The geodynamic evolution of the Gondwana–Laurasia boundary in Triassic times

Constraints from the tectono-magmatic cycles of the Southern Alps

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INTRODUCTION

The Triassic geodynamic evolution at the Gondwana–Laurasia boundary in the area now corresponding to the Southern Alps has been a subject of debate in the last five decades. The Southern Alps (Fig. 1), located at the northern margin of the Adriatic Plate, was marked by the development of carbonate platforms and basins and widespread magmatic activity during the Triassic (e.g., Gianolla et al., 1998; Lustrino et al., 2019). The Triassic magmatism in the Southern Alps, largely studied in detail in the eastern sector (e.g., Dolomites, Vicentinian Alps, Julian Alps, etc.), occurred in two major cycles. The first cycle, from the Middle to early Late Triassic (~243-235 Ma), was characterized by the emplacement of volcanics and intrusions of high-K calc-alkaline to shoshonitic geochemical signatures (Bonadiman et al., 1994; Lustrino et al., 2019; Storck et al., 2019; De Min et al., 2020; Casetta et al., 2021). This was followed, in the Late Triassic to Early Jurassic (~230-190 Ma) by a magmatic cycle with geochemical affinities varying from alkaline to transitional and tholeiitic (Cassinis et al., 2008; Casetta et al., 2019; De Min et al., 2020). In the central (i.e., Brescian PreAlps) and western (i.e., Ivrea-Verbano Zone, IVZ) sectors of the Southern Alps, many details and datasets on the Triassic magmatic events are however unavailable (Cassinis et al., 2008; Stähle et al., 1990, 2001; Mazzucchelli et al., 2010; Schaltegger et al., 2015; Galli et al., 2019; Bonazzi et al., 2020; Giovanardi et al., 2020). Due to this situation and the widespread hydrothermal alteration of outcrops, substantive correlation of the magmatic events that occurred in the different sectors of the Southern Alps (at the Gondwana–Laurasia boundary) during the Triassic is currently lacking. The relation of these magmatic events of the Southern Alps to the geodynamic environment during the Triassic is also complicated and strongly debated, particularly with respect to the Middle Triassic magmatism exhibiting high-K calc-alkaline to shoshonitic affinity in contrast to the extensional to transcurrent tectonics (Doglioni, 1987; Bonadiman et al., 1994; Gianolla et al., 1998) which was prevalent during this time.

Hence, to provide further constraints on the geodynamic evolution of the Gondwana–Laurasia boundary in Triassic times prior to the breakup of the Pangea, this thesis documents the results of detailed petrological, geochemical and isotopic studies on the Triassic–Early Jurassic magmatic events which occurred in the Southern Alps, particularly in the westernmost (IVZ) and eastern (Dolomites) sectors (Fig. 1). The orogenic mantle massifs exposed in the IVZ were also studied to provide first-hand constraints on the nature and evolution of the possible mantle sources of the Triassic magmatism in this area.

Research objectives

The objectives of the research included:

1) Comparison of the tectono-magmatic evolution of the westernmost Southern Alps (Ivrea-Verbano Zone) with respect to the eastern (Dolomites) and central (Brescian PreAlps) sectors.

2) Detailed characterization of the poorly-studied Late Triassic tectono-magmatic events of the Southern Alps. In this frame, invaluable constraints were provided by the investigation of the deep intrusions in the Ivrea-Verbano Zone.

3) Provide new geochronological and isotopic constraints (U-Pb, Lu-Hf, Sm-Nd, Rb-Sr, Pb-Pb) on the Southern Alps tectono-magmatic events.

4) Determine the origin and nature of crustal components in uprising mantle melts in the Southern Alps.

5) Unravel the nature, heterogeneity, and evolution of the subcontinental lithospheric mantle beneath the Southern Alps. In this case, the study of the Ivrea-Verbano Zone mantle peridotites also provided unique insights.

