The late Paleozoic paired metamorphic belt of southern Central Chile: Consequence of a near-trench thermal anomaly?

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Abstract

The hypothesis of a subduction-related Miyashiro-type paired metamorphic belt for the origin of the late Paleozoic igneous and metamorphic complex in the Andean Coastal Cordillera has remained unquestioned since its proposal in the early seventies. A synthesis of the advances in the study of these metamorphic rocks between 33°S and 42°S, revising field relations among geological units, and geochemical and geochronological data from the contemporaneous granitoids of the Coastal Batholith, highlights inconsistencies in this model. The record of short-lived forearc magmatism in the late Paleozoic intruding the partially synchronous accretionary prism, and geochemical and isotopic data from the igneous rocks indicating sources from the accretionary prism sediments and the back-top lithosphere, suggest a departure from typical subduction settings. I conclude that the anomalous configuration of the paired metamorphic belt and the associated Coastal Batholith resulted from a complex geodynamic process involving a near-trench thermal anomaly caused by the subduction of a trench parallel mid-ocean ridge.

Keywords: Paired metamorphic belts; accretionary prism; Coastal Cordillera; mid-ocean ridge subduction.

1. Introduction

The spatial arrangement of contemporaneous low-temperature/high-pressure metamorphic rocks and igneous intrusion-related high-temperature/low-pressure metamorphic rocks in Japan led Miyashiro to the novel idea that metamorphic belts could develop as a pair (Miyashiro, 1961).

Consolidation of the plate tectonic theory in the late 1960s provided a coherent framework for this idea, where paired metamorphic belts were explained as a direct result of the subduction process (Oxburgh and Turcotte, 1970; Ernst, 1971; Miyashiro, 1972; 1973). This was quantitatively demonstrated by the modeling of Oxburgh and Turcotte (1971), which showed that the oceanic plate subduction depresses the geotherm near the trench generating low-temperature/high-pressure metamorphism, which is preserved in the accretionary prism, and elevates the geotherm in the arc region causing high-temperature/low-pressure metamorphism (Fig. 1). Most recent studies have expanded this concept to collisional margins and included additional causes in subduction settings such as mid-ocean ridge-trench interactions and tectonic juxtaposition of laterally contemporaneous metamorphic belts (e.g., Brown, 1998a;b; 2009; 2010; Iwamori, 2000; Maruyama *et al*., 2010).

Early studies in southern Central Chile highlighted similarities between the metamorphic zoning of late Paleozoic rocks in the Andean Coastal Cordillera and those described in Japan by Miyashiro (1961). In that region, a parallel and coeval arrangement of contrasting geological units was interpreted as a subduction-related high-pressure/low-temperature metamorphism to the west and a volcanic arc-related low-pressure/high-temperature metamorphism to the east that developed along the southwestern Gondwana margin (González-Bonorino and Aguirre, 1970; González-Bonorino, 1971; Aguirre *et al*., 1972). In the last fifty years, numerous studies have supported the Pacific-type subduction hypothesis for the origin of the paired metamorphic belt in the Coastal Cordillera (Hervé et al., 1974; 1984; 2013; Hervé, 1988; Kato and Godoy 1995; Duhart *et al*., 2001; Glodny *et al.* 2005; 2008; Willner, 2005; Willner *et al.* 2005; Richter *et al.* 2007; Hyppolito *et al*., 2014a,b; 2015; Sigoña, 2016; Muñoz-Montecinos *et al*., 2020).

