The Zircon-Bearing Chromitites of the Phlogopite Peridotite of Finero (Ivrea Zone, Southern Alps): Evidence and Geochronology of a Metasomatized Mantle Slab

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INTRODUCTION

The phlogopite peridotite unit of the Finero Complex is a restitic harzburgite that records two metasomatic events. The first event is related to the intrusion of basaltic magma, which reacted with the pyroxene of the host harzburgite to produce chromitite pods with dunite haloes. It also produced secondary clinopyroxene and amphibole in the harzburgite and enriched harzburgite in Na and the light rare earth elements. The second metasomatic event is related to the later intrusion of clinopyroxenitic dykes. During this event, water-rich vapour penetrated the harzburgite along fractures and reacted with it to form phlogopite, thus enriching the rock in K. Chromitites host zircons that yield an age for the first metasomatic event of 207.9 ± 1.7 Ma, during which time extensional tectonics prevailed in the Southern Alps.

KEY WORDS: metasomatism; chromitite; zircon; geochronology; Finero
chromitite and related metasomatic events and place them within the tectonic evolution of the southern Alps.

**GEOLOGICAL AND PETROLOGICAL BACKGROUND**

The Finero mafic-ultramafic complex crops out as a concentrically zoned elliptic body covering an area of about 12 km × 2.5 km in the northern section of the Ivrea–Verbano Zone (northwestern Italy). It occurs within high-grade metasediments (kinzigites, stronalites) and metavolcanic rocks and consists, from the core outward, of an amphibole- and phlogopite-bearing peridotite known as the phlogopite peridotite unit, a layered internal zone of ultramafic and mafic rocks, an amphibole peridotite and an external gabbro (Fig. 1).

The phlogopite peridotite unit, whose thickness is unknown, forms an elongated body (10 km × 1 km) at the core of the Finero Complex, whose tectonic setting is broadly an antiform with a SSW–NNE axis. Its main distinct lithology is amphibole- and phlogopite-bearing harzburgite. Patches of dunite are common and often form irregularly shaped bodies that are associated with chromitites. Clinopyroxenite dykes and rare alkali pegmatites crosscut the harzburgite. The original relationships are partially obscured by later Alpidic deformation. The layered internal zone is 50–130 m thick and consists of cyclic units of amphibole websterite, amphibole peridotite, garnet-amphibole gabbro and anorthosite in layers of centimetre to decimetre thickness.

The rarely visible contacts to the phlogopite peridotite are usually affected by later tectonic events. The increasing content of modal olivine marks the transition from the layered internal zone to the amphibole peridotite, which is 200–300 m thick. This unit consists of dunite, wehrlite and lherzolite enriched in pargasitic amphibole. Thin layers of chromian spinel and patches of coarse-grained pargasite are locally found in this unit (Forbes et al., 1978). The external gabbro is 100–150 m thick and consists of garnet-amphibole gabbro containing rare pyroxenitic and anorthositic layers. The boundary of the amphibole peridotite is marked by a gradual increase of plagioclase in the ultramafic rocks. The transition to the metasedimentary Kinzigite Series is not clear because of the complex structural relationships that exist between the various lithologies of the Kinzigite Series and the external gabbro.

The harzburgite of phlogopite peridotite comprises 60–90% olivine, 5–20% orthopyroxene, 0–5% clinopyroxene, 0–10% amphibole, 0–5% spinel and up to 15% phlogopite (Coltorti & Siena, 1984). It has been interpreted to represent a slice of mantle that was metasomatically enriched in incompatible elements and tectonically emplaced into the crust (Coltorti & Siena, 1984; Cumming et al., 1987; Voshage et al., 1987; Hartmann & Wedepohl, 1993; Lu et al., 1997a, 1997b; Zanetti et al., 1999). Cumming et al. (1987) concluded on the basis of Pb-isotope data that the ultramafic and gabbroic rocks of the Finero Complex originated from a mantle that was contaminated by dehydration reactions in a downgoing oceanic slab. On the basis of a much broader set of data,
Hartmann & Wedepohl (1993) concluded that the Finero peridotite was depleted in incompatible elements by the extraction of a basaltic melt. It was then heterogeneously enriched in incompatible elements by one, or possibly two, fluid pulses that derived from a subducted crustal slab. Zanetti et al. (1999) proposed that the metasomatic agent was a melt derived from an eclogite-facies slab; this melt infiltrated the overhanging harzburgitic mantle wedge and formed clinopyroxenite dykes.