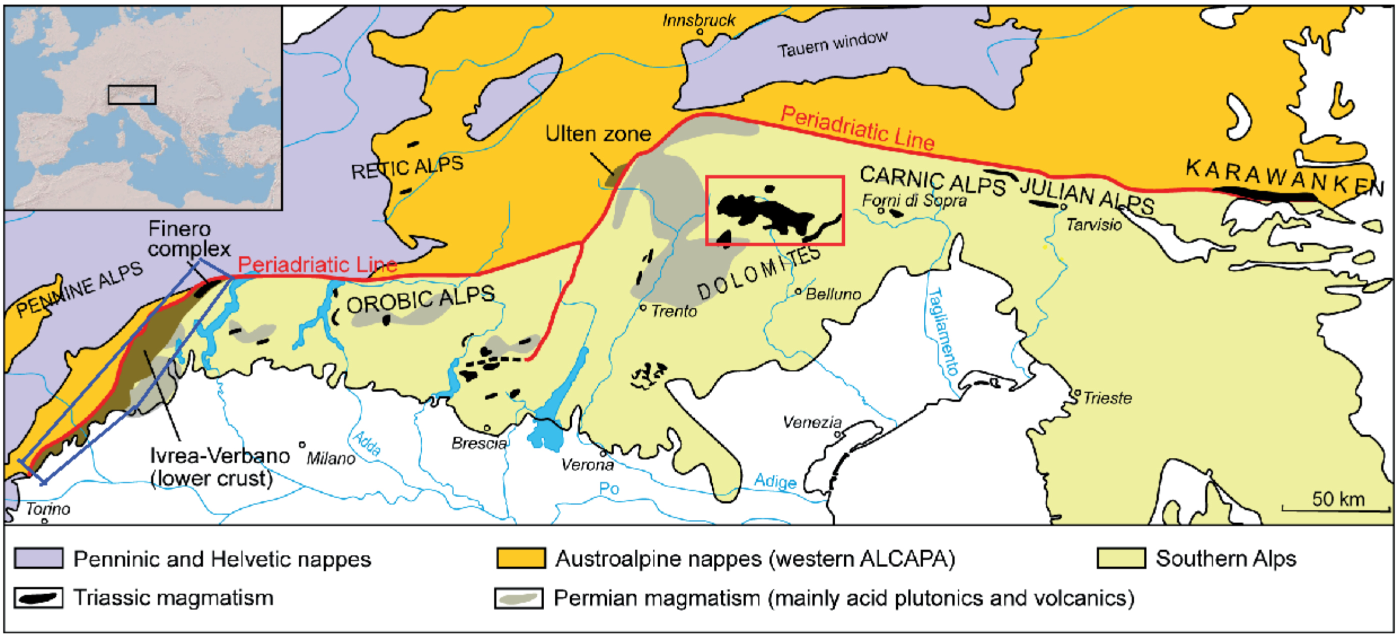

Figure 1 *Generalized geological map of the Southern Alps (modified after De Min et al., 2020) showing the locations of the Ivrea-Verbano Zone (marked in blue) and the Dolomites (marked in red), focus of the present research.*

SAMPLE SUITES, PETROGRAPHY AND ANALYTICAL METHODS

From the northern part of the Ivrea-Verbano Zone, western Southern Alps (Fig. 2), swarms of dykes of presumably Triassic to Early Jurassic ages, which intruded into the Finero Phlogopite Peridotite (FPP) massif, were sampled. These dykes range in composition from diorite to anorthosite, gabbro, and hornblendite, and sometimes contain cumulates of peridotite and clinopyroxenite. Detailed petrographic, mineral chemical, U-Pb zircon geochronology and Sr-Nd-Hf-Pb isotopic investigations were performed on these samples. Samples of the phlogopite-bearing harzburgite and websterite lithologies of the FPP were also collected and studied for their mineral and Sr-Nd-Hf-Pb isotopic composition.

In the central to southern parts of IVZ, lherzolitic massifs outcrop in Premosello, Balmuccia and Baldissero (Fig. 2). Samples of spinel-lherzolites, Cr-diopside pyroxenites and websterites were collected from these three massifs for mineral chemical and Nd-Hf isotopic studies.

