Detrital zircon U-Pb ages and Hf isotopic constraints on the terrigenous sediments of the Western Alps and their paleogeographic implications

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Abstract Detrital zircons from Cretaceous micaschist, late Eocene-earliest Oligocene sandstone and early Oligocene siltstone of the Western Alps fall into three main separable age clusters at 610–540 Ma, 490–430 Ma, and 340–280 Ma that correspond to the Cadomian (Neoproterozoic), Ordovician, and Variscan (Carboniferous) events widespread in western and central Europe. Hf isotopic results indicate that these three magmatic and tectonic episodes did not give rise to significant production of juvenile crust. A distinguishable group of Triassic zircons, around 250–200 Ma which is considered to derive from the Southern Alps, has been detected in the early Oligocene "Schistes à Blocs" formation and the Briançonnais "Flysch Noir". In contrast, this age group is absent in late Eocene to earliest Oligocene sandstones. In agreement with sedimentological studies, our results show that the main source areas of the Eocene sandstone were probably located in the European continent. The arrival of detritus from the Internal Zone occurred in early Oligocene, coeval with the tectonic rotation from northwestward to westward in the propagation of allochthonous units. Based on previous studies and our new data, we argue that the Briançonnais Zone was likely a paleorelief since the middle Eocene that accounts for the lack of detritus from the Adriatic units. Contemporary sediments were accumulated in the foredeep of the Adriatic plate. From Oligocene time onward, the blockage was cut through after a regional uplifting, and thus, the Internal Zone started to provide detritus into the western flexural basins.

1. Introduction

As one of the most studied orogens in the world, the Alps are regarded as a classical example of continental collision, orogenic uplift, exhumation of deep crustal rocks, and foreland basin evolution. From Late Cretaceous, the Western Alps were built from the collision between the Adriatic promontory which was a part of Africa and the European continent [*Dewey et al.*, 1989; *Stampfli et al.*, 1998; *Schmid and Kissling*, 2000; *Lemoine et al.*, 2000; *Rosenbaum and Lister*, 2005; *Lardeaux et al.*, 2006; *Dumont et al.*, 2011; *Malusà et al.*, 2011]. During these deep-seated lithospheric processes, syntectonic sedimentary basins record surface processes such as uplift and erosion that are keys to building up palinspastic restoration of the orogenic system and understanding the general evolution of the orogenic belt [e.g. *DeCelles and Giles*, 1996; *Sinclair*, 1997b; *Wang et al.*, 2013; *Malusà et al.*, 2015]. Hence, formation and erosion of mountain belts are temporally and spatially linked with basin subsidence and sedimentation. Despite that early orogenic events are often erased by postorogenic erosion or overprinted by late to posttectonic events, sedimentary basins may preserve crucial evidence of mountain building process as well as evidence for the nature and composition of the eroded orogen at different times in its history.

The arc-shaped Alpine orogen developed due to the Apulian microplate indentation against Europe [*Schmid and Kissling*, 2000; *Lemoine et al.*, 2000; *Rosenbaum and Lister*, 2005; *Lardeaux et al.*, 2006; *Dumont et al.*, 2011; *Malusà et al.*, 2011]. The Paleogene peripheral basins of the Western Alps in SE France received synorogenic sediments from middle Eocene to Pliocene with a progressive younging toward the west/northwest [*Ford et al.*, 1999; *Ford and Lickorish*, 2004]. Studies on the sedimentary series can reveal the uplift and erosion of the internal part of the belt as well as the basin propagation toward the foreland [*Sinclair*, 1997b; *Ford et al.*, 1999; *Ford and Lickorish*, 2004; *Morag et al.*, 2008].

Provenance studies can shed light on the relationship between sediment composition and exhumation/erosion of orogenic belts, and they thus provide a significant knowledge to interpret ancient basin fills. Sedimentological methods, including sequence stratigraphy, paleocurrent direction, sandstone

petrology, and heavy minerals analyses applied in the Alps, reveal the source area of the material deposited in the sedimentary basins [*Ivaldi*, 1987; *Sinclair*, 1997a; *Ford et al.*, 1999; *Gupta and Allen*, 2000; *Vinnels et al.*, 2010; *Jourdan et al.*, 2013, and references therein]. Recently, more sophisticated tools for provenance study, such as zircon U-Pb dating and Hf isotopes analyses, have been widely used in association with sedimentological studies in different orogenic belts [e.g., *Wu et al.*, 2007; *Wang et al.*, 2012]. Laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) U-Pb dating of detrital zircons provides lower time limits for sedimentary rocks and allows a better understanding of their provenance, whereas Hf isotope ratios on dated zircons provide further information on the origin of these zircons. Variations in sediment type and source area from the relief to the basin can be used as an exhumation indicator either by tectonic or erosional processes [*Wu et al.*, 2007; *Malusà et al.*, 2015]. A combined study on zircon U-Pb age and Hf isotopes can thus add significant insights into the characterization of sediment sources in different domains and give further constrains on the tectonic evolution of the Western Alps. In this study, we carried out U-Pb dating and Hf isotopic analysis of detrital zircons from representative sandstone and (meta) siltstone samples from syntectonic basins developed in the central part of the French Western Alps. The aim of this study is first to understand the sediment sources of these basins, second to assess the nature and age of the crust involved in the pre-Alpine and Alpine orogens, and finally to discuss the role of uplift and exhumation in the evolution of the internal part of the Western Alps.

2. Geological Setting

2.1. Tectonic Units of the Western Alps

The Alps registered the complex geodynamic evolution along the Eurasia-Africa boundary initially dominated by Triassic-Jurassic rifting, then Late Cretaceous-Paleogene subduction and collision [e.g., *Schmid and Kissling*, 2000; *Lemoine et al.*, 2000; *Rosenbaum and Lister*, 2005; *Malusà et al.*, 2015; *Zhao et al.*, 2015]. The Western Alps extend from west Switzerland to the north to the Mediterranean Sea to the south, on both sides of the Italian-French border in an arcuate shape. The strike of this belt progressively changes from NE-SW in the north, to N-S in the middle, and to E-W in the south (Figure 1). According to previous works, the western part of the orogen can be divided into several tectonic units separated by important regional faults, including from east to west, the Southern Alps (including units derived from the Adriatic paleomargin), the Periadriatic (or Insubric) fault, the Internal (or Penninic) Zones, the Penninic Frontal Thrust, and the External (or Dauphinois) Zones (Figure 1) [*Dal Piaz et al.*, 2001; *Rosenbaum and Lister*, 2005]. The belt is bounded by the perialpine Helvetic and Dauphiné molasse foreland basins to the NW and to the west and the Po plain hinterland basin to the east, respectively.

The Southern Alps consist of Variscan amphibolite and granulite facies metamorphic rocks of the Ivrea Zone overlain by Mesozoic sedimentary sequence. The Ivrea Zone represents the lower continental crust and a small part of the upper mantle of the Adriatic plate [*Schmid and Kissling*, 2000; *Schmid et al.*, 2004], separated from the Internal Zone by the Periadriatic fault, which was reworked as a lithosphere-scale dextral strike-slip fault during the Oligocene to Miocene [*Schmid et al.*, 1989; *Muller et al.*, 2001; *Stipp et al.*, 2002; *Bartel et al.*, 2014].

In the Internal Zone, the basement rocks of the Sesia unit and the Dent Blanche nappes show close affinities with those of the Ivrea Zone and are thus interpreted as klippen originated from Adria or as a microcontinental block derived from the Adriatic plate. The Sesia unit and the Dent Blanche nappes were incorporated into the Alpine stack of nappes during the Late Cretaceous, experiencing a Late Cretaceous (circa 65 Ma) high-pressure (HP) metamorphism [*Gebauer*, 1999; *Rubatto et al.*, 1999].

