Volcanology and petrology of Middle Triassic magmatism of the Dolomites (Southern Alps): Insights on architecture, dynamics and timescales of plumbing systems

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INTRODUCTION, GEOLOGICAL SETTING AND AIMS

Ancient magmatic systems offer crucial insights into processes typically hidden beneath active volcanoes. The Dolomites (Southern Alps, Italy) provide an exceptional case study, where both volcanic and plutonic rocks are well exposed and spatially connected. This rare preservation makes the region ideal for reconstructing the full architecture of a magmatic plumbing system. The Middle Triassic magmatic event, dated between ~237–242 Ma (Storck et al., 2019), shaped the NW Adria margin through the emplacement of volcanic and plutonic rocks across the South Alpine–Austroalpine domains, extending into the Dinarides and Hellenides (Sloman, 1989; Bonadiman et al., 1994; Pamić et al., 1998; Casetta et al., 2018a, b, 2019, 2021). In the Dolomites, extensive exposures of lava flows, plutons, volcaniclastic units, and dyke swarms are exceptionally well-preserved. The region was marked by high sedimentation rates in shallow marine carbonate platforms and intense localised extension (Doglioni, 1987). Despite this tectonic regime, the magmas exhibit orogenic geochemical characteristics, including LILE enrichment and depletion of Nb, Ta, and Ti. Various models have been proposed to explain this, such as inherited metasomatism from Variscan subduction (Sloman, 1989; Bonadiman et al., 1994).

