# Tracing the Oligocene-Miocene Evolution of the Western Alps Drainage Divide with Pebble Petrology, Geochemistry, and Raman Spectroscopy of Foreland Basin Deposits

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**ABSTRACT**

The formation of the western Alps topography is the result of continental collision between the Apulian and European plates. In this study, we trace the Early Oligocene to Early Miocene development of topography and the position of the drainage divide in the southern western Alps by analyzing the erosion products preserved in the pro-side (Montmaur and Barrême) and retro-side (Torino hills) foreland basins of this orogen. Using petrologic and geochemical analyses of basalt pebbles and Raman spectroscopy of serpentine sand grains and pebbles, we identify source lithologies, which are not easily detected with more commonly used detrital thermochronology. Lower Oligocene sediments of the pro-side foreland basin contain numerous basalt pebbles that share strong geochemical similarities with the Chenaillet obducted ophiolite (Montgenèvre massif). Other ophiolite-suite derived clasts, e.g., radiolarite or serpentinite appear widely in pro- and retro-side foreland sediments since about 30 Ma. This suggests a wider distribution of Chenaillet-type obducted ophiolite rocks in the western Alps during the Oligocene, but the exact locations, except for the Chenaillet, are unknown. Raman analysis on serpentine grains and pebbles from the retro-side foreland basin deposits documents a systematic trend from antigorite (high-grade metamorphic source rocks) to lizardite (low-grade metamorphic source rock) from the Early Oligocene to the Early Miocene. This trend is attributed to a westward growth of the paleo-Dora Riparia drainage basin in the southern western Alps. Ophiolite erosion and drainage divide shift were caused by the topographic evolution of the western Alps, which we suggest to be linked to the shift in convergence direction between the Apulian and Eurasian plates from N–S to E–W and the presence of the so-called Ivrea body mantle splinter acting as a vertical indenter beneath the western Alps at that time. The drainage patterns of the paleo-Durance and paleo-Doria Riparia Rivers seem to have remained stable since the Early Miocene. In comparison to the central Alps, the drainage divide shift in the southern western Alps occurred earlier than in the central Alps, but in both locations the trend from an internal to a more external position is the same.

**Online enhancements:** appendix.

## Introduction

The configuration of the drainage divide in the Alps from the Early Oligocene to the present has been a matter of debate over decades. Using sediment petrologic, geochemical, and thermochronologic techniques on foreland basin sedimentary rocks or numeric modeling, different scenarios of shifts in the central Alps drainage patterns have been proposed (e.g., Pfiffner 1986; Schlunegger et al. 1997, 1998; Kempf et al. 1999; Schlunegger and Willet 1999; Spiegel et al. 2000, 2001; Kuhlemann et al. 2001, 2002; Pfiffner et al. 2002; Schlunegger and Hinderer 2002; von Eynatten 2003; Spiegel et al. 2004; Garzanti and Malusa 2008). In this study we

Manuscript received February 22, 2012; accepted July 25, 2012.

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[The Journal of Geology, 2012, volume 120, p. 603–624] © 2012 by The University of Chicago.
 0022-1376/2012/12006-0002$15.00. DOI: 10.1086/667813

make a similar attempt for the drainage divide of the southern western Alps during the Oligocene.

The growth and erosional exhumation of the western Alps orogenic wedge from the Eocene to the Early Miocene is closely related to complex convergence between the Apulian and European plates and stacking of nappes of different metamorphic grade (e.g., Lardeaux et al. 2006; Yamato et al. 2008; Dumont et al. 2012). The evolution of this mountain belt is reflected by the composition of synorogenic sedimentary rocks in the pro- and retro-side foreland basins. In addition to sediment petrologic and heavy mineral studies on the provenance of Alpine foreland basin sediments (e.g., Evans and Mange-Rajetzki 1991; Garzanti et al. 2004, 2007; Vezzoli et al. 2004), recent thermochronologic work in the western Alps was focused on bedrock (Seward and Mancktelow 1994; Tricart et al. 2001, 2006, 2007; Ford et al. 2006; Schwartz et al. 2007) and detrital thermochronology (Carrapa et al. 2003; Morag et al. 2008; Bernet et al. 2009; Glotzbach et al. 2011; Malusà et al. 2011) in order to estimate rates of exhumation. The thermochronologic data hint at fast erosional exhumation, probably associated with the construction of topographic relief in the internal western Alps during the middle Oligocene (Morag et al. 2008; Bernet and Tricart 2011; Jourdan et al. 2012), similar to what has been proposed for the central Alps (e.g., Pfiffner 1986; Schlunegger et al. 1997; Kühni and Pfiffner 2001; Spiegel et al. 2000, 2001; Kuhlemann et al. 2001; Pfiffner et al. 2002; Schlunegger and Simpson 2002). However, the timing of relief development and the position of the drainage divide in the western Alps are not well known and significant (>1 km) topographic relief may not have formed until about 25 Ma, during the Late Oligocene (Garzanti and Malusà 2008; Malusà et al. 2009; Malusà and Garzanti 2012).

A key point in the evolution of the southern western Alps was the first deposition of pebbles derived from the internal western Alps in the pro-side foreland basin. This was first recognized with the description of so-called "exotic" pebbles in nineteenth century (e.g., Termier [1895] in Chauveau and Lemoine 1961). However, certain pebble lithologies, such as low-grade metamorphic basalt, were misidentified in the past (e.g., Bodelle 1971), justifying a reexamination of pebbles with ophiolitic affinity in the pro-side foreland basin. Ophiolites provide important information on the evolution of convergent mountain belts (Garzanti et al. 2007, 2010), and in particular serpentinite grains or pebbles are used in provenance studies (Garzanti et al. 1998, 2000, 2002), because the serpentinite mineralogy provides direct information on the metamorphic history of ophiolitic rocks (Rinaudo et al. 2003; Auzende et al. 2004, 2006; Groppo et al. 2006). Detrital serpentinite derived from hydrated peridotites are sufficiently resistant to fluvial transport (McBride and Picard 1987), which is useful for tracing potential sediment routing systems.

In a recent study, Schwartz et al. (2012) used Raman analyses for distinguishing different types of detrital serpentine in Oligocene to Miocene foreland basin deposits of the Barrême basin (fig. 1). Here we follow the same approach, using Raman analysis on serpentinite pebbles from the retro-side foreland basin of the Torino hills (fig. 1). In addition, we analyzed basalt pebbles from the Barrême and Montmaur basins (fig. 1) for major and trace element compositions in order to identify potential source regions. Because both, the Barrême basin and the Torino hills, contain Eocene to Early Miocene deposits, the detrital signal on both flanks of the western Alps can be compared and used for constraining the approximate position of the main drainage divide during the Oligocene.

## Geological Setting

***The Southern Internal Central Alps.*** The southern internal western Alps, which are the focus of this study, consist to the east of the Penninic frontal thrust of the nonmetamorphic Helminthoid flysch, the Briançonnais zone, and the Piedmont zone (fig. 1). During Eocene-Oligocene continental collision and formation of the western Alps, the Apulia-Europe convergence direction changed from SE–NW (Eocene to Early Oligocene) to E–W (middle to Late Oligocene; Ford et al. 2006). The shift in convergence direction, the so-called Oligocene revolution (Dumont et al. 2012), caused back-folding and back-thrusting of the Briançonnais zone and resulted in the present-day fan-shaped structure of the southern western Alps (Tricart 1984). This deformation led to surface uplift in the Briançonnais and Piedmont zones (Schwartz et al. 2007, 2009) and formation of topographic relief in the internal western Alps (Morag et al. 2008; Bernet and Tricart 2011). A third phase of ENE–WSW directed convergence during the Early Miocene has been proposed (Ford et al. 1999; Handy et al. 2010; Dumont et al. 2012), as extension developed in the core of the arc (Sue and Tricart 2002, 2003).

The Briançonnais zone consists mainly of Late Paleozoic to Mesozoic sedimentary rocks which were metamorphosed under greenschist facies conditions (Goffé et al. 2004 and references therein),

