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Mg-metasomatism of metagranitoids from the Alps: genesis and possible tectonic scenarios

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1	Mg-metasomatism of metagranitoids from the Alps:
2	genesis and possible tectonic scenarios
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13	
14	Keywords: metasomatism; trace-element geochemistry; stable isotope; ultramafic rocks;
15	seawater.
16	

1	ABSTRACT
2	Mg-metasomatic rocks (e.g., whiteschists, leucophyllites) derived from post-Variscan
3	granitoids are common in the Alps. Previously reported field, petrological, geochemical and fluid
4	inclusion data are combined to trace the genetic processes and the associated tectonic scenarios.
5	Although the heterogeneous data, many common features can be recognised in all of the continental
6	Mg-metasomatic rocks, indicating that the genetic process is likely common in the entire range of
7	the Alps. This process assumes highly channelised fluids-derived from ultramafic rocks
8	previously interacting with seawater-that infiltrated the continental crust along strain zones and
9	produced chromatographic fractionation of major and trace elements. Three tectonic scenarios,
10	involving distinct mantle sources, are proposed: rift-related ocean-continent transition, continental
11	subduction, and continent-continent collision. All these data suggest that the Mg-metasomatism was
12	diachronous and occurred at different structural levels during the Alpine history.
13	

1	Introduction
2	A number of studies have been devoted to whiteschists and other Mg-rich rocks belonging
3	to continental Units of the Alps. These widespread rocks display a simple MgO – $Al_2O_3 - SiO_2 - $
4	$H_2O \pm K_2O$ mineralogy, with rare FeO and almost absent CaO and Na ₂ O. Originally, their genesis
5	was ascribed to isochemical metamorphism of a sedimentary protolith (e.g. Chopin, 1981; Schertl et
6	al., 1991), but at present they are interpreted as metasomatic rocks generated by fluid-assisted
7	exchange of elements (e.g., Demény et al., 1997; Barnes et al., 2004; Sharp and Barnes, 2004;
8	Ferrando et al., 2009) or by relative enrichment of MgO due to fluid-assisted removal of other
9	components (Prochaska, 1985; Prochaska, 1991). Protoliths are usually orthogneiss/metagranitoid
10	(e.g., Prochaska et al., 1992; Sharp et al., 1993; Demény et al., 1997; Manatschal et al., 2000;
11	Pawling and Baumgartner, 2001; Barnes et al., 2004; Ferrando et al., 2009; Gabudianu Radulescu
12	et al., 2009), though, locally, volcanic rocks (Prochaska et al., 1997), paragneiss (Prochaska, 1985;
13	Prochaska, 1991; Prochaska et al., 1997), and metagabbro (Prochaska et al., 1997) are also
14	described.
15	Only few multidisciplinary studies were devoted to the characterisation of the metasomatic
16	fluid (Prochaska et al., 1997; Manatschal et al., 2000; Barnes et al., 2004; Ferrando et al., 2009)
17	and the proposed sources are: a) dehydration of serpentinites (e.g. Sharp et al., 1993; Demény et al.,
18	1997; Barnes et al., 2004; Ferrando et al., 2009); b) interaction between seawater and mantle rocks
19	(Manatschal et al., 2000); c) mixing between seawater or formation water and meteoric water
20	(Prochaska et al., 1997); d) dehydration of flysch (Selverstone et al., 1991) or of evaporitic
21	sediments (Gebauer et al., 1997); e) late-magmatic hydrothermal system (Pawling and
22	Baumgartner, 2001). Previous works are also in disagreement about the timing of metasomatism:
23	during late-Variscan magmatic hydrothermalism (Pawling and Baumgartner, 2001), during Tethyan
24	rifting (Gebauer et al., 1997; Manatschal et al., 2000), during prograde (Ferrando et al., 2009), peak
25	or early retrograde (e.g., Selverstone et al., 1991; Prochaska et al., 1992; Barnes et al., 2004) Alpine
26	metamorphism. However, the widespread presence of these rocks indicates that Mg-metasomatic

processes were relatively diffuse in the Alps, and some authors have recently suggested the
 possibility of a common genesis (Demény *et al.*, 1997; Schertl and Schreyer, 2008; Ferrando *et al.*,
 2009).

4 In this paper, the evidence for a common genesis of continental Mg-metasomatic rocks from 5 hosting granitoids is described, the genetic process is reported, the related tectonic scenarios are 6 proposed, and the timing of metasomatism is made part of Alpine history. These goals are obtained 7 by integration of available data on Mg-metasomatic rocks and hosting acid igneous protoliths. Only 8 these lithologies have been considered because: i) the characterisation of the fluid-rock chemical 9 exchange is favoured by the extreme difference in bulk-rock compositions, ii) most of works 10 focused on these lithologies, iii) the comparison among similar data is favoured. Kind (field, 11 petrography, whole-rock composition, stable isotope, fluid inclusions) and amount of collected data 12 are heterogeneous among the considered localities (Fig. 1 and Table S1) that, from SW to NE, belong to: 1) the Dora-Maira (Cadoppi, 1990; Le Bayon et al., 2006; Schertl and Schreyer, 2008; 13 14 Ferrando et al., 2009; Grevel et al., 2009), Gran Paradiso (Chopin, 1981; Le Goff and Ballèvre, 15 1990; Le Bayon et al., 2006), and Monte Rosa (Pawling and Baumgartner, 2001; Le Bayon et al., 16 2006) Massifs of the Brianconnais terrane (Penninic nappe), 2) the Tauern Window (Selverstone et 17 al., 1991; Barnes et al., 2004) of the Sub-Penninic nappe; 3) the Lower and Middle Austroalpine of 18 the Eastern Alps (Prochaska, 1985; Prochaska, 1991; Prochaska et al., 1992; Demény et al., 1997; 19 Prochaska et al., 1997; Manatschal et al., 2000). 20 21 [Figure 1] 22 23 A misleading nomenclature 24 The Mg-metasomatic rocks from the Alps have distinct misleading names. The term

- 25 "whiteschist" has a metamorphic meaning, and refers to light-coloured eclogite-facies Mg-
- 26 metasomatic schists (Fettes and Desmons, 2007) characterised by the mineral assemblage talc +

