EVOLUTION OF RODINGITIC DYKES: METASOMATISM AND METAMORPHISM IN THE MOUNT AVIC SERPENTINITES (ALPINE OPHIOLITES, SOUTHERN AOSTA VALLEY)

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Keywords: Rodingite, metasomatism, Piemonte ophiolite. Western Alps.

ABSTRACT

The Mount Avic ophiolite mainly consists of a large mass of serpentinites, which constitutes the base of a subunit of the Piemontese ophiolitic nappe. Serpentinites represent the mantle portion of the oceanic lithosphere of the Mesozoic Tethys and consist of antigorite-titanium clinohumite-diopside schists as products of oceanic metasomatism and tectono-metamorphic evolution of the Alpine orogeny, at the expense of abyssal peridotite mineral assemblage. The serpentinite mass includes metagabbro pods (without metasomatic alteration) and associated rodingitic dykes. Various rodingitic dykes can be distinguished on the basis of their mineralogical assemblages. The main assemblage consists of ugranditic garnet, chlorite ± diopside ± epidote ± vesuvianite. Other minerals as vesuvianite, epidote, scapolite, actinolite, and iron ores are typical accessories.

Rodingitization usually involves mafic rocks as gabbro and basalt associated with serpentinitized ultramafic rocks in the Archean - Paleoproterozoic mafic-ultramafic sequences (e.g., Anhaeusser, 1978; Schandl et al., 1989; Attoh et al., 2006), in the metamorphosed and un-metamorphosed ophiolitic complexes (e.g., Dubinska and Wiewiora, 1999; Hatzianagiou and Tiskouras, 2001; Hatzianagiou et al., 2003; Li et al., 2004; 2008), and in the present-day ocean floor (Honnorez and Kirst, 1975; Johnson, 1992; Fruh-Green et al., 1996; Kelemen et al., 2003). The chemical reactions that produce Ca-rich, SiO2-undersatured meta-

INTRODUCTION

The term “rodingite” has been introduced for the first time to describe altered gabbros from the New Zealand serpentinitic massif (Bell et al., 1911) and it has been employed for all rocks affected by Ca-metasomatism. The definition of rodingite proposed by “IUGS Subcommission on the Systematic of Metamorphic Rocks” (Zharikov et al., 2007) highlights that rodingite “is a metasomatic rock primarily composed of grossular-andradite garnet and calcic pyroxene”. Other minerals as vesuvianite, epidote, scapolite, and iron ores are typical accessories.

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GEOLOGICAL SETTING OF THE NW ALPS OPHIOLITES

The meta-ophiolites of the NW Alps (Fig. 1) are remnants of the Mesozoic Tethyan Ocean involved into subduction during the convergence between the European and African Plates, started in the Cretaceous (Bearth, 1967; Dal Piaz et al., 1972; Caby et al., 1978; Martinotti and Hunziker, 1984; Nicolas et al., 1990; Polino et al., 1990; Stampfl and Marchant, 1997). In the southern Swiss area and in the northern Aosta Valley (north of the Aosta-Ranzola fault, ARF in Fig. 1) two main Alpine ophiolite units have been defined: the Zermatt-Saas (ZS) Unit and the Combin (CO) Unit (Bearth, 1967; Dal Piaz and Ernst, 1978; Sartori and Thelin, 1987; Ballèvre and Merle, 1993; Michard et al., 1996). The ZS ophiolite represents the oceanic lithosphere of the Piemontese-Ligurian basin. It consists of former mantle rocks, today represented by antigorite-Ti-clinohumite schists cut by rodingitic dykes (Bearth, 1967; Dal Piaz, 1967), metagabbroic bodies (e.g., Allalin gabbro; Chinner and Dixon, 1973), and metabasalts (basalt flows, pillow lavas and hylacoliths) hosting sulphide-ore deposits. The ZS ophiolite is capped by a meta-sedimentary cover consisting of metacherts, some with manganiferous oxides and sili-

This paper documents the occurrence of rodingites within the Mount Avic massif, pertaining to the metaophiolite nappe system of the Italian Western Alps. Our aim is to describe in detail the mineralogical and textural features of rodingitic dykes and to discuss their metasomatic and meta-

metamorphic evolution.
metamorphic evolution during the Alpine orogeny. The ZS
is characterized by LT-HP to UHP mineral assemblages of
early Alpine age (e.g. garnet, omphacite, rutile, zoisite in
Fe-Ti-metagabbros and metamorphosed basalts; coesite in
metaquartzites). These assemblages attest a fossil subduc-
tion zone (Dal Piaz et al., 1972; Ernst and Dal Piaz, 1978;
Oberhaensli, 1980; Reinecke, 1991; Van der Klauw et al.,
1997). They were later overprinted, during a polyphase de-
compressional evolution, by blueschist (glaucophane, chlo-
ritoid, white mica) to greenschist (actinolite, albite, chlorite,
epidote) facies assemblages (Bearth, 1967; Dal Piaz and
Ernst, 1978; Barnicoat and Fry, 1986). Recent estimations
of the P-T conditions in the ZS Unit (Pfülwe eclogites and
glaucophanites) suggest a peak eclogite-facies metamor-
phism at 2.7-2.8 GPa and 580°C (Bucher et al., 2005). Glau-
cophane-bearing metabasalts, interpreted as being hydrated
during ocean-floor metamorphism, may be coeval with
eclogites deriving from unaltered basalts (Oberhaensli,
1982; Martin and Tartarotti, 1989; Bowtell, 1991). The CO
Unit mostly displays greenschist facies mineral associations
(actinolite, albite, chlorite, epidote), although rare blueschist
facies minerals (e.g., sodic amphibole) have been found
(Cortiana et al., 1999; Desmons et al., 1999).

In the southern Aosta Valley (NW Italian Alps), south of
the ARF (Fig. 1), metaophiolites belong to the Piemonte
ophiolitic nappe. Due to their lithological association and
metamorphic imprint, these ophiolites are similar to the ZS
Unit comprising antigorite-Ti-clinohumite-bearing serpent-
tines, minor Fe-Ti- and Mg-metagabbros, metabasalts, and
meta-sedimentary rocks that experienced early Alpine meta-
orphism under eclogite-blueschists facies conditions
(Baldelli et al., 1985; Castelli, 1985; Bällèvre et al., 1986;
Martin and Kienast, 1987; Benciolini et al., 1988; Martin
and Tartarotti, 1989; Novo et al., 1989; Tartarotti and Cau-
cia, 1993). The Mesozoic sequence is overthrust by the pre-
Triassic Austroalpine Mt. Emilus, Glacier Rafray and Tour
Ponton klippen (Fig. 1). The oceanic crustal units are well
exposed in the Clavalité - St. Marcel area (Fig. 1), where
they are mainly represented by eclogitic Fe-Ti- and Mg-
metagabbros, gabbro-derived metakosse, garnet-lawsonite
(pseudomorphed)-bearing glaucophanites including
eclogitic boudins, garnet-chloritoid chloriteschists, minor
talcschists (Nervo and Polino, 1977; Krutow-Mozgawa,
1988; Tartarotti, 1988; Martin and Tartarotti, 1989; Martin
et al., 2008). The meta-sedimentary cover mainly consists,
from bottom to top, of deep sea Mn-Fe-rich metacherts,
marble and calcschists which are equivalent to the Upper
Jurassic-Lower Cretaceous sediments of the Ligurian Apen-
nines (Tartarotti et al., 1986). The mantle section is repre-
sented by widespread serpentinite sheets and by a huge ser-
pentinite massif cropping out in the Mount Avic area (Figs.
1 and 2). Estimations of the peak P-T conditions in the St.

Fig. 1 - Tectonic sketch-map of the internal
NW Alps showing the occurrence of
metaophiolites (Baldelli et al., 1985). 1) Low-
er Penninic nappes and Valais calcschists
zone. 2) Subbriançonnais (a) and Briançon-
nais (b) units. 3) Upper Penninic Monte Rosa
(MR), Arcesa-Brusson (AB) and Gran Par-
adiso (GP) nappe system. 4) Piedmont Ophio-
lite nappe system: a) dominantly sedimentary
units including thin sheets derived from ocean
facing continental edges (Comb type); b)
dominantly ophiolitic units with eclogite
metamorphism (Zermatt-Saas type). 5) Aus-
troalpine Sesia-Lanzo (SL) and Dent Blanche
(DBL) nappe system, including Mt. Emilus
(E), Glacier Rafray (GR), Tour Ponton (TP)
and Santanel (S) southern Klippen. 6) South-
er Alps. ARF: Aosta-Ranzola fault. Grey
box represents the study area (Mount Avic
serpentinitic massif).
Marcel Valley ophiolites have been recently performed by Martin et al. (2008), yielding temperature values of $550 \pm 60 ^\circ C$ and pressure values of $2.1 \pm 0.3$ GPa, that are higher than those previously calculated in the same area by other authors.