In contrast, the Internal Crystalline Massifs, including Dora Maira, Gran Paradiso, and Monte Rosa, consist of Paleozoic rocks, mainly Carboniferous and Permian granitoids and sedimentary rocks that were subjected to a high pressure (HP) to ultrahigh pressure metamorphism, ascribed to the Paleogene continental subduction [*Chopin*, 1984; *Gebauer*, 1999; *Rubatto et al.*, 1999], which occurred 25–30 Ma later than that of the Sesia unit. The Internal Crystalline Massifs are tectonically overlain by the Piemonte Zone with dismembered ophiolitic rocks. Serpentinized ultramafics, mafic plutonic and volcanic rocks, and Middle Jurassic pelagic sedimentary rocks (radiolarian cherts, limestones, and breccias) represent the remnants of the Piemonte-Ligurian Ocean [*Lemoine et al.*, 1984; *Li et al.*, 2013]. The Schistes Lustrés consists of intensely foliated, folded, and metamorphosed calc-schists and mica schist of Cretaceous age [*De Wever and Caby*, 1981; *Lemoine et al.*,
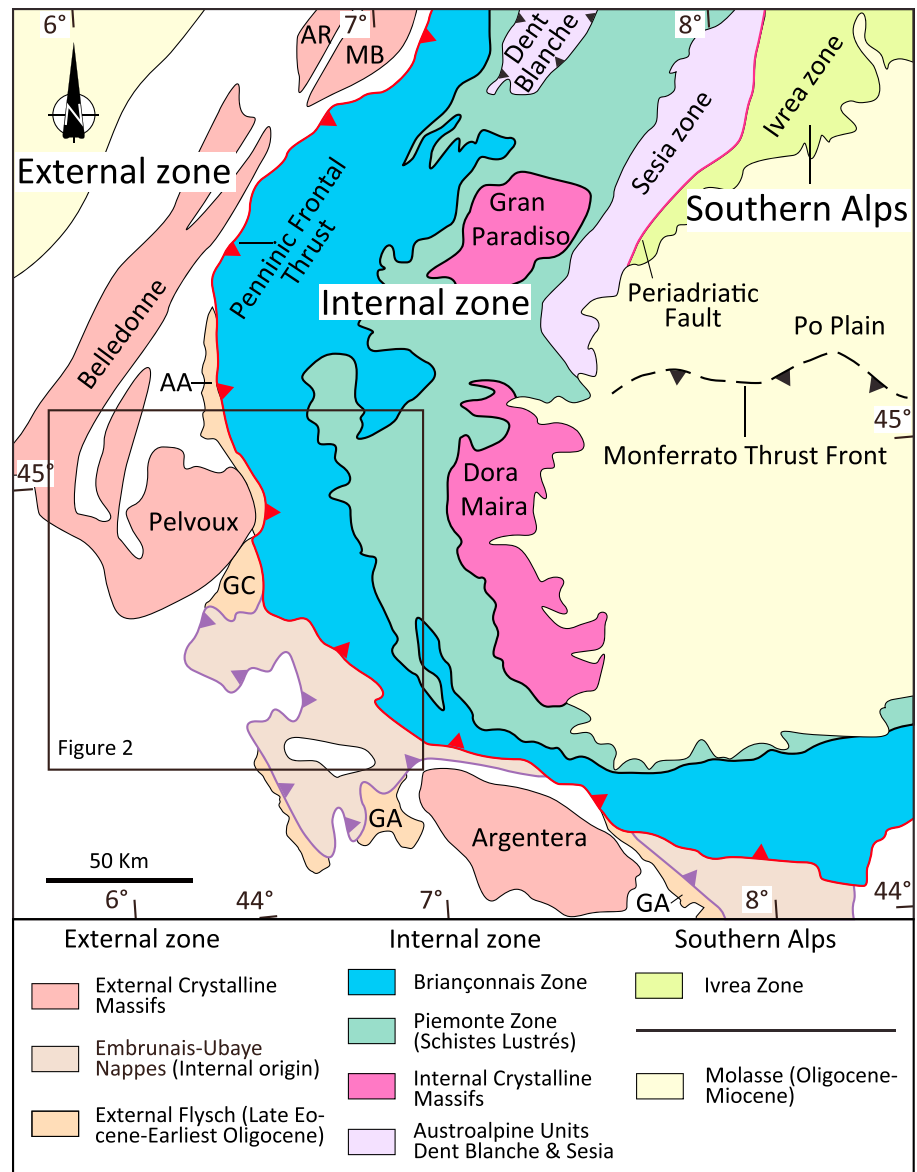
Figure 1. Tectonic sketch of the Western Alps [*Schmid et al.*, 2004]. AA: Aiguilles d'Arves Flysch. AR: Aiguilles Rouges. GC: Grès du Champsaur, GA: Grès d'Annot, and MB: Mont Blanc.

1984; *Agard et al.*, 2002]. Most of these rocks experienced a prograde HP-LT metamorphism at 60–55 Ma and two stages of exhumation during continental collision [e.g., *Reinecke*, 1991; *Rubatto et al.*, 1998; *Rubatto and Hermann*, 2003; *Agard et al.*, 2002, 2009; *Michard et al.*, 2004]. The Schistes Lustrés represents the deep part of an accretionary prism subjected to HP metamorphism during the subduction of the Piemonte-Ligurian Ocean beneath the Adriatic plate between Paleocene and Eocene (circa 60 to 40 Ma).

More to the west, the Briançonnais Zone consists of sedimentary series with a thick Triassic limestone and dolomite series, a condensed Jurassic-Cretaceous nodular limestone-marly mudstone succession, and a middle to late Eocene turbiditic formation called the Briançonnais Flysch Noir. Pre-Permian rocks are not exposed in the southern Briançonnais Zone, but Carboniferous sandstone, volcanic and granitic rocks, variously deformed and metamorphosed during the Alpine orogeny, crop out in the northern part, from Vanoise massif to the Briançon area [*Schmid and Kissiling*, 2000; *Michard et al.*, 2004].

The External Zone of the Western Alps comprises (i) the External Crystalline Massifs, namely, from north to south: Aar-Gotthard, Mount Blanc-Aiguilles Rouges, Belledonne-Pelvoux, and Argentera massifs, (ii) the
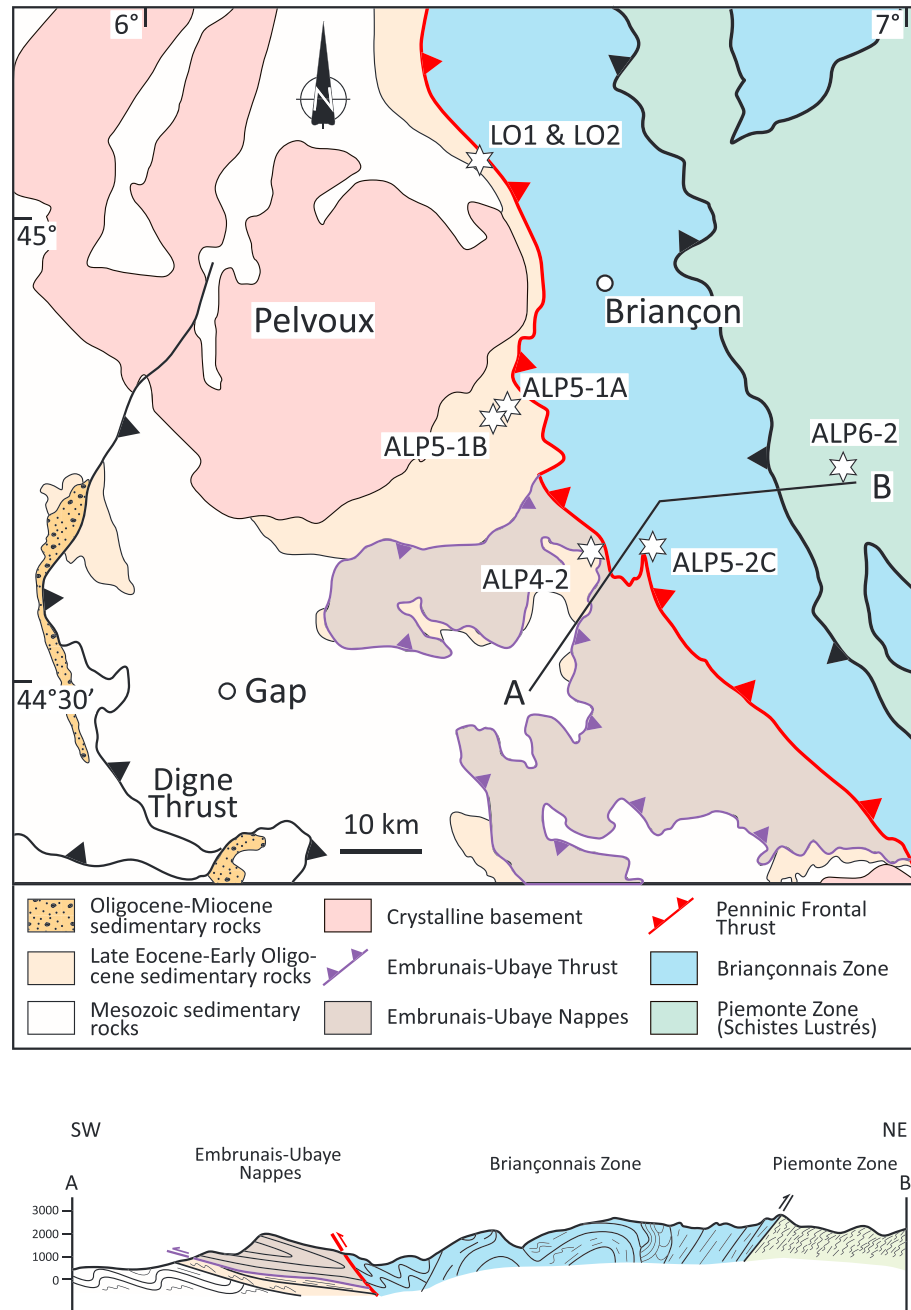
Figure 2. Geological map of the Alpine belt in the Gap-Briançon area (SE France) focusing on the Paleogene flexural basins (modified after *Ford et al.* [1999] and *Schwartz et al.* [2012]). The cross section show the general architecture of the study area (modified after *Lardeaux et al.* [2006]). For clarity, the detail of internal tectonic contacts is not shown in the map.

subalpine chains formed by a thick, carbonate dominated, Mesozoic sedimentary series, and (iii) a Paleogene syntectonic turbiditic formation progressively younging westward in front of the orogenic wedge [*Ford et al.*, 1999; *Ford and Lickorish*, 2004; *Schmid et al.*, 2004; *de Graciansky et al.*, 2011]. Between the Pelvoux and Argentera crystalline massifs and west of the Penninic Frontal Thrust, the Embrunais-Ubaye nappes form a stack of allochthonous thrust sheets of the Internal units with the Cretaceous Helminthoid flysch overlying Briançonnais and sub-Briançonnais units (Figure 2). The Helminthoid flysch that consists mainly of calcareous turbidites and siliciclastics may be considered as the nonmetamorphic lateral equivalent of the Schistes Lustrés [*Kerckhove*, 1969].

