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SPECIAL ISSUE: RESEARCH ON THE SOUTH WEST MARGIN OF GONDWANA

Were Phanerozoic (micro)continent-continent collisions frontal or oblique? Possible criteria and the Devonian collision of Chilenia with SW Gondwana as an example

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ABSTRACT. The understanding of ancient continent-continent collisions requires information on the type of accretion (frontal or oblique) of the colliding plates. The shape of the P-T path of a rock, which was metamorphosed during ongoing continent-continent collision, has so far been ignored to obtain this information. However, the consideration of corresponding P-T paths related to Phanerozoic orogens suggests that the shape of the burial path has the potential to distinguish between frontal (60-90° angle between collisional front and plate convergence direction) and oblique (<45°) collisions. In case of an oblique collision, the P-T path is nearly isothermal towards peak-pressure conditions. These conditions should be in the range of 12-20 kbar although somewhat higher pressures cannot be excluded. In this contribution, this finding is applied exemplary to the collision of SW Gondwana with microcontinent Chilenia being part of the Palaeozoic collage of microcontinents in the southern part of South America. However, only a single P-T path of a metasediment (Guarguaraz Complex) in the literature provides the requested information. This path is characterized by nearly isothermal burial reaching peak pressures of ~14 kbar at about 480 °C. Thus, it is suggested that the approach of Chilenia to Gondwana was oblique. The abundance of serpentinite bodies in the Guarguaraz Complex is not in conflict with this suggestion.

Keywords: Continent-continent collision, Chilenia, Gondwana, P-T evolution, Garnet.

RESUMEN. ¿Fueron frontales u oblicuas las colisiones (micro)continente-continente del Fanerozoico? Posibles criterios y la colisión devónica de Chilenia con el suroeste de Gondwana como ejemplo. La comprensión de antiguas colisiones continente-continente requiere información sobre el tipo de acreción (frontal u oblicua) de las placas en colisión. La forma de la trayectoria P-T de rocas metamorfizadas durante la colisión no ha sido considerada previamente para este propósito. Sin embargo, el análisis de trayectorias P-T en orógenos fanerozoicos sugiere que la forma de la trayectoria de enterramiento permite distinguir entre colisiones frontales (ángulo de 60-90° entre el frente de colisión y la dirección de convergencia de las placas) y oblicuas (<45°). En colisiones oblicuas, esta etapa de la trayectoria P-T es casi isotérmica hacia condiciones de presión máxima, típicamente en el rango de 12-20 kbar, aunque no se descartan valores mayores. En esta contribución, este enfoque se aplica a la colisión del suroeste de Gondwana con el microcontinente Chilenia, parte del ensamblaje paleozoico de microcontinentes en el sur de Sudamérica. No obstante, solo una trayectoria P-T publicada para un metasedimento del Complejo Guarguaraz proporciona la información requerida. Esta trayectoria muestra un enterramiento casi isotérmico, que alcanzó presiones máximas de ~14 kbar a ~480 °C. Estos resultados sugieren que la aproximación de Chilenia a Gondwana fue oblicua. La abundancia de cuerpos de serpentinitas en el Complejo Guarguaraz no contradice esta interpretación.

Palabras clave: Colisión continente-continente, Chilenia, Gondwana, Evolución P-T, Granate.

1. Introduction

Continent-continent collisions have taken place on Earth for a long time and led to numerous orogenic belts. As these collisions and belts are the results of drifting continental plates, the reconstructions of these past drifts require reliable criteria, of which data of palaeomagnetic measurements are important ones (*e.g.*, van der Voo, 1990; Dallanave, 2024). Other criteria such as the timing of opening and closure of subducted oceanic plates also provide constraints for these reconstructions (*e.g.*, Stampfli, 2000; Müller *et al.*, 2018). However, the available data are hardly precisely enough to reach palaeogeographic reconstructions, which are sufficiently reliable even for the younger Earth's history of the late Phanerozoic.

The type of continent-continent collision with respect to the convergence of continental plates leading either to frontal (60-90° angle between collisional front and the direction of the convergence of plates) or oblique (<45°) collisions is one of the problems in the plate reconstructions for the Phanerozoic. Usually, these collisions are considered to be frontal ones, but it will be shown later (see Section 2.1) that significantly oblique collisions are also common. Obliquely convergent plate boundaries are typically characterized by orogenic zones, which are bounded by major strike-slip faults oriented (sub)parallel to the plate boundary (Teyssier *et al.*, 1995). In this study, it is worked out what type of P-T trajectory is typical for rocks, which were part of a downgoing crust resulting from oblique continent-continent collision. It will be demonstrated that a nearly isothermal burial path is typical for this kind of collision.

The above finding is applied to SW South America. The question that remained unanswered for this region is how (*i.e.*, frontal or oblique) the various microplates, of which this area is mainly composed (*e.g.*, Ramos, 1988; Dalziel, 1997; Heredia and Folguera, 2025; see also Section 3.1), collided with Gondwana in the Palaeozoic. We refer here to the example of the Devonian collision of microcontinent Chilenia with SW Gondwana trying to answer the question whether this collision was frontal or oblique. Based on the criterion of a nearly isothermal burial path of a metasediment from the Guarguaraz Complex (Massonne and Calderón, 2008), an oblique Chilenia-Gondwana collision is suggested here.

2. Scenarios of Phanerozoic plate collisions including typical P-T paths

2.1. General situation

The Cenozoic collision of the Indian and Eurasian plates is considered to be the most typical continent-continent one that has led to an impressive orogen: the Himalayan ranges (Fig. 1). This orogen resulted from a frontal collision after the Tethys ocean floor between these continental plates was completely subducted. High-pressure (HP: >10 kbar) rocks formed still during this subduction. These rocks are important for the reconstruction of the collisional evolution, which is shown in the sketch of figure 2A. Rocks from the deeply subducted oceanic crust, eclogites and related rock types, were partly exhumed in the deep subduction channel and belong to the oldest rocks of the Cenozoic metamorphism (*ca.* 50 Ma) in the Himalayas (*e.g.*, Massonne and O'Brien, 2003). The corresponding P-T path is shown in figure 2B (yellow line). This path reached ultrahigh-pressure (UHP) conditions (*e.g.*, ≥28 kbar at 700 °C) as documented by relics of the SiO_2 polymorph coesite found in Himalayan eclogite (O'Brien *et al.*, 2001). Another P-T path exhibited in figure 2B (dark orange line) is related to an accretionary wedge system assumed to have formed at the margin of the Eurasian plate, which later collided with India. This path was taken from studies of the Palaeozoic accretionary complexes in Chile (and is addressed in Section 3.2). A third P-T path in figure 2B (cyan line) is related to a representative rock in the upper portion of the downgoing Indian plate that is presently (significantly later than stage III in figure 2A) at the Earth's surface due to tectonic processes. Derived peak pressures for such rocks are between 10 and 14 kbar (see Liu *et al.*, 2007; Iaccarino *et al.*, 2015) at temperatures above 600 °C. Other authors (*e.g.*, Kaneko *et al.*, 2003; Palin *et al.*, 2017), however, assumed a deep burial of the Indian crust to depth of up to 100 km (equivalent to ~30 kbar lithostatic pressure).

