A hidden Oligocene pluton linked to the Periadriatic Fault System beneath the Permian Bressanone pluton, Eastern Southern Alps

Dario Visonà[a], Paolo Nimis[a,*], Anna M. Fioretti[b], Matteo Massironi[a], Igor M. Villa[c,d]

[a]Dipartimento di Geoscienze, Università di Padova, Padova, Italy; [b]Institute of Geosciences and Earth Resources (IGG-CNR), Padova, Italy; [c]Centro Universitario Datazioni e Archeometria, Università di Milano Bicocca, Milano, Italy; [d]Institut für Geologie, Universität Bern, Bern, Switzerland

*: corresponding author

Paolo Nimis

Dipartimento di Geoscienze

Via G. Gradenigo 6

35131 Padova (Italy)

paolo.nimis@unipd.it

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The Bressanone (Brixen) pluton, cropping out at the culmination of the Southalpine indenter between the North Giudicarie and the Pustertal-Gailtal faults, is mainly composed of Permian granodiorite to granite, with minor gabbros and diorites in its southern part. New U–Pb SHRIMP zircon ages reveal two distinct crystallization episodes at 289.7 ± 3.2 and 280 ± 2.2 Ma, respectively. The pluton is affected by a hydrothermal potassic to sodic + Cu metasomatic alteration, which has long been ascribed to a late phase of the Permian magmatism. In contrast with this hypothesis, we report new ^{39}Ar–^{40}Ar data for different generations of metasomatic K-feldspar, which indicate formation ages between 35.3 ± 0.3 and 27.8 ± 0.5 Ma. This interval overlaps with the ages of the widespread "Periadriatic" calc-alkaline magmatism, which extends from the Western to the Eastern Alps straddling the Periadriatic Fault System. The observed hydrothermalism has geochemical characteristics compatible with those of the coeval calc-alkaline Periadriatic magmatism. These data altogether suggest the release of fluids from a hidden intrusion during the main stage of the Alpine orogenic magmatism. Our results provide the first evidence of Oligocene magmatic activity in the Southern Alps east of the Giudicarie Line, bridging the gap between the western-central and eastern Alpine magmatic plutons. A fairly continuous Oligocene magmatic belt straddling the Periadriatic Fault System is consistent with a triggering of the magmatism by slab steepening or slab break-off, either of which are considered to be an essential driver for the Miocene lithospheric rearrangement in the Eastern Alps. Our finding is particularly relevant given that the outcropping area of the Bressanone pluton is centred above the imaged subducting lithosphere gap that separates the Western-Central and the Eastern Alps, hence at a location where mantle upwelling should have been easier although no relevant magmatism was found to date.

Keywords: alkali metasomatism; hydrothermalism; U–Pb zircon ages; ^{39}Ar–^{40}Ar feldspar ages; Alpine magmatism; Eastern Alps

1. INTRODUCTION

The crystallization of a granitic magma can give rise to the release of various types of hydrothermal fluids. The composition of these fluids depends on the physical conditions of crystallization and on the initial composition of the magma and, in particular, on the concentration and nature of volatile species, which may control the nature of the liquidus phases and, thus, the compositional evolution of the melt (Pirajno 2003). The released magmatic-hydrothermal fluids tend to migrate upward under the influence of pressure gradients and may effectively transfer chemical components into the wall-rocks by advection and fluid infiltration through pores and fractures (Korzhinskii 1957; Anderson and Burnham 1965), and the consequent fluid–rock reactions (Helgeson 1971). These processes result in chemical and mineralogical modification of the wall-rocks (metasomatism) and deposition of hydrothermal minerals in open spaces, and may be associated with the formation of important disseminated, replacement or vein-type ore deposits (e.g. Sillitoe 2010). Alkali metasomatism, which involves the transfer of the alkali ions, mainly Na^+ and K^+, is one of the most typical early forms of metasomatism that occur within and around cooling granitic cupolas undergoing crystallization and fluid expulsion in several, chemically distinct stages. Albitite, microclinite, and potassic alteration (i.e. modal increase of K-bearing minerals such as K-feldspar, sericite, and biotite) in the core zones of porphyry metal systems are the most typical products of this type of metasomatism (Pirajno 2013). Evolution of the hydrothermal fluids upon migration due to cooling, depressurization and reaction with wall-rocks results in a transition from proximal alkali metasomatism to distal alteration types characterized by more abundant hydrous mineral assemblages (e.g. sericitic, argillic, etc.). Recognition of these distinctive alteration patterns may help identify paths of hydrothermal fluid circulation around magmatic centres and has long served as a guide to exploration of concealed mineral deposits (Govett 1983). Similarly, the presence of alteration patterns may provide indirect evidence for the occurrence of hidden magmatic bodies at depth.

In the present study, we discuss the origin of metasomatic rocks (‘red granites’ and associated products) within the Permian Bressanone (Brixen) granodiorite pluton, eastern Southern Alps, Italy. The Bressanone pluton is tectonically juxtaposed with fragments of an Alpine pluton (Pennes–Mules–Chienes lamellae) and medium to high-grade metamorphic units of the Alpine orogenic wedge by the northern segment of the Giudicarie fault system (NGFS), including the North Giudicarie and Merano-Mules faults, and by the Pustertal–Gailtal fault (PGF). These faults are important fault zones representing the easternmost sector of the more than 700 km-long Periadriatic Fault System (e.g. Müller *et al.* 2001; Pomella *et al.* 2011) (Figure 1). In the 1960s, geological and petrographic surveys documented the presence of wide hydrothermalized zones within the western portion of the pluton, associated with previously known abundant, but small-volume hydrothermal veins with polymetallic sulphides (Gasser 1913; Krauss 1916; Favretto and Nardi 1960; Favretto 1963). According to current interpretation, the hydrothermal products within the Bressanone intrusion are the result of the circulation of magmatic-hydrothermal fluids related to the late magmatic activity of the pluton in the Permian (Favretto and Nardi 1959; Favretto 1963). Based on new field, petrologic, geochemical and geochronological data, we argue that this hypothesis is not tenable and that a genetic link with Oligocene Alpine magmatism is instead most likely. Our results provide evidence that middle Eocene to early Oligocene orogenic magmatism was not limited to the central Southern Alps but occurred in a continuous belt also in its eastern sector.

2. GEOLOGICAL BACKGROUND

2.1. The Southalpine domain

The Paleozoic basement of the eastern Southern Alps is made of rocks which were generally unaffected by regional Alpine metamorphism (e.g. Bargossi *et al.* 2010 and references therein). The Brixen Metamorphic Basement is divided into two metapelitic and metapsammitic units (Poli and Zanferrari 1992). In particular an Early Ordovician unconformity separates the Cambrian Lower Pelitic-Psammitic Complex, containing Early Ordovician felsic metavolcanic rocks (Meli and Klötzli 2001), from the Middle Ordovician-Carboniferous Upper Pelitic-Psammitic Complex containing Silurian(?) mafic metavolcanic rocks (Arboit *et al.* 2019). During the Devonian-Carboniferous Variscan orogeny, these sequences underwent low temperature-low pressure metamorphism with the general development of a greenschist-facies paragenesis (Sassi and Spiess 1993). High-temperature low-pressure facies, characterized by a sillimanite–cordierite– corundum association, have only been found in relatively small volumes of metapelites north of Bressanone (Benciolini *et al.* 2006). The basement is characterized by scattered outcrops of metapelite affected by contact metamorphism responsible for static recrystallisation for up to 200 m from the granodiorite (Scolari and Zirpoli 1971; Wyhlidal *et al.* 2012). In the Permian, the Variscan metamorphic basement was affected by extensive calc-alkaline volcanic-plutonic activity (Figure 1). The related intrusive and volcanic rocks are broadly coeval and have ages between ca. 290 and 275 Ma (Bellieni *et al.* 2010 and references therein). Their similar petrological and geochemical features indicate that the magmas had a significant mantle component. The Permian magmatism is post-collisional and post-orogenic and developed during a period of lithospheric extension and crustal thinning, which affected the entire European Variscan belt (Barth *et al.* 1993; Bonin *et al.* 1993; Rottura *et al.* 1998; Schaltegger and

Brack 2007).

