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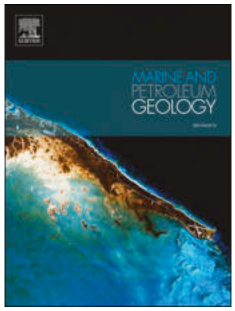


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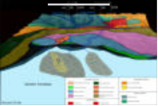

# Drainage pattern evolution during continental indentation in Central Alps: constraints from the sedimentary record of associated deep-water clastic offshoots

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*Abstract*

This work reconstructs the evolution of a source-to-sink system in a transpressional setting from compositional changes within its deep-water clastic offshoots. Field-based clast counts on 10 conglomerate beds of three transects, combined with petrographical and mineralogical (XRD) analyses on 14 samples, have been used to integrate the already-existing large dataset developed during more than 60 years of study on the Como Conglomerate (the base of the Gonfolite Lombarda Group, Chattian to Aquitanian – Northern Italy). The results shed a new light on the terranes involved in the production of sediments and further constrain the evolution of the fluvial drainage in response to the Cenozoic Adria indentation during the post-collisional phases of Alpine orogeny. In particular, it has been possible to track-back the steps during which paleorivers were connected, and later disconnected, with the basin due to the Oligo-Miocene activity of the right-lateral Periadriatic Fault System (PFS). During its transpressive movement, accommodating the Adria westward indentation, the PFS cumulated a total displacement increasing from ca. 20 km to the west, up to ca. 60 km, to the east. The results of this study also constrain the post-depositional kinematics of the clastic wedge, which was progressively rotated clockwise and thrust to its present-day position, onto the Southalpine Mesozoic sequence. This model represents a fundamental step forward in the comprehension of how tectonic indentation interacts with surface source-to-sink systems, and demonstrates that tectonic induced connections/disconnections of fluvial systems are as fundamental as exhumation processes in the transfer of sediments from source to sink areas.

*Keywords:* conglomerate; ultramafic detritus; Gonfolite Lombarda Group; paleo-drainage; Oligo-Miocene

## 1. Introduction

Exhumation processes triggered by continental indentation are fundamental for sediment production, because they favour the constant exposition of terranes to erosional processes (e.g., Malusà et al., 2016). Once liberated, sediments are then horizontally transferred to basins by river systems (Allen, 2008). Paths of such systems are strongly controlled by shallow tectonics. In particular, strike-slip deformation components are fundamentally important in the connection and disconnection of sediment pathways along source-to-sink systems (e.g., Replumaz et al., 2001; Gabrielse et al., 2006; Wang et al., 2014). However, these types of deformations are often ignored when reconstructing ancient sediment pathways.

Alpine peripheral basin sequences represent fundamental records that document how tectonic processes on collisional belts shape fluvial drainages during orogenic growth. Alpine peripheral basins have collected large volumes of sediments since the subduction stage in the Late Cretaceous (e.g., Winkler and Bernoulli, 1991; Bersezio et al., 1993), but it is only from the Paleogene and onwards that the onset of the collisional stage sourced high volumes of clastic detritus that was deposited within the depocenters (Di Giulio et al., 2001; Garzanti and Malusà, 2008; Sciunnach et al., 2010; Di Capua et al., 2016, 2021). Research attention has previously focused upon the Adriatic Foredeep sedimentary record, where clastic units preserve and record the progressive exhumation pathways of the belt axial terranes during the indentation of the Adriatic plate beneath the European plate (e.g., Carrapa and Di Giulio, 2001; Malusà et al., 2011, 2016; Critelli, 2018; Stalder et al., 2018; Lu et al., 2019). Pathways transferring sediments from the growing chain to the basins crosscut a transpressive fault system, known as Periadriatic Fault System (PFS), whose strike-slip movements were greater than vertical movements (Handy et al., 2005). The potential influence of this strike-slip deformation on the morphological evolution of the fluvial drainage system and resultant sedimentary successions requires further investigation.

Through a detailed literature review, integrated with field clast-counts, petrographical and mineralogical (XRD) analyses on the submarine sequences of the Como Conglomerate (base of the Gonfolite Lombarda Group, Northern Italy; Tremolada et al., 2010), this work reconstructs the progressive evolution of the source-to-sink system from the first incoming of coarse-grained detritus delivered by paleo-rivers and submarine canyon systems in the Chattian (late Oligocene) until the modern fluvial drainage configuration, that has been in-place after the Aquitanian (early Miocene). Newly described and characterised lithotypes within the central-western outcropping areas of the Formation allowed the identification of new source areas. This provided constraints to identify: 1) how many paleo-drainage systems were active during Oligo-Miocene times, that acted to drive the progradation of terrigenous detritus within the Adriatic foredeep; 2) sediment source areas; 3) how fluvial drainage systems reached the modern configuration; 4) post-depositional evolution of the clastic sequences, which has been rotated and thrust back onto the Mesozoic sequences in the southern part of the Southalpine domain, after the Burdigalian.

