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The Grand St Bernard - Briançonnais nappe system and the Paleozoic inheritance of the Western Alps unravelled by zircon U-Pb dating

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Key Points:

- First compelling radiometric evidence of Late Devonian orogenic magmatism in the European Alps
- Geochronologic record of a complex Ordovician to Permian tectonic evolution along the northern Gondwana margin
- Part of the Moldanubian domain was dismembered in the Late Carboniferous and is now accreted in the Alpine orogenic wedge.

Abstract

The continental crust involved in the Alpine orogeny was largely shaped by Paleozoic tectono-metamorphic and igneous events during oblique collision between Gondwana and Laurussia. In order to shed light on the pre-Alpine basement puzzle disrupted and re-amalgamated during the Tethyan rifting and the Alpine orogeny, we provide SHRIMP U-Pb zircon and geochemical whole rock data from selected basement units of the Grand St Bernard – Briançonnais nappe system in the Western Alps, and from the Penninic and Lower Austroalpine units in the Central Alps. Zircon U-Pb ages, ranging from 459.0 ± 2.3 Ma to 279.1 ± 1.1 Ma, provide evidence of a complex evolution along the northern margin of Gondwana including Ordovician transtension, Devonian subduction and Carboniferous-to-Permian tectonic reorganization. Original zircon U-Pb ages of 371 ± 0.9 Ma and 369.3 ± 1.5 Ma, from calcalkaline granitoids of the Grand Nomenon and Gneiss del Monte Canale units, provide the first compelling evidence of Late Devonian orogenic magmatism in the Alps. We propose that rocks belonging to these units were originally part of the Moldanubian domain, and were displaced towards the SW by Late Carboniferous strike-slip faulting. The resulting assemblage of basement units was disrupted by Permian tectonics and by Mesozoic opening of the Alpine Tethys. Remnants of the Moldanubian domain became either part of the European paleomargin (Grand Nomenon unit) or part of the Adriatic paleomargin (Gneiss del Monte Canale unit), to be finally accreted into the Alpine orogenic wedge during the Cenozoic.

Keywords: Variscan orogeny; microplate amalgamation; magmatism; geochronology; Alps

1. Introduction

The continental crust of stable Europe, from the Ibero-Armorican chain to the Bohemian massif, is largely shaped by the tectono-metamorphic and igneous events developed from the Ordovician to the Carboniferous during oblique collision between Gondwana and Laurussia and intervening Avalonia and Armorica microplates (Ballèvre et al., 2014; Edel et al., 2013; Hatcher, 2002;

Martınez Catalan et al., 1990; Neubauer, 2002; Shelley & Bossiere, 2000; Stampfli & Borel, 2002; von Raumer, 1981, 1998) forming ultimately the Pangea. In the future Alpine domain, the pre-Variscan and Variscan continental crust was fragmented by the break-up of Pangea starting from the Permian, and then reworked, accreted and partly rejuvenated by the Meso-Cenozoic Alpine orogeny (Dal Piaz et al., 2003; Handy et al., 2010; Malusà et al., 2015; Rosenbaum & Lister, 2005; Schmid et al., 2004). Despite the masking effects of the Alpine overprint, remnants of Permian, Variscan and older magmatic events are still recognized in some Adria-derived (Austroalpine) and Europe-derived (Penninic, Helvetic) units (Bonin et al., 1993; Desmons & Mercier, 1993; Thèlin et al., 1993), providing invaluable insights on the impact of Paleozoic inheritance on Alpine evolution. This article is mainly focused on the Paleozoic evolution of the Penninic basement units of the Grand St Bernard - Briançonnais nappe system (Western Alps), and provides new SHRIMP U-Pb zircon and geochemical whole rock analyses on gneissic bodies derived from acidic intrusive and subvolcanic protoliths sampled in the Ruitor, Leverogne, Grand Nomenon and Houillère units exposed in the Aosta Valley (NW Italy). Results are compared with unpublished data from similar granitoids exposed in the Central Alps, in the Lower-Penninic gneissic nappe of Monte Leone (Lepontine dome, Steck et al., 2013 and reference therein) and in the Lower-Austroalpine Gneiss del Monte Canale unit (Bernina nappe *s.l.*, Spillmann & Büchi, 1993). Our new geochemical and geochronological data are finally discussed within the framework of published U-Pb data from the broader Alpine region, shedding new light on the Paleozoic inheritance of the Western and Central Alps, and on the Variscan and pre-Variscan evolution of crustal domains later involved in the Alpine orogenic belt.

2. Geologic background

The Grand St Bernard - Briançonnais nappe system crops out along the entire arc of the Western Alps as a first-rank component of the Alpine orogenic wedge (Figure 1). It includes polycyclic Variscan and pre-Variscan basement rocks, monocyclic Upper Carboniferous - Lower Triassic siliciclastic successions, Permian igneous bodies and classic Meso-Cenozoic Briançonnais cover sequences (Bigi et al., 1990; Caby, 1968; Desmons & Mercier, 1993; Ellenberger, 1958; Gouffon, 1993; Sartori et al., 2006; Thèlin et al., 1993). These units display a Paleogene blueschist/greenschist facies metamorphic overprint, and are piled up within a double-vergent frontal wedge developed during the Alpine orogeny (Beltrando et al., 2010; Bucher & Bousquet, 2007; Malusà et al., 2005a, 2011; Polino et al., 2015). Along the Aosta Valley cross section, the monocyclic low-grade Houillère unit is exposed in the frontal part of the Paleogene frontal wedge (De Giusti et al., 2004; Elter, 1987; Polino et al., 2015), and is bounded to the SE by the Internal Houillèr Fault (Malusà et al., 2005b, 2009) (Figure 2). To the SE of this fault, on the rear part of the Paleogene frontal wedge, different basement units are stacked along NW-dipping shear zones chiefly marked by Piedmont zone calcschists (Govi, 1966; Malusà et al., 2005a, Polino et al., 2015). From the top to the bottom, these units are the Ruitor, Leverogne and Grand Nomenon units (Figure 2).

The Houillère unit (Figure 2) consists of low-grade metamorphic rocks derived from Namurian-Early Stephanian coal-bearing siliciclastic successions, Upper Carboniferous to Lower Triassic conglomerates and sandstones, and minor Triassic dolostones, evaporites and calcite marbles (Bertrand et al., 1996; Debelmas et al., 1991; Elter, 1987; Fabre, 1958; Franchi & Stella, 1903; Polino et al., 2015; Sartori et al., 2006). In the Aosta Valley, it includes the gneissic leucogranite of Costa Citrin, early interpreted as a Permian laccolith (Caby, 1974), and later dated as Visean-Namurian (Conventional U-Pb Isotope Dilution: intercept ages at 324 ± 17 Ma and 323 ±8 Ma; Bertrand et al., 1998), in contrast with available age constraints in their country rock. On the southern side of the Aosta Valley, similar rocks are also aligned along the Briançonnais Fault, which separates the Houillère unit in the hanging wall from the Sion-Courmayeur unit in the footwall (De Giusti et al., 2004; Elter, 1987; Polino et al., 2015).

The Ruitor unit (Caby, 1968; Desmons & Mercier, 1993; Malusà et al., 2005a) (Figure 2) is part of the so-called "Briançonnais External zone" together with the Pontis and Siviez-Mischabel basement units of the Swiss Alps (Burri, 1983; Gouffon, 1993; Sartori et al., 2006; Scheiber et al., 2014; Steck et al., 2001). Its polycyclic basement consists of metasedimentary sequences, massive-to-banded amphibolites and deformed Upper Cambrian-Ordovician and Permian intrusive and subvolcanic rocks (Bertrand et al., 1998, 2000b; Bussy et al., 1996a; Guillot et al., 2002; Scheiber et al., 2013), and was affected by two main metamorphic events (Baudin, 1987; Caby & Kienast, 1989; Desmons, 1992; Desmons et al., 1999; Detraz & Loubat, 1984; Thélin et al., 1993): an Alpine event under epidote-blueschist facies conditions (Dal Piaz, 1965; Polino et al., 2015; Schiavo, 1997) and a pre-Alpine event under amphibolite-facies condition dated at ca. 330 Ma (Bussy et al., 1996b; Giorgis et al., 1999; Markley et al., 1998). Evidence of an older eclogitic event is locally preserved in garnet-amphibolites (Schiavo, 1997).

The Leverogne and Grand Nomenon units (Figure 2) exposed farther east are classically referred to as the Briançonnais Internal zone (Amstutz, 1962; Cigolini, 1995; Dal Piaz & Govi, 1965; Debelmas et al., 1991; Desmons & Mercier, 1993; Elter, 1987; Polino et al., 2015), together with the Mont Fort nappe in the nearby Swiss Alps (Sartori et al., 2006; Thélin et al., 1993). These units show no evidence of the eclogitic relics and Variscan high-grade metamophic assemblages that are found in the basement rocks of the Briançonnais External zone (Bertrand et al., 2000b; Cigolini, 1995; Desmons et al., 1999a, 1999b; Guillot et al., 1991, 2012). The Leverogne unit (Figure 2) consists of garnet-chloritoid micaschist, garnet-glaucophane schists, fine-grained gneisses with poikilolastic albite, graphite-albite schists, massive quartzites, and abundant mafic and felsic igneous rocks with pervasive Alpine epidote-blueschist facies metamorphism and greenschist facies retrogression (Malusà et al., 2005a; Schiavo, 1997). Mafic rocks are garnet-glaucophanites and greenschists. Felsic rocks were emplaced in the Late Cambrian (Bertrand et al., 2000a, 2000b; Guillot et al., 1991), and are either referred to as Val di Rhêmes (Bertrand et al., 2000b) or

Changier (Polino et al., 2015) metagranophyres. The Grand Nomenon unit (Figure 2) includes a major metagranitoid body, corresponding to the Cogne-Valsavarenche pluton or Favret metagranodiorite of previous work (Amstutz, 1962; Bonin et al., 1993; Dal Piaz, 1928; Novarese, 1909; Polino et al., 2015). The host rock is a fine-grained metasedimentary sequence of garnet-biotite-chlorite-bearing albitic gneisses, minor quartz-rich schists, quartzites and dark graphitic phyllites, which are associated to lenses of foliated augengneiss and albite-epidote amphibolite (Polino et al., 2015). The host rock locally preserves a pre-Alpine epidote-amphibolite facies foliation, crosscut by metagranitoid body and only partly obliterated by Alpine greenschist-facies metamorphism (Malusà et al., 2005a). The metagranitoid body, hereafter referred to as Grand Nomenon pluton for the sake of simplicity, consists of massive to foliated greenschist-facies derivatives from calcalkaline tonalite and granodiorite, minor quartzdiorite, cumulus gabbro and aplitic dykes (Cigolini, 1995; Guillot et al., 2012). The intrusion age of the Grand Nomenon pluton is referred to the earliest Carboniferous based on U-Pb conventional IDTIMS (357 ± 24 Ma) and SHRIMP (356 ± 3 Ma) analyses of igneous zircons (Bertrand et al., 2000a). This age is unique among the Paleozoic magmatic rocks dated in the axial Western Alps. However, similar rocks are described in the Central Alps in the Gneiss del Monte Canale unit (Bonsignori et al., 1970; Boriani et al., 2012a; Nangeroni, 1957; Venzo & Schiavinato, 1970; Venzo et al., 1971;), traditionally ascribed to the Lower-Austroalpine Bernina nappe s.l. (Spillmann & Büchi, 1993) and exposed in the “Southern Steep Belt” to the north of the Insubric Fault (Milnes, 1974; Schmid et al., 1987) (Figure 1). The Gneiss del Monte Canale unit mainly consists of metagranodiorites with minor metatonalites, metadiorites and metagranites (hereafter referred to as Monte Canale pluton for the sake of simplicity), associated with metasediments and mafic rocks metamorphosed under greenschist facies conditions (Boriani et al., 2012a and references therein). The stable metamorphic mineral assemblage of these metagranodiorites consists of quartz, K-feldspar, albite, white mica, pale green amphibole locally with brown core, epidote, chlorite, and minor biotite (Ambiveri et al., 2007). The Monte Canale pluton is cut by coarse- to medium-grained leucogranites without apparent metamorphic overprint (Ambiveri et al., 2007). The contact with the nearby Upper Austroalpine units (Languard-Campo nappe, Bergomi & Boriani, 2012; Bianchi et al., 1981; Notarpietro & Gorla, 1981; Pace, 1966) is marked by a mylonitic belt, and both the Lower and Upper Austroalpine units are intruded by 310 - 300 Ma old granitoids (Boriani et al., 2012a; von Riet, 1984), suggesting that they were already juxtaposed at the time of emplacement of the Late Carboniferous granitoids.