1	kyanite, i.e. the high-pressure (HP) equivalent of the Mg-chlorite + quartz assemblage (Schreyer,
2	1968; Massonne, 1989). "Silvery micaschist" ("micascisti argentei") is a local term mainly used in
3	Western Alps to describes HP silvery-coloured quartz-talc-Mg-chlorite-phengite schists (e.g.,
4	Compagnoni and Lombardo, 1974). "Leucophyllite", a local term used in Central-Eastern Alps, is a
5	whitish-coloured quartz-muscovite-chlorite phyllite/schist metamorphosed under greenschist- or
6	amphibolite-facies conditions (Fettes and Desmons, 2007). Less commonly, these rocks are also
7	named "leuchtembergite (a Mg-chlorite)-bearing rocks" (Lelkes-Felvari et al., 1982). In Eastern
8	Alps, "Weißschiefer" is used to describe Mg-rich phyllonitic rocks (Prochaska et al., 1992; Schertl
9	and Schreyer, 2008 and references therein).
10	In this review, the generic term "Mg-metasomatic rock" is used for metasomatic lithologies
11	belonging to the MgO – Al_2O_3 – SiO_2 – $H_2O \pm K_2O \pm FeO$ system. For this reason, a gouge
12	occurring within metagranitoids from Err nappe (Manatschal et al., 2000) has also been considered.
13	
14	[Figure 2]
15	
16	Geologic and <i>P-T-t</i> outline
17	The European Alps (Fig. 1) are a double-vergent orogen resulting from the closure, due to
18	the convergence between Europe and Adria, of oceanic basins belonging to the Tethyan realm, i.e.
19	the Triassic Meliata-Vardar basin (or Neotethys) and the Jurassic Piemonte-Liguria and Cretaceous
20	Valais basins (or Alpine Tethys; Neubauer et al., 1999; Schmid et al., 2004, Rosenbaum and Lister,

21 2005; Beltrando *et al.*, 2010; Handy *et al.*, 2010; descriptions and references are deliberately not

22 exhaustive). The Briançonnais terrane, a micro-continent located between Valais and Piemonte-

- 23 Liguria basins, represented the passive continental margin of Europe before the opening of the
- 24 Valais basin (Fig. 2). At present, the Alpine Orogen is constituted by several nappes characterised
- 25 by distinct lithological associations and/or Alpine metamorphism. Tectonic Units constituting the

26 axial zone of the Alps experienced a diachronous metamorphic peak from greenschist- to ultra-high

pressure (UHP) eclogite-facies conditions (Fig. 1; Chopin, 1984; Reinecke, 1991; Frezzotti *et al.*,
 2001), and a subsequent rapid exhumation.

3 Mg-metasomatic rocks are recognised in Units belonging to both European and Adriatic 4 domains (see also Table S1). The Dora-Maira (sites 1 and 2), Gran Paradiso (site 3), and Monte 5 Rosa (site 4) Massifs (i.e., the Internal Crystalline Massifs) represent part of the continental 6 Brianconnais terrane surrounded by the oceanic Piemonte-Liguria terrane, both belonging to the 7 Penninic nappe of the Western Alps (Figs. 1 and 2). The structure is similar for all of the Massifs 8 and consists of a Variscan amphibolite-facies basement intruded by Permian (267–279 Ma; Bussy 9 and Cadoppi, 1996; Gebauer et al., 1997; Bertrand et al., 2000) granitoids, mainly converted to 10 orthogneiss during Alpine orogeny (43-34 Ma; Scaillet et al., 1990; Gebauer et al., 1997; Meffan-11 Main et al., 2004; Lapen et al., 2007; Gabudianu et al., 2009). Mg-metasomatic rocks from Dora-12 Maira occur in the Brossasco-Isasca Unit (Compagnoni et al., 1995; site 1)—that recorded UHP 13 metamorphism (730 °C and 4.0–4.5 GPa; Castelli et al., 2007; Ferrando et al., 2009; Table S1) 14 followed by retrograde recrystallisation up to greenschist-facies conditions (Hermann, 2003)—and 15 in the Upper Complex (Cadoppi et al., 2002; site 2), that experienced HP metamorphism at $500 \pm$ 16 50 °C and 0.9–1.5 GPa (Pognante and Sandrone, 1989; Cadoppi, 1990; Table S1). Samples from 17 Gran Paradiso Massif come from the northern area (Fig. 1), where an Alpine metamorphic peak at 18 515–600°C and 1.9–2.7 GPa (Table S1; Gabudianu *et al.*, 2009) is recorded. Samples from Monte 19 Rosa Massif (Fig. 1) experienced a metamorphic peak at T = 480-570 °C and 1.3 < P < 2.5 GPa 20 (Table S1; Pawling and Buamgartner, 2001; Lapen et al., 2007 and references therein). 21 In the Eastern Alps, Penninic and Sub-Penninic nappes are exposed in tectonic windows 22 within the Eastern Austroalpine basement (Schmid et al., 2004). The Tauern Window (site 5) is the 23 largest one (Fig. 1) and consists of oceanic crust (the Upper Schieferhülle), belonging to the 24 Piemonte-Liguria (the Glockner nappe) or Valais (the Matrei zone) basins (e.g., Kurz *et al.*, 2008), 25 and of an underlying continental crust (Dal Piaz et al., 2003). This is composed of a pre-Alpine 26 metamorphic complex (the Lower Schieferhülle) intruded by Carboniferous (~315 Ma) tonalites

1	and granodiorites, now forming the so called Zentralgneis (e.g., Selverstone et al., 1991). Mg-
2	metasomatic rocks occur in the western area, where the Alpine (~ 30 Ma; e.g., Christensen et al.,
3	1994) metamorphic peak reached 1.0 GPa and 550°C (Barnes et al., 2004 and references therein;
4	Table S1).
5	The Eastern Austroalpine is a pile of basement and cover nappes which extend from the
6	Swiss/Austrian border to the Pannonian basin. In the Austrian literature, it is subdivided into three
7	main nappes (Lower, Middle and Upper Austroalpine; e.g. Prochaska et al., 1992). From E to W
8	(Fig. 1), the Mg-metasomatic rocks considered in this paper occur in the Err nappe (Lower
9	Austroalpine), in the Gleinalmkristallin Complex (Middle Austroalpine), and in the Grobgneis
10	Complex (Lower Austroalpine), all of them consisting of Variscan basement, intruded by post-
11	Variscan (300 - 340 Ma; Thöni (1999); Nagy et al., 2002) granites. According to Manatschal
12	(1999), Manatschal and Bernoulli (1999) and Manatschal et al. (2000), the Lower Austroalpine Err
13	nappe (site 6; Fig. 1) remarkably preserves remnants of the distal Adriatic margin of the Piemonte-
14	Liguria basin (Fig. 2), and records Alpine conditions up to lowermost greenschist-facies (Table S1).
15	On the contrary, Alpine (~ 75- 80 Ma; Prochaska et al., 1992; Hoinkes et al., 1999; Nagy et al.,
16	2002) metamorphic peak occurred at $T = 460-480$ °C and $P > 0.4-0.5$ GPa (Table S1; Prochaska <i>et</i>
17	<i>al.</i> , 1992) in the Middle Austroalpine <i>Gleinalmkristallin Complex</i> (site 7), and at $T = 500-600$ °C
18	and $P = 0.8-1.3$ GPa (Table S1; Moine <i>et al.</i> , 1989; Demény <i>et al.</i> , 1997) in the Lower
19	Austroalpine Grobgneis Complex (sites 8-11; Fig. 1).
20	
21	[Figure 3]
22	
23	Mg-metasomatic rocks: evidence for a common genesis
24	The Mg-metasomatic rocks of the Alps considered in this work show similar field,
25	petrographic, geochemical and fluid inclusion features.
26	Field relationships