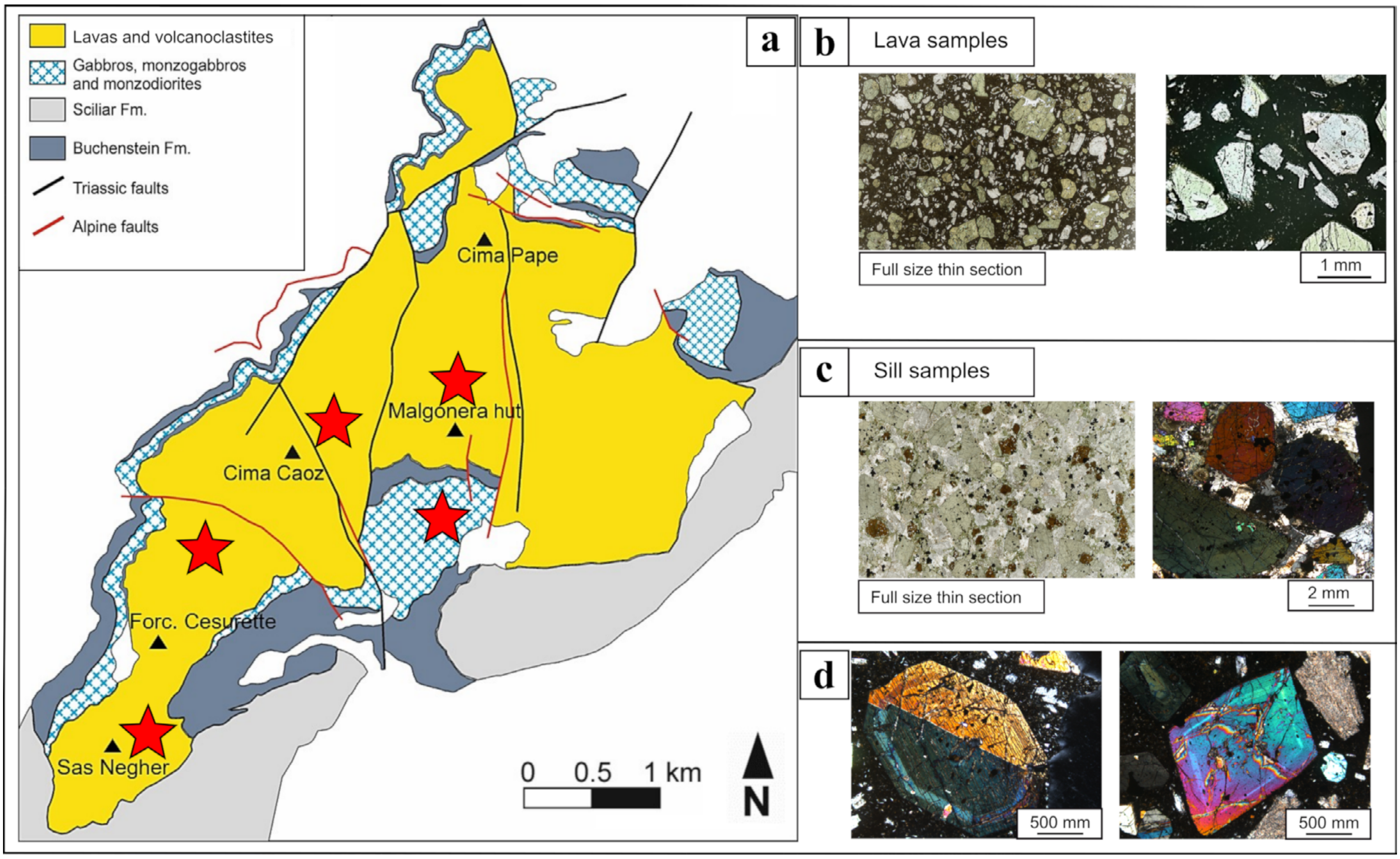

Figure 1 ***a)*** *Simplified geological map of the Cima Pape complex. Red stars indicate the sampling areas (modified from Nardini et al., 2022).* ***b)*** *Thin section scan and microphotograph of a representative lava sample.* ***c)*** *Thin section scan and microphotograph of a representative sample from the sill.* ***d)*** *Crossed-polar photomicrographs of clinopyroxene individuals showing high-Mg# and high-Cr intermediate band.*

This thesis aimed to reconstruct the geometry and dynamics of the main Dolomites' magmatic plumbing systems (*i.e.*, Predazzo, Mt. Monzoni, Cima Pape) by focusing on underexplored volcanic and subvolcanic rocks. Using tools typically applied to active volcanoes, the study treats the Dolomites as a natural-scale laboratory for volcanological research. The exceptional exposure of volcanic and intrusive rocks allows for direct comparison between surface and deep-crustal products, providing insights into magma storage and contributing to models of active systems. Additional objectives of the work were to define the petrology and geochemistry of the less-studied areas (*e.g.*, Cima Pape Complex, Sciliar) and improve the timeline of the magmatic pulses that composed the Middle Triassic occurrence in the Dolomites.

ANALITYCAL METHODS

Whole-rock major and trace element analyses of magmatic rocks considered were conducted at the Department of Physics and Earth Sciences, University of Ferrara (Italy), using an ARL Advant-XP automated wavelength-dispersive X-ray fluorescence spectrometer (WDXRF) and a Thermo Series X inductively coupled plasma mass spectrometer (ICP-MS). Major element analyses of mineral phases from representative samples were performed at the Department of Lithospheric Research, University of Vienna (Austria), using a CAMECA SXFive FE electron microprobe equipped with five WD and one ED spectrometers. Whole-rock $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ analyses were made at the Scottish Universities Environmental Research Centre (SUERC) by thermal ionisation mass spectrometry (TIMS). Trace element concentrations of clinopyroxene were measured at the CNR - Istituto di Georisorse of Pavia by laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS), while LA-ICP-MS element mapping of clinopyroxene was undertaken in the Imaging and Analysis Centre (IAC) at the Natural History Museum in London (NHM) using a Teledyne Iridia 193 nm system coupled to an Agilent 8900 ICP-MS. Detailed back-scattered electron (BSE) images for the diffusion chronometry calculations were acquired with the Jeol IT500 FEG-SEM and the FEI QUANTA 650 FEG-SEM, at the IAC at the NHM. Titanite crystals were analysed for U–Pb dating and simultaneous trace element analysis by laser ablation-inductively coupled-mass spectrometry (LA-ICP-MS) at the Institute of Geochemistry and Petrology, ETH Zurich, Switzerland, using a RESOlution S-155 (ASI/Applied Spectra) 193-nm ArF excimer laser ablation system connected to an Element XR (Thermo) sector-field ICP-mass spectrometer. Zircon separates were dated at Purdue University (Indiana, USA) through Isotope Dilution Thermal Ionisation Mass Spectrometry (ID-TIMS).

RESULTS AND DISCUSSION

The Cima Pape Complex

A comprehensive sampling campaign targeted both intrusive and effusive lithologies, including trachybasaltic to basaltic trachyandesitic lava flows, pillow breccias, and a 50–300 m thick gabbroic to monzodioritic sill (Fig. 1). The volcanic rocks are highly porphyritic (PI up to 50%) and dominated by clinopyroxene phenocrysts displaying complex zoning: augitic cores, concentric high-Mg# (up to 91) and Cr-rich diopsidic bands (up to 1.2 wt.%), and LILE- and LREE-enriched augitic rims. In contrast, clinopyroxenes in the sill are largely homogeneous and unzoned, reflecting slower cooling conditions.