The work demonstrates the fundamental role of lateral movements in the delivery of sediments to depocenters along strike-slip dominated orogenic settings. Beyond exhumation mechanisms, which drive the surficial exposure and (partially) the erosion rates of terranes in an orogenic belt, lateral movements rule the transfer of sediments to basins, connecting and disconnecting fluvial systems to their submarine counterparts. In addition, it also shows how the combination of precise provenance analyses with fieldwork paleocurrent data is fundamental for the definition of which tectonic process has led to final emplacement of any clastic sequence after their deposition.

## 2. Geological setting: Alpine source-to-sink system across the Oligo-Miocene boundary

### *2.1. The Source: tectonic setting of the Alpine Belt*

The Rupelian/Chattian boundary is the starting point of a tectonic revolution within the Alps. Volcanic activity ceased at ca. 30 Ma, and the exhumation of the Central part of the Alps began (Schmidt et al., 1996; Rosenberg, 2004; Garzanti and Malusà, 2008; Kapferer et al., 2012; Lu et al., 2018; Di Capua et al., 2021). This tectonic phase (the so-called "Insubric Phase" *Auct.*), is crucial in the morphogenic evolution of the belt. It resulted in the juxtaposition of the plutonic and mainly amphibolite-grade oceanic terranes of the Penninic domain against the high-grade metamorphic continental terranes of the Austroalpine domain, and the Varisican metamorphic, Permian volcanic and Mesozoic sedimentary sequences of the Southalpine domain (Fig. 1). The Southalpine domain already constituted a partially structured paleo-orogen since the Cretaceous, which supplied terrigenous detritus into peripheral basins of the Alps (e.g., Homewood, 1983; Winkler and Bernoulli, 1991; Bersezio et al., 1993; D'Adda et al., 2011; Zanchetta et al., 2011, 2015; Berger et al., 2012; Bini et al., 2015; Critelli, 2018). The final structural reorganization of the Southalpine domain occurred from the Miocene onwards, when a new tectonic phase (the so-called "Lombardic Phase" *Auct*.; e.g., Sciunnach et al., 2010; Tremolada et al., 2010; Sciunnach, 2014), drove the development of the southernmost fold-and-thrust stacks onto the northern margin of the Adriatic plate (Schumacher and Laubscher, 1996). This phase also involved the clastic wedge of the Gonfolite Lombarda Group from the Burdigalian (ca. 19 Ma), northward-directing backthrusting its sequences along the Monte Olimpino backthrust (Bernoulli et al., 1989; Cardinetti et al., 2005; Scaramuzzo et al., 2022; Figs. 1 – 3A).

#### *2.1.1. The Periadriatic Fault System (PFS)*

The PFS represents the main tectonic lineament longitudinally cutting across the Alpine chain. It is articulated in different segments, branches and related faults (from west to east: Canavese Line, Centovalli Line, Tonale Line, Giudicarie Line, Pustertal Line and Gailtal Line) and was active between ca. 35 and 15 Ma (e.g., Viola et al., 2001; Stipp et al., 2004; Handy et al., 2005). It accommodated the westward indentation of the Adria plate in dextral transpression (Schmidt et al., 1996; Handy et al., 2005; Figs. 1 and 2A) and drove a westward progressive uplift and exhumation of the northern block (e.g., Schmid et al. 1989), as suggested by available thermochronological data (Malusà et al., 2011, 2016 and ref. therein). During an initial stage (Rupelian), the fault facilitated the uprising of igneous intrusive systems feeding the so-called Periadriatic magmatic bodies (Rosenberg, 2004). Once the volcanism ceased, the area became the place of exhumation (e.g., Di Giulio et al., 2001; Nagel et al., 2002; Garzanti et al., 2008; Di Capua et al., 2016). An estimate of the amount of dextral displacement along the PFS is still debated: some Authors consider a displacement of ca. 60-50 km (Schmidt et al., 1989), others of ca. 30 km (Müller et al., 2001) or less (around 10-20 km - Garzanti and Malusà, 2008).

### *2.2. Paleo-rivers and paleo-canyons*

Little is known about the paleo-rivers that crosscut the boundary between the Lepontine dome, its western boundaries, and the Southalpine domain. These rivers act to transfer detritus from the internal parts of the chain to the foredeep basin. Garzanti and Malusà (2008) revise fission track ages of paleo-Ticino and paleo-Toce river thalwegs, concluding that both rivers were probably active since the Oligocene. The same authors also speculate about the possibility to extend the Oligocene age to the paleo-Mera river, but no geochronological constraints are available. Together with the paleo-Mera river, zircon detrital data of Malusà et al. (2016) highlight that an early Adda river potentially fed the Adriatic foredeep.

It is likely that the paleo-canyons connecting the subaerial to the submarine sedimentary system were located within the axes of the main pre-Alpine lakes: Lake Maggiore, Lake of Lugano and Lake of Como (Fig. 2). Those lakes hide tectonic lineaments active since at least the Mesozoic (Bini et al., 1978).