**FIELD RELATIONS**

The Mount Avic is a huge massif of serpentinitized mantle peridotite (Figs. 1 and 2) that crops out as a tectonic window south of the ARF, in the eastern part of the EW-trending Aosta Valley (Tartarotti and Martin, 1991; Diella et al., 1994; Fontana et al., this volume). The exposed serpentinite area is about 180 km$^2$ wide. In this paper we deal with the southern area of the Mount Avic serpentinite massif. Serpentinites contain metamorphosed mafic bodies and rodin-gites, with minor chloriteschist and talc-schist lenses. Metamorphosed mafic rocks occur either as tectonized pods, surrounded by serpentinites, or as tectonic sheets. The latter consist of mafic rocks with rodinitic reaction zones, often associated with calc-schists slices, and sulphide-rich epidosites. All these rock types build up a few hundreds meters-thick crustal unit overthrusting the Mount Avic serpentinite Unit (Fig. 3).

**Serpentinites**

Serpentinites occur as weakly to strongly deformed (mylonitic) rocks. Weakly deformed serpentinites are the most abundant rock type. Their weathered surface is ochre- to reddish-brown-coloured, whilst on the fresh surface these rocks are dark green to black. Mylonitic serpentinites are fine-grained and foliated, and frequently occur near the contact with other rock types, but mylonitic bands were also found within low-deformed serpentinites. Serpentine is finally observed as lined acicular crystals or fibres (cm-sized) restricted to dm-sized bands.

The serpentinite mainly consists of serpentine (0.1-1 mm-sized antigorite crystals; > 90 vol.% and magnetite (up to mm-sized, 5-10 vol.%, Fontana et al., this volume), defining the main foliation. Magnetite often occurs as mineral aggregates that mark the mineral lineation. Less serpentinated rocks consist of olivine (Fo$_{90-95}$), clinopyroxene (diopside), Ti-clinohumite, antigorite, tremolite, and late calcite. Olivine, diopside, and Ti-clinohumite occur as mm-sized porphyroblasts, often preserving relict mantle textures (see Fontana et al., this volume). Porphyroblasts are more or less recrystallized into finer acicular crystals or fibres (cm-sized). Metamorphosed mafic rocks (metabasite)

Metamorphosed mafic rocks mainly occur in the western side of the study area (Fig. 2), within the crustal unit overthrust on the serpentinite massif. We also observed m- to 100 m-sized mafic pods within the serpentinites. The contact between these pods and the host serpentinite is not rodinititized. Metamorphosed mafic rocks from the pods and those from the western crustal unit show similar features. We distinguished two main mafic rocks:

**Fig. 2 - Lithological map of the studied area in the Mount Avic serpentinite massif as obtained by original field mapping. Location of rodinitic dyke samples is reported. UTM coordinate system: Datum ED 1950; Zone 32N.**
Ca-amphibole-rich rocks (similar to the Mg-(Cr)-metagabbro cropping out in the ZS Unit and Clavalité - St. Marcel area; Martin and Tartarotti, 1989);

Ca-Na-amphibole-rich rocks (similar to the Fe-Ti-metagabbro and metabasalts cropping out in the ZS Unit and Clavalité - St. Marcel area; Martin and Tartarotti, 1989).

Transition from Ca-amphibole-rich rocks to Ca-Na-amphibole-rich rocks with eclogitic relics is always gradual. Ca-amphibole-rich metabasite consists of albite (40-50 vol. %), clinzoisite (up to 30 vol. %), amphibole (20-30 vol. %, Mg-hornblende and tremolite-actinolite), ± zoisite, ± Cr-amphibole (smaragdite), ± chlorite, ± quartz, ± white mica and fuchsite (Panseri, 2003; Fontana, 2005). The coarse-grained flaser-textured portions show mm-sized clinzoisite aggregates and mm- to cm-sized poikilitic albite including mm-sized amphibole (Mg-hornblende and tremolite-actinolite). Mg-hornblende, tremolite-actinolite, chlorite (0.1-1 mm) and mm-cm-sized fuchsite form discontinuous cleavage domains. These domains surround albite-clinzoisite eyes and mark a slight, wavy foliation. The fine-grained rock portions (0.1-1 mm-size) show the same mineralogical association, but they show a pervasive and continuous foliation, marked by Ca-amphibole + fuchsite cleavage domains and albite + clinzoisite laths. Ca-amphibole-rich metabasites are completely retrogressed to greenschist facies and do not show magmatic or HP mineral relics.

Ca-Na-amphibole-rich metabasites occur in small outcrops associated with Ca-amphibole-rich metabasite; they consist of eclogitic relics (omphacite up to 30 vol. % and Alm-Py-rich garnet ~ 20 vol. %), and of Na- and Ca-Na-amphibole (20-30 vol. %, glaucophane, barroisite-winchite, richterite-kathophorite), albite (10-20 vol. %), clinzoisite and zoisite (~ 10 vol. %), ± rutile, ± green biotite. The HP assemblage (garnet, omphacite and glaucophane) is partly retrogressed: fine-grained Ca-Na-amphibole replaces Na-amphibole at the rim (mm-cm-sized glaucophane); omphacite (mm to cm in size) is partially uralitized; chlorite and green biotite (up to 0.1 mm in size) overgrow garnet crystals. Fine-grained albite and Ca-amphibole (actinolite) form the low-P assemblage (greenschist facies). Metabasite samples commonly show a slight foliation marked by amphibole, but coarse-grained rocks characterized by a granoblastic texture were also observed.

Epidotes

The western crustal unit contains reddish tabular epidote bodies, up to 2m thick and 100m long. Epidote consists mainly of epidote, albite, ± diopside, ± quartz, ± Ca-(Na)-amphibole, ± chlorite, ± white mica, ± titanite, ± sulphide, ± magnetite (Buscemi, 2003). Boudinage and multi-stage folding affected these epidote bodies.

Metasedimentary rocks

Metasedimentary rocks (mostly calcschists) crop out near Gran Lac and Mont Bel Plat (Fig. 2). They form a 1- to 10 m thick tabular body interbedded with metabasite of the crustal unit. Calcschist consists of white mica, plagioclase, garnet, white-grey epidote, and calcite.

Rodolites

Rodolitic dykes are enclosed in serpentinites, especially in the southern and eastern sides of the study area. We often found a concentration of rodolitic dykes around metabasite pods (Figs. 2 and 4). This finding suggests a genetic relation between this latter rock and rodolites. The dykes, up to 2m- thick and several meters long, are always parallel to the serpentinite foliation and are surrounded by mm- cm-sized chlorite-rich layer, formally named blackwall. They are often deformed by boudinage or by a multi-stage folding. Rodolites are slightly deformed or show a weak foliation marked by chlorite and a mineralogical layering (garnet or vesuvianite or pyroxene layers interbedded with chlorite). By contrast, we locally observed strongly foliated rodolites. These latter crop out around some rodolitic dykes and are always surrounded by chlorite-rich blackwalls.

Rodolites consist of Ca-rich mineral assemblages: Ca-garnet, epidote, diopside, vesuvianite and calcite. Chlorite is present within the dykes and is the main mineral forming the blackwalls surrounding all the rodolitic dykes. The mineral assemblage is quite variable. At the outcrop scale, the following rodolite types were distinguished:

1- garnet-rodolitic dykes (Fig. 5a, largely cropping out around metabasite pods near Gran Lac and Lac de Leser): pink-redish-brown rodolitic dykes consisting of garnet, chlorite, ± pyroxene, ± vesuvianite;

2- vesuvianite-rodolitic dykes (Fig. 5b, near Cote Mouton, Tete des Hommes and Bec de Nona): yellow rodolite consisting of vesuvianite, chlorite, ± pyroxene, ± garnet;

3- foliated rodolites with diopside and chlorite, centimetric to decimetric in size, cropping out at the contact between garnet rodolitic dykes and serpentinite and bordered by a chloritic blackwall (Fig. 5c, near Cote Mouton and near Gran Lac); foliated rodolites with chlorite, green and white epidote, ± pyroxene (east of Gran Lac) enclosing thin rodolitic dykes (cm in size and consisting of garnet and chlorite);

4- rodolitic reaction zones at the contact between metabasite pods and serpentinites (south of Lac Cornue).