Evidence of pre-Variscan magmatism possibly resembling what observed in the Ruitor unit is instead reported in the Lower Penninic units of the Lepontine dome (Monte Leone nappe; Bergomi et al., 2007). In the Ossola Valley (NW Italy), the Lepontine nappe stack includes (from the bottom to the top) the Verampio, Antigorio, Pioda di Crana and Monte Leone nappes (Berger et al., 2005; Bigi et al., 1990; Escher et al., 1993; Grujic & Mancktelow, 1996; Maxelon & Mancktelow, 2005; Steck et al., 2013), mainly consisting of Upper Carboniferous - Lower Permian granitoids (305-290 Ma, Bergomi et al., 2007) with minor metapelites, marbles and amphibolite lenses. The Monte Leone nappe includes fine-grained banded orthogneisses and minor coarse-grained augengneiss interlayered with paragneisses, hornblende gneisses and amphibolites, and shows a penetrative amphibolite-facies metamorphic overprint of Alpine age that is common to other nappes of the Lepontine dome (Maxelon & Mancktelow, 2005, and references therein).

3. Sampling strategy and methods

Analyzed samples are metagranitoids and orthogneisses from the main tectonic units of the Grand St-Bernard nappe exposed in the Aosta valley. Dated samples (Figure 1 and 2) are two orthogneisses of the Ruitor unit (samples s1 and s2), the Changier metagranophyre of the Leverogne unit (sample s3), the metagranitoid of the Grand Nomenon pluton (sample s4), and the Costa Citrin metaleucogranite of the Houillère unit (sample s5). We have also analyzed some gneissic granitoids from the Monte Leone Nappe in the Lepontine dome (sample s6) and from the

Gneiss del Monte Canale unit in the Bernina nappe (sample s7) for comparison (Figure 1). Geochemical analyses of samples s1 to s7 were integrated by analysis of additional samples (see the full list of samples in the supporting information, Table TS02).

All samples were analyzed for major, minor and trace elements (results are listed in Table TS02). They are very fresh, with LOI (Loss On Ignition) in agreement with the modal abundance of hydrous phases. Samples selected for SHRIMP U-Pb dating (s1 to s7) are representative of granitoids occurring in each area (Figure 1) and the results are reported in Table TS01. We base our discussion on the Concordia ages calculated after Ludwig (1998) in a Tera-Wasserburg Concordia diagram (Tera & Wasserburg, 1972). Errors given for Concordia ages in the text are reported at 2σ level. A more detailed discussion of the methodology can be found in the supporting information (see also Black et al., 2003; Compston et al., 1992; Ludwig, 2003a; 2003b; Nasdala et al., 2008; Schöne et al., 2006; Stacey & Kramers, 1975; Steiger & Jäger, 1977; Williams, 1998).

4. Results

SHRIMP U-Pb and whole rock geochemical analyses are listed in Table TS01 and TS02, respectively. They are shown in Figures 3, 4 and 5, and described in full below. Sample locations, petrography and ages are summarized in Table TS03.

4.1 Zircon U-Pb geochronology

Grand St Bernard - Ruitor unit (samples s1 and s2**)**. Zircons from samples s1 (Basse Tête augengneiss) and s2 (Les Lacerandes augengneiss, Thèlin et al., 1993) share similar size, shape and internal CL texture. They are transparent, colorless, prismatic and euhedral in shape. They show a variable size (150-300 μm long) with an aspect ratio (width-to-length) from 1:2 to 1:3. Some of them contain small apatite inclusions. In CL imaging (Figure 3h-s1, s2), they present inherited cores mantled by magmatic overgrowths showing a faint and concentric zoning (Corfu et al., 2003 and references therein). U (145-707 ppm) and Th (15-96 ppm) contents, as well as Th/U (0.1-0.5) ratios confirm their magmatic origin (Table TS01; Hoskin & Schaltegger, 2003 and references therein). Inherited cores from both samples mainly span over a small time interval of concordant and nearly concordant ages from 829.3 ± 10.6 to 567.8 ± 4.1 Ma (Table TS01), which can be roughly grouped into clusters of Cryogenian (687 ± 18.5 to 829.3 ± 10.6 Ma) and Ediacaran (567.8 ± 4.1 to 605.3 ± 8.8 Ma) ages. Only one inherited core yielded a Paleoproterozoic age of 2016.2 ± 71.8 Ma (Table TS01). SHRIMP U-Pb analyses performed on magmatic overgrowths turned out Concordia ages of 459.0 ± 2.3 Ma (n = number of analyses = 14; MSWD = Mean Square of Weighted Deviates = 0.2; Prob. = Probability of fit = 1.0) and 456.4 ± 2.4 Ma (n = 15; MSWD = 0.1; Prob. = 1.0) for samples s1 and s2, respectively (Figure 3a and b). We interpret these Late Ordovician ages as the time of crystallization of the granitic protholiths. Guillot et al. (2002) reported Ordovician emplacement ages (IDTIMS and SIMS U-Pb analyses on zircon; upper intercepts at 460 ± 7, 468 ± 22, 469 ± 15 and 471 ± 5 Ma) for other orthogneiss protholiths occurring in the Ruitor basement on the southern side of the Aosta Valley.

Grand St Bernard - Leverogne unit (sample s3). Zircons from sample s3 are pale pink, transparent, prismatic and euhedral in shape and rich of inclusions. They are 150-200 up to 300 μm in length, with an aspect ratio of 1:2. Highly metamict grains are abundant in the selected zircon population. In CL images, metamict zircons have dark cores surrounded by highly luminescent and structureless rims. Few SHRIMP U-Pb analyses (e.g., spots 1.1, 2.1 and 6.1, Table TS01) carried out on these rims produced discordant and meaningless ages probably due to the presence of a high proportion of common lead (Table TS01). Zircons without metamict alteration show thin and faint concentric and oscillatory zoning (Figure 3h-s3), with typical U (122-762 ppm), Th (25-202 ppm) and Th/U (0.1-1) magmatic values (Table TS01). Eighteen SHRIMP U-Pb analyses performed on core and rims produced a Middle Ordovician Concordia age of 465.0 ± 2.5 Ma (MSWD = 0.3;

Prob. = 1.0; Figure 3c), which can be regarded as the emplacement age of the metagranophyre protholith. Only one inherited core Ediacaran in age has been observed.

Grand St Bernard - Grand Nomenon unit (sample s4). Zircons from sample s4 are pale pink in color and transparent to cloudy. They are mainly euhedral and prismatic in shape, although a few have irregular faces with smoothed edges. They are predominantly 100 – 200 μm in length, with an aspect ratio of 1:2-2.5. Apatite is the main inclusion. Fracturing is often associated with brownish metamict areas. They present a fine magmatic growth zonation (Figure 3h-s4) and sector zoning defined by patches of relative CL brightness. CL textures along with high U (632-1827 ppm) and Th (177-897 ppm) contents and Th/U (0.3-05) ratios (Table TS01) suggest an igneous origin for these zircon grains. SHRIMP U-Pb analyses performed both on cores and rims provided a Late Devonian Concordia age of 371 ± 0.9 Ma (n = 17; MSWD = 0.5; Prob. = 1.0; Figure 3d), which represents the emplacement age of the protholith. Only one Ediacaran inherited core was measured (Table TS01).

Grand St Bernard - Houillère unit (sample s5). Zircons from sample s5 are pink, transparent and euhedral needle-like crystals up to 250-300 μm long, with an aspect ratio of 1:2. They are rich in inclusions. Some stubby and highly metamict zircons are present. In CL imaging, they have typical magmatic concentric and oscillatory zoning (Figure 3h-s5). CL textures, U (77-2150 ppm) and Th (90-1261 ppm) contents, as well as Th/U (0.2-0.5) ratios (Table TS01) suggest a magmatic origin for these zircon grains. SHRIMP U-Pb analyses both on cores and rims yielded an Early Permian Concordia age of 279.1 ± 1.1 Ma (n = 14; MSWD = 0.4; Prob. = 1.0; Figure 3e), which is our best estimate as emplacement age of the protholith. One spot analysis performed on stubby and highly metamict zircon produced an apparent older and discordant age of 334.0 ± 3.8 Ma probably due to a high proportion of common lead (spot 8.1; Table TS01). Bertrand et al. (1998) reported two poorly constrained upper intercept ages at 324 ± 24 and 323 ± 7 Ma (IDTIMS U-Pb on zircon) for two metagranites occurring in the Houillère unit at the Costa Citrin locality.

Lepontine dome - Monte Leone (sample s6). A nearly undeformed sample was selected for SHRIMP geochronology. Zircons in sample s6 are colorless and transparent with apatite as main inclusions. They are mainly euhedral and prismatic in shape, predominantly 100 – 200 μm in length, with an aspect ratio of 1:1.5. In CL images, zircon grains present typical magmatic concentric and oscillatory growth from core to rim (Figure 3h-s6). Some zircon grains show instead inherited cores surrounded by magmatic overgrowths. The ages of inherited cores range from 563 ± 8 to 962 ± 10 Ma (Table TS01). Thirteen spot analyses performed both on well-defined concentric and oscillatory zoning and on magmatic overgrowths gave a concordant age of 457.9 ± 3.5 Ma (Figure 3f). According to zircon textures and U-Th geochemistry (U=137-590 ppm, Th=24-214 ppm, Th/U=0.1-0.4), this age could be interpreted as the emplacement age of the protolith of the Ordovician metagranitoids.

Lower Austroalpine – Gneiss del Monte Canale unit (sample s7). Zircons from sample s7 are pale pink to colorless and transparent to cloudy, with apatite as main inclusion. Zircons are mostly euhedral and prismatic in shape, 150 – 200 μm in length, and with an aspect ratio of about 1:2. In CL images (Figure 3h-s7), zircon texture is mainly characterized by concentric and oscillatory zoning, which suggests along with U (547-1968 ppm), Th (161-856 ppm) and Th/U (0.2-0.5) values an igneous origin (Table TS01). Only few grains have inherited cores. Fifteen SHRIMP spot analyses performed both on cores and rims provided a Late Devonian Concordia age of 369.3 ± 1.5 Ma (n = 15; MSWD = 0.3; Prob. = 1.0; Figure 3g), which represents the emplacement age of the granitoid. This age is similar within error to the emplacement age obtained from the Grand Nomenon sample.