The Dolomites in the eastern sector of the Southern Alps preserve abundant volcano-sedimentary sequences and plutonic complexes largely formed during the Middle Triassic (Fig. 1). Basaltic lavas and dykes from these Middle Triassic sequences were sampled. The samples were analyzed for their whole-rock, mineral chemical and Sr-Nd-Hf-Pb isotopic composition.

Geochemical, geochronological and isotopic characterizations of sampled rocks were largely focused on the analysis of mineral phases after detailed petrography in order to overcome the limitation imposed by the high degree of alteration of Triassic outcrops in the Southern Alps. The analysis of different generations of minerals and the systematic core-to-rim analysis also provided the opportunity for unraveling and tracing geochemical changes recorded by the studied rocks.

RESULTS AND DISCUSSION

Transition from orogenic-like to anorogenic magmatism in the Ivrea-Verbano Zone, western Southern Alps

The Ivrea-Verbano Zone (Fig. 2) is an iconic upper mantle to lower continental crust sequence of the Adriatic Plate and represents a unique opportunity to investigate the tectono-magmatic events that occurred at the Gondwana–Laurussia boundary from Late Paleozoic to Early Mesozoic. New geochemical, U-Pb zircon geochronology and Sr-Nd-Hf-Pb isotopic data documented for alkali-rich dyke swarms which intruded the Finero Phlogopite Peridotite (northern IVZ) provide geological constraints on the nature, origin and evolution of Triassic-Early Jurassic magmatism in the Southern Alps. The studied dykes are amphibole- and phlogopite-bearing and show geochemical features varying between two end-member groups (Fig. 3a-b). A dyke group is characterized by HFSE-poor, Al-rich amphibole (Al_2O_3 up to 16 wt.%) with high LILE and LREE contents, high radiogenic $^{87}Sr/^{86}Sr_{(i)}$ (0.704732 to 0.704934) and low radiogenic Nd isotopes ($\varepsilon Nd_{(i)}$ from –0.1 to –0.7) (Fig. 3). The composition of this dyke group points to an "orogenic-like" affinity, and is very similar to the composition of Middle Triassic lavas from the Dolomites (Fig. 3b; Lustrino et al., 2019; De Min et al., 2020; Casetta et al., 2021) suggesting that dykes of this group (which are all zircon-free) may be of Middle Triassic age. The mineralogy, trace elements and Sr-Nd-Hf-Pb isotopic composition of these dykes suggest segregation from evolved mantle melts containing significant amounts of recycled continental crust components. This dyke group was interpreted to have been largely derived from metasomatized lithospheric mantle sources.

The second group is HFSE-rich with Al-poorer amphibole enriched in LILE and LREE, low radiogenic $^{87}Sr/^{86}Sr_{(i)}$ (0.703761–0.704103) and higher radiogenic Nd isotopes ($\varepsilon Nd_{(i)}$ from +3.4 to +5.4) pointing to an "anorogenic" alkaline affinity and asthenospheric to deep lithospheric mantle sources (Fig. 3a-b). Zircons from dykes of this group show concordant $^{206}Pb/^{238}U$ ages varying from 216 ± 9 Ma to 191 ± 10 Ma (Late Triassic-Early Jurassic). The highly variable $\varepsilon Hf_{(i)}$ values (+15.4 to -0.4) measured in situ on zircons from these dykes point to the heterogeneous, variably depleted nature of their asthenospheric to deep lithospheric mantle sources.

Further evidence that the orogenic-like magmatism in the IVZ predates the alkaline anorogenic magmatism is provided by some dykes which show both orogenic-like and anorogenic affinities. Amphibole in the central part of dykes belonging to this group is enriched in HFSE and grades to HFSE-poor composition towards the margins, suggesting that an HFSE-poor dyke was intruded and overprinted by HFSE-rich melt(s).

The results of this study confirm a geochemical change of the Triassic-Early Jurassic magmatism of the IVZ from orogenic-like magmatism, typical of post-collisional settings, to anorogenic alkaline magmatism, common in intraplate to extensional settings, and places a temporal correlation of Early Mesozoic magmatism in the IVZ to those in the eastern and central sectors of the Southern Alps (see Ogunyele et al., 2024a; Bonazzi et al., 2024).