Fig. 3 - Simplified litho-stratigraphic section of the Mount Avic ophiolite. Calcschist and serpentinite in the Crustal Unit are tectonically interlayered.
They consist of m-20m-thick tabular bodies characterized by garnet, green epidote, chlorite and calcite veins. Mineralogical layering, marked by alternating garnet and epidote levels (Fig. 5d), is parallel to the edge of the reaction zones.

We also mapped (near Cote Mouton and Tete des Hommes; see Fig. 2) and analyzed some mixed garnet/vesuvianite rodingitic dykes, usually characterized by garnet-chlorite core and vesuvianite-chlorite rim (Fig. 5e). The transition from garnet to vesuvianite zones is gradual.

Finally, we observed pyroxene-rich dykes surrounded by a mm-sized chlorite-rich blackwall, namely:
- pyroxene-epidote dykes: white-grey dykes with pyroxene, epidote (clinozoisite or zoisite) and chlorite, cropping out near Cote Mouton (see Fig. 2);
- pyroxene dykes (Fig. 5f): white rocks cropping out north of Pisonet and near Col de Lac Blanc. They consist of diopside, minor chlorite, and locally show reddish alteration coating (Col de Lac Bland dyke, see Fig. 2).

Pyroxene-rich dykes cannot be considered as rodingites s.s. because of the lack of garnet or vesuvianite.

**Petrography and Mineral Composition of the Mount Avic Rodingites**

In order to understand the structure and evolution of the Mount Avic ophiolitic complex and metasomatic events, we performed thin section studies on rodingite samples. We also carried out EDS analyses to characterize the rodingite mineral assemblages. Mineral chemistry data and backscattered images were collected by scanning electron microscope (SEM) Cambridge System Stereoscan 360, equipped with Energy Dispersive X-ray Spectroscopy (EDS Link ISIS), at the Consiglio Nazionale delle Ricerche (CNR)-Department of Earth Sciences (Milano University). The correction program used is ZAF4 (Pouchou and Pichoir, 1985). Operating conditions were as follows: accelerating voltage = 20 kV; working distance = 25 mm; probe beam = 400 pA; count time = 50 s. Selected analyses representing the mineral composition of rodingite samples are summarized in Tables 1 and 2. We also performed XRD analyses with a PANalytical X’Pert Pro MPD powder diffractometer, equipped with an X’Celerator multichannel detector, with CuKalpa wavelength (1.5418 Å). The data collections were from 5 to 90° 2θ, with a step size of about 0.02° and a counting time of 25 seconds per step.

Rodingite types that were distinguished in the field also show distinct mineral assemblages and mineral composition. A chloritic blackwall surrounds all rodingite dykes and mainly consists of chlorite (90-95 vol.%), with minor magnetite. It also shows low concentrations of garnet, diopside, or vesuvianite. Chloritic blackwalls often show gradual transition to rodingite and to serpentinite.

**Garnet-rodingitic dykes**

Garnet-rodingitic dykes mainly consist of garnet (up to 80 vol.%) and chlorite (20-50 vol.%, Fig. 6a), with variable amounts of diopside (0-30 vol.%), spinel group minerals (mostly magnetite) or more rarely titanite, epidote, clinozoisite and ilmenite. Grain size ranges from mm- to cm-. Granoblastic texture is the most common, although a strong foliation marked by chlorite and garnet layers may be occasionally present. Locally, we observed diopside with mechanical twinning, surrounded by chlorite foliation. Transition from the rodingite dyke to its blackwall is gradual and characterized by an increasing amount of chlorite and by a penetrative foliation. The blackwall consists of chlorite (90-95 vol.%, up to mm in size) ± garnet, ± magnetite.

Garnet is mainly grossular (up to 95%). XRD analyses evidence the lack of hydrogrossular and other hydrogarnets. Locally Cr-rich-garnet (46% uvarovite, 47% grossular; sample AV91, Fig. 6b) grows at the rim of chromite or chromite-hercynite series mineral (see sample AV128, Table 3). We also observed Ca-Fe-rich-garnet (58-63% grossular, 24-30% almandine, 4-11% andradite) in samples AV103 and AV105 (Ca-Fe-garnet-rodingitic dykes from...
## Table 1 - Representative EDS analyses of rodingite minerals: chlorite and garnet.

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<tr>
<th>Analyses</th>
<th>99-166</th>
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Chlorite classification on the basis of Hey (1954).
Table 2 - Representative EDS analyses of rodingite minerals: epidote, vesuvianite, and pyroxene.

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Fe³⁺ + Fe²⁺ | 0.7 | 0.7 | 1.2 | 0.7 |
Al (VI) | 0.2 | 0.2 | 0.1 | 0.0 |
Site B | 0.9 | 0.9 | 1.2 | 0.7 |
Ca | 19.1 | 19.0 | 18.3 | 19.3 |
Na | 0.0 | 0.0 | 0.4 | 0.0 |
K | 0.0 | 0.0 | 0.0 | 0.0 |
Site Ca | 19.1 | 19.1 | 18.8 | 19.3 |
Xₐ (Fe³⁺) | 0.7 | 0.7 | 0.6 | 0.5 |
Xₐ (Fe²⁺) | 0.9 | 0.9 | 0.7 | 0.6 |
Fe²⁺ + Fe³⁺ | 92.9 | 98.4 | 79.3 | 65.95 | 98.6 | 85.2 | 98.9 | 99.8 |
Wo | 51.2 | 50.8 | 53.4 | 54.49 | 49.3 | 53.6 | 51.8 | 50.7 |
En | 46.0 | 45.7 | 42.5 | 42.46 | 48.3 | 44.5 | 48.2 | 48.5 |
Fs | 2.8 | 3.5 | 4.1 | 3.05 | 2.4 | 2.0 | 0.9 | 0.9 |
Id | 0.0 | 0.0 | 2.1 | 9.14 | 0.0 | 0.5 | 0.0 | 0.0 |
Arg | 0.0 | 0.0 | 18.6 | 24.91 | 0.0 | 14.3 | 9.3 | 0.0 |
Xₐ (Fe³⁺) | 0.9 | 0.9 | 0.7 | 0.6 |
Xₐ (Fe²⁺) | 0.9 | 0.9 | 0.7 | 0.6 |
"
Fig. 5 - Photographs of rodingite dykes. a) Boudinaged rodingitic dyke (1 m thick and 10 m long) with garnet, chlorite assemblage and minor pyroxene and vesuvianite. b) Vesuvianite-rodin- 
gitic dyke deformed by boudinage. c) Folded foliated rodingites with cm-sized garnet rodingite. d) Rodingitic reaction zone with garnet-rich (GRL) and epidote-rich (ERL) lay-
ers. e) Photo and sketch of rodingite dyke with garnet + chlorite core, vesuvianite + chlorite rim and the chlorite-rich blackwall. f) Photo and sketch of a folded pyroxene-rodin-
gitic dyke.
Fig. 6 - Photomicrographs of rodingites (abbreviations according to Siivola and Schmid, 2007). a) Garnet-rodingitic dykes: chlorite, garnet and minor diopside are the main components. b) BSE image and EDS analyses of sample AV91 (garnet-rodingitic dyke): chromite-hercynite series mineral surrounded by Cr-garnet. c) Sample AV143 (garnet-rodingitic dyke): diopside 1 surrounded by garnet layer and chlorite + diopside 2. d) Sample AV89 (garnet-rodingitic dyke): subgrained diopside 1 surrounded by garnet + chlorite + diopside 2. e) Sample AV128 (mixed garnet/vesuvianite-rodingitic dyke): chromite-hercynite series mineral surrounded by Cr-garnet (photomicrograph on the left; BSE image, and EDS analyses on the right). f) Sample AV129 (mixed garnet/vesuvianite-rodingitic dyke): zoned vesuvianite, chlorite and garnet. Andraditic garnet surrounds coarse-grained chlorite.
south of Gran Lac), that are also characterized by abundant titanite. Samples AV103 and AV105 also show Fe-rich-chlorite, classified on the basis of Hey (1954) as ripidolite, pycnochlorite, and clinochlore with high Fe values. Other minerals are epidote and allanite (mm-sized). Chlorite of other samples has a quite homogeneous composition with high Mg contents (clinochlore and rarely sheridanite and penninite). Pyroxene, when present, is diopside with high Mg and Ca contents and $X_{\text{Mg}}$[$Fe^{tot}] > 0.90 \ (X_{\text{Mg}}[Fe^{tot}] = Mg/(Mg + Fe^{tot}) \text{ molar})$. Only pyroxene from samples AV103 and AV105 is Na-diopside or omphacite ($X_{\text{Mg}}[Fe^{tot}] = 0.67-0.73$; Table 2).