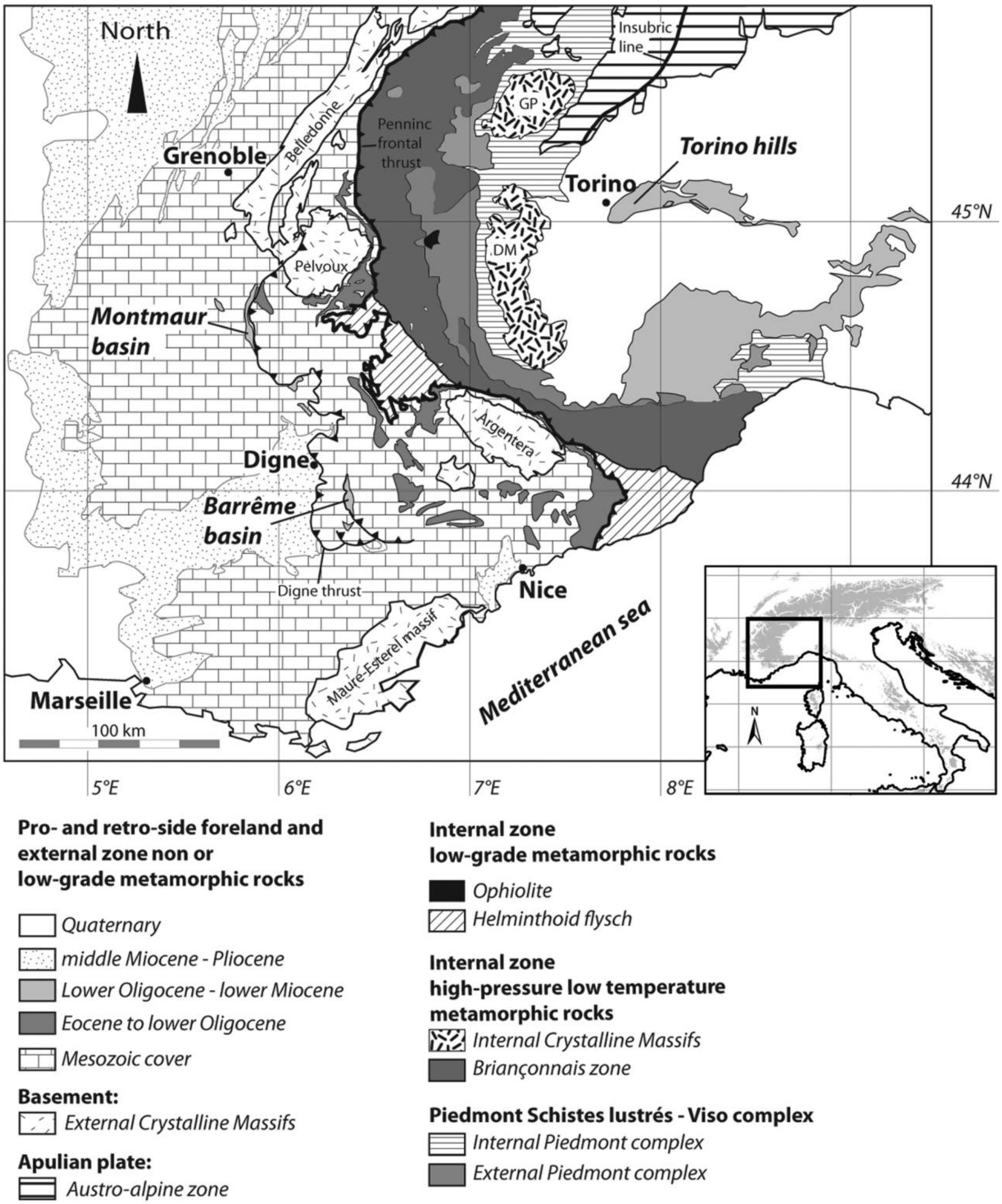



**Figure 1.** Simplified geological map of the southern western Alps showing the study areas of the Montmaur and Barrême basins in the pro-side and the Torino hills in the retro-side foreland basins. DM = Dora-Maira massif, GP = Gran Paradiso massif.

and pre-Alpine magmatic and high-grade metamorphic crystalline basement rocks also metamorphosed during the Alpine orogeny. The Piedmont zone consists of different structural levels of the paleo-subduction wedge. From W to E these are the Chenaillet obducted ophiolite, the blueschist facies accretionary wedge of the Schistes lustrés, a serpentinite subduction channel (Monviso), and the HP to UHP eclogitized pre-Alpine basement of the Dora-Maira massif. The Late Jurassic Chenaillet ophiolite represents an obducted portion of the Tethyan oceanic crust, which escaped alpine metamorphism but shows evidence of low-grade ocean floor metamorphism (Barféty et al. 1995; Goffé et al. 2004; Chalot-Prat 2005; Schwartz et al. 2007; Manatschal et al. 2011 with reference therein). This unit consists of serpentinized peridotites, gabbros, alkali syenites, pillow basalt, and dolerites (e.g., Lagabrielle and Lemoine 1997; Chalot-Prat 2005; Manatschal and Muntener 2009).

The Schistes lustrés consist of high-pressure units including metamorphic pelites and limestones and enclose kilometric olistoliths and tectonic boudins of Triassic dolomites or Jurassic ophiolites (Tricart and Lemoine 1986; Deville et al. 1992; Lemoine and Tricart 1993). Burial under blueschist facies conditions during the Late Cretaceous to Early Eocene times built an accretionary wedge, which was strongly deformed when continental collision commenced in late Eocene times (Agard et al. 2002; Lardeaux et al. 2006; Tricart and Schwartz 2006). The metamorphic conditions ranged from low-temperature (LT) blueschist facies conditions in the western (external) part to high-temperature (HT) blueschist facies conditions in the eastern (internal) part of the Piedmont complex (Tricart and Schwartz 2006; Bousquet et al. 2008; Schwartz et al. 2009).

The eclogite ophiolite units of the Monviso and Rocciavrè massifs were squeezed between the Schistes lustrés complex and the eclogitized pre-Alpine basement. They contain large remnants of the Tethyan oceanic lithosphere that were strongly deformed and metamorphosed under eclogite-facies conditions (Lombardo et al. 1978; Schwartz et al. 2000; Rubatto and Hermann 2003; Angiboust and Agard 2010) during the Eocene (Duchêne et al. 1997) and exhumed under the subduction serpentinite channel dynamics proposed by Schwartz et al. (2001) and Guillot et al. (2009). Located in the lowermost structural position, the Dora-Maira eclogitized pre-Alpine basement (fig. 1) corresponds to a stack of deeply subducted continental basement slices (>100 km; Chopin et al. 1991) involved in a "domelike" structure. This pile of thin (<1 km) high- to ultra-high-pressure metamorphic units overlies the lowermost Pinerolo-Sanfront blueschist unit along a thrust contact. The latter unit is similar, with respect to their lithologies, structural position, and metamorphic evolution to the Briançonnais basement slices. Before 35 Ma the rocks of the Briançonnais zone, the Schistes lustrés complex, the eclogitized Monviso ophiolite, and the Dora-Maira massif (Chopin et al. 1991; Schwartz 2000; Rubatto and Hermann 2001; Agard et al. 2002; Angiboust et al. 2011, 2012; Lanari et al. 2012; Strzerzynski et al. 2012) were deeply buried from 40 km (Briançonnais zone) to >100 km (Dora-Maira massif), experiencing different cooling histories (fig. 2), as it is reflected in the present-day bedrock fission-track data (Tricart et al. 2007; Schwartz et al. 2007). With continental collision from 35 Ma onward, all these units were exhumed toward the surface (e.g., Schwartz et al. 2009).

***The Pro-Side Foreland Basin.*** Alpine foreland basin remnants with Eocene to Early Miocene sedimentary rocks are rare in the southeast of France. In this study we focused on the Barrême and Montmaur basins (fig. 1). The Barrême basin, located on the Digne thrust sheet about 60 km to the west of the Penninic frontal thrust contains the Calcaire à Nummulites, the Marne Bleues, the Grès de Ville turbidites, the Conglomérat de Clumanc and Saint Lions, the Molasse Rouge, Série Grise and Série Saumon, as well as the Grès Verts (fig. 3). For this study, only the Oligocene Grès de Ville (~31–30 Ma), the Conglomérat de Clumanc and Conglomérat de Saint Lions, and the Early Miocene Grès Verts are of interest. The Conglomérat de Clumanc and the Conglomérat de Saint Lions were deposited at the same time (~29 Ma; Callec, 2001), at a short distance from each other (fig. 4; also see Evans et al. 2004). These two conglomerate units are mainly composed of local limestone pebbles but also contain some pebbles derived from the internal western Alps (Gubler 1958; Chauveau and Lemoine 1961; Evans and Mange-Rajetzky 1991; Cordey et al. 2012). Paleo-current markers indicate predominately NE to SW directed sediment transport. The stratigraphic age of the Conglomérat de Montmaur is not well known and only based on correlation with other foreland basin deposits (fig. 3; Graciansky et al. 1982). This conglomerate unit contains pebbles derived from the internal western Alps.

***The Retro-Side Foreland Basin.*** The Torino hills, to the east of Torino, contain the Eocene to Miocene remnants of the western Alps retro-side foreland basin (fig. 1). The Torino hills are an asymmetric west axial plunge anticline (fig. 5; Mosca et al. 2007). In the core of the anticline the Eocene

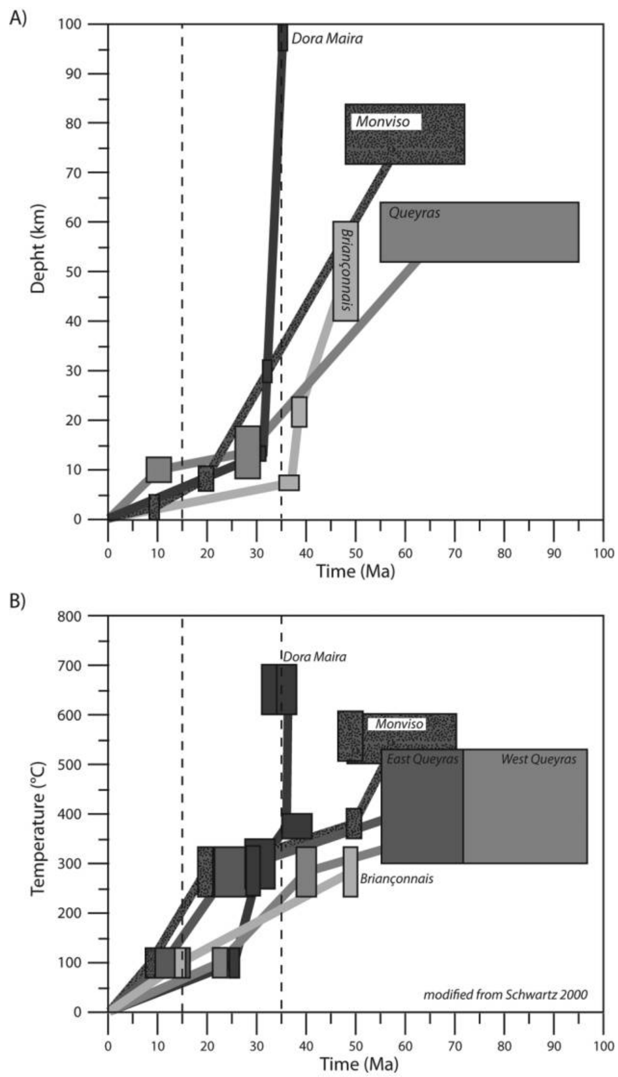



**Figure 2.** Temperature versus time (modified from Schwartz 2000) and depth versus time diagram. Data of Briançonnais come from Lanari et al. (2012) and Strzerzynski et al. (2012). Data of the Schistes lustrés from Schwartz (2000) and Agard et al. (2002). Monviso data are from Angiboust et al. (2011, 2012) and Schwartz (2000). Data of the Dora Maira massif are from Chopin et al. (1991) and Rubatto and Hermann (2001).

