DOI: 10.19276/plinius.2019.01002

THERMOBAROMETRY, GEOCHRONOLOGY AND PETROLOGICAL EVOLUTION OF THE MIDDLE-LATE TRIASSIC MAGMATIC PRODUCTS IN THE DOLOMITIC AREA (SOUTHERN ALPS)

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INTRODUCTION

The volcano-plutonic rocks of the Dolomitic Area represent a significant and intriguing portion of a widespread magmatic event that, during Middle-Late Triassic, affected several areas of the nowadays Europe, including Carpathians, Dinarides, Hellenides, as well as the Austroalpine and Southalpine domains (Castellarin *et al.*, 1988; Beccaluva *et al.*, 2005). In the Dolomitic Area, this event was characterized by the emission of huge amounts of poorly differentiated magmas over an area of about 2000 km^2, in a relatively limited time span (from 238.0±0.05 to 237.579±0.042 Ma; Abbas *et al.*, 2018; Storck *et al.*, 2019). Such massive effusive activity was accompanied by the concomitant and/or immediately subsequent (237.3 ± 1.0/238.075 ± 0.087 Ma; Storck *et al.*, 2019) emplacement of scattered pyroxenitic/gabbroic to syenitic/syenogranitic plutons. Later on, a volumetrically limited pulse, entirely constituted by lamprophyric dykes, intruded both the volcanic and plutonic rocks. The volcano-plutonic complexes of the Dolomitic Area crop out at Predazzo, Mt. Monzoni and Cima Pape (Trento-Belluno provinces, NE Italy; Fig. 1) and constitute the most intriguing and well-preserved portion of the magmatic event that affected the Southalpine domain during Triassic. Indeed, they are ideal "petrologic laboratories", representing snapshots of ancient magmatic plumbing systems, crystallized during and/or immediately after the eruption of the overlying volcanic products.

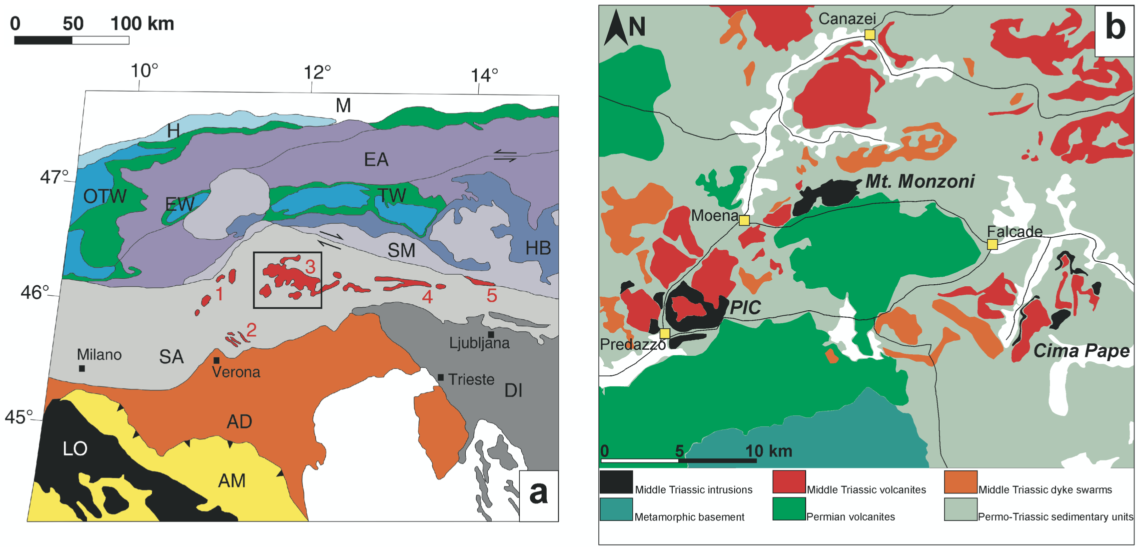

Fig. 1 - (a) Distribution of the Triassic magmatism (modified after Casetta *et al.*, 2018a). LO: Ligurian Ophiolites; AM: deformed Adriatic margin; AD: Adriatic Microplate; SA: Southern Alps; DI: Dinarides; SM: Southern margin of Meliata; HB: Eoalpine High-Pressure Belt; TW: Tauern tectonic Window; EW: Engadine tectonic Window; OTW: Ossola-Tessin tectonic Window; EA: Eastern Austroalpine; H: Helvetic domain; M: Molasse foredeep. Areas affected by Middle Triassic magmatism: 1: Brescian Alps; 2: Alto Vicentino; 3: Dolomitic Area; 4: Carnia; 5: Karawanken. (b) Sketch of the distribution of the Middle Triassic intrusive bodies (PIC, Mt. Monzoni and Cima Pape), volcanic/volcanoclastic sequences and dyke swarms in the Dolomitic Area (modified from Abbas *et al.*, 2018).

The possibility to constrain theoretical and experimental modeling by means of field evidence, together with the high compositional variability of the intrusive rocks and the articulated tectonic/geodynamic framework of the area, attracted the interest of scientists since the beginning of the 19th century. Mt. Monzoni and Predazzo plutons played also a predominant role in the birth of the petrography, constituting the type locality of the monzonitic rocks. After having been at the heart of the petrographic debates for decades, the study of the magmatic rocks of the Dolomitic Area was abandoned in the '90s, notwithstanding the various geological problems remained unsolved. Among them, the main outstanding topics are those related to the emplacement conditions of the intrusive bodies and the relationships between tectonics and magmatism, both at local and at geodynamic scale (Castellarin *et al.*, 1982; Sloman, 1989).