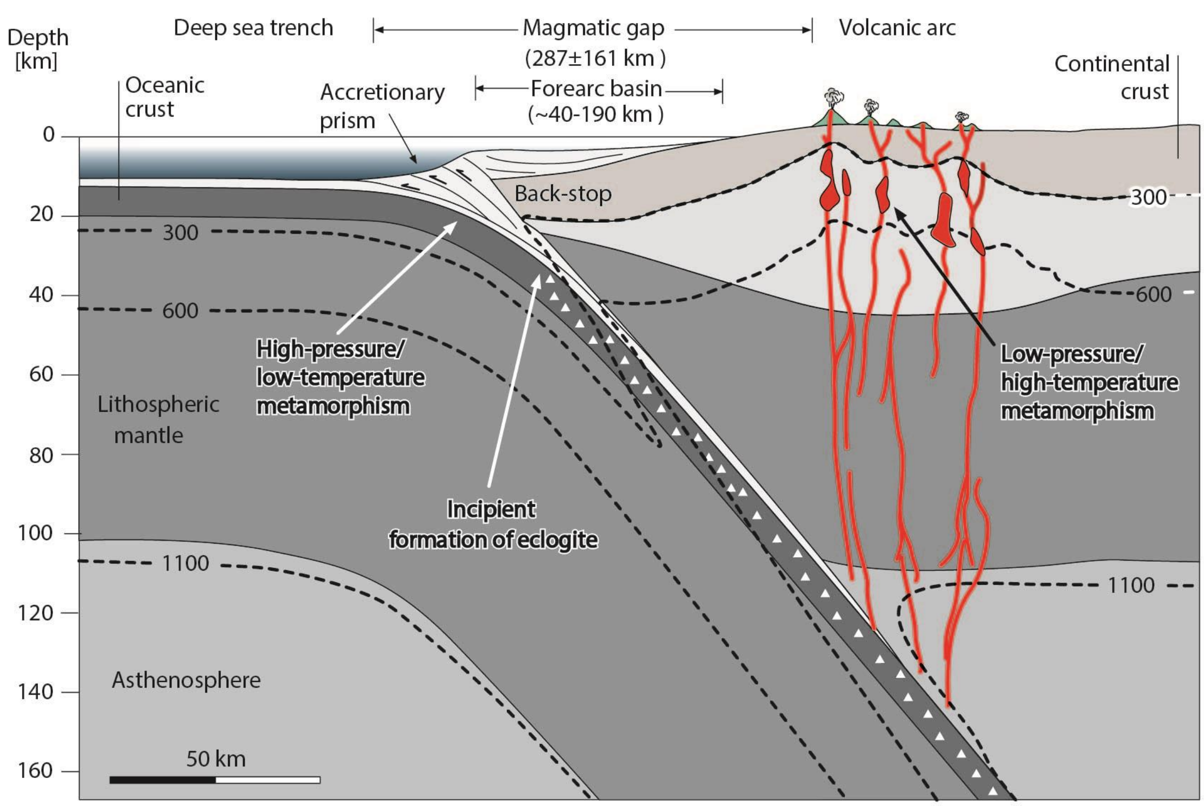

Figure 1. Cross section through an active continental margin (modified from Frisch et al. 2010) showing the approximate thermal structure in normal subduction settings, main areas of the subduction system, and zones with contrasting metamorphism (Schubert and Turcotte, 1975). Average arc-trench gap is from the Earthbyte group's website (https://www.earthbyte.org/calculating-arc-trench-distances-using-the-smithsonian-global volcanism-project-database/) *and forearc basin width range is from Noda (2016).*

In this contribution, I first provide a synthesis of the advances in the study of these metamorphic rocks and the Coastal Batholith (Fig. 2). Then, I discuss key field-based observations, along with geochemical and geochronological data from the contemporaneous granitoids, and contrast these data with our current understanding of the anatomy and dynamics of subduction zones. This analysis highlights major inconsistencies in the Pacific-type subduction hypothesis for the origin of the paired metamorphic belt of the Coastal Cordillera and suggests a more complex late Paleozoic geodynamic setting than previously acknowledged.

2. Paired metamorphic belt of the Coastal Cordillera in southern Central Chile

Subduction complexes of Late Paleozoic and Mesozoic ages form a lengthy chain of >2000 km extending from 32°-54°S that developed along the southwestern margin of Gondwana (Hervé, 1988). This revision deals with the basement rocks in the Coastal Cordillera of South Central Chile, which extends between 32°S and 42°S, and is mostly concentrated on metasedimentary and igneous units north of the Lanalhue fault zone (~39°S), where these form a contemporaneous paired metamorphic belt (Fig. 2a). This area holds well-preserved outcrops of a late Carboniferous-Early Permian metamorphic complex to the west and a contemporaneous batholith to the east jointly interpreted as recording early subduction stages beneath southwest Gondwana (González-Bonorino 1970, 1971; González-Bonorino y Aguirre 1970; Aguirre *et al.* 1972; Hervé 1977; 1988; Hervé *et al.* 1974; 1984; 2003; 2013; Mpodozis and Ramos; 1989; Beck *et al*., 1991; Martin *et al.*, 1991; Kato and Godoy 1995; Duhart *et al.*, 2001; Willner 2005; Willner *et al.* 2004; 2005; 2008; Glodny *et al.* 2005; 2006; 2008) (Fig. 2a,b). In the following subsections, I summarize the main characteristics of this igneous-metamorphic belt. In this synthesis, I focus on the most general aspects of this belt, which are profound enough to highlight arguable aspects of the geodynamic model proposed so far. In-depth details on metamorphic complexes and igneous rocks can be found in the references provided in the text.

2.1 Paired metamorphic belt of southern Central Chile

The pioneering studies in the late Paleozoic basement rocks of Coastal Cordillera of southern Central Chile by González-Bonorino and Aguirre (1970) and González-Bonorino (1971) identified the Pichilemu, Curepto, and Nirivilo metamorphic facies series that depict a progressive appearance of mineral zones and facies formed under diverse pressure, temperature, and tectonic regimes. The metamorphic complex was later divided by Aguirre *et al.* (1972) into the Western and the Eastern Series (Fig. 2a). The former are intensely deformed oceanic-derived high-pressure/low-temperature units with sedimentary and basaltic protoliths of abyssal and trench environments, whereas the latter are associated with less deformed trench-to-forearc metasedimentary rocks of very-low grade overprinted by low-pressure/high-temperature metamorphism (González-Bonorino, 1971; Aguirre *et al*., 1972; Hervé *et al*., 1984; Hervé, 1988; Willner, 2005; Hyppolito *et al*., 2014a,b; 2015).

The late Paleozoic convergent stage that gave place to this accretionary complex was preceded by a short-lived Devonian−early Carboniferous passive margin setting (~400–340 Ma, Willner *et al.*, 2008, 2011 or 420-370 Ma, Hervé *et al*., 2013) that changed to a convergent margin with eastward polarity after ~340 Ma. Multi-method geochronological and structural studies indicate that the accretionary prism would have grown from ~320 to ~224 Ma through frontal accretion in the Eastern Series and basal accretion in the Western series with W and SW vergence (Lohrmann, 2002; Glodny *et al*., 2005; Willner *et al*., 2005; Richter *et al*., 2007) (Fig. 3). However, Richter *et al*. (2007) suggested that the deepest portion of the Eastern Series was also affected by basal accretion. Field-based analyses indicate that the nature of the contact between the Western and Eastern Series is regionally variable, changing locally from transitional to tectonic (González-Bonorino, 1971; Davidson *et al*., 1987; Richter *et al*., 2007; Willner *et al*,. 2009; Glodney *et al*., 2008) (Fig. 2b). Maximum depositional ages obtained from detrital zircon dating in the metasediments indicate early and late Carboniferous ages for the Eastern and Western series, respectively, with a provenance from older Gondwana margin basement of the Pampean (~530-510 Ma) and Famatinian (~470 Ma) belts, including reworked cratonic material, and Carboniferous magmatism east of the present-day Andes (Duhart *et al*., 2001; Willner *et al.*, 2008; Hervé *et al*, 2013). However, south of the Lanalhue fault zone Permian maximum depositional ages have been documented in the Western Series with detritus derived from the Choiyoi province (~287-245 Ma) or subvolcanic plutonic rocks in the North Patagonian massif (~290-260 Ma) (Hervé *et al.*, 2013). The Western Series is formed by schists and phyllites that contain metre- to kilometre-sized slices of metabasites of high-pressure greenschists, epidote and garnet amphibolites, and blueschists (Kato, 1985; Hervé, 1988; Shira *et al*., 1990; Kato and Godoy 1995; Willner *et al.* 2004; Willner