A careful look at figure 1 reveals that, besides the Himalayan ranges, additional orogens formed by the India-Eurasia collision that are characterized by the appearance of ophiolite belts with significant proportions of serpentinite bodies (*e.g.*, Ovung *et al.*, 2021). Focusing on the orogen, in which the Burma microplate was involved, the corresponding ranges are most likely related to an oblique continent-continent

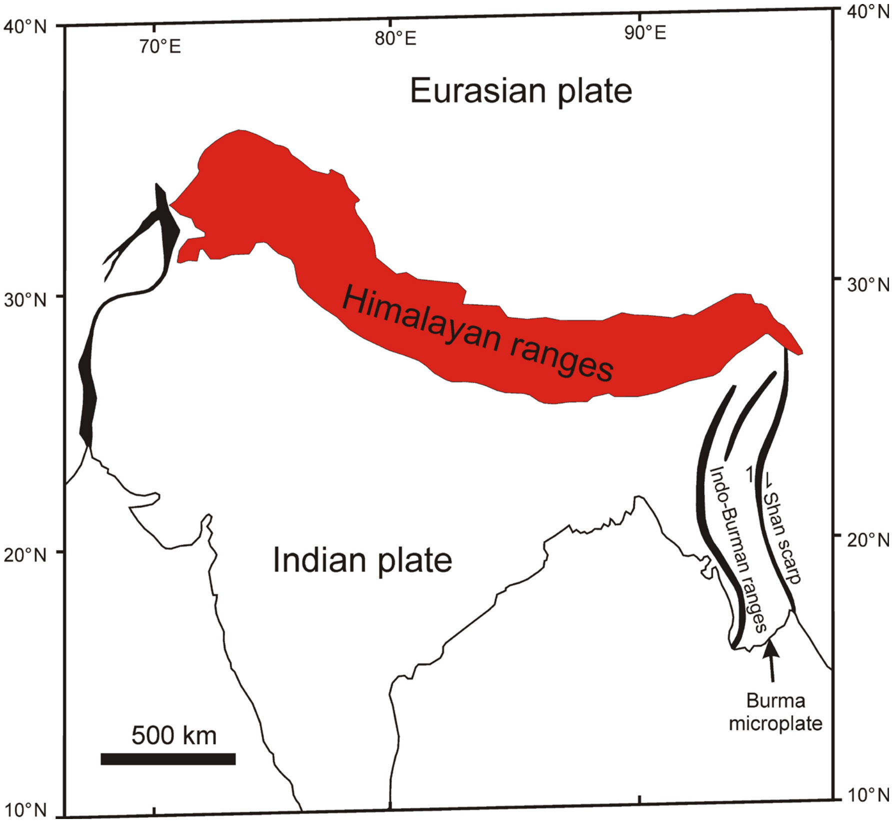

FIG. 1. Geotectonic situation after the collision of the Indian and Eurasian plates modified after Dhital (2015). The Himalayan ranges resulting from this collision are shown in red. "Ophiolites, their klippen, and associated rocks" (Dhital, 2015) are presented in black. Among the black areas is the Shan scarp that is related to the Sagaing Fault, a major strike-slip fault (see the half arrows).

collision also discernible by a major transpressional strike-slip fault system (Rangin *et al.*, 2013; Naing *et al.*, 2023). Among the rocks in Myanmar that are exposed near such a major fault are, for example, HP rocks of the blueschist facies (P-T conditions of 16-19 kbar and 470-540 °C: Nyunt *et al.*, 2017; pressure conditions of 12-17 kbar for jadeitite: Harlow *et al.*, 2015).

2.2. Cenozoic plate collision forming the European Alps

The European Alps might be the best studied orogen on Earth. However, this orogen is complicated (Dal Piaz *et al.*, 2003; Handy *et al.*, 2010), because metamorphic rocks, which are characterized by P-T paths pointing to a frontal collision of microcontinent Adria (upper plate) with the European plate in the late Eocene (*e.g.*, Bonnet *et al.*, 2022), occur only in the Western Alps. In this part of the Alps, rocks with P-T paths similar to the yellow one in figure 2B occur (*e.g.*, Groppo *et al.*, 2019). The same is true for rocks from the upper part of the subducted European plate with P-T conditions similar to the cyan path in figure 2B as derived, for example, by Massonne (2015), and those of the former accretionary wedge (Tricart and Schwartz, 2006; compare with the dark orange path in figure 2B). The Cenozoic evolution of the Eastern Alps including (portions of) the Central Alps is different. The most plausible reason is that NE Adria collided with Europe obliquely (see Dewey *et al.*, 1998). This type of collision leading to continental subduction was considered by Li *et al.* (2023) for the Eocene evolution of the Eastern Alps being compatible with: (1) a narrow ocean between eastern Adria and Europe at the beginning of the Cenozoic (see Agard and Handy, 2021); (2) the occurrence of a