The aim of this study was the reconstruction of the chemico-physical features and temporal evolution of the Triassic intrusive/hypabyssal bodies of the Dolomitic Area. To address these topics, particular attention was given to the Predazzo multi-pulse intrusion, where different magmatic units, as well as their cross-cutting relationships, are preserved. Detailed field and petrological investigations, together with thermobarometric, oxybarometric, hygrometric and isotopic models, were put forward to identify the main intensive and extensive parameters of these ancient plumbing system/s, as well as to unravel the major processes acting during magma emplacement and differentiation. Additionally, the first complete petrological, geochemical and geochronological characterization of the lamprophyric dykes intruded in the plutonic bodies enabled to frame the generation and emplacement of such alkaline melts within the temporal evolution of the Dolomitic Area and of the whole Southern Alps magmatism.

GEOLOGICAL AND GEODYNAMIC SETTING

The geodynamic framework of the Austroalpine-Southalpine domains during Middle-Late Triassic is a challenging topic, mainly because of the variety of magmas erupted over a short time span in a relatively limited area, whose tectonic features have been also subsequently obscured by the Alpine orogenesis. Between 239±3 and 227±6 Ma, magmas with orogenic-like (high K-calc-alkaline to shoshonitic) affinity intruded in the Southern Alps, Dynarides and Hellenides (Beccaluva *et al.*, 2005). Almost simultaneously, alkaline magmas intruded between 231±1 and 227±7 Ma along the Periadriatic lineament (Karawanken) and in the Carpathians (Ditrau) area (Lippolt & Pidgeon, 1974). Volcano-plutonic sequences cropping out in the Brescian Alps, Alto Vicentino-Valsugana, Dolomitic, Carnia areas (Italy) and the Karawanken region (Austria) represent the magmatism of the Southern Alps domain (Fig. 1). The concomitance between the diffuse orogenic-like signature of these rocks and a general extensional-transtensional tectonic regimes (Doglioni, 1987) led many authors to propose several geodynamic scenarios for the Southern Alps during Middle Triassic. They include: *i*) aborted rifting in a passive margin (Bernoulli & Lemoine, 1980); *ii*) active mantle upwelling (Stähle *et al.*, 2001); *iii*) arc system at the Paleo-Tethys NW limb (Castellarin *et al.*, 1988); *iv*) back-arc development connected to the subduction of the Paleo-Tethys (Stampfli & Borel, 2004); *v*) anorogenic rifting with subduction signature inherited from the Hercynian orogeny (Sloman, 1989; Bonadiman *et al.*, 1994; Beltràn-Trivino *et al.*, 2016).

The magmatic sequences of the Dolomitic Area

In the Dolomitic Area, volcanites, intrusive bodies and dykes emplaced in a more or less shallow marine environment, characterized by the presence of isolated carbonate platforms elevated over deep marine basins (Gianolla *et al.*, 2010). The earlier phase of the Middle Triassic volcanism was characterized by predominant explosive activity in result of water-magma interaction. Afterwards, the eruption style moved towards a more effusive nature, characterized by the production of submarine pillow lavas, pillow breccias, lava breccias and hyaloclastites, as well as of subaerial lava flows, all of them with basaltic/trachybasaltic to latitic composition and high-K calc-alkaline to shoshonitic affinity. The intrusive bodies are rare and limited in volume (< 10 km^3 in total; Fig. 1). The Mt. Monzoni body (238.190±0.05 Ma; Storck *et al.*, 2019) and the Cima Pape sill are composed of biotite ± amphibole-bearing gabbros/clinopyroxenites to syenites, generated by fractional crystallization processes from parental basaltic/trachybasaltic magmas. Mt. Monzoni is a NE-SW elongated pluton, intruded into the Permo-Triassic volcanic and sedimentary formations, and its emplacement was probably controlled by a syngenetic ESE–WNW trascurrent tectonics that created the condition for the intrusion and differentiation of magma in shallow crust. The Cima Pape body is a 50-70 to 300 m thick sill intruded into the Permo-Triassic sedimentary formations, as well as in the overlying volcanic/volcanoclastic deposits (Gasparotto & Simboli, 1991; Bonadiman *et al.*, 1994). The gradual textural transition, locally organized in columnar structures, between this sill and the overlying lavas led many authors to speculate about its shallow depth of emplacement. The Predazzo Intrusive Complex (PIC) is a ring-like shaped multi-pulse pluton composed of biotite- and amphibole-bearing pyroxenitic/gabbroic to syenitic/syenogranitic rocks. Zircon U-Pb age data from the syenogranitic and monzodioritic rocks suggest that PIC intruded the Permo-Triassic volcanic and sedimentary formations between 237.3 ± 1.0 Ma and 238.075 ± 0.087 Ma (Storck *et al.*, 2019). An articulated swarm of dykes, decimetric to metric in thickness, cut both the PIC, Mt. Monzoni and Cima Pape intrusions, the overlying volcanic/volcanoclastic sequences and the Permo-Triassic host rocks. These dykes range in composition from basanitic/basaltic to trachytic, and show the same orogenic-like (high-K calc-alkaline to shoshonitic) affinity as the corresponding plutonic bodies. A minor portion of the dyke swarm, mainly cropping out in the Predazzo-Mt. Monzoni area, is composed of alkaline lamprophyres.

ANALYTICAL METHODS

Whole-rock major/trace element analyses of Mt. Monzoni, Cima Pape and PIC rocks were carried out at the Department of Physics and Earth Sciences (University of Ferrara, Italy) by means of an ARL Advant-XP automated Wavelength Dispersive X-Ray Fluorescence Spectrometer (WDXRF) and a Thermo Series X inductively coupled plasma-mass spectrometer (ICP-MS). Mineral phase major element analyses on representative samples were carried out at the Department of Lithospheric Research, University of Wien (Austria) using a CAMECA SX100 electron microprobe equipped with four WD and one ED spectrometers. Trace element analyses of pyroxene and amphibole crystals was determined at the CNR - Istituto di Georisorse of Pavia (Italy) by laser ablation microprobe-inductively coupled plasma-mass spectrometry (LAM-ICP-MS). Whole-rock $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ analyses were made at the Scottish Universities Environmental Research Centre (SUERC) of Glasgow (UK) by thermal ionization mass spectrometry (TIMS). $^{40}Ar/^{39}Ar$ datings were performed at the Radiogenic Laboratory of the SUERC. For a more detailed list of all the analytical procedures, see Casetta *et al.* (2018b, 2019).