2005; Hyppolito *et al*., 2014a). The latter (~9.5–11 kbar, and 350–385ºC) are scarce and the record of high-pressure conditions is given by greenschists that bear Na–

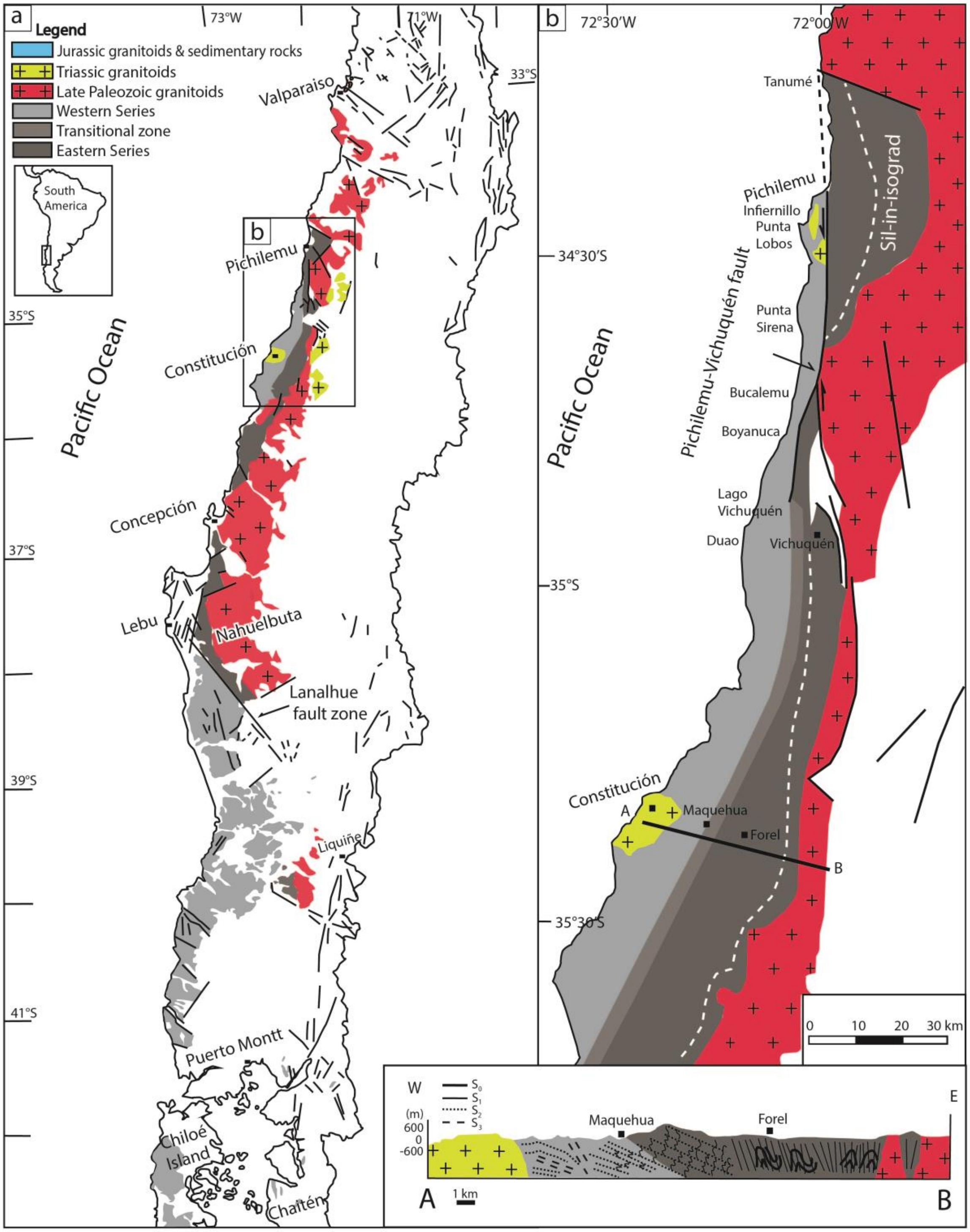

Figure 2. a) Geological sketch map of the studied area (34–42°S) showing the late Paleozoic metamorphic complexes and late Paleozoic and Triassic granitoids from the Coastal Batholith.

Figure modified from Hervé et al. (2013). b) Geological map of the Coastal Cordillera at Pichilemu and Constitución regions (34°-35°40'S) with cross section A-B. Figure modified from Willner et al. (2009).