**ANALYTICAL METHODS**

Chemical analyses of minerals were carried out using the ARL-SEMQ microprobe at the University of Milan. Operating conditions were 15 kV acceleration voltage, beam current of 20 nA for all elements and 3 μm spot size. Rare earth element (REE) analyses of amphiboles and clinopyroxenes were carried out with the CAMECA IMS-3f ion probe at Woods Hole Oceanographic Institution. The primary beam was operated at a current of ~20 nA and focused to a spot of ~20 μm in diameter. An energy offset of the secondary ion beam of ~60 V was employed. Accuracy was monitored by periodic analysis of Kilbourne Hole augite KH-1, the composition of which is known (Irving & Frey, 1984). The relative 2σ error based on several tens of analyses of KH-1 is ~15% for each REE. The data are presented normalized to the CI chondrite composition of Anders & Grevesse (1989).

Isotope analyses of zircons were carried out at ETH Zentrum, Zurich. Rock samples were crushed by hand and the zircon fragments handpicked under a binocular microscope. Some samples were air-abraded to eliminate marginal zones where Pb had been lost. Total Pb blanks for multigrain analyses ranged from 20 to 10 pg. The analytical procedures have been reported by von Quadt (1997).

**RESULTS**

**Texture and petrography**

The plagioclase peridotite is a composite unit made up of harzburgite, clinopyroxenite, dunite and chromitite. The high MgO values of harzburgitic bulk-rock samples coupled with relatively low concentrations of Al₂O₃, CaO, and TiO₂ indicate its strongly restitic character (Grieco, 1998a). Compared with the two other main peridotitic bodies of the Ivrea–Verbano Zone, namely Balmuccia and Baldissero peridotites, Finero harzburgite is more depleted (Hartmann & Wedepohl, 1993; Zanetti et al., 1999). The mg-number of olivine varies from 0.90 to 0.92, the mg-number of orthopyroxene from 0.91 to 0.92 and the α-number of spinel from 0.48 to 0.60. The metasomatic processes that affected the plagioclase peridotite led to extreme modification of this original lithology by enrichment in incompatible elements and growth of new phases such as clinopyroxene, amphibole and phlogopite.

Clinopyroxenites form dykes of centimetre to decimetre thickness that are discordant with or slightly discordant to the main harzburgite foliation. Their contact with harzburgite is always sharp and marked by a strong colour contrast, so that they are a very distinctive feature in the field, even where rocks are altered. At the contact, reaction products between the clinopyroxenite and the host harzburgite and transitional changes in modal composition are not observed. Only in one outcrop at Alpe Polonia can a clinopyroxenite dyke be observed to intersect a dunite body. The dykes contain clinopyroxene as the main constituent and minor but variable amounts of orthopyroxene, amphibole, phlogopite and rare olivine. All phases that are present both in the host harzburgite and in the clinopyroxenite dykes, except phlogopite, show more evolved compositions in the latter, indicating that the two rocks did not equilibrate with each other. Thus in the clinopyroxenite dykes mg-numbers are 0.87–0.88 for olivine, 0.92–0.94 for clinopyroxene and 0.87–0.89 for amphibole, whereas in harzburgite at the dyke contact mg-numbers are 0.91–0.93 for olivine, 0.91–0.92 for orthopyroxene, 0.95–0.96 for clinopyroxene and 0.91–0.94 for amphibole.