Shoshonitic orogenic-like magmatism in the Dolomites and correlation to IVZ magmatism

The new collection of basaltic lavas and dykes from the Dolomites (eastern Southern Alps) show shoshonitic orogenic-like affinity characterized by depleted HFSE (Nb-Ta-Ti), and enriched Pb, LILE and LREE compositions coupled with enriched "crust-like" Sr-Nd isotopes, typical of Middle Triassic magmatism in the area (Fig. 3b). Combined with whole-rock Hf (first-ever dataset) and Pb isotopes, the composition of the studied lavas and dykes indicate a close similarity to the IVZ HFSE-poor dykes with "orogenic-like" affinity. The new Hf ($\varepsilon Hf_{(i)}$: +3.8 to –2.8) and Pb (EM-II like) isotopic composition of the Dolomitic lavas and dykes, in combination with the geochemical composition of the IVZ HFSE-poor dykes further support the derivation of the Southern Alps Middle Triassic orogenic-like magmatism from heterogeneous, metasomatized lithospheric mantle sources containing large amounts of recycled continental (and possibly oceanic) crust materials. Interrelation between whole-rock trace elements and isotopic ratios further confirms

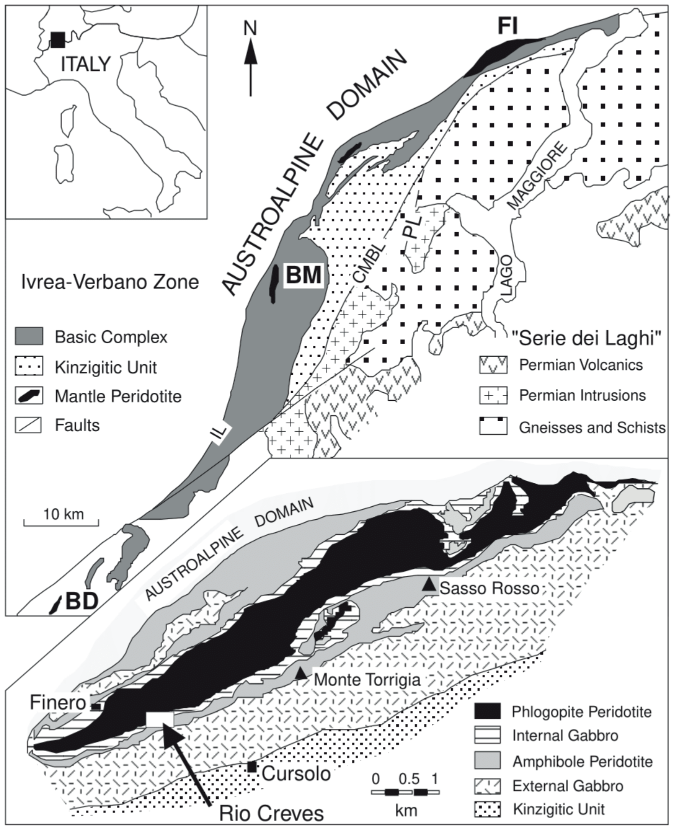

*Figure 2 Geological maps of the **a)** Ivrea-Verbano Zone and **b)** the Finero Complex (indicated as FI in **a)** where the studied dykes and phlogopite-peridotite massif were sampled. The location of the three lherzolitic massifs at Premosello, Balmuccia (BM) and Baldissero (BD) are indicated in **(a)**. IL – Insubric Line, PL – Pogallo Line, CMBL – Cossato-Mergozzo-Brissago Line (Zanetti et al., 1999).*

the limited role of post-melting crustal contamination processes in the evolution of the Southern Alps orogenic-like magmatism.

To reconcile the geochemical and isotopic signatures of the Southern Alps Triassic–Early Jurassic magmatisms with geodynamic aspects, we proposed a model in which the magmatisms were triggered by the Paleotethys subduction but the recycled continental crust materials in the mantle sources of these magmatisms are related to crustal materials brought down to mantle depths by the Variscan and/or older subduction events, as well as by the delamination of the roots of the Variscan chain (see Ogunyele et al., 2024a).