Ca amphibole and phengite (~7–9.3 kbar, and 380–420°C) and indicate a subduction-related metamorphic gradient in the range of ~11–16 °C/km (Willner, 2005). Local occurrences of garnet-bearing mica schists in the Punta Sirena region record the highest temperature conditions (retrograde conditions in the range 9.6−14.7 kbar and 390–440°C, at ~320 Ma) and a counter-clockwise P−T path (Willner, 2005) (Fig. 2b). Zircon dating of accreted sediments and ^{40}Ar–^{39}Ar cooling ages in phengite from high-pressure greenschists from the Western Series indicates that basal accretion began at ~308 Ma (Willner *et al*., 2005, 2008; 2009, 2012; Hyppolito *et al*., 2014b) (Fig. 3). As demonstrated by Hyppolito *et al.* (2015), basal accretion preceded both the peak of blueschist metamorphism at ~300 Ma in the Pichilemu region (Willner *et al*., 2005) and cooling of the Eastern Series in the interval 301–292 Ma (Fig. 3). During the evolution of the accretionary complex these rocks reached depths of 10-50 km, and were later exhumed at variable rates ranging from 0.03-2.0 mm/year (Willner *et al*., 2004; Willner, 2005; Willner *et al*., 2005; Kato *et al*., 2008; Hyppolito *et al*., 2014b). Geochemical and isotopic studies indicate that metabasites from the Western Series are ocean-derived tholeiitic and alkali basalts, with N-MORB, E-MORB, and OIB signatures (Kato, 1985; Hervé, 1988; Kato & Godoy, 1995; Schira *et al*., 1990; Hyppolito *et al*., 2014a). These metabasites are interpreted as formed in an oceanic basin setting characterized by shallow and deep mantle sources, such as plume-influenced mid-ocean ridge (Hyppolito *et al*., 2014a).

The Eastern Series is formed by psammo-pelitic sequences associated with early Carboniferous trench and Devonian passive margin sedimentary deposits that preserve bedding and sedimentary structures (e.g., Hervé, 1988; Willner, 2005; Glodny *et al*., 2008). The Eastern Series is classically understood as the rear part of the late Paleozoic accretionary wedge, reflecting a position transitional to the backstop area (Hervé, 1988; Willner *et al*., 2000; Glodny *et al*., 2008) (Fig. 4). During the development of the accretionary wedge, the Eastern Series was intruded by late Paleozoic granitoids belonging to the Coastal Batholith causing a metamorphic overprinting at 3 kbar (296–301 Ma, $^{40}Ar/^{39}Ar$ muscovite plateau ages, Willner *et al*., 2005) of the very low-grade frontal accretion-related metamorphism (Willner *et al*., 2005; Glodny *et al*., 2008; Hervé *et al*., 2013; Deckart *et al*., 2014) (Fig. 2a,b). Metamorphism in the Eastern Series records increasing metamorphic grade from west to east, from greenschist to amphibolite and locally granulite facies conditions and thermobarometric studies indicate high-temperature/low-pressure metamorphic conditions in the range of 720–400°C and 2.5–3.5 kbar (Aguirre *et al.* 1972; Hervé, 1977; Willner

2005; Willner et al., 2005; Hyppolito et al., 2015). According to Hyppolito *et al.* (2015), the thermal overprint occurred after the frontal accretion-related deformation (D1) and likely before or early during the development of a penetrative foliation (S2) (Fig. 3). A contemporaneous paired metamorphic belt in southern Central Chile has been corroborated by the age range for the high-temperature metamorphism in the Eastern Series that falls into the time span determined for the peak of high-pressure metamorphism in the Western Series at 292–320 Ma (Willner *et al.* 2005; Hyppolito *et al*., 2015) (Fig. 3).

3.2 The Coastal Batholith of south Central Chile

The Coastal Batholith crops out between 33°S and 38°20'S along the Coastal Cordillera, and is dislocated to the east by the Lanalhue strike-slip fault at 40°S (Glodney *et al*., 2008) (Fig. 2a).This is a large composite calc-alkaline igneous body of meta- to peraluminous composition mostly made of tonalite, granodiorites, and granite with minor diorite that intruded syn- and post-tectonically metamorphic rocks of the Eastern series (Cordani *et al.*, 1976; Hervé *et al.*, 1988; 2013; Parada, 1999; Parada *et al*., 1999; 2007; Charrier *et al.*, 2015). More locally, equivalent mafic rocks have also been described intruding in basally accreted rocks of the Choapa Metamorphic Complex (~318 Ma, Sigoña, 2016). Radiometric ages obtained in previous studies along the length of the batholith yielded Late Carboniferous (Pennsylvanian) ages, mostly between ~300 and 320 Ma, indicating a short-lived magmatic event (K-Ar, Cordani *et al*., 1976; Rb-Sr isochron ages, Shibata *et al*., 1984; U-Pb zircon ages, Godoy and Loske, 1988; Rb-Sr isochron and K-Ar ages, Hervé *et al*., 1988; K/Ar and $^{40}Ar/^{39}Ar$, Beck *et al*., 1991, K-Ar ages, Martin *et al.* 1991; U-Pb zircon ages, Gana and Tosdal, 1996; Rb-Sr isochron, Lucassen *et al.*, 2004; two-point Rb-Sr ages, Glodny *et al*., 2008; U-Pb zircon ages, Pineda and Calderón, 2008; U-Pb SHRIMP zircon ages, Deckart *et al*., 2014). As mentioned in the previous subsection, the intrusion of this large igneous body is responsible for the metamorphic overprint at around 300 Ma on the eastern side of Eastern Series (e.g., Willner *et al*., 2005; Hyppolito *et al*., 2015) (Figs. 2b and 3). Also, ages for the metamorphic peaks on the basally accreted Western Series indicate that metamorphism overlapped with the intrusion of the Coastal Batholith (Willner et al., 2005; Hervé *et al.* 2013) (Fig. 3).

