), which intruded the metamorphic complexes. The protolith of the EAMC was likely deposited in a passive margin setting and at the Puerto Edén area underwent Late Jurassic sillimanite grade and migmatite local metamorphic conditions. It is suspected, but not proven, that the Cordillera Darwin Metamorphic Complex is a higher grade metamorphic equivalent of the EAMC. West of the SPB, paleo subduction complexes occur and are represented by the allochtonous Madre de Dios terrane. This terrane is composed of the ocean floor lithologies of the Denaro Complex topped by the Tarlton limestones that represent a guyot assemblage. The low grade continent derived Duque de York complex was deposited down top of the ocean floor lithologies. Further west, the blueschist bearing Middle Jurassic Diego de Almagro Complex, with psammopelitic, mafic and siliceous volcanic rock protoliths, evolved deep in a subduction zone during the Cretaceous. The possibility that the Antarctic Peninsula was located west of the present margin of South America is discussed.

KEYWORDS **Metamorphic Complexes. Late Paleozoic. Jurassic. Blueschists. Subduction Zone.**

INTRODUCTION

In the Patagonian and Fuegian Andes, metamorphic rock units crop out quite extensively. They have been usually referred to as a 'metamorphic basement' in respect to the well bedded Mesozoic and Cenozoic sedimentary and volcanic units. In the latter, it is possible to investigate the age and geologic evolution through the classic stratigraphic and paleontologic methods. On the contrary, the 'metamorphic basement' is mostly composed of polydeformed rocks, where no conventional stratigraphic logging can be carried out and very scarce or no biostratigraphic evidence has been yielded.

The application of new methodologies, as SHRIMP U-Pb determination of the detrital zircon age spectra, geochemical provenance analysis and determination of metamorphic P-T conditions, has allowed during the past decade to acquire new insights on the geological evolution of the 'metamorphic basement' of the Patagonian Andes. As a consequence, units differing in depositional and metamorphic ages, geodynamic setting and metamorphic characteristics have been identified. This paper deals with the summarized description of these units, their lithologies, metamorphic characteristics and geodynamic significance in the setting of the Patagonian and Fuegian Andes.

THE PATAGONIAN ANDES

The Patagonian Andes comprise a relatively low mountain belt, which bears witness of processes spanning from late Paleozoic to present. The backbone of the Patagonian Andes is the Mesozoic to Cenozoic Southern Patagonian batholith (SPB), whose earliest components intrude into low grade metamorphic complexes that crop out West and East of the continuous batholithic belt. These complexes were classically considered to be time equivalent, as represented in the 1:1.000.000 Geologic Map of Chile (Escobar et al., 1980). Nevertheless, research work in the last decade has modified this previous view and allows proposing a subdivision of these extensively outcropping metamorphic units (Fig. 1).

Eastern Andes Metamorphic Complex (EAMC)

This unit consists mainly of polydeformed turbidite successions, with minor limestone bodies and metabasites. It includes the previously defined Cochrane and Lago General Carrera units (Lagally, 1975), Bahía de la Lancha and Río Lácteo Fms, as well as the Staines Complex (Allen, 1982). The regional metamorphic grade is in the greenschist facies or lower and higher

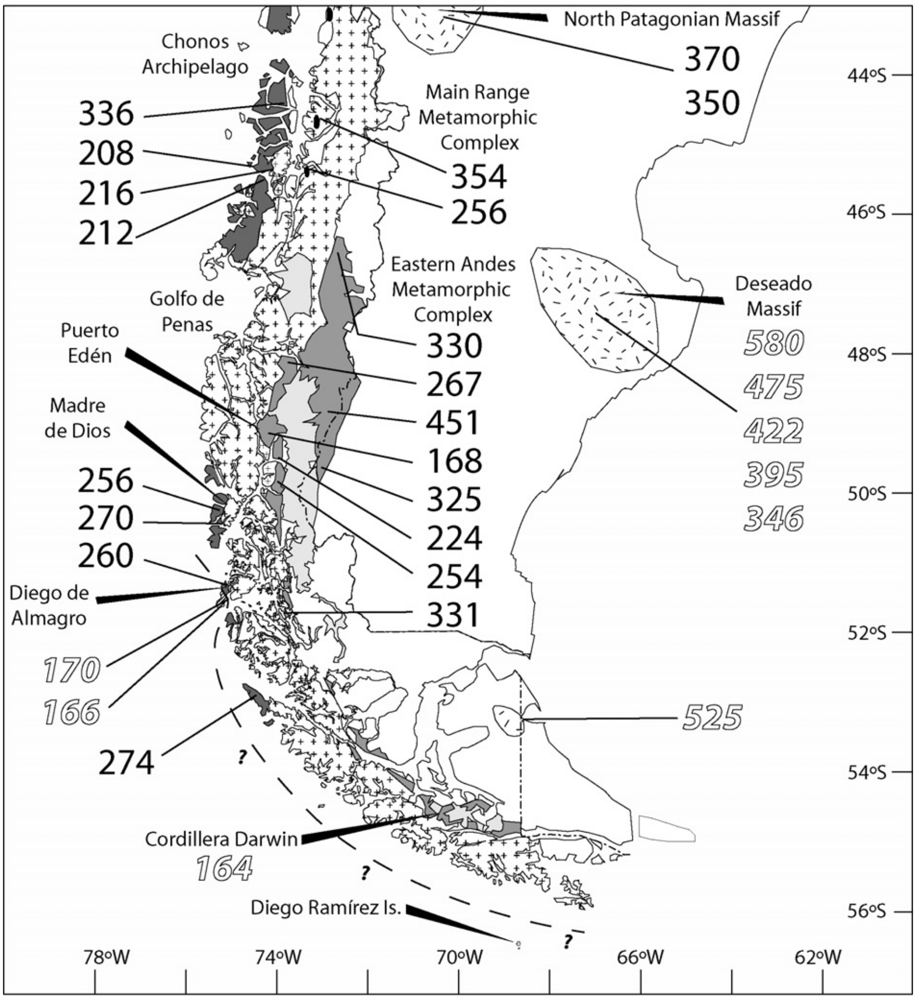

FIGURE 1 **Distribution of basement outcrops in the southern extra-Andean region and of plutonic rocks and metamorphic complexes in the Andean areas. Legend: Basement outcrops of North Patagonian, Deseado and Tierra del Fuego Massifs (Non oriented short lines). Metamorphic Complexes in the Patagonian and Fuegian Andes: Coastal accretionary complexes (darker gray); Eastern Andes and Cordillera Darwin metamorphic complexes (intermediate gray). Mesozoic-Cenozoic Patagonian batholith (cross pattern). Modified from Hervé et al., 2006). The Patagonian ice fields distribution is also indicated (lighter gray). The bold numbers indicate the youngest detrital zircon U-Pb SHRIMP ages in Ma from metasedimentary rocks. The hollow italic numbers indicate U-Pb crystallization ages of igneous rocks that were later involved in the metamorphism. The ages of the basement outcrops in the North Patagonian Massif and the Deseado Massif are from Rapela et al. (2003b); the basement dating of Tierra del Fuego from Söllner et al. (2000). The segmented line in the southern areas indicates the supposed eastern boundary of Diego de Almagro Complex supposed to include the Diego Ramírez islands, where Mesozoic blueschists have been described (Wilson et al., 1989).**