Whole-rock geochemistry confirmed a SiO_2-saturated, shoshonitic affinity typical of orogenic magmatism (Peccerillo and Taylor, 1975), and Sr-Nd isotopic signatures ($^{87}Sr/^{86}Sr_i$ = 0.7045–0.7050; $^{143}Nd/^{144}Nd_i$ = 0.51223–0.51228) highlighted derivation from an enriched lithospheric mantle source (Bonadiman et al., 1994; Lustrino et al., 2019). Thermobarometric and hygrometric modelling (Putirka, 2008; Perinelli et al., 2016) revealed a vertically zoned plumbing system: augitic cores crystallised at 7–14 km depth from evolved, H_2O-rich melts (T = 1035–1075°C; H_2O = 2.6–3.8 wt.%), followed by the injection of hotter, more primitive basaltic magmas (T = 1130–1150°C; H_2O = 2.1–2.8 wt.%) responsible for the formation of high-Mg#, Cr-rich diopsidic bands. Rim re-equilibration with hybrid magmas occurred during later stages of ascent, while microphenocrysts and outer rims crystallised under shallow conditions (50–150 MPa; T = 975–1010°C). The zoned clinopyroxene population observed for the first time in the Dolomitic area is similar to those reported in the products of active volcanoes such as Stromboli and Etna which is consistent with similar processes among plumbing systems (Giacomoni et al., 2014, 2016; Petrone et al., 2018; Di Stefano et al., 2020). These findings provide the first investigation into the pressure and temperature conditions of magma storage in the ancient Cima Pape volcano alongside the first evidence of recharge and mixing dynamics in the Dolomites, captured through crystal-scale zoning. The study underscored the utility of clinopyroxene zoning as a tool for reconstructing magmatic processes and highlights how fossil systems like Cima Pape can serve as analogues for modern volcanism, advancing our understanding of Mid-Triassic magmatism and crustal evolution in the Southern Alps.

Magma mixing in the Dolomites: dynamics and timescales

Starting from the outcomes of the investigation on the Cima Pape complex, this study aimed to reconstruct the architecture and dynamics of ancient magma plumbing systems in all the main Middle Triassic volcano-plutonic complexes of the Dolomites (Southern Alps). The set of magmatic rocks investigated for this study involved only volcanic and subvolcanic (*i.e.*, dykes) samples from Predazzo, Mt. Monzoni, Cima Pape and Sciliar, all exhibiting transitional to alkaline basaltic to trachybasaltic compositions and porphyritic textures (PI 30-55%). The zoning pattern observed in the clinopyroxene population hosted by the rocks from Cima Pape is also present in the other centres. Augitic cores (Mg# 67–78) are typically mantled by high-Mg#, Cr-rich diopsidic bands (Mg# 77–91; Cr_2O_3 up to 1.2 wt.%) and overgrown by augitic rims with or without oscillatory zoning. However, the zoning pattern became more complex: Textural types include diopsidic, resorbed to highly resorbed and/or patchy cores, as well as sector-zoned varieties, along with aggregates or glomerocrysts that share zoning histories, indicating complex crystallisation environments (Fig. 2). To codify this diversity, a classification of the clinopyroxene has been made: Type A crystals with augitic cores (subtype A0 = unzoned augite; A1 = augitic core with one diopsidic band; A2 = augitic core with multiple diopsidic bands), Type B crystals with diopsidic cores (B0 = no bands; B1 = one diopsidic band; B2 = multiple bands), and Type C crystals showing sector zoning (C0 = sector-zoned augite; C1 = sector-zoned with diopsidic band).

The compositions of resorbed and patchy diopsidic cores are mirrored by diopside in clinopyroxenitic xenoliths from the Latemar area, which is in equilibrium with a trachybasaltic melt. Diopsidic cores in lava and dyke samples, likely representing fragments of a deeper reservoir subsequently cannibalised during mafic recharge events. Whole-rock and melt inclusion chemistry confirms a shoshonitic signature, consistent with mantle-derived magmas metasomatised during earlier Variscan subduction (Bonadiman et al., 1994; Casetta et al., 2021), and supports prior interpretations