We finally studied two samples characterized by high diopside contents (sample AV89 near Gran Lac and sample AV143 near Lac Couverte, diopside-grossular-rodingitic dykes). These samples exhibit a different texture and modal composition with respect to other garnet-rodingites (diopside up to 65 vol.%, chlorite 5-25 vol.% and garnet 10-40 vol.%), but similar mineral compositions. These two samples contain mm-sized porphyroblasts of diopside (diopside 1, Fig. 6c), locally subgrained (Fig. 6d). A second-stage, fine-grained diopside (0.1 mm-sized diopside 2) pertains to the main rodingite assemblage (grossular, diopside, and chlorite) or it occurs in diopside-chlorite-layers interbedded with garnet layers.

Mixed garnet/vesuvianite-rodingitic dykes
Serpentinite near Cote Mouton and Tete des Hommes (see Fig. 2) contains abundant bimodal garnet-rich and vesuvianite-rich rodingitic dykes. Garnet-rich samples show petrographic features similar to those of garnet rodingitic dykes: garnet 60-80 vol.%, chlorite 20-40 vol.%, ± diopside. Grainsize ranges from 0.1 mm to 1 cm. Garnet contains grossular up to 96% and some Cr-rich-garnet (38-50% uvarovite, 39-48% grossular, 8-13% andradite) surrounding chromite-hercynite series mineral (Fig. 6c, Table 3). Chlorites are classified as clinochlore or sheridanite; diopside shows high Ca-Mg values (XMg [Fetot] > 0.95) and low Fe-Na values. Locally we observed grossular crystals replaced by vesuvianite.

Other samples (e.g., sample AV129) exhibit petrographic features that are transitional between those of garnet-rich and vesuvianite-rich rodingitic dykes, being characterized by vesuvianite (40-50 vol.%), chlorite (20-30 vol.%), and garnet (20-30 vol.%). In these samples, vesuvianite is coarse-grained (2-4 mm in size), shows a concentric zonation (Fig. 6f) and quite homogeneous chemical composition ($X_{\text{Mg}}[Fe^{tot}] = 0.68-0.76$). Mm-sized garnet is grossular (up to 97%), but we also analyzed Fe-Cr-rich garnet clusters (up to 40% andradite and 12% uvarovite) around large chlorite crystals (Fig. 6f). Chlorite shows low Fe and Si contents (clinochlore).

Vesuvianite-rich samples (e.g., sample AV134) are quite similar to vesuvianite rodingitic dykes and consist of mm-cm-sized vesuvianite (up to 95 vol.%), mm-sized chlorite (5-45 vol.%), and rare diopside. Vesuvianite is characterized by a large $X_{\text{Mg}}$ range ($X_{\text{Mg}}[Fe^{tot}] = 0.62-0.79$). Chlorite shows clinochlore composition. Diopside presents high Ca-Mg values ($X_{\text{Mg}}[Fe^{tot}] > 0.95$). Garnet presents high Ca and Fe values (andradite 60-80%).

Vesuvianite-rodingitic dykes
Yellow-green coloured rodingitic dykes consist of vesuvianite (50-95 vol.%), chlorite (5-45 vol.%), ± diopside (up to 15 vol.%), ± garnet (often concentrated in veins). Grainsize ranges from 0.1 mm (sample AV140) to 2 mm (sample AV130 and sample AV148). Chlorite and vesuvianite layers mark the rock foliation. Vesuvianite shows $X_{\text{Mg}}[Fe^{tot}] = 0.47-0.64$. Chlorite is mainly classified as clinochlore, with minor penninite and sheridanite (low Fe and Si contents). Diopside is characterized by high Ca-Mg values ($X_{\text{Mg}}[Fe^{tot}] > 0.94$). Some veins, up to 2 cm-thick and several-cm long, are filled with garnet, minor chlorite, diopside, and vesuvianite. Garnet shows high Ca contents (grossular > 86%). In contrast, garnet from the sample AV140 shows high Fe values (andradite > 63%). Vesuvianite grows around garnet and some coarse-grained vesuvianite veins cut garnet veins.

Foliated rodingites
The foliated rodingites at the contact between garnet-rodingitic dykes and serpentinites (sample AV127 and AV100) mainly consist of diopside (65-90 vol.%), chlorite

Table 3 - Representative EDS analyses of spinels (chromite-hercynite) in rodingite.
(10-25 vol.%), with minor garnet (up to 10 vol.%). Grain-size ranges from 0.05 to 0.5 mm. Diopside and chlorite layers are interbedded and mark a strong foliation (Fig. 7a), folded by at least two subsequent deformation phases. Chlorite shows high Mg values (clinochlore); diopside exhibits low Fe contents ($X_{Mg}[Fe^{2+}] > 0.90$). Near the chlorite-rich blackwall, garnet of the foliated rodingites shows high Ca contents (63-79% grossular) and locally high Cr values (39% grossular, 26% uvarovite and 22% andradite). In the latter case, Cr-rich garnet surrounds relics of chrome-hercynite series mineral (Table 3).

The foliated rodingites enclosing thin rodingite dykes (e.g. sample AV93) are characterized by chlorite (40 vol.%), clinozoisite-zoisite (∼30 vol.%), epidote (20 vol.%) and diopside (up to 10 vol.%). Foliation is here defined by chlorite cleavage domains and diopside-zoisite microlithons (Fig. 7b). Mm-sized epidote crystals are completely surrounded by the rock foliation.

**Rodingitic reaction zones**

The contact between serpentinites and metabasite pods is not usually rodingitized, but we locally observed evidence of rodingitization in Ca-amphibole rich metabasite samples (south of Gran Lac), where mm-sized diopside and calcite grow over the main mineral assemblage. Near the metabasite/serpentinite contact, we also recognized rodingitic reaction zones up to 10 m-thick and 50 m long (sample AV119). These metasomatic rocks consist of layers distinguished by different colours and mineral assemblages (Fig. 7c); reddish layers with 0.1-1 mm-sized crystals are made up of Ca-garnet (more than 50 vol.%), calcite (∼20 vol.%), epidote (∼10 vol.%), Ca-amphibole (∼10 vol.%) and chlorite (∼10 vol.%); green layers with mm-sized crystals consist of epidote (50-80 vol.%), diopside (∼20 vol.%), calcite (up to 10 vol.%), Ca-amphibole (∼5 vol.%), chlorite (∼5 vol.%). Chlorite and amphibole also form the blackwall (sample AV118) between rodingite and serpentinite.

Garnet in both layer types shows high Ca and Fe values (grossular 50%, almandine 20-30%, andradite 10-20%). Locally, diopside has relatively high Na contents and may be classified as Na-diopside (Table 2). $Fe^{2+}$ values of epidote are higher than 1.3 c.f.u. Finally, chlorite is classified as pycnochlorite or diabantite (high Fe contents).

**Pyroxene-epidote dykes**

Samples AV124 and 125 consist of diopside (25-45 vol.%), clinozoisite-zoisite (20-60 vol.%) and chlorite (15-35 vol.%). Two different pyroxene generations occur (diopside 1 and diopside 2): coarse-grained diopside 1 (mm-sized crystals with mechanical twinning) is wrapped by foliation marked by fine grained chlorite, diopside 2 and clinozoisite-zoisite layers (Fig. 7d). Zoisite and clinozoisite show a textural equilibrium. Pyroxene presents homogeneous chemical compositions, with high Mg and Ca contents ($X_{Mg}[Fe^{2+}] > 0.9$), but we occasionally analyzed diopside 1 core with higher Al and Na contents (∼10% of jadeite). Chlorite is quite uniform in composition (clinochlore).