grade rocks occur only in the contact aureoles of Mesozoic to Cenozoic intrusions (Calderón, 2000; Valdés, 2005). Hervé et al. (2003) concluded that this unit includes sedimentary components deposited during the Late Devonian- Early Carboniferous, as well as younger ranging into the Permian deposits in their western outcrop areas. Hervé et al. (1998), Faúndez et al. (2002), Ramírez (2002), Augustsson and Bahlburg (2002) and Lacassie (2003), mainly based on provenance considerations from petrographic and geochemical data, suggest that these turbidites 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. A combination of the U-Pb detrital zircon ages and of Fission Track age data on the same zircons enabled Thomson and Hervé (2002) to conclude that they were metamorphosed before the Late Permian, under lower P/T metamorphic conditions than those that are generally typical of accretionary complexes (Ramírez et al., 2005; see Table 1).

Low-grade metapelites in the EAMC consist mainly of quartz, albite, white mica (muscovite and phengite) and chlorite and suitable P-T constraints are those given by the structure and composition of rock forming phyllosilicates. Combining geothermometers (Kübler index in white mica, Kübler, 1968; and Si^{IV} content in chlorite, Cathelineau, 1988), geobarometers (b parameter in K-white mica, Guidotti and Sassi, 1986; and Si^{IV} content in phengite, Massonne and Szpurka, 1997) and thermodynamic calculations, Ramírez et al. (2005) determined metamorphic temperatures varying between 300 and 390°C with a mean pressure of 4 ± 1.2 kbar. Nevertheless, Ramírez et al., (2005) noticed variation in P-T estimates regarding the size of the white mica used for x-ray diffraction (< 2μm fraction) and electron microprobe (> 8μm) analyses and they suggest that both mica populations record different conditions during the P-T rock evolution. Contact metamorphism near the eastern margin of the Patagonian batholith and satellite plutons led the transformation of very fine grained metapelites to fine- to medium-grained schists with low-pressure amphibolite facies mineral assemblages consisting of quartz, muscovite, albite, biotite, andalusite, cordierite, sillimanite (fibrolite), K-feldspar and corundum.

TABLE 1 **Main characteristics of some metamorphic complexes in the Patagonian and Fuegian Andes.**

Metamorphic Complex	Lithology	Maximum Pressure (kbar)	Maximum Temperature (°C)	Methods	Ages of emplacement and metamorphism (Ma)	Reference for peak P-T conditions
Chonos	Metapsammopelitic schists, metabasites, meta-ironstone.	(E) 5.5 (W) 10	250 - 280 380 - 500	Si content in white mica; Grt-Amph;Thermodynamic calculations (GeoClac).	213 - 198 *	Willner et al., 2000
Denaro	Metabasites, metacherts.	ca. 5	ca. 260	Si content in white mica; Chlorite thermometer	234 -195 *	Sepúlveda et al., 2007
Diego de Almagro	Mica-schists, blueschists, amphibolite, ultramafic rocks; orthogneisses.	(BS) 9.5 - 13.5 (GA) 11.2 - 13.2 (OG) 4.9 - 6.5	380 - 450 460 - 565 580 - 690	Si content in white mica; Pseudosections, thermobarometric calculations	157 - 110	Willner et al., 2004
Eastern Andes	Metapsammopelitic schists, metabasites, marble.	4.0 ± 1.2	320 - 380	b-parameter of K-white mica; Chlorite geothermometer	364 - 250 *	Ramírez et al., 2005
Puerto Edén	Metapelitic schists, gneisses, migmatites and granites; amphibolites.	3.0 - 4.5	600 - 700	Grt-Bt; Grt-Pl-Als-Qz.	150	Calderón et al., 2007
Cordillera Darwin	Metapelitic schists, amphibolites.	6.5 - 7.5	575 - 625	Grt-Bt; Grt-Chl; Grt-Hbl; Grt-Pl-Als-Qz; Grt-Pl-Hbl-Qz; Grt-Pl-Ms-Bt; GRIPS; GRAIL	164 - 86	Kohn et al., 1993

Puerto Edén Igneous and Metamorphic Complex (PEIMC)

It consists of medium- to high grade metamorphic rocks, migmatites and plutonic rocks, which crop out east of the South Patagonian batholith (49ºS). Schists and gneisses at Puerto Edén, formerly studied by Watters (1964), comprise quartz, muscovite, plagioclase, biotite, pinnitized cordierite, andalusite (some with inclusions of staurolite), sillimanite and K-feldspar with tourmaline, zircon, apatite, corundum, graphite and Fe-Ti oxides as accessory phases. Medium- to coarse-grained gneisses are panallotromorphic rocks consisting of variable proportions of quartz, plagioclase and K-feldspar, with elongate inclusions of quartz bands and biotite and sillimanite schlieren with interstitial blasts of pinnite (after cordierite), K-felsdpar, albite and retrograde muscovite. The common occurrence of retrograde muscovite in gneisses and migmatites reflects that the retrograde path of metamorphism and anatexis crossed over the intersection between the muscovite dehydration-melting reaction and of the minimum melting of granite curve. Foliated garnet-bearing leucogranites and felsic pegmatites crop up mostly in terrains of sillimanite gneisses and/or stromatitic migmatites.

The critical metamorphic assemblages and their textural relations in schists and gneisses, in addition to the garnet-biotite and GASP geothermobarometry (Holdaway, 2000, 2001) performed in phases of a centimetre-wide leucosome within sillimanite gneisses, indicate a high-temperature-low-pressure and nearly isobaric metamorphic and partial melting event superimposed on the greenschist facies metamorphic rocks of the EAMC (Calderón, 2005; Calderón et al., 2007). Metamorphic overgrowths on zircons in sillimanite paragneisses record a Late Jurassic (ca. 150 Ma) age taken as evidence of local gneiss formation under in situ anatectic conditions during the emplacement of the Jurassic components of the batholith (Hervé et al., 2003).