Marne di Monte Piano Formation is exposed, which is interpreted as distal Alpine marine deposits (Festa et al. 2011). This distal deposit is overlain by more proximal turbidites of the Early Oligocene Cardona Formation (fig. 2). The Late Oligocene Antognola Formation is composed of conglomeratic submarine canyon channel deposits and adjacent finer-grained pebble to gravel channel levee deposits. Pebble imbrication indicates current directions from the NW to the SE. A deepening of the depositional environment at the beginning of the Burdigalian is indicated by deposition of the Lower Marne a Pterapodi. This unit is followed by the clastic, sandy to conglomeratic Termofourà Formation, which is in turn overlain by the clastic Baldissero Formation.

The Torino hills pebbles show a range of lithologies, derived from different zones of the internal western Alps and the southern Alps (Elter et al. 1966; Polino et al. 1991). The pebbles include lithologies such as granite, granodiorite, gneiss, schist, and quartzite, but also siltstone and dolomite from the sedimentary cover of the western Alpine crystalline rocks. Remarkable are also ophiolite suite pebbles, such as radiolarite, serpentinite, eclogitic mafic rocks, and pelagic limestone (Polino et al. 1991). Based on macroscopic observations alone, the majority of the ophiolite suite pebbles seem to be nonmetamorphosed, but some serpentinite pebbles were derived from source areas that experienced blueschist facies metamorphic conditions. In the Early Oligocene part of the Cardona Formation to the east of Rivodora (fig. 1), the proximal turbidite unit is composed at the base of rounded felsic crystalline pebbles. To the west of Rivodora, small serpentinite pebbles can be observed in the finer pebble fraction. During the Late Oligocene the proportions of pebbles with ophiolite affinity increased successively. By Aquitanian times eclogite pebbles appeared in low proportions (2%) but increased up to 10% by Langhian times (Polino et al. 1991).

## Methods

In the field, pebble population densities were determined by counting up to 100 pebbles along randomly positioned lines. Pebbles were identified macroscopically, distinguishing sedimentary (limestone, dolomite, sandstone, siltstone, mudrock, and radiolarite), metamorphic (gneiss, schist, and serpentinite) and igneous (granite, gabbro, granodiorite, diorite, basalt, and rhyolite) pebbles. To test the grain size dependence of pebble lithology populations, we differentiated population densities for small pebbles (30–64 mm) and cobbles (65–256 mm).

***Basalt Pebble Petrology and Geochemistry.*** Ten basalt pebbles were collected from the Barrême basin, one from the Conglomérat de Clumanc, and nine from the Conglomérat de Saint Lions. Three basalt pebbles were collected from the Conglomérat de Montmaur. For all samples thin sections were examined with an Olympus BX41 petrographic microscope.

All 13 samples were analyzed for major and trace

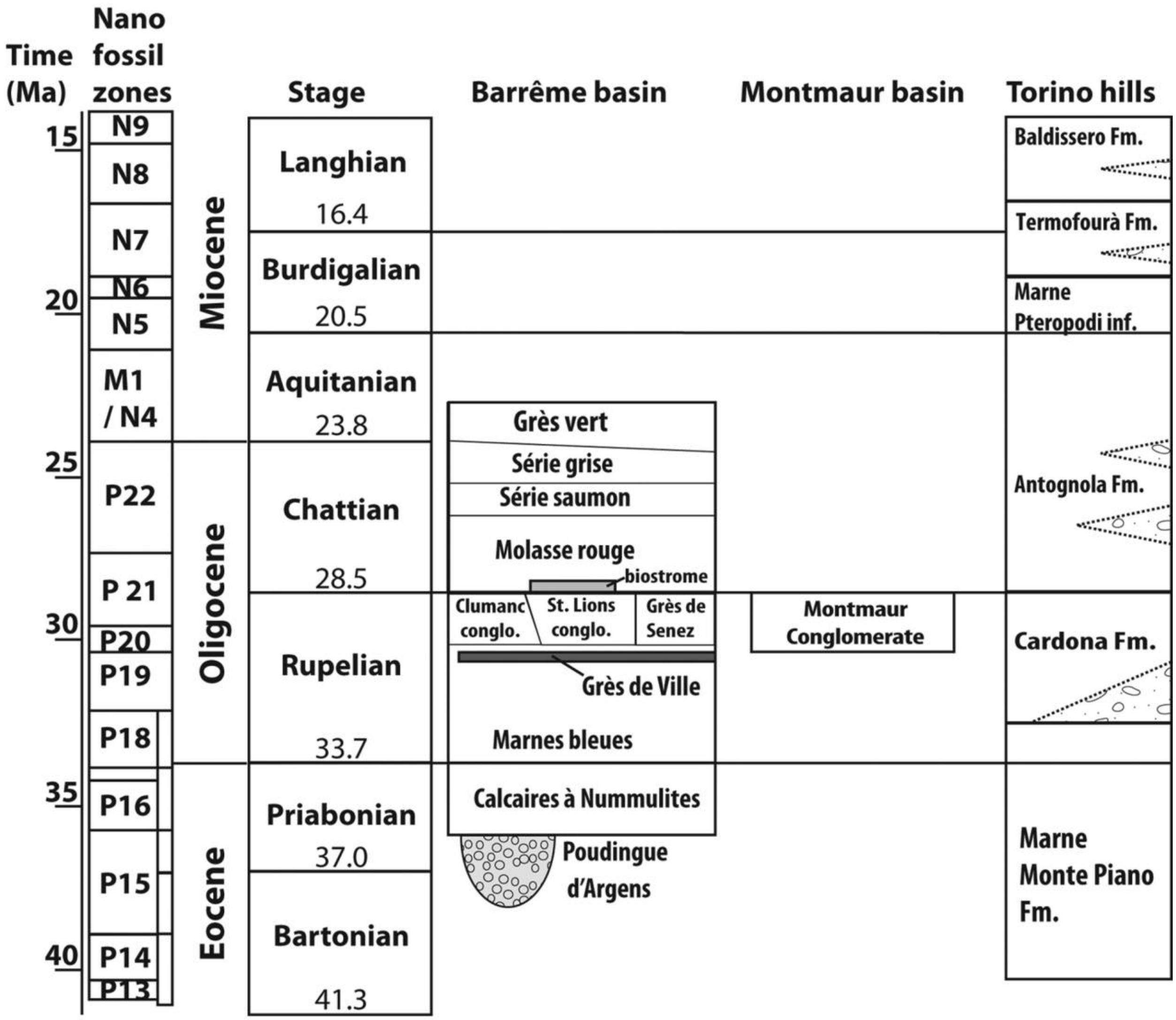



**Figure 3.** Simplified stratigraphy of the Barrême and Montmaur basins, based on Callec (2001; for the pro-side foreland basin) and the Torino hills, based on Festa et al. (2011; for the retro-side foreland basin).

elements at the geochemistry laboratory at the Institut des Sciences de la Terre, Grenoble, France. The samples were crushed and pulverized in an agate mortar to minimize the risk of contamination. Major elements were measured using a Perkin Elmer 3000 DV ICP-AES after dissolution of the rock powder in a mixture of concentrated HF-$HNO_3$ acids. Trace elements were measured using an Agilent 7500ce ICP-MS after dissolution of the rock powder in Savillex Teflon containers using ultra pure concentrated HF and $HNO_3$. Details of the entire analytical procedure are those described in Chauvel et al. (2011). Accuracy and precision of the measurements are estimated at >5% as can be evaluated by the measurement of the international rock standards BR and BE-N (basalt at Esseu la Côte near Nancy), BHVO-2 (basalt from Kilauea, Hawaii, Halemauman crater), and BR24 (basalt from Bora Bora Island, Polynesia).

***Raman Analysis and Serpentine Characteristics.*** Serpentine minerals are phyllosilicates containing up to 13 wt% water and form during the hydration of mafic to ultra mafic rocks. Serpentine minerals, with simplified structure formulae $(Mg, Fe^{2+})_3 Si_2O_5(OH)_4$, are made of superposed 1 : 1 alternating tetrahedral and octahedral sheets. Different spatial arrangements of these layers result in three main serpentine minerals lizardite, chrysotile, and antigorite. The layers are flat in lizardite, rolled in chrysotile, and have a curved and modulated structure in antigorite (e.g., Wicks and O'Hanley 1988). Serpentine in high-grade metamorphic rocks is pre-