**Pyroxene dykes**

Two samples of pyroxene dykes (samples AV113 and AV138) show abundant coarse-grained diopside and a small amount of chlorite (less than 5 vol.%). Cm-sized pyroxenes define a pervasive foliation (Fig. 7e). The transition from the dyke to the mm-sized chloritic blackwall is sharp. Diopside shows high Mg and Ca contents ($X_{Mg}[Fe^{2+}] \sim 0.95$). Chlorite exhibits low Al and Fe contents (penninite).

**Mineral composition summary**

The EDS chemical analyses of main rodingitic minerals (chlorite, garnet, epidote, pyroxene, and vesuvianite) are summarized in the Tables 1 and 2 and represented by plots (Fig. 8), which compare the main rodingite types. Chlorite is classified on the basis of Hey (1954) and the analyses may be subdivided in three main groups (Fig. 8a):

- low-Si and low-Fe chlorite in garnet-, vesuvianite- and pyroxene-epidote rodingites (mostly low-Fe-clinochlore)
- low-Si and high-Fe chlorite of rodingitic reaction zone and Ca-Fe-garnet rodingites (high-Fe-clinochlore, ripidolite, pycnochlorite, and diabantite)
- high-Si and low-Fe chlorite of pyroxene rodingites and foliated rodingites.

Garnet analyses mark the difference between two main groups of rodingites. The first group includes rodingitic reaction zones and Fe-garnet rodingites. It is characterized by garnet with the lowest ugrandite (60-80%) and the highest almandine values (20-40%, Fig. 8b). The second group includes the other garnet rodingites, showing ugrandite-rich garnets. Garnet-rich rodingites show ugrandite composition trend from grossular to uvarovite (Fig. 8c). Different, vesuvianite-rich rodingites show grossular-andradite trend (Fig. 8c).

Epidote mineral composition shows three main groups (Fig. 8d): Fe-epidote, Fe-rich clinozoisite, and Fe-poor-epidotes (clinozoisite and zoisite). Fe-epidote occurs in rodingitic reaction zones and Ca-Fe-garnet rodingites; Fe-rich clinozoisite is present in vesuvianite-rich and garnet-rich rodingites; clinozoisite and zoisite are contained in pyroxene-epidote dykes.

Pyroxene shows a quite uniform chemical composition, with very high Ca and Mg contents: the analyzed pyroxene crystals may be mostly classified as pure diopside with Wo percentages around 50%. Ca-Fe-garnet-rodigonitic dykes and rodingitic reaction zones show pyroxenes with higher Na and Fe values, which are classified as Na-diopside or omphacite (Table 2).

Finally, we obtained vesuvianite analyses that show a large $X_{Mg}$ and Al range (Fig. 8e). Different chemical compositions do not reflect any internal vesuvianite zonation. High-Fe vesuvianite crystals show purple anomalous interference colours, whereas low-Fe vesuvianites are brown-yellow.

**DISCUSSION**

Petrographic features and distribution of the Mount Avic rodingites are summarized in Table 4. The main mineralogical assemblage of the studied rocks is represented by ugranditic garnet + chlorite ± diopside ± epidote ± vesuvianite, but we also observed other mineral assemblages in the rodingitic dykes, as well as in foliated rodingites, and rodingitic reaction zones. Various assemblages and structures that characterize the Mount Avic rodingites are inferred to be related to the chemistry of the protolith (probably mafic dykes within serpentinite), to the extent of rodin-
gitization during oceanic serpentinization, and to the Alpine evolution (from HP metamorphism, to decompressional stage) that affected the Mount Avic massif as well as the Piemonte ophiolitic nappe.

In the following, the formation of different types of rodingites is discussed, and metamorphic reactions are proposed. All the metamorphic reactions reported in the following paragraphs are in part taken from the literature and in part suggested after modification from published works. All reactions are intended to be dependent on the composition, pressure and temperature of circulating fluids (Li et al., 2008).

Garnet-rodingitic dykes

In accord with Coleman (1967) garnet in rodingites grows from anorthite:

\[3 \text{anorthite} + \text{Ca}^{2+} + 2 \text{H}_2\text{O} \rightarrow 2 \text{clinozoisite} + 2 \text{H}^+ \quad (1a)\]

\[2 \text{clinozoisite} + 5 \text{Ca}^{2+} + 13 \text{H}_2\text{O} \rightarrow 3 \text{hydrogrossular} + 1.5 \text{SiO}_2 + 10 \text{H}^+ \quad (1b)\]

or

\[1.5 \text{anorthite} + 0.5 \text{Ca}^{2+} + 1.5 \text{H}_2\text{O} \rightarrow \text{prehnite} + \text{H}^+ + 0.5 \text{Al}_2\text{O}_3 \quad (1c)\]

\[\text{prehnite} + 4 \text{Ca}^{2+} + \text{Al}_2\text{O}_3 + 6 \text{H}_2\text{O} \rightarrow 2 \text{hydrogrossular} + 8 \text{H}^+ \quad (1d)\]

At the same time pyroxene and amphibole breakdown produces chlorite. By these reactions we can understand the

Fig. 7 - Photomicrographs of rodingites (abbreviations according to Siivola and Schmid, 2007). a) Sample AV93 (foliated rodingite): chloritic cleavage domain and diopside-epidote layers mark the foliation. b) Sample AV127 (foliated rodingites): chloritic cleavage domain interbedded with diopside layers. c) Sample AV136 (rodingitic reaction zone): garnet and epidote layers. Epidote overgrows garnet near layer boundaries. d) Sample AV124 (pyroxene-epidote-rodingitic dyke): diopside 1 surrounded by diopside 2 and chlorite foliation. e) Sample AV113 (pyroxene-rodingitic dyke): cm-sized diopside that marks the foliation.
evolution from a gabbroic/dioritic protolith to a rodingitic assemblage with hydrogrossular and chlorite, but the Mount Avic garnet-rodingites often show a more complex assemblage and garnet is always grossular instead of hydrogrossular.

Grossular-rodingitic dykes
Rodingites with garnet characterized by high grossular contents are the most widespread in the world (Table 5). The main assemblage of these rocks, similar to grossular-rodingitic dykes from Mount Avic, is quite uniform in the Archean - Paleoproterozoic mafic-ultramafic sequences, in both metamorphosed and un-metamorphosed ophiolitic complexes. The protolith is generally a mafic rock (gabbro, diorite or basalts). The analyzed samples from Mount Avic display some textural relics that may be interpreted as pre-metasomatic minerals. Similar relics occur in the rodingites from the Vumba Schist Belt in Botswana (Mogessie and Rammlmair, 1994). Chromite/hercynite series minerals, surrounded by uvarovite rich garnet (see Fig. 6b), could be interpreted as due to the following reaction, modified after Mogessie and Rammlmair (1994):

$$\text{Al-Fe-ugrandite} + \text{chromite} \rightarrow \text{Cr-Al-Fe-ugrandite} + \text{chromite-hercynite} \ (2)$$

Textures and mineral chemistry suggest an Al-Cr exchange between ugranditic garnet and spinel during this reaction (Al-Fe-ugrandite + Cr = Cr-Al-Fe-ugrandite + Al; chromite + Al = chrome-hydrzincite + Cr). Chromite represents the magmatic relic of the rodingite protolith. Uvarovite garnet could have grown during a metasomatic event, at the same time or after grossular-andradite crystallization. The main rodingitic assemblage (ugranditic garnet, chlorite, ± diopside 1, ± diopside 2, ± epidote) probably grew during an early oceanic metasomatic event (at the same time of uvarovite) according to the reaction proposed by Hatzigianiotou et al. (2003):

$$\text{plagioclase} + \text{clinoxyroxene} + \text{H}_2\text{O} + \text{Ca}^{2+} \rightarrow \text{epidote} + \text{grossular} + \text{zoisite} + \text{SiO}_2 + 2 \text{H}^+ \ (5)$$

Diopside 2 abundance is strictly related to diopside 1 content. The observed textures suggest that diopside 2 is the product of diopside 1 dynamic recrystallization, probably developed during the early Alpine evolution. So, diopside 1 could have grown during oceanic rodingitization, while diopside 2 is the product of recrystallization during the Alpine deformation.