Based on the analysis of Carboniferous mafic enclaves Parada *et al.* (1999) noted that in terms of Y, La, and Nb, these have geochemical signatures of continental basalts derived from an enriched lithospheric mantle. These authors indicated that the Sr–Nd isotope data (Initial $^{87}Sr/^{86}Sr$ = 0.7057 - 0.7098 and εNd = -2 - -4) suggest that these mafic rocks were derived from primary enriched mantle-derived magmas. Lucassen *et al.* (2004) also found enriched isotopic compositions in the late Paleozoic Nahuelbuta granitoids presenting initial $^{87}Sr/^{86}Sr$ ratios between 0.705 and

0.715 and εNd values between -2.5 and -7.5 (Fig. 2a). These authors noted that the REE patterns in late Paleozoic rocks of the Coastal Batholith are similar to those of the metamorphic accretionary basement and an average upper continental crust that together, with their isotopic composition, indicate a crustal origin. Recently, Deckart *et al.* (2014) showed that Lu-Hf isotopic analyses on zircon grains with ages between ~320 and 300 Ma have initial εHf(i) values from +1.67 - -5.64, with most of the analyses between +1 and -4 epsilon units and the T_{DM2} in these rocks suggest Mesoproterozoic crustal residence ages. These authors also presented δ_{18}O ratios from the dated zircon grains ranging from 6.4 - 8.6‰ with a prominent group with values between 6.0 and 7.5‰ and a minor group between 8.0 and 9.0‰. According to Deckart *et al.* (2014), these data indicate that the magmas were likely derived from crustal sources with a prominent sedimentary input as suggested by the elevated δ_{18}O values. However, as pointed out by these authors, a mantle input cannot be completely ruled out. Therefore, geochemical and isotopic data suggest that the Coastal Batholith has a high proportion of reworked old crustal material, indicating that either the magmas assimilated large amounts of metasediments from Eastern Series, which represent reworked old continental crust, and/or that the Eastern Series was partly underlain by an old continental back-stop basement (Parada *et al.*, 1999; Lucassen *et al.*, 2004; Glodny *et al.*, 2006; Deckart *et al.*, 2014).

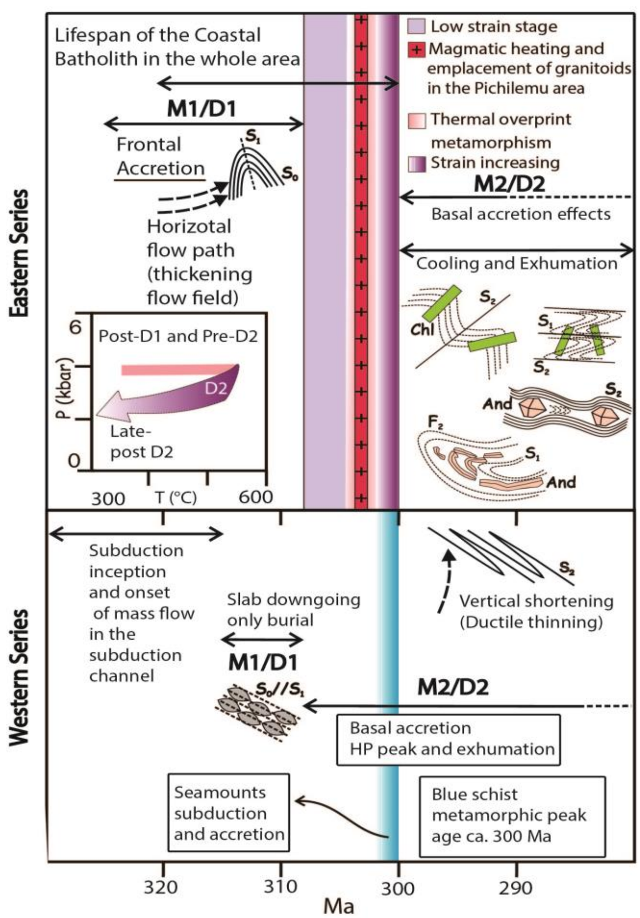

Figure 3. Image depicting the temporal relations between deformation in Western and Eastern series, and the overall evolution of the accretionary wedge in the Pichilemu region. Figure modified from Hyppolito et al. (2015). See text for discussion.

The geodynamic context of the Coastal Batholith is classically interpreted as a subduction setting where this igneous body represents part of the large southwestern Gondwana magmatic arc (Hervé *et al*., 1988; Parada, 1990; Parada *et al*., 1999; 2007; Lucassen *et al*., 2004; Charrier *et al.*, 2007; 2015; Deckart *et al.*, 2014; del Rey *et al.*, 2016; Oliveros *et al.*, 2020; among others). According to the regional analysis of Charrier *et al.* (2015), differences in peak metamorphic ages in accretionary complexes north of 33°S and the contrasting ages of igneous rocks south and north of this latitude likely indicates a major segmentation in the ancient convergent margin.

3. Discussion: A circum-Pacific Miyashiro-type or a forearc paired metamorphic belt in south Central Chile?

The hypothesis of a circum-Pacific Miyashiro-type paired metamorphic belt for the origin of the late Paleozoic igneous-metamorphic complexes of south Central Chile has remained unquestioned since its proposal in the seventies (González-Bonorino and Aguirre, 1970; González-Bonorino, 1971; Aguirre *et al.*, 1972; Hervé *et al*., 1974, 1984, 2013; Hervé, 1988; Kato, 1985; Kato and Godoy 1995; Duhart *et al*., 2001; Glodny *et al.* 2005; 2008; Willner 2005; Willner *et al.* 2005; Richter *et al.* 2007; Hyppolito *et al*., 2014a,b; 2015; Muñoz-Montecinos *et al*., 2020). Below I argue that field relations between the metamorphic and igneous units, and possibly the time and geochemistry of the Coastal Batholith, highlight inconsistencies in this model and are not compatible with our current understanding of typical subduction zones.