Continental crust recycling in the upper mantle beneath the Southern Alps and relation to Triassic magmatism: Evidence from the Finero Phlogopite Peridotite

The detailed petrological, geochemical and isotopic study of Triassic-Early Jurassic magmatic and volcanic rocks from the Southern Alps have provided evidence for the occurrence of the heterogeneous continental crust-contaminated mantle beneath the region. To provide further evidence for the recycling of continental crust materials in the subcontinental lithospheric mantle (SCLM) beneath the Southern Alps and relate this

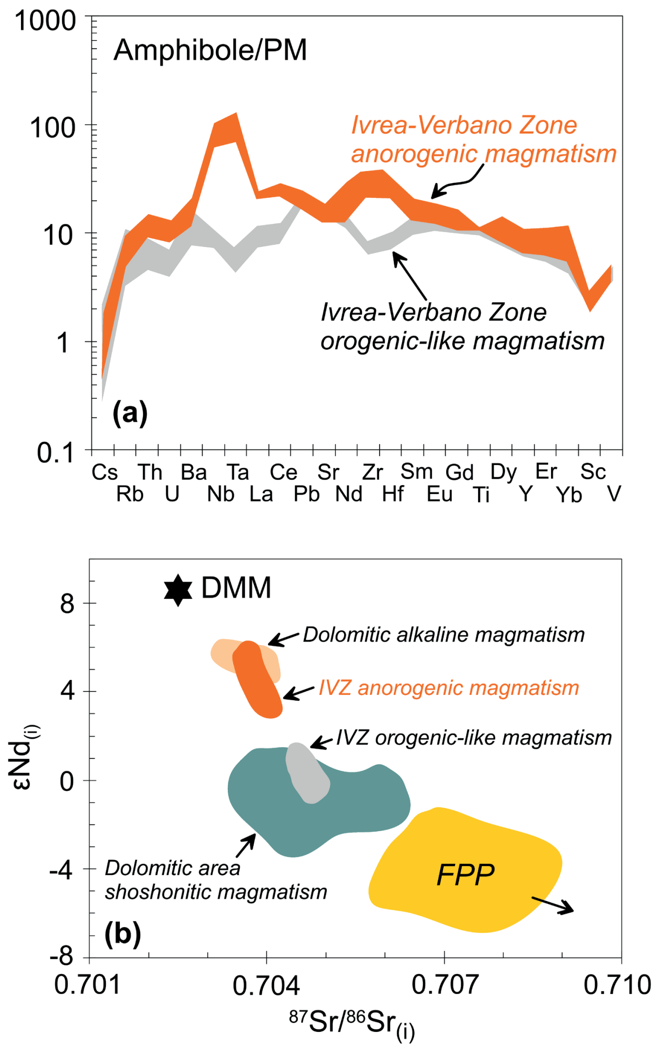

Figure 3 a) *PM-normalized incompatible trace elements compositions of amphiboles from Triassic orogenic-like and anorogenic magmatic rocks from Finero, Ivrea-Verbano Zone.* ***b)*** *$\varepsilon Nd_{(i)}$ and $^{87}Sr/^{86}Sr_{(i)}$ composition of the IVZ and Dolomitic Triassic orogenic-like and anorogenic magmatisms. The composition of the Finero Phlogopite Peridotite (FPP, 300 Ma) and Depleted MORB Mantle (DMM, 200 Ma) are also plotted. Plotted data are from this study and literature (Voshage et al., 1987; Stähle et al., 2001; Casetta et al., 2019, 2021; Lustrino et al., 2019; De Min et al., 2020; Giovanardi et al., 2020).*

mantle composition to the Triassic magmatic events, the orogenic mantle massifs exposed in the IVZ are important. The Finero Phlogopite Peridotite (FPP) which hosts abundant Triassic-Early Jurassic dyke swarms is particularly relevant in this investigation, as the FPP based on mineralogical and trace element characters could represent, at least, a close analogue of the mantle sources of the Southern Alps Middle Triassic orogenic-like magmatism (Casetta et al., 2021; Ogunyele et al., 2024a).