The Permian volcanic complex of the eastern Southern Alps (Athesian Volcanic Complex) is bounded to the north and north-west by the M. Croce–Ivigna–Bressanone plutonic complex, which is separated from the Austroalpine units by the NGFS and PGF. North of the Bressanone pluton, two main younger plutons, Rensen and Vedrette di Ries, with allanite Th-U-Pb ages of 31.7 and 32.2 Ma, respectively (Barth *et al.* 1989; Romer and Siegesmund 2003), and several so-called "tonalitic lamellae" (Dal Piaz 1926), aged 39.9–32.2 Ma (Pomella *et al.* 2011), occur along the NGFS and PGF (e.g. the Mules and, at the easternmost margin of the Bressanone Pluton, Chienes lamellae; Figure 2a). The Rensen and Vedrette di Ries plutons and the tonalitic lamellae, as well as several other plutons intruded along the NGFS and PGF, are products of the "Periadriatic" magmatism in the Alps, which started in the middle–late Eocene and lasted for ca. 15 Ma, with pluton ages clustered between 42 and 28 Ma (Bergomi *et al.* 2015 and references therein). The tonalitic lamellae form an irregular belt wrung between the Austroalpine and Southalpine metamorphic basements and were interpreted as the result of melt channelling from a deep source region into the Periadriatic Fault System (Rosenberg 2004). In the interpretation by Pomella et al. (2011, 2012) the tonalitic lamellae cropping out along the North Giudicarie Fault were proposed to be sheared off from the Adamello batholith during indentation of the Southalpine units, based on the considerable left-lateral strike slip displacement accommodated by the NGFS, most of which has been thought to have taken place since the late Oligocene along the North Giudicarie segment (Pomella et al. 2011, 2012; Klotz et al. 2019; Verwater et al. 2021).

The late Eocene–Oligocene magmatism in the Alps has formerly been explained as the expression of a break-off of the subducting European plate and the consequent mantle upwelling (e.g. Blackenburg and Davis 1995; Schmid *et al.* 2013; Handy *et al.* 2014). This event could have been pivotal for a potential reversal of the subduction polarity in the Eastern Alps, which is suggested by tomographic imaging produced in the last decades (Lippitsch *et al.* 2003; Kissling *et al.* 2006; Zhao *et al.* 2016; Kästle *et al.* 2020) and is thought to have taken place since the Miocene (Schmid *et al.* 2004, 2013; Handy *et al.* 2014). In particular, whereas in the Western and Central Alps a steep southward European plate subduction is well imaged by teleseismic tomography, in the Eastern Alps the setting is unclear and the partial involvement of the Adria lithosphere in a northward subduction cannot be excluded. In more recent years, high quality seismic tomography from denser seismic arrays has questioned the slab break-off model at least for the Western and Central Alps, where the lateral and down-dipping continuity of the subducting European slab is apparent (Zhao *et al.* 2016). This means that the Oligocene magmatism could instead have been generated by slab steepening and consequent mantle suction and corner flow as testified by northward decreasing of U-Pb ages of the Periadriatic intrusions in North-Western and Central Alps (Ji *et al*. 2019).

Whatever the mechanism responsible of the Cenozoic magmatism, a slab gap is apparent between the two opposite lithospheric settings of the Western-Central and Eastern Alps. This gap is exactly centred underneath the Bressanone pluton in plan view (e.g. Lippitsch *et al.* 2003; Kissling *et al.* 2006; Mitterbauer *et al.* 2011; Zhao *et al.* 2016). It is thus reasonable to speculate that mantle upwelling and magmatic intrusion should have been favoured in this key location, despite their evidence being limited to the sporadic tonalitic lamellae along the Periadriatic Fault System.

2.2 The Bressanone pluton

The Bressanone intrusive body is mainly composed of granodiorite to granite, with minor gabbro to diorite intrusive units located in the southern part of the pluton (see Online Resource Figure S1, modal QAPF classification diagram). The emplacement age of the Bressanone pluton was first reported to be 282±14 Ma (Rb–Sr whole-rock age; Del Moro and Visonà 1982). Recent dating carried out by Chemical Abrasion Thermal Ionization Mass Spectrometry (CA-TIMS) on five zircon grains separated from the Bressanone gabbroic complex of Dosso Lives (Lufiskofel, Figure 2A) provided a very precise $^{206}Pb/^{238}U$ age of 281.78 ± 0.04 Ma (Boscaini *et al.* 2020), confirming the link between gabbros and granodiorites/granites. Indeed, frequent mixing and mingling features are observed at the contacts between the mafic and felsic intrusions, suggesting comagmatic emplacement events (Bonin *et al.* 1993). In its north-western corner, where the pluton is in tectonic contact with the Austroalpine units and with the Pennes and Mules tonalitic lamellae (Visonà 1976; Pomella *et al.* 2011; Schiavo *et al.* 2015) (Figure 2B), the intrusion consists of granodiorite, granite (biotite and hornblende-bearing or garnet-bearing) and cordierite leucogranites with less frequent aplites and rare pegmatites (Visonà 1977). The granodiorite and the granite (hereafter GG) are white-grey, medium- to coarse-grained, mostly equigranular, rarely porphyritic rocks (Bellieni *et al.* 1979). The cordierite leucogranite typically crops out near the western side of the gabbro body and are finer and equigranular leucocratic rocks (Visonà 1980; Thöny *et al.* 2009).

The essential mineralogical assemblages of these granitoid rocks consist of variable modal proportions of quartz, K-feldspar, plagioclase, brown biotite and rare pargasitic hornblende, garnet and Fe-rich cordierite (sekaninaite; Visonà 1977, 1980). These rocks, as well as their microgranular mafic and schistose enclaves, may show an extensive hydrothermal alteration and exhibit a pink to dark red colour (Figure 3). The most altered GG (termed “graniti rossi”, i.e., “red granites” by Favretto and Nardi 1959) are cut by a dense stockwork of millimetric hydrothermal dark green or whitish veinlets mainly made of epidote or prehnite and frequently forming E–W elongated patches within the main intrusion (Figure 2B). In the same area, a network of hydrothermal quartz or quartz–calcite veins, sometimes with polymetallic sulphide mineralization (sphalerite, galena, chalcopyrite, pyrite) and, locally, fluorite and barite, cuts the plutonic rocks with two prevalent trends, NE–SW and E–W, respectively (Favretto 1963). These trends correspond to the directions of the NGFS and PGF, which intersect each other in this area (Figure 1). Based on field evidence, the "red granites" appear to be associated with the quartz-calcite veins (Favretto 1963). Locally, further reddish centimetric halos occur around millimetric fractures with various infills, which are spatially unrelated to the main hydrothermal vein network (Figure 4).

3. SAMPLE MATERIALS

Samples were collected in the central-western sector of the Bressanone pluton, between Fortezza (Franzensfeste), Mules and Montaccio di Pennes (Tatschspitze), close to and within the "red-granite" area, where alterations follow ca. E–W trends potentially related to the PGF (Figure 1). Thirteen "red granite" and seven GG samples, including three cordierite leucogranites, were collected for geochemical analyses.

Two samples of the main pluton (a granodiorite, sample 213, and a leucogranite, sample 320) were selected for U–Pb SHRIMP zircon dating. Sample 213 was collected from the right bank of the Isarco (Eisack) river 500 m north of the locality Le Cave (Gasstein). It is a white-grey, coarse-grained equigranular biotite granodiorite, containing plagioclase, quartz, K-feldspar, biotite, and rare hornblende. The calcic core of plagioclase (35% An) is mainly altered into kaolinite and sericite. Apatite, zircon, ilmenite, monazite and epidote are present in accessory amounts. Sample 320 was sampled from the Mt. Sella (Sattelspitze) leucogranitic stock, which intrudes the granodiorite south-west of Fortezza (Franzensfeste). It is an equigranular fine-grained two-mica cordierite granite, which consists of perthite, quartz, plagioclase, white mica, biotite and subhedral Fe-cordierite. Apatite, ilmenite and zircon are present in accessory quantities and are often included within cordierite and biotite.

An altered hydrothermal-metasomatic sample, exhibiting a red halo overprinting a pegmatite (sample 254, Riol, SW of Fortezza; Figure 2b), was collected for Ar–Ar dating. From this sample, four different feldspar varieties were separated by handpicking: one white plagioclase chip from the pegmatite (254a), one pink (254b) and one red (254c) K-feldspar chips from the same thin section counterface, and one pink-red chip (254d) from the same hand specimen, ca. 2–3 cm away from the thin section.