Coastal accretionary complexes

The Chonos Metamorphic Complex (CMC), the Madre de Dios Accretionary Complex (MDAC) and the Diego de Almagro Metamorphic Complex (DAMC) crop out West of the Patagonian batholith from North to South (Fig. 1).

The CMC consists predominantly of metaturbidites (Pimpirev et al., 1999), with more restricted occurrences of metabasites and metacherts. Broken formations are conspicuous. 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 split into two (Eastern and Western) belts by Hervé et al. (1981a). 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.

The mineralogy of metamorphic rocks of the CMC has been studied in detail by Willner et al. (2000) and Ramírez et al. (2005). Psammopelitic rocks in the Eastern belt comprise 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. Metamorphic mineral assemblages recorded in interleaved lenses of metabasites, which kept original pillow structure and subophitic texture, comprise 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 consist 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. Chemical zoning in garnet is rather irregular and inclusions of quartz, epidote and titanite, as well as rare amphibole and chlorite, are regular within it. 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.

The P-T evolution of the CMC metamorphic rocks has been established by the above-mentioned authors, through the examination of metamorphic mineral assemblages, the structure and composition of critical phases, empirical and experimental geothermobarometers (e.g. Graham and Powell, 1984) and thermodynamic calculations of numerous and relevant mineral equilibrium with the GeoCalc software package of Brown et al. (1989). 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. Instead, Ramírez et al. (2005) established higher temperatures for the Eastern belt, varying between 310-390°C, and a mean pressure of ca. 5 kbar. In summary the CMC was metamorphosed under high P/T metamorphic conditions (see Table 1) before or during the Early Jurassic (Thomson and Hervé, 2002), in a metamorphic event referred to here as the Chonide orogeny.

The MDAC is composed of three tectonically interleaved lithostratigraphic units: the Tarlton limestone (TL), the Denaro (DC) and the Duque de York (DYC) 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 DC). This oceanic substrate was composed of pillow basalts, radiolarian and Mn- and Fe-bearing cherts probably included in an oceanic ridge environment, away from the continental influence of Gondwanaland. This exotic terrane was later accreted to the continental margin during the early Mesozoic. The DYC is a turbiditic succession, which was deposited uncomformably over the TL and the DC, when they reached the vicinity of the continental margin (Forsythe and Mpodozis, 1979, 1983). The DYC includes radiolarian cherts at Desolación island, which indicate an Early Permian deposition age (Yoshiaki, pers. comm) and detrital zircons of late Early Permian age in all main outcrops of the unit. The Duque de York Complex, and probably the underlying TL and DC units, were metamorphosed before or during the earliest Jurassic (Thomson and Hervé, 2002) under low grade metamorphic conditions.

The low grade metamorphism of the three units of the MDAC has been sparsely studied and only the metamorphic characteristics of the Denaro Complex (Sepúlveda et al., 2007) are shown in Table 1. According to these authors, metabasalts preserve relic igneous phases, augite and chromite, and comprise metamorphic mineral assemblages consisting of albite, chlorite, epidote, pumpellyite, stilpnomelane, titanite, garnet (grandite), white mica (phengite), actinolite, titanomagnetite and quartz. A temperature of ca. 260°C and a pressure of 5 kbar were estimated taking into account the Si^{IV} content in chlorite and phengite, respectively. These values suggest that the Madre de Dios Accretionary complex was frontally accreted in a subduction zone environment.

Combination of petrographic and geochemical analyses (Lacassie, 2003) indicates that these rocks (DYC) were derived from a geochemically intermediate igneous source, with composition, similar to a granodiorite originated on a dissected continental magmatic arc where the erosion had enough time to expose its plutonic roots. The DYC basin was probably adjacent to the continental crust of Gondwanaland, in an active margin tectonic setting (Faúndez et al., 2002; Lacassie, 2003).

Paleomagnetic data on the Tarlton limestone and the Denaro complex (Rapalini et al., 2001) indicate that these units have experimented a very large counterclockwise rotation (117 ± 29.9º), with negligible paleolatitude anomaly, after Early Cretaceous remagnetization by the thermal influence of the South Patagonian batholith. This evidence allowed Rapalini et al. (2001) to conclude that the involved rock units accreted to the Gondwana margin from the NW instead of from the SW (Fig. 2) as had been previously suggested by Forsythe and Mpodozis (1979, 1983) on the basis of structural studies.

The DAMC is composed of two sub-units of differing metamorphic imprint, one composed of garnet amphibolites and blueschists, 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 (Fig. 3), respectively, which are coeval to the generation of the silicic Large Igneous Province at El Deseado Massiff in Patagonia (Pankhurst and Rapela, 1995). 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).

The mineralogy of the DAMC metamorphic rocks is well described by Willner et al. (2004). The amphibolites consist of Ca-amphibole (hornblende and actinolite), epidote, chlorite, albite, quartz, phengite, titanite and subordinate garnet (partially altered to chlorite), calcite,

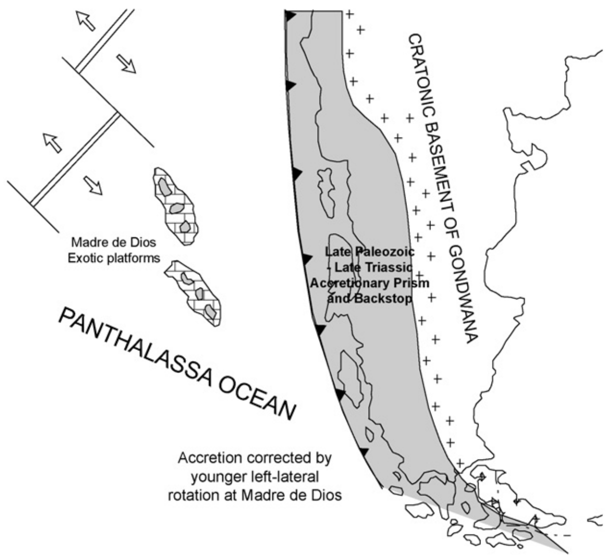

FIGURE 2 **Paleogeographic sketch (modified from Rapalini et al., 2001) depicting the southwest direction of docking and amalgamation of the Madre de Dios carbonate platform to the south western Gondwana margin during the Late Permian or Triassic. See location in Figure 1 and further explanation in the text.**