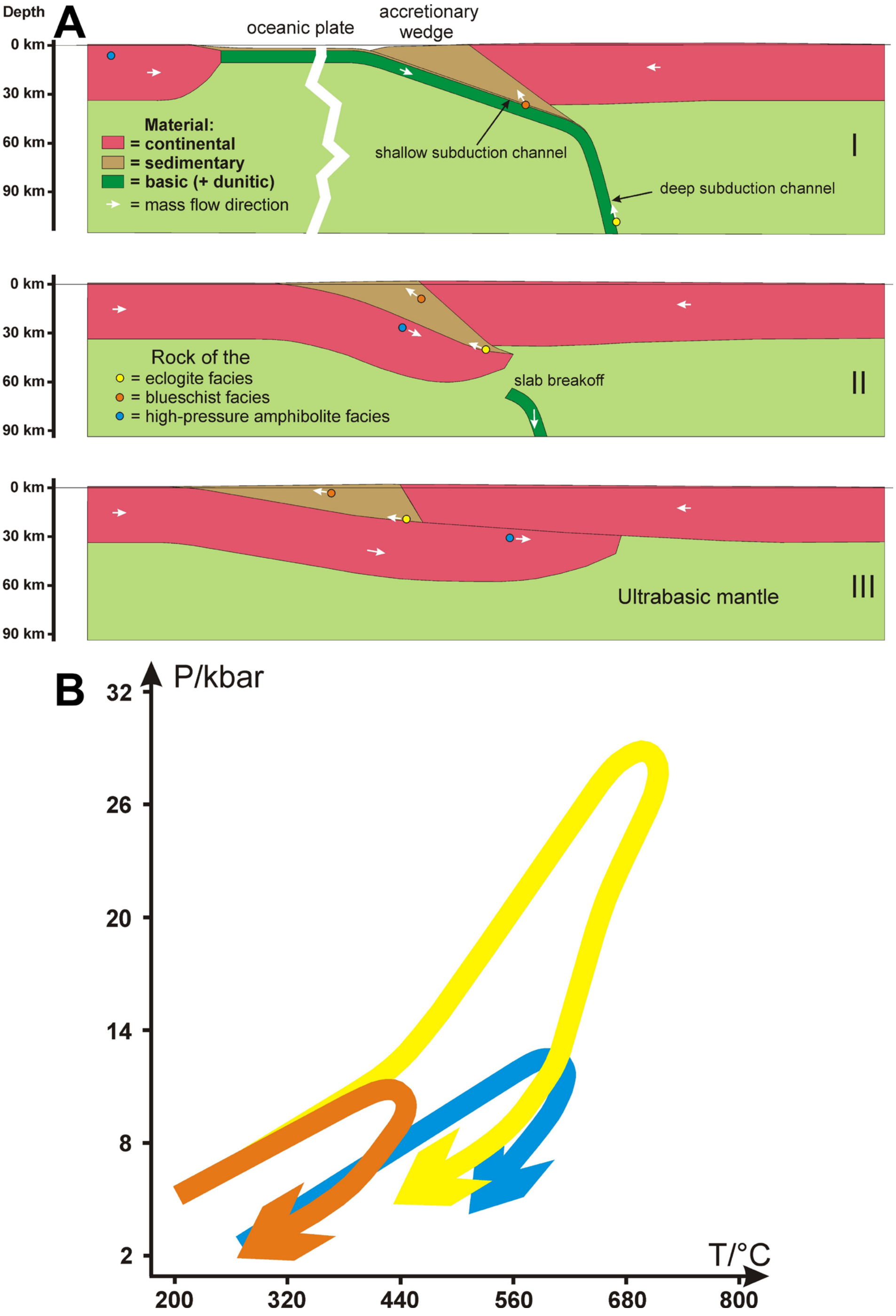

FIG. 2. **A.** Geotectonic scenario of a typical frontal collision of continental plates (stages II and III) that was preceded by subduction of an oceanic plate (stage I) between these continental plates. **B.** Typical P-T paths for the three rock markers in A. The colours of these paths are the same as the related markers. The rock (yellow) that is deeply subducted and exhumed in the deep subduction channel reached very high peak pressures (29 kbar is already in the realm of ultrahigh-pressure metamorphism). The rock (dark orange) that was involved in the accretionary wedge by basal accretion (see the Chilean example in Section 3.2) was metamorphosed at blueschist-facies conditions. The rock (cyan) in the downgoing plate during continent-continent collision, reached similar peak pressures (around 11 kbar), however, at clearly higher temperatures and, thus, at the high-pressure amphibolite facies.

major strike-slip fault system, the Periadriatic Fault System (Handy *et al.*, 2005); and (3) the appearance of ultrabasic bodies close to this fault system (*e.g.*, De Hoog *et al.*, 2009). The corresponding P-T path for the Eocene evolution of a metasediment from the Eastern Alps (Pohorje Mountains; Li *et al.*, 2021), assigned to the European plate, is shown in figure 3 (black path). This path is characterized by nearly isothermal burial to peak-pressure conditions of 20 kbar at about 580 °C.

2.3. Palaeozoic oblique plate collisions in Europe and NE North America

Oblique continent-continent collisions have also been proposed for Palaeozoic orogens in Europe (Kroner *et al.*, 2016; for the Variscan orogen in general: *e.g.*, Franke, 2000) and NE North America (Appalachian orogen in Canada in general: Williams, 1979; van Staal *et al.*, 2009). Both orogens are characterized by the occurrence of major transpressive strike-slip fault systems.

A studied rock in Newfoundland (eclogite; Massonne, 2024a), part of the downgoing margin of Laurentia, crops out close to the Baie Verte Line (Slavinski *et al.*, 2010), which is a major shear zone. Larger serpentinite bodies occur at this shear zone as well. The addressed eclogite was metamorphosed during the Taconic orogeny in the Early to Middle Ordovician (van Staal and Zagorevski, 2020). The burial P-T path of this rock is characterized again by nearly isothermal burial. Peak-pressure conditions were approximately 19 kbar at 570 °C (light grey path in figure 3).