The FPP is a pervasively metasomatized orogenic peridotite massif in northern IVZ formed by well-equilibrated phlogopite- and amphibole-bearing harzburgites, dunites and pyroxenites (websterites and orthopyroxenites). Bulk-rock peridotite composition is characterized by large MgO contents. Accordingly, all mineral phases from the peridotite exhibit a depleted geochemical character, such as high Mg# (in all the silicates) and Cr# (in all silicates and spinel), being geochemically similar to the highly depleted peridotites formed in supra-subduction zones. Despite the depletion in incompatible elements, the clinopyroxene from the peridotite and websterite show selective enrichments in LILE and LREE, and strong fractionation in the L- versus M-HREE. Similarly, amphiboles are also enriched in LILE, LREE and Pb, and strongly depleted in HFSE (Nb, Ta, Zr, Hf, and Ti). In terms of radiogenic isotope composition, amphiboles from the peridotite and websterite are characterized by high $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$ with Δ8/4 and Δ7/4 ranging from 61.6–64.5 and 12.3–14.9, respectively. This elevated Pb isotopic signature is coupled with radiogenic $^{87}Sr/^{86}Sr_{(i)}$ (0.706746–0.707632), and unradiogenic $\varepsilon Nd_{(i)}$ (–1.9 to –3.2) and $\varepsilon Hf_{(i)}$ (+0.1 to –1.9) (Fig. 3b). As a whole, the geochemical and isotopic signatures of the Finero phlogopite peridotite suggest that the upper mantle was metasomatized by hydrous silica-saturated melts with a geochemical affinity similar to that of the continental crust. We thereby propose that these metasomatizing melts were largely derived from the partial melting of continental crust subducted and/or delaminated into the upper mantle during the Variscan orogenic cycle (i.e., Pangea amalgamation), an event likely occurring in the Upper Carboniferous to Lower Permian times. We conclude that the event of recycling of continental crust and metasomatism within the upper mantle, as testified by the Finero peridotite, represents a deep expression of the mantle-derived magmatism with continental crust components documented in the IVZ and widespread in the other sectors of the Southern Alps until the Late Triassic-Early Jurassic.

Time of accretion of IVZ lherzolites and geodynamic evolution of Adriatic Plate

Orogenic lherzolite massifs outcropping at Premosello, Balmuccia and Baldissero in central to southern IVZ represent unique fragments of the subcontinental lithospheric mantle (SCLM) underlying the Southern Alps (in Adriatic Plate) which were tectonically exhumed to crustal levels, probably since the end of the Variscan orogeny (e.g., Decarlis et al., 2023). New mineral chemical and Nd isotopic data coupled with the first-ever Hf isotopic data on Sp-lherzolite and pyroxenite samples from these massifs place fundamental constraints on the timing, mechanism and geodynamic environment of accretion of the IVZ lherzolitic mantle to the Adriatic SCLM.

Major and trace elements composition of mineral phases (Ol, Opx, Cpx, Sp) from the IVZ lherzolites indicate that they range from residual to melt-reacted peridotites, and are similar to abyssal peridotites. Geochemical modelling of REE patterns of Cpx suggests that the Balmuccia and Baldissero peridotites experienced ~5% fractional melting of a DM-like source, whereas Premosello peridotite recorded relatively higher fractional