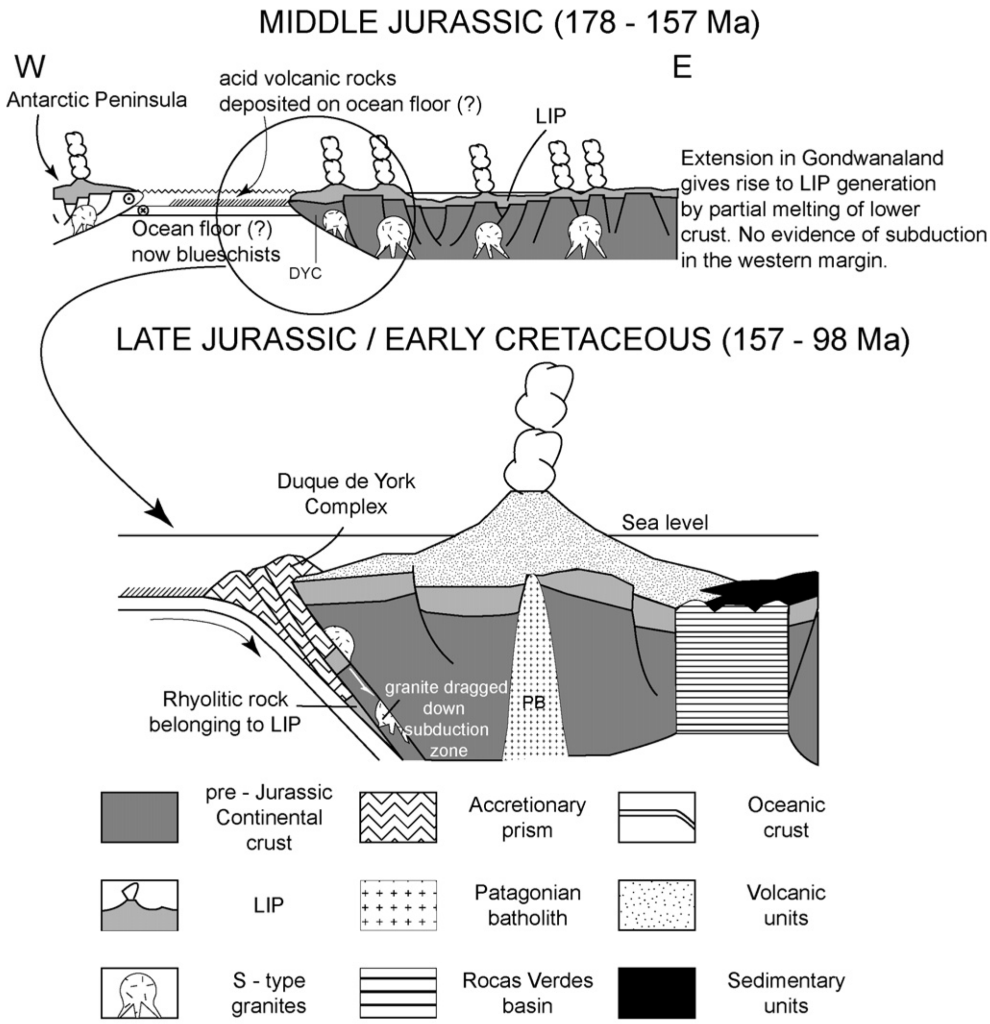

FIGURE 3 | **Top cross section sketch: The active volcanism represented resulted in the generation, along the western margin of Gondwana, of the volcanoclastic and volcanic Tobífera Fm. Part of this unit was deposited on the oceanic floor of an extensional basin, which separated the Antarctic Peninsula from the continental margin. DYC: Duque de York Complex; LIP: Large Igneous Province. The ages indicated are from Hervé and Fanning (2003) and represent the variation of U-Pb SHRIMP zircon ages in a micaschist with rhyolitic protoliths. Bottom cross section sketch: Subduction scenario starting at 157 Ma (Hervé et al., 2007). LIP: Large Igneous Province; PB: Patagonian Batholith.**

ilmenite, apatite and pyrite. The blueschists comprise two generations of blue amphibole (early glaucophane and late Na-rich actinolite), epidote, albite, quartz, phengite, chlorite, titanite and lesser amounts of calcite, apatite and magnetite. 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.

The composition of white mica, thermobarometric calculations and the building of pseudosections allowed Willner et al. (2004) to establish the 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. 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 ca. 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 (Fig. 3; Hervé et al., 1998).

At Diego Ramírez islands, pillow basalts and metasedimentary rocks form a crush mélange (Wilson et al., 1989) with glaucophane - bearing metamorphic assemblages. A Middle Jurassic Rb-Sr whole rock error chron in the metasedimentary rocks (Davidson et al., 1989) suggests that these rocks can be correlated with those of the DAMC.

Extra Andean Patagonia

The pre-Mesozoic metasedimentary and plutonic units of the extra Andean Patagonia that crop out at the Deseado Massif (Fig. 1) have been studied recently by Pankhurst et al. (2003) and Rapela et al. (2003a). They have dated metasedimentary rocks of probable latest Neoproterozoic depositional age and plutonic bodies of Cambrian, Ordovician and Late Silurian to Early Carboniferous age (Fig. 1). Sollner et al. (2000) dated at 530 Ma orthogneisses recovered from the bottom of oil wells in northern Tierra de Fuego, suggesting that early Paleozoic rocks may extend over large tracts of southern Patagonia under the Mesozoic- Cenozoic cover.

THE FUEGIAN ANDES

The Cordillera Darwin Metamorphic Complex

The basement rocks of Cordillera Darwin in the Fuegian Andes consist of metasedimentary and metavolcanic units, of supposed late Paleozoic to early Mesozoic age, which have a Mesozoic metamorphic imprint particular to that area (Kohn et al., 1995). This metamorphism is characterized by the generation of biotite, staurolite, kyanite and sillimanite zones, which are also unique among the metamorphic basement complexes of the Patagonian and Fuegian Andes. Several authors (Dalziel and Cortés, 1972; Nelson et al., 1980; Dalziel, 1981, 1986) have suggested that their protoliths formed as an accretionary wedge on the pre-Middle Jurassic Pacific margin of South America. However, it is not known at present 1) if these metamorphic rocks of Cordillera Darwin were originally part of the Eastern Andes Metamorphic Complex**,** which is probably not a late Paleozoic accretionary complex but served as a backstop during the generation of the accretionary wedge (Augustsson and Bahlburg, 2003); or 2) if they were part of the Coastal Accretionary Complexes of the Patagonian Andes. Within the metamorphic complex an orthogneiss with Middle Jurassic (157 ± 7 Ma, Rb-Sr whole rock isochron, Hervé et al., 1981b; 164 ±1 Ma, U-Pb zircon, Mukasa and Dalziel, 1996) ages and the mafic dyke swarm it contains, were involved in the regional metamorphism. Nelson et al. (1980) have suggested that silicic volcanic rocks which are part of the protolith of the complex might be part of the Middle to Late Jurassic Tobífera Fm.