THE PREDAZZO INTRUSIVE COMPLEX (PIC)

Field characters and petrological evolution

The PIC (Fig. 2) is a ring-like shaped multi-pulse pluton with an overall volume of about 4.5 km^3. Whole rock major/trace element and mineral chemistry results, together with detailed field surveys, enabled to discriminate between the three magmatic suites that compose the PIC, which are named Shoshonitic Silica Saturated (SS), Shoshonitic Silica Undersaturated (SU) and Granitic Unit (GU). The SS and SU suites are composed of pyroxenites/gabbros to syenites, respectively quartz- and nepheline-bearing, whereas the GU is constituted by quartz- and biotite-bearing granites/syenogranites (Fig. 2). All PIC rocks are characterized by marked Nb-Ta-Ti negative anomalies and a strong Pb enrichment. Together with the common modal occurrence of biotite, amphibole and the late magnetite crystallization, these features confirm the orogenic-like affinity of PIC rocks. The progressive differentiation trends of both the SS and SU series are marked by the appearance of a significant Eu negative anomaly, particularly evident in the more evolved syenites. The SU suite is characterized by lower K/Na ratios, as well as by higher HFSE and LREE contents, with respect to the SS and GU ones. The GU granites/syenogranites differ from the SS and SU suites in terms of silica saturation, FeO, MgO, K_2O and Rb contents. Amphibole is Al-, Na-, and K-enriched in SU rocks with respect to SS ones, while iron-rich biotite is typical of GU rocks. These features suggest that SS and SU suites were generated by two different parental magmas, likely derived from spatial and/or temporal heterogeneous sources.

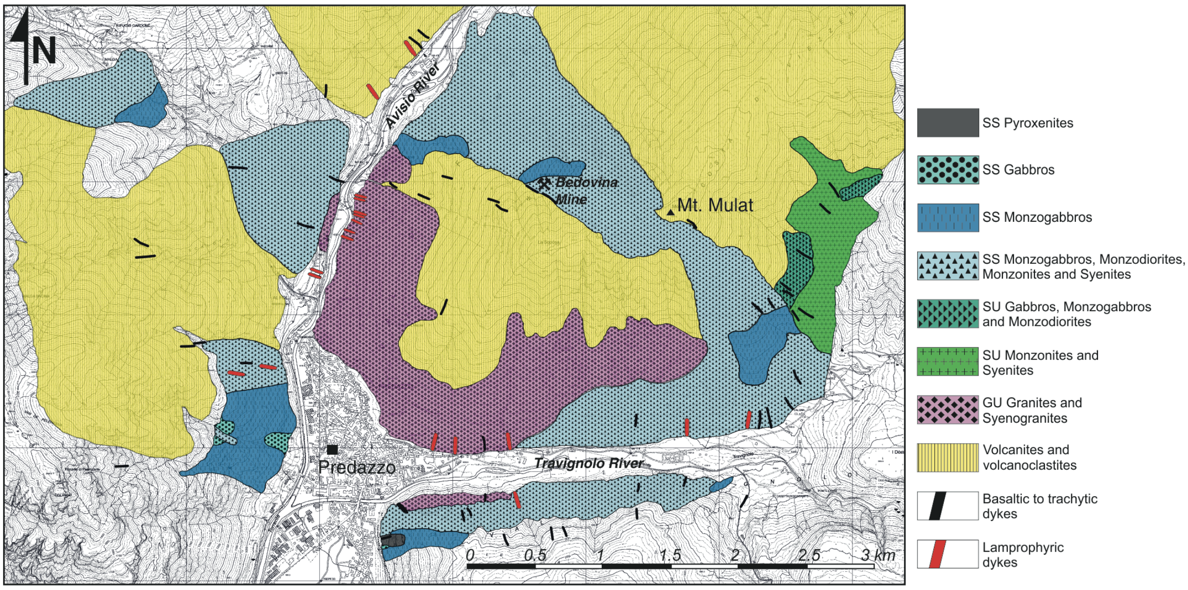

Fig. 2 - Simplified geological map of the PIC (modified from Casetta *et al.*, 2018b, 2019).

Major element mass balance calculations and fractional crystallization models developed by means of Rayleigh distillation equations on trace elements enabled to simulate the differentiation trends of PIC rocks, considering an almost closed system (Petersen *et al.*, 1980; Bonadiman *et al.*, 1994). Results showed that the most differentiated SS and SU syenites are generated by about 80-90% fractional crystallization of starting monzogabbroic-like (*i.e.*, trachybasaltic) melts. The accuracy of the models was supported by: *i*) the similarity between the modelled cumulitic products and the natural pyroxenitic/gabbroic to monzodioritic rocks found within the complex; *ii*) the numerical match between the calculated and the real compositions (Casetta *et al.*, 2018a). The relationship between the GU granites/syenogranites and the main SS-SU suites remained unsolved. The estimated volume of the GU body (1.1 km^3) is unrealistically larger than that of the SS/SU syenites (≤ 0.25 km^3), taking also into account the high fractional crystallization degrees from which syenites generated. This data speaks against a genesis via simple fractional crystallization from the SS/SU syenitic products, indicating instead a genesis by magmatic differentiation from a calc-alkaline parental melt, the primitive/intermediate products of which are not exposed in the PIC area. On the other hand, GU rocks are similar to the Middle Triassic calc-alkaline/high-K calc-alkaline rhyolites found in Carnia and Alto Vicentino regions (Barbieri *et al.*, 1982; Gianolla, 1992), and could represent their intrusive counterpart. An accurate field study of the cross-cutting relationships between the three units enabled to reconstruct the temporal evolution of the PIC (Fig. 3). A first most voluminous SS pulse (3.1 km^3), emplaced as nowadays appears in the external part of the complex, was followed by the GU intrusion (1.1 km^3) in the central portion, and by the eastward emplacement of the SU batch (0.3 km^3). This latter likely represent an ultimate batch of melt generated in the vanishing stage of the magmatic event. A magmatic transitional contact was also identified between the PIC and the surrounding volcanites. This feature, together with the lack of 'caldera-filling'-like materials, led to exclude the presence of a calderic collapse structure in the area, invoked by several authors to explain the ring-shape of the complex (Doglioni, 1984).