4.2 Geochemistry

Grand St Bernard - Ruitor unit. The Upper Ordovician granitoids collected in the Ruitor unit are metaluminous to peraluminous granites [A/CNK = molar $Al_2O_3/(CaO+Na_2O+K_2O)$ = 1.06 – 1.18] (Figure 4a and b), and lie in the high-K calcalkaline field of the K_2O vs SiO_2 diagram (Figure 4c;

Peccerillo & Taylor, 1976). According to the classification proposed by Frost et al. (2001), they are magnesian metagranites (Figure 4d) straddling the boundary between the calc-alkalic and alkali-calcic fields (Figure 4e). On the primitive mantle (PM) normalized multi-element variation diagram (Figure 5a), they show typical calcalkaline patterns with enrichment in LILE (Large Ion Lithophile Elements) over HFSE (High Field Strength Elements), troughs at Sr-P, Nb and Ti and peaks at Th, K and Pb. They are also enriched in LREE (Light Rare Earth Elements) with respect to HREE (Heavy Rare Earth Elements) (Figure 5b), and they show $(La/Yb)_N$ = 12.23 – 13.01 and negative Eu anomalies (Eu/Eu* = 0.59 – 0.62).

Grand St Bernard - Leverogne unit. The Middle Ordovician granophyres of the Leverogne unit are mainly metaluminous (A/CNK = 0.98 – 1.03) alkali granites with silica content of 75.2 – 75.6 wt% (Figure 4a and b). They have high K_2O content (Figure 4c), are ferroan granitoids and plot in the alkali-calcic field (Figure 4d and e). FeO^{tot}/MgO ratios vary from 4.8 to 11.1 with an average of 7.3 that is higher than values observed in I-type, S-type and M-type granites (Whalen et al., 1987). They are also characterized by high Ga/Al ratios (10,000*Ga/Al > 2.6) and high Zr+Nb+Ce+Y concentrations (446 - 467 ppm), suggesting an A-type geochemical character (Whalen et al., 1987). On the PM-normalized multi-element variation diagram (Figure 5c), they are characterized by negative Ba, Nb, P, Zr and Ti, and positive Rb, Th-U and K anomalies. The samples are enriched in LREE relative to HREE (Figure 5d), with positive LREE slope [$(La/Sm)_N$ = 2.84 – 3.11], relatively flat HREE [$(Gd/Yb)_N$ = 1.16 – 1.26] and a pronounced Eu anomaly (Eu/Eu* = 0.17 – 0.21).

Grand St Bernard - Grand Nomenon unit. The Upper Devonian granitoids from the Grand Nomenon pluton are metaluminous (A/CNK = 0.75 – 0.91) diorites and granodiorites (Figure 4a and b) showing high-K calcalkaline affinity (Figure 4c). They plot as magnesian calc-alkalic granitoids (Figure 4d and e). On PM normalized multi-element variation diagram (Figure 5e), they are enriched in LILE with respect to HFSE with troughs at Rb-Ba, Nb-Ta, P and Ti, and peaks at K, Pb and Nd-Zr. They present LREE enrichment over HREE (Figure 5f), with $(La/Yb)_N$ =7.36 – 20.67 and slight negative Eu anomalies (Eu/Eu* = 0.77 – 0.79).

The most evolved sample (SiO_2 > 75 wt%) is a peraluminous (A/CNK = 1.16) and high-K calcalkaline leucogranite (Figure 4a, b and c) plotting in the ferroan and calc-alkalic field (Figure 4d and e).

Grand St Bernard - Houillère unit. The Costa Citrin gneissic body of the Houillère unit derives from a metaluminous (A/CNK = 0.99) Lower Permian granite (Figure 4a and b), with high silica (SiO_2 = 73.81 wt%) and total alkali ($Na_2O + K_2O$ = 9.09) contents and high FeO^{tot}/Mg (= 5.9) and K_2O/Na_2O (= 1.23) ratios. It plots close to the boundary between high-K calcalkaline and shoshonitic series in the K_2O vs. SiO_2 diagram (Figure 4c). Although its agpaitic index of 0.90 supports its A-type geochemical feature, this sample is not strictly A-type but more likely transitional. In fact, it does not satisfy an A-type chemical signature in terms of trace elements, such as low 10,000*Ga/Al (< 2.6) ratio and Zr + Nb + Ce + Y content (Whalen et al., 1987). The PM normalized pattern shows LILE enrichment over HFSE, with troughs at Ba, Nb, P, Zr and Ti, and peaks at U, K and Pb (Figure 5g). The REE pattern is enriched in LREE relative HREE (Figure 5h), with $(La/Sm)_N$ = 4.43, flat HREE pattern [$(Gd/Yb)_N$ = 1.16) and negative Eu anomaly (Eu/Eu* = 0.31).

Lepontine dome - Monte Leone. The Upper Ordovician Monte Leone granitoids are mainly granitic in composition and generally metaluminous to peraluminous, with A/CNK ratio close to 1 (0.9-1.2) and A/NK ratio between 1 and 2 (Figure 4a and b). All samples follow a typical calcalkaline trend and plot in the high-K calcalkaline field (Figure 4c). On the PM-normalized diagram, they are enriched in LILE (Cs, Rb, Ba, Th, U, K) with respect to HFSE and show marked negative P, Ba, Nb and positive Pb and Zr spikes (Figure 5a). Their REE pattern is characterized by LREE enrichment (100 – 300 times) compared to HREE (6-20 times; $(La/Yb)_N$ = 5.5 - 12.6) and by a negative Eu anomaly (Eu/Eu* = 0.46-0.72) (Figure 5b).

Lower Austroalpine – Gneiss del Monte Canale unit. The Upper Devonian samples from the Monte Canale pluton are dioritic to granitic in composition with high-K calc-alkaline affinity and a metaluminous character (A/CNK = 0.85-1.09) (Figure 4a, b and c). They plot as magnesian granitoids straddling the alkali-calcic and calc-alkalic boundary (Figure 4d and e). On the PM-normalized multi-element variation diagram (Figure 5e), they are enriched in LILE over HFSE, with peaks at Pb and Zr and troughs at Ba, Nb and Ti. Their REE pattern is characterized by enrichment in LREE (40-130 times) over HREE (6-25 times), a slightly positive Eu anomaly (Eu/Eu* = 0.90 - 0.98) and $(La/Yb)_N$ = 8-11 (Figure 5f). The leucogranites present high-silica content (SiO_2 > 75 wt%), peraluminous character (A/CNK>1.2) but scattered K_2O content (Figure 4b and c). They are mainly magnesian granites straddling calc-alkalic and alkali-calcic fields in Figure 4d and e.

5. Discussion

Age, paleogeographic significance and tectonic evolution of orthogneisses in the pre-Mesozoic basements across southern Europe and the Alps have long been the subject of interest and controversies. The Paleozoic inheritance of the basement units exposed in the Central and Western Alps is supported by groups of modern isotope dating, which are interpreted as a mark of magmatic and metamorphic events occurring before and after the unconformable deposition of Upper Carboniferous coal-bearing sedimentary rocks atop the Variscan orogenic belt (Dal Piaz, 1939). Evidence of Late Proterozoic to Cambrian and even older events is provided by U-Pb ages on zircons from metasediments (Gauthiez et al., 2011; Manzotti et al., 2015, 2016) and igneous bodies from various basement units of the Alpine belt (Bussien et al., 2011; Neubauer, 2002; Poller, 1997, Schaltegger et al., 1997; Scheiber et al., 2014; Schulz et al., 2008). At that time, these units were probably assembled to the Gondwana margin, to be later tectonically dismembered and re-amalgamated since the Devonian during the Variscan orogeny (Stampfli & Borel, 2002; von Raumer et al., 2013). Unfortunately, geochemical and geochronologic datasets about Variscan and pre-Variscan protoliths in the Central and Western Alps are largely incomplete, and most geochronologic ages are referred to low-retentivity isotopic systems.

5.1. Ordovician magmatic cycle

Upper Cambrian-Ordovician magmatic rocks are distributed from Iberia to the Bohemian Massif through the Pyrenées and the French Massif Central (Ballèvre et al., 2014; Castiñeira et al., 2008; Friedl et al., 2004; Melleton et al., 2010; Sanchez-Garcıa et al., 2003). Current geodynamic reconstructions generally agree about the occurrence of a Cambrian to Early Ordovician active continental margin all along northern Gondwana, associated to the southward subduction of the Iapetus Ocean (Kroner & Romer, 2013; von Raumer & Stampfli, 2008). By contrast, the interpretation of post-Early Ordovician magmatism is problematic, and several models have been proposed so far for the post-Cambrian evolution of the northern Gondwana margin (e.g., Kroner & Romer, 2013; von Raumer et al., 2013).

In the Alpine domains, Ordovician granitoids and coeval basic rocks cover a time span ranging from 480 Ma to 420 Ma (Neubauer, 2002; Schaltegger & Gebauer, 1999; von Raumer et al., 2002). According to data presented in this work, high-K metaluminous to peraluminous calcalkaline granites were emplaced during the Late Ordovician in the Ruitor unit (459.0 ± 2.3 and 456.4 ± 2.4 Ma) and in the Monte Leone basement (457.9 ± 3.5 Ma) (Figure 3a, b and f). In the Grand St Bernard - Briançonnais nappe system (Figure 6), other geochemically similar granitic protoliths (Figure 5a and b) are documented in the Ruitor (468 ± 22, 465 ± 11, 460 ± 7 Ma, Guillot et al., 2002), Siviez-Mischabel (~460 Ma, Genier et al., 2008), Sapey (Modane metagranites: 452 ± 5 Ma; Bertrand et al., 2000a) and Ligurian Briançonnais (470 – 455 Ma, Gaggero et al., 2004) basement units. Metagranitoids with similar age (Figure 6) and geochemistry (Figure 5a and b) are also preserved in the Dora-Maira unit (457 ± 2 Ma, Bussy & Cadoppi, 1996), the Lower Penninic units of the Central Alps (Gruff Complex: 453 ± 8.4 Ma, Galli et al., 2011; Adula Nappe: Garenstock augengneiss 446 - 460 Ma and Rossa orthogneiss 455 - 460 Ma, Caravagna-Sani et al., 2014; 457 ±

4 Ma, Liati et al., 2009; Sambuco nappe: 464.3 ± 8 Ma, Bussien et al., 2011), the Eastern Austroalpine nappes (Languard-Campo: 448 ± 14 Ma, Boriani et al., 2012a; Silvretta: "Younger Orthogneiss" 451 ± 2 Ma, Flisch, 1987), and the Southern Alps (Serie dei Laghi: 450 - 460 Ma, Pezzotta & Pinarelli, 1994; Fioraro Complex: 462 ± 11 Ma, Bergomi et al., 2004).

The geochemical features of these rocks (high LILE/HFSE, LREE/HFSE and Th/Yb ratios, low Nb content, negative Nb and positive Pb spikes; Figure 5a and b) could be consistent with those of modern continental and island arc granitoids (e.g., Tatsumi & Eggins, 1995), and may be interpreted as the arc to backarc evolution of a convergent plate margin (Schaltegger et al., 1997; Stampfli et al., 2011). However, their geochemical calcalkaline signature may not necessarily imply a direct linkage with a coeval supra-subduction setting, but may result from a range of shallow processes such as mixing of distinct magma batches, fractional crystallization and interaction with crustal components. Granites with calcalkaline geochemical signatures are observed, for instance, in transtentional-extensional settings characterized by a heterogeneously metasomatized sub-continental mantle, such as the Cenozoic Basin and Range Province in the US (Hawkesworth et al., 1995) and the Permian igneous province in Europe (Dal Piaz, 1993; Dal Piaz & Martin, 1998; Marotta & Spalla, 2007; Schaltegger & Brack, 2007). Plutonic rocks of intermediate composition generally dominate modern active continental margins (Wilson, 1989), whereas continental rift zones often show a geochemically bimodal magmatism, with calcalkaline granites and alkali granites (granophyres) associated to minor basic rocks and layered gabbro-peridotite batholiths (Costa & Rey, 1995; Wilson et al, 2004). In the latter case, many different magma types, possibly including I-type and S-type granites as well as alkaline to tholeiitic basalts, are expected after melting of lower crust and mantle sources (Finger & Steyrer, 1995; Floyd et al., 2000).