4. PETROGRAPHY OF THE ALTERED ROCKS

4.1 The "red granites"

The red granites show a medium- to coarse-grained texture, similar to that of the surrounding GG, and are often cross-cut by a network of up to 2 mm-wide, dark green or whitish veinlets (Figure 4). On average, the "red granites" have a lower quartz content than their host rocks and rarely show vuggy textures; the hydrothermal alteration is variably marked by formation of secondary K-feldspar and/or albite, dissolution of quartz, chloritization of biotite and crystallization of secondary intergranular quartz, carbonate, epidote, chlorite, sericite/muscovite, and biotite. The original magmatic hypidiomorphic texture is modified due to partial to almost total replacement of quartz by turbid (reddish) K-feldspar and albite (Figure 5A), which may occur in very variable volumetric ratios. The secondary K-feldspar replaces the magmatic plagioclase from cracks or crystal borders and is accompanied by formation of tiny colourless sericite lamellae and albite. In places, the secondary reddish K-feldspar overgrows relict crystals of magmatic K-feldspar. In some cases, the contact between the two generations of K-feldspar is marked by myrmekites. In a few cases, K-feldspar and quartz form thin intergranular films around primary and secondary minerals. In turn, K-feldspar (primary and secondary) is mantled by albite (Figure 5B) and more rarely forms a chessboard texture with it (Figure 5C). Secondary albite is never replaced or mantled by K-feldspar. Some intensely altered rocks are transformed into red albitites made of equant albite, chlorite, scarce white mica lamellae and mostly intergranular sericite. The above transformations are accompanied by replacement of biotite and, when present, amphibole by chlorite (titanite) and, in places, by formation of small muscovite lamellae and new biotite. In some samples, quartz has completely disappeared in favour of turbid K-feldspar and albite, which forms millimetric euhedral crystals in a matrix of smaller crystals, leaving dissolution voids that give the rock a vuggy appearance (Figure 5D). The altered rocks are cut by widespread veinlets, which may contain calcite, epidote, chlorite, K-feldspar, sericite, limonitized pyrite ± quartz in very variable proportions.

In the areas surrounding the red alteration, the GG minerals locally show incipient deformation and alteration, which are mainly concentrated along centimetric bands. Deformation is indicated by undulose extinction and irregular grain boundaries of quartz and by fracturing and bending of plagioclase and biotite grains. Alteration is shown by transformation of calcic cores of plagioclase into kaolinite, sericite and, rarely, zoisite, and of biotite into chlorite, sometimes with formation of small muscovite lamellae and, more rarely, epidote (Favretto and Nardi 1959; Visonà 1977). Cataclastic fabrics are rare, and usually consist of networks of up to a few millimetre-wide fractures; in this case, the angular rock fragments are surrounded by chlorite and the fine-grained matrix usually contains albite-chlorite veinlets (< 0.5 mm).

4.2 Veins with red halos

Prehnite-rich and epidote-rich millimetric (up to 2 mm wide) veins with red halos occur in the granodiorite around of the "red granites". In the *prehnite-rich veins* (e.g. sample 276, Figure 4A), prehnite is the dominant mineral and often forms radial aggregates that protrude from the selvages into the vein. Other minerals are reddish-brown K-feldspar, scarce yellow-pleochroic epidote, apatite, euhedral poikilitic quartz and rare chlorite. K-feldspar, epidote and chlorite may also occur in the country-rock along the vein selvages or in microfractures of the magmatic minerals. The *epidote-rich veins* (e.g. sample 254, Figure 4B) contain variable proportions of yellow-pleochroic epidote, K-feldspar, albite, calcite, chlorite and quartz, sometimes with minor amounts of limonitized pyrite. Both vein types may show incomplete infill textures, with small-elongated cavities aligned parallel to the selvages.

4.3 The red halos

Near the selvages of the prehnite-rich and epidote-rich veins, the magmatic minerals of the host-rocks are fractured and deeply altered. The quartz grains show undulose extinction and are extensively replaced by K-feldspar. Biotite is completely replaced by chlorite and opaque minerals. Plagioclase has albitic composition and contains numerous tiny lamellae of colourless phyllosilicate; it is frequently corroded and replaced by K-feldspar. K-feldspar is abundant and forms both euhedral crystals with albite mantles and intergranular grains; it is always dark red and weakly perthitic. Small anhedral quartz grains are interstitial to the larger feldspar and quartz crystals. The intensity of alteration rapidly decreases away from the veins. At a distance of about two centimetres, the country-rock has its normal grey colour, but the minerals still show the effects of deformation and alteration: quartz shows undulose extinction and irregular grain boundaries; plagioclase exhibits large cores replaced by kaolinite and sericite and an albitic rim; biotite is deformed and partially transformed into chlorite + opaques ± titanite; K-feldspar is weakly kaolinitized.

5. GEOCHEMISTRY

Major and selected trace element whole-rock analyses of thirteen metasomatized rocks ("red granites") and of eight samples of unaltered rocks (five GG and three cordierite leucogranites) are reported in Table 1. Based on petrographic features, eleven of the metasomatized rocks are granodiorites or granites (GG) and two are mafic microgranular enclaves (MME).

The covariations of several elements vs. yttrium are shown in Figure 6. The use of Y as reference is suggested by its strict relation with the degree of magmatic evolution and weak mobility in aqueous fluids under hydrothermal conditions. This ensures robust comparisons between altered and unaltered rocks. Considering the covariations of major elements vs. Y, the "red granites" generally overlap with the unaltered rocks (GG) for MgO and TiO_2 (one outlier, 273), but occupy wider fields for SiO_2, Al_2O_3, Fe_2O_{3tot}, CaO, Na_2O and K_2O (Figure 6). We note that the two samples with the lowest SiO_2 contents (275 and 375) are richer in Al_2O_3 and that most of those that are rich in Na_2O have lower CaO content, as expected for plagioclase albitization. As for the trace elements, Rb and Sr show a similar behaviour as Ca. Among chalcophile metals, only Cu and, locally, Zn are noteworthy, because they are higher in the "red granites". As expected, Th is positively correlated with Y and shows a similar range in the "red granites" and in the GG. The MME are clearly distinct by their higher

Y concentrations, but show a range in Al_2O_3, Na_2O, K_2O, and CaO similar to that shown by the "red granites" (Figure 6).

The three analysed cordierite-bearing leucogranites are shown in the same plots for comparative purposes. They exhibit lower CaO, MgO, TiO_2, Fe_2O_{3tot}, Sr and Zr, but, on average, higher Rb contents and A/CNK ratios than the GG (Table 1). These features suggest derivation from anatexis of alluminiferous metapelites.

As for the REE (Figure 7), the red granites show similar patterns and similar or slightly lower REE concentrations as compared with the GG and cordierite leucogranites. By contrast, the "red" MME 310 is characterized by a Light REE (LREE)-depleted, bell-shaped pattern resembling that of typical basic igneous rocks, but with a moderate La/Nd fractionation.

6. GEOCHRONOLOGY

6.1. U–Pb SHRIMP zircon dating of the main pluton

Zircon grains from three lithologically different samples from the Bressanone pluton were separated and analysed by Sensitive High-Resolution Ion MicroProbe (see Online Resource 1.3, analytical methods) to obtain the age of their host rock. All analytical data are listed in the Supplementary Material (Online Resource, Table S2).

The selected samples from the main GG suite are one coarse-grained equigranular biotite granite (sample 213; see Figure 2 for location) and one fine-grained two-mica cordierite granite (samples 320). Zircon analyses were mostly carried out on magmatically zoned crystal rims, aiming at defining the age of crystallization and emplacement of its host rock.

Sample 213 contains abundant 100–300 µm-large, euhedral clear zircon grains with abundant inclusions, among which apatite, small radioactive minerals (monazite?)

and fluid inclusions were identified. Based on CL imaging, zircon crystals display thin oscillatory magmatic zoning and sometimes include round inherited, discordant zircon cores. SHRIMP U–Pb analyses carried out on 9 grains yielded a concordant age of 279.9 ± 2.2 Ma (Figure 8), which we interpret as the crystallization age of the rock. Five slightly older euhedral magmatic grains yield a mean $^{206}Pb/^{238}U$ age of 289.7 ± 3.2 Ma (MSWD 0.04; probability 0.997) and provide evidence of zircon inheritance from an older magmatic phase.

Sample 320. In this cordierite granite the zircon grains are small (up to 150 µm), full of cracks, euhedral and locally show rounded tips. In transmitted light and CL, zircon shows intense metamictic alteration marking the planes of the original zoning. CL imaging shows traces of the original thin magmatic zoning of zircon, which now appears smoothed and partially obliterated, possibly due to interaction with later fluids. U–Pb–Th SHRIMP analysis was carried out on nine rims of eight crystals. The analyses turned out to be mostly discordant and we could not define a coherent population of ages suitable for a precise dating. Four grains (401.1, 401.2, 402.1, 407.1) have U and Th contents >1000 ppm and high common lead and are deeply altered; two grains, ca. 995 and 465 Ma old, respectively, represent inheritance from the source crustal rocks. A single grain (408.1) yields a $^{206}Pb/^{238}U$ age of 281.9 ± 2.4 Ma that is consistent with the emplacement age obtained from sample 213.