Pelitic schists consist of quartz, plagioclase, muscovite, biotite, chlorite, garnet, staurolite, ilmenite, kyanite and sillimanite (fibrolite). Metabasites contain garnet, plagioclase, hornblende, biotite, chlorite, quartz, epidote, titanite and ilmenite. Kohn et al. (1993) determined the metamorphic P-T conditions and path using the composition of mineral pairs and cation-exchange geothermobarometers (e.g. Graham and Powell, 1989; Berman, 1990; Hoisch, 1990) and the differential thermodynamic method of Spear (1989) and established that metamorphic rocks crystallized within the kyanite stability field and that the P-T path segments constitute a clockwise P-T trajectory. These authors consider that the metamorphic P-T path is consistent with the interpretation that

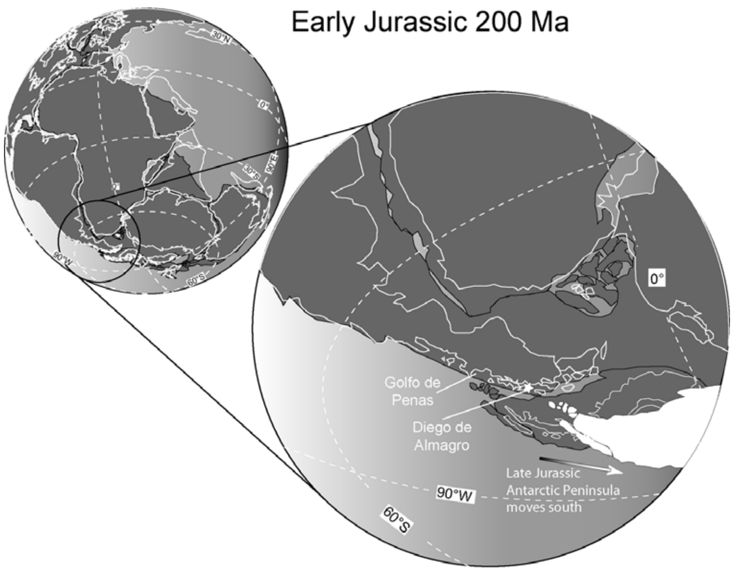

FIGURE 4 | **An interpretation of the geotectonic setting of the Gondwana continental margin during the Early Jurassic extensional event. The Antarctic Peninsula, previously forming part of the continental margin, split (Fig. 3) and then drifted southward. This fact allowed subduction to start around the present day continental margin, south of Golfo de Penas. This subduction gave rise to the Diego de Almagro Metamorphic Complex (Fig. 1) and the later evolution of the margin. From Hervé and Fanning (2003).**

Cordillera Darwin represents an extensionally exhumed metamorphic core complex.

CONCLUDING REMARKS. GEODYNAMIC CONSIDERATIONS

The EAMC (Figs. 1 and 2) was deposited in a passive margin environment, and its detrital zircon age spectra show Gondwanan affinities. The source areas could have been located in the older rocks of the Atlantic margin of Patagonia as El Deseado Massif or in South Africa and Antarctica (Hervé et al., 2003). It is not known if the EAMC is in place with respect to the older continental blocks, or if it has been displaced.

On the contrary, the western accretionary complexes have evolved in subduction zone environments, where accretion of ocean floor basaltic material is recorded (Figs. 2 to 5). However, in opposition to previous assumptions, there is no indications of late Paleozoic subduction in the Patagonian Andes. The Chonos Metamorphic Complex, which contains high-pressure- low-temperature metamorphic rocks (Table 1) reveals a subduction event near the Triassic - Jurassic boundary, as indicated by late Triassic dedtrital zircon ages and Early Jurassic FT zircon ages. The corresponding magmatic arc might have been the largely coeval Sub Cordilleran Batholith (Rapela et al., 2003b). The Madre de Dios Accretionary Complex appears to represent a composite exotic terrane, probably frontally accreted to the Gondwana margin during the same Late Triassic – Early Jurassic Chonide event as the Chonos metamorphic Complex (Figs. 1 and 2). The provenance of the Duque de York Complex, characterized by a major Early Permian zircon component, is not easily attached to a contemporaneous magmatic arc in Patagonia, where Permian igneous rocks do not crop out extensively (Figs. 1, 3 and 5). Lacassie (2003) suggests a far travelled origin for the MDAC, which would have collided with the Gondwana margin in the southeastern Pacific area (present coordinates) and then transported along the margin to its present position, following a geodynamic model proposed by Cawood et al. (2000).

Hervé and Fanning (2003) have suggested that the Late Jurassic – Cretaceous evolution of the Diego de Almagro Metamorphic Complex in a subduction zone on the western margin of Gondwana (Figs. 3 and 4), only occurred after the Antarctic Peninsula, which could have been located outboard of the present continental margin (Lawver et al., 1998), started to drift south and allowed subduction to occur near the present day continental margin (Fig. 5).

A synthesis of the proposed P-T evolution of the described metamorphic complexes as referred to in this work is provided (Fig. 6). The differences between the coastal accretionary complexes, which evolved in P/T regimes characterized by geothermal gradients between 10 and 20º C/km, and the EAMC and Cordillera Darwin metamorphic complexes are evident. Only the first ones are considered to be typical of subduction zone environments. The lack of jadeite and aragonite suggests that the subduction was slow, or that the subducting oceanic lithosphere was rather young and hot, and thus the extreme P-T conditions found in some of the other circum-pacific subduction complexes were not attained.