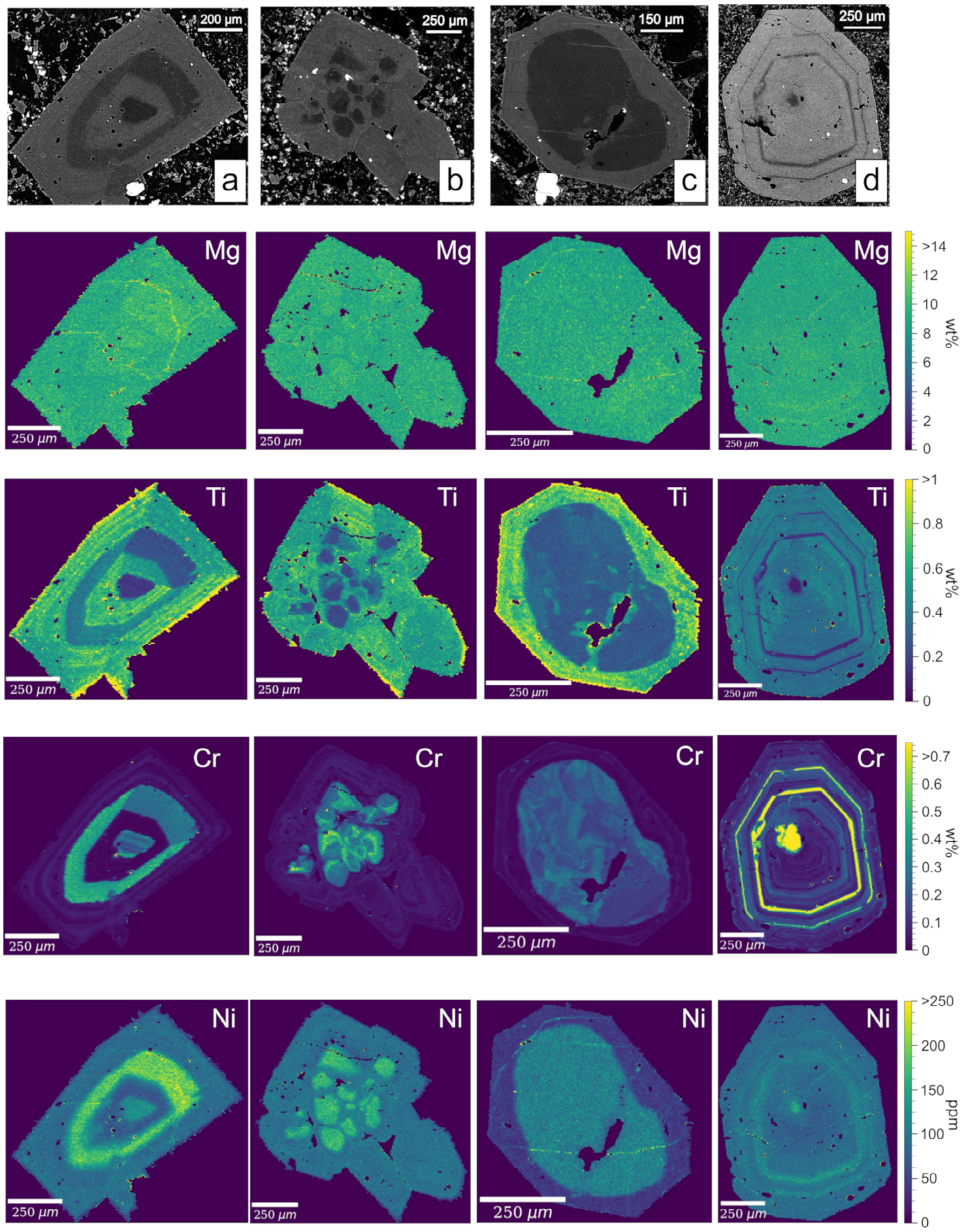

Figure 2 Major and trace element chemical mapping of clinopyroxene crystals from the Dolomites. BSE images (top) and quantitative chemical mapping of Mg, Ti, Cr and Ni for four representative clinopyroxene crystals. ***a)*** Type B1, ***b)*** and ***c)*** Type B0 (mottled core and resorbed diopsidic) and ***d)*** B2 (highly resorbed diopsidic core) from left to right (from Nardini et al., 2024).

of calc-alkaline magmatism in an extensional regime. Thermobarometric modeling using clinopyroxene-only formulations (Wang et al., 2021; Higgins et al., 2022) combined with clinopyroxene-based melt hygrometry (Perinelli et al., 2016) reveals that augitic domains crystallised at mid-crustal levels (5–8.5 km, 150–250 MPa) from trachyandesitic melts (T = 1044–1118°C, H_2O ≈ 2.8 wt.%), while the diopsidic zones record injection of more primitive, hotter trachybasaltic magmas (T = 1056–1170°C). The deepest pressures (300–500 MPa; 10–17 km) are associated with patchy-zoned and highly resorbed diopsidic cores, indicating crystal storage and recycling from a lower crustal mush (Fig. 3).

Diffusion chronometry using Fe–Mg interdiffusion profiles through the NIDIS model (Petrone et al., 2016) resolved magma recharge and mixing timescales from weeks to decades, with differences between the centres (Fig. 4).

Type B0 clinopyroxenes from Mt. Monzoni suggested rapid pre-eruptive ascent (< 1 year), whereas Types A1–A2 and B1–B2 crystals from Cima Pape and Predazzo indicated prolonged residence (up to 80 years), likely reflecting differing thermal regimes and conduit connectivity (Fig. 4). The occurrence of double plateaux in diopsidic bands and anomalous diffusion gradients further testifies to instant growth rates and incomplete melt mixing. Sector zoning and Ti-enrichment in lavas indicate variable undercooling rates, reinforcing the interpretation of dynamic, convective magmatic systems with evolving physical conditions. Overall, the study provided compelling evidence for episodic magma recharge, antecryst recycling, and polybaric crystallisation within the Middle Triassic vertically-extended plumbing systems in the Dolomites. The consistent patterns of clinopyroxene chemistry and zoning across different centres suggest regionally coherent magma dynamics, while local differences in zoning style, diffusion rates, and undercooling reflect individual reservoir histories.