In the Grand St Bernard - Briançonnais basements, the pre-Variscan magmatic cycle generally starts with ~500 Ma old granophyres and granites (Scheiber et al., 2014). These rocks are sometimes ascribed to the continental rifting that preceded the opening of the Rheic Ocean along the northern Gondwana margin (von Raumer et al., 2013), as possibly confirmed by the occurrence of a ~496 Ma old plagiogranite in the Chamrousse ophiolite (Helvetic Belledonne massif, Ménot et al., 1988). Metagranophyres from the Levorogne unit (sample s3) share a ferroan and metaluminous geochemical behavior with the Val di Rhêmes – Changier granophyre (Figure 5c and d) dated at 511 ± 9 Ma by Bertrand et al. (2000b). However, our sample s3 yielded a much younger emplacement age of 465.0 ± 2.5 Ma (Figure 3c). Ages of ~500 Ma were instead obtained in metamict zircon grains from sample s3, but they were discarded due to their high proportion of common Pb (Table TS01). As a result, the Leverogne metagranophyres fall in the same time interval (470 - 450 Ma) of both calcalkaline granites and volumetrically minor basic rocks described in the Briançonnais basement. The Middle to Upper Ordovician protoliths of these Briançonnais orthogneisses are generally intruded within pelitic and arenaceous successions of Late Neoproterozoic to Cambrian age, as indicated by inherited zircon cores in our analyzed samples (Table TS01). They are closely associated with boudins of mafic rocks (eclogites) and massive to banded amphibolite sills (Thèlin et al., 1993). The eclogitic protoliths recognized in the Ruitor and Siviez-Mischabel basements are not dated yet, but protolith ages of 468 ± 22 and 471 ± 5 Ma were determined for banded amphibolites of the Ruitor unit (Guillot et al., 2002). Similar ages were also found in gabbroic sills of the Mont Fort basement that are emplaced within a coeval volcanic-detrital succession (456.7 - 460 Ma; Gauthiez et al., 2011), and in mafic rocks from the Ligurian Briançonnais (469 ± 6 Ma, Gaggero et al., 2004; Giacomini et al., 2007), the Helvetic External Massifs (463 +3/-2 and 458 ± 5 Ma, Bussy et al., 2011; 467 +5/-4 and 471 +6/-7 Ma, Oberli et al., 1994; 453 +3/-2 Ma, Paquette et al., 1989; 462 ± 6 Ma, Rubatto et al., 2001; 478 ± 5 Ma, Schaltegger et al., 2003) and the Eastern Austroalpine Silvretta nappe (467 ± 14 Ma, Poller, 1997).

The occurrence of such bimodal magmatism in a relatively short time interval (470-450 Ma) is supportive of magma emplacement within a transtentional to extensional setting along the northern Gondwana margin, which is also in line with the high-T metamorphic event at 450-420 Ma reported in the Eastern Austroalpine and Helvetic domains (Rode et al., 2012; Schulz et al., 2008; Thöny et al., 2008; von Raumer et al., 2013). These bimodal magmatic features are common to all of the pre-Variscan basement units of the Central and Western Alps, which may suggest that all of these units were possibly part of the same thinned-continental-crust domain in northern Gondwana during Middle to Late Ordovician times.

5.2. Devonian magmatic cycle

The Variscan belt is generally envisaged as a collage of terranes (Matte et al., 1990; Stampfli & Borel, 2002) variously assembled from the Late Devonian to the Early Permian along the southern margin of Laurussia (including the Avalonia microcontinent), with generation and exhumation of granulites and eclogites, partial melting and formation of anatectic migmatites, emplacement of granitoids and development of sedimentary basins. A number of plutons intruded the Variscan belt in a time window of ~80 Ma (Figure 7a). An early pre-collisional pulse of medium to high-K calcalkaline melts developed in the Late Devonian to Early Carboniferous (380 - 345 Ma). It was followed by syn-orogenic high-K calcalkaline to shoshonitic magmatism at 345 - 330 Ma, and then by the intrusion of post-collision magmas at 330 - 300 Ma, associated with penetrative low-pressure and high-temperature regional metamorphism and anatectic migmatites (e.g., Žák et al., 2014). Evidence of this evolution is partly preserved in the Grand St Bernard nappe (Grand Nomenon pluton) and in the Lower-Austroalpine Bernina nappe (Monte Canale pluton). Our analyses of the Grand Nomenon pluton provided a Late Devonian age of 371 ± 0.9 Ma (Figure 3d), interpreted as the age of the protolith, which is slightly older than the age previously reported by Bertrand et al. (2000b) (upper intercepts at 363 ± 24 and 353 ± 3 Ma). In our samples, data spots between 350 and 360 Ma were discarded because of suspect Pb loss (Table TS01). A quite similar Late Devonian emplacement age of 369.3 ± 1.5 Ma was determined for the metagranodioritic protholith of the Monte Canale pluton (Figure 3g). Therefore, the Grand Nomenon and the Monte Canale plutons not only share a similar lithology (mainly metagranodiorites with minor metadiorites and metagranites) and geochemical trends (Figure 4 and 5e-f, high-K magnesian calcalkaline granitoids), but also the same emplacement age (Figure 3d and g). The less evolved samples (SiO_2 < 60%, Figure 5e and f inset), where the effects of fractional crystallization and crust contamination are not expected to mask the primary features of the magma source, show deep troughs in HFSE on PM-normalized diagrams coupled with strong enrichment of hydrous-fluid mobile LILE, resulting in high LILE/HFSE (e.g., Ba/Nb > 27.4), LREE/HFSE (La/Nb >1.8) and Th/Yb (> 7.65) ratios, which are typical of a supra-subduction setting (Tatsumi & Eggins, 1995; Wilson, 1989). This is also suggested by the quite primitive radiogenic isotopic signature of the Grand Nomenon metadiorites (Nd_{360} from –1.2 to +0.9, $^{87}Sr/^{86}Sr_{360}$ from 0.7054 to 0.7063, Guillot et al., 2012).

The Grand Nomenon and Monte Canale plutons may have Alpine counterparts in the 374 ± 10 Ma old high-K calcalkaline metagranodiorite from the Penninic basement of the Tauern window (Zwolferkogel gneiss, Eichhorn et al., 2000), in the Devonian-Carboniferous Rennfeld metatonalite suite and trondhjemite from the easternmost Austroalpine (Neubauer et al., 2003) and in the Helvetic domain where a Devono-Dinantian age is cited by Guillot & Ménot (2009) (Figure 7a). In the stable European basement north of the Alps, coeval and geochemically comparable granitoids (Figure 5e and f) are exposed in the Bohemian Massif (380–370 Ma, Kosler et al., 1995; Venera et al., 2000; Žák et al., 2011), in the northern French Massif Central (380-350 Ma, Faure et al., 2005; Pin & Paquette, 2002) and in the southern Armorican domain (373 +6/-11 Ma, Faure et al., 2005, and references therein) (Figure 7a).

A number of ~340 Ma old syn-collisional shoshonitic granites were dated in Corsica (e.g., Rossi et al., 2009) and in the External Crystalline Massifs (Guillot & Ménot, 2009), whereas post-collisional granites were emplaced at ~340 Ma in the Eastern Alps (Eichhorn et al., 2000) and at 320-315 Ma in the Helvetic domain (Guillot & Ménot, 2009; Rubatto et al., 2001), Sardinia and Corsica (Rossi et al., 2009) (Figure 7a). The Monte Canale pluton, metamorphosed under greenschist facies condition, is cut by a coarse-grained peraluminous leucogranite (Figure 4; Monte

Canale samples with SiO_2> 75 wt%) intruded at ~320 Ma (von Quadt et al., 1994). The Late Devonian emplacement of the Monte Canale pluton pre-dates the Variscan collision, whereas the crosscutting unmetamorphosed leucogranites were emplaced in a post-collisional setting. Both magmatic suites were later intruded by Upper Carboniferous high-K calcalkaline tonalites to granites (310-300 Ma; Boriani et al., 2012a; von Riet, 1984). The Grand Nomenon granitoids are similarly intruded by coarse-grained peraluminous leucogranites, which might be coeval with those crosscutting the Monte Canale pluton (Figure 4; Grand Nomenon sample with SiO_2> 75 wt%), but no Late Carboniferous igneous ages are reported from the Grand St Bernard igneous bodies.

Even though the Gneiss del Monte Canale and the Grand Nomenon units may partly share their magmatic evolution with the Helvetic External Massifs (Guillot & Ménot, 2009; Rubatto et al., 2001) and the Eastern Alps (Eichhorn et al., 2000), many uncertainties arise about their linkage with potential counterparts in stable Europe. According to von Raumer et al. (2013), the Late Devonian-Early Carboniferous arc-related magmatism would be the result of the southward subduction of the Rheic Ocean beneath a composite peri-Gondwana terrane. Guillot and Ménot (2009) proposed an extensional back arc setting for the Late Devonian to Dinantian magmatism in the Helvetic domain, possibly associated to the southeastward subduction of the Saxo-Thuringian Ocean. Rossi et al. (2009) suggested for the Silurian–Devonian magmatism of Corsica-Sardinia a northward oceanic subduction beneath Armorica, possibly followed by oblique continental collision between Armorica and Gondwana during the Late Devonian-Early Carboniferous. Neubauer and Handler (1999) proposed a northward subduction of a pre-Carboniferous oceanic basin beneath the southern margin of the Moldanubian domain, in order to explain the Late Devonian-Early Carboniferous magmatism in the Eastern Alps. Discriminating among the above tectonic models is beyond the aims of this study. However, the Variscan orogeny was also characterized by relevant orogen-parallel tectonic displacements as attested by the occurrence of major strike-slip shear zones (Carosi et al., 2012; Edel et al., 2013; Eichhorn et al., 2000; Guillot & Ménot, 2009; Hatcher, 2002;

Martınez Catalan et al., 1990; Shelley & Bossiere, 2000; von Raumer, 1998). The present-day relative position of the Grand Nomenon and Monte Canale plutons compared to their potential counterparts in stable Europe may thus reflect a complex geodynamic scenario involving terrane dispersion by well-documented dextral shear zones active along the boundary of the Moldanubian domain (Figure 7b), followed by Early Permian transtension, Mesozoic rifting and Alpine nappe stacking.

5.3. Permian magmatic cycle

The Late Carboniferous to Early Mesozoic was a period of general plate reorganization, marking the evolution from compressional to extensional tectonics. In the Western Alps, Early Permian emplacement of mafic melts at depth (Dal Piaz, 1993; Manzotti et al, 2017; Marotta & Spalla, 2007, and references therein) was associated with (and followed by) bimodal volcanism and intrusion of granites and pegmatites in the upper crust (Dal Piaz & Martin, 1998; Dallagiovanna et al., 2009; Schaltegger & Brack, 2007; Schaltegger & Gebauer, 1999).