The geological configuration of subduction zones indicates that the contemporaneous arc and accretionary prism systems do not overlap and that both develop under contrasting geothermal gradients, which constitute the foundations of Miyashiro's concept of paired metamorphic belts (e.g., Oxburgh and Turcotte, 1971; Stern, 2002) (Fig. 1). Global analyses of active subduction zones indicate that average arc-trench gaps are 287±161 km (https://www.earthbyte.org/calculating-arc-trench-distances-using-the-smithsonian-global volcanism-project-database/) and the rear areas of accretionary prisms are commonly separated from arc regions by ~40-190 km wide forearc basins (Noda, 2016) (Figs. 1 and 4). Notably, this distance could be larger if forearc fold-and thrust belts are present as recently recognized in some areas of the Andes (e.g., Armijo *et al*. 2015; Riesner *et al*., 2018; Martinez *et al*., 2020; Encinas *et al*., 2020). Volcanic arcs and accretionary prisms do not superpose even in subduction settings with the highest known slab angles, such as Mariana-type subduction zones with up to 90° dipping slabs (Uyeda and Kanamori, 1979). An apparent superposition of these two systems is possible when subsequent tectonic processes, such as strike-slip or forearc underthrusting, juxtapose the geological record of both areas (e.g., Brown *et al.*, 1998a,b; 2010). In the case of the igneous-metamorphic complexes in the Coastal Cordillera between 33°S and 42°S, a tectonic superposition of both belts is ruled out by field relations, and despite subsequent deformation during Andean orogeny, an in-situ formation has been demonstrated (e.g., Willner *et al*., 2005). Detailed mapping in the last decades has confirmed early observations on the intrusive nature of the contact between the Coastal Batholith and the Eastern Series, and established a transitional contact between the latter and the Western Series at several latitudes (González-Bonorino, 1971; Davidson *et al.*, 1987; Richter *et al.*, 2007; Willner *et al*., 2009) (Fig. 2b). Also, Sigoña (2016) documented ~318 Ma mafic dykes associated with the Coastal Batholith intruding high-pressure/low-temperature rocks at 31°30'S. The latter observations constitute a challenge for the interpretation of a circum-Pacific-type paired metamorphic belt for late Paleozoic rocks in this area. The fact that throughout the development of the accretionary wedge, the frontally accreted Eastern Series was intruded by the partially contemporaneous Coastal Batholith (~320-300 Ma) (Willner *et al*., 2005; Hervé *et al*., 2013, 2014; Deckart *et al*., 2014), indicate a geodynamic setting that departs substantially from typical subduction zones (Fig. 4). In the latter, magmatic activity is usually concentrated several kilometers away from the accretionary prisms and is developed above a mantle wedge (e.g., Stern, 2002; Tatsumi, 2005; Gerya and Meilick, 2011) (Figs. 1 and 4). A major implication of the proximity of the igneous activity to the paleo-trench is that the proposed magmatic arc nature of the Coastal Batholith is untenable (e.g., Hervé, 1988; Parada, 1990; Parada *et al*., 1999; 2007; Lucassen *et al*., 2004; Deckart *et al*., 2014; Sigoña, 2016). The abnormal character of the Coastal Batholith is not only limited to the conspicuous emplacement site within the overall subduction system (Fig. 4). Deckart *et al.* (2014) already highlighted that the short period of time of batholith emplacement (~20 Ma) and the petrogenetic features indicating a major source from the accretionary prism metasediments and/or the back-stop lithosphere (Parada, 1990; Parada *et al*., 1999; Lucassen *et al*., 2004) contrast those of typical cordilleran batholiths. The latter, are commonly formed along tens or hundred million years through multiple pulses of magmatism with variable mantle wedge and crust inputs depending, among other parameters, on the upper-plate nature and thickness (e.g., Ducea *et al.*, 2015). Indeed, these key observations have been integrated in evolutionary models of most recent studies at these latitudes depicting a magmatic activity to the east that intrudes the frontally accreted Eastern series and interacts with a potential back-stop lithosphere during magma ascent (e.g., Glodney et al., 2008;

Hyppolito et al., 2014b; Díaz-Alvarado *et al*., 2019). However, the geodynamic meaning of such an unusual geological configuration has been overlooked so far, and a continental arc setting was suggested in the latter and subsequent studies as well (e.g., del Rey *et al*., 2016; Oliveros *et al*., 2020).

According to Willner *et al*. (2004; 2005), deep transport of a considerable volume of sediments below the upper mantle wedge during subduction initiation could have provided hydrous fluids triggering fluid-flux mantle melting and magmatism at the earliest stage in the evolution of the paired metamorphic belt. However, the latter cannot effectively explain the mainly crustal-like sources in the Coastal Batholith (Parada, 1990; Parada *et al*., 1999; Lucassen *et al.*, 2004; Deckart *et al.*, 2014). Alternatively, Deckart *et al.* (2014) proposed that deeply subducted sediments could have been melted at mantle depths, which is compatible with isotopic values of the Coastal Batholith. Nevertheless, in either case, deep sediment subduction up to the mantle wedge within a shallow subduction setting, as inferred at the onset of convergence in this region (Willner *et al*., 2004), would have still triggered magmatism far from the accretionary prism. The latter is also confirmed by 2-D numerical modeling studies where buoyant plumes of partially melted sediments in the mantle wedge ascend several kilometers away from accretionary prisms impacting beneath the arc and backarc areas, even at normal slab angles (30-45°) (Gerya and Yuen, 2003; Gerya and Meilick, 2011)