1	In all of the localities, the Mg-metasomatic rocks occur in the centre of shear zones within
2	metagranitoid/orthogneiss. Differences in tectono-metamorphic conditions are reflected on
3	differences in the involved lithologies—e.g, cataclasite and gauges (Piz d'Err – Piz Bial area;
4	Manatschal et al., 2000) vs orthogneiss and schist (other localities; e.g., Cadoppi, 1990; Selverstone
5	et al., 1991; Prochaska et al., 1992; Demény et al., 1997; Pawling and Baumgartner, 2001; Schertl
6	and Schreyer, 2008)—and in the field relationships—e.g., continuous layers (Piz d'Err – Piz Bial
7	area, Eastern Alps; e.g., Selverstone et al., 1991; Prochaska et al., 1992; Demény et al., 1997;
8	Manatschal et al., 2000) vs lens-like bodies (Western Alps; e.g., Cadoppi, 1990; Pawling and
9	Baumgartner, 2001; Schertl and Schreyer, 2008)—as schematised in Fig. 3 and Table S1. As it
10	approaches to the centre of shear zone, the hosting metagranitoid appears progressively enriched in
11	micas and, then, in Mg-rich minerals (Fig. 3 and Table S1; e.g., Cadoppi, 1990; Selverstone et al.,
12	1991; Prochaska et al., 1992; Demény et al., 1997; Pawling and Baumgartner, 2001; Schertl and
13	Schreyer, 2008).
14	
14 15	[Figure 4]
14 15 16	[Figure 4]
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1	only the igneous K-feldspar is still preserved, whereas HP-UHP minerals replaces the magmatic
2	ones (Table S2; Cadoppi, 1990; Compagnoni et al., 1995; Pawling and Baumgartner, 2001).
3	Granitic rocks show (Na ₂ O + K ₂ O + CaO) and MgO contents mainly ranging from 7 to 10 wt% and
4	from 0.2 to 1.5 wt%, respectively (Fig. 4). All of the samples have similar trace-element pattern
5	(Fig. 5a), characterised by moderate enrichments in Cs, Rb, Th, Pb, U, K-the lower values
6	collected in the Lower Austroalpine-and by moderate-to-strong depletions in Cr, Ni, Sr, Ti, Ba
7	with respect to the average continental crust (Rudnik and Gao, 2005). These patterns match with
8	that of Crd granite from the Lachlan Fold Belt (LFB), for which an origin from mixed sources
9	(mantle-derived magmas and older crustal rocks) has been proposed (Kemp and Hawkesworth,
10	2005).
11	Class 1 consists of the transition rocks (Table S2) located between protolith and
12	metasomatic rocks (Prochaska et al., 1992; Demény et al., 1997; Prochaska et al., 1997; Manatschal
13	et al., 2000; Pawling and Baumgartner, 2001; Schertl and Scheryer, 2008). They are schists (Dora-
14	Maira Massif), gneisses (Monte Rosa Massif; Middle and Lower Austroalpine) or cataclasites (Piz
15	d'Err - Piz Bial area) characterised by the presence of white mica (phengite or muscovite) or illite
16	(in the cataclasite; Table S2). These rocks show (Na ₂ O + K ₂ O + CaO) and MgO contents mainly
17	from 5.5 to 8 wt% and from 0.4 to 4 wt%, respectively (Fig. 4). The trace-element pattern (Fig. 5b)
18	is similar to that of class 0 rocks, indicating their genetic relationship. A positive anomaly of Pb is
19	observed in some samples from Err. The evident variations in Rb, Ba, K, Sr and P-from strongly
20	enriched to strongly depleted with respect to the average continental crust (Rudnik and Gao,
21	2005)—should be related to different amounts of Ca- and K-rich minerals.
22	
23	[Figure 5]
24	
25	Class 2 consists of Mg-bearing rocks (whiteschists, Prp quartzite, gouge, Ms-Qtz-phyllonite,
26	leucophyllite) located in (or near) the centre of the shear zone. Mineral assemblage and,

1	consequently, structure are related to experienced P-T conditions (Table S2). Variable amounts of
2	quartz/coesite, Mg-rich minerals (Mg-chlorite, Mg-chloritoid, talc, pyrope, ellenbergerite, Mg-
3	dumortierite, bearthite, wagnerite), and K-rich minerals (illite, muscovite, biotite, phlogopite,
4	phengite) have been observed even in small outcrops (e.g., Prochaska et al., 1992; Compagnoni et
5	al., 1995; Bussy and Cadoppi, 1996; Demény et al., 1997; Prochaska et al., 1997; Manatschal et al.,
6	2000; Pawling and Baumgartner, 2001; Gabudianu et al., 2009). These rocks usually show high
7	MgO (from 2.0 to 8.0 wt%) and low (Na ₂ O + K ₂ O + CaO) contents (from 1.5 to 6.0 wt%; Table
8	S6). With respect to the average continental crust (Rudnik and Gao, 2005), trace-element patterns
9	show little enrichments in Rb, Th, U, Ta, and depletion in Sr, Cr, Ni and Ti (Fig. 5c), other elements
10	ranging from enriched to depleted. The evident variations in Pb, P and, locally, HFSE, Y and HREE
11	are probably due to different modal amounts of relative compatible minerals (e.g., apatite, garnet).
12	Class 3 comprises rocks, located in the centre of the strain zone, showing the highest Mg
13	content. They are almost monomineralic and consist of Mg-chlorite or garnet, depending on $P-T$
14	conditions (Table S2). Minor amounts of other Mg-rich minerals (e.g., talc, chloritoid) and kyanite
15	are usually present, whereas quartz/coesite and micas are subordinate or absent (e.g., Chopin, 1981;
16	Prochaska et al., 1992; Pawling and Baumgartner, 2001; Schertl and Scheryer, 2008). In the Monte
17	Rosa Massif, calcite is also present (Pawling and Baumgartner, 2001). Class 3 rocks show a very
18	low (Na ₂ O + K ₂ O + CaO) content (< 1 wt%) and a very high (from 20 to 30 wt%) MgO content
19	(Fig. 4). With respect to the average continental crust (Rudnik and Gao, 2005), the trace-element
20	pattern shows moderate to strong depletion in K, Sr, Sm, Ba, Rb, LREE and MREE, and small
21	enrichment in Nb, Zr, Y, and Th. Ni vary from depleted to enriched (Fig. 5d).
22	In Tauern Window, protoliths (class 0) are peraluminous granodiorites (CIPW norm; Table
23	S2; Selverstone <i>et al.</i> , 1991) in which $(Na_2O + K_2O + CaO)$ and MgO contents range from 6.69 to
24	8.04 wt% and from 2.18 to 2.93 wt%, respectively. Weak enrichments in Rb, Ba, Nb, and
25	depletions in Ti, Cr and Ni (Fig. 6b) are observed with respect to the average continental crust
26	(Rudnik and Gao, 2005). Also in this case, the patterns match with those from the Lachlan Fold