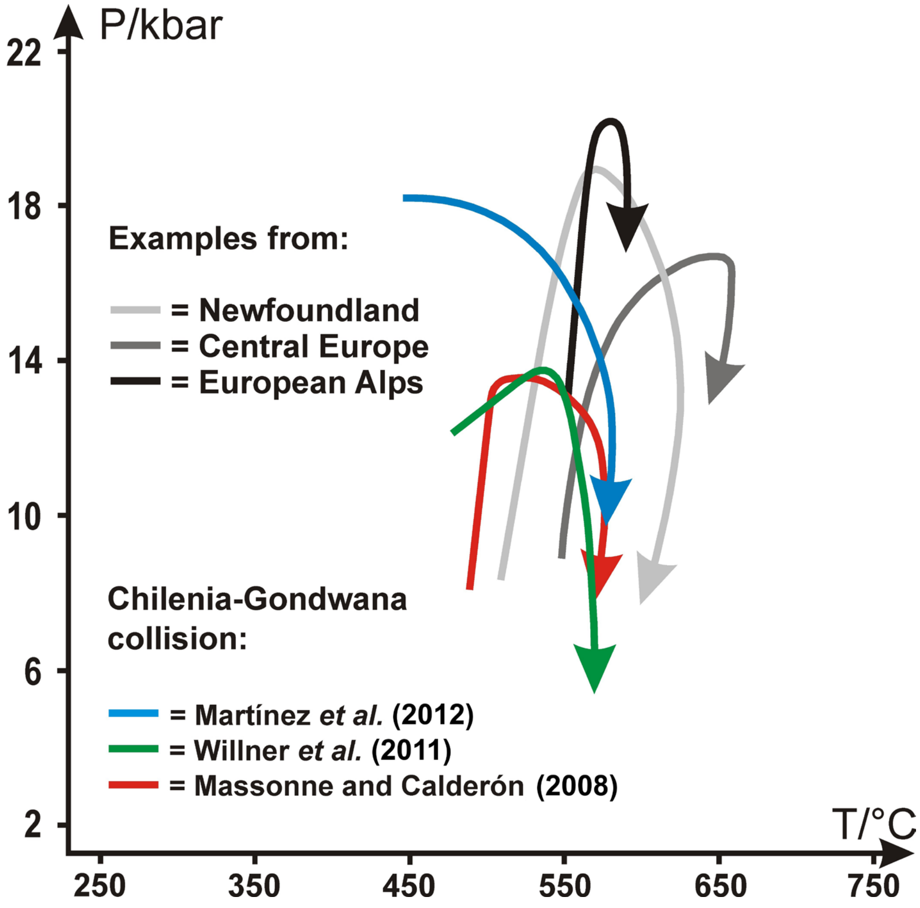

FIG. 3. P-T paths that were derived for various high-pressure (HP) metamorphic rocks (for sources see text). In colour: studied rocks resulting from the collision of Chilenia with SW Gondwana (see Section 3.2). In different grey tones: two paths for Palaeozoic HP metamorphic rocks (see Section 2.3) and one for Cenozoic ones (European Alps, Section 2.2) being examples for oblique continent-continent collisions.

Metamorphic rocks, for which burial paths could be reconstructed, are also very rare in the well-studied Variscan orogen. Two examples are presented. An eclogite from the southern Armorican massif in France was studied by Massonne and Li (2022). This rock occurs in the Les Essarts HP unit of the Vendean zone (Godard, 2001), close to a major fault system. In this unit, ultrabasic and eclogitic rocks form km-sized bodies boudinaged parallel to this system. These rocks experienced HP metamorphism in the Devonian together with the surrounding gneisses (Bosse *et al.*, 2024). The HP metamorphism at peak pressures of 20 kbar was reached at 570 °C by nearly isothermal burial (Massonne and Li, 2022). Another rock, a metasediment that experienced a similar P-T path (grey path in figure 3) with peak-pressure conditions of 17 kbar (Massonne, 2024b), occurs in the Erzgebirge Crystalline Complex (Germany-Czech Republic). The location of this rock in the Gneiss-Eclogite Unit of this complex is, in fact, not very close to ultrabasic bodies and a major strike-slip fault system of the Variscan orogen, but a nearly isothermal burial path was suggested to reach the peak-pressure conditions at 338 Ma. This age is common in the Erzgebirge Crystalline Complex (see Kröner and Willner, 1998; Werner and Lippolt, 2000). The aforementioned peak P-T conditions can also be related to gneiss (Kryl *et al.*, 2021), the typical rock type in the Gneiss-Eclogite Unit, and eclogite bodies therein (Massonne, 2011).

3. Concise overview of the geological setting of Chile-Argentina in the Palaeozoic

3.1. Plate collage

The southern part of South America is a collage of microplates (see figure 4) that were accreted to Gondwana predominantly in Palaeozoic times (Rapalini, 2005). The relative positions of these microplates are broadly accepted (cf. Ramos, 1988; Hervé *et al.*, 2018). The same concerns the timing of the accretion of microplates to the west of the Rio de la Plata Craton. Pampia and Cuyania reached their present positions in Cambrian to Silurian times (*e.g.*, Vujovich *et al.*, 2004; Casquet *et al.*, 2018, 2021). Chilenia followed in the Devonian (Mpodozis and Ramos, 1990; Willner *et al.*, 2011). Nevertheless, the Palaeozoic orogenic evolution of the margin of SW Gondwana is one of the most debated subjects in the southern part of South America, since contrasting palaeotectonic scenarios of (micro) continent-continent collisions have been proposed in the last decades (Marcos *et al.*, 2023, and references therein). For example, the boundaries between these microplates are still under debate (Heredia and Folguera, 2025), mainly because the addressed region is partly covered by Cenozoic and late Mesozoic sedimentary and igneous rocks. More difficult to assess is the original position of these microplates that travelled and were subsequently attached to SW Gondwana. For instance, it was speculated that Cuyania was originally part of Laurentia and separated from Gondwana by a wide ocean (Thomas and Astini, 1996: accretion at ~455 Ma). Another but similar plate constellation with a narrow ocean was envisaged by other researchers (*e.g.*, Dalla Salda *et al.*, 1992).

Another example relates to the accretion of Patagonia and the North Patagonian Massif (for locations see figure 4). This combined microplate collided with an already existing plate collage in Carboniferous to Early Permian times after rifting off another part of Gondwana (Rapalini *et al.*, 2010). However, this part was assigned to different regions of Antarctica by Pankhurst *et al.* (2006) and Ramos and Naipauer (2014). In addition, Pankhurst *et al.* (2006) suggested that Patagonia and a microplate exposed in the North Patagonian Massif drifted separately and, thus, collided at different times with the supercontinent. Again, other views of the collisional situation appeared in the literature (*e.g.*, Gregori *et al.*, 2008, 2013).

Moreover, the assessment of the microplate configurations in southern South America at various times is impeded by additional factors. A major one is related to multiple collisional events, which can have affected the accreted microplates and their suture zones (*e.g.*, Serra-Varela *et al.*, 2022; Bianchi *et al.*, 2024).