Diopside-grossular-rodingitic dykes
Diopside rich rodingites, everywhere showing grossular or andradite (Table 6), are less widespread than grossular-rodingites, but they crop out in the Archean - Paleoproterozoic mafic-ultramafic sequences, in the metamorphosed and un-metamorphosed ophiolitic complexes. Chlorite, epidote, and vesuvianite are often reported. Protoliths are invariably mafic rocks and some authors report diopside as a magmatic relic (Dal Piaz et al., 1980).

In the diopside-grossular-rodingitic dykes from Mount Avic, diopside 1 porphyroblasts, locally subgrained, are textural relics (Figs. 6c, d, and 7a), surrounded by main rodingite assemblage. Diopside 1 crystals probably are textural relics of magmatic clinoxyroxene that have been Ca-enriched and Fe-depleted during the first metasomatic stage, according to the qualitative reaction modified after Li et al. (2008):

$$\text{plagioclase} + \text{clinoxyroxene} + \text{H}_2\text{O} + \text{Ca}^{2+} \rightarrow \text{grossular} + \text{chlorite} + \text{diopside} \ (6)$$

Diopside 2, as in the grossular-rodingites, is the product of diopside 1 recrystallization during Alpine evolution. Grossular, chlorite, and epidote growth follows reactions (3), (4), and (5).

Ca-Fe-garnet-rodingitic dykes
Garnet rodingite dykes with high Fe contents have not been reported in previous rodingite studies. The reactions that produced the metasomatic assemblage were probably the same of grossular-rodingites, but the protolith is quite differ-
Fig. 8 - Composition plots of rodingite minerals. a) Chlorites classification (Hey, 1954) on the basis of 28 O recalculation. Analyzed chlorites from rodingites and chlorite-rich blackwalls are not distinguished. b-c) Garnet classification on the basis of 12 O recalculation. d) Fe$_{eq}$ - Al$^{3+}$ plot for epidote on the basis of 25 O recalculation. e) X$_{Mg}$ - Al$_{tot}$ vesuvianite plot on the basis of 50 cations recalculation. Abbreviations according to Siivola and Schmid (2007).
Table 5 - Summary of (hydro)grossular-rodingites reported in literature, similar to Mount Avic rodingitic dykes.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Occurrence</th>
<th>Igneous assemblage (Protolith)</th>
<th>Metasomatic/metamorphic assemblage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Ballarini, 1984)</td>
<td>Skiros island, Greece</td>
<td>Pl, Px (Gabbro)</td>
<td>Grg, Chl, Ves</td>
<td>Rodigite lens within serpentinite</td>
</tr>
<tr>
<td>(Bamba et al., 1969)</td>
<td>Nukabira mine, Hokkaido, Japan</td>
<td>Grg</td>
<td>Grg, Cr-Grt, Ves, Chl, Cal, Pectolite</td>
<td>Rodigite in serpentinite</td>
</tr>
<tr>
<td>(Bloxam, 1954)</td>
<td>Girvan-Ballantrae complex, Ayrshire</td>
<td>Grg, Px (Gabbro)</td>
<td>Hydro-Grg, Ves, Chl, Sph, Ab, Kfs, Ves, Cal</td>
<td>Altered and gneissitic gabbro in serpentinite</td>
</tr>
<tr>
<td>(Christidis et al., 1998)</td>
<td>Vourinos ophiolite complex</td>
<td>Hbl, Aug (Gabbro)</td>
<td>Hydro-Grg, Chl, Ves, Sph</td>
<td>Rodigite dykes in serpentitized harzburgite with chrome ore</td>
</tr>
<tr>
<td>(Coleman, 1966)</td>
<td>Dun Mountain (New Zealand)</td>
<td>Gabbro</td>
<td>Hydro-Grg, Ves, Chl, Ves, Sph</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Coleman, 1967)</td>
<td>Whangamoa Area (New Zealand)</td>
<td>Gabbro</td>
<td>Hydro-Grg, Chl</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Coffman, 1969)</td>
<td>Silvertale-Wellford Area (New Zealand)</td>
<td>Gabbro</td>
<td>Hydro-Grg, Ves, Chl, Sph</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Donizzi et al., 2004a)</td>
<td>USA Western Coast (Oregon)</td>
<td>Gabbro</td>
<td>Hydro-Grg, Ves, Chl, Sph</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Donizzi et al., 2004b)</td>
<td>USA Western Coast (Washington)</td>
<td>Gabbro</td>
<td>Hydro-Grg, Ves, Chl, Sph</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Dal Piaz, 1969)</td>
<td>Givoletto, Lanzo, W Alps, Italy</td>
<td>Pl, Di (Gabbro)</td>
<td>Hydro-Grg, Ves, Chl, Sph</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Donizzi et al., 2004a)</td>
<td>Valles d' Ayas, NW Alps, Italy</td>
<td>Grg</td>
<td>Hydro-Grg, Ves, Chl, Sph</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Dubinska et al., 2004b)</td>
<td>Lower Silesia, Poland</td>
<td>Grg</td>
<td>Ves, Di</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Dubinska et al., 2004b)</td>
<td>Jordanow-Glogelow Bohemian Massif, Poland</td>
<td>Grg</td>
<td>Ves, Di, Cr, Chl, Pph</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Flinn, 1999)</td>
<td>Vord Hill Klippe, Shetland-Ophiolite, Nelson, Dun Mountain, New Zealand</td>
<td>Pl, Px (Gabbro)</td>
<td>Grg, Ves, Ep, Chl, Sph</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Grange, 1927)</td>
<td></td>
<td>Grg</td>
<td>Ves, Di</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Hatzigianiotou and Tsikouras, 2001)</td>
<td>Samothraki Ophiolite, NE Aegean, Greece</td>
<td>Diorite</td>
<td>Grg, Ves, Chl, Di, Ep</td>
<td>Rodigite I within serpentinite</td>
</tr>
<tr>
<td>(Li et al., 2004; Li et al., 2008)</td>
<td>Zermatt, Zermatt-Saas Ophiolites, CH</td>
<td>Cpx (Basalt)</td>
<td>Hydro-Grg, Ves, Chl, Di, Ep</td>
<td>Rodigite II within serpentinite</td>
</tr>
<tr>
<td>(Li et al., 2004; Li et al., 2008)</td>
<td>Zermatt, Zermatt-Saas Ophiolites, CH</td>
<td>Cpx (Basalt)</td>
<td>Hydro-Grg, Ves, Chl, Di, Ep</td>
<td>Rodigite II within serpentinite</td>
</tr>
<tr>
<td>(Li et al., 2007)</td>
<td>Western Tianshan, China</td>
<td>Eclogite</td>
<td>Hydro-Grg, Ves, Chl, Di, Ep</td>
<td>Rodigite II within serpentinite</td>
</tr>
<tr>
<td>(Mittweide and Schandl, 1992)</td>
<td>Appalachian Piedmont, South Carolina, USA</td>
<td>Di, Am (deformed Gabbro)</td>
<td>Ves, Ep, Zr, Di, Chl</td>
<td>Coarse-grained rodigite</td>
</tr>
<tr>
<td>(Morse and Rammlmair, 1994)</td>
<td>Vumba Schist Belt, Botswana, Africa</td>
<td>Chl (Granoite)</td>
<td>Grg, Ves, Chl, Di, Ep</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Normand and Williams-Jones, 2007)</td>
<td>JM asbestos mine, Asbestos, Quebec</td>
<td>Diorite</td>
<td>Grg, Ves, Chl, Di, Ep</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Normand and Williams-Jones, 2007)</td>
<td>JM asbestos mine, Asbestos, Quebec</td>
<td>Diorite</td>
<td>Grg, Ves, Chl, Di, Ep</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Osett Héméndez, 1999)</td>
<td>Sierra de Guanajuato, Mexico</td>
<td>Pl, Cpx, Ap (Gabbro)</td>
<td>Grg, Ves, Chl, Di, Ep</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Puga et al., 1999)</td>
<td>Mulhacen Complex, SE Spain</td>
<td>Dolerite</td>
<td>Ves, Chl, Di, Ep</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Puccioni, 2002)</td>
<td>Valmalenco, Italy</td>
<td>Basalt</td>
<td>Ves, Chl, Di, Ep</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Quiser et al., 1970)</td>
<td>Narzani Sar, Malakand, West Pakistan</td>
<td>Gabbro</td>
<td>Ves, Chl, Di, Ep</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Scarrow et al., 1999)</td>
<td>Mindyak, Southern Uralis</td>
<td>Gabbro</td>
<td>Ves, Chl, Di, Ep</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Schandl et al., 1990)</td>
<td>Bowman asbestos mine, Ontatio</td>
<td>Gabbro</td>
<td>Ves, Chl, Di</td>
<td>Rodigite within serpentinite</td>
</tr>
</tbody>
</table>