1	Belt (Hbl granite; Kemp and Hawkesworth, 2005). Rocks belonging to class 1 are Bt-Phg schists,
2	and those belonging to class 2 and 3 are Grt-Chl-St schists (Table S2; Selverstone et al., 1991;
3	Barnes <i>et al.</i> , 2004). Bt-Phg schists show (Na ₂ O + K ₂ O + CaO) and MgO contents from 6 to 10
4	wt% and from 6.5 to 11 wt%, respectively (Fig. 6a). Enrichments in Rb, K, Ba, Nb, P, and
5	depletions in Cr, Ni, Sr (Fig. 6c) are recorded with respect to the average continental crust (Rudnik
6	and Gao, 2005). The rocks from class 2 show (Na ₂ O + K ₂ O + CaO) and MgO contents from 4.5 to
7	5.5. wt% and from 13 to 14 wt%, respectively (Fig. 6a), and enrichments in Rb, K, Nb, P and
8	depletions in Ni and Sr (Fig. 6c) with respect to the average continental crust (Rudnik and Gao,
9	2005). The only sample belonging to class 3 shows very low (Na ₂ O + K ₂ O + CaO) content (< 2
10	wt%), high MgO content (about 13 wt%; Fig. 6a), enrichments in Nb and P and depletions in Rb,
11	Ba, K, Sr, Zr, Cr (Fig. 6c) with respect to the average continental crust (Rudnik and Gao, 2005).
12	
13	[Figure 6]
14	
14 15	Chemical composition of metasomatic fluids and their isotopic signature
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14 15 16 17	Chemical composition of metasomatic fluids and their isotopic signature In all of the localities, the chemical composition of metasomatic fluids is achievable by indirect (mass transfer) and/or direct (fluid inclusions) methods. The use of isocon diagrams (Grant,
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 14 15 16 17 18 19 20 21 22 23 24 25 	Chemical composition of metasomatic fluids and their isotopic signature In all of the localities, the chemical composition of metasomatic fluids is achievable by indirect (mass transfer) and/or direct (fluid inclusions) methods. The use of isocon diagrams (Grant, 1986) should be the correct way to evaluate element gain and loss among the classes of metasomatism (e.g., Selverstone <i>et al.</i> , 1991; Demény <i>et al.</i> , 1997; Manatschal <i>et al.</i> , 2000; Pawling and Baumgartner, 2001), but the lack of data from many samples prevent its use in this work. Because samples belonging to the same metasomatic class show similar major- and trace-element composition, the average of element concentrations for each class can be considered, in first approximation, representative for all of the samples. In Fig. 3, plot of the average of element concentrations in classes 1, 2 and 3 relative to class 0 is shown (see also Table S3). Data from Tauern Window are reported separately and are locally too scarce and, maybe, affected by

1 a chromatographic fractionation of some major and trace elements from class 0 to class 3. A 2 progressive decrease in Na, Ca and Sr contents from class 1 to class 3 is evident. The K and Rb 3 contents increase in class 2 and strongly decrease in class 3, whereas the Si content usually remains 4 constant up to class 2 and always decreases in class 3, in agreement with the modal variations of 5 micas and quartz/coesite, respectively. A progressive increase in Mg, Ni and H₂O is evident toward 6 the centre of the strain zones, and a minor increase in Fe and Cr is also probable (Fig. 3). These data 7 indicate that the metasomatic fluid was an aqueous fluid releasing Mg, Ni, Fe, Cr and incorporating 8 alkalis, Ca, Si and LILE.

9 A direct way to obtain the chemical composition of the fluid is by fluid inclusion study. 10 Ferrando et al. (2009) demonstrate that the metasomatic fluid generating the UHP whiteschists of 11 the Brossasco-Isasca Unit was a Mg-Cl-rich (up to 28 NaCleg in wt%) aqueous fluid containing 12 minor amounts of dissolved cations (Na, Al, Si). In some localities of the Lower Austroalpine, Prochaska et al. (1997) propose a metasomatic aqueous fluid containing Mg-but also Ca and 13 minor Na, Al and Fe-and showing an increase of salinity (up to 35 NaCleq in wt%) from top to 14 15 bottom of the Unit. In conclusion, mass transfer and fluid inclusions data point to a high-salinity Si-16 undersaturated aqueous fluid containing Mg, but probably also Ni, Fe, and Cr. All of the 17 metasomatic rocks were generated by progressive release of Mg, Ni, Fe, Cr and incorporation of 18 alkalis, Ca, Si and LILE from the metasomatic fluid. The hypothesis of a relative enrichment of 19 MgO due to removal of the other components (e.g., Prochaska, 1985) seems to be unconvincing 20 because it would imply an unlikely metasomatic fluid only able to remove, but not to release, 21 elements. Stable isotope data (δ^{18} O and δ D; Table S8 and Fig. 3) collected on mineral-separates and/or 22 23 whole-rock from 7 of 10 localities (Prochaska et al., 1992; Sharp et al., 1993; Demény et al., 1997; Prochaska et al., 1997; Manatschal et al., 2000; Barnes et al., 2004) are similar. The least-altered 24 25 granitic samples of class 0 shows values close to 11‰, confirming the crustal anatectic origin

suggested by the trace-element pattern (Demény et al., 1997; Manatschal et al., 2000; Barnes et al.,