3.2. Chilenia

Chilenia is part of the collage of microplates mentioned above (Fig. 4). Although some authors consider this microplate as hypothetical (*e.g.*, Dahlquist *et al.*, 2025), there are many arguments in the literature that suggest the existence of Chilenia (*e.g.*, Willner *et al.*, 2025). However, this microplate is almost not exposed, so its limits are

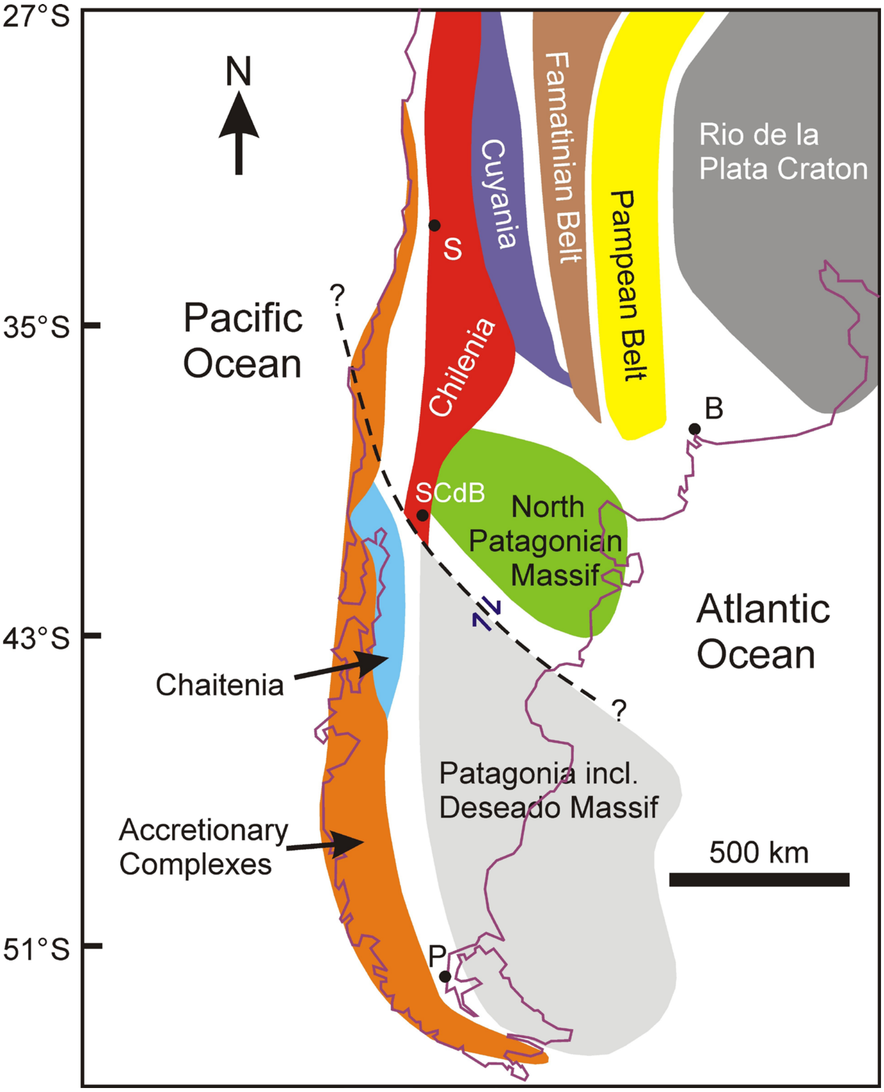

FIG. 4. Geotectonic structure of the southern part of South America mainly in terms of accreted microplates (modified after Hervé *et al.,* 2018). Differing from the original, the area of Chilenia could have been extended to the south as argued in the text. The strike-slip fault (broken line) is purely speculative concerning position and movement in the Late Devonian-early Carboniferous. Black dots mark towns (**B**: Bahía Blanca, **P**: Punta Arenas, **SCdB**: San Carlos de Bariloche) and the city of Santiago de Chile (S).

broadly uncertain (see below). As this microplate is subject of our considerations, studies related to it are reviewed here in more detail.

Outcrops of the boundary region between Chilenia and Cuyania occur between latitudes 29-34° S. Metasediments and metabasites, which experienced relatively high peak pressures, and ultrabasic rocks such as serpentinites are typical for this boundary region (Boedo *et al.*, 2021). Peak pressures of 7.0-9.3 kbar at temperatures around 370 °C were reported for metasediments and metabasites exposed between 32.1° and 32.2° S (Peñasco Formation; Boedo *et al.*, 2016). The Guarguaraz Complex (Gregori and Bjerg, 1997; López and Gregori, 2004) in the Argentine Frontal Cordillera at around 33.4° S (same latitude as that of Santiago de Chile) is another outcropping boundary region. This complex is composed of metasediments, metamorphosed sills of basic rocks, and serpentinite bodies. The occurrence of basic and ultrabasic rocks and their geochemical signatures let López de Azarevich *et al.* (2009) to interpret them as part of Ordovician ophiolites (see also Davis *et al.*, 1999). The medium-grade metasediments have a HP signature with peak-pressure conditions around 14 kbar at temperatures between 500 and 550 °C (red and green paths in figure 3; Massonne and Calderón, 2008; Willner *et al.*, 2011) resulting from the Chilenia-Gondwana collisional event. This event in the Guarguaraz Complex was dated by Lu-Hf mineral isochrons (garnet-hornblende in two amphibolites or garnet-white mica in a metapelite, two grain size fractions of one mineral and the whole rock) at 390±2 Ma; a $^{40}Ar/^{39}Ar$ plateau age (step heating of single, large phengite grains) of 353±1 Ma was additionally obtained (Willner *et al.*, 2011).

Similar Early-Mid Devonian zircon ages were also determined for rocks at latitude 40° S (north of San Carlos de Bariloche) by Varela *et al.* (2005). HP medium-grade metasediments that experienced peak-pressure conditions of 18 kbar were reported to occur at latitude 41.2° S (Colohuincul Complex), some km southwest of San Carlos de Bariloche (light blue path in figure 3; Martínez *et al.*, 2012). Th-U-Pb dating of monazite in these metasediments yielded ages of 391.7±4.0 and 350.4±5.8 Ma (Martínez *et al.*, 2012). Because of the coincidence of HP medium-grade metamorphism and late Palaeozoic ages of the metasediments at the Guarguaraz and Colohuincul complexes, the Chilenia-Gondwana collision was also assigned to metamorphic rocks close to San Carlos de Bariloche (Martínez *et al.*, 2012). However, Oriolo *et al.* (2019) proposed peak metamorphic conditions of about 650 °C and 11 kbar at ~300 Ma (in situ Th-U-Pb monazite dating) for an area west of San Carlos de Bariloche.