Timing and Evolution of Predazzo Magmatism

The Middle Triassic magmatism in the Predazzo area is marked by the emplacement and eruption of compositionally diverse magma batches within a short time frame. New geological surveys documented the presence of phonolite dykes cutting across Middle Triassic volcanic sequences. These phonolites have porphyritic texture (Pl 5-10%) and are sodalite- and aegirine-bearing, with titanite, apatite, and magnetite as accessory phases. Geochemically, they retain a distinct orogenic-like trace element signature, with enrichment in LILE and LREE and depletion in Nb–Ta–Ti, in line with other

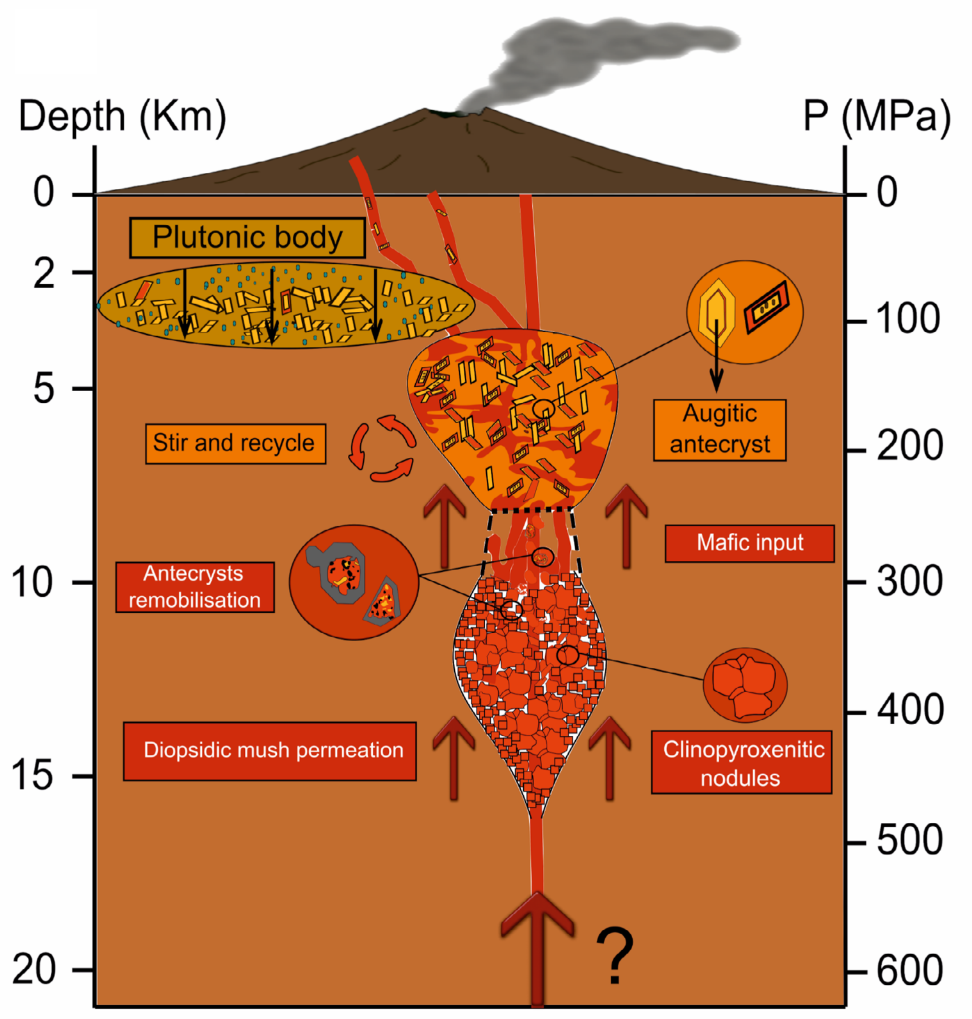

Figure 3 *Sketch of a general feeding system beneath the Mid-Triassic volcanoes in the Dolomites. The mafic input recycles diopsidic antecrysts permeating the diopsidic mush (witnessed by clinopyroxenitic nodules) in the shallower trachyandesitic magma reservoir (Type B crystals) and mantle the augitic antecrysts (previously formed in the more evolved reservoir) with diopsidic bands (Type A1 and A2 crystals) (modified from Nardini et al., 2024).*