Polyphase deformation during the Alpine orogeny has been documented and interpreted as the consequence of different stages of the tectonic evolution [*Dumont et al.*, 2011, 2012]. The general tectonic style of the External Zone in the Western Alps corresponds to a fold-and-thrust belt, where geophysical results show a well-imaged décollement layer between the lower and upper crust [*Schmid et al.*, 1996]. However, in the External Crystalline Massifs, Variscan granites and metamorphic rocks experienced locally an early Oligocene ductile shearing coeval with a greenschist facies metamorphism [*Leloup et al.*, 2005; *Simon-Labric et al.*, 2009; *Bellahsen et al.*, 2012]. In the Internal Zone, the original structure was modified by top-to-the-E back thrusting, and thereby exhibits a complex double-verging shape [*Schmid and Kissling*, 2000].

2.2. Paleogene Sequences in the Western Alps

In response to the continental collision between the Adriatic and European plates, the Alpine foreland basins developed successively from SE to NW, toward the External Zone, coeval with the migration of the orogenic front. Extending from Switzerland to Austria, the North Alpine Foreland Basin comprises late Eocene-earliest Oligocene flysch deposited above the Mesozoic cover of the European passive margin [*Lihou*, 1996; *Sinclair*, 1997a]. This basin is followed by the Oligocene to early Miocene molasse basin that lacks significant deformation except within the thrust sheets [*Ford and Lickorish*, 2004]. The flexural foreland basin nearly disappears in the south subalpine chains where Miocene terrigenous sediments are relatively thin, locally preserved only in the Bas Dauphiné and Digne-Valensole basins [*de Graciansky et al.*, 1971; *Ford et al.*, 1999].

In the Briançonnais Zone of the Western Alps, middle-late Eocene sedimentary series, so-called "Flysch Noir," contains carbonates, pelites, and conglomerates [*Michard and Martinotti*, 2002]. Olistoliths originated from the Helminthoid Flysch are found in the lower part of this series. In the External Zone, the Paleogene-Neogene sedimentary basins can be divided into two sequences, namely, (i) middle to late Eocene/early Oligocene deep marine sediments (including turbiditic flysch) and (ii) middle Oligocene to late Miocene shallow marine, fluviatile, and continental sediments (molasse) [*Sinclair*, 1997a; *Joseph and Lomas*, 2004]. The first stage of sedimentation leads to the deposition of the late Eocene to earliest Oligocene Nummulitic series that is classically subdivided into three parts, from bottom to top: (1) the Nummulitic limestone, (2) the Globigerine marl, and (3) the turbiditic sequence [*Waibel*, 1990; *Ford et al.*, 1999; *Ford and Lickorish*, 2004]. Regionally, the turbiditic sequence received different names such as Annot sandstone (Grès d'Annot) in the south (north of Nice), Champsaur sandstone (Grès du Champsaur) along the southern border of the Pelvoux massif, Aiguilles d'Arves flysch (Flysch des Aiguilles d'Arves) to the east of the Belledone massif, and Taveyanne sandstone (Grès de Taveyanne) farther north in Savoie (Figure 1).

Underlying the Embrunais-Ubaye nappes (Figure 2), an early Oligocene Schistes à Blocs Formation is interpreted as olistostrome capping the Nummulitic series. This formation also records the termination of the basin of Nummulitic series by advancing Alpine thrusting [*Merle and Brun*, 1984; *Joseph and Lomas*, 2004].

3. Analytical Methods

3.1. U-Pb Dating

Zircons were obtained from samples using standard heavy liquid and magnetic separation techniques. Handpicked zircon grains were mounted in epoxy resin and then polished to reveal the cores for analysis. Those grains were randomly selected in difference sizes to avoid the age bias on those size-dependent grains. All zircons were photographed in transmitted and reflected light by a petrographic microscope, and cathodoluminescence images were obtained by a CAMECA electron microscope in order to reveal their internal structures. According to these images, zircon grains on difference sizes and features were selected for dating.

Laser ablation ICP-MS zircon U-Pb analyses were conducted on an Agilent 7500a ICP-MS equipped with a 193 nm laser, housed at the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing. U-Th-Pb ratios and absolute abundances were determined relative to the standard zircon (91500 and GJ-1). Analytical procedures were the same as those described by *Xie et al.* [2008]. The frequency of laser system was 10 Hz. Gas flow rate of highly purified He as the carrier gas was 0.7 L/mn; auxiliary gas Ar was 1.13 L/mn. The spot diameter was 44 μm in size. Total acquisition time of one spot was 45 s. Correction of common lead followed the method described by *Andersen* [2002]. Data were processed with the GLITTER

program [*van Achterbergh et al.*, 2001]. Uncertainties on individual analyses in data tables were reported at a 1σ level. Data plot was carried out using the Density Plotter program [*Vermeesch*, 2012]. Zircon ages younger than 1000 Ma were based on $^{206}Pb/^{238}U$ ratios, and ages older than 1000 Ma were based on $^{207}Pb/^{206}Pb$ ratios. In this study, we excluded zircon age analyses with >10% discordance.

3.2. Zircon Lu-Hf Isotopes

Zircon Lu-Hf isotopic analysis was carried out in situ on a Neptune multicollector ICP-MS equipped with a Geolas-193 laser ablation system at the Institute of Geology and Geophysics, Chinese Academy of Sciences. Previously analyzed zircon grains for U-Pb isotopes were chosen for Lu-Hf isotopic analyses based on detailed analytical procedures in *Wu et al.* [2006]. The beam diameter was 60 μm, with a laser repetition rate of 10 Hz at 100 mJ. During the analytical period, the weighted mean $^{176}Hf/^{177}Hf$ ratios of the zircon standards GJ-1 (0.281999 ± 6, 2σ, $n = 34$) and MUD (0.282503 ± 7, 2σ, $n = 34$) are in good agreement with reported values [*Woodhead and Hergt*, 2005; *Morel et al.*, 2008].

4. Results

4.1. Zircon U-Pb Dating

Representative rocks from the Paleogene flysch basins, the Schistes Lustrés unit, and the Oligocene "Schistes à Blocs" Formation are collected for detrital zircon U-Pb analysis (Figure 3 and Table 1). ALP6-2 is sampled from the Cretaceous Schistes Lustrés unit (Figure 3a), ALP5-2C is collected in the Guil Valley from the middle Eocene Briançonnais Flysch Noir (Figure 3b), LO1 and LO2 are collected from the Aiguilles d'Arves flysch to the north of the Pelvoux crystalline massif, ALP5-1A and ALP5-1B are from the Champsaur sandstone (Figures 3c and 3d), and ALP4-2 is collected from the terrigenous matrix of the Schistes à Blocs Formation (Figure 3e). LA-ICP-MS U-Pb ages on zircon grains from seven samples are summarized in Table S1 in the supporting information, along with detailed location and feature (magmatic or metamorphic) of each analyzed spot.

ALP6-2 exhibits a relatively narrow age spectrum mostly ranging between 200 Ma and 600 Ma (Figures 4a and 5g). This dominant age group has continuous age distribution with one major age peak around 330 Ma. Furthermore, ages around 220 Ma, absent in other samples, is obtained in this sample.

ALP5-2C has a dominant age group between 270 and 330 Ma, and the spectrum shows a continuous distribution pattern from 240 to 680 Ma (Figures 4b and 5f). Within 59 analyzed spots, three zircons with age >1000 Ma have been found, whereas some young ages (<200 Ma) are also dated.

The detrital zircon U-Pb ages of sample LO1 show dominantly Phanerozoic age clusters, with two major peaks at ~320 Ma and ~480 Ma (Figures 4c and 5b). Some Precambrian zircons including two grains at ~2600 Ma have also been detected in this sample. Detrital zircon U-Pb ages of sample LO2 cluster around 300 Ma and 450 Ma, and the age spectrum exhibits continuous distribution from 280 Ma to 650 Ma. In contrast, older zircons with ages >1000 Ma are not found in LO2 (Figures 4d and 5c). The youngest zircon ages are 269 Ma and 289 Ma for LO1 and LO2, respectively.

The age spectra of ALP5-1A and ALP5-1B show similar clusters at 280–330 Ma and 420–500 Ma, whereas ALP5-1A has a major age cluster at 550–620 Ma (Figures 4e, 4f, 5d, and 5e). Precambrian detrital zircons are rare in both samples. It is also noteworthy that samples ALP5-1A and ALP5-1B do not include Paleogene zircons.

Zircon ages of ALP4-2 range from 136 Ma to 935 Ma with a continuous group from 220 Ma to 640 Ma (Figures 4g and 5a). Age clusters at 240–330 Ma, 440–480 Ma, and 560–580 Ma are dominant in the spectrum, whereas Triassic grains are also found. Two zircon grains show Precambrian ages at ~2000 Ma and one at ~2500 Ma, respectively.