Dunite bodies are common and scattered throughout the plagioclase peridotite but they are much less evident in the field and virtually undistinguishable from harzburgite when altered. The dunites are composed of 90–95% modal olivine, the other minerals being spinel and orthopyroxene. Clinopyroxene and amphibole are locally present. The contact between the dunite and surrounding harzburgite is gradational and expressed in the changing marginal zones where Pb had been lost. Total Pb blanks for multigrain analyses ranged from 20 to 10 pg. The analytical procedures have been reported by von Quadt (1997).
phases, with modal concentrations up to 7 and 18%, respectively. Clinopyroxene and type I amphibole (see below) show primary magmatic relationships with olivine and chromite. The minor phases include olivine and orthopyroxene. The accessory phases include base metal sulphides, base metal alloys, platinum group element minerals, Ti oxides and zircons. Phlogopite is very rare in chromitites and crosscuts all the other phases. Type I amphibole is often observed to be corroded and replaced by a symplectitic assemblage of Cr-spinel (type III chromite) and phlogopite, possibly as a result of reaction of the original assemblage with metasomatizing fluid.

**Mineral chemistry**

Three textural types of chromite may be distinguished (Table 1, Fig. 2). Type I chromite consists of small, individual rounded grains scattered throughout harzburgite; type II chromite makes up the massive chromitites, is coarse grained and chemically zoned and for type I and II, with lower 

\[
\text{mg}-\text{number} = \frac{\text{Fo} - \text{An}}{\text{Fo} + \text{An}}
\]


and TiO_2 contents (0·07–0·7) (Fig. 6) than peridotites of Balmuccia and Baldissero. On the other hand, [\text{LREE}]_N values (0·8–20) of the most metasomatized harzburgite samples are higher than those of the Balmuccia and Baldissero peridotites (0·2–1) (Hartmann & Wedepohl, 1993). Chromitite is systematically enriched in LREE relative to all harzburgite samples (Table 3, Fig. 6). Thus, in the former La ranges from 0·86 to 3·26 ppm and (La/Yb)_N from 29·8 to 112·8, whereas in harzburgite the respective ranges are 0·07–0·67 ppm and 4·4–16·6.

All three types of amphiboles show strong LREE enrichment (Table 4, Fig. 7), with (La/Yb)_N ranging between 6·39 and 25·62, but differ in total REE contents. Type I amphiboles are lower and more variable in LREE contents and exhibit slightly higher Eu anomalies compared with type II and III amphiboles. The main distinction, however, concerns the Nd value, defined as Nd* = Nd/\text{SQRT(Ce \times Sm)},. Type I and II amphiboles have Nd* >1 whereas type III amphiboles have Nd* <1, resulting in a concave-upward LREE pattern for types I and II and a concave-downward pattern for type III amphibole.

**Rare earth element geochemistry**

At Finero the least metasomatized harzburgite samples show the most depleted whole-rock REE patterns. These rocks have lower normalized light rare earth element ([\text{LREE}]_N) values (0·07–0·7) (Fig. 6) than peridotites of Balmuccia and Baldissero. On the other hand, [\text{LREE}]_N values (0·8–20) of the most metasomatized harzburgite samples are higher than those of the Balmuccia and Baldissero peridotites (0·2–1) (Hartmann & Wedepohl, 1993). Chromitite is systematically enriched in LREE relative to all harzburgite samples (Table 3, Fig. 6). Thus, in the former La ranges from 0·86 to 3·26 ppm and (La/Yb)_N from 29·8 to 112·8, whereas in harzburgite the respective ranges are 0·07–0·67 ppm and 4·4–16·6.