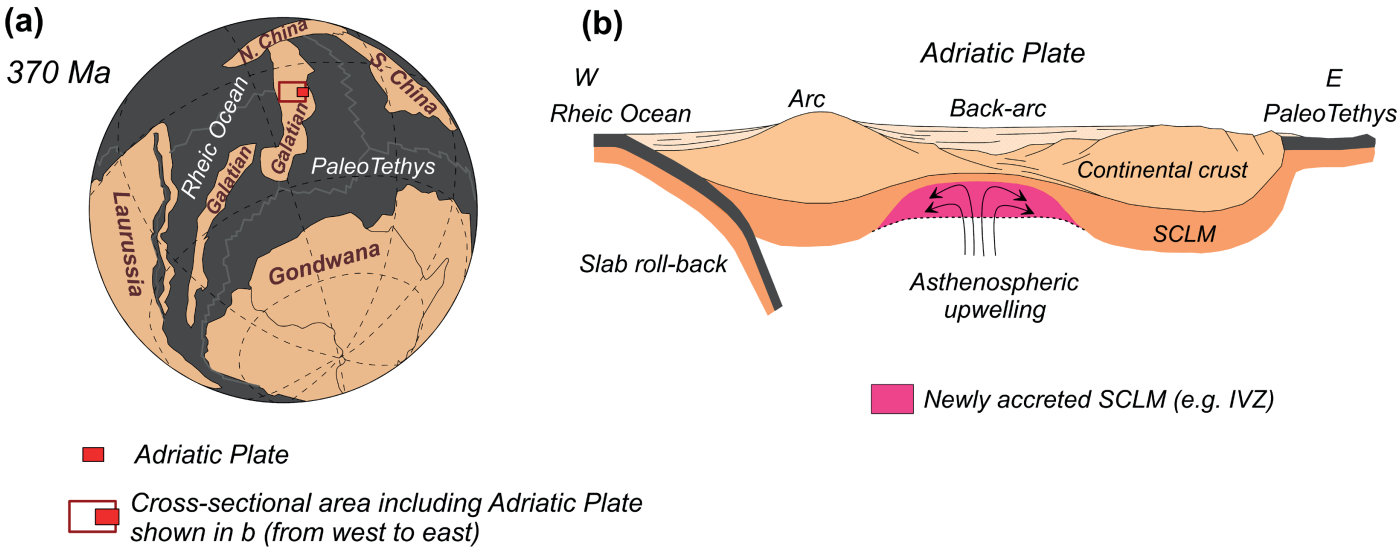

***Figure 4 a)** Global reconstruction of the Devonian showing the location of the Adriatic Plate within the Galatian terrane (modified after von Raumer et al., 2013). **b)** Schematic model of accretion of the IVZ lherzolitic SCLM by asthenospheric upwelling in the Devonian (adapted from Siegesmund et al., 2021).*

melting (~10-12%). All lherzolite samples, except for a few from Balmuccia and Baldissero, show slight enrichment in LREE indicative of metasomatic enrichment during and/or after partial melting. The present-day Nd-Hf isotopic compositions of Cpx further confirm the difference between the three peridotite bodies. Cpx samples from the three mantle massifs display large variations in present-day $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ isotope ratios, with Balmuccia and Baldissero samples plotting along the mantle Nd-Hf isotope array and the Premosello samples plotting above the array. Taken as a whole, the three mantle massifs preserve well-defined correlations between present-day Nd-Hf isotope ratios and parent-daughter ratios, which yielded errorchrons of 370 Ma, with an uncertainty of ± 20 Ma, exceptionally consistent for both Sm-Nd and Lu-Hf systematics. This age is also consistent with Sm-Nd pseudo-isochrons (378 ± 48 Ma, 390 Ma; Obermiller et al, 1992; Obermiller, 1994) and peak Paleozoic Re depletion ages (350–500 Ma; Mazzucchelli et al., 2010; Wang et al., 2013) previously reported for the Balmuccia and Baldissero lherzolites.

Although the Balmuccia and Baldissero lherzolites show peak Paleozoic Re depletion ages (T_{RD}), these massifs also preserve a few Proterozoic depletion ages (up to 1.6 Ga). These Proterozoic ages could imply that the IVZ lherzolitic mantle is an ancient depleted (i.e., cratonic) mantle that was metasomatised (or re-fertilized) around 370 Ma. If this was the case, however, the samples might not have preserved similar errorchrons in both Nd and Hf systematics. Moreso, when the Nd-Hf isotopic composition of all lherzolite Cpx samples from the three studied massifs are corrected to 370 Ma, highly radiogenic signatures ascribable to any significant melting event in the Proterozoic were not found. Rather, Premosello peridotites exhibit initial Nd-Hf isotopes ($\varepsilon Nd_{(i)}$ = +4.3 to +6.4, $\varepsilon Hf_{(i)}$ = +2.3 to +7.1) similar to Balmuccia and Baldissero peridotites ($\varepsilon Nd_{(i)}$ = +2.9 to +5.8, $\varepsilon Hf_{(i)}$ = +5.5 to +16.4) suggesting that prior to ca. 370 Ma, the three peridotite bodies had similar isotopic and geochemical compositions. The few unradiogenic $^{187}Os/^{188}Os$ isotopes which yielded Proterozoic Re depletion ages in the IVZ lherzolites may, therefore, be interpreted as the composition of ancient mantle lithosphere relics delaminated and entrapped in an upwelling asthenosphere. Hence, rather than portions of an ancient depleted (cratonic) SCLM refertilized in more 'recent' times, we prefer the possibility that the three peridotite bodies were in the asthenospheric mantle and evolved with a similar geochemical composition until ca. 370 Ma.