Thermobarometry, oxybarometry, hygrometry, and EC-AFC modeling

The textural/compositional homogeneity of the main cumulus phases of PIC rocks (*i.e.*, clinopyroxene and plagioclase), together with the scarce efficiency of syn- to post-crystallization diffusion processes on the large-sized crystals, enabled to hypothesize that their composition is directly function of the physical conditions at which they formed and segregated from the progressively differentiating melt. In this scenario, the chemical features of the main mineral phases inside SS and SU rocks were used to retrieve information on the *T*-*P*-fO_2 conditions and H_2O content of the melts from which they generated.

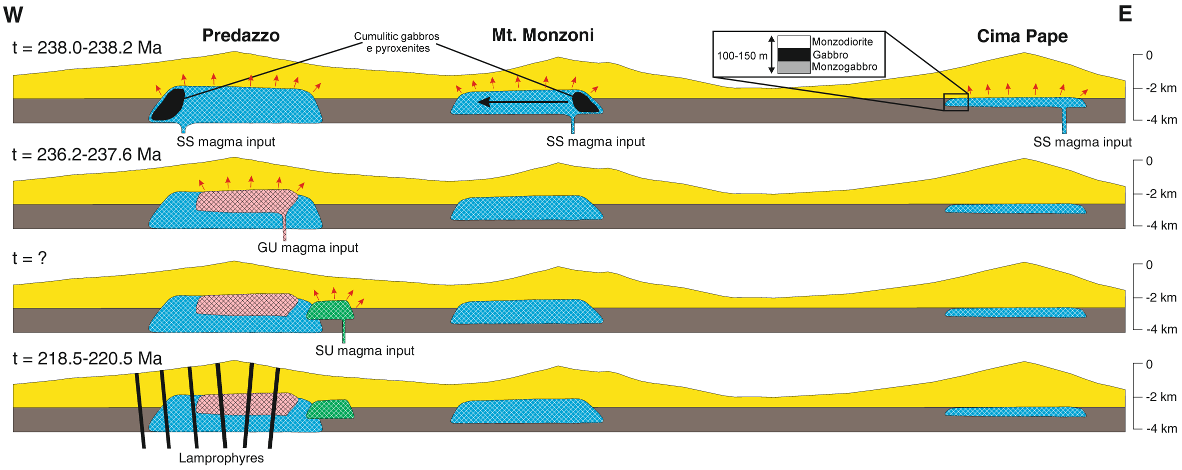

Fig. 3 - West to East interpretative sketch of the evolutionary sequence of the Middle-Late Triassic magmatism in the Dolomitic Area. A first emplacement of the Shoshonitic Silica Saturated (SS) intrusive batches at Predazzo, Mt. Monzoni and Cima Pape was followed by the intrusion of the Granitic Unit and the Shoshonitic Silica Undersaturated (SU) batch at Predazzo. Finally, at 218.5-220.5 Ma, alkaline lamprophyres intruded in and around the PIC. The black arrow inside Mt. Monzoni pluton indicates the differentiation trend hypothesized by Bonadiman *et al.* (1994). Black bodies represent cumulitic gabbros and pyroxenites. Inset shows the stratigraphy of Cima Pape sill.

An evident disequilibrium between clinopyroxene/plagioclase and their host rocks suggests that the mafic cumulitic rocks of the complex formed during the initial stages of fractionation of the trachybasaltic melts. On the other hand, the less magnesian clinopyroxene crystals tracked in syenites were almost in equilibrium with their host rocks, corroborating the assumption that the more differentiated rocks resemble the composition of melts and approach the eutectic of the system (Casetta *et al.*, 2018b). Once evaluated the disequilibrium between clinopyroxene/plagioclase and host rock, these phases were traced back to their ideal equilibrium conditions. An iterative procedure, based on the application of selected mineral-melt thermobarometric/hygrometric equations (Putirka *et al.*, 1996; Putirka, 2008; Lange *et al.*, 2009) and the use of Rhyolite-MELTS (Gualda *et al.*, 2012) calibrations, was put forward to retrieve the *T*-*P*-H_2O parameters of the less evolved melts in the feeding system. The "classical" thermobarometric/oxybarometric equations for intrusive rocks (Burkhard, 1991; Anderson, 1996; Henry *et al.*, 2005) were then used to verify the previous results and constrain the *T*-*P*-fO_2 and H_2O conditions of the later crystallization stages. Results showed that the SS and SU batches shared a common thermal regime, cooling from ~1000-1100°C (cumulus assemblage) down to ~600°C (intercumulus assemblage). The crystallization *P* resulted between 40 and 170 MPa for both the SS and SU bodies, yielding a depth of 1.4-5.6 km ($\Delta P/\Delta z$ of 29 MPa/km), suggesting that PIC intruded in shallow crust. H_2O and fO_2 estimates indicated that SU primary magmas were characterized by lower H_2O content and oxidizing conditions than the SS ones (1.0-1.5 vs. 2.0-2.5 H_2O wt%; -0.1/+0.33 vs. +0.2/+0.7 ΔFMQ, respectively). Hygrometers indicated highly hydrated conditions of magmas and progressive H_2O enrichment during differentiation. Despite the common thermobarometric evolution and slightly different water contents, SS and SU bodies are distinguishable in terms of initial Sr-Nd isotopic ratios (0.7039-0.7052 $^{87}Sr/^{86}Sr_i$ and 0.512191-0.512247 $^{143}Nd/^{144}Nd_i$ SS rocks; 0.7047-0.7063 $^{87}Sr/^{86}Sr_i$ and 0.512261-0.512289 $^{143}Nd/^{144}Nd_i$ SU rocks). On the other hand, both suites plot in the enriched mantle source field (EM I), speaking in favour of the presence of a subduction-related component in the mantle beneath Southern Alps during Middle Triassic (Bonadiman *et al.*, 1994; Zanetti *et al.*, 2013). EC-AFC models (Spera & Bohrson, 2001) showed that the assimilation of Permo-Triassic crustal components (Voshage *et al.*, 1990) by a starting SS magma could not account for the higher $^{143}Nd/^{144}Nd$ of the SU batch. This result ruled out any possible derivation of the SU suite from the SS one, and led to hypothesize that the Nd isotopic enrichment of SU rocks could reflect a primary feature of their mantle source. The same models demonstrated that both suites assimilated small proportions of crustal components (5-6%), and that the Sr-Nd isotopic signature of the Middle Triassic magmas is consistent with the presence of an Ivrea-like basement beneath the Dolomitic Area. If examined in the light of their temporal relationships, the major, trace element and Sr-Nd isotopic signature of the SS and SU suites highlighted the progressive depletion of the mantle source beneath the Southern Alps.