1	2004), whereas other samples show isotope disequilibrium due to the metasomatic process (Sharp et
2	al., 1993; Demény et al., 1997). Transition rocks (class 1) from Tauern (Barnes et al., 2004) and
3	Sopron (Demény <i>et al.</i> , 1997) show high δD values, suggesting an isotopic re-equilibration during
4	metasomatism. This re-equilibration, observed also in the Middle Austroalpine (Prochaska et al.,
5	1992), is not recorded in Err, where δ^{18} O values of protolith are still preserved (Manatschal <i>et al.</i> ,
6	2000). Where measured, δ^{18} O and δ D data from Mg-metasomatic rocks (classes 2 and 3) are
7	relatively consistent and show an increase in δD values and a decrease in $\delta^{18}O$ values with respect
8	to the corresponding samples from classes 0 and 1 (Prochaska et al., 1992; Sharp et al., 1993;
9	Demény et al., 1997; Manatschal et al., 2000; Barnes et al., 2004). All of the authors interpret these
10	variations as the evidence for an isotopic re-equilibration due to influx of metasomatic fluids
11	characterised by low $\delta^{18}O$ and high δD values, typical marks for seawater. Interaction with meteoric
12	water is negligible and only locally observed in Lower Austroalpine (Prochaska et al., 1997) and
13	Tauern Window (Barnes et al., 2004).
14	
14 15	[Figure 7]
14 15 16	[Figure 7]
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 14 15 16 17 18 19 20 21 22 23 24 25 	[Figure 7] Genesis of Mg-metasomatic rocks and possible tectonic scenarios The continental Mg-metasomatic rocks considered in this work show similar field, petrographic, geochemical and fluid inclusion features, indicating that their genetic process is likely the same in the entire range of the Alps. This process, as already proposed by some authors (Sharp <i>et al.</i> , 1993; Demény <i>et al.</i> , 1997; Manatschal <i>et al.</i> , 2000; Barnes <i>et al.</i> , 2004; Sharp and Barnes, 2004; Ferrando <i>et al.</i> , 2009), must assume i) highly channelised metasomatic fluids infiltrating the continental crust and ii) chromatographic fractionation of major and trace elements. The fluid composition (a Si-undersaturated Ni-Mg-rich brine with Fe and Cr) and its "oceanic" (seawater) signature suggest an origin from serpentinised ultramafics. An evaporitic source (Gebauer <i>et al.</i> ,

1	δ^{18} O signature and containing high amounts of F, Li and B, and lacking Ni and Cr (Moine <i>et al.</i> ,
2	1981; Moore and Waters, 1990). Also a late-magmatic hydrothermal source (Pawling and
3	Baumgartner, 2001) should be excluded because the hydrothermal alteration of a granite does not
4	produce Mg enrichments (Parneix and Petit, 1991; Nishimoto and Yoshida, 2010).
5	Fig. 7 schematises the possible process generating the Mg-metasomatic rocks. Extensive
6	dehydration of oceanic serpentinites releases Si-undersaturated Ni-Mg-rich brines characterised by
7	high δD values. These metasomatic fluids infiltrate continental crust along high-permeability
8	conduits (i.e., strain zones) and are channelized over significant distances. It is noteworthy that the
9	flux of the channelised fluid could even have been similar to that observed in high-level
10	hydrothermal systems (McCaig, 1997). Along the flow path, ion exchange between fluid and
11	granitoid modifies the fluid composition through progressive precipitation of Mg, Ni, Fe and Cr,
12	and dissolution of alkalis, Ca, Si and LILE toward the centre of the strain zone. Moreover, a further
13	fractionation occurs from the ultramafic source to the continental rocks, as revealed by the increase
14	of Ni and Cr contents in continental Mg-metasomatic rocks that occur in close spatial association
15	with ultramafic bodies (Err: Manatschal et al., 2000; Tauern Window: Selverstone et al., 1991;
16	Barnes et al., 2004).
17	
18	[Figure 8]
19	
20	At least three tectonic scenarios can be proposed, in which this genetic process could occur
21	along faults juxtaposing hydrated mantle with continental crust: rift-related ocean-continent
22	transition, continental subduction, and continent-continent collision (Fig. 8). The rift-related ocean-
23	continent transition (Fig. 8a) is characterised by large-scale, low-angle detachment faults related to

thinning and break-up of continental crust and to mantle exhumation. In this geological context, 24 25 marine fluids penetrate and interact with the exhumed mantle before to be channelised into the 26 continental crust along the detachment faults (Manatschal et al., 2000 and reference therein). The

fluid flow is upward and its driving force is supposed to be a thermal fluid convection associated
 with mantle exhumation (Manatschal and Nievergelt, 1997).

3 At present, an univocal tectonic model for the continental subduction is lacking (e.g., 4 Stöckhert and Gerya, 2005; Agard *et al.*, 2009) and a discussion about the cutting-edge models is 5 beyond the aim of this work. The most important point is that all of these models assume a tectonic 6 association between oceanic serpentinites and continental crust. During subduction, antigorite from 7 serpentinites progressively dehydrates in a narrow range of *P*-*T* conditions (Sharp and Barnes, 8 2004). Part of the high amounts of produced metasomatic fluids percolates and hydrates the 9 overlying mantle wedge, and part of them are channelised along the main convergent structures and 10 infiltrates the subducted continental crust (Fig. 8b). Arguments on direction of channelised fluid 11 flow and on its driving force are strictly related to the tectonic model considered. Usually, the main 12 driving force is considered to be a high fluid pressure, that allows long-distance fluid transport 13 along shear zones and/or induces microfractures and vein-network formation (Zack and John, 2007). 14

15 The third geological context is the continent-continent collision (and exhumation), in which 16 oceanic, continental and mantle-wedge tectonic Units are imbricated to form the belt, and major 17 extensional shear zones accommodate their exhumation (Fig. 8c). Dehydration of oceanic or 18 mantle-wedge serpentinites during exhumation releases metasomatic fluids that are channelised 19 upward along extensional shear zones. Local mixing with meteoric water percolating from the 20 surface could occur. The temperature at which the serpentinites dehydrate affects the fluid mobility. 21 At $T > 550^{\circ}$ C, large volumes of high-mobile metasomatic fluid are released and channelised, 22 whereas at lower T low-mobile metasomatic fluids generate blackwall zones at the contacts between 23 serpentinite and wall rock (Barnes et al., 2004).