6.2. ^{39}Ar–^{40}Ar dating of the metasomatic events

Stepwise heating analyses were performed on “red” K-feldspars from an epidote-rich metasomatic halo overprinting a pegmatite (sample 254, SW of Fortezza; see Figure 2 for location; see Online Resource 1.3, analytical methods). Chip 254d was analysed after ^{37}Ar had decayed and provides no information about its Ca/K ratio; the three chips

254a, 254b and 254c had a well-resolved ^{37}Ar signal.

All four chips of halo sample 254 yield disturbed age spectra (Figures 9A, 10A) and disturbed Cl/K–age and Ca/K–age correlations (Figures 9B–C and 10B–D). The observation of chronological and compositional discordance suggests that at least five mineral generations were present in the cm-sized rock sample 254: the magmatic plagioclase, its alteration product, and several (at least three) generations of metasomatic K-feldspar. The inventory of the feldspar generations is constrained by the common-denominator three-isotope correlation diagrams (Villa *et al.* 1996; Villa 2001). Figures 9B-C show the Ca/K–age and Cl/K–age correlation diagrams for plagioclase chip 254a and pink K-feldspar chip 254b (as a representative of the three metasomatic chips). Neither chip defines a linear trend, as would happen in the case of a simple binary mixture (Villa 2001) between a primary mineral and a secondary alteration phase. In particular, the plagioclase requires at least three components, i.e., the original magmatic mineral was modified by two (or more) different secondary reactions. In the absence of TEM work, which was not available in the present project, it was not possible to assess the presence of potential secondary phases that may be < 1 μm. Nonetheless, none of the secondary reactions that affected the plagioclase involved a reactant that had the Ca/Cl/K or the age signature of the pink-red metasomatic feldspars. The primary age of the plagioclase is likely to be $\geq 241 \pm 3$ Ma. The precise age is not considered decisive, as it is clear that the pegmatite was emplaced during the Variscan magmatic cycle (Del Moro and Visonà 1982).

The three metasomatic K-feldspars 254b–d yielded broadly similar data, but with resolvable individual differences. Their age can be constrained by the steps having the lowest Cl/K ratio, as feldspars are nominally Cl-free (Smith 1974). The three samples describe different trajectories in the Cl/Ca/K correlation diagrams and in the

Cl/K–age correlation diagram (Figures 10a–d and 11). For each sample, the minimum polygon that encloses the data points (Villa 2001) is a triangle, whose vertices represent the feldspar generations in the samples. All three K-feldspar samples are compatible with a protracted growth and fluid-assisted recrystallization history. The different positions of the data points in the correlation diagrams are explained by the formation of the haloes by separate individual pulses of aqueous fluids that differed slightly in their composition. The inventory of the metasomatic phases can be exemplified by Figure 11. The pink and red K-feldspars, 254b and 254c, show two similar V-shaped trajectories, each requiring the mixing of three end-members. The first heating step of red feldspar plots as a Cl-rich end-member, R1, having a Cl/Ca ratio $\geq$ 1.24 and an apparent age $\geq$ 87 Ma, which possibly represents nm-sized relicts from the magmatic host of the hydrothermal vein; the three subsequent steps define a trend with a positive slope, which has a cusp at end-member R2 (Cl/Ca = 0.03, apparent age = 41.4 $\pm$ 0.2 Ma); this step has the highest Ca/K ratio of the sample (Supplementary Table S2); at higher temperature, the trend acquires a negative slope and points towards an end-member R3 with Cl/Ca $\geq$ 0.7 and an age $\leq$ 33.9 $\pm$ 0.3 Ma. Since the abscissa (Cl/Ca) and the ordinate (Ar*/K) do not have a common denominator, the mixing trends are not necessarily straight lines. The pink feldspar starts with a low-temperature end-member P1 (different from R1: Cl/Ca $\geq$ 1.7, apparent age $\geq$ 57 Ma), reaching a cusp at P2 (Cl/Ca = 0.08, age = 34.5 $\pm$ 0.2 Ma), then trending towards end-member P3 similar or identical to R3.

The chemical and chronological record of the multiple K-feldspar generations preserved at few cm from each other should not distract from the robust observation that the metasomatism was Eo-Oligocenic. The main hydrothermal circulation that produced over 80 % of the K-feldspar mass occurred between ca. 35 and ca. 28 Ma. The bulk K concentration of K-feldspar 254d is about twice as high as that of 254b and 254c; this suggests a higher modal abundance of late-stage adularia, which would also explain its younger age.

7. DISCUSSION

The new U–Pb SHRIMP zircon ages from two samples of the Bressanone pluton record at least two main crystallization events. The younger age of ca. 280 Ma records the final crystallization age of the GG suite. The older age of ca. 289 Ma, observed in individual grains of both samples, is fully consistent with the age of the oldest volcanic activity of 290.7 ± 3 Ma and 289.0 ± 3 Ma documented in the Athesian Volcanic Complex (Visonà *et al.* 2007). This new datum confirms that widespread Early Permian crustal melting affected the source region of the Bressanone pluton almost 10 Ma before final emplacement and crystallization of the pluton itself.

The frequent fracture zones with associated cataclasites that dissect the Bressanone pluton provided an ideal pathway for circulation of fluids and/or residual melts. The reactions caused by ions transported by the infiltrating fluids resulted in the formation of hydrothermal-metasomatic minerals (Helgeson 1971; Pirajno 2013). The open-system mass transfer mediated by the metasomatic fluids can be traced by the connections between microstructures and geochemical signatures. A prime example are the red haloes around fractures, which could extend to increasingly large rock volumes.

Based on microtextural observations, mass transfer mainly involved addition of alkali cations (Na^+, K^+) and loss of silica. The newly formed turbid K-feldspar and/or albite form mantles around sericitized plagioclase or K-feldspar. Albite shows acquired chessboard textures. Quartz is corroded and replaced by albite and/or K-feldspar. Vuggy textures (Figure 5) attest SiO_2 loss. These transformations are accompanied by destabilization of magmatic biotite ± amphibole and formation of chlorite ± rutile and, in sample 310, of muscovite and second-generation biotite. In summary, the retrograde reaction sequence is the following: (1) K-feldspar replaces plagioclase; (2) albite replaces plagioclase and K-feldspar; (3) SiO_2 is dissolved and removed; (4) sericite overgrows or replaces K-feldspar, with further SiO_2 loss; (5) plagioclase is replaced by albite + epidote. The observed equilibrium mineral assemblages in the metasomatized rocks are biotite + muscovite + chlorite + rutile + quartz and biotite + chlorite + epidote ± hornblende.

The gain and loss of major elements in the metasomatized rocks is illustrated by the Harker (Figure 6) and Debon and Le Fort's (1983) millicationic diagrams (Supplementary Figure S2). The Na_2O increase is associated with the decrease of CaO, Sr, Rb and Ba and reflects plagioclase albitization and development of the chessboard texture (albite + sericite formation and albitization of K-feldspar by K–Na exchange, samples 224A and 266). The SiO_2 depletion, and the correlated increase of Al_2O_3, Na_2O and K_2O in samples 275, 310 and 375 reflects the disappearance of quartz phenocrysts (dequartzification/episyenitization) and the ensuing modal increase of alkali feldspars. Formation of muscovite after K-feldspar in sample 310 is evidenced by the positive P value in the millicationic diagram (Supplementary Figure S2). The presence of prehnite in the prehnite-rich veins indicates temperatures ≤ ca. 350 °C (at 3 kbar; Liou *et al.* 1983) for the circulating fluids. For the epidote-rich veins, higher temperatures cannot be excluded.

The observed transition from potassic to sodic alteration during the alkali-rich hydrothermal stage can be interpreted in the light of the typical evolution of fluids released by granitic magmas (Pirajno 2013): during magma crystallization in a closed system, volatiles in the residual melt increase, albite fractionation is enhanced and K-rich fluids are formed, resulting in transfer of K to the wall rocks; subsequent removal of volatiles from the melt due to second boiling or opening of the system favours crystallization and fractionation of K-feldspar and consequent release of Na-enriched fluids. The observed transition from alkali metasomatism to sericite and/or chlorite alteration also reflects the evolution from high-T (450–600 °C), high-K^+/H^+ fluids to lower-T, lower-K^+/H^+ fluids that is commonly reported in magmatic-hydrothermal systems (Seedorf *et al.* 2005).

In the field, we observe a spatial transition from the high-T, pervasive alkali alteration with Cu gain ("red granites") to low-T sericitization and chloritization, and finally to localized hydrothermal deposition in cross-cutting low-T polymetallic sulphide veins with wall-rock silicification and/or calcitization (see also Favretto 1963). This sequence may reflect sourcing of fluids from increasing depth in the pluton as it progressively cooled and crystallized, possibly accompanied by mixing with downwelling near-surface waters. Mixing of magmatic fluids with meteoric waters can occur at depths of several km (Bulle *et al.* 2020) and likely occurred in the vicinity of the active Periadriatic Fault System, which provided a pathway for enhanced water infiltration (e.g. Badertscher *et al*. 2002).