Several Devonian calcalkaline plutons occur to the south of 33° S in the Frontal Cordillera, which were considered as part of a magmatic arc (Dahlquist *et al.*, 2022). Devonian ages (U-Pb zircon, 384±3 and 383±2 Ma) were also reported from igneous rocks north of Chaitén (at latitudes 42.0° and 42.75° S) by Hervé *et al.* (2016). These authors interpreted their results as evidence for the existence of a Devonian island arc chain that was located close to Patagonia and attached to this microcontinent later (Hervé *et al.*, 2018). This island arc was called Chaitenia (Fig. 4). In fact, a relation to Chilenia was not regarded by Hervé *et al.* (2016, 2018), but it will be discussed in this study. At least, Plissart *et al.* (2026) considered Chaitenia as a back-arc system, the opening of which was linked to the Chilenia collision. Rocks formed by a Devonian magmatism were also proved to occur at the south-western margin of the North Patagonian Massif (Rapela *et al.*, 2021).

West of Chilenia, no further continental plate was accreted, but the subduction of oceanic crust at least since the Carboniferous (*e.g.*, Willner *et al.*, 2005; Muñoz-Montecinos *et al.*, 2024) has led to accretionary wedges (Hervé, 1988). The ages of the exposed accretionary complexes (see figure 4) are still late Palaeozoic at latitudes 38-43° S (*e.g.*, Willner *et al.*, 2005; Hervé *et al.*, 2013). The dominant rock types in these fossil accretionary wedges are metamorphosed immature clastic sedimentary rocks, but basic rocks and relatively large km-sized slices of ultrabasic rocks (serpentinites) also occur (*e.g.*, Plissart *et al.*, 2019). Studies of these wedges in Chile have contributed to the understanding of their formation in general (*e.g.*, Richter *et al.*, 2007; Massonne and Willner, 2008). During a late evolution of an already thick accretionary wedge, basal accretion of various materials occurs, which are mainly foredeep sediments. Such rocks travel on top of the downgoing oceanic plate, being involved in the shallow subduction channel, and likely experience P-T conditions along a geotherm towards the peak conditions. These peak conditions are those of the blueschist facies (*e.g.*, Willner *et al.*, 2000; see also figure 2). It seems to be typical that the subducted rocks, which experienced the highest peak pressures (11-16 kbar), underwent a counter-clockwise P-T path in the Carboniferous accretionary complexes of Chile (Willner *et al.*, 2004; Hyppolito *et al.*, 2014; Plissart *et al.*, 2026). A Carboniferous magmatic arc related to the subduction below Chilenia occurs in the Chilean Coastal Cordillera (Deckart *et al.*, 2014; Maksaev *et al.*, 2014); however, this arc might be displaced to the east by more than 100 km to occur south of 38° S on the Argentine side of the Andes (Yoya *et al.*, 2023).

4. Discussion

4.1. General remarks

The frontal collision of India and Eurasia has formed a major orogen on Earth, but this collision was also accompanied by oblique continent-continent collisions

(Section 2.1). Also, the Cenozoic formation of the European Alps was caused by the frontal (Western Alps) and oblique (Eastern Alps) collision of Adria with the European plate (Section 2.2). Thus, oblique continent-continent collisions must be common.

In Section 2, it was pointed out that such oblique collisions result in specific characteristics; among them is the part of the P-T path of a metamorphic rock that indicates nearly isothermal burial. A geodynamic model is presented in figure 5 that should explain what could cause this characteristic. The oblique approach of continental plates that are separated by a narrow oceanic basin (<500 km width), in fact, results in subduction of the (proto)oceanic crust but not in the evolution of a deep subduction channel, in which deeply subducted eclogite and related rocks are exhumed (Fig. 2A, yellow marker). It is assumed here that the subduction of an oceanic basin with a minimum width of 1,000 km can generate a corresponding channel flow. Consequently, UHP eclogites occur only in specific Phanerozoic orogens (here: Himalayan ranges, Western Alps; for other ones see, *e.g.*, Gilotti, 2013), the formation of which was preceded by the subduction of an oceanic basin with sufficient width (>1,000 km). Orogens formed by oblique collision commonly lack UHP rocks. An exception is the above addressed Erzgebirge Crystalline Complex (Section 2.3), where UHP rocks such as eclogite (Massonne, 2013) occur in the Gneiss-Eclogite Unit. However, these rocks were generated by UHP-HP crystallization of melts, which formed in the mantle after delamination of crustal material (see Massonne, 2023, and references therein).

After subduction of the (proto)oceanic crust during early oblique collision, continental crust follows by a continental subduction process (Fig. 5, stage II) resulting in a steeply dipping subduction zone. For Cenozoic orogens, such a zone might still be discernible by a nearly vertically dipping high-velocity anomaly in the mantle as it was found beneath the Eastern Alps (Paffrath *et al.*, 2021). Because of buoyancy forces, the continental crust (except some delaminated portions) should reach a maximum depth of 70 km (20 kbar lithostatic pressure), which was estimated according to the above considerations (see the P-T paths in figure 3).

It is important to discuss this maximum depth, because another process also leads to a P-T path characterized by nearly isothermal burial to great depths (>70 km) in Phanerozoic subduction zones. This process, called tectonic erosion, brings material from the upper continental plate into the subduction zone (Massonne and Li, 2020) as long as the collision of continental and oceanic plates is ongoing. For example, eclogite bodies occur in gneiss of the Malpica-Tuy zone as a result of the Variscan continent-continent collision in northwestern Spain. Such a body experienced a nearly isothermal burial path with peak-pressure conditions of 24 kbar at 630 °C (Li *et al.*, 2017). This path was interpreted as burial in a subduction zone after tectonic erosion and before continent-continent collision (Massonne and Li, 2020). However, the Malpica-Tuy zone is a major strike-slip structure (Díez Fernández and Martínez Catalán, 2012), so that it could be argued that eventually oblique collision of continental plates played a role. In any case, an uncertainty range must be considered for the estimation of both the upper pressure (20 kbar) and lower pressure (suggested as 12 kbar) limits for continental rocks involved in continental subduction.