24

25 Mg-metasomatic rocks in the Alpine history

1	At present, the Alps comprise two orogens: an older Late Cretaceous orogen due to the
2	closure of the Meliata-Vardar basin (Neotethys) and preserved in the Eastern Alps, and a younger
3	Cenozoic (Eocene-Oligocene boundary) orogen due to the closure of the Piemonte-Liguria and
4	Valais basins (Alpine Tethys) and preserved in the Western Alps (Handy et al., 2010 and references
5	therein). Mg-metasomatic rocks considered in this work become from both orogens. The age of
6	metasomatism proposed by previous authors is different among the localities (Table S1), supporting
7	the presence of diachronous processes in the Alps. Moreover, field and petrological data described
8	above show variations (e.g., lacking vs pervasive Alpine deformation; LP-LT vs UHP-MT mineral
9	assemblages) that can only be referred to Mg-metasomatic processes operating within different
10	structural levels of the Alpine chain and through distinct geodynamic regimes.
11	
12	[Figure 9]
13	
14	A temporal sequence of the Mg-metasomatic events related to Alpine history is shown in
15	Fig. 9. The earliest Mg-metasomatic events involving (meta)granitoids probably occurred during
16	Tethys opening and involved portions of continental crust, belonging to both Europe and Adria
17	(Fig. 2), along the ocean-continent transition. The sub-continental mantle exposed at the seafloor
18	interacted with seawater and the resulting fluids were channelised into the continental crust along
19	rift-related detachment systems (Fig. 8a). This geological event is well recorded in the Err domain
20	(Fig. 9), where it was responsible for the genesis of gouges (Manatschal et al., 2000) during the
21	Early Jurassic (late Pliensbachian - early Toarcian) opening of the Piemonte Liguria basin.
22	Other Mg-metasomatic events occurred at the closure of the Tethyan basins and during the
23	subsequent continent-continent collision and exhumation. During continental subduction, oceanic
24	serpentinites belonging to distinct basins (Fig. 2) progressively dehydrated and part of the released
25	fluids infiltrated the juxtaposed continental crust along main tectonic structures (Fig. 8b). During
26	the continent-continent collision and exhumation (Fig. 8c), a further Mg-metasomatic event

1	occurred along extensional shear zones and was promoted by fluids probably originated from
2	portions of both oceanic crust and hydrated mantle-wedge. In the Eastern Alps, the Sopron Mg-
3	metasomatic rocks formed though continental subduction at about 80-70 Ma (Demény et al., 1997),
4	i.e. during the Eastern Alps orogeny (Fig. 9). Likely, the oceanic serpentinites involved in this
5	process belonged to the Meliata-Vardar basin because, at that time, the Piemonte-Liguria and Valais
6	basins just started their closure (Handy et al., 2010; Fig. 9). During the same orogeny, the Mg-
7	metasomatic rocks of the Austrian Lower and Middle Austroalpine formed via continent-continent
8	collision and exhumation (Prochaska, 1985; Prochaska, 1991; Prochaska et al., 1992; Prochaska et
9	al., 1997; Table S1; Fig. 9). More recently, at about 45-20 Ma (i.e., during the Western Alpine
10	orogeny), similar Mg-metasomatic events occurred in the Western and Central Alps. In the
11	Southern Dora-Maira (Western Alps), Mg-metasomatic rocks formed during continental subduction
12	(Sharp and Barnes, 2004; Ferrando et al., 2009; Table S1; Fig. 9), whereas in the Tauern Window
13	(Central Alps) they formed during continent-continent collision or exhumation (Selverstone et al.,
14	1991; Barnes et al., 2004; Table S1; Fig. 9).
15	Concerning the other localities considered in this study, current data indicate that the Mg-
16	metasomatic rocks from Monte Rosa, Gran Paradiso, and northern Dora-Maira formed before the
17	continent-continent collision related to the Western Alpine orogeny, although the geological context
18	is still enigmatic (Fig. 9). Multidisciplinary studies, combining petrological, geochemical (major
19	and trace elements, stable isotopes) geochronological and fluid inclusion data, would be necessary
20	to discriminate between rift-related ocean-continent transition and continental subduction as
21	possible tectonic scenarios.
22	
23	Concluding remarks
24	Continental Mg-metasomatic rocks in metagranitoids are relatively common in the Alps and

Continental Mg-metasomatic rocks in metagranitoids are relatively common in the Alps and occur in the palaeogeographic realms of both Europe and Adria (Fig. 1). This review indicates that all of these lithologies generated along strain zones by influx of external fluids coming from

ultramafic rocks that previously interacted with seawater. This process could have occurred during
distinct geological events (Fig. 8): i) the opening of the Tethyan basins, ii) the continental
subduction after the closure of these basins, iii) the collision and exhumation of the tectonic Units
constituting the Alpine Orogen. In these scenarios, three kinds of ultramafic rocks could have
originated the metasomatic fluid (Fig. 8): a) sub-continental ultramafic rocks hydrated during
rifting, b) subducted oceanic serpentinites belonging to distinct Tethyan basins, c) mantle-wedge
ultramafic rocks hydrated during subduction.

8 The tectonic scenarios proposed in this study point to a metasomatic process more extended 9 (in space and time) than previously believed. The continental tectonic Units most involved in the 10 Alpine history (e.g., Dora-Maira, Gran Paradiso, Monte Rosa) could have experienced more than a 11 single Mg-metasomatic event and the fluid should have originated, from time to time, from distinct 12 mantle sources. Moreover, similar tectonic scenarios could be invoked also for other Mgmetasomatic products widespread in continental, but also oceanic, Units of the Alps, such as: Mg-13 14 metasomatic rocks observed in other lithologies (e.g., volcanic rocks, paragneiss and metagabbro; 15 Lelkes-Felvari et al., 1982; Prochaska, 1985; Prochaska, 1991; Prochaska et al., 1997; Scambelluri 16 and Rampone, 1999), Cr-Ni-Mg-rich veins (e.g., Spandler et al., 2011) and some deposits of Mg-17 rich mineral (talc, magnesite, dolomite, emerald; e.g., Prochaska, 1989; Kiesl et al., 1990; Sandrone 18 et al., 1990; Ferrini et al., 1991 and references therein) which origin is still debated. 19 A multidisciplinary approach is useful to test these hypotheses. Meso- and micro-structural

observations, *P-T-t* data, whole-rock trace element contents (in particular Cr, Ni, Li, B, F), stable isotope data (δ^{18} O, δ D, δ^{37} Cl, δ^{11} B, δ^{7} Li), and fluid inclusion data could allow to distinguish distinct metasomatic events, to trace the source of the metasomatic fluid and its chromatographic fractionation during infiltration in the continental crust, and to define the timing of metasomatism and its possible diachronous distribution in the orogenic evolution.