The observed Oligocene ages of metasomatism, however, are in contrast with the interpretation of the entire hydrothermal activity exclusively as part of the late-magmatic evolution of the Bressanone pluton as originally proposed by Favretto (1963) and Morgante (1974). On one hand, the multipulse character of the metasomatic events is in line with independent evidence that aqueous alteration is rarely a monogenetic, on-off process instantaneously creating a uniform retrograde paragenesis (e.g. Bulle *et al.* 2020; Kang *et al.* 2020). On the other hand, given the new geochronological constraints, the hydrothermal fluids responsible for this metasomatism must have derived either from deep crustal units undergoing metamorphic devolatilization or from hidden intrusions during the Alpine orogeny.

The Alpine intrusion hypothesis is consistent with the geochemical evolution of the metasomatism (see above). This hypothesis is also coherent with the widespread Periadriatic calc-alkaline magmatism, which extends from the Western to the Eastern Alps straddling the Periadriatic Fault System, with intrusion ages clustering in the 34–28-Ma interval (Dal Piaz and Venturelli 1983; Rosenberg 2004; Pomella *et al.* 2011; Bergomi *et al.* 2015). In particular, the "tonalitic lamellae" at the northern margin of the Bressanone pluton (Pennes and Mules) have an age of 39-32 Ma (Pomella *et al.* 2011), which overlaps with the age interval of 35.3–27.8 Ma proposed here for the prolonged alkali metasomatism. The Oligocene hydrothermal alteration of the Bressanone pluton is also contemporaneous with the Adamello pluton to the SW and the Rensen and Vedrette di Ries plutons to the NE. The observed nearly continuous chain of small magmatic bodies (the "tonalitic lamellae" of Dal Piaz 1926), which were reported within the Giudicarie–Passiria fault system (Rosenberg 2004) and were extensively sheared along the NGFS (Pomella *et al.* 2011), suggests that conditions for partial melting were repeatedly and almost simultaneously reached along the entire central-eastern Periadriatic Fault System. Although a detailed reappraisal of the "tonalitic lamellae" is beyond the scope of the present work, we note that these magmatic bodies all have different immobile trace-element signatures. In the Zr/Ti vs. Y/Al plot (Figure 12), fields of data for samples from the individual "lamellae" show little or no overlap with one another and with the Presanella intrusions (Adamello) near the Tonale fault of the Periadriatic Fault System. The larger spread of the samples from the Presanella pluton is consistent with its multiphase character and large chronological heterogeneity (Schaltegger *et al.* 2019). The geochemical variability of the "tonalitic lamellae", which could not be resolved by considering absolute concentrations of individual trace elements (cf. Pomella *et al*. 2011), suggests that their magmas were not consanguineous. Thus, the "lamellae" are unlikely to be all portions of the same magmatic body. More likely, each magma pod was the product of a distinct local melting episode. These melting episodes probably occurred during a regional climax in the late Eocene–early Oligocene, which could also be responsible for the magmatism in the nearby Bressanone area.

In the context of the Alpine belt evolution, evidence for magmatic activity in the Bressanone area represents the missing puzzle piece that strengthens the hypothesis of a continuous mantle upwelling during the late Eocene–early Oligocene due to European slab-steepening and corner flow (e.g. Ji *et al.* 2019) or slab break-off (e.g. Schmid *et al.* 2013; Handy *et al.* 2014) (Figure 13). It is noteworthy that by restoring the estimated 40 to 47 km of sinistral strike slip displacement along the NGFS since the late Oligocene (Verwater *et al.* 2021) the roughly E-W alteration halos of the Bressanone granitoid is brought in line with the Eocene-Oligocene Periadriatic belt of magmatic intrusions (Figure 14a). In this framework, the hidden Oligocene pluton beneath the Permian Bressanone pluton could represent one of the products of magma generation and intrusion induced by mantle upwelling at the slab gap imaged by teleseismic tomography underneath the Central–Eastern Alps (Lippitsch *et al.* 2003; Kissling *et al.* 2006; Zhao *et al.* 2016; Kästle *et al.* 2020) (Figure 14b).

8. CONCLUSIONS

The Bressanone pluton records two main magmatic crystallization events at ca. 289 Ma and 280 Ma, which match the ages of early and main stages of volcanism in the Athesian Volcanic District (Visonà *et al.* 2007). Subsequent hydrothermal activity is indicated by alkali metasomatism producing red feldspars dated to the Oligocene (35 to 28 Ma) and by spatially associated sericitization, chloritization, and low-T polymetallic sulphide veins. The observed alkali + Cu-rich hydrothermalism is coeval and has geochemical characteristics compatible with the calc-alkaline Periadriatic magmatism of Oligocene age. This indicates that in the Bressanone area shallow intrusions repeatedly released fluids that infiltrated the overlying Permian pluton through a fault/fracture network, causing widespread hydrothermal metasomatism.

Our results provide the first clue of Oligocene magmatic activity in the South Alpine domain east of the Giudicarie fault. The evidence that the magmatic belt straddling the Periadriatic Fault System is more continuous than previously thought supports the hypothesis of a continuous mantle upwelling during the Oligocene and partially solves the conundrum of why the surface magmatic expression at the slab gap between the Central and the Eastern Alps appears so limited.

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REFERENCES

Arboit, F., Chew, D., Visonà, D. Massironi, M., Sciascia, F., Benedetti, G., and Rodani S., 2019, The geodynamic evolution of the Italian South Alpine basement from the Ediacaran to the Carboniferous: was the South Alpine terrane part of the Peri-Gondwana arc-forming terranes? Gondwana Research, v. 65, p. 17–30. https://doi.org/10.1016/j.

Anderson, G.M., and Burnham, C.W., 1965, The solubility of quartz in supercritical water. American Journal of Science, v. 263, p. 494–511.

Badertscher, N.P., Abart, R., Burkhard, M., and McCaig, A., 2002, Fluid flow pathways along the Glarus overthrust derived from stable and Sr-isotope patterns. American Journal of Science, v. 302, p. 517–547. https://doi.org/10.2475/ajs.302.6.517

Bargossi, G.M., Bove, G., Cucato, M., Gregnanin, A., Morelli, C., Moretti, A., Poli, S., Zanchetta, S., and Zanchi, A., 2010, Note illustrative della Carta Geologica d'Italia, foglio 013: Merano. Roma, Servizio Geologico d'Italia, ISPRA.

Barth, S., Oberly, F., and Meier, M., 1989, U–Th–Pb systematic of morphologically characterized zircon and allanite: a high-resolution isotopic study of the Alpine Rensen pluton (Northern Italy). Earth and Planetary Science Letters, v. 95, p. 235–254.

Barth, S., Oberli, F., Meier, M., Blattner, P., Bargossi, G.M., and Di Battistini, G., 1993, The evolution of a calc-alkaline basic to silicic magma system: geochemical and Rb–Sr, Sm–Nd, and O^{18}/O^{16} isotopic evidence from the Late Hercynian Atesina–Cima d'Asta volcano–plutonic complex, Northern Italy. Geochimica et Cosmochimica Acta, v. 57, p. 4285–4300.

Bellieni, G., Molin, G. and Visona', D., 1979, The petrogenetic significance of the garnets in the intrusive massifs of Bressanone and Vedrette di Ries (Eastern Alps - Italy). Neues Jahrbuch fur Geologie und Palaontologie. Abhandlungen, v. 136, p. 238–253.

Bellieni, G., Fioretti, A.M., Marzoli, A., and Visonà, D., 2010, Permo-Paleogene magmatism in the eastern Alps. Rendiconti Lincei-Scienze Fisiche e Naturali, v. 21, Suppl 1, p. 51–71.

von Blanckenburg, F., and Davies, J. H., 1995, Slab breakoff: A model for syncollisional magmatism and tectonics in the Alps. Tectonics, v. 14, p. 120–131. https://doi.org/10.1029/94TC02051

Bergomi, M.A., Zanchetta, A., and Tunesi, A., 2015, The Tertiary dike magmatism in the Southern Alps: geochronological data and geodynamic significance. International Journal of Earth Sciences (Geol. Rundsch.), v. 104, p. 449–473. doi 10.1007/s00531-014-1087-5

Bonin, B., Brandlein, P, Bussy, F., Desmons, J., Eggenberger, U., Finger, F., Graf, K., Marro, C., Mercolli, I., Oberhansli, R., Ploquin, A., Von Quadt, A., Von Raumer, J., Schaltegger, U., Steyrer, H.P., Visonà, D., and Vivier, G., 1993, Late Variscan magmatic evolution of the Alpine basement, *in* Von Raumer, J., and Neubauer, F., *eds*, The pre-Mesozoic geology in the Alps. Springer-Verlag, Heidelberg, p. 169–199.