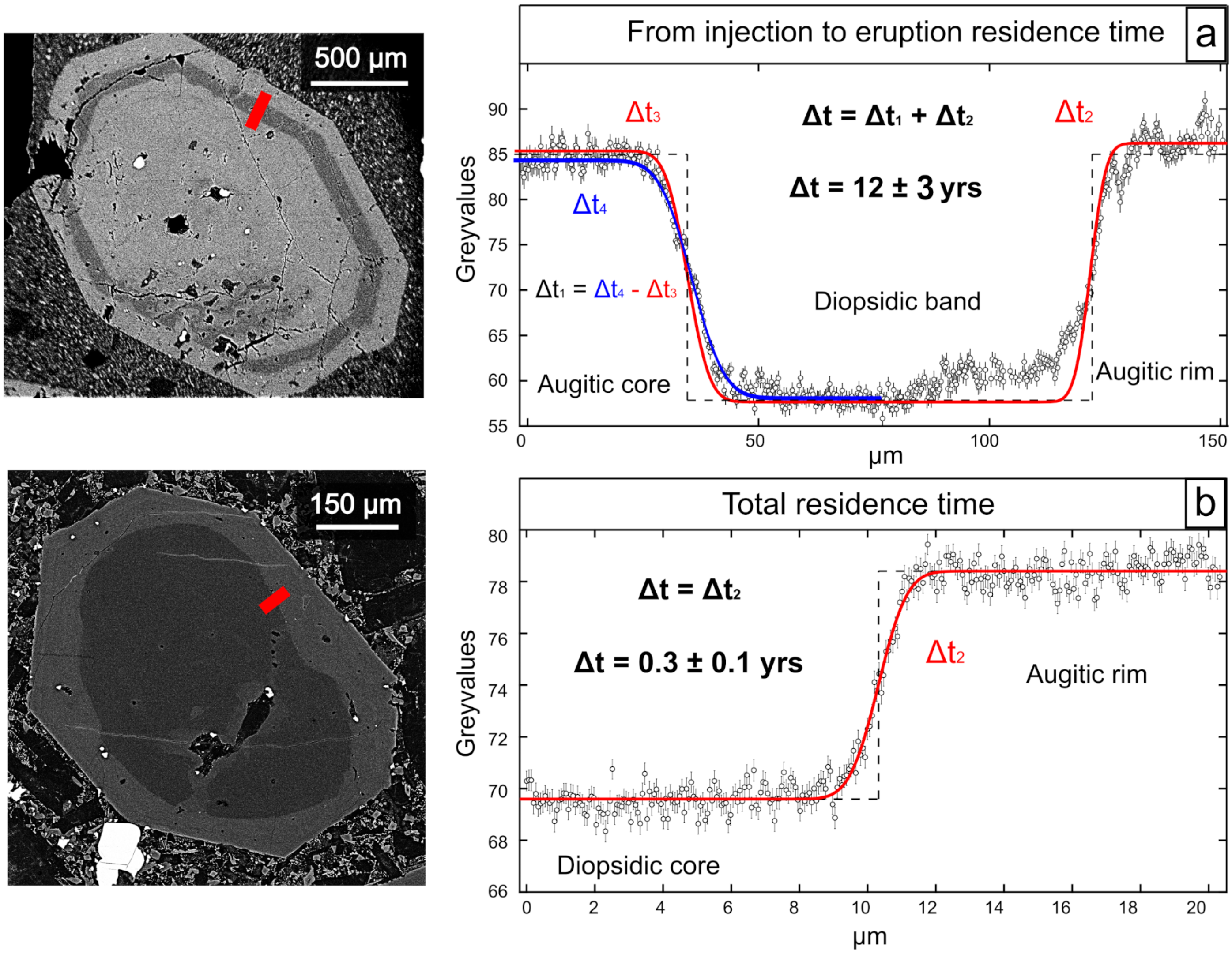

Figure 4 *Grey value diffusion profiles of two representative clinopyroxene crystals from the Dolomites calculated inside the red area of the associated BSE-SEM images.* ***a)*** *Diffusion profile of a crystal from Cima Pape; the computation expresses the timescale from mafic injection to the eruption.* ***b)*** *Diffusion chronometry on a crystal from Mt. Monzoni expressing the total residence time of the diopsidic antecryst in the evolved magma (at the evolved magma conditions of T), which corresponds to the time from the mafic input to the eruption (modified from Nardini et al., 2024). For the explanation of Δt_1, Δt_2, Δt_3 and Δt_4, the reader is referred to Petrone et al. (2016) or Nardini et al. (2024).*

Mid-Triassic magmas of the region and in contrast to other alkaline subvolcanic manifestations present in the area (*i.e.*, lamprophyres; Casetta et al., 2019).

Titanite and zircon U–Pb geochronology on phonolite dykes and representative samples from every magmatic suites of the Predazzo pluton (Silica Saturated suite (SS); Silica Undersaturated suite (SU) and Granitic Unit (GU); see Casetta et al., 2018a, b) represented the first complete chronological framework for the Predazzo volcano-plutonic complex. Zircon dating of the plutonic units yields crystallisation ages between 237.97 ± 0.15 Ma and 238.31 ± 0.13 Ma, while titanite dating from phonolitic dykes indicates emplacement between 233.8 ± 3.1 Ma and 238.1 ± 4.5 Ma (Fig. 5). These overlapping age ranges, coupled with the presence of sodalite as phenocryst, confirmed that both silica-saturated and -undersaturated magmas were emplaced in a geologically brief interval during the Middle Trias, consistent with earlier studies (Casetta et al., 2018a, b). Additionally, phonolite dykes age is coherent with those of volcanic and plutonic manifestations documented in literature (Storck et al., 2020). Mineral-based thermometry and hygrometry indicate that the phonolites represent volatile-rich (H_2O = 8 ± 0.6 wt.%), REE-enriched, highly differentiated melts, emplaced at relatively low temperatures (752–868°C), potentially driving associated Cu–W mineralisation. Comparison with subvolcanic rocks from the Central (Edolo) and Western Alps (Finero) highlights the regional persistence of this signature across the Southalpine domain before the opening of the Alpine Tethys.