4.2. Zircon Hf-Isotope Analyses

Lu-Hf isotope analyses were performed on spots in the same zircon internal domains that were analyzed for U-Pb isotopic composition. The concordia age obtained from the same sample was used for calculating the initial Hf isotopic ratios and crustal model ages. Diagrams of $\varepsilon_{Hf}(t)$ values are shown in Figure 6, and data are summarized in Table S2.
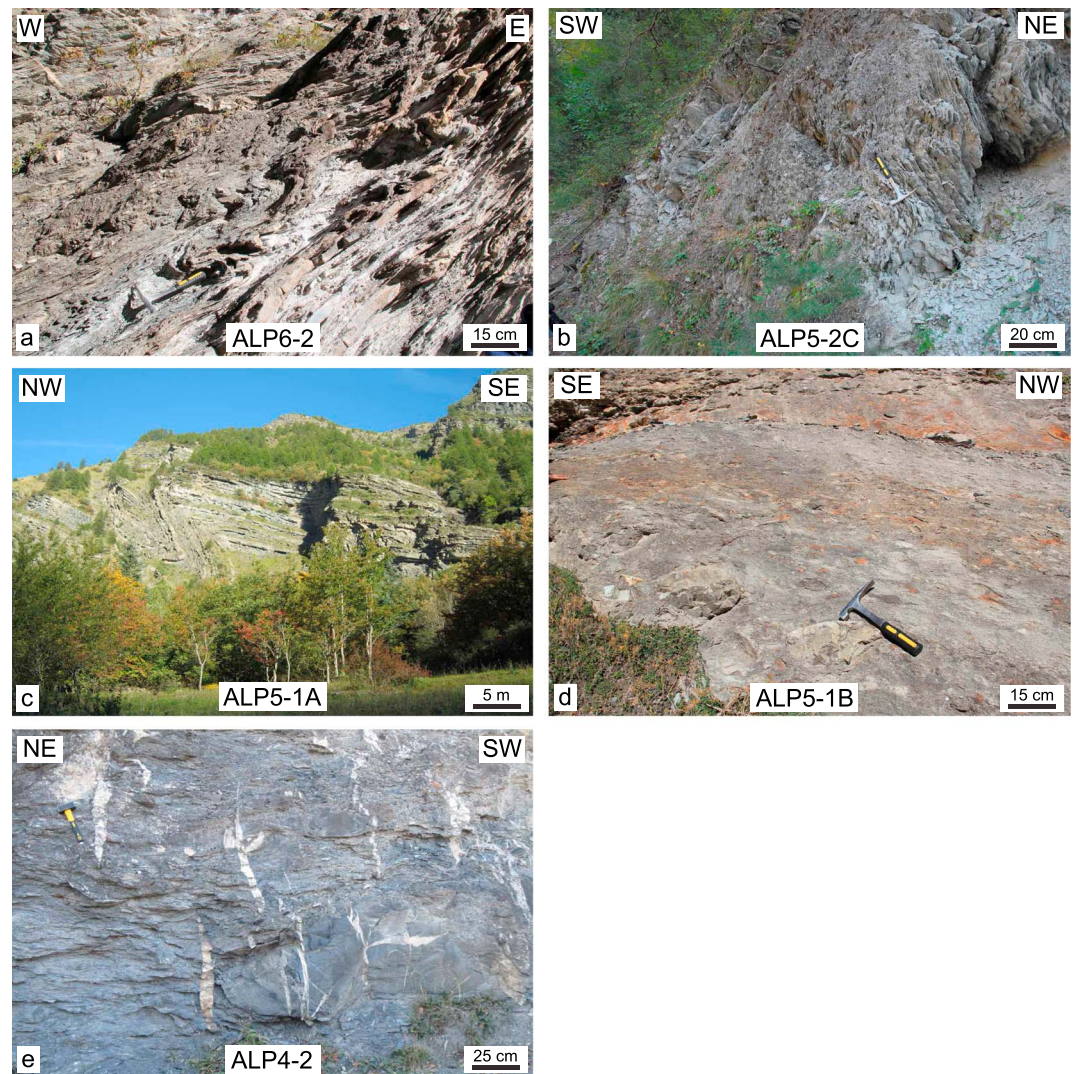
Figure 3. Representative field photos of outcrops. (a) ALP6-2 from the Schistes Lustrés. This calcschist is metamorphosed under HP/LT conditions and deformed by tight folds. (b) ALP5-2C from middle Eocene sandstone/siltstone of the Briançonnais turbidite (Flysch noir). (c) ALP5-1A from late Eocene sandstone in the Southern sub-alpine Grès du Champsaur basin. (d) ALP5-1B from late Eocene basal conglomerate below the late Eocene Flysch sequence in the Southern Sub-alpine Grès du Champsaur basin. (e) ALP4-2 from the Early Oligocene Schistes à blocs showing sheared olistoliths.

The Hf isotopic composition for detrital zircons clustering between 200 and 650 Ma show a consistent range of $\varepsilon_{Hf}(t)$ values from −10 to +10. Despite some abnormal values with $\varepsilon_{Hf}(t)$ higher than the depleted mantle line, only several points can reach the depleted mantle line, and points with $\varepsilon_{Hf}(t)$ value < −20 are also rare (Figure 6). The calculated T_{DM2} ages of most of the Phanerozoic zircons range from 1.0 Ga to 2.0 Ga, but some older ages >2.5 Ga also exist in the analyzed samples (Figures 7).

Table 1. List of Collected Samples

Sample No.	Lithology	Formation	Location	GPS	Deposition Age
Alp 4-2	Arenite matrix	Schistes à blocs	SW of Guillestre	N44°37.149′; E06°32.908′	Early Oligocene
Alp 5-1A	Arenite	Grès du Champsaur	Fournel valley	N44°47.616′; E06°28.851′	Late Eocene to Earliest Oligocene
Alp 5-1B	Conglomerate	Base of Grès du Champsaur	Fournel valley	N44°47.247′; E06°27.602′	Late Eocene-Earliest Oligocene
LO1	Sandstone	Flysch des Aguilles d'Arves	NE of Briançon	N45°02.598′; E06°24.884′	Late Eocene-Earliest Oligocene
LO2	Sandstone	Flysch des Aguilles d'Arves	NE of Briançon	N45°02.598′; E06°24.884′	Late Eocene-Earliest Oligocene
Alp 5-2C	Siltstone	Flysch Noir of Briançonnais Zone	Guil valley	N44°40.402′; E06°41.185′	Middle Eocene
Alp 6-2	Mica schist	Schistes Lustrés nappe	Queyras	N44°47.268′; E06°52.993′	Late Cretaceous
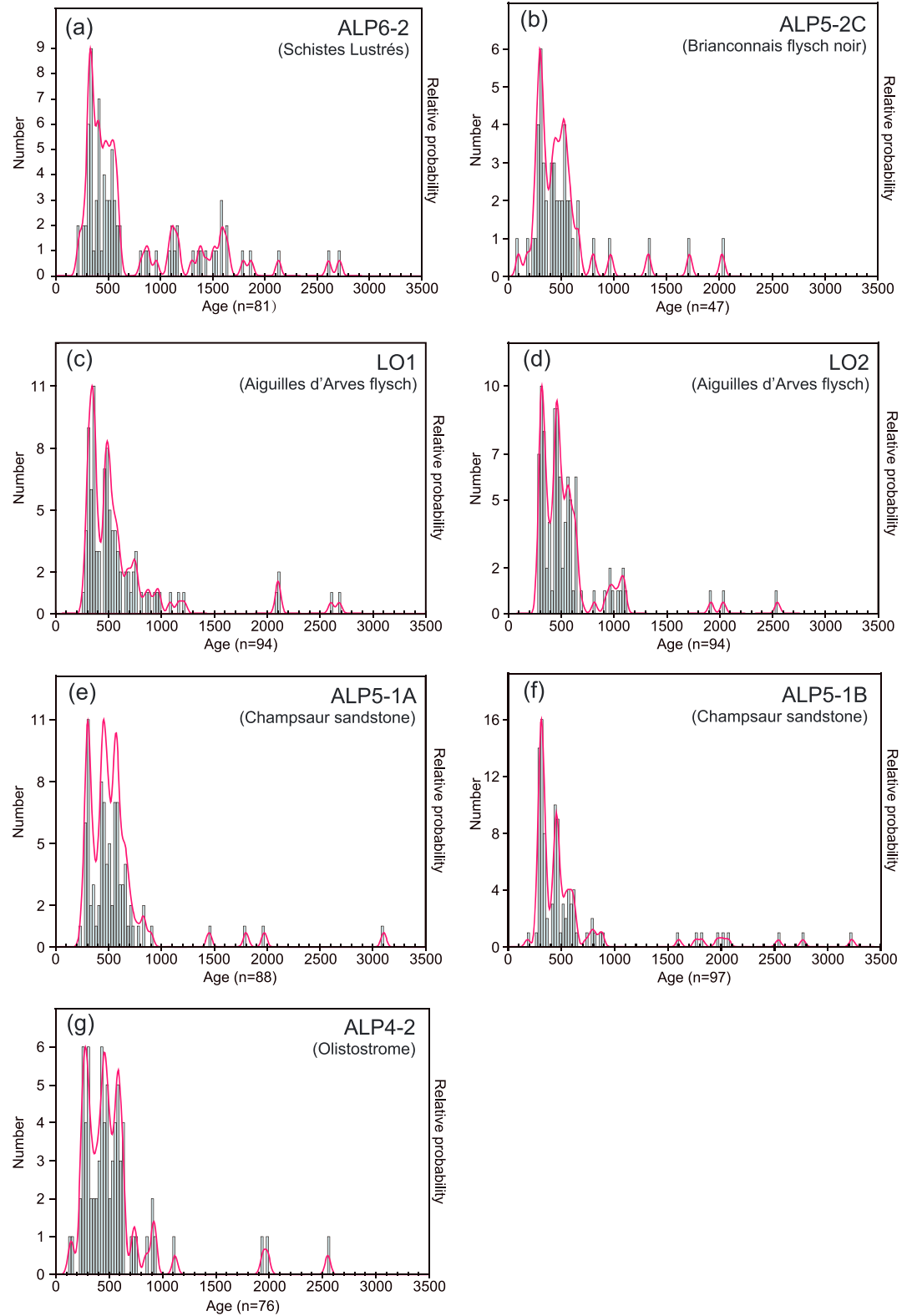
Figure 4. Probability diagrams of U-Pb ages of the detrital zircons from the Western Alps (bin width is 50). (a) ALP6-2. (b) ALP5-2C. (c) LO1. (d) LO2. (e) ALP5-1A. (f) ALP5-1B. (g) ALP4-2.
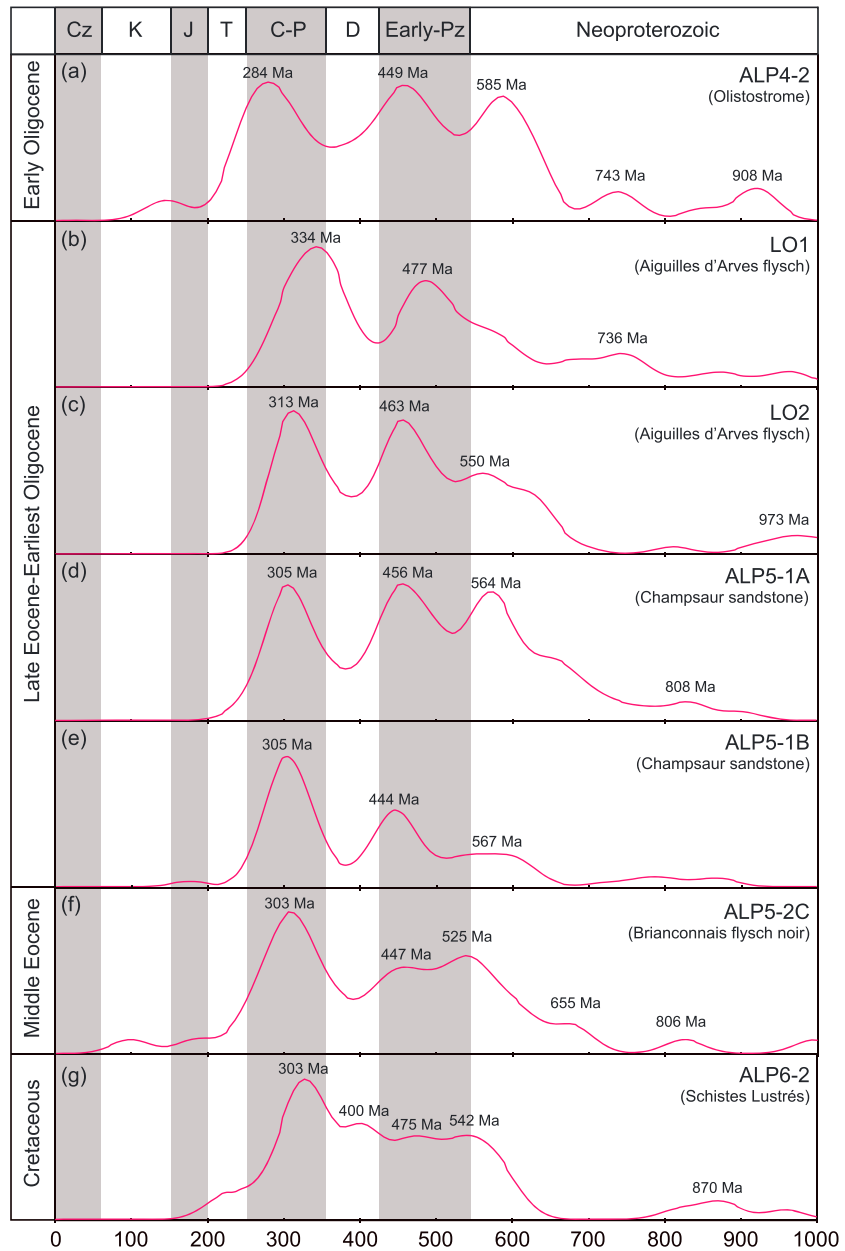
Figure 5. A detailed view on probability diagrams of U-Pb ages between 0 and 1000 Ma. Early Paleozoic, Carboniferous-Permian, and Late Neoproterozoic peaks are the main signatures of these rocks. Triassic zircons are only found in Oligocene, middle Eocene, and Cretaceous samples. Zircons with Alpine orogen ages (<100 Ma) are absent in all samples.