THE MT. MONZONI AND CIMA PAPE INTRUSIVE BODIES

Common geochemical features characterize the limited volume of Middle Triassic intrusions of PIC, Mt. Monzoni and Cima Pape, which share a common orogenic-like (shoshonitic) affinity. The mineral paragenesis and composition of Mt. Monzoni and Cima Pape rocks, as well as their whole-rock HFSE and LREE distribution, are consistent with those of the previously called SS suite. The Sr-Nd isotopic signature of Mt. Monzoni and Cima Pape rocks plot in the EM I field. Notwithstanding similar $^{143}Nd/^{144}Nd_i$ ratios, Mt. Monzoni rocks have slightly lower $^{87}Sr/^{86}Sr_i$ values with respect to Cima Pape intrusives. When compared to the PIC, a clear correspondence between Mt. Monzoni rocks and the SS suite can be identified, whereas Cima Pape intrusives have quite higher $^{87}Sr/^{86}Sr_i$ ratios. According to these findings, it can be assumed that the SS suite represents the first and most significant pulse that characterized the Middle Triassic magmatic event in the Dolomitic Area, in terms of both volumetric abundance and areal distribution. Two main EC-AFC models were developed to evaluate the interactions between Mt. Monzoni-Cima Pape rocks and the Southern Alps crustal basement. Models showed that small amounts of crustal assimilation (3-4%) are able to explain the Sr-Nd isotopic variability of Mt. Monzoni and Cima Pape rocks. The Sr isotopic variability of Mt. Monzoni rocks is probably function of syn-emplacement contamination of magmas by the carbonate host rocks (Bonadiman *et al.*, 1994), a process that could be particularly efficient in such small intrusive bodies. The obtained results confirm that, as in case of PIC, fractional crystallization was the main process acting during magma differentiation in Mt. Monzoni and Cima Pape intrusions. Selected thermobarometric equations were applied to amphibole, biotite and amphibole-plagioclase pairs in the intercumulus assemblage of Mt. Monzoni rocks to unravel the *T-P* path of the later crystallization stages. Results yielded a *T-P* interval of 719-747°C and 30-98 MPa, *i.e.* an emplacement depth of about 1.0-3.6 km, in great accordance with what proposed for PIC (1.4-5.6 km). The intense state of alteration of biotite and amphibole in Cima Pape rocks prevented their analysis and thus the estimate of their emplacement depth. However, the existence of a grain size gradual textural transition between the intrusives and the overlying volcanites both at Predazzo and Cima Pape could be an indirect evidence of the shallow nature of the Cima Pape sill.

THE LAMPROPHYRIC DYKES

The relationships between the alkaline lamprophyres and the host Middle Triassic volcano-plutonic complexes (Fig. 2) is an intriguing topic and a key factor for deciphering the evolution of the magmatism of the Dolomitic Area. These lamprophyres (camptonites) are composed of pargasitic to kaersutitic-hastingsitic (and rare sadanagaitic) amphibole, plagioclase, aluminian- to titanian-diopside, olivine, K-feldspar and Ti-magnetite ± accessory phases (ilmenite, titanite, apatite and analcime). Carbonate is also present as pseudomorphous phase in replacement of olivine, in secondary veins/fractures, or as major constituent of small (200-250 μm in diameter) spherical ocelli, variably distributed and surrounded by the tangential growth of plagioclase, amphibole and/or clinopyroxene crystals. Lamprophyres are moderately to strongly SiO_2-undersaturated, and are characterized by Ni and Cr contents of 237-24 and 585-14 ppm, respectively. $^{40}Ar/^{39}Ar$ datings yielded crystallization ages of 218.90 ± 0.59/0.66 to 219.70 ± 0.73/0.85 Ma for lamprophyres, suggesting that they belong to a distinct and subsequent magmatic event with respect to the one that produced PIC, Mt. Monzoni and Cima Pape shoshonitic rocks (i.e. 239.04±0.04 to 237.77±0.05 Ma; Storck *et al.*, 2019). This chronological gap is also reinforced by some geochemical discrepancies, such as the lack of any Ta-Nb-Ti and U-Th negative anomaly, which suggests the involvement of an OIB-like component in lamprophyres mantle source. Their $^{87}Sr/^{86}Sr_i$ and $^{143}Nd/^{144}Nd_i$ ratios plot close to the DMM end-member, pointing towards a genesis from a mantle source more depleted than the EM I-like source that produced the Middle Triassic orogenic-like rocks. At shallow depth, the ascent of lamprophyric melts was probably favoured by extensional-trastensional dynamics, to which these rocks are often associated. The occurrence of extensional regimes during lamprophyres ascent was also suggested by the *T-P* path of crystallization of amphibole and clinopyroxene, calculated by means of selected thermobarometric equations (Putirka *et al.*, 1996; Putirka, 2008, 2016). Results showed that lamprophyres crystallization started at 24 km and continued towards the surface, at least until 8 km. Such an interval is consistent with the presence of a polybaric vertical plumbing system and suggests that the fractional crystallization and (small-scale) mixing processes recorded by amphibole crystals inside lamprophyres took place "en route" to the surface, without implying the presence of magma ponding zones. Mantle melting models suggest that low melting percentages (1.0-2.5%) of a fertile garnet-amphibole-bearing lherzolite (probably at a depth of about 70-80 km) can account for the generation of the lamprophyric melts.