Volcano-Plutonic Link and Evidence of Magma Recharge in Plutonic Rocks

Clinopyroxene crystals from mafic intrusive rocks in the Dolomites (Predazzo, Mt. Monzoni, and Cima Pape) have been selected to investigate their texture (if any) in response to the plumbing system dynamics studied in lava and dyke samples. Only the most mafic rocks have been chosen (augite-bearing clinopyroxenites, gabbros and monzogabbros) based on two main

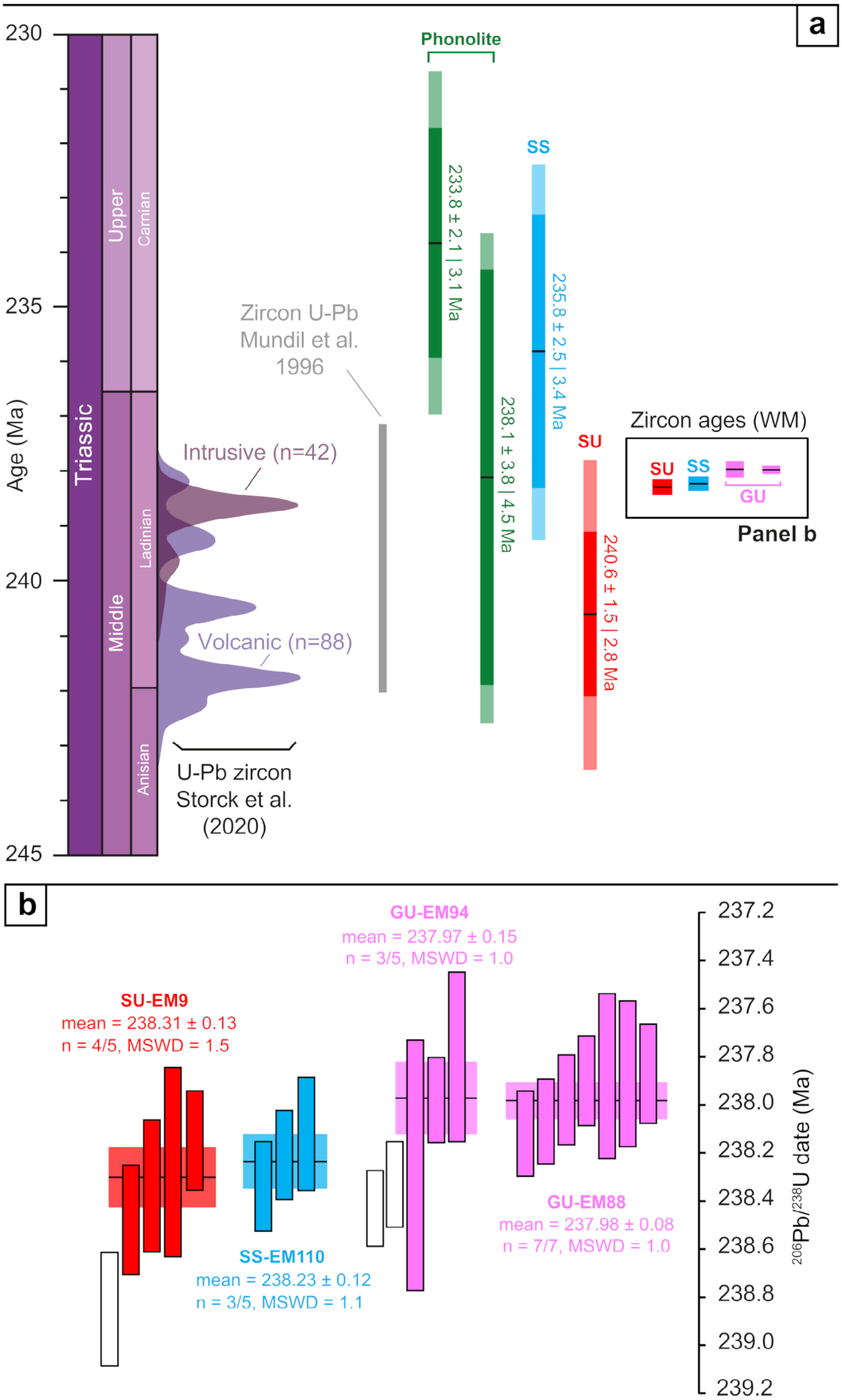

Figure 5 a) *U-Pb ages on titanites obtained in this work compared to literature studies on the same area (Storck et al., 2020).* ***b)*** *Rank-order plot of CA-ID-TIMS zircon dates. Coloured bars represent Th-corrected ID-TIMS $^{206}Pb/^{238}U$ dates of individual zircon crystals with their 2σ uncertainty (from Nardini et al., 2025).*