5. Discussion

5.1. Sources of Detrital Zircons of the Western Alps

Before discussing the provenance of the sediments of the basins, we first characterize the possible sources of these detrital zircons in the Western Alps in order to limit the options. Since the Middle Jurassic, the opening of the Piemonte-Ligurian Ocean separated the Adriatic and the European continental plates [*Lemoine et al.*, 2000; *Rosenbaum and Lister*, 2005]. However, despite their insulation by different branches of the Alpine Tethys Ocean, these continents or microcontinents were all derived from the Gondwana part of the Pangea supercontinent, which was built up after the completion of the Late Paleozoic Variscan orogeny. Thus, western Europe, Adria, and the possible intervening microcontinents exhibit a similar crustal composition and pre-Alpine tectonic inheritance [*Dal Piaz et al.*, 2001; *von Raumer et al.*, 2003].
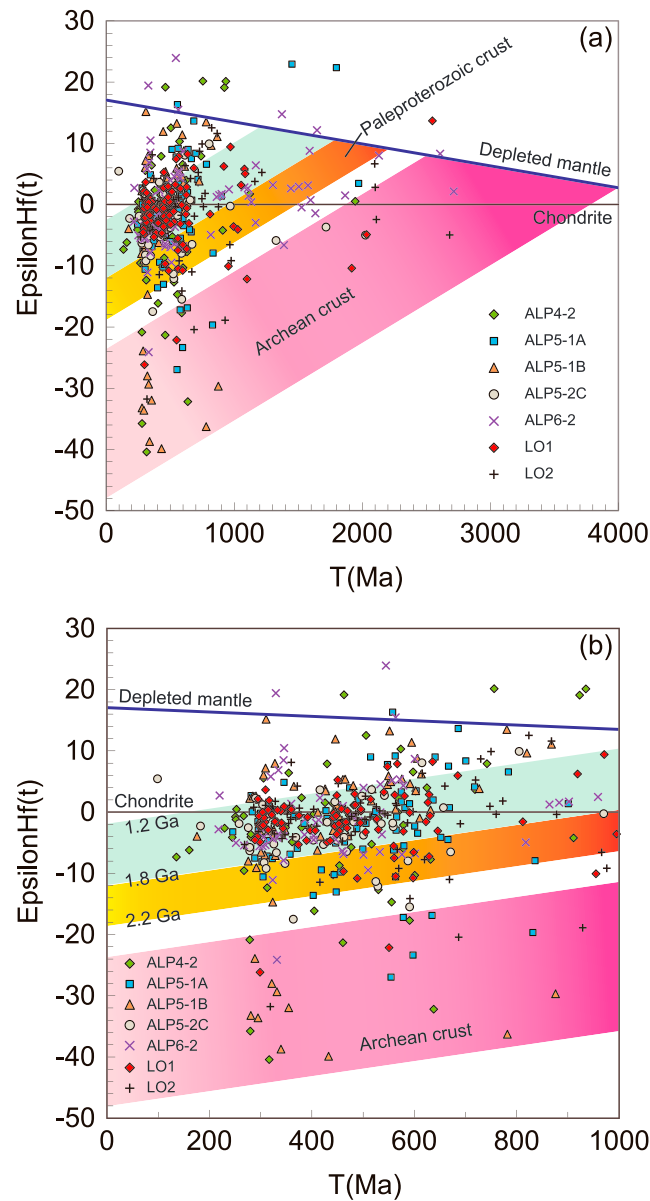
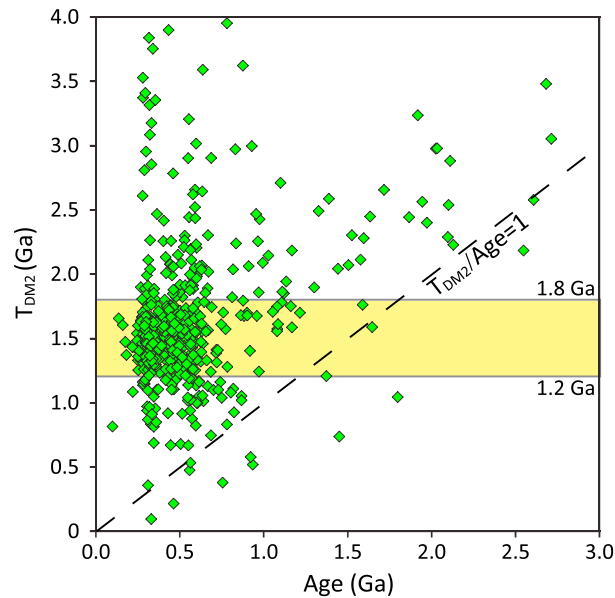**Figure 6.** (a) Temporal variations of εHf(t) values of the studied detrital zircons at 0–4000 Ma. The crustal evolution ranges comes from *Linnemann et al.* [2014]. Most zircons are plotted in the crustal evolution zone between 1.2 Ga and 1.8 Ga, but some Archean data are present in consistence with the range of the Archean crust. For younger zircons, (b) diagram of εHf(t) value versus age with zircons at 0–1000 Ma. In this detailed view on the three age groups at 280–340, 430–490, and 540–610 Ma, the middle one has less mantle component and old crust contribution than the other two groups.