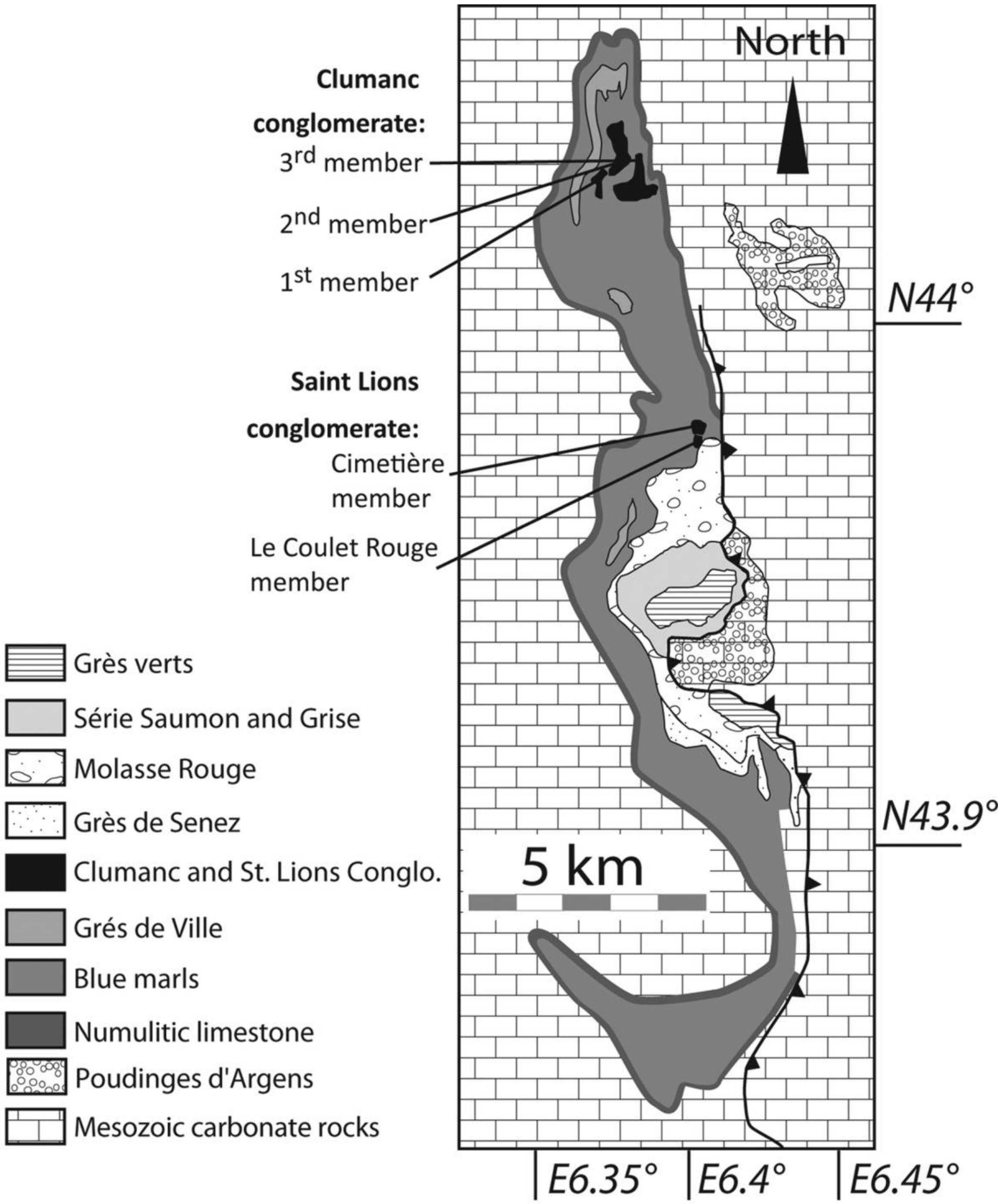



**Figure 4.** Geological map of the Barrême basin (modified after Evans and Elliot 1999).

dominantly antigorite (Scambelluri et al. 1995; Trommsdorff et al. 1998; Auzende et al. 2002, 2006; Li et al. 2004; Padron-Navarta et al. 2008; Guillot et al. 2009). Lizardite and chrysotile are the main varieties present in low-grade metamorphic serpentinites, formed by ocean floor metamorphism of oceanic crust (Evans 2004; Andréani et al. 2007). Recently, Schwartz et al. (2012) showed that antigorite replaces progressively lizardite under intermediate blueschist facies conditions (300°–390°C) and is the sole serpentine phase under high-grade blueschist to eclogites facies conditions (>390°C).

Vibrational Raman spectroscopy is an efficient method for identifying different serpentine species

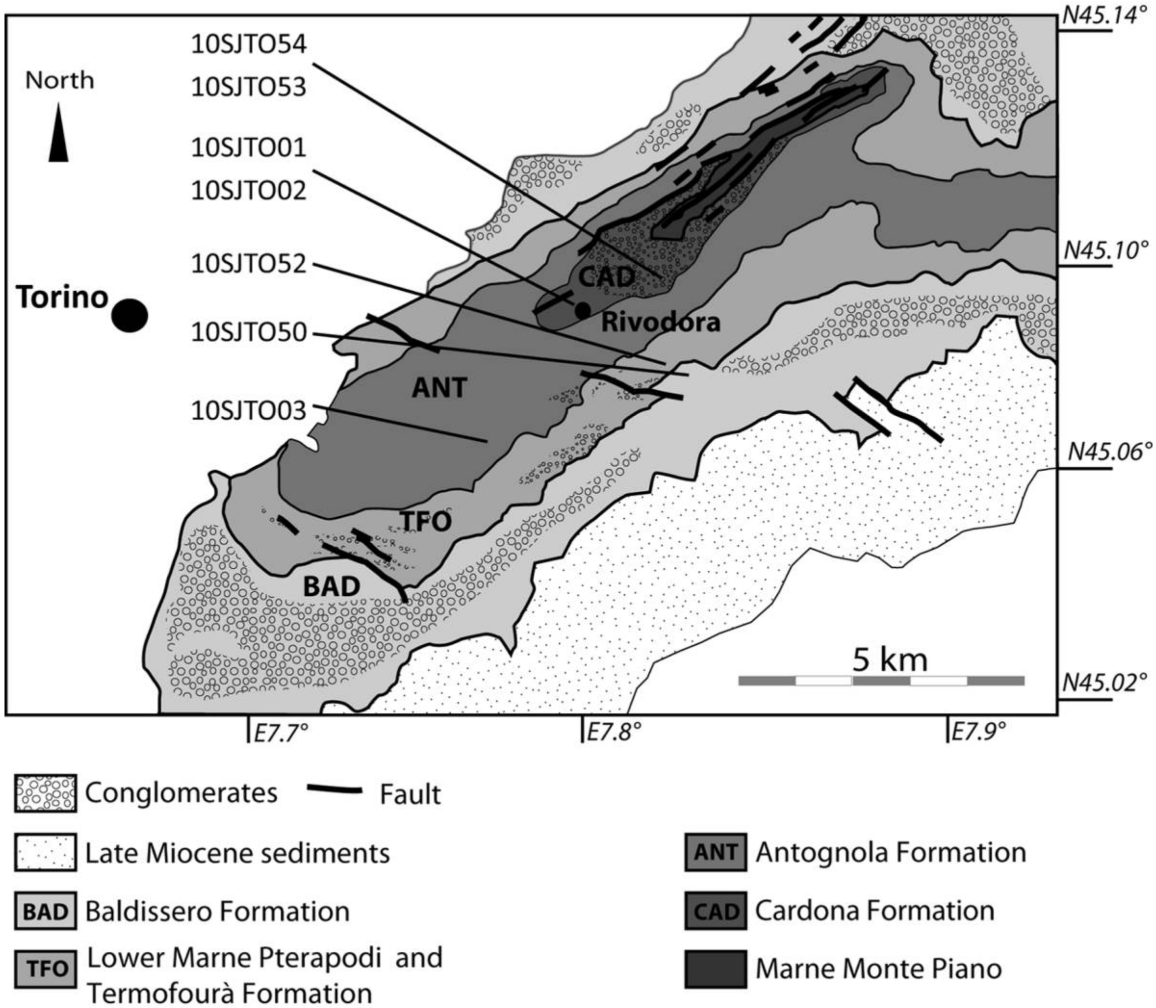



**Figure 5.** Approximate sample locations in the Torino hills, shown on a geologic map modified after Festa et al. (2011). CAD = Cardona Formation, ANT = Antognola Formation, TFO = Termofourà Formation, BAD = Baldissero Formation.

(Rinaudo et al. 2003; Auzende et al. 2004; Groppo 2006). This method is based on the precise position of characteristic peak locations in low (200–1200 $cm^{-1}$) and high (3600–3750 $cm^{-1}$) wave number intervals. Raman spectroscopy for this study was done at the Laboratoire des Sciences de la Terre of the Ecole Normale Supérieure at Lyon, France, with a Horiba Jobin-Yvon LabRam HR800 spectrometer. The light source was an argon-ion laser which provides a monochromatic light in the visible range, with a wavelength of 514.5 nm. An OlympusTM BX30 open microscope equipped with $\times 50$ and $\times 100$ objectives was coupled to the spectrometer to focus the laser beam to a 1–3-$\mu$m spot diameter. The Raman signal was collected in the backscattered direction. Acquisition time span was about 90 s, distributed during three accumulation cycles, with a laser output power on the sample adjusted between 10 and 20 mW. The spectral resolution was 1 $cm^{-1}$ using 1800 gr/mm grating. For all spectra the assignments of the band position and band width were determined using the Peakfit software. Sand and pebble samples were analyzed directly after cleaning them with alcohol.

## Results

On average, the Barrême and Montmaur basin conglomerates consist of 13% low-grade metamorphic basalt pebbles (see table A1, available in the online edition or from the *Journal of Geology* office). This value is fairly stable between the different levels of the Conglomérat de Montmaur and Conglomérat de Saint Lions but more variable for the Conglomérat de Clumanc. The lower Conglomérat de Clumanc member pebbles are up to 99% limestone pebbles, while pebbles in the upper member are up to 80% limestone and up to 20% metamorphic and igneous rock pebbles (table A1). Considering grain size, the proportion of limestone cobbles is even higher, as no metamorphic or igneous cobbles were found (tables A2, available in the online edition or from the *Journal of Geology* office).

***Basalt Pebble Petrology.*** Of the 13 basalt pebbles collected for petrologic and geochemical analyses eight have a porphyritic texture with a glassy matrix and plagioclase phenocrysts that were highly altered to chlorite. The other five samples are basalt pebbles without plagioclase phenocrysts, but also strongly altered to chlorite (see table A3, available in the online edition or from the *Journal of Geology* office).