reasons: *i)* to compare effusive rocks with their intrusive equivalents–gabbros and clinopyroxenites were selected because the effusive rocks are primarily basalts to basaltic trachyandesites; *ii)* the most mafic plutonic rocks are richest in clinopyroxene, which consistently serves as the dominant primary cumulus mineral. Textural and compositional studies on clinopyroxene populations reveal compelling evidence for magma mixing. As already observed in lavas and dykes clinopyroxene population (Nardini et al., 2024), two distinct compositional domains, augitic and diopsidic, were identified across all intrusions, with diopsidic zones marked by higher Mg# (79-90) and Cr_2O_3 (up to 0.6 wt.%) contents compared to augite (Mg# 62-77; Cr_2O_3 < 0.1 wt.%). Zoning patterns, including diopsidic cores and bands, indicate the periodic intrusion of more primitive melts into crystallising magma bodies, mirroring patterns observed in volcanic rocks from the same region (Nardini et al., 2022, 2024). Pressure estimations on clinopyroxene significantly refined the depth of the main, more evolved ponding zone, indicating shallower levels (1.5 and 5.5 km) than previously calculated within the volcanic rocks. Additionally, it is now possible to distinguish between different formation pressures of the diopsidic cores and bands. The diopsidic cores appear to have formed at greater depths than the associated bands, a difference not observed in the volcanic equivalents. This discrepancy provides further evidence in support of the model developed through textural and compositional analysis of clinopyroxenes in effusive rocks.

The newly acquired pressure data for diopsidic cores crystallisation closely match the pressure estimates for the Latemar nodules (Nardini et al., 2024). This supports the interpretation that these cores are older diopside crystal fragments from the Latemar nodules, entrained by the mafic input and transported to shallower levels of the magmatic plumbing system. Ultimately, these nodules became incorporated into lavas and dykes, leading to their present-day exposure.

The preservation of compositional zoning, despite the expected diffusive re-equilibration in plutonic settings, supports earlier inferences of rapid cooling for the Predazzo and Mt. Monzoni plutons (Bonadiman et al., 1994; Casetta et al., 2018a). The connection between these intrusive textures and coeval volcanic counterparts strengthens the volcano-plutonic link and reveals the geometry of vertically structured magma storage zones. Furthermore, the presence of diopsidic rims and bands unique to intrusive rocks suggests crystallisation events not preserved in surface products, offering direct insight into processes often inferred in active systems.

CONCLUSIONS AND FUTURE PERSPECTIVES

This thesis makes a comprehensive contribution to the understanding of Middle Triassic magmatism in the Southern Alps, providing enhancements in both the fine-scale dynamics of magma systems and the broader geological framework of the region.

At the small scale, detailed petrological and geochemical analyses of clinopyroxene crystals from key volcano-plutonic complexes like Predazzo, Mt. Monzoni, Cima Pape, and pivotal magmatic manifestations near the Sciliar and Lateman carbonate platforms have allowed the reconstruction of magma plumbing systems with unprecedented resolution. The results indicate that volcanism in these centres was governed by episodic magma recharge events from deep-seated mafic inputs that remobilised mid-crustal mush zones before feeding shallower reservoirs, with crystallisation sequences and convection processes revealing complex magmatic interactions. Tectonic processes, particularly trans-tensive regimes, were shown to play a pivotal role in facilitating magma ascent and eruption, especially in centres like Predazzo and Cima Pape, where diffusion chronometry on clinopyroxene crystals revealed years to decades of injection to eruption timescales. These interpretations were further refined through complementary studies on intrusive and ultramafic rocks, offering new insight into the deeper magmatic roots of these systems and proposing a refined methodology for plumbing system reconstruction, exploring the volcano-plutonic link.

At the large scale, this work has provided the first integrated petrological, geochemical, and isotopic characterisation of the Cima Pape volcano-plutonic complex in recent literature, establishing a clearer picture of its magmatic evolution and emplacement history. Additionally, the first documentation and dating of phonolitic dykes within the Predazzo complex have expanded the known compositional diversity of its subvolcanic units. Zircon and titanite U-Pb geochronology on phonolite dykes and coeval intrusive rocks has refined the timeline of magmatism at the Predazzo complex, highlighting a prolonged orogenic-like magmatism lasting into the Upper Triassic and distinguishing it from later rift-related lamprophyric events.

Altogether, this research significantly enhances our knowledge of Middle Triassic volcanic and plutonic processes in the Dolomites. It not only documents new magmatic episodes and reservoir dynamics but also establishes an innovative framework for the study of ancient and active volcanic systems. The approaches and results outlined here have the potential to inform future investigations into magma storage, transport, and eruption triggering, critical elements in both academic research and volcanic hazard assessment.

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