To the west of the Piemonte-Ligurian Ocean, pre-Alpine magmatic and metamorphic rocks are widespread in the European continent. The French Massif Central, the Maures massif, the Corsica and Sardinia islands, the External and Internal Crystalline Massifs, and the basement of the Briançonnais Zone are the main exposures adjacent to or within the Western Alps. As two of the largest areas where Variscan metamorphic and plutonic rocks are exposed, the French Massif Central and Massif Armoricain experienced a long-term evolution from Cambrian to Permian [*Matte*, 2001; *Faure et al.*, 2005, 2008, 2010; *Ballèvre et al.*, 2009]. Geochronological studies corroborate the presence of Neoproterozoic, Early Paleozoic, and Late Paleozoic magmatic and meta-morphic events. Two age peaks at 580–520 Ma and 490–450 Ma recorded by magmatic zircons [*Cocherie et al.*, 2005; *Melleton et al.*, 2010] are relevant to the geodynamic processes that occurred along the northern peri-Gondwana regions, namely, a series of Late Neoproterozoic-Early Cambrian tectonothermal events that formed the Cadomian belt [*von Raumer et al.*, 2003; *Linnemann et al.*, 2007, 2008], and the Late Cambrian-Ordovician magmatism developed during the drifting from Gondwana of microcontinental stripes [*Matte*, 2001; *von Raumer et al.*, 2003]. During the Variscan orogeny, a complex history with several metamorphic and magmatic events between 380 and 290 Ma has been recognized, and a large volume of postorogenic granitic intrusions was emplaced [*Pin and Peucat*, 1986; *Faure et al.*, 2005, 2008, 2009]. Furthermore, in the Neogene volcanic rocks of the Eastern Massif Central, high-temperature (HT) para-gneiss enclaves yield that Triassic to Jurassic zircon ages are related to the Mesozoic thermal overprint during the pre-Alpine rifting [*Rossi et al.*, 2006; *Melleton et al.*, 2010].

A wealth of zircon ages indicative of the Variscan tectonic-magmatic-metamorphic events has been identified in the External Crystalline Massifs [*Debon and Lemmet*, 1999; *Schaltegger et al.*, 2003; *Guillot et al.*, 2009; *von Raumer et al.*, 2009; *Rubatto et al.*, 2010]. Though most magmatic rocks yield a major age group between 330 and 290 Ma, metamorphic rocks reveal Ordovician and Neoproterozoic fingerprints

Figure 7. The two stage model Hf age T_{DM2} versus age plot for detrital zircons, showing the source of zircons. Most of the zircon Hf model ages are older than their crystallization ages, indicating a formation from remelting of older crustal rocks crystallized during previous events.

recorded in the Variscan basement [*Schaltegger*, 1993; *Bussy and von Raumer*, 1993; *Schaltegger and Gebauer*, 1999; *von Raumer et al.*, 1999, and references therein].

In Corsica and Sardinia, large amounts of granitic magmas were emplaced during Carboniferous and Permian times with four episodes at ~350 Ma, 345–335 Ma, 305–290 Ma, and ~280 Ma, respectively [*Cocherie et al.*, 2005; *Paquette et al.*, 2003; *Rossi et al.*, 2006, 2009; *Li et al.*, 2014]. In agreement with the geochronology of the other Variscan areas, metasedimentary rocks dated in Sardinia have two main age clusters in 480–450 Ma and 650–550 Ma [*Giacomini et al.*, 2006]. In addition, zircon dating of high-grade metamorphic rocks reveals detrital zircon ages at 240 Ma, but the corresponding magmatic or metamorphic events are missing [*Rossi et al.*, 2006].

On the southern side of the Alpine Tethys, the Southern Alps have the same constituents of basement rocks that comprise Variscan magmatic-metamorphic suites [*Vavra et al.*, 1996, 1999; *Schaltegger and Brack*, 2007; *Marocchi et al.*, 2008; *Sinigoi et al.*, 2011], Cambrian-Ordovician sediments [*Gansser and Pantic*, 1988], and Ordovician granitoids [*Boriani et al.*, 1995]. However, a difference between the northern and southern margins of the Piemonte-Ligurian Ocean is the Triassic magmatism developed in the central and eastern Alps, where Triassic volcanic and volcaniclastic formations are identified [*Furrer et al.*, 2008], whereas contemporaneous plutonism is almost absent in the northern Alpine margin, except rare Late Triassic intracontinental basaltic lavas in the External Zone [*Dumont*, 1998]. To the east of the Insubric line, *Zanetti et al.* [2013] dated a gabbroic intrusion of the Finero Mafic Complex of the Ivrea-Verbano Zone at 232 Ma by using zircon U-Pb methods. Stratigraphic studies of the volcano-sedimentary sequences, combined with geochemical and geochronological data, indicate that the Triassic magmatism of the Adriatic domain occurred between 240 Ma and 230 Ma [*Mundil et al.*, 1996; *Cassinis et al.*, 2008]. Single zircon ages from 220 Ma to 200 Ma have also been detected and are attributed to high-temperature hydrothermal fluid circulation [*Vavra et al.*, 1996, 1999; *Maino et al.*, 2012; *Zanetti et al.*, 2013].

To summarize, the External Crystalline Massifs of the Western Alps yield similar magmatic age patterns than that documented in the Variscan massifs outside of the Alpine orogen, such as the French Massif Central, Maures Massif, Corsica, and Sardinia. On the eastern margin of the Alpine Tethys, the Adriatic paleomargin shows pre-Mesozoic age clusters comparable to the western margin, but Triassic ages related to continental rifting of the Piemonte-Ligurian Ocean can be regarded as the most notable feature to distinguish the European and Adriatic provenance of the detritus that filled up the sedimentary basins.

5.2. Provenance Analysis

According to our new data, three major age peaks are identified from these sediments at 610–540 Ma, 490–430 Ma, and 340–280 Ma (Figure 8), which are related to Cadomian (Neoproterozoic), Early Paleozoic (Ordovician-Silurian), and Late Variscan (Carboniferous-Permian) events, respectively. Nonetheless, the discussion in section 5.1 suggests that a composite pre-Alpine history of magmatic and metamorphic events has been recorded in both the European and the Adriatic plates. It is thus necessary to analyze our data in detail to unravel the possible provenance for these samples.
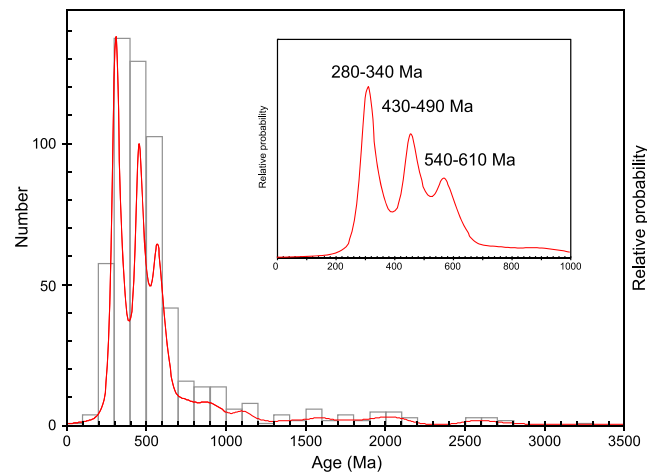
Figure 8. Probability density diagram of zircons from all samples. The insert is a detailed view of zircons between 0 and 1000 Ma.

The sample ALP6-2 (Schistes Lustrés) is characterized by distinct Precambrian age clusters at 800–1200 Ma and 1350–1650 Ma (Figure 4a), whereas Precambrian rocks in the European plate and Adriatic plate with ages >800 Ma are not exposed. Such old ages are probably obtained from multiple recycled grains captured in younger igneous or sedimentary rocks [*Schaltegger*, 1993; *Böhm*, 1996; *Poller*, 1997; *Schaltegger and Gebauer*, 1999; *Bertrand et al.*, 2000; *Guillot et al.*, 2002]. In comparison to zircon U-Pb data from the Gondwana, the detritus with 800–1650 Ma zircons were provided by Proterozoic formations which received abundant Precambrian zircons from the West African Craton, the Amazonian or sub-Saharan cratons [*Schaltegger*, 1993; *Böhm*, 1996; *Avigad et al.*, 2003; *Linnemann et al.*, 2014; *Lin et al.*, 2016]. Since the discrimination of Precambrian age data remains unclear, these zircons could be derived from either the European plate or the Adriatic plate in the Cretaceous. As above mentioned, the Triassic magmatism can be regarded as the most distinctive signature of the Southern Alps. The Triassic ages of this sample are therefore linked to the hydrothermal event that occurred during the Late Triassic rifting [*Vavra et al.*, 1996, 1999; *Bertotti*, 2001; *Zanetti et al.*, 2013]. This feature is more likely indicative of a paleogeographic position along the southern Tethys margin.

For late Eocene to earliest Oligocene flysch in the External Zone, samples ALP5-1A and ALP5-1B from the Champsaur sandstone both show comparable Phanerozoic zircon U-Pb age pattern (Figures 5d and 5e). However, the Neoproterozoic-Early Paleozoic age peaks are missing in the ALP5-1B sample. This can be interpreted as the result of provenance change or input from other sources that occurred in between the deposition of different sandstone layers. The lack of Mesozoic zircons in the Champsaur sandstone excludes a significant influx of materials from the Southern Alps during its deposition. Despite locally developed deformation, paleocurrent analysis of the Champsaur sandstone indicates that the detritus were mainly derived from the southeast and the west when they were deposited in front of the Alpine Orogen [*Gupta and Allen*, 2000; *Vinnels et al.*, 2010]. In addition, the typology of zircon grains also suggests a provenance from Corsica-Sardinia [*Jean et al.*, 1985]. This result is consistent with the studies on the southern basins filled by the Annot Sandstone, arguing for interconnected basins developed around the perimeter of the SW Alps during the late Eocene-Oligocene time [*Ford et al.*, 1999, 2006; *Joseph and Lomas*, 2004].