Geodynamic implications

The lamprophyres of the Dolomitic Area are temporally, spatially and geochemically correlable to several magmatic occurrences of the Southern Alps and Carpathians area. In the Ditrau area (Carpathians), in fact, late-stage alkaline lamprophyres intruded a Middle-Triassic (231-227 Ma) alkaline intrusion. Notwithstanding a slight relative depletion in Th, U, Nb, Zr and LREE with respect to the Ditrau ones, the Dolomitic Area lamprophyres have comparable Sr-Nd isotopic signature, suggesting that similar mantle sources were involved in their genesis. Batki *et al.* (2014) hypothesized that Ditrau lamprophyres generated in an early extensional phase of the Middle Triassic to Jurassic rifting that separated the Getic microplate from the Bucovinian margin, thus in the Alpine Tethys rift portion located northward of the Meliata basin (Stampfli *et al.*, 2002). Precursors of the Tethys opening were also documented in the Brescian Alps, where intra-plate tholeiites with depleted Sr-Nd isotopic signature emplaced almost simultaneously to the studied lamprophyres (217±3 Ma; Cassinis *et al.*, 2008). Coeval magmatic occurrences (from 225±13 to 190-212.5 Ma) were recognized in the Western Alps, where alkaline dykes, generated from upwelling mantle with a significant asthenospheric contribution, intruded in the Finero area (Stähle *et al.*, 2001; Schaltegger *et al.*, 2015). Similar ages were also reported for the metasomatic apatite-rich and chromitite layers formed in the Finero peridotite, thought to belong, together with the above-mentioned dykes, to a unique alkaline-carbonatitic magmatic event formed during mantle upwelling in a continental rifting setting (Zaccarini *et al.*, 2004; Malitch *et al.*, 2017). The 219.22 ± 0.46/0.73 Ma occurrence of alkaline lamprophyres in the Dolomitic Area could be easily incorporated in such context, taking into account their similarity to the alkaline dykes and apatite-bearing assemblages cropping out at Finero. This parallelism is also supported by the presence, in the studied lamprophyres, of primary carbonatitic-like ocelli compositionally comparable to the interstitial dolomitic grains found in the Finero peridotite (Zanetti *et al.*, 1999). In such circumstances, the studied lamprophyres were likely part of the alkaline-carbonatitic magmatic event that intruded the subcontinental mantle portion beneath the Southern Alps during Late Triassic. This magmatic phase was unrelated to the previous, subduction-related, K- and LILE-rich metasomatic episode that led to the formation of amphibole and phlogopite in the Finero peridotite (Morishita *et al.*, 2008). Rather than representing a late-stage episode connected to the orogenic-like magmatism of the Dolomitic Area, lamprophyres could be considered, together with the Brescian Alps basalts and the Ditrau and Finero dykes, as Late Triassic precursors of the rifting stage connected to the Alpine Tethys opening. This hypothesis is supported by their depleted Sr-Nd isotopic signature, consistent with a genesis from a mantle source influenced by an asthenospheric contribution. Further evidence is provided by their incompatible elements distribution: more than enriched in Nb and Ta, in fact, they are U-, Th-, K- and La-depleted with respect to the host shoshonitic rocks. This feature, consistent with a gradual change of the magmatism from orogenic-like to anorogenic, agrees well with a progressive depletion of the mantle source beneath the Southern Alps domain.

CONCLUSIONS

The Triassic magmatism of the Dolomitic Area plays a key role in the discovery and interpretation of the geodynamic evolution of the Southern Alps between the Hercynian orogeny and the opening of the Alpine Tethys. In this study, a petrological, geochemical and geochronological study of the intrusive/hypabyssal bodies cropping out at Predazzo, Mt. Monzoni and Cima Pape enabled to frame the magmatism of the Dolomitic Area in the complex evolution of the Southalpine domain during Middle and Late Triassic. Field evidence and geochemical data suggest that the intrusives of the Dolomitic Area can be subdivided into three different suites (Fig. 3), typified by orogenic-like (shoshonitic) affinity, Nb-Ta-Ti negative anomalies, LILE enrichment, and EM I-like Sr-Nd isotopic signature. Predazzo and Mt. Monzoni plutons crystallized at similar shallow depth (1.0-5.6 km). Whole-rock geochemistry suggest that low degree of crustal assimilation and local syn-emplacement contamination occurred during magma ascent and emplacement, even if fractional crystallization was the main process acting during differentiation. The EM I-like isotopic signature of the rocks speaks in favour of the presence of a subduction-related component in the Southern Alps mantle during Middle Triassic, even if the geochemical features of the emplaced magmas suggest its slight gradual depletion with time. The first $^{40}Ar/^{39}Ar$ datings obtained on the alkaline lamprophyric dykes yielded an emplacement age of 219.22 ± 0.46/0.73 Ma, suggesting an origin unrelated to the older (Middle Triassic) and short-lived (700 ka) orogenic-like magmatism of the host intrusive rocks (Fig. 3). The temporal/geochemical correlation between lamprophyres and several magmatic occurrences of the Southern Alps and Carpathians led to consider the formers as part of a widespread alkaline-carbonatitic magmatic event that intruded the subcontinental mantle during Late Triassic. Rather than being a late-stage expression of the Middle Triassic orogenic-like magmatism of the Dolomitic Area, lamprophyres marked the shift of the Southern Alps magmatism towards an anorogenic nature, in response to the asthenospheric influx related to the opening of the Alpine Tethys.