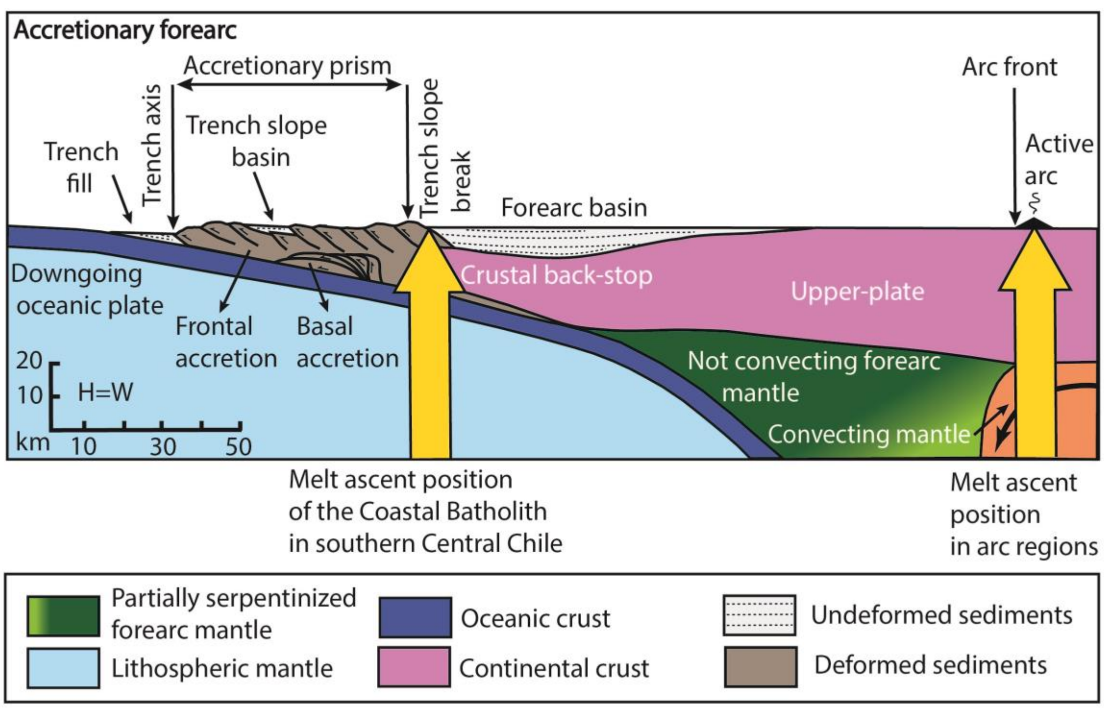

Figure 4. Cross-section at scale of an accretionary forearc (modified after Stern, 2002). This image illustrates the unusual setting where the Coastal Batholith of southern Central Chile was emplaced during the late Paleozoic.

In order to trigger substantial magmatic activity in the overall cold forearc region, a thermal anomaly is needed below the rear part of the late Paleozoic accretionary prism. Although not common in normal subduction zones, forearc magmatism and related high-temperature/low-pressure metamorphism have been documented in recent and ancient convergent settings in association with asthenosphere upwelling produced by the development of slab gaps (e.g., Uyeda and Miyashiro, 1974; Marshak and Karig, 1977; DeLong and Fox, 1979; Iwamori, 2000; Wakabayashi, 2004; Santosh and Kusky, 2010; see Gianni and Perez-Luján, 2021, for a recent synthesis). Slab windows or gaps are openings in the downgoing plate that allow hot sub-slab asthenosphere to flow through the slab hole impacting beneath the upper-plate margin. This phenomena influences the arc and backarc magmatism (e.g., Abratis, and Wörner, G., 2001; Rosenbaun *et al*., 2008; Thorkelson *et al*., 2011), the upper-plate thermal structure (Roche et al., 2018; Ávila and Dávila, 2018), the mantle flow in subduction zones, and the overall plate kinematics (Guillaume *et al*., 2010; Király *et al*., 2020). Slab gap development can be produced by several processes but mostly results from two general causes. One is the presence of buoyancy anomalies in the downgoing plate such as oceanic plateaus, aseismic ridges, or continental fragments (e.g., Cloos, 1993) that resist subduction and lead to slab ruptures. The latter could be caused by local slab necking forming holes within the downgoing plate (e.g., Király *et al*., 2020), vertical slab tearing (e.g., Rosenbaun *et al*., 2008), or by propagation of horizontal tears (e.g., Wortel and Spakman, 2000). The other cause of slab gap development comprises the divergence or reactivation and separation of a preexisting plate discontinuity such as the separation of an active spreading center during subduction (Uyeda and Miyashiro, 1974; DeLong and Fox, 1979; Marshak and Karig, 1977; Dickinson and Snyder, 1979) or a major fault onboard the oceanic plate such as fracture zones and transform faults (e.g., Pesicek *et al*., 2012). Although most of the processes forming slab gaps induce more or less similar magmatic and thermal effects in the upper-plate, mid-ocean ridge subduction is characterized by a substantial impact on the forearc area. In that region, ridge subduction may cause uplift and unconformity development, local ophiolites emplacement, near-trench MORB (Mid-Ocean-Ridge-Basalt) intrusions, felsic magmatism by crustal anatexis of the accretionary prism (*blow-torch effect*, DeLong *et al*., 1979), and low-pressure/high-temperature metamorphism (Marshak and Karig, 1977; DeLong *et al*., 1979; Nelson *et al*., 1993; Underwood et al., 1993; see Sisson *et al*., 2003, for a synthesis). In this context, heating and melting of the accretionary prism can take place with or without cessation of subduction (Underwood et al., 1993;