The Aiguilles d'Arves flysch is the northern lateral equivalent of the Annot sandstone and the Champsaur sandstone. Compared with samples of the Champsaur sandstone, LO1 and LO2 include similar age groups at 300–320 Ma, 450–480 Ma, which correspond to the Variscan and Ordovician rifting events. It is also note-worthy that Mesozoic zircons are absent in LO1 and LO2, which remove the possibility that the late Eocene-earliest Oligocene basin received its materials from the Southern Alps. Studies of detrital minerals in the Aiguilles d'Arves flysch have also shown that this flysch basin was filled by a terrigenous source originated from the Pelvoux Massif [*Ivaldi*, 1987].

For the Briançonnais Flysch Noir of the Internal Zone, our data from sample ALP5-2C exhibit an age pattern distinctive from the late Eocene-earliest Oligocene flysch of the External Zone. Ages at ~450 Ma are no longer dominant, but Early Mesozoic ages are present, arguing for an origin from the Adriatic units (Figure 5f). Although the sampling positions of the Eocene flysch in the Internal and External Zones are quite close, the initial distance between the two sedimentary basins was larger, due to the significant shortening accommodated by the tectonic imbrication of the Internal Zone [*Lardeaux et al.*, 2006; *Dumont et al.*, 2011]. Therefore, the Southern Alps were the source area during the deposition of the middle Eocene flysch in the Internal Zone.

The sample ALP4-2 of the Schistes à Blocs Formation has a dominant age group at 220–290 Ma that are different from the late Eocene-earliest Oligocene flysch samples of the External Zone but resemble to the middle Eocene Flysch Noir ALP5-2C of the Internal Zone (Figure 5a). The Triassic ages are similar with those of the magmatic rocks from the Ivrea Zone [*Vavra et al.*, 1996, 1999; *Maino et al.*, 2012; *Zanetti et al.*, 2013]. It is thus suggested that after the early Oligocene, some zircon grains probably come from the Internal Zone, where the materials from the Southern Alps were redeposited. Thus, the provenance for the Schistes à Blocs Formation changed to a mixing of European continent and the Adriatic (Southern Alps) sources.

In summary, our detrital zircon U-Pb data indicate that the European continent was the dominant source for the sedimentary supply in the syntectonic basins developed from Eocene to Oligocene in the Western Alps. However, detritus from the Adriatic units were incorporated in the Late Cretaceous Schistes Lustrés, middle Eocene Flysch Noir, and early Oligocene Schistes à Blocs, but are absent in the late Eocene flysch of the External Zone. The presence of materials from the Southern Alps can therefore be regarded as a significant indicator of exhumation and erosion of the Alpine Orogen, which will be further discussed.

5.3. Implications for Crustal Growth in the Western Alps

A history of crustal evolution can be derived from the detrital zircons of the foreland basin sediments by comparing detrital zircon Hf crust formation ages with their igneous crystallization ages. Our new zircon data show three distinct groups of concordant ages at 610–540 Ma, 490–430 Ma, and 340–280 Ma (Figure 8), whereas the Hf model ages show a relatively concentrated distribution around 1.5 Ga (Figure 7), which is consistent with previous results [*Schaltegger and Gebauer*, 1999]. In Figure 7, most of the zircon Hf model ages (T_{DM2}) are much older than their crystallization ages, indicating a formation from remelting of older crustal rocks crystallized during the previous Cadomian, pre-Variscan, and Variscan crust formation events. Except some points with abnormally high εHf(t) value, none of the εHf(t) values for the rest of zircons plot on the depleted mantle line, so the isotopic signature of zircons has possibly been affected by crustal contamination. Some very old sources with Hf model ages >3.5 Ga are found in zircons from 300 Ma to 900 Ma but lacking in those older than 1.0 Ga. A potential Eoarchean source may be ascribed to the origin of these zircons. In contrast, Hf model ages between 2.5 Ga and 3.5 Ga are more common in zircons with all crystallization ages, as indicative of abundant Neoarchean to Paleoarchean sources during the crust formation stages.

Similarity and difference are both demonstrated in Figure 6 for the age groups at 280–340 Ma, 430–490 Ma, 540–610 Ma. These groups exhibit a scattered distribution of εHf(t) values with a majority of points concentrated close to the chondrite line (Figure 6a). However, in a detailed view of these plots, most of the zircons at 540–610 Ma have a εHf(t) range from +10 to −15, which is comparable with the zircons at 280–340 Ma, whereas a major part of εHf(t) values of the 430–490 Ma zircons vary between +5 and −6. This variation of εHf(t) values can thus be interpreted in two ways: (1) the Late Paleozoic (Variscan), Ordovician (pre-Variscan), and Neoproterozoic (Cadomian) magmatic rocks were derived from similar basement rocks at 1.2–1.8 Ga and (2) these rocks were generated by mixing between newly formed magmas derived from the mantle and older crustal materials. According to previous results, zircons at 1.2–1.8 Ga are rare, and contemporary rocks have not been documented yet in the Alpine orogen or adjacent regions [*Schaltegger*, 1993; *Giacomini et al.*, 2006; *Melleton et al.*, 2010, and references therein]. For instance, Neoproterozoic sediments in Europe are characteristic of a "western African gap" that refers to a lack of zircon dates at 1.0–1.8 Ga but includes clusters of Neoproterozoic and Paleoproterozoic ages [*Linnemann et al.*, 2007]. Based on detrital zircon U-Pb dating and Hf isotopic study on Cadomian igneous and sedimentary rocks, *Linnemann et al.* [2014] proposed that the Cadomian juvenile arc magmatism was contaminated by recycling of Paleoproterozoic and Archean crust. During Ordovician times, the rifting event that broke up the northern Gondwana margin to form several microcontinent ribbons produced widespread felsic magmatism with abundant crustal-derived granitoids and volcanic rocks. The occurrence of basic rocks also shows a mantle contribution [*Pin and Marini*, 1993; *Giacomini et al.*, 2006]. In some Variscan plutons, mafic enclaves and plutonic dykes, point to an input of asthenospheric mantle source injected in the continental crust [*Pin and Duthou*, 1990; *Pin*, 1991; *Bussy et al.*, 2000]. On the basis of geochemical and isotopic data, magma mixing with source materials from subcontinental lithospheric mantle and crust has also been documented in the External Crystalline Massifs [*Debon et al.*, 1998; *Debon and Lemmet*, 1999; *Paquette et al.*, 2003; *Schaltegger and Brack*, 2007]. By integration of the above-mentioned evidence, it is likely that these magmatic rocks have experienced mixing processes with magmas of different origins, rather than generated from Late Paleoproterozoic to Mesoproterozoic crust as the only origin.

In contrast with abundant pre-Mesozoic zircons in the sedimentary sequences, Mesozoic and Cenozoic ages are very rare or even absent, leading to an exceptional but meaningful phenomenon that the magmatic episodes coeval with the Pangea breakup, rifting, and Piemonte-Ligurian Ocean opening and closure are weakly represented in the sediment record. As one of classic examples of magma-poor rifted margins, the Alpine Tethyan margins were locally characterized by extremely extended crust with thickness <10 km and exhumed mantle, but few rift-related intrusive rocks [*Manatschal*, 2004; *Beltrando et al.*, 2014]. From the Late Cretaceous to Eocene, the Alpine orogen experienced a complex tectonic evolution from subduction to collision. Despite some Late Cretaceous to early Eocene bentonitic ash layers in the Late Cretaceous-Eocene Schlieren flysch, contemporaneous magmatic rocks are lacking [*Winkler et al.*, 1990]. In order to find evidence of arc magmatism, several geologists conducted detrital U-Pb zircon dating on sandstones related to the subduction and collision settings from the central Alps, but a similar detrital zircon age pattern to our study has been discovered from Eocene sandstone in the northern part of the Western Alps, characterized by a dominant Carboniferous age peak, and a subordinate Ordovician age peak, without Late Cretaceous to Paleogene ages. [*Bütler et al.*, 2011; *Beltrán-Triviño et al.*, 2013; *Malusà et al.*, 2013]. Although current geochronological studies on Alpine flyschs are still insufficient to make a final conclusion, on the basis of existing knowledge, it is reasonable to infer that the Alpine subduction did not generate significant continental crustal growth in the Late Mesozoic and Cenozoic.