The aforementioned steeply dipping subduction of continental material in case of an oblique continent-continent collision (Fig. 5) rapidly brings this material to great depths and, thus, results in burial paths that are characterized by a clear pressure increase at only slightly rising temperature (Fig. 3). On the contrary, the beginning of (shallow) subduction of continental material on top of the oceanic crust or in the tip of the downgoing continental plate leads to both rising pressure and temperature, resulting in P-T paths approximately following geotherms (see figure 2B).

Melting of the most deeply subducted continental crust can occur at the highest pressures reached or during the early uplift of corresponding HP rocks (stage III of figure 5) formed in the environment of an oblique continent-continent collision. This is implied by Eocene to Miocene plutons at the Periadriatic Fault System (see Section 2.2) along the Eastern and Central Alps (*e.g.*, Ji *et al.*, 2019). The melts of these plutons are of intermediate to acidic calcalkaline character (dominantly tonalitic-granodioritic) and are, thus, geochemically similar to plutons in magmatic arcs, which are also generated by melting of mantle and continental crust (*e.g.*, von Blanckenburg *et al.*, 1992; Pamić and Palinkaš, 2000; Bonin, 2004). The uplift process of the addressed HP rocks can tectonically move them away from the transpressional fault system (see Dewey *et al.*, 1998) and re-arrange them in a

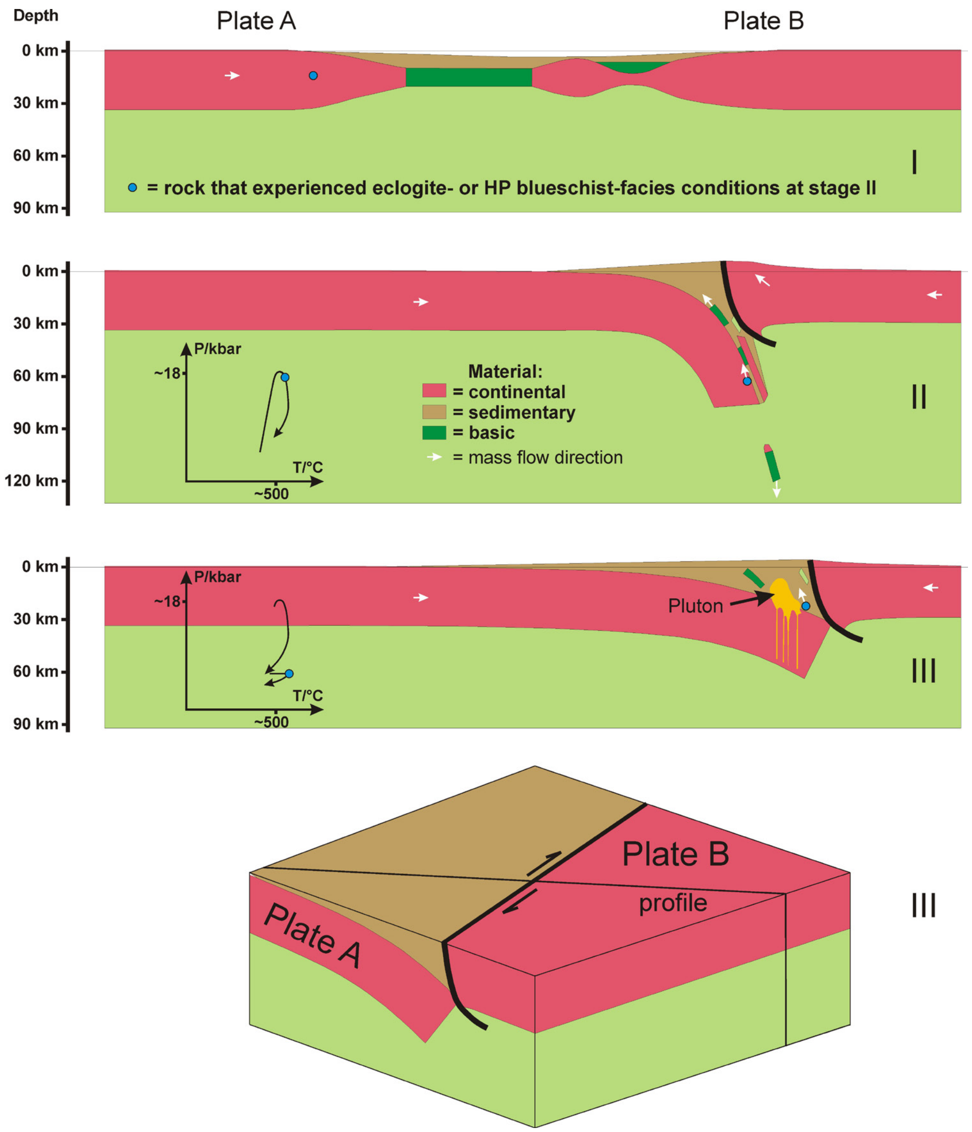

FIG. 5. Geotectonic scenario of an oblique continent-continent collision modified after Li *et al.* (2023). A small oceanic basin or proto-oceanic crust develops in an extensional tectonic regime to its maximum width at stage I. Afterwards, this basin is closed by obliquely approaching continental plates A and B. This process culminates in the generation of a major transpressional strike-slip fault system (thick black line in the profiles and block diagram) and steep subduction of Plate A (called here continental subduction). The other plate is rather obducting simultaneously. Continental subduction (stage II) is followed by the ascent of continental material but further subduction of basic (+mantle) eclogitized material. A relevant P-T path for the subducted continental material (cyan marker) is shown on the left-hand side. The rock presented by the cyan marker experiences contact metamorphism (stage III, which refers to the block diagram as well) at relatively low pressures as it is located close to a pluton (see P-T path). This pluton is fed by intermediate to acidic melts generated at deep levels of the subducted continental crust probably also influenced by mantle fluids.

nappe pile, which is, for example, obvious in the Erzgebirge Crystalline Complex and its surroundings (*e.g.*, Hallas *et al.*, 2021). However, the alignment of calcalkaline plutons commonly occurs at the suture (major strike-slip fault) of obliquely collided continental plates, whereas these other plutons are arranged in a zone (magmatic arc) with a considerable distance to the collision front at frontal collision.