***Basalt Pebble Geochemistry.*** The results of major and trace element analyses are given in tables tables A4A and A4B, available in the online edition or from the *Journal of Geology* office. The 13 basalt samples plot in the alkali basalt, trachy-basalt, and basaltic trachy-andesite fields in the $Na_2O+K_2O$ versus $SiO_2$ diagram (fig. 6*A*). All but one sample plot in the alkali basalt field of the $Na_2O$ versus $SiO_2$ diagram (fig. 6*B*) or in the low-K subalkali basalt field in the $K_2O$ versus $SiO_2$ diagram (fig. 6*C*). Using the trace element contents, three different groups can be identified (fig. 7). Group A, which only consists of sample LP081 from the Clumanc conglomerate, is characterized by high concentrations of incompatible elements and a large negative Nb-Ta anomaly, a pattern quite similar to those of andesitic basalts found in the Champsaur area (Boyet et al. 2001). Group B samples have positive Nb-Ta, Zr-Hf, and Li anomalies and are relatively depleted in Rb, Ba and Th. Group C samples are generally similar to group B samples, but they lack the positive Nb-Ta anomaly. The most fluid-mobile trace elements (Cs, Rb, Ba, Pb, and U) generally scatter in groups B and C, while the less fluid-mobile elements such as the rare earth elements and the high-field elements of group B and C samples display almost flat patterns (fig. 7).

***Serpentine Raman Analysis.*** Results of Raman analyses of the Torino hills samples are shown in table 1, and exemplary spectra are presented in figure 8. While serpentinite pebbles of the Early Oligocene Cardona Formation consist exclusively of antigorite, both antigorite and lizardite occur in the late Oligocene to Early Miocene Antognola Formation. Serpentinite pebbles from a quarry outcrop in the Antognola Formation (sample 10SJTO06) contain either only antigorite or both antigorite and lizardite. Finer-grained sediments from the Antognola Formation (sample 10SJTO03), sand between 200 $\mu$m and 2 mm, gravel between 2 and 4 mm, and small pebbles between 4 mm and 3 cm, show variable results with respect to the type of serpentine. Antigorite makes up 91% of the sand-sized serpentinite fraction but only 75% of the gravel and pebble sized serpentinite (table 1). The amount of lizardite and the lizardite-antigorite composite minerals increases in the Termafourà Formation, with 82% in the sand sample (10SJTO52) and 25% for the pebble sample (10SJTO51).

## Discussion

The clastic sediments preserved in the Barrême and Montmaur basins on the pro-side and the Torino hills on the retro-side record the erosion of the western Alps from the Early Oligocene to the Early Miocene. The timing of appearance or disappearance of certain pebble lithologies or serpentine types in the different basins provides information on sediment source areas and on the change of the position of the drainage divide in the western Alps during the Late Paleogene.

***Pebble Petrology and Geochemistry.*** All carbonate rock pebbles in the Oligocene pro-side foreland basin conglomerates were derived locally from the Mesozoic sedimentary cover rocks. Of more interest with respect to their provenance are trachy-basalts and basaltic trachy-andesites pebbles that we analyzed in this study (fig. 6*A*). These pebbles show signs of low-grade metamorphic chloritization, as seen in thin sections, but no neocrystallization or deformation were observed. The geochemical analyses show that all the samples have low $K_2O$ values, resulting in a low-K subalkali basalt signal (fig. 6*C*). It is likely that K was partially leached from the rocks during low-grade metamorphism and/or weathering. The flat trace element patterns of these basalt samples (fig. 7) are comparable to patterns observed in ophiolites worldwide and the chloritization is symptomatic of seawater alteration. All these features hint at an ophiolite source.

In order to better determine the source of the basalt pebbles, we compare the petrologic and trace element data of our basalt pebbles to existing data from the Chenaillet obducted ophiolite (fig. 7) at the western front of the iedmont zone (fig. 1). Basalts from the eastern side of the Chenaillet summit were described as having a porphyritic texture with plagioclase phenocrysts (Chalot-Prat 2005), like most of the pebbles collected from the Barrême and Montmaur basins. In addition, the trace ele-

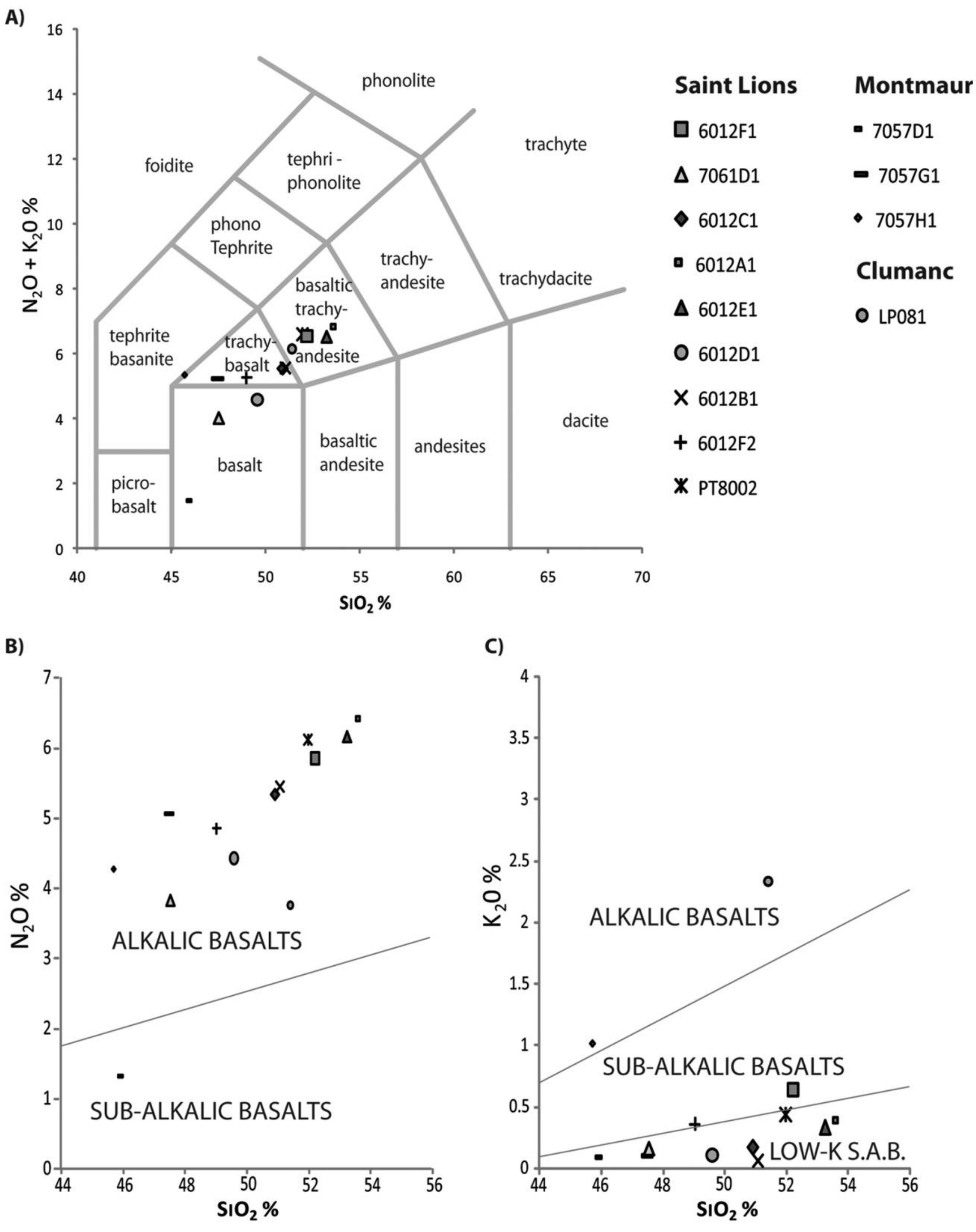



**Figure 6.** Major element data of 13 basalt pebbles collected from Oligocene conglomerates at Clumanc and Saint Lions in the Barrême basin and in the Montmaur basin. *A*, $Na_2O$+$K_2O$ versus $SiO_2$ diagram. All samples plot in the basalt, trachy-basalt and basaltic trachy-andesite fields and are not andesites. *B*, $Na_2O$ versus $SiO_2$ diagram. With the exception of one sample, all samples plot in the alkali basalt field. *C*, $K_2O$ versus $SiO_2$ diagram. Most samples plot in the low-K subalkali basalt (S.A.B.) field.