5.4. Implication for the Uplift and Erosion of the Western Alpine Orogen

Detrital zircon U-Pb dating of sedimentary rocks from the Western Alps shows similar age patterns with abundant rocks from European basement that are involved into the Variscan, pre-Variscan, and Cadomian geodynamic events. Among the seven samples of terrigenous rocks, two groups can be separated: group A (LO1, LO2, ALP5-1A, and ALP5-1B) without Triassic age peaks, and group B (ALP4-2, ALP5-2C, and ALP6-2) with Triassic age peaks. The group A exclusively consists of four late Eocene-earliest Oligocene flysch samples from the External Zone, whereas the group B contains one Cretaceous mica schist (Schistes Lustrés), one middle Eocene flysch from the Internal Zone, and one Oligocene siltstone (Schistes à Blocs). Since the Triassic ages can be considered as representative from the Adriatic margin, the Schistes Lustrés should have received detritus from the Southern Alps. In addition, this result implies that all the external late Eocene-earliest Oligocene flysch samples have received a very limited contribution of detritus from the Schistes Lustrés, which provided sediments to the middle Eocene Flysch Noir in the Internal Zone. Hence, the oceanic unit, included in the Schistes Lustrés Unit, with Mesozoic zircons, has already been exhumed and eroded during the middle Eocene [*Agard et al.*, 2002], but a geographical barrier existed between the flysch basins of the External Zone and the Internal Zone that blocked detritus during the late Eocene-earliest Oligocene flysch sedimentation. Although the formation of this barrier is still poorly constrained, back thrusting of the Briançonnais Zone is tenable to give rise to its uplifting and caused the obstruction of detritus from the Adriatic units.

Since early Oligocene times, the source areas of the external foreland basins began to include the Internal Zone as suggested by the small amount of Triassic zircons. This is consistent with the occurrence of pebbles of HP metamorphic rocks in the Barrême Basin. The arrival of these blueschist and serpentinite pebbles reveals a significant tectonic event that raised the topography of the Internal Alps [*de Graciansky et al.*, 1971; *Morag et al.*, 2008; *Schwartz et al.*, 2012]. This tectonic process gave rise to the topographic growth of the Internal Zone of the Western Alps [*Morag et al.*, 2008], providing an important source of sediments for basins surrounding the Western Alps. To the east, the Paleogene Piedmont basin on the Po Plain received abundant Eocene to Oligocene phengitic white micas, implying provenance from the Schistes Lustrés and the Internal Crystalline Massifs [*Carrapa et al.*, 2004a, 2004b]. This detrital supply from high-grade metamorphic rocks continued as shown by age spectra of modern river sediments [*Resentini and Malusà*, 2012; *Malusà et al.*, 2013]. On the contrary, as shown by previous studies [*Morag et al.*, 2008; *Jourdan et al.*, 2013], detrital zircons at 65–35 Ma related to the Alpine orogeny are rarely preserved in the late Eocene to Oligocene sediments of the foreland basin, and thus, the Internal Zone could not be a major sediment source to the western flexural basins. All these results are in good agreement with the provenance study for Oligocene sedimentary rocks, pointing to a topographic high in the Briançonnais Zone preventing the influx from the eastern part of the Internal Zone [*Schwartz et al.*, 2012; *Jourdan et al.*, 2013]. Moreover, this topographic high may be built as early as middle Eocene, because the eroded materials from the Schistes Lustrés are only found in the Flysch Noir.
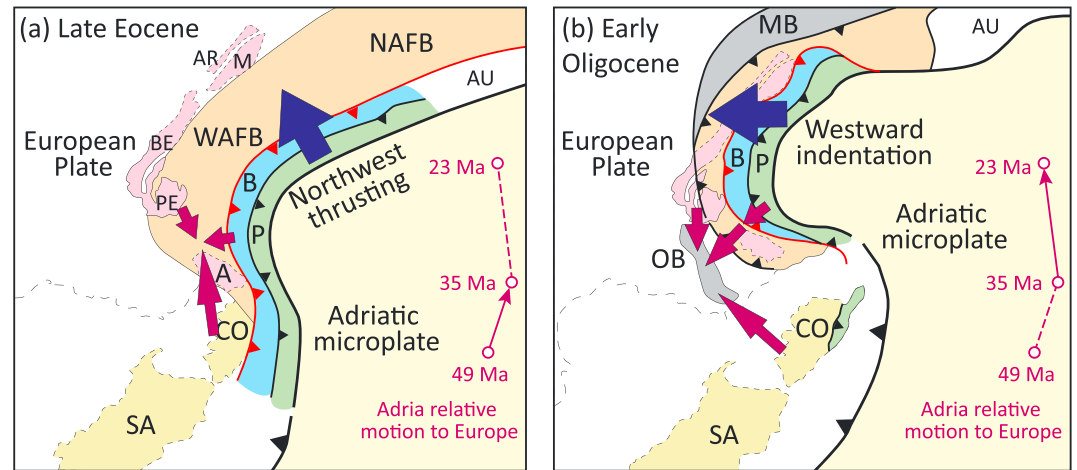
Figure 9. Late Eocene (a) and Early Oligocene (b) paleogeographic maps of the Western Alps showing the source areas for the terrigenous material, including the directions of sediment supply in the syntectonic sedimentary basins (modified after *Dumont et al.* [2011] and *Malusà et al.* [2015]). Adria motion relative to Europe is from *Jolivet and Faccenna* [2000]. A: Argentera. AR: Aiguilles Rouges. AU: Austroalpine Unit. B: Briançonnais Zone. BE: Belledonne. CO: Corsica. M: Mont Blanc. MB: Molasse Basin. NAFB: North Alpine Foreland Basin. OB: Oligocene Basins including the Digne, Devoluy and Barrême Basins. P: Piemonte Zone. PE: Pelvoux. SA: Sardinia. WAFB: Western Alpine Flexural Basin.

In the light of these results, we can thus propose a tentative tectonic model for the Eocene and Oligocene evolution of the Western Alps. During the Eocene, the Western Alps were characterized by top-to-the NW thrusting resulted from the early stages of the Adria-Europe collision [*Schmid and Kissling*, 2000; *Ford et al.*, 2006; *Dumont et al.*, 2011, 2012]. The flexural turbiditic basin represented by the Annot sandstone and its equivalents was rapidly migrating from SE to NW across the European margin during the late Eocene [*Ford et al.*, 2006], but, as indicated by our detrital zircon age data, the major source was located in the European continent (Figure 9a). During this period, the entire Briançonnais Zone overthrust onto the foreland basin and the Schistes Lustres by thrusting and back-thrusting, respectively, and thereby experienced significant uplifting [*Michard et al.*, 2004; *Lardeaux et al.*, 2006]. Hence, the Briançonnais Zone served as a geographical barrier between the Piemonte-Ligurian Oceanic material and the late Eocene to earliest Oligocene basin, preventing the westward transport from the Internal Zone. Paleocurrent directions also attest that the Corsica and Sardinia were the major provenance areas of the late Eocene-earliest Oligocene turbiditic deposits [*Sinclair*, 1997a; *Joseph and Lomas*, 2004; *Vinnels et al.*, 2010; *Malusà et al.*, 2016a].

A significant change of tectonic regime of the Western Alps occurred around the Eocene/Oligocene boundary characterized by a shift from northwestward to westward thrusting of the Internal Zone [*Stampfli et al.*, 2002; *Ford et al.*, 2006; *Dumont et al.*, 2011, 2012]. Following this shift, sediment supply increased considerably in overfilled basins in the North Alps, hinting a high relief in the Internal Zone [*Schlunegger et al.*, 1997; *Sinclair*, 1997a; *Ford et al.*, 2006]. In Oligocene-Miocene formations, age peaks at 40–30 Ma document the exposure of rocks related to the Paleogene Alpine orogen in the Internal Zone [*Malusà et al.*, 2016b]. In the western part of the Paleogene Piedmont Basin, high Si white micas of Eocene-Oligocene ages are discovered in the early Oligocene sediments, confirming the exhumation of Alpine high-pressure metamorphic rocks [*Carrapa et al.*, 2004a, 2004b]. Coevally, signals from the Schistes Lustrés, or perhaps the Southern Alps, started to be detected in the early Oligocene Schistes à Blocs of the Western Alps, indicating that the persistent paleorelief of the Briançonnais Zone only allowed a small amount of sediments to be transported through this topographic barrier. However, the Alpine-aged zircons are lacking. In fact, the basement of the Alpine orogen was formed by the Variscan or older magmatic-metamorphic rocks [*Debon and Lemmet*, 1999; *Schaltegger et al.*, 2003; *Guillot et al.*, 2009; *von Raumer et al.*, 2009; *Rubatto et al.*, 2010]. This scarcity of the Alpine ages can also be exaggerated by partial resetting of the chronological systems in these rocks [*Agard et al.*, 2002, 2009]. Nevertheless, the eastern part of the Internal Zone experienced a significant exhumation in the Oligocene and thus commenced to feed the Oligocene foreland basin.

6. Conclusion

Detrital zircon U-Pb dating results from seven samples in the Western Alps demonstrate major age peaks at 280–340 Ma, 430–490 Ma, and 540–610 Ma that correspond to the Variscan, Ordovician, and Cadomian events, respectively, whereas Hf isotopic results indicate that these three events did not give rise to significant continental growth with mantle addition.

Our data also shed new light on the late Eocene to early Oligocene foreland basin evolution of the Western Alps. Consistent with previous studies, the source areas of the Eocene flysch were mainly located inside the European continent, including Corsica and Sardinia to the south, the Briançonnais Zone to the east, and the External Crystalline Massifs (mainly Pelvoux). A new model is proposed here. During the tectonic shift from the Cretaceous-Eocene northwestward propagation to the Oligocene-Miocene westward indentation of the Adriatic plate, the foreland basins document a change of material provenance from the Internal Zone, as indicated by the arrival of Triassic detrital zircons in the early Oligocene strata. During the Eocene, despite the low paleorelief of the Western Alps, the lack of detritus from the internal part of the orogen (Adria margin and ocean-derived units) within the External foreland basins is interpreted as a result of an uplift of the Briançonnais Zone, which was able to block the sediment supply. As the crustal shortening continued, the Internal Zone became a characteristic provenance area for the western foreland basin.

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