The Houillère unit includes the Lower Permian (279.1 ± 1.1 Ma, Figure 3e) Costa Citrin leucogranite, which shows high-K transitional affinity. Coeval and geochemically similar granitoids (Figures 5g, h and 6) and volcanics crop out both in the Briançonnais External zone (Randa augengneiss: 269 ± 2 Ma, Bussy et al., 1996b; Le Bautsé orthogneiss: 290 ± 4 and 272 ± 4, Scheiber et al., 2014) and in the Briançonnais Internal zone (Mont Fort nappe, Goli d'Aget ignimbritic metarhyolite: 267 - 280 Ma, Derron et al., 2006; Laget metaignimbrite: 267 - 282 Ma, Bussy et al., 1996b) of the Grand St Bernard – Briançonnais nappe system (Figure 6). Permian magmatic zircon cores are reported from metamorphic granite bodies (267 ± 1 and 272 ± 2 Ma) in the Valaisan units atop the Penninic Frontal Thrust (Versoyen zone; Beltrando et al., 2007). Discordant intrusions of porphyritic granite within Variscan high-grade paragneisses and migmatites are dated as Lower Permian in the eclogitized continental crust units of Monte Rosa (270 ± 4 and 268 ± 4 Ma, Pawlig & Baumgartner, 2001; 272 ± 4 Ma, Liati et al., 2001), Gran Paradiso (269 ± 6 and 277±4 Ma, Bertrand et al., 2000a; 277 ± 4 and 272 ± 3 Ma, Bertrand et al., 2005; 269 ± 6.5 and 270.2 ± 5 Ma, Ring et al., 2005) and Dora-Maira (275 - 276, Gebauer et al., 1997; 290 ± 2, 288 ± 2 and 283 - 267 Ma, Bussy & Cadoppi, 1996) (Figure 6). Similar intrusion ages are also reported, for the Austroalpine units of the Western Alps, in the metagranites and augengneisses of the Dent Blanche (Arolla series: 289 ± 2 Ma, Bussy et al., 1998), Mt Emilius (293 ± 3 Ma, Bussy et al., 1998) and Sesia-Lanzo (Mucrone: 286 ± 2 Ma, Paquette et al., 1989) (Figure 6). The age of volcanic rocks in the Briançonnais units of the Ligurian Alps ranges from 286 ± 3 to 273 ± 2 Ma (Dallagiovanna et al., 2009). In the Central Alps, basement units with Briançonnais affinity s.l. include gneissic granitoids derived from Permian protoliths (Roffna Complex in Suretta nappe: 290-265 Ma, Marquer et al., 1998; Scheiber et al., 2013; Truzzo granite in Tambò nappe: 268±0.8 Ma, Marquer et al., 1998) (Figure 6). Early Permian acidic igneous products are also widespread in the western-central Southern Alps (e.g., Gretter et al., 2013; Pinarelli et al., 1988; Schaltegger & Brack, 1999, 2007) (Figure 6). There is general consensus in connecting the Early Permian calc-alkaline magmatism in the Alps with the incoming lithospheric thinning and strike-slip tectonics that was followed, after the Mid-Permian magmatic gap, by regional extension and K-rich volcanics in the Late Permian (Dallagiovanna et al., 2009; Schaltegger & Brack, 2007). Moreover, the Late Variscan collapse seems to have developed diachronously, with ages getting progressively younger from the internal to the external zones of the Variscan belt (Dallagiovanna et al., 2009 and reference therein). The oldest igneous bodies are dated at 310–296 Ma in the Helvetic External Massifs (Bussy et al., 2000; Guerrot & Debon, 2000), 320–280 Ma in Sardinia (Oggiano et al., 2007), 307–300 Ma in Corsica (Cocherie et al., 1994; Paquette et al., 2003; Rossi et al., 2009; Tommasini et al., 1995), 310–290 Ma in the Lepontine dome (Bergomi et al., 2007; Bussien et al., 2011) and 310-300 Ma in the Bernina nappe (Boriani et al., 2012; von Riet, 1984). Relatively younger bodies (≤ 290 Ma; e.g., Schaltegger & Brack, 2007) occur instead in the Adria-derived Dent Blanche-Sesia basements (293-286 and 285-260 Ma, respectively) and in the Southern Alps

(Figure 6). In this regard, the occurrence of Late Variscan igneous bodies in the Bernina nappe (310-300 Ma, Boriani et al., 2012a) could be supportive of a more internal position of these rocks within the Variscan belt. On the other hand, the absence of Upper Carboniferous magmatic products and the occurrence of Lower Permian intrusives and volcanics may point to a more external position for the External Briançonnais units, i.e., closer to the Gondwana foreland. The similarity of Lower Permian magmatic products in the Briançonnais, Austroalpine and Southalpine domains, both in terms of geochemical affinity (Figure 5g and h) and intrusion age (Figure 6), are consistent with the classic palinspastic reconstructions of the westernmost segment of the future Alpine region before the onset of Tethyan rifting, and consequent development of the European and Adriatic passive margins later involved in the Alpine orogeny (e.g., Beltrando et al., 2014; Malusà et al., 2016).

5.4. Paleogeographic implications

Based on the geochemical and geochronological data presented here, along with literature data on the Western and Central Alps with particular regard to the basement units of the Helvetic External Massifs and the Southern Alps that poorly suffered or escaped at all the Alpine metamorphism, we can speculate as follows:

(1) The pre-Variscan features of the studied basement units mimic those of other Alpine domains (e.g., Southern Alps, Pinarelli & Boriani, 2007) with Late Neoproterozoic and/or Cambrian pelitic-arenaceous successions intruded by basic and acidic igneous rocks within the framework of a Middle to Late Ordovician transtensional to extensional geodynamic setting. Because this pre-Variscan scenario is common to many other Gondwana-derived Alpine domains, we can consider that the pre-Variscan Briançonnais basements were all part of the thinned Gondwana margin.

(2) The Briançonnais and Bernina basement units preserve evidence of the Late Devonian to Carboniferous Variscan evolution. In the Ruitor, and other polycyclic basements of the

Briançonnais External zone, the Variscan orogeny is only documented by metamorphic fabrics and polyphase mineral assemblages. Metasediments and associated bodies of gneissic granitoids display relicts of an amphibolite facies metamorphism dated at ~330 Ma, whereas mafic rocks also preserve, in places, evidence of an early high-pressure event not dated yet in the External Briançonnais. This Variscan metamorphic evolution is common to other basement units of the Alps (e.g., Southern Alps, Pinarelli & Boriani, 2007), in which a main amphibolite facies metamorphism is locally preceded by a high-pressure event dated at ~400 Ma in Sardinia, ~392-376 Ma in the Ligurian Briançonnais (Giacomini et al., 2007), ~340 Ma in the Helvetic Argentera massif (Rubatto et al., 2010), ~340 and ~380 Ma in the Adula nappe of the Lepontine dome (Liati et al., 2009), ~351 Ma in the Silvretta nappe (Ladenhauf et al., 2001) and 340 – 360 Ma in the Eastern Austroalpine (Melcher & Meisel, 2004; Miller & Thöni, 1995; Thöni, 2003; Tumiati et al., 2003). By contrast, basement rocks of the Briançonnais Internal zone escaped both high-pressure and high-temperature Variscan metamorphism, but they were intruded (Grand Nomenon unit), along with the Bernina nappe (Gneiss del Monte Canale unit), by Upper Devonian arc-related plutons metamorphosed under greenschist facies conditions, and then crosscut by a ~320 Ma old peraluminous leucogranite. The Late Devonian magmatism highlights a close relationship of these basement units with the Bohemian Massif, the southern Armorican Massif and the northern French Massifs Central (Figure 7a). In this view, the polycyclic units of the Briançonnais Internal zone and the Bernina nappe were probably part of the Moldanubian domain (Figure 7b) and were possibly displaced towards the SW by dextral strike-slip faulting in the Late Carboniferous (Carosi et al., 2012; Edel et al., 2013; Guillot & Ménot, 2009; Matte, 2001; Muttoni et al., 2003) (Figure 7b), probably between 320 and 300 Ma as already proposed by Giacomini et al. (2007) and Rolland et al. (2009).

(3) From the Late Carboniferous to the Early Permian, the future Alpine domain was characterized by a change of geodynamic regime, from Variscan collision to post-Variscan

transtension and lithospheric extension propagating across a collage of terranes of different age and tectono-thermal history (Dallagiovanna et al., 2009; Manzotti et al., 2014; Marotta & Spalla, 2007; Schuster & Stüwe, 2008; Spalla et al., 2014; von Raumer et al., 2013). The Variscan orogenic belt was dismembered by dextral shear zones, in turn probably connected to the incoming Palaeo-Tethys subduction beneath Eurasia. Strike–slip faulting and lithospheric extension were associated to the emplacement of post-collisional igneous bodies from crustal and subcrustal sources, as well as to the opening and infilling of intramontane basins in the Houillère zone and, later on, in the Helvetic and westernmost Southalpine domains. The common occurrence of Lower Permian magmatic rocks (Figure 6) in the Houillère and Internal Briançonnais units, in the Southalpine basement and in the Austroalpine units of Dent Blanche and Sesia-Lanzo suggest that all of these units were already amalgamated before the opening of the Alpine Tethys. Despite the Variscan inheritance was of primary importance in shaping the European and Adriatic continental margins (Guillot et al., 2009; Malusà et al., 2015; 2016), the remnants of the Moldanubian domain represented by the Grand Nomenon and Gneiss del Monte Canale units became part of opposite continental margins facing the Alpine Tethys (Figure 7b), and are now accreted in the Alpine orogenic wedge either as part of the Europe-derived Grand St Bernard nappe (Grand Nomenon unit) or as part of the Adria-derived Austroalpine nappes (Gneiss del Monte Canale unit).

6. Conclusions

New SHRIMP U-Pb zircon and geochemical whole rock analyses carried out on gneissic igneous bodies of the Grand St Bernard - Briançonnais nappe system of the Western Alps and surrounding units, shed new light on the Paleozoic evolution of the Variscan and pre-Variscan continental crust involved in the Alpine orogeny, leading to the following main conclusions:

1) The Grand St Bernard - Briançonnais nappe system preserves the evidence of a complex tectonic evolution at the northern margin of Gondwana, starting from transtension in the

Ordovician, followed by subduction in the Devonian and final terrane amalgamation before the onset of Alpine orogeny.

2) Basement units of the Briançonnais Internal zone (Grand Nomenon unit) and Bernina nappe (Gneiss del Monte Canale unit) were intruded by high-K calcalkaline granitoids in the Late Devonian. Geochronological analyses on the Grand Nomenon and Monte Canale plutons provide the first compelling evidence of Late Devonian magmatism in the Alps.
3) The Briançonnais Internal zone and the Bernina nappe were possibly part of the Moldanubian domain, and were displaced towards the SW by strike-slip faulting in the Late Carboniferous (Figure 7b).
4) The resulting Late Carboniferous assemblage of Variscan and pre-Variscan basement units was dismembered by strike–slip tectonics during the Permian and by the opening of the Alpine Tethys during the Mesozoic. At that time, remnants of the Moldanubian domain now exposed in the Alps became part either of the European (Grand Nomenon unit) or of the Adriatic (Gneiss del Monte Canale unit) paleomargin (Figure 7b), to be finally accreted in the Alpine orogenic wedge during the Cenozoic.