Boscaini, A., Marzoli, A., Davies, J.F.H.I., Chiaradia, M., Bertrand, H., Zanetti, A., Visonà, D., De Min, A., and Jourdan, F., 2020, Permian post-collisional basic magmatism from Corsica to the Southeastern Alps. Lithos, v. 376–377, 105733. https//doi.org/10.1016/j.lithos.2020.105733.

Bulle, F., Rubatto, D., Ruggieri, G., Luisier, C. Villa, I.M., and Baumgartner, L., 2020, Episodic hydrothermal alteration recorded by microscale oxygen isotope analysis of white mica in the Larderello-Travale Geothermal Field, Italy. Chemical Geology, v. 532, 119288. https://doi.org/10.1016/j.chemgeo.2019.119288

Dal Piaz, G., 1926, Il confine alpino-dinarico dall'Adamello al massiccio di Monte Croce nell'Alto Adige. Atti Accademia Sc. Veneto-Trentino-Istriana, v. 17, p. 1–7.

Dal Piaz, G.V., and Venturelli, G., 1983, Brevi riflessioni sul magmatismo post-ofiolitico nel quadro dell'evoluzione spazio-temporale delle Alpi. Memorie Società Geologica Italiana, v. 26, p. 5–20.

Debon, F., and LeFort, P., 1983, A cationic classification of common plutonic rocks and their magmatic associations: principles, method, applications. Bulletin de Minéralogie, v. 111, p. 493–510.

Del Moro A., and Visonà D., 1982, The epiplutonic Hercynian complex of Bressanone (Brixen, Eastern Alps, Italy). Petrologic and radiometric data. Neues Jahrbuch fur Mineralogie Abhandlungen, v. 145, p. 66–85.

Favretto, L., 1963, Le mineralizzazioni del massiccio granitico di Bressanone fra la Valle di Dosso e l'Alpe Valnisca. Studi Trentini di Scienze Naturali, Anno LX N. 1, p. 123–149.

Favretto, L., and Nardi, M., 1959, Il granito di Bressanone nella zona fra la valle di Dosso e l'Alpe Valnisca. Pubblicazioni dell'Istituto di Mineralogia Università di Trieste, n. 7 (1959). Bollettino Società Adriatica delle Scienze, v. 51 (1960).

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Gasser, G., 1913, Die Mineralien Tirols. Innsbruck.

Govett, G.J.S., 1983, Rock Geochemistry in Mineral Exploration. Handbook of Exploration Geochemistry, v. 3. Amsterdam, Elsevier.

Handy, M.R., Ustaszewski, K., and Kissling, E., 2014, Reconstructing the Alps–Carpathians–Dinarides as a key to understanding switches in subduction polarity, slab gaps and surface motion. International Journal of Earth Sciences, v. 104, p. 1–26. https://doi.org/10.1007/s00531-014-1060-3

Helgeson, H.C., 1971, Kinetics of mass transfer among silicates and aqueous solutions, Geochimica et Cosmochimica Acta, v. 35, p. 421–469.

Ji, W-Q., Malusà, M.G:, Tiepolo, M., Langone, A., Zhao, L., and Wu F-Y, 2019, Synchronous Periadriatic magmatism in the Western and Central Alps in the absence of slab breakoff. Terra Nova, v. 31, p. 120–128. https://doi.org/10.1111/ter.12377

Kang, J.S., Wille, M., Hofmann, B.A., Strauss, H., and Villa, I.M., 2020, Heterogeneous lead isotopic compositions of sulfide minerals from a hydrothermal replacement deposit (Janggun mine, South Korea). Ore Geology Reviews, v. 122, 103527. https://doi.org/10.1016/j.oregeorev.2020.103527

Kästle, E.D., Rosenberg, C., Boschi, L., Bellahsen, N., Meier, T., and El-Sharkawy, A. 2020, Slab break-offs in the Alpine subduction zone. International Journal of Earth Sciences, v. 109, p. 587–603. https://doi.org/10.1007/s00531-020-01821-z

Kissling, E., Schmid, S.M., Lippitsch, R., Ansorge, J., and Fugenschuh, B., 2006, Lithosphere structure and tectonic evolution of the Alpine arc: new evidence from high-resolution teleseismic tomography. Geological Society London, Memoirs, v. 32, p. 129–145. https://doi.org/10.1144/GSL.MEM.2006.032.01.08

Klotz, T., Pomella, H., Reiter, M., Fueenschuh, B.,and Zattin, M., 2019, Differential uplift on the boundary between the Eastern and Southern European Alps: Thermochronologic constraints from Brenner Basis Tunnel. Terra Nova, v. 31, p. 281–294. https://doi.org/10.1111/ter.12398

Korzhinskii, D.S., 1957, Physico-chemical basement of the mineral parageneses analysis. Nauka Publ., Moscow; Second edition, 1973; (Theoretic basement of the mineral parageneses analysis). Nauka Publishing, Moscow. (In Russian); French edition, 1957. Bases physico-chimiques de l'analyse des parageneses de mineraux. Bureau. Recherches geol. et Minieres. Serv. d'inform. Geol. Trad. № 2294.

Kraus, M., 1916, Über einige Alpine Erzlagerstätten. Bergbau und Hütte, v. 2.

Liou J.G., Kim H.S., and Maruyama S., 1983, Prehnite – epidote equilibria and their petrologic applications. Journal of Petrology, v. 24, p. 321–342. https://doi.org/10.1093/petrology/24.4.321

Lippitsch, R., Kissling, E., and Ansorge, J., 2003, Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography. Journal of Geophysical Research-Solid Earth, v. 108(B8), 2376. https://doi.org/10.1029/2002JB002016

Marocchi, M., Morelli, C., Mair, V., Klötzli, U., and Bargossi, G.M., 2008, Evolution of Large Silicic Magma Systems: new U–Pb zircon data on the NW Permian Athesian Volcanic Group (Southern Alps, Italy). Journal of Geology, v. 116, p. 480–498. https://doi:10.1086/590135

Mitterbauer, U., Behm, M., Brückl, E., Lippitsch, R., Guterch, A., Keller, G.R., Koslovskaya, E., Rumpfhuber, E-M., and Šumanovac, F., 2011, Shape and origin of the East-Alpine slab constrained by the ALPASS teleseismic model. Tectonophysics, v. 510, p. 195–206. https://doi.org/10.1016/j.tecto.2011.07.001.

Morgante, S., 1974, Il massiccio granitico di Bressanone (Alto Adige). Memorie Museo Tridentino di Scienze Naturali, v. 20, p. 67–157.

Morgante, S., D'Ambrosi, C., Favretto, L., Leonardon, G., Nardi, M., and Roberti, D., 1965, Carta geopetrografica del massiccio granitico di Bressanone, scale 1:50.000. Istituto di Mineralogia Università Trieste.

Müller, W., Prosser, G., Mancktelow, N., Villa, I., Kelley, S., Viola, G., and Oberli, F., 2001, Geochronological constraints on the evolution of the Periadriatic Fault System (Alps). International Journal of Earth Sciences, v. 90, p. 623–653. https://doi.org/10.1007/s005310000187

Nommensen, L., 2009, A petrological and geochronological comparison between the Presanella intrusion of the Adamello pluton and the magmatic lamellae from the North Giudicarie fault zone (Southern Alps, northern Italy). Diploma thesis, Albert-Ludwigs-Universität Freiburg, p. 67.

Pirajno, F., 2013, Effects of metasomatism on mineral systems and their host rocks: alkali metasomatism, skarns, greisens, tourmalinites, rodingites, black-wall alteration and listvenites. Metasomatism and mineral systems *in* Harlov, D.E., and Austrheim, H., *eds.*, Metasomatism and the Chemical Transformation of Rock, Lecture Notes in Earth System Sciences. Springer-Verlag Berlin Heidelberg, p. 203–247. https://doi.org/10.1007/978-3-642-28394-9_1

Poli, M.E., and Zanferrari, A., 1992, The Agordo basement (NE Italy): a 500 Ma-long geological record in the Southalpine crust. IGCP No. 276, Newsletter v. 5, p. 283–296.

Pomella, H., Klotzli, U., Scholger, R., Stipp, M., and Fugenschuh, B., 2011, The Northern Giudicarie and the Meran-Mauls fault (Alps, Northern Italy) in the light of new paleomagnetic and geochronological data from boudinaged Eo-/Oligocene tonalities. International Journal of Earth Sciences, v. 100, p. 1827–1850. https://doi.org/10.1007/s00531-010-0612-4.