REFERENCES

Abbas, H., Michail, M., Cifelli, F., Mattei, M., Gianolla, P., Lustrino, M., Carminati, E. (2018): Emplacement modes of the Ladinian plutonic rocks of the Dolomites: Insights from anisotropy of magnetic susceptibility. *J. Struct. Geol.*, **113**, 42-61.

Anderson, J.L. (1996): Status of thermobarometry in granitic batholiths. *Geol. S. Am. S.*, **315**, 125-138.

Barbieri, G., De Vecchi, G.P., De Zanche, V., Mietto, P., Sedea, R. (1982): Stratigrafia e petrologia del magmatismo triassico nell'area di Recoaro. Guida alla geologia del Sudalpino centro-orientale. *Guide Geologiche Regionali S.G.I.*, 179-187.

Batki, A., Pál-Molnár, E., Dobosi, G., Skelton, A. (2014): Petrogenetic significance of ocellar camptonite dykes in the Ditr□u Alkaline Massif, Romania. *Lithos*, **200**, 181-196.

Beccaluva, L., Coltorti, M., Saccani, E., Siena, F., Zeda, O. (2005): Triassic magmatism and Jurassic ophiolites at the margins of the Adria Plate. *In*: "Crop Project: Deep Seismic Exploration of the Central Mediterranean and Italy", I.R. Finetti ed. *Elsevier* **28**, 607-622.

Beltrán-Triviño, A., Winkler, W., von Quadt, A., Gallhofer, D. (2016): Triassic magmatism on the transition from Variscan to Alpine cycles: evidence from U–Pb, Hf, and geochemistry of detrital minerals. *Swiss J. Geosci.*, **109(3)**, 309-328.

Bernoulli, D. & Lemoine, M. (1980): Birth and early evolution of the Tethys: the overall situation. *Mémoir. Bureau Res. Geol. Min.*, **115**, 168-179.

Bonadiman, C., Coltorti, M., Siena, F. (1994): Petrogenesis and T-fO_2 estimates of Mt. Monzoni complex (Central Dolomites, Southern Alps): a Triassic shoshonitic intrusion in a trascurrent geodynamic setting. *Eur. J. Mineral.*, **6**, 943-966.

Burkhard, D.J.M. (1991): Temperature and redox path of biotite-bearing intrusives: a method of estimation applied to S- and I-type granites from Australia. *Earth Planet. Sci. Lett.*, **104**, 89-98.

Casetta, F., Coltorti, M., Marrocchino, E. (2018a): Petrological evolution of the Middle Triassic Predazzo Intrusive Complex, Italian Alps. *Int. Geol. Rev.*, **60**, 977-997.

Casetta, F., Coltorti, M., Ickert, R.B., Bonadiman, C., Giacomoni, P.P., Ntaflos, T. (2018b): Intrusion of shoshonitic magmas at shallow crustal depth: *T-P* path, H_2O estimates, and AFC modeling of the Middle Triassic Predazzo Intrusive Complex (Southern Alps, Italy). *Contrib. Mineral. Petr.*, **173**, 57.

Casetta, F., Ickert, R.B., Mark, D.F., Bonadiman, C., Giacomoni, P.P., Ntaflos, T., Coltorti, M. (2019): The alkaline lamprophyres of the Dolomitic Area (Southern Alps, Italy): markers of the Late Triassic change from orogenic-like to anorogenic magmatism. *J. Petrol.*, **60**, 1263-1298.

Cassinis, G., Cortesogno, L., Gaggero, L., Perotti, C.R., Buzzi, L. (2008): Permian to Triassic geodynamic and magmatic evolution of the Brescian Prealps (eastern Lombardy, Italy): *Ital. J. Geosci.*, **127(3)**, 501-518.

Castellarin, A., Lucchini, F., Rossi, P.L., Sartori, L., Simboli, G., Sommavilla, E. (1982): Note geologiche sulle intrusioni di Predazzo e dei M. Monzoni. Guida alla geologia del Sudalpino centro-orientale. *Guide Geologiche Regionali S.G.I.*, 211-219.

Castellarin, A., Lucchini, F., Rossi, P.L., Selli, L., Simboli, G. (1988): The Middle Triassic magmatic-tectonic arc development in the Southern Alps. *Tectonophysics*, **146(1-4)**, 79-89.

Doglioni, C. (1984): Triassic diapiric structure in the central Dolomites (Northen Italy): *Eclogae Geol. Helv.*, **77**, 2.

Doglioni, C. (1987): Tectonics of the Dolomites (Southern Alps, Northern Italy): *J. Struct. Geol.*, **9**, 181-193.

Gasparotto, G. & Simboli, G. (1991): Mineralogia, petrografia e schemi evolutivi delle magmatiti triassiche del complesso di Cima Pape (Dolomiti Orientali). *Minera. Petrogr. Acta*, **34**, 205-234.

Gianolla, P. (1992): Evoluzione mediotriassica del vulcanismo di Rio Freddo (Api Giulie, Italia). *Mem. Sci. Geol.*, **44**, 193-209.

Gianolla, P., Avanzini, M., Breda, A., Kustatscher, E., Nereo, P., Roghi, G., Furin, S., Massari, F., Picotti, V., Stefani, M. (2010): Dolomites, 7th International Triassic Field Workshop, Field trip to the World Heritage Site of the Tethyan Triassic. September 5-10 2010, Dolomites, Southern Alps, Italy. With the adesion of Fondazione Dolomiti-Dolomiten-Dolomites-Dolomitis Unesco, 122 pp.