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Although the major element compositions of clinopyroxene in chromitite and harzburgite are similar, their REE patterns strongly differ (Table 4, Fig. 8). Relict clinopyroxene grains in restitic harzburgite show the lowest LREE contents and the lowest (La/Yb)_N values (2·7
Later-formed subhedral clinopyroxene grains in both harzburgite or chromitite show higher LREE contents and \((\text{La}/\text{Yb})_N\) values (8.1–16.0), with patterns similar to those of type I amphibole. Rare clinopyroxene grains, growing on and thus post-dating orthopyroxene within chromitites, show the highest LREE contents but \((\text{La}/\text{Yb})_N\) values (8.6 and 12.5) comparable with early formed clinopyroxene. Finally, clinopyroxene grains of clinopyroxenite show patterns similar to those within chromitite but with lower \((\text{La}/\text{Ce})_N\) values (0.99 vs 1.14–1.44).

**Zircon U–Pb data**

Zircons are irregularly distributed within the chromitites. In polished sections, 10–25 grains, with dimensions of up to 600 μm across, were observed in areas of <50 mm². Zircon grains also occur aligned parallel to chrome bands. Most grains are subhedral to anhedral and often observed to form aggregates of up to four crystals between olivine and chromite. No zoning is visible, and the zircons are virtually free of inclusions. The petrographic relations suggest that the zircons crystallized together with the main constituents of the chromitite from a partial melt. Cathodoluminescence revealed curved, mostly diffuse zoning patterns that do not reflect the crystal outlines (Fig. 9). No relics of oscillatory zoning were observed. The relatively high and heterogeneous trace element distribution and the absence of relics of oscillatory zoning support zircon crystallization from a volatile-rich magma.

Four grain-size fractions, which also included fragments of originally larger crystals, were analysed. The U concentrations vary between 1120 and 1240 ppm (Table 5).

The regression line (Fig. 10) yields an upper intercept age of 207.9 ± 1.7/−1.3 Ma and a lower intercept at −7 ± 71 Ma. The slightly discordant ages of the largest and smallest size fractions indicate a mild disturbance of their U–Pb systems, which, according to the lower intercept age, occurred recently, possibly in the laboratory. There is no evidence of an inherited age, and thus the upper intercept age is taken as the age of zircon crystallization.

The age of 207.9 ± 1.7/−1.3 Ma is significantly higher than the age of 195 ± 4 Ma that we obtained on zircons from an alkali pegmatite intruding phlogopite peridotite at Rio Creves, in the northern portion of the Finero Complex. From the pegmatite Stahlé et al. (1990) reported a zircon evaporation age of 225 ± 13 Ma. Zircons from a pegmatitic plagioclase vein at the contact between the hornblende peridotite and the external gabbro in Val Boschetto (northeastern portion of the complex) did not yield a dataset that defines a precise age. However, from one fraction we obtained within the error limits a concordant age of 202 ± 1 Ma, which contrasts with the concordant age of 212.5 ± 0.5 Ma obtained by Oppizzi & Schaltegger (1999) in zircon fragments from a similar vein in the neighbouring Val di Capolo. These data will be discussed elsewhere.

**DISCUSSION**

**Petrogenesis**

Dunite has been frequently observed to envelop chromitite bodies in tectonized peridotites (Augé, 1987; Leblanc & Ceuleneer, 1992; Leblanc & Nicolas, 1992; Melcher et al., 1997). The presence of restitic dunites containing Cr-spinel may result from partial melting of spinel peridotite, followed by melt extraction (Jaques & Green, 1980). This mechanism does not explain the field relations at Finero, however. Another possibility relates the formation of dunites to the assimilation of pyroxene by an olivine-saturated melt intruded from greater depth (Kelemen, 1990). The reaction is driven by the fact that melt, which would have been in equilibrium with peridotite at greater depth, is not in equilibrium with the lower-pressure and cooler peridotite. Upon intrusion, the melt thus reacts with both clinopyroxene and...
of water because water lowers the liquidus of silicate minerals much more than that of chromite and thus has the effect of expanding the stability field of chromite (Nicholson & Mathez, 1991).