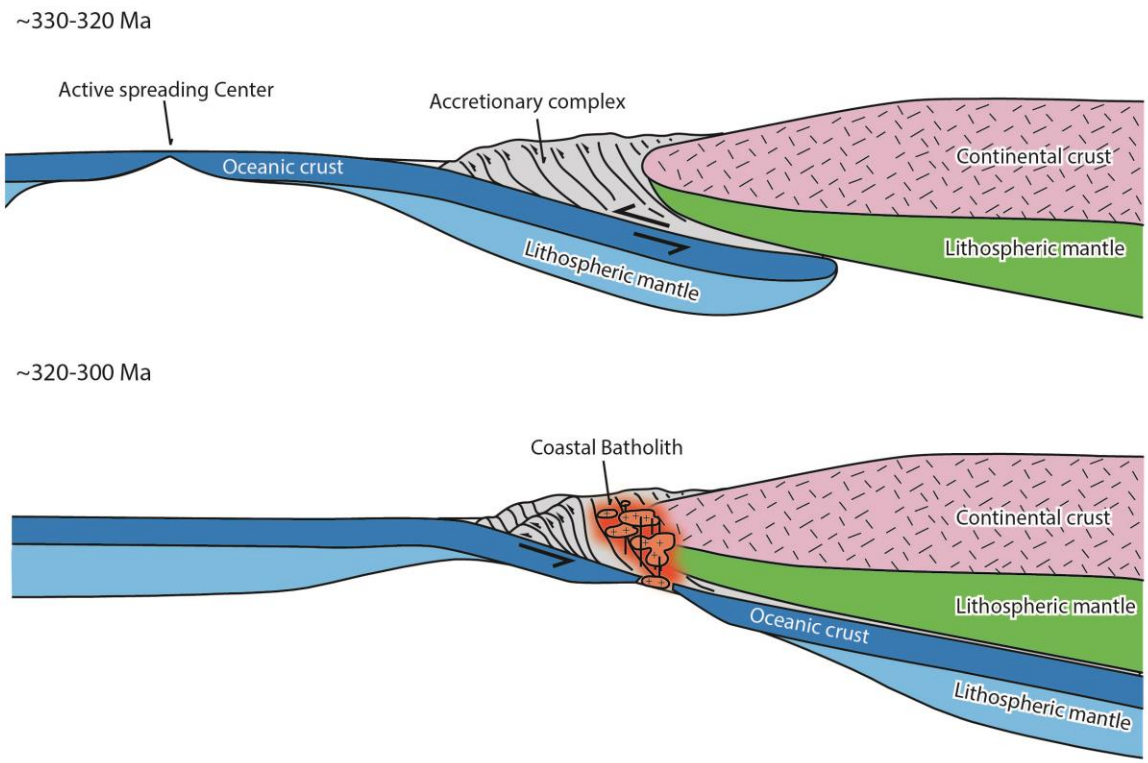

Figure 5. Conceptual model of a forearc paired metamorphic belt for the origin of the igneous-metamorphic complexes of the Coastal Cordillera of southern Central Chile (33°-40°S (modified from Wakabayashi, 2004).

Brown, 1998b; Iwamori, 2000). Subduction of a trench-parallel mid-ocean ridge segment could be a possible explanation for the short-lived thermal anomaly (~20 Ma) beneath the rear part of the late Paleozoic accretionary prism and the formation of the Coastal Batholith (Fig. 5). According to the 2-D numerical modeling of Iwamori (2000) initial mid-ocean ridge subduction can drive high-temperature/low-pressure metamorphism and magmatism before the opening of a slab window explaining near-trench granitoids coexisting with paired metamorphic belts. The latter study found that ridge crest subduction produces a substantial thermal anomaly that depending on plate kinematics can be dissipated in up to 30 Myr after the ridge subduction event. Hence, subduction of an active spreading center and possibly the incipient ridge opening during initial subduction could have provided the necessary heat and fluids to melt materials from the rear accretionary prism and back-stop lithosphere, which is compatible with the isotopic and geochemical signatures of the Coastal Batholith (Parada, 1990; Parada *et al.*, 1999; Lucassen *et al.*, 2004; Deckart *et al.*, 2014) (Fig. 5). Local occurrences of equivalent forearc magmatic activity along the coast at 28°30-

29°30’S described by Creixell *et al*. (2016) likely indicate that a similar process could have taken place to the north of the study area. Therefore, the igneous-metamorphic rocks of the Coastal Cordillera of southern Central Chile (33°-42°S) could have been formed as a forearc-type paired metamorphic belt, whose spatio-temporal relations indicate an origin associated with a near-trench thermal anomaly (Fig. 5). The short time spanned between the onset of subduction and the forearc magmatism (~20 Myr), and the apparent lack of an arc region to the east, attesting for subduction magnitudes below the critical slab dehydration depth (120± 40 km, Tatsumi, 2005) necessary for fluid flux melting in the mantle wedge, indicate that the ridge would have been located relatively near the Devonian passive margin of southwest Gondwana (Fig 5).

4. Conclusion

A revision of metamorphic rocks and the contemporaneous igneous intrusions along the coast of southern Central Chile challenges the pioneering hypothesis of a subduction-related Miyashiro-type paired metamorphic belt for the origin of this igneous-metamorphic complex. The short-lived intrusion of the Coastal Batholith in the rear area of the partially synchronous accretionary wedge, and geochemical and isotopic data from the igneous rocks indicating substantial participation of sources from the accretionary prism and the back-top lithosphere, are not compatible with typical subduction settings. I suggest that the igneous-metamorphic rocks from the study area formed as a forearc-type paired metamorphic belt. The latter would have resulted from a near-trench thermal anomaly triggered by the subduction of a mid-ocean ridge crest in late Paleozoic times.

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Declarations of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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