Pomella, H., Stipp, M., and Fuegenshuh, B., 2012, Thermochronological record of thrusting and strike-slip faulting along the Giudicarie fault system (Alps, Northern Italy). Tectonophysics, v. 579, p. 118–130. https://doi.org/10.1016/j.tecto.2012.04.015

Romer, R.L., and Siegesmund, S., 2003, Why allanite may swindle about its true age. Contributions to Mineralogy and Petrology, v. 146, p. 297–307. https://doi.org/10.1007/s00410-003-0494-6

Rosenberg, C.L., 2004, Shear zones and magma ascent: A model based on a review of the Tertiary magmatism in the Alps. Tectonics, v. 23, TC3002, https://doi.org/10.1029/2003TC001526

Rottura, A., Bargossi, G.M., Caggianelli, A., Del Moro, A., Visonà, D., and Tranne, C.A., 1998, Origin and significance of the Permian high-K calc-alkaline magmatism in the central-eastern Southern Alps, Italy. Lithos, v. 45, p. 329–348. https://doi.org/10.1016/S0024-4937(98)00038-3

Sançar, T., Zabcı, C., Akyüz, H.S., Sunal, G., and Villa, I.M., 2015, Distributed transpressive continental deformation: The Varto Fault Zone, eastern Turkey. Tectonophysics, v. 661, p. 99–111. https://doi.org/10.1016/j.tecto.2015.08.018

Sassi, F.P., and Spiess, R., 1993, The South-Alpine Metamorphic Basement in the Eastern Alps *in* von Raumer, J, and Neubauer, F., *eds.*, Pre-Mesozoic Geology in the Alps. Springer, Berlin Heidelberg New York, p. 599–607.

Schaltegger, U., and Brack, P., 2007, Crustal-scale magmatic systems during intracontinental strike-slip tectonics: U, Pb and Hf isotopic constraints from Permian magmatic rocks of the Southern Alps. International Journal of Earth Sciences, v. 96, p. 1131–1151. https://doi.org/10.1007/s00531-006-0165-8

Schaltegger, A., Nowak, A., Ulianov, A., Fisher, C.M., Gerdes, A., Spikings, R., Whitehouse, M.J., Bindeman, I., Hanchar, J.M., Duff, J., Vervoort, J.D., Sheldrake, T., Caricchi, L., Brack, P., and Müntener, O., 2019, Zircon petrochronology and ^{40}Ar/^{39}Ar thermochronology of the Adamello intrusive suite, N. Italy: Monitoring the growth and decay of an incrementally assembled magmatic system. Journal of Petrology, v. 60, p. 701–722. https://doi.org/10.1093/petrology/egz010

Schmid, S.M., Fügenschuh, B., Kissling, E., and Schuster, R., 2004, Tectonic map and overall architecture of the Alpine orogen. Eclogae Geologicae Helvetiae, v. 97, p. 93–117. https://doi.org/10.1007/s00015-004-1113-x

Scolari, A., and Zirpoli, G., 1971, Fenomeni di metamorfismo di contatto nella fillade sudalpina indotti dal massiccio granitico di Bressanone (Alto Adige). Memorie del Museo Tridentino di Scienze Naturali, v. 18, p. 173–222.

Seedorf, E., Dilles, J.H., Proffett, J.M., Jr, Einaudi, M.T., Zurcher, L., Stavast, J.A., Johnson, D.A. and Barton, M.D., 2005, Porphyry deposits: characteristics and origin of hypogene features. Economic Geology, 100th Anniv. Vol., p. 251–298.

Schiavo, A., Dal Piaz, G.V., Monopoli, B., Bistacchi, A., Dal Piaz, G., Massironi, M., and Toffolon, G., 2014, Geology of the Brenner Pass-Fortezza transect, Italian Eastern Alps. Journal of Maps, v. 11, p. 201–215. https://doi.org/10.1080/17445647.2014.980337

Schmid, S.M., Fügenschuh, B., Kissling, E., and Schuster, R., 2004, Tectonic map and overall architecture of the Alpine orogen. Eclogae Geologicae Helvetiae, v. 97, p. 93–117. https://doi.org/10.1007/s00015-004-1113-x

Schmid, S.M., Scharf, A., Handy, M.R., and Rosenberg, C.L., 2013, The Tauern Window (Eastern Alps, Austria): A new tectonic map, with cross-sections and a tectonometamorphic synthesis. Swiss Journal of Geosciences, v. 106(1), p. 1–32. https://doi.org/10.1007/s00015-013-0123-y

Sillitoe, R.H., 2010. Porphyry copper systems. Economic Geology, v. 105, p. 3–41. https://doi.org/10.2113/gsecongeo.105.1.3

Formattato: Italiano (Italia)

Sun, S.-S., and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basalts implications for mantle composition and processes, *in* Magmatism in the Ocean Basins, Saunders, A.D., and Norry, M.J., *eds.*, Geological Society Special Publication, London, p. 313–345.

Thöny, W.F., Wyhlidal, S., Tropper, P., and Mair, V., 2009, Petrology of a cordierite-andalusite-bearing granite from the Sattelspitze (Monte Sella), Franzensfeste (South-Tyrol, Italy). Mitteilungen der Österreichischen Mineralogischen Gesellschaft, v. 155, p. 269–277.

Verwater, V.F., Le Breton, E., Handy, M.R., Picotti, V., Najafabadi, A.J., and Haberland C., 2021, Neogene kinematics of the Giudicarie Belt and eastern Southern Alpine orogenic front (northern Italy). Solid Earth, v. 12, p. 1309–1334. https://doi.org/10.5194/se-12-1309-2021

Villa, I.M., 2001, Radiogenic isotopes in fluid inclusions. Lithos, v. 55, p. 115–124. https://doi.org/10.1016/S0024-4937(00)00041-4

Villa, I.M., 2015, Immobile trace element discrimination of near-cogenetic eruptions: AGU Fall Meeting, San Francisco, December 2015. Abstract 79302.

Villa, I.M., Grobéty, B., Kelley, S.P., Trigila, R., and Wieler, R., 1996, Assessing Ar transport paths and mechanisms for McClure Mountains hornblende. Contributions to Mineralogy and Petrology, v. 126, p. 67–80. https://doi.org/10.1007/s004100050236

Villa, I.M., and Hanchar, J.M., 2017, Age discordance and mineralogy. American Mineralogist, v. 102, p. 2422–2439. https://doi.org/10.2138/am-2017-6084

Villa, I.M., and Williams, M.L., 2013, Geochronology of metasomatic events, *in* Harlov, D.E., and Austrheim, H., *eds.*, Metasomatism and the chemical transformation of rock. Springer, Heidelberg, p. 171–202. https://doi.org/10.1007/978-3-642-28394-9

Visonà, D., 1977, Contributo alla conoscenza del Massiccio di Bressanone (Alpi Orientali). Rendiconti Società Italiana di Mineralogia e Petrografia, v. 33, p. 647–665.

Visonà, D., 1980, Lo stock di granito a cordierite del M. Sella nel Massiccio di Bressanone (Alpi Orientali). Rendiconti Società Italiana di Mineralogia e Petrografia, v. 36, p. 91–106.

Visonà, D., 1983, Cumulate-like textures and chemistry in the Bressanone (Brixen) granodiorite (Eastern Alps, Italy). A new genetic approach. Chemical Geology, v. 40, p. 279–282. https://doi.org/10.1016/0009-2541(83)90034-7

Visonà, D., 1986, Chilled margins and commingling of magmas in the Bressanone (Brixen) Hercynian granodiorites (Eastern Alps, northern Italy). Chemical Geology, v. 56, p. 33–44. https://doi.org/10.1016/0009-2541(86)90108-7

Visonà, D., Folin, M., Peccerillo, A., and Tonegatti, D., 1989, Fluorine and chlorine distribution in Southalpine Hercynian rocks from Eastern and Central Alps. Periodico di Mineralogia, v. 58, p. 133-150.

Wyhlidal, S., Thöny, W. F., Tropper, P., Kaindl, R., Hauzenberger, C., and Mair, V., 2012, Petrology of contact metamorphic metapelites from the southern rim of the Permian Brixen Granodiorite (South Tyrol, italy). Mineralogy and Petrology v. 106, p. 173–191. doi10.1007/s00710-012-0240-8.