Several observations argue for such an origin of the dunite–chromitite assemblage in the Finero phlogopite peridotite and relate to this process the widespread crystallization of clinopyroxene and amphibole. First, clinopyroxene and amphibole are virtually absent in dunites but abundant, albeit heterogeneously distributed, in the harzburgite and hence their crystallization cannot be related to a later event that affected both lithologies. In the harzburgite, REE patterns indicate that both primary and metasomatic clinopyroxene are present. Second, dunite and chromitite always occur together. Also, the REE contents and LREE/HREE (heavy REE) ratios of the chromitites are systematically higher than those of the harzburgite, suggesting that chromitite formation is related to the first metasomatic episode that affected the phlogopite peridotite. Therefore, the dunite must be related to this event also. Third, the high TiO$_2$ contents and correlated Mg and Cr contents of chromite in the chromitites are consistent with their crystallization from melt. In contrast, type I chromite in the harzburgite is interpreted as the original spinel that was enriched in Cr and depleted in Ti during melt extraction from harzburgite. That happened, of course, well before the rocks were metasomatized by mafic melt.

Clinopyroxene, amphibole and zircon crystallized from the residual melt, which may also have become vapour saturated at some point during the evolution, although there are no specific features of the rock to indicate whether or when this might have happened. In any case, the continued reaction of the last residual melt with the solid assemblage under conditions of low melt/rock ratio resulted in (1) the enrichment of chromite in Cr and Mg, and (2) the crystallization of films of type II amphibole at chromite–clinopyroxene boundaries. Orthopyroxene and clinopyroxene were consumed by this metasomatic reaction, as proposed by Neal (1988) for New Caledonia peridotites. A reaction for Mg end members can be written as

$$24\text{MgAlCrO}_4 + 16\text{CaMgSi}_2\text{O}_6 + 14\text{Mg}_2\text{Si}_2\text{O}_6 + 8\text{H}_2\text{O} + 4\text{Na}_2\text{O} \rightarrow 8\text{NaCa}_2\text{Mg}_3\text{Al}_5\text{Si}_8\text{O}_{22}(\text{OH})_2 + 12\text{MgCr}_2\text{O}_4 + 12\text{Mg}_2\text{SiO}_4$$

This accounts for the peculiar zoning of the Finero chromitites as a function of the silicate assemblage around them. Cr$_2$O$_3$ depletion in chromite from core to the rim is a common feature of chromite crystallized from melt (Leblanc & Ceuleneer, 1992), and is related to an early stage of crystallization, with contemporaneous formation of olivine. During a later stage of crystallization, after the growth of pyroxenes and type I amphibole, intergranular films of melt were able to change the rim composition

![Fig. 3. Cr-number vs mg-number core–rim zoning of Finero chromitites as a function of the contact mineral: (a) olivine; (b) orthopyroxene; (c) clinopyroxene.](image-url)
Table 1: Representative analyses of chromite (wt %) from Finero phlogopite peridotite

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<td>0.20</td>
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<td>0.00</td>
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<td>0.01</td>
<td>0.17</td>
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<td>0.03</td>
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<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
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<td>Total</td>
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<td>101.18</td>
<td>99.38</td>
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<td>100.24</td>
<td>100.60</td>
<td>99.39</td>
<td>99.90</td>
<td>100.05</td>
<td>99.65</td>
<td>99.30</td>
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</tr>
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</table>

Fig. 4. Analyses of amphiboles in an AlIV vs (Na + K)A diagram.

of chromite, enriching it in Cr2O3, according to the above reaction. The result is a mosaic-like zoning where a single grain of chromite can show both depletion and enrichment of Cr2O3 from core to the rim, depending on the phase in contact with any portion of the rim.