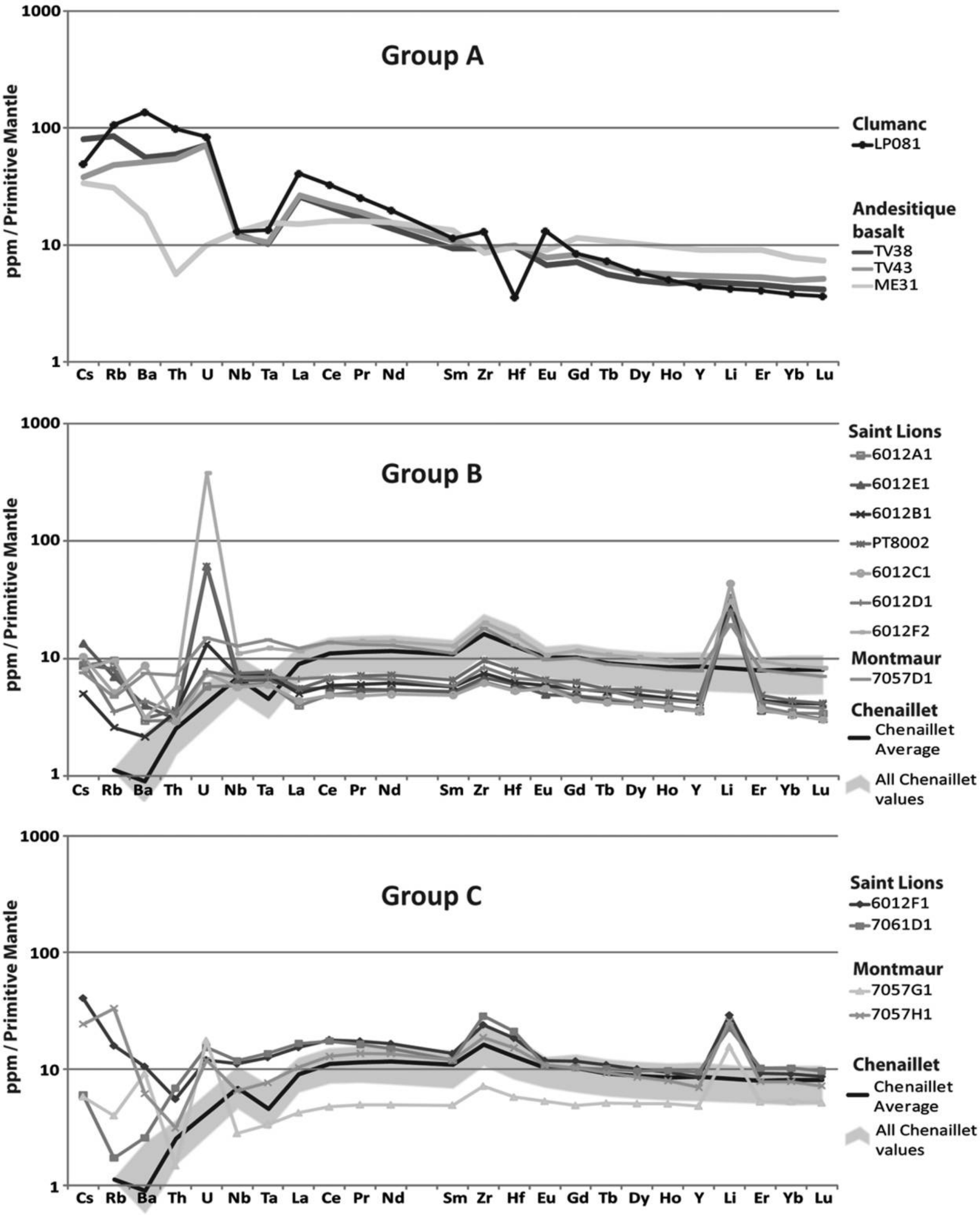



**Figure 7.** The 13 analyzed basalt samples can be divided into three groups based on their trace element patterns. Trace element values were normalized to primitive mantle (McDonough and Sun 1995). Shown for comparison, the andesitic basalt data of samples TV38, TV34 (Taveyannaz sandstone), and ME31 (Champsaur sandstone) are from Boyet (2001), and the Chenaillet data are from Chalot-Pratt (2005).

**Table 1.** Serpentine Raman Analysis

| Sample | Formation | Depositional age (Ma) | Grain size (mm) | *N* | No. spectra | Antigorite (%) | Antigorite-lizardite (%) | Lizardite (%) | Lizardite-chrysotile (%) | Chrysotile (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| 10SJTO51 | Termofourà | 16–20 | 10–40 | 3 | 18 | 66 | 33 | ... | ... | ... |
| | | | 70 | 1 | 6 | 100 | ... | ... | ... | ... |
| 10SJTO52 | Termofourà | 16–20 | .2–2 | 11 | 25 | 18 | 9 | 36 | 18 | 9 |
| 10SJTO03 | Antognola | 20–28 | .2–2 | 11 | 23 | 91 | ... | 9 | ... | ... |
| | | | 2–4 | 12 | 27 | 75 | 8 | 17 | ... | ... |
| | | | 4–10 | 20 | 47 | 75 | 5 | 9 | ... | ... |
| 10SJTO06 | Antognola | 20–28 | 5–20 | 3 | 16 | 100 | ... | ... | ... | ... |
| 10SJTO01 | Cardona | 28–33 | 80 | 1 | 4 | 100 | ... | ... | ... | ... |

ment patterns of the Chenaillet basalts are basically flat and show positive Hf-Zr anomalies (fig. 7) like the detrital basalt pebbles from the Montmaur and Barrême basins. We therefore think that the basalt pebbles originate from a Chenaillet-type obducted ophiolite within the internal western Alps or from the Chenaillet massif itself.

***Detrital Serpentinite.*** In the Barrême basin a major shift in sediment provenance directions from southern sources (Maures-Estérel massif, Corsica, Sardinia; Evans and Mange-Rajetzky 1991; Joseph and Lomas 2004) to northeastern and eastern sources in the internal western Alps and external Mesozoic sedimentary rocks is most likely related to a major change in the geodynamic framework of the western Alps at around 30 Ma (Dumont et al. 2012). The first serpentinite pebbles and grains observed in the Conglomérat de Clumanc were deposited after this shift in provenance and were derived from the internal Piedmont complex (Schwartz et al. 2012). Serpentinite pebbles or grains are absent in the Molasse Rouge (Evans and Mange-Rajetzky 1991) but reappear at the end of the Late Oligocene in the Série Grise. Serpentine grains are an important component in the Early Miocene Grès Verts (Evans and Mange-Rajetzky 1991). Raman analyses of the Grès Verts indicate the presence of both lizardite and antigorite species (Schwartz et al. 2012). The presence of both species in the Grès Verts hints at possible sediment source areas in the internal and/or external Piedmont complex.

In the Torino hills the first occurrence of serpentinite, consisting purely of antigorite, is observed in the upper part of the Early Oligocene Cardona Formation. In the Late Oligocene to Early Miocene Antognola Formation lizardite is systematically associated with antigorite. The proportion of lizardite increases from the Antognola Formation to the Termafourà Formation (Burdigalian) particularly in the sand-sized fraction (table 1).

According to Polino et al. (1991) the proportion of metamorphic pebbles in the Oligocene to Miocene deposits of the Torino hills increased over time. For example, the proportion of eclogite clasts deposited during the Burdigalian is 2%, but 10% during the Langhian. This increasing proportion of high-grade metamorphic pebbles testifies to the increasing exhumation of eclogite in the internal western Alps. During the same period, the proportion of low-grade metamorphic serpentinite pebbles also increased.

It is of interest to know where the different serpentine types are present in the southern western Alps today. Antigorite can be found in the HT blueschist of the Schistes lustrés in the Piedmont zone and in the eclogitic ophiolite units of Monviso and Rocciavré in the internal Piedmont complex (Li et al. 2004; Auzende et al. 2006; Groppo et al. 2006; Schwartz et al. 2012). The composite lizardite-antigorite assemblage is present in the LT blueschist of the Schistes lustrés (external Piedmont complex), while solely lizardite is known to occur in the in the Chenaillet ophiolite (Montgenèvre massif) further to the west (Schwartz et al. 2012). Chryzotile is a retrogressed product of high-grade serpentinites and is present in all units (Auzende et al. 2006).

The signal of predominantly antigorite in the Early Oligocene and more lizardite in the Late Oligocene and Miocene sediments has been detected in the foreland on both sides of the orogen (Schwartz et al. 2012 and this study). Obviously, during the Early Oligocene only the antigorite-bearing units were effectively eroded. In the Late Oligocene and Early Miocene sedimentary rocks of the Torino hills the composition of serpentine varies as a function of grain size, with antigorite being more abundant in the coarser-grained fraction. This is could be an effect of the closer proximity of antigorite-bearing source rocks compared to lizardite-antigorite-bearing source rocks and the long-distance transport need for lizardite-antigorite grains to be deposited in the basin. The same can be ob-