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FIGURES

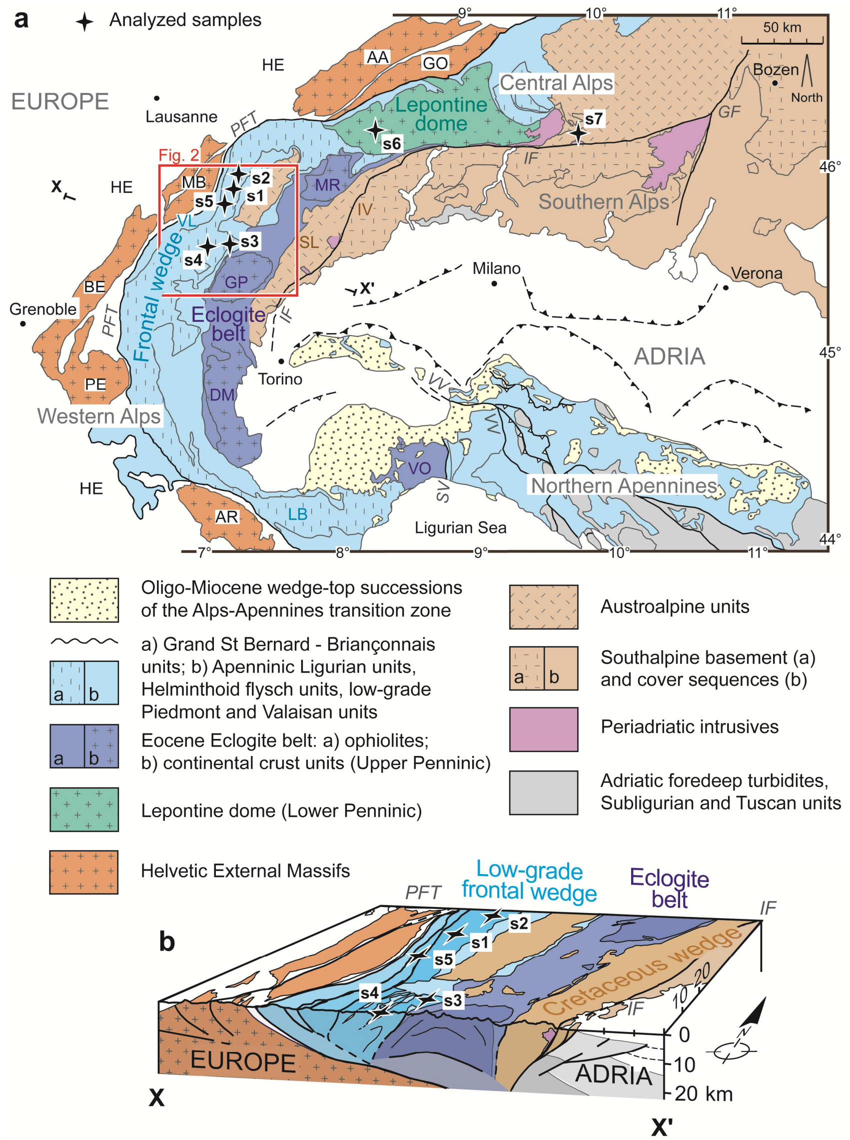

Figure 1. (a) Tectonic sketch map of the Western and Central Alps; (b) 3D model of the Western Alps along cross section X-X' (after Malusà et al., 2015). Black stars indicate the location of dated samples (s1 to s7). Acronyms: AA, Aar; AR, Argentera; BE, Belledonne; DM, Dora-Maira; GF, Giudicarie Fault; GO, Gotthard; GP, Gran Paradiso HE, Helvetic; IF, Insubric Fault; IV, Ivrea-Verbano; LB, Ligurian Briançonnais; MB, Mont Blanc; MR, Monte Rosa; PE, Pelvoux; PFT, Penninic Frontal Thrust; SL, Sesia-Lanzo; SV, Sestri-Voltaggio Fault; VO, Voltri; VV, Villalvernia-Varzi Fault.

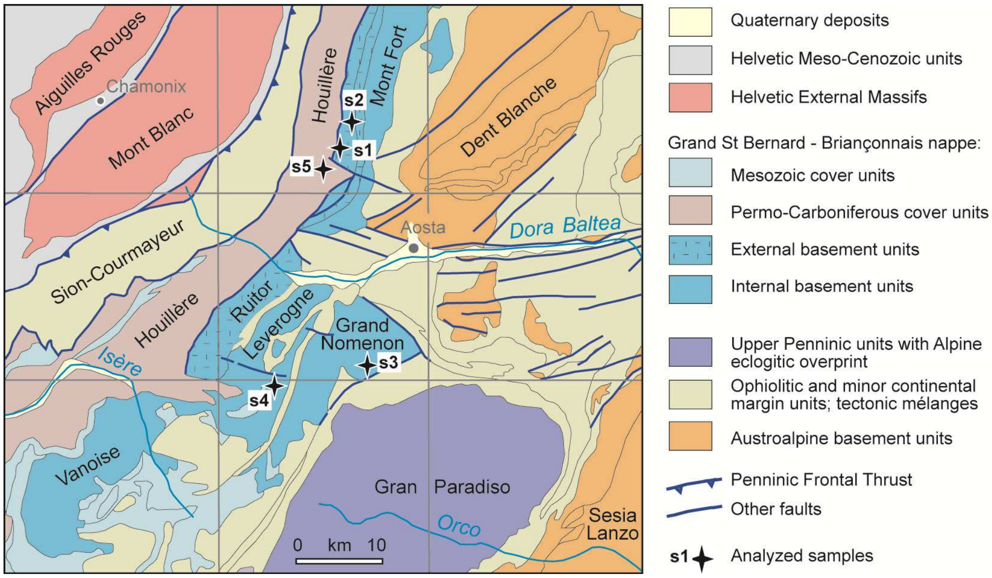

Figure 2. Tectonic map of the Grand St Bernard – Briançonnais nappe system and surrounding units in the Aosta Valley (modified after Polino et al., 2015; post-metamorphic faults after Malusà et al., 2009).

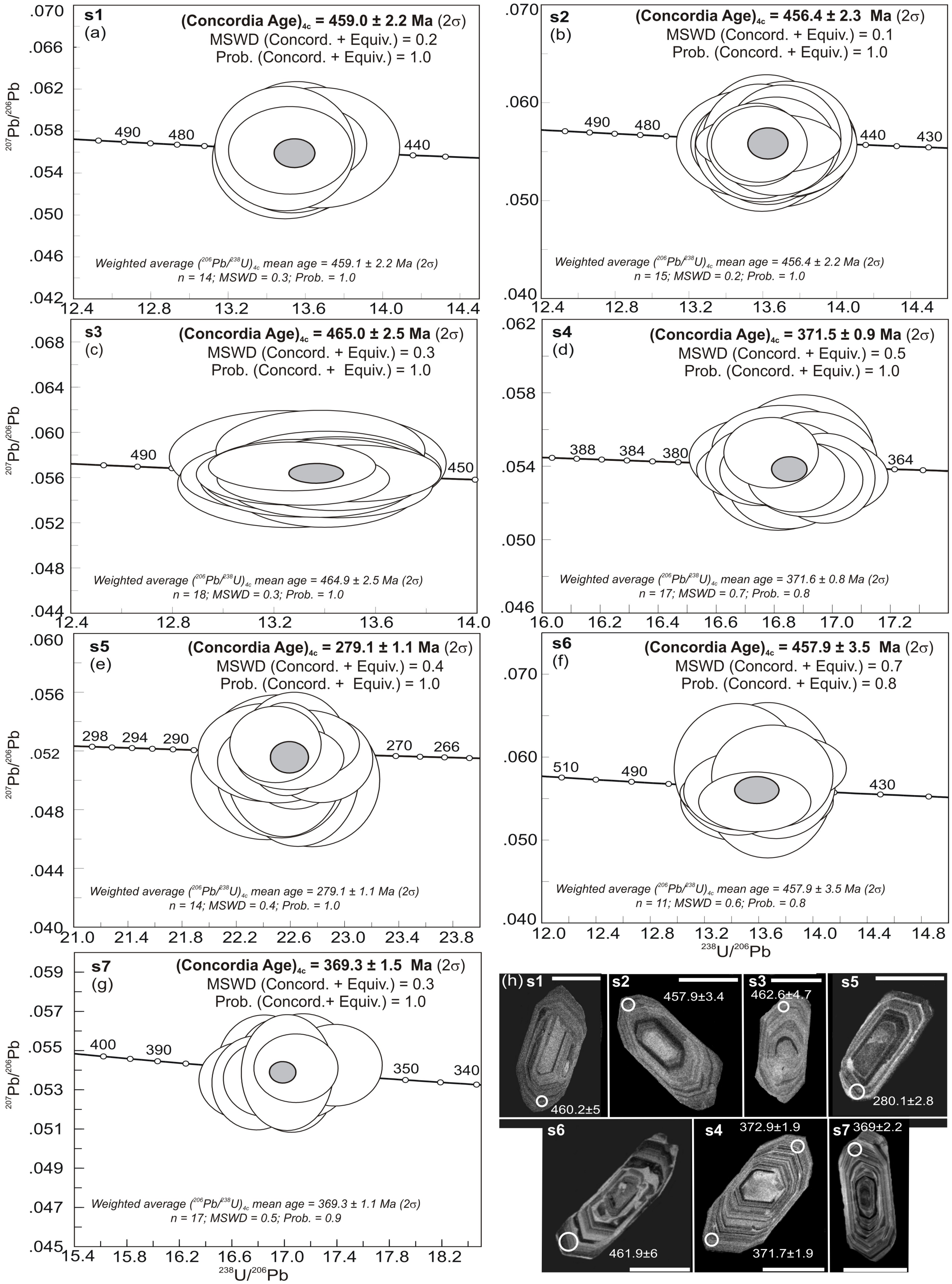
s1
(a)
(Concordia Age)4c = 459.0 ± 2.2 Ma (2σ)
MSWD (Concord. + Equiv.) = 0.2
Prob. (Concord. + Equiv.) = 1.0
Weighted average (206Pb/238U)4c mean age = 459.1 ± 2.2 Ma (2σ)
n = 14; MSWD = 0.3; Prob. = 1.0
s2
(b)
(Concordia Age)4c = 456.4 ± 2.3 Ma (2σ)
MSWD (Concord. + Equiv.) = 0.1
Prob. (Concord. + Equiv.) = 1.0
Weighted average (206Pb/238U)4c mean age = 456.4 ± 2.2 Ma (2σ)
n = 15; MSWD = 0.2; Prob. = 1.0
s3
(c)
(Concordia Age)4c = 465.0 ± 2.5 Ma (2σ)
MSWD (Concord. + Equiv.) = 0.3
Prob. (Concord. + Equiv.) = 1.0
Weighted average (206Pb/238U)4c mean age = 464.9 ± 2.5 Ma (2σ)
n = 18; MSWD = 0.3; Prob. = 1.0
s4
(d)
(Concordia Age)4c = 371.5 ± 0.9 Ma (2σ)
MSWD (Concord. + Equiv.) = 0.5
Prob. (Concord. + Equiv.) = 1.0
Weighted average (206Pb/238U)4c mean age = 371.6 ± 0.8 Ma (2σ)
n = 17; MSWD = 0.7; Prob. = 0.8
s5
(e)
(Concordia Age)4c = 279.1 ± 1.1 Ma (2σ)
MSWD (Concord. + Equiv.) = 0.4
Prob. (Concord. + Equiv.) = 1.0
Weighted average (206Pb/238U)4c mean age = 279.1 ± 1.1 Ma (2σ)
n = 14; MSWD = 0.4; Prob. = 1.0
s6
(f)
(Concordia Age)4c = 457.9 ± 3.5 Ma (2σ)
MSWD (Concord. + Equiv.) = 0.7
Prob. (Concord. + Equiv.) = 0.8
Weighted average (206Pb/238U)4c mean age = 457.9 ± 3.5 Ma (2σ)
n = 11; MSWD = 0.6; Prob. = 0.8
s7
(g)
(Concordia Age)4c = 369.3 ± 1.5 Ma (2σ)
MSWD (Concord. + Equiv.) = 0.3
Prob. (Concord.+ Equiv.) = 1.0
Weighted average (206Pb/238U)4c mean age = 369.3 ± 1.1 Ma (2σ)
n = 17; MSWD = 0.5; Prob. = 0.9
207Pb/206Pb
238U/206Pb
(h) s1
460.2±5
s2
457.9±3.4
s3
462.6±4.7
s5
280.1±2.8
s6
461.9±6
s4
372.9±1.9
371.7±1.9
s7
369±2.2

Figure 3. (a-g) Tera-Wasserburg Concordia diagrams (Tera & Wasserburg, 1972) for samples s1 to s5 from the Grand St Bernard – Briançonnais nappe system, s6 from the Monte Leone nappe, and s7 from the Gneiss del Monte Canale unit. Dark gray ellipses represent Concordia ages; subscript 4c indicates ^{204}Pb common lead correction. Individual error ellipses are given at 2-sigma level; n: number of analyses; Equiv.: Equivalence; MSWD: Mean Square of Weighted Deviates; Prob.: Probability of fit. (h) CL images of representative zircon grains. Circles indicate locations for U-Pb dating by SHRIMP; numbers denote ^{206}Pb/^{238}U ages with 1-sigma error; white bars are 100 μm.