There is no evidence to relate the formation of phlogopite to the processes that gave rise to the formation of the dunite–chromitite bodies. Phlogopite is very rare in

Fig. 5. Amphibole compositions in a Ti vs K diagram and in an mg-number vs Al2O3 diagram.
Table 2: Representative analyses of amphiboles (wt %) from Finero phlogopite peridotite

<table>
<thead>
<tr>
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<th>Type III</th>
</tr>
</thead>
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<td>cv3a</td>
<td>pr1a</td>
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<td>45.22</td>
<td>44.80</td>
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<tr>
<td>TiO₂</td>
<td>0.49</td>
<td>0.50</td>
<td>0.51</td>
</tr>
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<td>Al₂O₃</td>
<td>1.97</td>
<td>1.84</td>
<td>1.70</td>
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<td>Cr₂O₃</td>
<td>3.65</td>
<td>3.98</td>
<td>4.23</td>
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<td>FeO*</td>
<td>0.05</td>
<td>0.06</td>
<td>0.05</td>
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<tr>
<td>MgO</td>
<td>19.56</td>
<td>18.49</td>
<td>18.63</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.36</td>
<td>2.20</td>
<td>2.21</td>
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<td>0.87</td>
<td>0.84</td>
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<td>2.10</td>
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<tr>
<td>Total</td>
<td>99.03</td>
<td>99.60</td>
<td>99.28</td>
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Fig. 6. Whole-rock chondrite-normalized REE patterns of chromitite and harzburgite.

Fig. 7. Chondrite-normalized REE patterns of amphibole.

These lithologies. Textural evidence points to a later crystallization of phlogopite under different conditions. The phlogopite and Cr-spinel symplectites associated with type I amphibole show that phlogopite formed under disequilibrium conditions after the crystallization of type I amphibole. This suggests a later, perhaps independent metasomatic event. Phlogopite is a common mineral in the clinopyroxenitic
Table 3: REE and trace elements (ppm) of Finero phlogopite peridotite

<table>
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<tr>
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<th></th>
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<td>0.86</td>
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<td>1.42</td>
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<td>0.01</td>
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<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
</tr>
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<td>0.0234</td>
<td>0.013</td>
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<td>n.d.</td>
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<td>0.01</td>
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<td>n.a.</td>
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<td>n.d.</td>
<td>0.02</td>
</tr>
<tr>
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<td>0.0417</td>
<td>0.05</td>
<td>n.a.</td>
<td>0.1348</td>
<td>0.1</td>
<td>n.a.</td>
<td>0.06</td>
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<td>0.01</td>
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<td>n.a.</td>
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<td>n.d.</td>
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<td>0.0026</td>
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<td>n.d.</td>
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</tr>
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<td>108</td>
<td>106</td>
<td>190</td>
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<td>97</td>
<td>139</td>
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<tr>
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<td>2965</td>
<td>3748</td>
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<td>156000</td>
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<td>2900</td>
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<tr>
<td>Ni</td>
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<td>2383</td>
<td>2152</td>
<td>910</td>
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<td>1637</td>
<td>1800</td>
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</tr>
<tr>
<td>Rb</td>
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<td>n.d.</td>
<td>n.d.</td>
<td>0.6</td>
<td>n.d.</td>
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<td>Sb</td>
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<td>n.d.</td>
<td>63.3</td>
<td>50</td>
<td>n.d.</td>
<td>57</td>
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Dykes that, at least in one case, were observed to crosscut dunite. Phlogopite crystallization in the harzburgite is attributed to the percolation of a later, water-rich melt from which clinopyroxenite dykes crystallized. The melt penetrated the host rock along structural planes, accounting for the much more heterogeneous and structurally controlled distribution of phlogopite than of clinopyroxene and amphibole. This argues also for a lower temperature for this second metamorphic event.