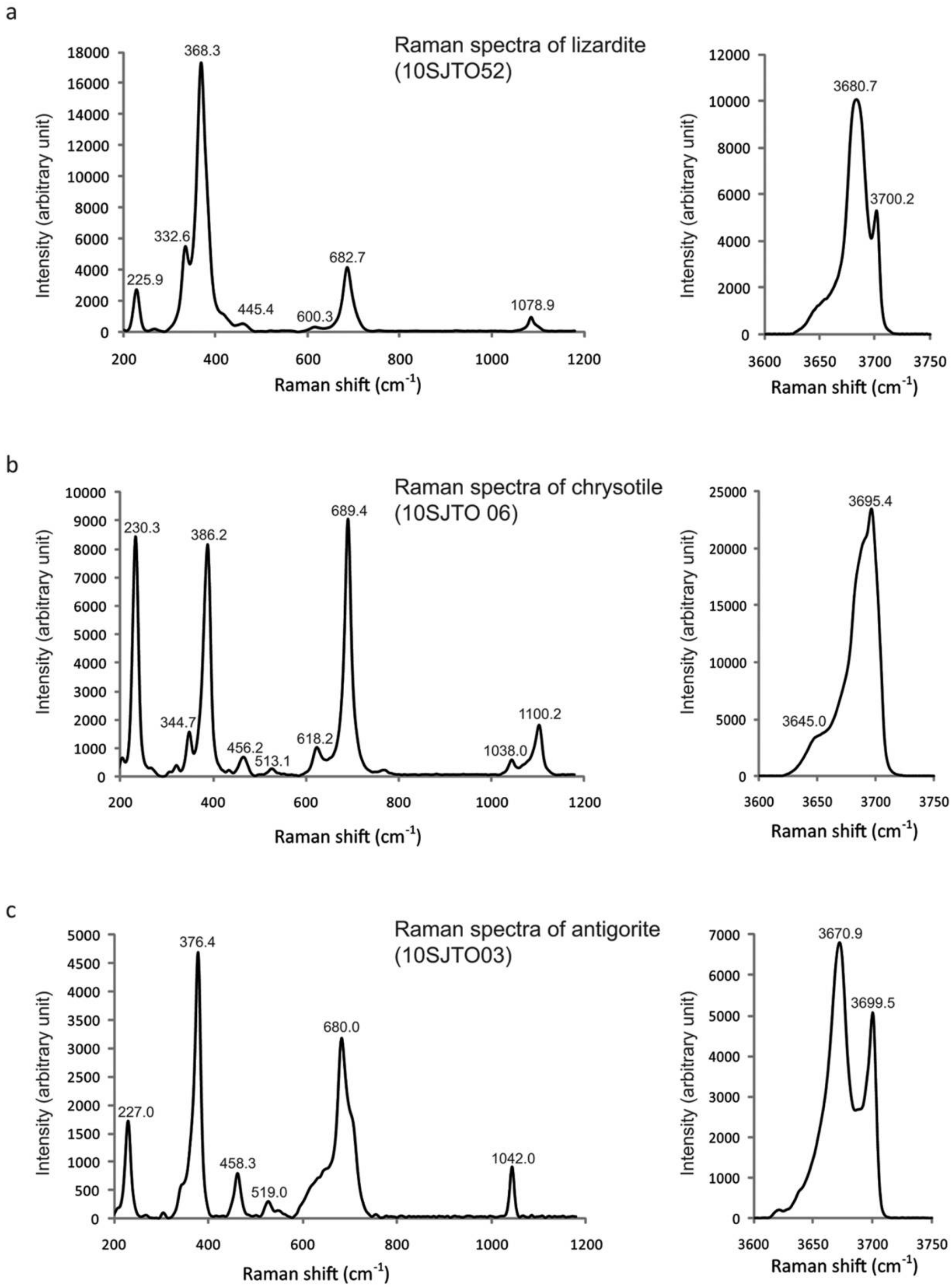
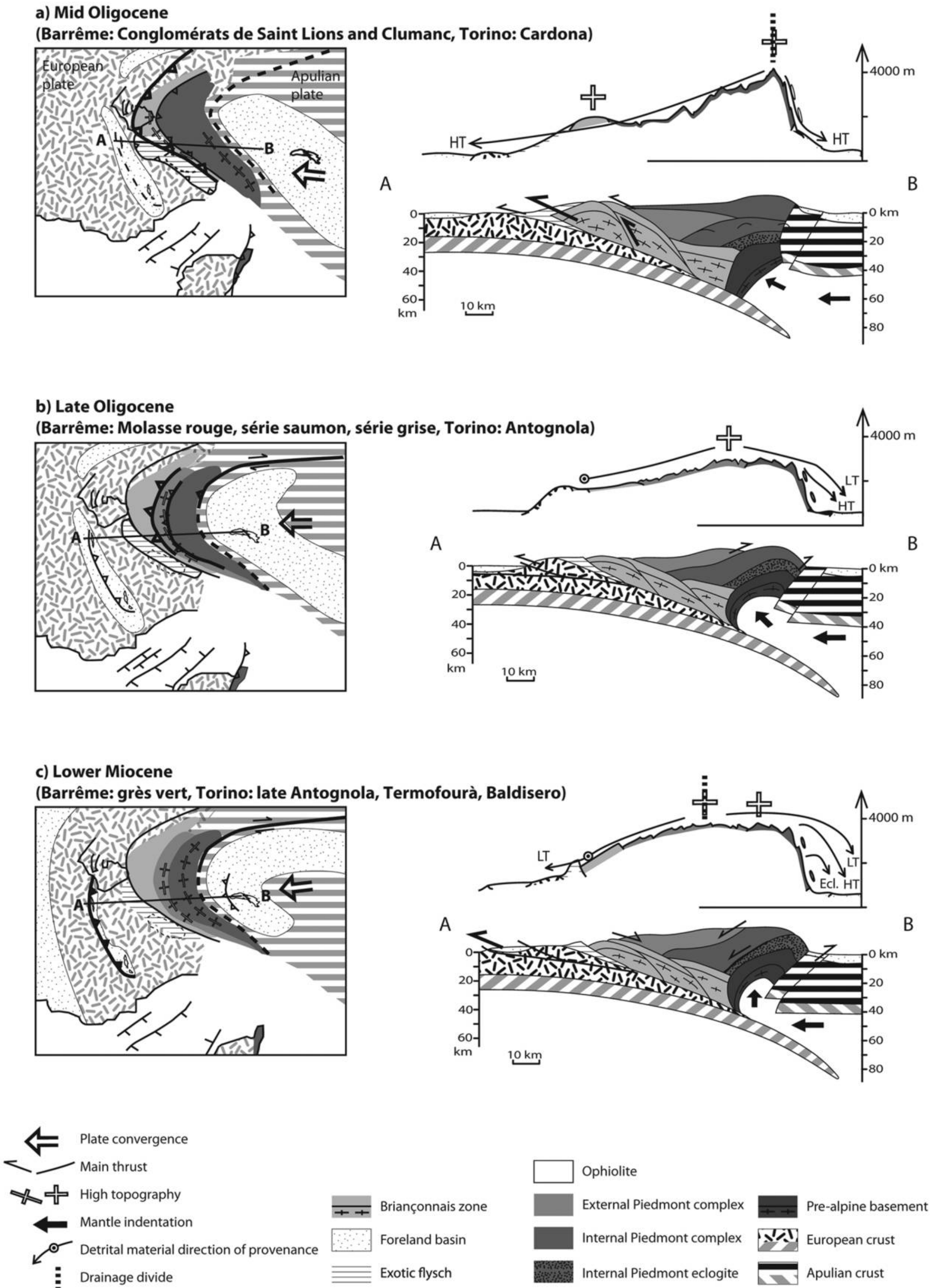



**Figure 8.** Typical Raman spectra of serpentine minerals lizardite (*a*), chrysotile (*b*), and antigorite (*c*) from Tornio hills samples 10SJTO52, 10SJTO06, and 10SJTO03, respectively. Samples 10SJTO52 and 10SJTO03 are coarse-grained sand samples, while sample 10SJTO06 is a serpentinite pebble.



a) Mid Oligocene
(Barrême: Conglomérats de Saint Lions and Clumanc, Torino: Cardona)
European plate
Apulian plate
A
B
HT
HT
4000 m
0
20
40
60
km
10 km
0 km
20
40
60
80
b) Late Oligocene
(Barrême: Molasse rouge, série saumon, série grise, Torino: Antognola)
A
B
LT
HT
4000 m
0
20
40
60
km
10 km
0 km
20
40
60
80
c) Lower Miocene
(Barrême: grès vert, Torino: late Antognola, Termofourà, Baldisero)
A
B
LT
LT
Ecl.
HT
4000 m
0
20
40
60
km
10 km
0 km
20
40
60
80
Plate convergence
Main thrust
High topography
Mantle indentation
Detrital material direction of provenance
Drainage divide
Briançonnais zone
Foreland basin
Exotic flysch
Ophiolite
External Piedmont complex
Internal Piedmont complex
Internal Piedmont eclogite
Pre-alpine basement
European crust
Apulian crust

served for the Burdigalian Termafourà Formation, where lizardite is more abundant in sandy deposits than in the conglomerates.

***Drainage Systems and Position of the Drainage Divide.*** The question is did the position of the drainage divide in the southern western Alps change over time, as it has been proposed for the central Alps, or did it remain more or less in the same position as it is today? As shown above, the trace element analyses of the basalt pebbles collected from the Conglomérat de Saint Lions in the Barrême basin point to a Chenaillet-type ophiolite in the front of the Piedmont zone in the internal western Alps as the most likely source. In contrast, the antigorite-bearing serpentinite pebbles from the contemporaneous Conglomérat de Clumanc point to the internal Piedmont complex as the most likely source (Schwartz et al. 2012). This indicates that the Early Oligocene paleo-Durance drainage system—which delivered sediments to the Barrême basin—extended at least to the internal Piedmont complex (fig. 9*A*), similar to the drainage pattern today. During the Late Oligocene, the Barrême basin did not receive any serpentine grains (Evans and Mange-Rajetzky 1991), indicating an interruption in the sediment supply from the internal Piedmont complex. Schwartz et al. (2012) proposed that this change in sediment provenance coincides with thrusting of the Digne nappe (Gidon 1997) and growth of the Saint Lions anticline (Evans and Elliott 1999). These tectonic events possibly disturbed the paleo-Durance drainage system. The abundant deposition of lizardite and antigorite grains again in the Early Miocene Grès Verts (Evans and Mange-Rajetzky 1991; Schwartz et al. 2012), underlines the redevelopment of the Durance drainage system by incision of the newly created topography (fig. 9).