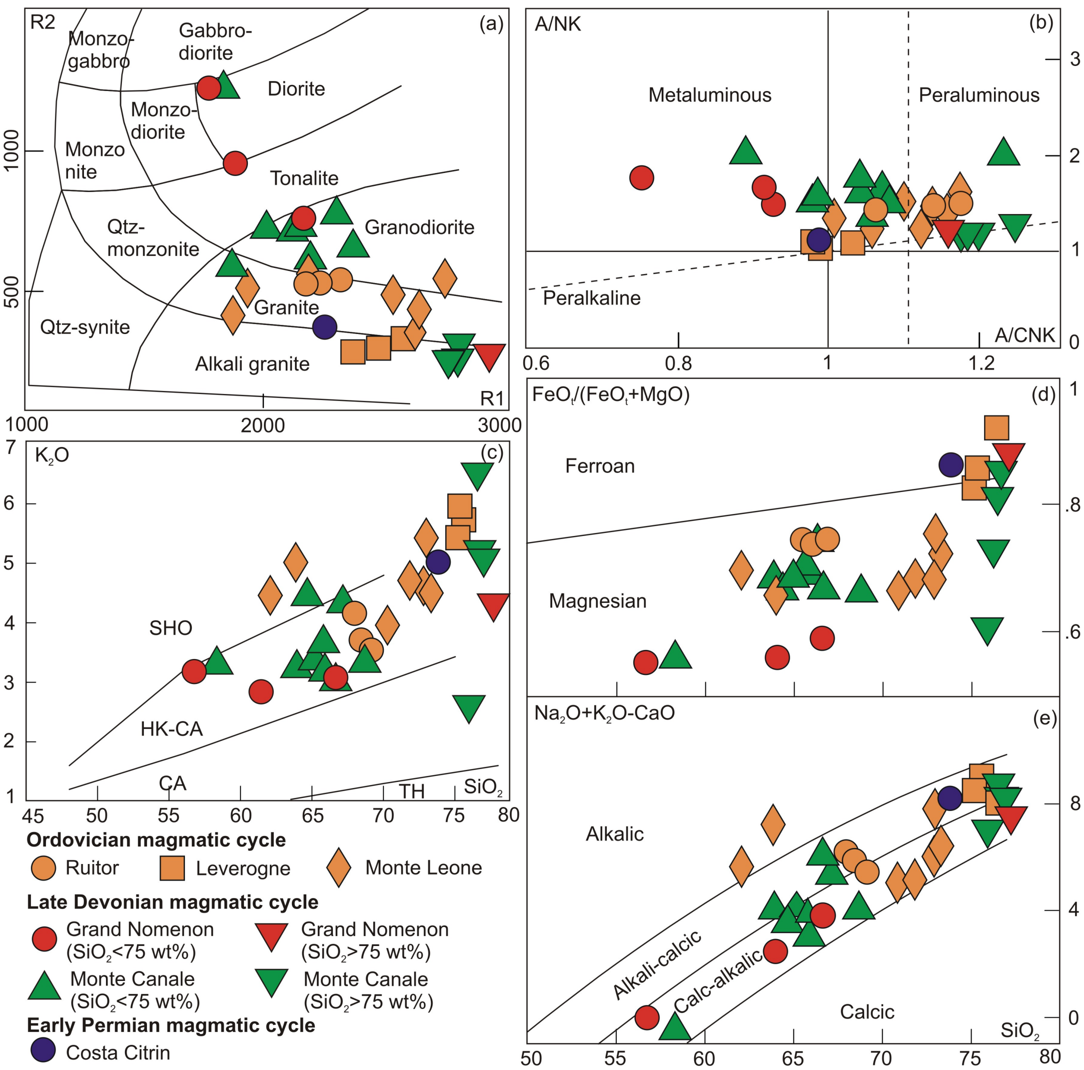

Figure 4. Classification of analyzed samples based on geochemical data. a) R1-R2 classification diagram of the De la Roche et al. (1980). R1 (millications)=4Si–11(Na+K)–2(Fe+Ti) and R2 (millications)=6Ca+2Mg+Al; b) A/NK [molar ratio $Al_2O_3/(Na_2O+K_2O)$] vs A/CNK [molar ratio $Al_2O_3/(CaO+Na_2O+K_2O)$]; c) K_2O (wt%) vs SiO_2 (wt%) classification diagram of Peccerillo & Taylor, 1976. TH: Tholeiitic series, CA: calcalkaline series, HK-CA: high-K calcalkaline series, SHO: shoshonite; d) $FeO_t/(FeO_t+MgO)$ vs SiO_2 (wt%) discrimination diagram of Frost et al. (2001); e) $K_2O+Na_2O–CaO$ (wt%) vs SiO_2 (wt%) discrimination diagram of Frost et al. (2001).

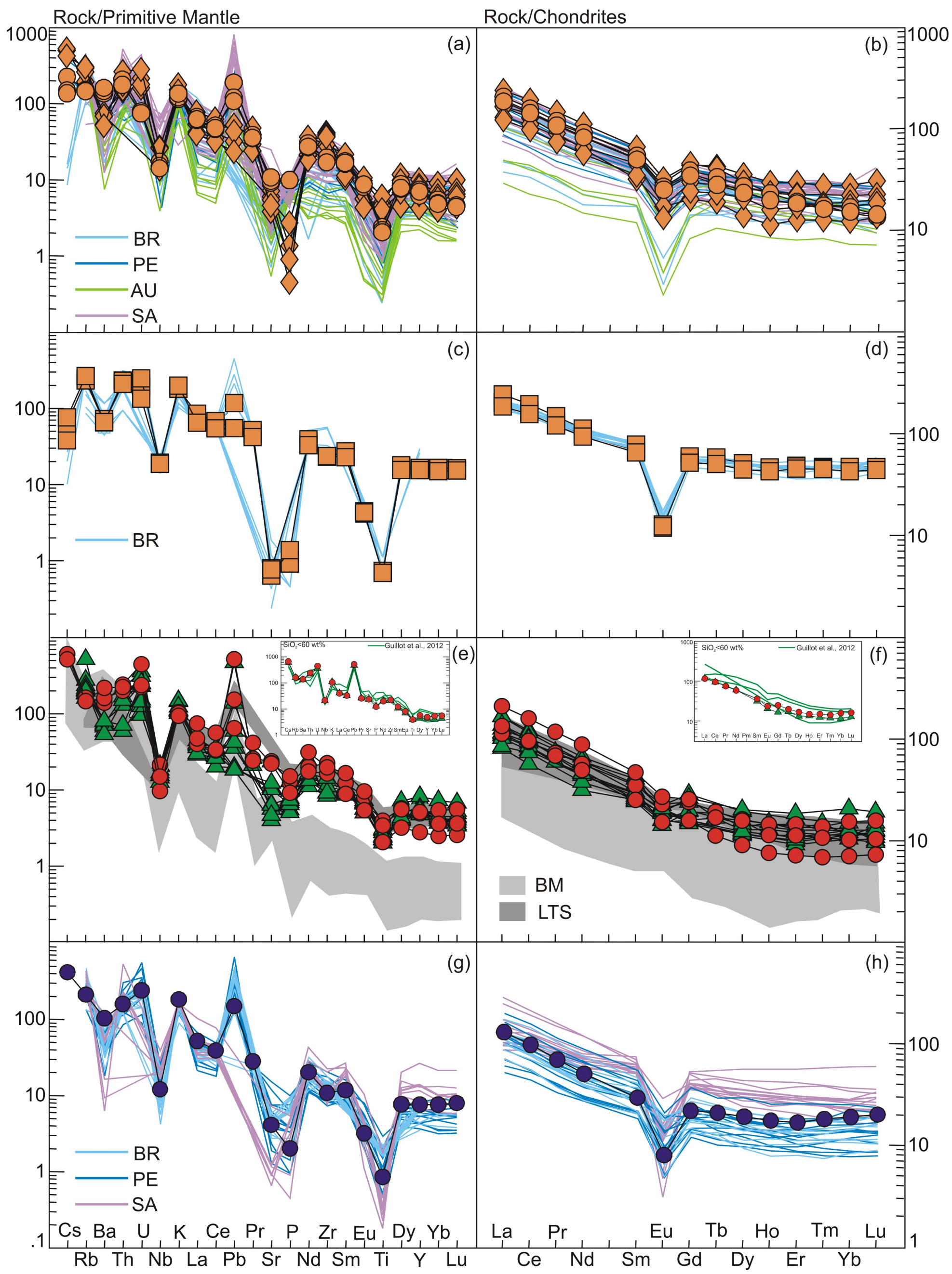

Figure 5. (a-c-e-g) Primitive mantle (PM) normalized trace element (Sun & McDonough, 1989) and (b-d-f-h) Chondrite-normalized rare earth (REE) element (Sun & McDonough, 1989) diagrams for analyzed samples (symbols as in Figure 4). In (a), (b), (c) and (d), Middle to Upper Ordovician orthogneisses from Briançonnais (BR), other Penninic (PE), Austroalpine (AU) and Southalpine (SA) basements are plotted for comparison. Data sources. BR: Guillot et al. (2002), Beucler et al.

(2000), Cosma (1999), Bertrand et al. (1998), Bussy & Cadoppi (1996), Guillot et al. (1993) and Thélin et al. (1993); PE: Caravagna-Sani et al. (2014) and Bussien et al. (2011); AU: Boriani et al. (2012a) and Schaltegger et al. (1997); SA: Pezzotta and Pinarelli (1994). In (e) and (f), fields of Upper Devonian granitoids from Bohemian Massif (BM) and French Limousin Tonalite Suite (LTS) are plotted for comparison. Data sources. BM: Žák et al. (2011, 2014) and Janousek et al. (2000, 2004); LTS: Shaw et al. (1993). Inset: (e) PM and (f) REE normalized multi-element variation diagrams for samples with SiO_2<60 wt% compared with those of Guillot et al. (2012). In (g) and (h), Lower Permian magmatic products from Briançonnais (BR), other Penninic (PE) and Southalpine (SA) domains are plotted for comparison. Data sources. BR: Pawlig & Baumgartner (2001), Bertrand et al. (1998), Marquer et al. (1998) and Bussy and Cadoppi (1996); PE: Caravagna-Sani et al. (2014) and Galli et al. (2012); SA: Pinarelli et al. (1988) and Bakos et al. (1990).