Supported by isotopic and trace elements modeling, it is hypothesized that at ca. 370 Ma, an intrinsically homogenous asthenospheric mantle section suffered variable degrees of partial melting (i.e., up to 12% in Premosello, ~5% in Balmuccia and Baldissero) plus different extents of nearly contemporaneous refertilization which partly obscured the depletion signatures. It is therefore argued that the two errorchrons pointing to ca. 370 Ma may represent the age of depletion for both the residual and refertilized peridotites, also coinciding with the timing of the metasomatic event for the refertilized rocks.

In light of the Nd-Hf isotopic evidence herein presented combined with previously reported Sm-Nd pseudo-isochrons and peak Paleozoic Re depletion ages, we constrain the accretion of the lherzolitic SCLM beneath the IVZ to the Upper Devonian (i.e., 370 ± 20 Ma). At that time, the Adriatic Plate was part of the Galatian terrane (Fig. 4a), a continental ribbon detached from Gondwana and accreted to the margin of Laurussia shortly before the Late Carboniferous Variscan collision (von Raumer et al., 2013). At ca. 370 Ma, the northern and western borders of the Galatian terrane were characterized by a long-lasting extension in a back-arc region caused by the subduction of the Rheic Ocean, whereas the southern and eastern ones were passive margins of the Paleo-Tethys. The lithospheric thinning led to the development of large basins associated with intrabasinal magmatism, starting from ca. 370 Ma and well documented in both Southern Alps and Austroalpine units (Siegesmund et al., 2021). In this framework, we propose that the IVZ lherzolitic massifs were accreted to the Adriatic SCLM through asthenospheric upwelling triggered by Variscan intra-continental extension in a back-arc setting related to the subduction of the Rheic Ocean (Fig. 4b). Hence, rather than the product of recent processes of rejuvenation of old cratonic roots, we here suggest formation of the IVZ lherzolitic SCLM in "recent" continental back-arc settings, where a combination of low-degree melting and nearly contemporaneous melt migration produce fertile mantle lithologies (see Ogunyele et al., 2024b).

CONCLUSION

This thesis unravels the complex tectono-magmatic evolution of the Southern Alps during the Triassic with a special focus on the westernmost (IVZ) and eastern (Dolomites) sectors of the region. A multidisciplinary approach including detailed field observation, petrography, mineral chemistry, U-Pb zircon geochronology, isotope geochemistry and geochemical modeling was applied to suites of Triassic to Early Jurassic magmatic and volcanic rocks outcropping in the Southern Alps. Additional constraints were provided from lherzolitic to harzburgitic mantle massifs outcropping in the IVZ. The detailed petrological, geochemical and geochronological studies in the Southern Alps document a shift of the Triassic magmatism from orogenic-like to anorogenic alkaline affinity throughout the region. This geochemical shift is related to a change in the mantle sources of these contrasting magmatisms from a metasomatized lithospheric mantle containing a significant amount of recycled continental crust components (similar to Finero phlogopite peridotite) to variably depleted asthenospheric sources. A revised geodynamic model is proposed whereby the magmatisms were triggered by the Paleotethys subduction but the recycled continental crust materials in the mantle sources of these magmatisms are related to crustal materials brought down to mantle depths by the Variscan and/or older subduction events, as well as by delamination of the roots of the Variscan chain. The recycling of continental crust materials in the mantle beneath the Southern Alps is further testified to by the Finero peridotite.

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