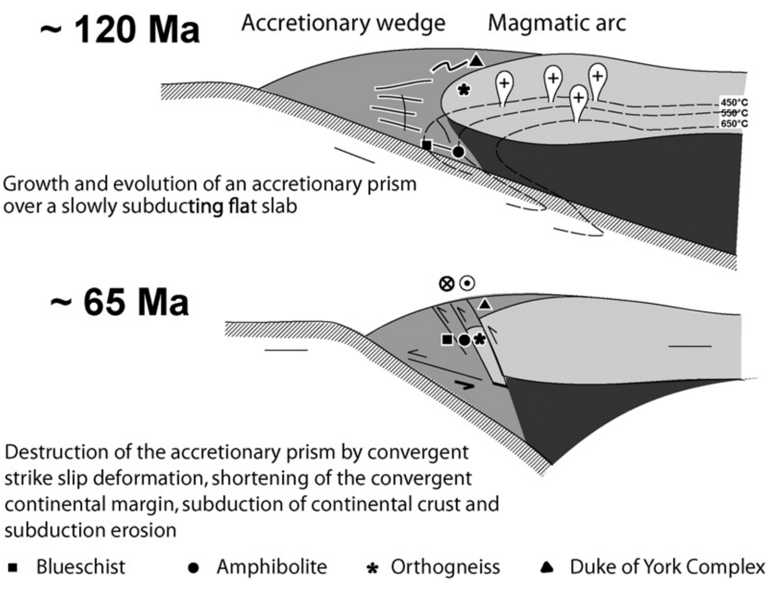

FIGURE 5 **Geotectonic setting from Willner et al. (2004) for the development of the Diego de Almagro Metamorphic complex (Fig. 1), which explains the convergence of the three different P-T trajectories found in the complex and represented in Figure 6. Tectonic erosion of the continental margin is implied. The indicated ages are indicative of the time suggested for each process.**

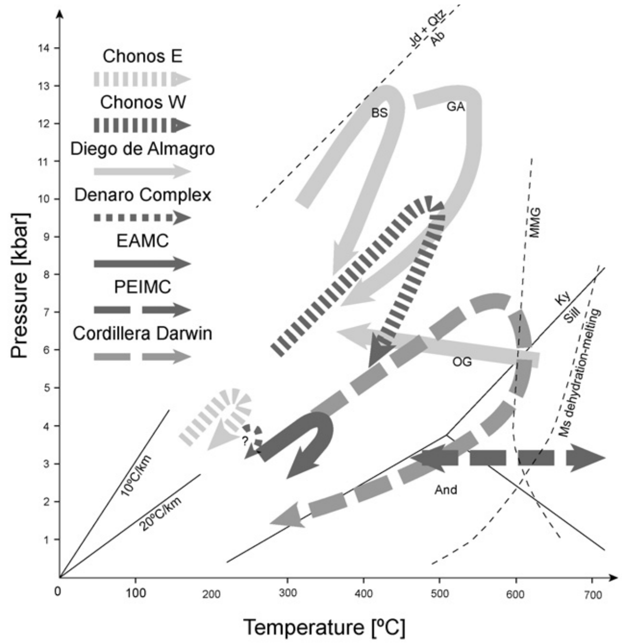

FIGURE 6 | **A compilation of P-T-t trajectories for the different units of the 'metamorphic basement' complexes of the Patagonian and Fuegian Andes (see location in Figure 1). The sources of information are: Chonos Metamorphic Complex - Willner et al., 2000; Eastern Andes Metamorphic Complex – Ramírez et al. 2005; Puerto Edén Igneous and Metamorphic Complex - Calderón et al., 2007 ; Denaro Complex – Sepúlveda et al., 2007; Diego de Almagro Metamorphic Complex - Willner et al., 2004; Cordillera Darwin Metamorphic Complex - Kohn et al., 1995. The curves GA, BS and OG refer to different units within the Diego de Almagro Metamorphic Complex. Aluminium silicate invariant point, minimum melting of granite (MMG) and muscovite dehydration-melting reaction from Spear et al. (1999). The MMG is displaced to lower temperatures due to the release of Boron during the prograde breakdown of tourmaline.**

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REFERENCES

Allen, R.B., 1982. Geología de la Cordillera Sarmiento, Andes Patagónicos entre los 51º y 52º Lat. Sur, Magallanes, Chile. Servicio Nacional de Geología y Minería, Santiago, Boletín 38, 46 pp.

Augustsson, C., Bahlburg, H., 2003. Active or passive continental margin? Geochemical and Nd isotope constraints of metasediments in the backstop of a pre-Andean accretionary wedge in southernmost Chile (46º30' – 48º30'S). In: Mc.Cann, T., Saintot, A. (eds). Tracing Tectonic Deformation Using the sedimentary record, Geological Society of London, Special Publications, 208, 253-268.

Augustsson, C., Münker, C., Bahlburg, H., Fanning, C.M., 2006. Provenance of late Palaeozoic metasediments of the SW South American Gondwana margin: a combined U–Pb and Hf-isotope study of single detrital zircons. Journal of the Geological Society, London, 163, 983–995.

Brown, T.H., Berman, R.G., Perkins, E.H., 1989. Ge0-Calc: software package for calculation and display of pressure-temperature-composition phase diagrams using an IBM or compatible personal computer. Computers and Geosciences, 14, 279-289.

Calderón, M., 2000. Metamorfismo de contacto en el margen oriental del batolito Sur-Patagónico (48° -50°30´ S), Magallanes, Chile. Graduation Thesis. Universidad de Chile, 70 pp.

Calderón, M., 2005. Metamorfismo de alta temperatura y baja presión en rocas del basamento metamórfico en Puerto Edén. MSc Thesis. Departamento de Geología, Universidad de Chile, 102 pp.

Calderón, M., Hervé, F., Tassinari, C.G., Pankhurst, R.J., Godoy, E., Massonne, H.-J., Theye, T., 2007. Petrogenesis of the Puerto Edén Igneous and Metamorphic Complex, Magallanes, Chile: Late Jurassic syndeformational anatexis of metapelites and granitoid magma genesis. Lithos, 93, 17-38.

Cathelineau, M., 1988. Cation site occupancy in chlorites and illites as afunction of temperature. Clay Minerals, 23, 471-485.

Cawood, P.A., Landis, C.A., Nemchin, A.A., Hada, S., 2002. Permian fragmentation, accretion and subsequent translation of a low-latitude Tethyan seamount to the high-latitude east Gondwana margin: evidence from detrital zircon age data. Geological Magazine, 139(2), 131-144.

Dalziel, I.W.D., 1981. Back-arc extension in the southern Andes. A review and critical reappraisal. Philosophical Transactions of the Royal Society of London, A300, 319-335.