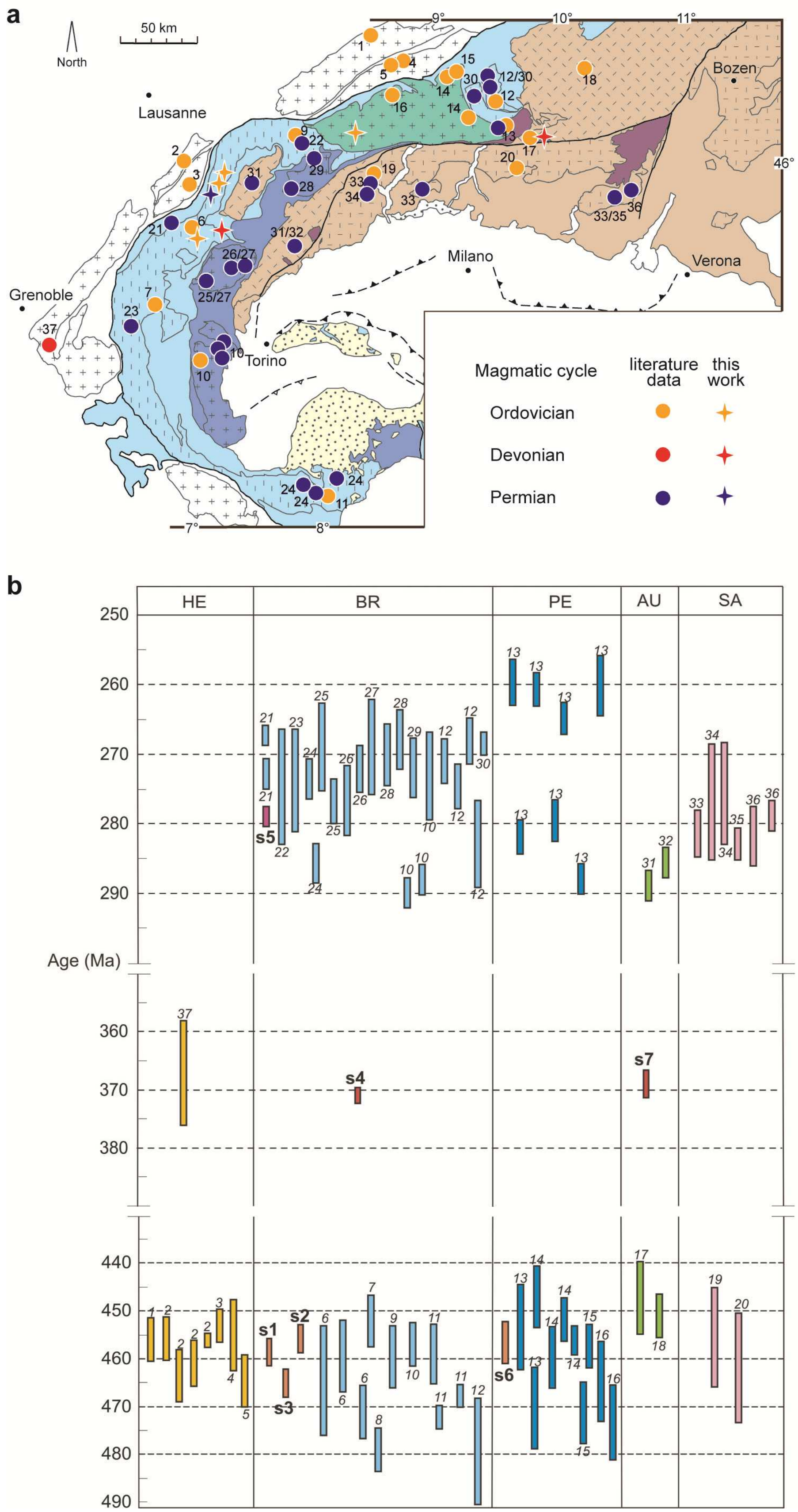
a
b
50 km
North
Lausanne
Grenoble
Torino
Milano
Verona
Bozen
Magmatic cycle
literature data
this work
Ordovician
Devonian
Permian
HE
BR
PE
AU
SA
Age (Ma)

Figure 6. Age map (a) and table distribution (b) of the Middle to Upper Ordovician, Upper Devonian and Lower Permian granitic protoliths in the Western and Central Alps to the West of the Giudicarie Fault (numbers 1 to 37 indicate literature data): 1) Schaltegger et al. (2003), 2) Bussy et al. (2011), 3) Bussy & von Raumer (1994), 4) Schaltegger (1994), 5) Oberli et al. (1994), 6) Guillot et al. (2002), 7) Bertrand et al. (2000a), 8) Bertrand & Leterrier (1997), 9) Genier et al. (2008), 10) Bussy & Cadoppi (1996), 11) Gaggero et al. (2004), 12) Scheiber et al. (2013), 13) Galli et al. (2012), 14) Caravagna-Sani et al. (2014), 15) Liati et al. (2009), 16) Bussien et al. (2011), 17) Boriani et al. (2012a), 18) Flisch (1987), 19) Pezzotta & Pinarelli (1994), 20) Bergomi et al. (2004), 21) Beltrando et al., (2007), 22) Bussy et al. (1996b), 23) Derron et al. (2006), 24) Dallagiovanna et al. (2009), 25) Bertrand et al. (2000a), 26) Bertrand et al. (2005), 27) Ring et al. (2005), 28) Pawlig & Baumgartner (2001), 29) Liati et al. (2001), 30) Marquer et al. (1998), 31) Bussy et al. (1998), 32) Paquette et al. (1989), 33) Schaltegger & Brack (2007), 34) Pinarelli et al. (1988), 35) Schaltegger & Brack (1999), 36) Gretter et al. (2013), 37) cited in Guillot and Ménot (2009). Emplacement ages of basic protoliths are cited in the text. HE: Helvetic; BR: Briançonnais; PE: other Penninic; AU: Austroalpine; SA: Southalpine.

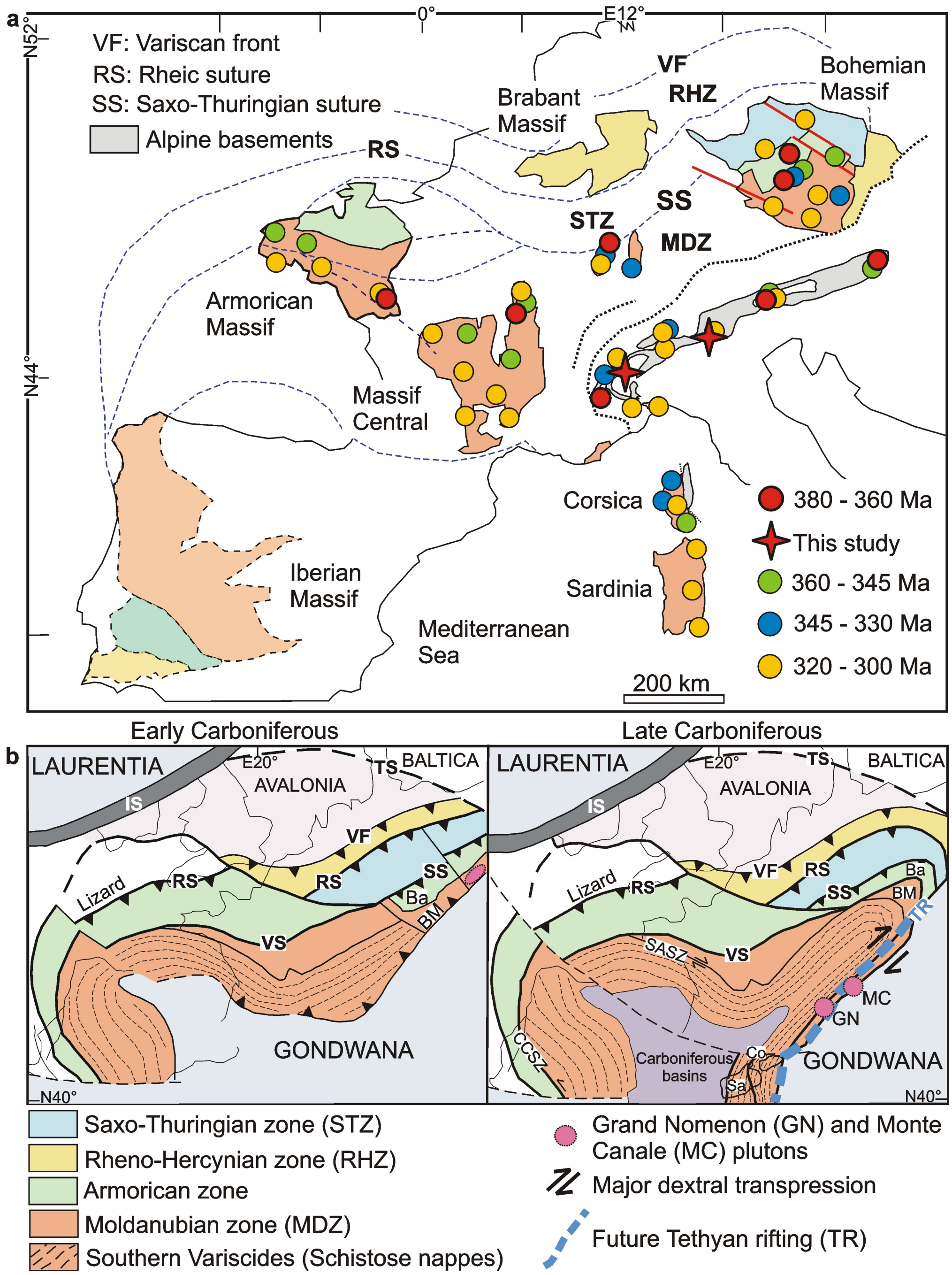

Figure 7. a) Simplified sketch map of the European Variscides (modified after Faure et al., 2005; Guillot & Ménot, 2009; Žák et al., 2014) showing basement distribution and representative Late Devonian to Late Carboniferous magmatic pulses (based on this work and literature data from Debon & Lemmet, 1999; Eichhorn et al., 2000; Faure et al., 2005; Guillot & Ménot, 2009;

Neubauer et al., 2003; Rossi et al., 2009; Schaltegger, 2000; Tabaud et al., 2014; Žák et al., 2014); b) Inferred position of the Grand Nomenon and Monte Canale plutons in the Variscan belt of western Europe during the Early and Late Carboniferous (modified after Carosi et al., 2012; Duchesne et al., 2013; Edel et al., 2013; Guillot & Ménot, 2009, Matte, 2001; Rossi et al., 2009). Major dextral transpression at 320–300 Ma according to Rolland et al. (2009). Ba: Barradian unit; BM: Bohemian Massif; CCSZ: Coimbra-Cordoba Shear Zone; Co: Corsica; IS: Iapetus suture; Sa: Sardinia; SASZ: South Armorican Shear Zone; TS: Tornquist suture; VS: eo-Variscan suture.

SUPPORTING INFORMATION:

Supplementary Table TS01: SHRIMP U-Pb analyses

Supplementary Table TS02: Whole rock compositions

Supplementary Table TS03: Sample locations, petrography and geochronology

Supplementary Methods