Finally, Mg-metasomatic rocks probably have a crucial role in large scale tectonic events
(not only Alpine) because on their rheological behaviour. In Mg-rich rocks (class 3) along shear

1	zones, it is possible that the occurrence of talc (and maybe also of Mg-chlorite and other
2	phyllosilicates) instead of pyrope could reduce fault strength and induce stable sliding (e.g., Soda
3	and Takagi, 2010; Moore and Lockner, 2011).
4	However, to improve the knowledge on Mg-metasomatism in continental and oceanic rocks
5	and on its role in mechanical properties of faults, further studies on fluid/mineral element
6	partitioning, on physical-chemical parameters (P-T-X) affecting composition and mobility of the
7	metasomatic fluid, on rheological behaviour of Mg-metasomatic rocks, and on other genetic
8	tectonic scenarios (e.g., oceanic subduction, accretionary prism) are needed.
9	
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1	Fig. 1.
2	Tectonic sketch map of the Alps modified from Prochaska (1989), Neubauer et al. (1999),
3	Pohl and Belocky (1999), Dal Piaz et al. (2003); Ferrando et al. (2004), Schmid et al. (2004),
4	Handy et al. (2010). The occurrences of the studied Mg-metasomatic rocks is reported: (1) Valle
5	Po-Val Varaita (Le Bayon et al., 2006; Schertl and Schreyer, 2008; Ferrando et al., 2009; Grevel et
6	al., 2009); (2) Val di Susa (Cadoppi, 1990); (3) Valnontey-Valleille-Bardoney area (Chopin, 1981;
7	Le Goff and Ballèvre, 1990; Le Bayon et al., 2006); (4) Val d'Ayas (Pawling and Baumgartner,
8	2001; Le Bayon et al., 2006); (5) Pifisch region (Selverstone et al., 1991; Barnes et al., 2004); (6)
9	Err nappe (Manatschal et al., 2000); (7) Weißkirchen (Prochaska, 1985; Prochaska et al., 1992); (8)
10	Hollersgraben, Außberegg, S-Pacher, Ratten, Vorau (Prochaska et al., 1997); (9) Klingfurth
11	(Prochaska et al., 1997); (10) Sopron (Demény et al., 1997; Prochaska et al., 1997). Occurrence of
12	diamond and/or coesite is shown with a star symbol.
13	Fig. 2.
14	Early Cretaceous reconstruction of the Alps. Modified after Rosenbaum and Lister (2005).
15	Where necessary, the name of the corresponding Alpine nappe is reported in brackets.
16	Fig. 3.
17	Schematic sketch showing field relationships of hosting and Mg-metasomatic rocks, from
18	wallrock to the centre of the shear zone (arbitrary scale of outcrops). Stable isotope (δ^{18} O and δ D)
19	data ranges for each classes and average of element concentrations in classes 1, 2 and 3 relative to
20	class 0 for granitic and granodioritic protoliths (note the different Y scale) are also reported. VLP:
21	very-low pressure rocks (gouges from Err); UHP: ultra-high pressure rocks (pyrope-whiteschists
22	from Dora-Maira); MP-HP: medium-to-high pressure rocks (Mg-metasomatic rocks from other
23	localities). Toward the centre of the strain zones, an increase in Mg, Ni, H ₂ O, δD —and, maybe, in
24	Fe—and a decrease in Na, K, Rb, Ba, Ca, Sr, Si and δ^{18} O is evident.
25	Fig. 4.

1	Diagram showing the $(Na_2O + K_2O + CaO)$ content vs. the MgO content for samples with
2	granitic protolith and belonging to the four classes of metasomatism. A progressive increase in
3	MgO and decrease in $(Na_2O + K_2O + CaO)$ contents is evident from class 0 to class 3.
4	Fig. 5.
5	Trace-element pattern of rocks of granitic protoliths and belonging to class 0 (a), class 1 (1),
6	class 2 (c), and class 3 (d) of metasomatism. Patterns are normalised to the average continental crust
7	(Rudnick and Gao, 2005). In Fig. 5a, trace-element composition of Crd granite from the Lachlan
8	Fold Belt (LFB; Kemp and Hawkesworth, 2005) is reported for comparison.
9	Fig. 6.
10	Major- (a) and trace-element (b, c) diagrams of rocks from Tauern Window (granodioritic
11	protolith) belonging to classes 0-3. Trace-element patterns are normalised to the average continental
12	crust (Rudnick and Gao, 2005). In Fig. 6b, trace-element composition of Hbl granite from the
13	Lachlan Fold Belt (LFB; Kemp and Hawkesworth, 2005) is reported for comparison.
14	Fig. 7.
15	Schematic sketch showing the genetic process of the Mg-metasomatic rocks. This process,
16	assumes highly channelised fluids-derived from ultramafic rocks that has previously interacted
17	with seawater-infiltrating the continental crust along strain zones and producing chromatographic
18	fractionation of major and trace elements. Font-size of elements is qualitatively related to their
19	amount released or incorporated by the fluid.
20	Fig. 8.
21	Tectonic models for fluid flow along faults juxtaposing hydrated mantle and continental
22	crust. (a) Rift-related ocean-continent transition: seawater fluids interact with mantle rocks before to
23	be channelised along large-scale detachments. Modified from Manatschal et al. (2000). (b)
24	Continental subduction: part of fluids released during HP/UHP dehydration of tectonically
25	associated oceanic serpentinites are channelised along main convergent structures. Modified from
26	Agard et al. (2009). (c) Continent-continent collision: fluid generated by local dehydration of

1	serpentinites are channelised along major extensional shear zones. Modified from Agard et al.
2	(2009).
3	Fig. 9.
4	Timetable, related to Alpine history, of the Mg-metasomatic events recorded in the localities
5	considered in this work (see text for details). The Eastern Alps orogeny (Late Cretaceous), due to
6	the closure of the Meliata-Vardar basin, and the Western Alps orogeny (Cenozoic), due to the
7	closure of the Piemonte-Liguria and Valais basins, are well distinguishable.
8	
9	Supplementary material
10	Table S1
11	Summary of geologic, metamorphic, and field data referring to the localities considered in
12	this work. The number of the locality refers to that reported in Fig. 1.
13	Table S2
14	Summary of petrographic and geochemical data that refer to rocks belonging to class 0 of
15	metasomatism (i.e., protolith). The number of the locality refers to that reported in Fig. 1. Mineral
16	abbreviation after Fettes and Desmons (2007). Amp: amphibole; Bea: bearthite; Ell: ellenbergerite;
17	Mg-Dum: Mg-dumortierite; Opm: opaque mineral; Wag: Wagnerite.
18	Table S3
19	Average (in ppm, except LOI in wt%) of some major- and trace-element concentrations in
20	samples belonging to the four classes of metasomatism.
21	Table S4
22	Major- (wt% oxide) and trace-element (ppm) compositions of rocks belonging to class 0 of
23	metasomatism (protolith). mg# = MgO/(MgO+FeO _{TOT}); a: Ferrando <i>et al.</i> (2009); b: Schertl and
24	Schreyer (2008); c: Grevel et al. (2009); d: Cadoppi (1990); e: Le Goff and Ballèvre (1990); f:
25	Pawling and Baumgartner (2001); g: Barnes et al. (2004); h: Selverstone et al. (1991); i:

1	Manatschal et al. (2000); j: Prochaska et al. (1992); k: Prochaska et al. (1997); l: Demény et al.
2	(1997).
3	Table S5
4	Major- (wt% oxide) and trace-element (ppm) compositions of rocks belonging to class 1 of
5	metasomatism (transition rocks). $mg\# = MgO/(MgO+FeO_{TOT})$; a: Schertl and Schreyer (2008); b:
6	Pawling and Baumgartner (2001); c: Barnes et al. (2004); d: Selverstone et al. (1991); e:
7	Manatschal et al. (2000); f: Prochaska et al. (1992); g: Prochaska et al. (1997); h: Demény et al.
8	(1997).
9	Table S6
10	Major- (wt% oxide) and trace-element (ppm) compositions of rocks belonging to class 2 of
11	metasomatism (Mg-bearing rocks). mg# = MgO/(MgO+FeO _{TOT}); a: Ferrando <i>et al.</i> (2009); b:
12	Schertl and Schreyer (2008); c: Grevel et al. (2009); d: Le Bayon et al. (2006); e: Cadoppi (1990);
13	f: Chopin (1981); g: Pawling and Baumgartner (2001); h: Selverstone et al. (1991); i: Manatschal et
14	al. (2000); j: Prochaska et al. (1992); k: Prochaska (1985); l: Prochaska et al. (1997); m: Demény et
15	<i>al.</i> (1997).
16	Table S7
17	Major- (wt% oxide) and trace-element (ppm) compositions of rocks belonging to class 3 of
18	metasomatism (Mg-rich rocks). $mg\# = MgO/(MgO+FeO_{TOT})$; a: Schertl and Schreyer (2008); b:
19	Chopin (1981); c: Barnes et al. (2004); d: Prochaska et al. (1992); e: Prochaska (1985).
20	Table S8
21	Oxygen, hydrogen and carbon isotopic composition of mineral separates from rocks
22	belonging to the four classes of metasomatism. *: average; a: Sharp et al. (1993); b: Barnes et al.
23	(2004); c: Manatschal et al. (2000); d: Demény et al. (1997); e: Prochaska et al. (1992); f:
24	Prochaska et al. (1997); g: Pawling and Baumgartner (2001).
25	



Tectonic sketch map of the Alps modified from Prochaska (1989), Neubauer et al. (1999), Pohl and Belocky (1999), Dal Piaz et al. (2003); Ferrando et al. (2004), Schmid et al. (2004), Handy et al. (2010). The occurrences of the studied Mg-metasomatic rocks is reported: (1) Valle Po-Val Varaita (Le Bayon et al., 2006; Schertl and Schreyer, 2008; Ferrando et al., 2009; Grevel et al., 2009); (2) Val di Susa (Cadoppi, 1990); (3) Valnontey-Valleille-Bardoney area (Chopin, 1981; Le Goff and Ballèvre, 1990; Le Bayon et al., 2006); (4) Val d'Ayas (Pawling and Baumgartner, 2001; Le Bayon et al., 2006); (5) Pifisch region (Selverstone et al., 1991; Barnes et al., 2004); (6) Err nappe (Manatschal et al., 2000); (7) Weißkirchen (Prochaska, 1985; Prochaska et al., 1992); (8) Hollersgraben, Außberegg, S-Pacher, Ratten, Vorau (Prochaska et al., 1997); (9) Klingfurth (Prochaska et al., 1997); (10) Sopron (Demény et al., 1997; Prochaska et al., 1997). Occurrence of diamond and/or coesite is shown with a star symbol. 94x45mm (300 x 300 DPI)



Early Cretaceous reconstruction of the Alps. Modified after Rosenbaum and Lister (2005). Where necessary, the name of the corresponding Alpine nappe is reported in brackets. 93x101mm (300 x 300 DPI)



Schematic sketch showing field relationships of hosting and Mg-metasomatic rocks, from wallrock to the centre of the shear zone (arbitrary scale of outcrops). Stable isotope (δ180 and δD) data ranges for each classes and average of element concentrations in classes 1, 2 and 3 relative to class 0 for granitic and granodioritic protoliths (note the different Y scale) are also reported. VLP: very-low pressure rocks (gouges from Err); UHP: ultra-high pressure rocks (pyrope-whiteschists from Dora-Maira); MP-HP: medium-to-high pressure rocks (Mg-metasomatic rocks from other localities). Toward the centre of the strain zones, an increase in Mg, Ni, H2O, δD—and, maybe, in Fe—and a decrease in Na, K, Rb, Ba, Ca, Sr, Si and δ180 is evident.

247x307mm (300 x 300 DPI)



Diagram showing the (Na2O + K2O + CaO) content vs. the MgO content for samples with granitic protolith and belonging to the four classes of metasomatism. A progressive increase in MgO and decrease in (Na2O + K2O + CaO) contents is evident from class 0 to class 3. 106x91mm (300 x 300 DPI)



Trace-element pattern of rocks of granitic protoliths and belonging to class 0 (a), class 1 (1), class 2 (c), and class 3 (d) of metasomatism. Patterns are normalised to the average continental crust (Rudnick and Gao, 2005). In Fig. 5a, trace-element composition of Crd granite from the Lachlan Fold Belt (LFB; Kemp and Hawkesworth, 2005) is reported for comparison. 217x504mm (300 x 300 DPI)



Major- (a) and trace-element (b, c) diagrams of rocks from Tauern Window (granodioritic protolith) belonging to classes 0-3. Trace-element patterns are normalised to the average continental crust (Rudnick and Gao, 2005). In Fig. 6b, trace-element composition of Hbl granite from the Lachlan Fold Belt (LFB; Kemp and Hawkesworth, 2005) is reported for comparison. 195x395mm (300 x 300 DPI)



Schematic sketch showing the genetic process of the Mg-metasomatic rocks. This process, assumes highly channelised fluids—derived from ultramafic rocks that has previously interacted with seawater—infiltrating the continental crust along strain zones and producing chromatographic fractionation of major and trace elements. Font-size of elements is qualitatively related to their amount released or incorporated by the fluid. 92x196mm (300 x 300 DPI)



Tectonic models for fluid flow along faults juxtaposing hydrated mantle and continental crust. (a) Rift-related ocean-continent transition: seawater fluids interact with mantle rocks before to be channelised along large-scale detachments. Modified from Manatschal et al. (2000). (b) Continental subduction: part of fluids released during HP/UHP dehydration of tectonically associated oceanic serpentinites are channelised along main convergent structures. Modified from Agard et al. (2009). (c) Continent-continent collision: fluid generated by local dehydration of serpentinites are channelised along major extensional shear zones. Modified from Agard et al. (2009). 212x284mm (300 x 300 DPI)



Timetable, related to Alpine history, of the Mg-metasomatic events recorded in the localities considered in this work (see text for details). The Eastern Alps orogeny (Late Cretaceous), due to the closure of the Meliata-Vardar basin, and the Western Alps orogeny (Cenozoic), due to the closure of the Piemonte-Liguria and Valais basins, are well distinguishable. 188x176mm (300 x 300 DPI)