Do the Torino hills deposits show the same development? Using the time of the first occurrence and the abundance of different serpentine species in the Torino hill deposits, we propose the following scenario for the drainage pattern development. Antigorite-bearing pebbles arrived in the retro-side foreland basin 2–3 m.yr. before they appeared in the pro-side foreland basin. In addition the antigorite-bearing pebbles are in general larger in the Torino hills than in the Barrême basin deposits. This indicates erosion of antigorite-bearing rocks, like the HT blueschist of the internal Piedmont zone or the Monviso eclogites, which at that time probably still covered the present-day Dora-Maira massif. The production of conglomerates implies the creation of topographic relief. We interpret the earlier arrival and larger grain size of the antigorite pebbles in the Torino hills as a closer proximity to the source and the position of the drainage divide in the internal Piedmont zone (fig. 9*A*). The first appearance of mixed lizardite-antigorite grains and pebbles in the Torino hills sediments indicates erosion of low-

**Figure 9.** Schematic reconstruction of the geodynamic and topographic evolution of the southern western Alps from the Early Oligocene to the Early Miocene. The geodynamic reconstructions are based on and modified from previous reconstructions by Michard et al. (2002), Schmid et al. (2004), Mosca et al. (2010), Handy et al. (2010), and Schwartz et al. (2012). The reconstruction is based on results from this study and Schwartz et al. (2012), and thermochronologic data of Tricart et al. (2001, 2007) and Schwartz et al. (2007). LT = low-temperature serpentine (composite lizardite-antigorite); HT = high-temperature serpentine (antigorite); Ecl = eclogite pebbles. *a*, During the mid-Oligocene pebbles derived from the internal western Alps are deposited in the pro- and retro-side foreland basins (Conglomérat de Clumanc and Conglomérat de Saint Lions in the Barrême basin, Cardona Formation in the Torino hills). The convergence direction between the Apulian and European plates was close to E–W (Schmid and Kissling 2000; Handy et al. 2010; Dumont et al. 2012), and the Penninic thrust system was active (Tricart et al. 2001) and partially covered the Pelvoux massif (Simon Labric et al. 2009). Surface uplift and exhumation of high-pressure (HP) rocks in the Piedmont complex was controlled by top-to-the-west shearing and associated vertical indentation of the Ivrea body mantle splinter, causing high topography and relief in the internal Piedmont complex, allowing the transport of HT serpentine to both foreland basins. *b*, Late Oligocene initiation of the Digne thrust (Gidon 1997) created a topographic barrier which caused a temporary change in the paleo-Durance drainage system (Morag et al. 2008). As a result the Barrême basin was no longer supplied with serpentine from the internal Piedmont complex. During the Late Oligocene back-folding and back-thrusting affected the internal western Alps (Tricart 1984; Roure et al. 1989; Tricart and Schwartz 2006; Tricart and Sue 2006; Strzerzynski et al. 2011). The retro-side foreland basin received LT and HT serpentinite clasts at that time. *c*, During the Early Miocene E–W convergence continued. The Ivrea body mantle sliver became a steep indenter and continued to vertically support the internal crystalline massifs and the internal Piedmont complex, permitting the tilting and back-folding of these units as well as the peeling off of the Briançonnais zone (Rolland et al. 2000; Schmid and Kissling 2000; Tricart et al. 2004; Schwartz et al. 2009). The retro-side foreland basin received LT and HT serpentine and eclogite pebbles. The drainage divide for the paleo-Dora Riparia drainage shifted to the external Piedmont zone. A color version of this figure is available online.

grade metamorphic serpentinite units to the west of the high-grade metamorphic serpentinite units. This can be interpreted as a westward extension of the drainage area of the paleo-Dora Riparia system into the LT blueschist bearing the Schistes lustrés complex. The progressive migration of the drainage divide to the west may have been caused by the development of high topography in the external Piedmont complex (fig. *9B*, *9C*). From the Late Oligocene to Early-mid Miocene the trend of less antigorite and more lizardite continued in the sand-sized fraction (table 1), which shows a mixing of different serpentine species, while the pebble fraction was still dominated by antigorite pebbles from proximal sources (fig. *9D*). This means by Early Miocene times the paleo-Dora Riparia drainage had reached the Chenaillet obducted ophiolite at the east side of the Montgenèvre massif, similar to the drainage pattern today. Therefore, if these two scenarios proposed here for the paleo-Durance and paleo-Dora Riparia drainage systems are correct, then (*a*) the paleo-Durance system, which is located to the south of the paleo-Dora Riparia system, became smaller over time while the paleo-Dora Riparia system was growing to the west, and (*b*) the position of the drainage divide in the southern western Alps has remained unchanged since the Early Miocene.

***Linking Geodynamics and the Development of Topography.*** The question is what caused the surface uplift and change in the position of the drainage divide in the southern western Alps? At the Eocene to Oligocene transition the N-S convergence between the Apulian and European plates changed to become E-W oriented (Schmid and Kissling 2000; Ford et al. 2006; Handy et al. 2010; Dumont et al. 2012). This shift in the convergence direction is a consequence of the rotation of the Apulian plate. During the Early Oligocene, continuous convergence and rotation of the Apulian plate caused detachment of part of the Apulian mantle, the so-called Ivrea body mantle sliver (Schmid et al. 1987; Paul et al. 2001; Handy et al. 2010). Topographic (Paul et al. 2001) and gravimetric data (Schreiber et al. 2010) indicate for a presence of the Ivrea body below the Dora-Maira massif at ~10 km depth. The emplacement of the Ivrea body mantle sliver has consequences for the exhumation of the HP units in the internal Alps and the development of the topography (Schwartz 2000; Ford et al. 2006; Lardeaux et al. 2006). During convergence the Ivrea body mantle sliver became a steep indenter, acting as a kind of a backstop that vertically supported the compression of the internal crystalline massifs, the Monviso ophiolite, and the Piedmont Schistes lustrés complex, permitting the tilting and backfolding of these units and the peeling off of the Briançonnais zone (fig. 9; Rolland et al. 2000; Schmid and Kissling 2000; Tricart et al. 2004; Schwartz et al. 2009). Estimates of fast rates of erosional exhumation, based on white mica $^{40}Ar/^{39}Ar$ (Morag et al. 2008) and detrital zircon fission-track data (Bernet and Tricart 2011; Jourdan et al. 2012) from Oligocene sedimentary rocks in the Barrême basin, were interpreted by those authors of indicating the formation of possibly 2–3-km-high topography in the internal western Alps at about 30 Ma. Here we suggest that, supported by the Ivrea body indenter, mountainous topography formed in the internal Piedmont zone during the Early Oligocene, with development of the paleo-Durance draining to the west. Because of continuous continental collision during E-W convergence, deformation shifted to the west in mid- to Late Oligocene times. The paleo-Dora Riparia drainage followed this development with westward extension of the drainage area. During that time, the Briançonnais Frontal Thrust (fig. 9) caused the rapid formation of high topography in the Briançonnais zone (e.g., Tricart et al. 2001), which was incised by the redeveloping paleo-Durance drainage systems. Therefore, the continuation of convergence caused the westward propagation of the thrust system and the growth of the topography during the Late Oligocene to Early Miocene. This westward growth of the topography allowed the drainage divide to migrate westward in the northern part of the southern western Alps, permitting the appearance of lizardite in the retro-side foreland basin but temporarily prohibiting the transport of sediments derived from the internal Piedmont complex to the pro-side foreland basin during the Late Oligocene (fig. 9).

For the central Alps and the Swiss Molasse basin, Pfiffner et al. (2002) studied the drainage pattern evolution by modeling lithospheric flexure in response to sedimentary loading and orogenic wedge charge. In this model it appears that the Ivrea body acted in the central Alps like a charge on the European lithosphere during the Oligocene, contributing to its flexure and therefore to the creation of accomodation space in the pro-side foreland. In comparison, the Ivrea body in the southern western Alps appears to have moved mainly vertically during the Oligocene (Schreiber et al. 2010), supporting surface uplift. After erosion of the sedimentary cover and Austroalpine units during the Early Oligocene, the Swiss molasse basin began receiving detritus from Penninic units of the Lepontine dome, starting as early as 31 Ma (Schlunegger et al.

1997, 1998; von Eynatten et al. 1999; Spiegel et al. 2000, 2001, 2004; Kuhleman et al. 2002). While the timing of the drainage divide shift in the central Alps is still debated (e.g., Schlunegger et al. 1998; Kuhlemann et al. 2001; Spiegel et al. 2001; Pfiffner et al. 2002; Schlunegger and Simpson 2002), it is obvious that in both the central Alps and the southern western Alps, the drainage divide shifted from the internal part to the external part of the Alps during collision.

## Conclusions

Using petrological and geochemical analyses of basalt pebbles from the Barrême basin, as well as new and published Raman spectroscopy of serpentine sand grains and pebbles from the Torino hills and the Barrême basin, we show how the drainage pattern and the position of the drainage divide changed during the Oligocene in the southern western Alps.

The geochemical analyses of the basalt pebbles from the mid-Oligocene Conglomérat de Saint Lions and Conglomérat de Montmaur in the pro-side foreland basin suggest that the basalt pebbles originated from a Chenaillet-type obducted ophiolite. However, the extent of surface exposure of obducted ophiolite in the internal Alps at that time is not known and a detailed study of ophiolite pebbles in the retro-side basin is needed to address this question.

The comparison of Raman spectroscopic analyses of serpentine grains and pebbles from the pro- and retro-side foreland basin indicates that the paleo-Durance drained the southern part of the Piedmont zone and the Briançonnais zone toward the west as early as 30–28 Ma. At this time the main drainage divide was located in the internal Piedmont zone. The paleo-Durance drainage system was temporarily disturbed by creation of topography along the Briançonnais frontal thrust during the Oligocene but was reestablished by the Early Miocene, corresponding to the present-day Durance drainage.

The evolution of the antigorite, lizardite-antigorite, and lizardite abundance in the retro-side foreland basin sediments from the Early Oligocene to the Early Miocene supports a westward migration of the main drainage divide for the paleo-Dora Riparia drainage system, north of the Durance drainage, to reach its present-day location near Chenaillet. The increase of pebbles with ophiolite affinity in the retro-side is a consequence of the back-folding of the eastern flank of the western Alps. The peeling off and back-folding of the Briançonnais zone and the tilting of the Schistes lustrés was supported by the Ivrea body mantle sliver, which acted as a vertical indenter during Early Oligocene continental collision. As a consequence, the Ivrea body had indirectly a strong control on the development of the western Alps topography and erosion. Since the Early Miocene the paleo-Durance and paleo-Dora Riparia drainage systems have been stable and, while the timing of the shift in the drainage dive in the southern western Alps seems to predate the drainage divide shift in the central Alps, they both show the same trend from an internal to a more external position.

### ACKNOWLEDGMENTS

This research was supported by an Agence Nationale de la Recherche ERD-ALPS (Erosion and Relief Development in the Western Alps) grant. We thank N. Arndt and C. Poggi, for their help with major and trace element analysis and interpretation. We gratefully acknowledge constructive reviews by F. Schlunegger and E. Garzanti and the support by Editor D. Rowley, which helped to improve and focus the manuscript.

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