Yardley, B.W.D., 2013, The chemical composition of metasomatic fluids in the crust, *in* Harlov, D.E., and Austrheim, H., *eds*, Metasomatism and the chemical transformation of rock, Lecture Notes in Earth System Sciences., Springer-Verlag Berlin Heidelberg 2013, p. 17–51. https://doi.org/10.1007/978-3-642-28394-9_1

Zhao, L., Paul, A., Malusà, M.G., Xu, X., Zheng, T., Solarino, S., Guillot, S., Schwartz, S., Dumont, T., Salimbeni, S., Aubert, C., Pondrelli, S., Wang, Q., and Zhu, R., 2016, Continuity of the Alpine slab unraveled by high-resolution P wave tomography. Journal of Geophysical Research-Solid Earth, v. 121(12), p. 8720–8737. https://doi.org/10.1002/2016JB013310

Zharikov, V.A., Pertsev, N.N., Rusinov, V.L., Callegari, E., and Fettes, D.J., 2007, Metasomatism and metasomatic rocks. Recommendations by the IUGS subcommission on the systematics of metamorphic rocks, 9. http://www.bgs.ac.uk/scmr/docs/papers/paper_9.pdf

CAPTIONS

Table 1. Geochemical compositions of Bressanone "red granites" and representative granites and granodiorites (GG).

Table S1. SHRIMP U–Pb zircon data for the Bressanone GG.

Table S2. ^{39}Ar–^{40}Ar results for K-feldspars from sample 254 (Riol). Ar isotopes in ml, all uncertainties as 1 standard deviation.

Table S3. Compilation of geochemical data for Bressanone granites and granodiorites (GG) and microgranular mafic enclaves (MME). Data sources: (a) Visonà (1977), (b) Visonà (1986); (c) Visonà (1983). F and Cl data after Visonà *et al.* (1989). Other data: this work.

Figure 1. Tectonic scheme of the Cenozoic Periadriatic magmatic province in the Central and Eastern Alps (modified after Schmid et al. 2004). Intrusive bodies, major dikes and major faults of Cenozoic age are shown. Shading indicates areas with Cenozoic dykes or stocks (Rosenberg, 2004; Bergomi *et al.* 2015). Abbreviations for plutons as follows: A Adamello–Presanella, B Bergell, R Rensen, VR Vedrette di Ries, Sm Samoclevo, Ru Rumo, Ln Lana.

Figure 2. Geological sketch map of Bressanone pluton displaying the hydrothermalized area (red granites), and locations of samples selected for geochemistry (open circles) and U–Pb zircon (filled squares: samples 213, 320, 1980) and Ar–Ar feldspar (filled circle: sample 254) dating. The Mules, Pennes (Pe) and Chienes (Ch) Oligocene lamellae are also shown.

Figure 3. Panoramic view of the westernmost portion of the 'red granites' area, south-east of Pennes Pass. In the foreground, Periadriatic fault breccia on whitish tonalitic lamellae; in the background, the vast outcrop of reddish altered Bressanone granitoids. Photograph taken looking South-East.

Figure 4. Reddish halos around fractures. (a) Granodiorite 276. The white infill contains mainly of prehnite, K-feldspar, scarce epidote, apatite, quartz and rare chlorite. (b)

Pegmatite granite 254. The green infill (arrow) mainly consists of epidote, K-feldspar, albite, and minor calcite, chlorite, quartz and limonitized pyrite.

Figure 5. (a) Sample 219. Partial to almost total replacement of quartz by turbid, reddish K-feldspar (Kfs) and albite (Ab); late K-feldspar and quartz (Qtz) form thin intergranular films around primary and secondary minerals. (b) Sample 271A. K-feldspar is mantled by albite. (c) Sample 224A. Chessboard texture of albite with K-feldspar (Ab_c). (d) Sample 275. Dissolution voids giving the rock a vuggy appearance.

Figure 6. Covariations of major and trace elements vs. yttrium of Bressanone pluton rocks.

Figure 7. Chondrite-normalized (Sun and McDonough, 1989) REE patterns of Bressanone pluton rocks.

Figure 8. Conventional concordia plot for the studied samples. Error ellipses shown at 2σ level.

Figure 9. (a) ^{39}Ar–^{40}Ar stepwise heating data and age spectrum of plagioclase 254a from Riol (PF39 stands for Percentage Fraction of ^{39}Ar). Step ages range between 240.7 ± 1.4 and 140.1 ± 3.6 Ma. (b) Cl/K–age, and (c) Ca/K–age common-denominator isotope correlation diagram for plagioclase 254a (crosses). Data for the pink metasomatic K-feldspar 254b (pink circles; see Figure 10 for more details) are shown for comparison. In both correlation diagrams the scatter of the points indicate a polyphase mix with $n \geq 3$ phases; the Variscan plagioclase underwent several ($n \geq 2$) chemically open-system events.

Figure 10. (a) ^{39}Ar–^{40}Ar stepwise heating data and age spectra of red and pink metasomatic K-feldspar samples 254b and 254c. Step ages cluster between ca. 35 and 40 Ma. (b) Three-isotope Ca/K–age correlation diagram. The triangle shape of the correlation requires three feldspar generations. (c) Three-isotope Cl/K–age correlation diagram, including red-pink K-feldspar 254d. Two generations appear to dominate the trend, a Cl-rich one, possibly relict, and an Eo–Oligocene one. The detail of the Eo–Oligocene ages is shown in (d). (d) Three-isotope Cl/K–age correlation diagram. The alkali metasomatism extended until ca. 28 Ma.

Figure 11. Age vs. Cl/Ca correlation diagram for pink and red K-feldspar samples 254b-c. The arrows labelled R1 to R3 and P1 to P3 denote trends for different K-feldspar generations inferred from the data for the red and pink sample, respectively. Note that the mixing trends are not necessarily straight lines, as abscissa and ordinate do not have a common denominator.

Figure 12. Zr/Ti versus Y/Al molar diagram (Villa 2015; Sançar *et al.* 2015) for samples from the Presanella (Adamello) and Rensen plutons and six tonalitic lamellae cropping out near the Periadriatic Fault System. The diagram is stable relative to weathering and low-grade alteration and provides a robust chemical fingerprinting of magma chamber processes. Y/Al mainly depends on fractionation of garnet, xenotime and monazite and on the degree of partial melting. Zr/Ti is modified by phases (rutile, titanite, zircon, ilmenite, biotite, etc.) that neither accommodate nor fractionate trivalent cations and thus provides an independent magmatogenic fingerprint. Narrow clusters may suggest (but do not prove) cogenicity, whereas distant immobile trace element signatures rule it out. Trace element data after Nommensen (2009) and Pomella *et al.* (2011). U-Pb ages after Pomella *et al.* (2011).

Figure 13. Interpretive cross sections underneath the Central–Eastern Alps at the time of emplacement of the late Eocene–early Oligocene Periadriatic magmatic province. The Periadriatic intrusions (e.g. Rensen pluton and tonalitic lamellae) are displayed in black and the altered Bressanone pluton in grey. The intrusions and the associated hydrothermal alterations are attributed to mantle upwelling due to (A) slab steepening (e.g. Ji *et al.* 2019) or (B) slab break-off (e.g. Schmid *et al.* 2013). PFS: Periadriatic Fault System. Green: Penninic nappes belonging to the European crust. Orange: Austroalpine nappes and South Alpine domain pertaining to the Adria crust.

Figure 14. (a) Inferred tectonic scheme of the Central–Eastern Alps in late Eocene–early Oligocene, showing the main fault systems in red. The reconstruction is consistent with the estimated 40–47 km of sinistral strike slip displacement along the NGFS since the late Oligocene (Verwater *et al.* 2021). The wide and continuous E-W shaded grey belt represents the inferred area where magma upwelling gave rise to multiple intrusions. The extent of the belt is based on the restored location of the main plutons (shown for geographic reference) and of the Cenozoic dykes (Rosenberg, 2004; Bergomi *et al.* 2015).

The alteration halos of the Brixen pluton (star) are clearly within the belt. (b) Tectonic scheme of the Central–Eastern Alps showing the main fault systems in red and the projection of the positive velocity anomalies dVp > 2% imaged by teleseismic tomography at 120 km (shaded violet) (Kaulakov *et al.* 2009). The area in between is interpreted as a slab gap where mantle upwelling should have been favored during the emplacement of the Periadriatic magmatic province in the late Paleogene. The shaded gray area encloses the area where surface expressions of the Cenozoic mantle upwelling (plutons and dykes) have been documented. Abbreviations for main plutons in (a) and (b): B Bregaglia; A Adamello; R Rensen; VR Vedrette di Ries.

Figure S1. Modal compositions of Bressanone intrusive complex rocks in the QAP portion of the Le Maitre *et al.* (2002) classification diagram. Dots: main body; square: Dosso Lives body. Source of data: Visonà (1977, 1980, 1983, 1995) and Visonà *et al.* (1987).

Figure S2. Composition of Bressanone rocks in the millicationic diagram of Debon and Le Fort (1983).