Dalziel, I.W.D., 1986. Collision and Cordilleran orogenesis: an Andean perspective. In: Coward, M.P., Ries, A.C. (eds). Collision Tectonics. Geological Society, Special Publication, 19, 389-404.

Dalziel, I.W.D., Cortés, R., 1972. Tectonic style of the southernmost Andes and the Antarctandes. 24th International Geological Congress, Section 3, 316-327.

Davidson, J., Mpodozis, C., Godoy, E., Hervé, F., Muñoz, N., 1989. Jurassic accretion of a high buoyancy guyot in southernmost South America: the Diego Ramírez Islands. Revista Geológica de Chile, 16, 247-251.

Douglass R.C., Nestell M.K., 1976. Late Paleozoic foraminifera from southern Chile. US Geological Survey Special Paper, 858, 49 pp.

Escobar, F., et al., 1980. Mapa Geológico de Chile, Scale 1:1.000.000. Instituto de Investigaciones Geológicas, Santiago.

Fang Z-j, Boucot, A., Covacevich, V., Hervé, F., 1998. Discovery of Late Triassic fossils in the Chonos Metamorphic Complex, Southern Chile. Revista Geológica de Chile, 25(2), 165-173.

Faúndez V., Hervé F., Lacassie J.P., 2002. Provenance studies of pre-late Jurassic metaturbidite successions of the Patagonian Andes, southern Chile. New Zealand Journal of Geology and Geophysics, 45(4), 411-425.

Forsythe, R., 1981. Geological investigations of pre-Late Jurassic terranes in the southernmost Andes. Doctoral thesis. Columbia University, 298 pp.

Forsythe, R., 1982. The late Paleozoic and Early Mesozoic evolution of southern South America: A plate tectonic interpretation. Journal of the Geological Society of London, 139, 671-682.

Forsythe, R.D., Mpodozis, C., 1979. El Archipiélago Madre de Dios, Patagonia Occidental, Magallanes: rasgos generales de la estratigrafía y estructura del basamento pre Jurásico Superior. Revista Geológica de Chile, 7, 13-29.

Forsythe, R.D., Mpodozis, C., 1983. Geología del Basamento pre-Jurásico Superior en el archipiélago Madre de Dios, Magallanes, Chile. Servicio Nacional de Geología y Minería, Santiago, Boletín, 39, 63 pp.

Graham, C.M., Powell, R., 1984. A garnet–hornblende geo-thermometer and application to the Peloma Schist, southern Caliinfornia. Journal of Metamorphic Geology, 2, 13-32.

Guidotti, C., Sassi, F., 1986. Classification and correlation of metamorphic facies series by means of muscovite b_0 data from low-grade metapelites. Neues Jahrbuch für Mineralogie Abhandlungen, 157, 363-380.

Hervé, F., Fanning, C.M., 2000. Late Triassic zircons in metaturbidites of the Chonos Metamorphic Complex, southern Chile. Revista Geológica de Chile, 28(1), 91- 104.

Hervé, F., Fanning, C.M., 2003. Early Cretaceous subduction of continental crust at the Diego de Almagro archipelago, southern Chile. Episodes, 26(4), 285-289.

Hervé, F., Fanning, C.M., Pankhurst, R.J., 2003. Detrital Zircon Age Patterns and Provenance in the metamorphic complexes of Southern Chile. Journal of South American Earth Sciences, 16, 107-123.

Hervé, F., Miller, H., Pimpirev, C., 2006. Patagonia-Antarctica connections before Gondwana break-up. In: Fütterer, D.K., Dmaske, D., Kleinschmidt, G., Miller, H., Tessensohn, F. (eds.). Antarctica: Contributions to global earth sciences. Berlin Heidelberg- New York, Springer-Verlag, 217-228.

Hervé, F., Mpodozis, C., Davidson, J., Godoy, E., 1981a. Observaciones estructurales y petrográficas en el basamento metamórfico del Archipiélago de los Chonos entre el Canal King y el Canal Ninualac, Aisén. Revista Geológica de Chile, 13-14, 3-16.

Hervé, F., Nelson, E., Kawashita, K., Suárez, M., 1981b. New isotopic ages and the timing of orogenic events in the Cordillera Darwin, southernmost Chilean Andes, Earth & Planetary Science Letters, 55, 257-265.

Hervé, F., Pankhurst, R.J., Fanning, C.M., Calderón, M., Yaxley, G.M., 2007. The South Patagonian batholith: 150 my of granite magmatism on a plate margin. Lithos, 97, 373-394.

Hervé, F., Aguirre, L., Godoy, E., Massone, H-J., Morata, D., Pankhurst, R.J., Ramírez, E., Sepúlveda, V., Willner, A., 1998. Nuevos antecedentes acerca de la edad y las condiciones P-T de los Complejos Metamórficos en Aysén, Chile. X Congreso Latinoamericano de Geología, Buenoss Aires, vol. II, 134-137.

Hervé, F., Prior, D., López, G., Ramos, V.A., Rapalini, A., Thomson, S., Lacassie, J.P., Fanning, M., 1999. Mesozoic blueschists from Diego de Almagro, southern Chile. II South American Symposium on Isotope Geology, Córdoba, Actas, (Extended Abstract), 318-321.

Hoisch, T.D., 1990. Empirical calibration of six geobarometers for the mineral assemblage quartz + muscovite + biotite + plagioclase + garnet. Contribution to Mineralogy and Petrology, 104, 225-34.

Holdaway, M.J., 2000. Application of new experimental and garnet Margules data to the garnet–biotite geothermometer. American Mineralogist, 85, 881-892.

Holdaway, M.J., 2001. Recalibration of the GASP geobarometer in light of recent garnet and plagioclase activity models and versions of the garnet–biotite geothermometer. American Mineralogist, 86, 1117-1129.

Kohn, M.J., Spear, F., Dalziel, I.W.D., 1993. Metamorphic P-T Paths from Cordillera Darwin, a Core Complex in Tierra del Fuego, Chile. Journal of Petrology, 34, 3, 519-542.

Kohn, M.J., Spear, F.S., Harrison, T.M., Dalziel, I.W.D., 1995. $^{40}Ar/^{39}Ar$ geochronology and P-T-t paths from the Cordillera Darwin metamorphic complex, Tierra del Fuego, Chile. Journal of Metamorphic Geology, 13(2), 251-270.

Kübler, B., 1968. Evaluation quantitative du métamorphisme par la cristallinité de l'illite. Bulletin du Centre du Recherches du Pau, 2(2), 385-397.