Abbreviations according to Säiviola and Schmid (2007).
Table 6 - Summary of various kinds of rodingites reported in literature, similar to Mount Avic rodingitic dykes.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Occurrence</th>
<th>Igneous assemblage (Protolith)</th>
<th>Metamorphic assemblage</th>
<th>Description</th>
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<tbody>
<tr>
<td>Diopside-grossular-rodigites</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Dal Piaz et al., 1980)</td>
<td>Valtonanche, Western Alps, Italy</td>
<td>Di (Gabbro)</td>
<td>Di, Gss/Adr, Ep, Chl, Ves</td>
<td>Rodigitic gabbro dykes within serpentinite</td>
</tr>
<tr>
<td>(Evans et al., 1979; Evans et al., 1981)</td>
<td>Cima di Gagnone, Central Alps, CH</td>
<td>(Gabbro, basalt)</td>
<td>Di, Gss/Adr, Ep, Hbl, Ves, Chl, Clintonite, Ttn, Prr, Ti-Adr,</td>
<td>Rodigite boudin and layer in ultramafic schists (serpentinite)</td>
</tr>
<tr>
<td>(Grice and Gasparinii, 1981)</td>
<td>Jeffrey Mine, Quebec</td>
<td></td>
<td>Di, Gss, Ves, Serpentinite</td>
<td>Rodigite dyke within serpentinitized dunite</td>
</tr>
<tr>
<td>(Hatzianagnostou et al., 2003)</td>
<td>Lesvos island, NE Aegean, Greece</td>
<td>(Gabbro)</td>
<td>Di, Gss, Eps/Co, Chl, Vuagnatite</td>
<td>Rodigite dykes</td>
</tr>
<tr>
<td>(Mogessie and Ramlmairi, 1994)</td>
<td>Vumba Schist Belt, Botswana, Africa</td>
<td>(Gabbro)</td>
<td>Di, Eps, Gss/Uvt, Cr, pl, Qz</td>
<td>Rodigite within serpentinite</td>
</tr>
<tr>
<td>(Puga et al., 1999)</td>
<td>Mulhacen Complex, SE Spain</td>
<td>(Dolerite)</td>
<td>Di, Grr (pyroslipite)</td>
<td>Rodigites within serpentinitized dunite</td>
</tr>
<tr>
<td>(Schandl et al., 1989)</td>
<td>Abitibi Greenstone Belt, Ontario, Canada</td>
<td>(Gabbro, diabase, pyroxenite, lamprophyric andesite)</td>
<td>Di, hydro-Grs, Ep, Phh, Tr, Ves, Ttn, Chl, Phl</td>
<td>Rodigites within serpentinitized dunite</td>
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</table>

Vesuvianite-rodigites

<table>
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<tr>
<th>Reference</th>
<th>Occurrence</th>
<th>Igneous assemblage (Protolith)</th>
<th>Metamorphic assemblage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dubinska and Wiewiora, 1999</td>
<td>Przemilow, Bohemian Massif, Poland</td>
<td>Di</td>
<td>Ves, Chl/Vrm, Ap, Zn</td>
<td>Rodigite/metarodigite boudins within serpentinite</td>
</tr>
<tr>
<td>Dubinska et al., 2004a</td>
<td>Lower Silesia, Poland</td>
<td></td>
<td>Ves, Grs, Adr, Ep, Phl</td>
<td>Rodigite in serpentinite massif</td>
</tr>
<tr>
<td>Li et al., 2004; Li et al., 2008</td>
<td>Zermatt, Zermatt-Saus Ophiolites, CH</td>
<td>(Eclogite)</td>
<td>Chl, Ves, hydro-Adr,</td>
<td>“Rodigite III” within serpentinite</td>
</tr>
<tr>
<td>Li et al., 2007</td>
<td>Western Tianshan, China</td>
<td></td>
<td>Ves, Chl, hydro-Grs, Di</td>
<td>Vesuvianite-rodigite</td>
</tr>
<tr>
<td>(Normand and Williams-Jones, 2007)</td>
<td>JM asbestos mine, Asbestos, Quebec</td>
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<td>Ves, Cpx,</td>
<td>Vesuvianite-rich veins</td>
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 Epidote-rich-rodigites

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<th>Reference</th>
<th>Occurrence</th>
<th>Igneous assemblage (Protolith)</th>
<th>Metamorphic assemblage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dubinska et al., 2004a</td>
<td>Lower Silesia, Poland</td>
<td>Ab, Ap, Zn</td>
<td>Czo, Gss, Chl, Di, Afs, Phh, Tnn</td>
<td>Czo-rodigite in serpentinitized massif</td>
</tr>
<tr>
<td>Dubinska et al., 2004a</td>
<td>Lower Silesia, Poland</td>
<td>Di</td>
<td>Ep, Gss, Clintonite, Sp, Di, Am</td>
<td>Clintonite-rodigite in serpentinitized massif</td>
</tr>
<tr>
<td>Wittwee and Schandl, 1992</td>
<td>Appalachian Piedmont, South Carolina, USA</td>
<td>Pl, Qz, Cpx, A, (sedimentary rocks)</td>
<td>Ep, Qz, Chl, Tnn</td>
<td>Fine-grained rodigite</td>
</tr>
<tr>
<td>O’Hanley et al., 1992</td>
<td>Cassiar, British Columbia, Canada</td>
<td></td>
<td>Czo, Tr, Phh, Grs, Di</td>
<td>Fine-grained rodigite within serpentinite</td>
</tr>
<tr>
<td>Attoll et al., 2006</td>
<td>Dixcove greenstone belt, SW Ghana</td>
<td>Pl</td>
<td>Ep, Zo, Act, Chl</td>
<td>Rodigite blocks and pods within serpentinitized ultramafic rocks</td>
</tr>
<tr>
<td>Hatzianagnostou and Tsikouras, 2001</td>
<td>Samothraki Ophiolite, NE Aegean, Greece</td>
<td>(Diorite)</td>
<td>Ep, Cal, Di, Phh, Chl, Ab</td>
<td>Rodigite boudins and pods within serpentinitized dunite</td>
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</table>

Rodingite reaction zones

<table>
<thead>
<tr>
<th>Reference</th>
<th>Occurrence</th>
<th>Igneous assemblage (Protolith)</th>
<th>Metamorphic assemblage</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Dal Piaz, 1969</td>
<td>Cogne, NW Alps, Italy</td>
<td>(Marble with silicates)</td>
<td>Gss, Di, Ep, Wo, Act, Chl, Mag</td>
<td>Rodigite reaction zones</td>
</tr>
<tr>
<td>Dal Piaz, 1969</td>
<td>Balangero, W Alps, Italy</td>
<td>Tnn, A, Zrn</td>
<td>Gss, Di</td>
<td>Rodigite reaction zones</td>
</tr>
<tr>
<td>Dal Piaz, 1969</td>
<td>Montjuvet, NW Alps, Italy</td>
<td>(Marble with silicates)</td>
<td>Ep, Zo, Di, Tr, Grr, Qz, Ab</td>
<td>Rodigite along serpentinite/quartz diorite contact</td>
</tr>
<tr>
<td>Leblanc and Lhooabi, 1988</td>
<td>Bou Azzer, Morocco</td>
<td>Pl, Bi, Qz, Zrn, Ap, Tnn, Aln</td>
<td>Grr, Cpx, Ep, Phh, Cal, Ca-Am, Chl, Ab, Kfs</td>
<td>Rodigite gabbro in thrust contact with serpentinitized dunite</td>
</tr>
<tr>
<td>(Normand and Williams-Jones, 2007)</td>
<td>JM asbestos mine, Asbestos, Quebec</td>
<td>(Slate)</td>
<td>hydro-Grs, Zo, Cpx, Phh, Grs</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations according to Siivola and Schmid (2007).
ent. Ca-Fe-garnet-rodinogitic dykes (samples AV103 and AV105) crop out close to a Ca-Na-ampibole metabasite body with eclogitic relics (see Figs. 2 and 4): we suggest that Ca-Fe-garnet-rodinogitic dykes as well as metabasite with Ca-Na-ampibole derive from similar Fe-rich mafic rocks. The rodinogitic dykes and the metabasite show mineral assemblages that highlight their HP Alpine evolution. However, the occurrence of HP, Ca-rich mineral assemblage (grossular-almandine, omphacite or Na-diopside) has been recorded only within the dykes and not in the nearby metabasite body. This evidence suggests that dykes have been metasomatized before the subduction-related metamorphic peak, while the metabasite suffered the HP Alpine evolution without rodinogitization. We thus infer that grossular-almandine, omphacite or Na-diopside represent the products of Alpine recrystallization of a previous mineral assemblage affected by oceanic metasomatism. A similar evolution has been suggested by Bocchio et al. (2000) for rodinogitized Fe-Ti-metagabbros of the Aosta Valley and Soana Valley (Piemonte).