The very high REE and LREE/HREE ratio of clinopyroxenite is due to their high clinopyroxene content. The final, water-rich melt, which metasomatized the harzburgite, although rich in incompatible elements such as K, was not strongly enriched in LREE. This is because the $D_{\text{cpx/melt}}$ of LREE is much higher than $D_{\text{ol/melt}}$ or $D_{\text{olivine/melt}}$, so, although crystallization of chromite and olivine in the dunite–chromitite assemblage can account for an early increase of LREE content of melt, crystallization of large amounts of clinopyroxene in the clinopyroxenite dykes would not have resulted in such an increased content of LREE in the residual melt. Thus, the metasomatising melt did not greatly modify the original absolute or relative REE contents of the peridotites, and it resulted in phlogopite that is not particularly enriched in REE. The Sr and Nd isotope data reported by Voshage et al. (1987), Hartmann & Wedepohl (1993) and Lu et al. (1997) show mantle signatures for the external gabbro (except a few outliers), the amphibole peridotite, the layered internal zone, the phlogopite-free harzburgite and the alkali pegmatite (Stähle et al., 1990) ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7026 - 0.7047$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.5125 - 0.5133$), although a small crustal contribution (<10%) cannot be ruled out. By contrast, the phlogopite-bearing harzburgite shows a clear crustal imprint ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70625 - 0.70832$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.5122 - 0.5123$). Pb isotope ratios are sensitive to crustal contamination and the Pb isotopic compositions of all lithologies of the Finero
Table 4: Major elements and REE of amphiboles and clinopyroxenes of Finero phlogopite peridotite

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<th>Lithology: Peridotite / Chromitite / Clinopyroxenite</th>
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<th>Type II</th>
<th>Type III</th>
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<td>1.7</td>
<td>1.76</td>
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<td>99.28</td>
<td>98.98</td>
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<th>b1a6</th>
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<tr>
<td>TiO₂</td>
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<td>Cr₂O₃</td>
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**Clinopyroxenes**

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GRIECO et al. ZIRCON-BEARING CHROMITITES, FINERO

distinctly more crustal \( \frac{^{206}Pb}{^{204}Pb} = 18.58 \), \( \frac{^{207}Pb}{^{204}Pb} = 15.625 \). The absence of Pb contamination in the rocks enveloping the Pb-contaminated phlogopite peridotite argues strongly against Pb transport by metamorphic fluids coming from the metasedimentary cover. Hence the source of metasomatic fluids that affected the phlogopite peridotite can be attributed to a contaminated mantle.

**Age relations**

The geochronology of the Finero Complex is poorly known. Voshage et al. (1987) reported a Rb–Sr whole-rock isochron from six phlogopite-bearing peridotites and one phlogopite pyroxenite that yielded an age of 293 ± 13 Ma and an initial \( ^{87}Sr/^{86}Sr \) of 0.7063 ± 0.0006. They interpreted this as the age of K metasomatism. From paired phlogopite–amphibole samples, Hartmann & Wedepohl (1993) obtained Rb–Sr ages ranging from 225 ± 5 to 163 ± 4 Ma and with \( ^{87}Sr/^{86}Sr \)I of 0.7061–0.7082. However, amphiboles from phlogopite-free samples have \( ^{87}Sr/^{86}Sr \) ratios varying from 0.7031 to 0.7034.

Hunziker (1974) reported a K-Ar age defined by phlogopite and hornblende of 180 Ma, which is identical to the Rb-Sr phlogopite age. Individual K-Ar ages of amphibole as well as phlogopite appear to be biased by excess \( ^{40}Ar \). They range from 206 to 220 Ma for phlogopite and exceed 1200 Ma for hornblende (Hunziker, 1974).

Lu et al. (1997) tentatively interpreted whole-rock Sm-Nd data from the amphibole peridotite as defining an isochron with an age of 533 ± 20 Ma, which is consistent with the Pb–Pb zircon evaporation age of 549 ± 12 Ma from the layered internal zone. Sm-Nd data of garnet, clinopyroxene, plagioclase and amphibole from the layered internal zone yielded internal isochrons indicating a concordant age of 215 ± 15 Ma, which was attributed to a reheating event in which temperatures exceeded 600°C.