Gualda, G.A.R., Ghiorso, M.S., Lemons, R.V., Carley, T.L. (2012): Rhyolite-MELTS: a modified calibration of MELTS optimized for silica-rich, fluid-bearing magmatic systems: *J. Petrol.*, **53**, 875-890.

Henry, D.J., Guidotti, C.V., Thomson, J.A. (2005): The Ti-saturation surface for low-to-medium pressure metapelitic biotites: Implications for geothermometry and Ti-substitution mechanisms. *Am. Mineral.*, **90(2-3)**, 316-328.

Lange, R.A., Frey, H.M., Hector, J. (2009): A thermodynamic model for the plagioclase-liquid hygrometer/thermometer. *Am. Mineral.*, **94(4)**, 494-506.

Lippolt, H. & Pidgeon, R. (1974): Isotopic mineral ages of a diorite from the Eisenkappel intrusion, Austria. *Z. Naturforsch.*, **29a**.

Malitch, K.N., Belousova, E.A., Griffin, W.L., Badanina, I.Y., Knauf, V.V., O'Reilly, S.Y., Pearson, N.J. (2017): Laurite and zircon from the Finero chromitites (Italy): New insights into evolution of the subcontinental mantle. *Ore Geol. Rev.*, **90**, 210-225.

Morishita, T., Hattori, K.H., Terada, K., Matsumoto, T., Yamamoto, K., Takebe, M., Ishida, Y., Tamura, A., Arai, S. (2008): Geochemistry of apatite-rich layers in the Finero phlogopite–peridotite massif (Italian Western Alps) and ion microprobe dating of apatite. *Chem. Geol.*, **251**, 99-111.

Petersen, J.S., Morten, L., Simboli, G., Lucchini, F. (1980): REE abundances in the Predazzo-Monzoni intrusive complex, Dolomites, North Italy. *Riv. Ital. Paleontol. S.*, **85**, 1065-1080.

Putirka, K.D. (2008): Thermometers and barometers for volcanic systems. *Rev. Mineral. Geochem.*, **69(1)**, 61-120.

Putirka, K.D. (2016): Amphibole thermometers and barometers for igneous systems and some implications for eruption mechanisms of felsic magmas at arc volcanoes. *Am. Mineral.*, **101**, 841-858.

Putirka, K.D., Johnson, M., Kinzler, R., Longhi, J., Walker, D. (1996): Thermobarometry of mafic igneous rocks based on clinopyroxene-liquid equilibria, 0-30 kbar. *Contrib. Mineral. Petr.*, **123(1)**, 92-108.

Schaltegger, U., Ulianov, A., Müntener, O., Ovtcharova, M., Peytcheva, I., Vonlanthen, P., Vennemann, T., Antognini, M., Girlanda, F. (2015): Megacrystic zircon with planar fractures in miaskite-type nepheline pegmatites formed at high pressures in the lower crust (Ivrea Zone, southern Alps, Switzerland). *Am. Mineral.*, **100**, 83-94.

Sloman, L.E. (1989): Triassic shoshonites from the dolomites, northern Italy: alkaline arc rocks in a strike-slip setting. *J. Geophys. Res.-Sol. Ea.*, **94(B4)**, 4655-4666.

Spera, F.J. & Bohrson, W.A. (2001): Energy-constrained open-system magmatic processes I: General model and energy-constrained assimilation and fractional crystallization (EC-AFC) formulation. *J. Petrol.*, **42(5)**, 999-1018.

Stähle, V., Frenzel, G., Hess, J.C., Saupé, F., Schmidt, S.T., Schneider, W. (2001): Permian metabasalt and Triassic alkaline dykes in the northern Ivrea zone: clues to the post-Variscan geodynamic evolution of the Southern Alps. *Schweiz. Miner. Petrog.*, **81(1)**, 1-21.

Stampfli, G.M., Borel, G.D., Marchant, R., Mosar, J. (2002): Western Alps geological constraints on western Tethyan reconstructions. *J. Virtual Expl.*, **8**, 77.

Stampfli, G.M. & Borel, G.D. (2004): The TRANSMED transects in space and time: constraints on the paleotectonic evolution of the Mediterranean domain. *In*: "The TRANSMED Atlas: The Mediterranean region from crust to mantle", W. Cavazza, F.M. Roure, W. Spakman, G.M. Stampfli, P.A. Ziegler, eds. Springer-Verlag, Heidelberg-Berlin (Germany), 53-80.

Storck, J.C., Brack, P., Wotzlaw, J.F., Ulmer, P. (2019): Timing and evolution of Middle Triassic magmatism in the Southern Alps (Northern Italy). *J. Geol. Soc. London*, **176(2)**, 253-268.

Voshage, H., Hofmann, A.W., Mazzucchelli, M., Rivalenti, G., Sinigoi, S., Raczek, I., Demarchi, G. (1990): Isotopic evidence from the Ivrea Zone for a hybrid lower crust formed by magmatic underplating. *Nature*, **347(6295)**, 731-736.

Zaccarini, F., Stumpfl, E.F., Garuti, G. (2004): Zirconolite and Zr-Th-U minerals in chromitites of the Finero complex, Western Alps, Italy: evidence for carbonatite-type metasomatism in a subcontinental mantle plume. *Can. Mineral.*, **42(6)**, 1825-1845.

Zanetti, A., Mazzucchelli, M., Rivalenti, G., Vannucci, R. (1999): The Finero phlogopite-peridotite massif: an example of subduction-related metasomatism. *Contrib. Mineral. Petr.*, **134(2-3)**, 107-122.

Zanetti, A., Mazzucchelli, M., Sinigoi, S., Giovanardi, T., Peressini, G., Fanning, M. (2013): SHRIMP U-Pb Zircon Triassic intrusion age of the Finero mafic complex (Ivrea–Verbano zone, Western Alps) and its geodynamic implications. *J. Petrol.*, **54(11)**, 2235-2265.