Vesuvianite-rodinogites

Vesuvianite-rich-rodinogites were reported in metamorphosed and un-metamorphosed mafic complexes (Table 6), as well as in rodinogitic veins dragged along the Middle Atlantic Ridge (Honnorez and Kirst, 1975). Vesuvianite-rodinogites also show chlorite, garnet, epidote and clinopyroxene.

In the Mount Avic massif, vesuvianite often occurs at the rims of garnet-rodinogitic dykes and petrographic observations suggest the crystallization of vesuvianite from garnet. The vesuvianite-rodinogites also show textural relics similar to those of grossular rodinogites (chromite/hercynite series minerals, surrounded by uvarovitic garnet, see Fig. 6e).

On the basis of the observed structures, textures and mineral assemblages, we suggest the following qualitative reactions, modified after Li et al. (2008), for vesuvianite crystallization:

\[
grossular + chlorite + H_2O \rightarrow vesuvianite + SiO_2 \quad (6a)
grossular + diopside + H_2O \rightarrow vesuvianite + chlorite + SiO_2 \quad (6b)
\]

These reactions do not need Ca supplies (typical of oceanic metasomatism), so vesuvianite may be a metamorphic Alpine product. Li et al. (2008) highlight that all the reactions producing vesuvianite in the ZS ophiolites could have been developed during the Alpine evolution. According to these authors, reaction (6a) may be referred to early Alpine metamorphism (about 400°C and 1.5 Ga); reaction (6b) probably took place during the ophiolite uplift and late Alpine metamorphism (about 500°C and 1 Ga).

Foliated rodinogites

In this paper foliated rodinogites near garnet-rodinogites are reported for the first time. The assemblage is similar to that of some grossular-rodinogitic dykes, but we also observed chromite/hercynite relics, surrounded by uvarovite and Ca-Cr-garnet. Foliated rodinogites may represent lenses of strongly deformed garnet-rodinogites. Alpine deformation produced mineralogical layering and strong recrystallization of diopside 1 in fine-grained diopside 2.

Rodinogitic reaction zones

Rodinogitic reaction zones are reported in most of the ophiolitic massifs from the Alps (Table 6), often occurring between metasedimentary rocks and serpentinite. In the Mount Avic massif we report for the first time a rodinogitic reaction zone between serpentinite and metabasite pods. This reaction zone shows structural and petrographic features similar to those found in a reaction zone from Balangero quarry (Dal Piaz, 1969). The Balangero reaction zone occurs at the contact between serpentinite and gneiss/micaschist and shows garnet-rich-layers interbedded with diopside-rich-levels, similarly to the Mount Avic rodinogitic reaction zone. This similarity suggests that locally the rodinogite mineral assemblage may be related to Ca-rich fluid composition more than to the protolith composition, probably reflecting high fluid/rock ratios.

Pyroxene-epidote and pyroxene dykes

Epidote-rich-rodinogites are reported from many mafic complexes (Table 6), but not from Alpine ophiolites. Moreover, pyroxene-epidote-dykes from Mount Avic are quite different from other epidote-rich-rodinogites reported in literature, because of the lack of garnet and prehnite and the high modal contents of diopside. However, we highlight some petrographic similarities between the Mount Avic pyroxene-epidote rodinogites and metasomatic rocks from Samothraki Ophiolite (Hatzipanagiotou and Tsikouras, 2001 - Table 6), for which these authors suggest a dioritic protolith.

Pyroxene-epidote dykes display an unusual mineral assemblage, reported here for the first time, even though they show the same structure of other rodinogitic dykes as well as a mm-sized chloritic blackwall.

SUMMARY AND CONCLUSIONS

The Mount Avic massif mainly consists of serpentinites including mafic and metasomatic rocks. Following Tartarotti et al. (1998), this mafic/ultramafic part of the ophiolitic sequence was a mantle fragment exposed on the Tethys ocean floor before subduction. Metabasites and rodinogites are interpreted as deriving, respectively, from gabbroic bodies and dykes that intruded mantle rocks. On the other hand, the lack of a continuous gabbroic layer and a dominant mantle ultramafic component, has been also observed for the Northern Apennine ophiolites (Tribuzio et al., 2000). The Mount Avic and Northern Apennine lithosphere sections fit well the slow-spreading ridge model of discontinuous magmatic crust (e.g. Cannat, 1993; Lagabrielle et al., 1998).

Fieldwork, petrographic studies, and EDS analyses of the Mount Avic rodinogites allow to recognize some peculiar features of these metasomatic rocks. Rodinogites occur as boudinaged and folded dykes, up to 2m- thick and several meters-long, within the serpentinite massif and are always surrounded by a chlorite-rich blackwall. Rodinogitic dykes mostly consist of ugranditic garnet, chlorite ± diopside ± epidote ± vesuvianite, but we also recognized other mineral assemblages (vesuvianite-chlorite-, diopside-epidote-chlorite-, diopside-chlorite-rodinogitic dykes) as well as foliated rodinogites and rodinogitic reaction zones.

Mineral chemistry analyses of chlorite, garnet, and epidote indicate the presence of Fe-rich and Fe-poor rodinogites, most probably due to different protoliths. Rodinogitic reaction zones and Ca-Fe-garnet rodinogites exhibit chlorite, garnet and epidote with the highest Fe values and pyroxene with high Fe and Na contents, probably due to a Fe-Na-
Vesuvianite may be an Alpine product from grossular-rodingite assemblage (according to Li et al., 2008). Vesuvianite-rich rodingites are typical of metamorphosed serpentinitic complexes (Dubinska and Wiewiora, 1999; Dubinska et al., 2004a; Li et al., 2004; 2007; 2008), while not metamorphosed ophiolites and the modern oceanic crust show only vesuvianite veins and restricted vesuvianite bodies (Honnorez and Kirst, 1975). We hypothesize that vesuvianite rodingites grew on the previous main rodingite assemblage (garnet, chlorite) during early Alpine metamorphism following reaction (6a). The large water supply, necessary to vesuvianite crystallization, may be derived from chlorite blackwall and surrounding serpentinite.

Finally, we observed that metabasite pods are not metasomatized and a selective rodingitization affects only dykes. These features have a speculative genetic model illustrated in Fig. 9. Following the model of a discontinuous magmatic crust, as proposed for the Jurassic Ligurian Tethys by Tribuzio et al. (2000), we envisage the occurrence of relatively small mafic bodies intruded in a mantle peridotite (partially serpentinized) exposed on the ocean floor. Intrusion and magmatic evolution also produced mafic dykes (Fig. 9a). Macro- and micro-fractures as well as faults, related to extensional tectonics in a spreading regime, allowed fluids circulation that supports serpentinization and rodingitization event. c) Ca-rich fluid may saturate the oceanic lithosphere over a cracking front and produce a complete rodingitization of the dykes. 1) Sedimentary cover. 2) Basalt flows. 3) Mafic bodies. 4) Peridotite or partially serpentinized peridotite. 5) Mafic dykes. 6) Macro-fractures and faults in the serpentinitized peridotite. 7) Partially rodingitized dykes. 8) Macro- and micro-fractures in the serpentinitized peridotite. 9) Rodingitized dykes.

ACKNOWLEDGMENTS

The authors are grateful to J. Honnorez and B. Tsikouras for reviewing and commenting the earlier version of the manuscript. We appreciate revision and comments by A. Montanini that greatly improved the text. This study was supported by FIRST 2004 provided by Università degli Studi di Milano.

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Received, April 14, 2008
Accepted, November 21, 2008