Lacassie, J.P., 2003. Estudio de la Proveniencia Sedimentaria de los Complejos Metamórficos de los Andes Patagónicos (46°-51° Lat. S), mediante la aplicación de redes neuronales e isótopos estables. Doctoral Thesis. Universidad de Chile, 119 pp.

Lagally, U., 1975. Geologische Untersuchungen mi Gebiet Lake General Carrera - Lake Cochrane, Prov. Aysen/Chile unter besorender Berücksichtigung des Grundgebirges und seiner tektonik. Doctoral Thesis. Universität München, 143 pp.

Lawver, L.A., Dalziel, I.W.D., Gahagan, L.M., 1998. A tight fit Early Mesozoic Gondwana, a plate reconstruction perspective. Tokyo. Memoirs of the National Institute for Polar Research, Special Issue, 53, 214 -229.

Ling, H.Y., Forsythe, R.D., Douglass, C.R., 1985. Late Paleozoic microfaunas from Southernmost Chile and their relation to Gondwanaland forearc development. Geology, 13, 357-360.

Massonne, H.J., Szpurka, Z., 1997. Thermodynamic properties of white micas on the basis of high-pressure experiments in the systems K_2O-MgO-Al_2O_3-SiO_2-H_2O and K_2O-FeO-Al_2O_3-SiO_2-H_2O. Lithos, 41, 229–250.

Mukasa, S., Dalziel, I.W.D., 1996. Southernmost Andes and South Georgia Island, North Scotia Ridge: zircon U-Pb and muscovite Ar - Ar age constraints on tectonic evolution of southwestern Gondwanaland. Journal of South American Earth Sciences, 9, 349-365.

Nelson, E., Dalziel, I.W.D., Milnes, A.G., 1980. Structural geology of the Cordillera Darwin: Collision style orogenesis in the southernmost Chilean Andes. Eclogae Geologicae Helveticae, 73, 727-751.

Olivares, B., Cembrano, J., Hervé, F., López, G., Prior, D., 2003. Geometría y cinemática de la Zona de Cizalle Seno Arcabuz, Andes patagónicos, Chile. Revista Geológica de Chile, 30(1), 39-52.

Pankhurst, R.J., Rapela, C., 1995. Production of Jurassic rhyolite by anatexis of the lower crust of Patagonia. Earth and Planetary Science Letters, 134, 23-36.

Pankhurst, R.J., Rapela, C.W., Loske, W.P., Marquez, M., Fanning, C.M., 2003. Chronological study of the pre-Permian basement rocks of southern Patagonia. Journal of South American Earth Sciences, 16, 27-44.

Pimpirev, C., Miller, H., Hervé, F., 1999. Preliminary results on the lithofacies and palaeoenvironmental interpretation of the Paleozoic turbidite sequence in Chonos Archipielago, Southern Chile. Comunicaciones, 48-49, 3-12.

Ramírez, E., 2002. Geotermobarometría en metapelitas de complejos metamórficos de Aysen, Chile. Doctoral Thesis. Universidad de Chile, 143 pp.

Ramírez, E., Hervé, F., Kelm, U., Sassi, R., 2005. P-T conditions of metapelites from metamorphic complexes in Aysen, Chile. Journal of South American Earth Science, 19, 373-386.

Rapalini, A.E., Hervé, F., Ramos, V.A., Singer, S., 2001. Paleomagnetic evidence for a very large counterclockwise rotation of the Madre de Dios Archipelago, Southern Chile. Earth Planetary Science Letters, 184(2), 471-487.

Rapela, C.W., Pankhurst, R.J., Fanning, M.J., 2003a. The Early Jurassic Subcordilleran Plutonic Belt of Patagonia (42°-44°S): Proto Pacific subduction coeval with the Karroo mantle plume. X Congreso Geológico Chileno, Concepción, Proceedings. (CD-ROM).

Rapela, C.W., Pankhurst, R.J., Fanning, C.M., Grecco, L.E., 2003b. Basement evolution of the Sierra de la Ventana Fold Belt: new evidence for Cambrian continental rifting along the southern margin of Gondwana. Journal of the Geological Society, London, 160, 613-628.

Sepúlveda, F.A., Hervé, F., Calderón, M., Lacassie, J.P., 2007. Petrological and geochemical characteristics of metamorphic and igneous units from the allochthonous Madre de Dios Terrane, Southern Chile. Gondwana Research, doi: 10.1016/j.gr.2007.06.004

Söllner F., Miller, H., Hervé, M., 2000. An Early Cambrian granodiorite age from the pre-Andean basement of Tierra del Fuego (Chile): the missing link between South America and Antarctica? Journal of South American Earth Sciences, 13, 163-177.

Spear, F., 1989. Metamorphic pressure-temperature-time paths. International Geological Congress Short Course number S29B. American Geophysical Union, Short Course in Geology, 7, 102 pp.

Spear, F., Kohn, M., Cheney, J., 1999. P-T path from anatectic pelites. Contributions to Mineralogy and Petrology, 134, 17-32.

Thomson, S.N., Hervé, F., 2002. New time constraints for the age of metamorphism at the ancestral Pacific Gondwana margin of southern Chile. Revista Geológica de Chile, 29(2), 255-271.

Valdés, A., 2005. Petrología de la aureola metamórfica de contacto del plutón monzogranítico Río Murta, XI región de Aysén, Chile. Graduation thesis. Universidad de Concepción, 143 pp.

Watters, W., 1964. Geological work at Puerto Edén, Wellington island, southern Chile. Transactions of the Royal Society of New Zealand (Geology), 2, 155-168.

Willner, A., Hervé, F., Massonne, H.-J., 2000. Mineral Chemistry and Pressure- Temperature Evolution of Two Contrasting High-pressure-Low-temperature Belts in the Chonos Archipelago, Southern Chile. Journal of Petrology, 41(3), 309-330.

Willner, A.P., Hervé, F., Thomson, S.N., Massonne, H.-J., 2004. Converging PT-paths of Mesozoic HP-LT metamorphic units (Diego de Almagro Island, Southern Chile, 51°30`S): Evidence for juxtaposition during late shortening of an active continental margin. Mineralogy and Petrology, 81, 43-84.

Wilson, T.J., Hanson, R.E., Grunow, A.M., 1989. Multistage melange formation within an accretionary complex, Diego Ramírez Islands, southern Chile. Geology, 17, 11-14.

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