Ultrabasic (serpentinized) rocks can occur in various geotectonic environments of continent-

continent collisions. It was pointed out above that (hydrated) mantle rocks were found in accretionary wedges as well as in suture zones of obliquely collided continental plates. The type of mantle rock being involved in the accretionary wedge is always a plagioclase- or spinel-bearing lherzolite (or harzburgite, dunite), whereas garnet peridotite can: (1) become part of the deep subduction channel with its upwards-directed mass flow (Fig. 2A), and (2) be included in continental subduction with buoyancy-driven uplift of predominant felsic rocks (Fig. 5). Thus, the occurrence of mantle rocks, which contain either primary spinel or garnet, in suture zones is not diagnostic for frontal or oblique continent-continent collisions.

4.2. Application to the Chilenia-Gondwana collision

Using the above findings and the three P-T paths in figure 3 for metasediments of the collisional belt formed by the Chilenia-Gondwana collision, it can be suggested that this collision was oblique. This statement can be hold despite only one (Guarguaraz Complex: Massonne and Calderón, 2008) of the three paths shows a nearly isothermal burial part, whereas the other two start very close to the peak pressure. This is compatible with the general observation that the early metamorphic evolution is usually erased in rocks. The reason for that is the complete reaction of early formed metamorphic minerals unless they are preserved as inclusions in minerals of the peak metamorphism. Among these peak metamorphic minerals, garnet predominates generally. In the rock studied by Massonne and Calderón (2008), an early garnet formed at relatively low pressures (8 kbar; see figure 3) and was preserved in further growing garnet of the peak-pressure metamorphism. In principle, other minerals can also be preserved in garnet and contribute to the understanding of the early metamorphic evolution. As we broadly have to rely on garnet as container to preserve early formed minerals, it must be considered that this mineral suffers from overstepping its stability field during prograde metamorphic evolution (Castro and Spear, 2017; Spear, 2017). The consequence is that a late formation of garnet in a metamorphic rock can prevent the important preservation of early formed minerals. Then, one cannot recognize whether the prograde path towards peak-pressure conditions is characterized by a nearly isothermal pressure increase or a P-T evolution approximately along an isotherm as the cyan and dark orange paths in figure 2B.

Before finally judging if a continent-continent collision was frontal or oblique, other criteria should be considered. In case of the Devonian Chilenia-Gondwana collision, it can be noted that ultrabasic bodies are related to the HP metasediments (Boedo *et al.*, 2021, and references therein). However, a metasediment-serpentinite relation is not diagnostic for frontal or oblique continent-continent collisions as pointed out in the previous section.

The geotectonic position of plutons composed predominantly of calcalkaline tonalite to granodiorite is another point as also outlined in the previous section. The Devonian calcalkaline plutons in the Frontal Cordillera (Section 3.2) might follow the Chilenia-Gondwana suture, although they were considered as magmatic arc by Dahlquist *et al.* (2022). In context with the unknown extension of Chilenia south of 39° S, the interpretation of the Devonian plutons of Chaitenia (Hervé *et al.*, 2018) should be also reconsidered. In fact, they were also interpreted as part of a magmatic arc, but they could instead mark the suture of an oblique collision with involvement of, for example, a southern part of Chilenia. This would, however, require a displacement of the alignment of the Devonian plutons in the 39-41° S latitude range (see the speculative strike-slip fault in figure 4). Metamorphic rocks in the San Carlos de Bariloche area point to a collisional event in the Devonian (Martínez *et al.*, 2012). The question is whether the medium-grade HP metasediments (Martínez *et al.*, 2012; Oriolo *et al.*, 2019) there can be, indeed, related to a collision of Chilenia and Gondwana. Oriolo *et al.* (2019) determined monazite ages at about 300 Ma for these rocks, which seem to exclude that these HP rocks formed by the Chilenia collision. However, monazite ages rather indicate the youngest orogenic events (*e.g.*, Li *et al.*, 2025). Thus, the aforementioned multiple collisional events in the accretion of microplates in the southern part of South America could have obscured a Devonian age for the addressed HP rocks.

The reason for the oblique collision of Chilenia with Gondwana could be the northward movement (relative to the present geographical orientation) of North America (Laurentia) with respect to South America (Gondwana) in the Palaeozoic. The corresponding plates were probably never separated by a wide ocean in this period but rather by small oceanic basins. An oblique continent-continent collision occurred when such a basin was closed. Afterwards, a new basin opened leaving a microcontinent (including Pampia and Cuyania: *e.g.*, Martin *et al.*, 2020) attached to Gondwana behind during the northward movement of Laurentia. Such a scenario would be consistent with previous ideas by Dalla Salda *et al.* (1992), Dalziel (1997), and others suggesting that the collisions of Pampia and Cuyania with Gondwana in the early Palaeozoic were oblique as well. An indication could be that these collisions did not lead to HP rocks with peak pressures of more than 20 kbar (*e.g.*, Willner *et al.*, 2023) and eclogite bodies as typical for frontal continent-continent collisions (see Section 2.1), but a detailed scrutiny of the literature in regard to the metamorphic evolution of rocks at the boundaries of Pampia and Cuyania and their geotectonic setting is outside the scope of this study. Laurentia moved so far northwards in the Carboniferous that a frontal oceanic-continental collision became possible leading to the formation of the Chilean accretionary wedges.

5. Conclusions

The following conclusions result from this study: 1) Oblique continent-continent collisions in the Phanerozoic are more common than usually thought. 2) This type of collision can be recognized by a P-T path that shows an early metamorphic evolution characterized by nearly isothermal burial and peak pressures in the range of approximately 12 to 20 kbar. 3) The occurrence of ultrabasic (serpentinized) rocks in the range of suture zones of obliquely collided continental plates are common. Excellent examples are the ophiolite-rich orogens related to the India-Eurasia collision, such as the Indo-Burman ranges. However, ultrabasic rocks can be also involved in an accretionary wedge or the type of extrusion wedge, which contains deeply subducted crustal material and hydrated mantle (see, *e.g.*, Ernst, 2005), as a result of frontal collision. 4) The formation of a chain of calcalkaline plutonic bodies is not typical of frontal or oblique continent-continent collisions. However, the positions of such chains are different because the one at the suture zone points to oblique collisions, whereas those 100-300 km (magmatic arc) from this suture (trench during oceanic and continental plate collision) characterize frontal collisions. Moreover, the chain of calcalkaline plutons forms just after continental subduction, whereas the magmatic arc develops already before a frontal continent-continent collision. 5) The collision of Chilenia with SW Gondwana was probably oblique. 6) There is a certain probability that Chilenia extends to 40.5° S. A further extension to the south after a speculative displacement to the west in the late Devonian - early Carboniferous cannot be ruled out.

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