As already mentioned, the textural evidence indicates that zircon grew late in the crystallization history of chromitite. The zircon age of 207.9 ± 1.7/−1.3 Ma thus dates the crystallization of the chromitites and hence the first metasomatic episode. The formation of the alkali pegmatite at Rio Creves (195 ± 4 Ma) post-dates the age of the chromitite formation. The zircon ages of pegmatitic plagioclase veins in Val Boschetto and Val di Capolo indicate that their formation covered a considerable time span that overlaps the formation of the chromitites. Thus, magmatic activities covering a time span of 20–30 my occurred in the Ivrea Zone during the Triassic period of rifting in the southern Alps. This event is also recorded elsewhere in the Ivrea Zone by zircon and monazite ages of 210–220 Ma (Vavra et al., 1996).
Table 5: U and Pb concentrations and isotopic ratios for different zircon fractions

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<tr>
<th>Sample</th>
<th>Fraction</th>
<th>Wt (µm)</th>
<th>U (ppm)</th>
<th>Pb_{rat} (ppm)</th>
<th>Pb_{lead} (ppm)</th>
<th>206Pb/204Pb</th>
<th>207Pb/204Pb</th>
<th>208Pb/204Pb</th>
<th>206Pb/207Pb</th>
<th>207Pb/208Pb</th>
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harzburgite. This behaviour may indicate that the process occurred at a relatively shallow crustal level and a low temperature. Interaction with the host rock was mainly restricted to K metasomatism of the peridotite, phlogopite being the result of metasomatic interaction. The growth of phlogopite is structurally controlled, and always related to the last ductile deformation event of phlogopite peridotite, before more recent faulting.

The age of these metasomatic events coincided in time with a period of extensional tectonics in the southern Alps (Bertotti, 1991), which implies a passive uplift of the subcontinental mantle. We envisage that during this uplift partial melts developed in a previously metasomatically enriched mantle. These melts rich in fluids and incompatible elements did not rise very far. Instead, they reacted with and modified the surrounding mantle peridotite.

**CONCLUSIONS**

Petrographic and chemical data on Finero phlogopite peridotite indicate two metasomatic events. One is related to the formation of dunite and chromitite bodies 208 ± 2 my ago and the other to the formation of clinopyroxene dunites. These dunite–chromitite bodies formed by the reaction of mafic melt and the host peridotite. Clinopyroxene and amphibole crystallized from the residual melt, which also invaded the harzburgite to produce amphibole and enriched the rock in Na and incompatible elements (LREE). The evolving melt also affected the chromites by reversing their magmatic zoning.

The second event is the intrusion of the phlogopite-bearing clinopyroxene dunites. The melt hardly interacted with the host rock and did not equilibrate with the host harzburgite. This behaviour may indicate that the process occurred at a relatively shallow crustal level and a low temperature. Interaction with the host rock was mainly restricted to K metasomatism of the peridotite, phlogopite being the result of metasomatic interaction. The growth of phlogopite is structurally controlled, and always related to the last ductile deformation event of phlogopite peridotite, before more recent faulting.

The age of these metasomatic events coincided in time with a period of extensional tectonics in the southern Alps (Bertotti, 1991), which implies a passive uplift of the subcontinental mantle. We envisage that during this uplift partial melts developed in a previously metasomatically enriched mantle. These melts rich in fluids and incompatible elements did not rise very far. Instead, they reacted with and modified the surrounding mantle peridotite.

**ACKNOWLEDGEMENTS**

This work was completed while the first author was at Dipartimento di Scienze della Terra, Università degli Studi di Milano, as recipient of a Post-Doctoral Research Fellowship. The research was partially supported by NSF grant EAR9316129 to E.A.M. and a grant from CNR (Centro Nazionale delle Ricerche). The mineral analyses were carried out with the assistance of D. Biondelli (electron microprobe) and N. Shimizu (ion microprobe). We thank B. Ferretti, V. Soi and A. Galletti for their help during field-work, and A. Tunesi for her cartographic support and constructive criticism.

**REFERENCES**