### *2.3. The Sink: the Como Conglomerate*

The term *Como Conglomerate* previously referred to one of the lowermost Formations of the Gonfolite Lombarda Group, which is a submarine clastic wedge accumulated between the Upper Oligocene and the Lower Miocene (Gelati et al., 1988; Bernoulli et al., 1993). This Formation was identified and described around the town of Como and stratigraphically correlated to the west with coeval conglomerate rock units outcropping to the west toward the town of Varese, as well as around the town of Sesto Calende (Fig. 1; Gelati et al., 1988; Bersezio et al., 1993; Di Giulio et al., 2001). This study uses the term *Como Conglomerate* as proposed by Tremolada et al. (2010) and Bini et al. (2015), therefore subdividing it into a lower member, the Villa Olmo Conglomerate (ca. 27.6 – ca. 26.8 Ma – Chattian, Upper Oligocene), and an upper member, the Camerlata Member (ca. 26.8 Ma – ca. 22.9 Ma, Chattian to Lower Aquitanian, Upper Oligocene to Lower Miocene; Fig. 2B).

The Villa Olmo Conglomerate includes beds of conglomerates and minor sandstones with paleocurrents trending toward southwest (Gelati et al., 1988). Clast associations within the layers are largely composed of metamorphic detritus eroded from the Southalpine basement and the growing Lepontine Dome (Fig. 1), and more minor sourcing from: volcano-sedimentary material deriving from the Permo-Mesozoic terranes of the Southalpine nappes between Varese (Italy) and Lugano (Switzerland); Eocene calcareous detritus of the unroofed carbonate platform feeding the Ternate-Travedona Formation; low volumes of volcanic and plutonic detritus of the Oligocene Bergell magmatic system (Giger and Hurford, 1989; Bernoulli et al., 1993; Bersezio et al., 1993; Carrapa and Di Giulio, 2001; Di Giulio et al., 2001; Zattin and Zuffa, 2004; Malusà et al., 2011; Bini et al., 2015; Di Capua et al., 2016; Coletti et al., 2016; Lu et al., 2019). This lithological association is termed the "Villa Olmo Conglomerate Association" (VOCA) in this study.

The Camerlata Member includes beds of conglomerates and minor sandstones with paleocurrents trending toward southwest in the eastern side of the Formation, toward south and minorly southeast in the western side of the Formation (Gelati et al., 1988). Beds are dominantly composed of plutono-metamorphic detritus derived from the Lepontine Dome and rare amounts of sedimentary detritus from the Mesozoic covers, which disappear in the uppermost layers of the member (Carrapa and Di Giulio, 2001; Di Giulio et al., 2001; Zattin and Zuffa, 2004; Malusà et al., 2011, 2016). This lithological association is termed the "Camerlata Member Association" (CMA) in this study.

#### *2.3.1. The Lisanza Well*

Below the town of Lisanza (Fig. 3A), the Como Conglomerate has been intersected in an exploration well by ENI in the 1980s. The sedimentary sequence (Oligocene to Lower Miocene - Aquitanian) is repeated by a reverse fault. The technical description, available at https://www.videpi.com/videpi/pozzi/dettaglio.asp?cod=3322., indicates that the Como Conglomerate in the well is composed of a wide spectrum of lithologies, including Upper Triassic to Jurassic dolostones, limestones and cherts, igneous rocks, and metamorphic lithotypes. Clasts, even bigger than 20 cm in diameter, have been documented for all the mentioned lithotypes.

#### *2.3.2. Tonalite boulders of the Bergell Pluton within the Como Conglomerate*

The Bergell Pluton (Fig. 1) is a composited plutonic body within the Lepontine Dome, made up of an elongate tonalite tail and a granodiorite central body (Fig. 1) (Rosenberg, 2004). It provided large volumes of plutonic detritus to the Como Conglomerate since the beginning of its exhumation (lower Oligocene) (e.g., Carrapa and Di Giulio, 2001; Garzanti and Malusà, 2008). Within the tonalite detritus, Giger and Hurford (1989) distinguish two groups based on textural characteristics and K/Ar ages. The first group, documented in the Villa Olmo Conglomerate and in the basal part of the Camerlata Member from Como to Lisanza, is represented by tonalite detritus derived from the eastern part of the Bergell Pluton, and shows an undisturbed magmatic texture that formed within shallow crustal levels and yields K/Ar ages of ≥31 Ma. The second group of tonalite detritus is only documented within the Como Conglomerate, derived from the western part of the Bergell Pluton, shows deformed and recrystallized textures formed at deeper crustal levels, and yields K/Ar ages younger than 30 Ma.

## 3. Methodology

Three transects were identified to investigate the composition of the central and western outcropping areas of the Como Conglomerate (Fig. 3). This includes field-based clast counts, characterizing all the clasts in an area of ca. 4 $m^2$. The first transect, (*Rodero Transect)* runs from Gaggiolo to Rodero and comprises four conglomerate beds; the second transect, named the (*Valmorea Transect)* runs along the ancient railway of Valmorea and comprises three conglomerate beds. The last transect (*Mercallo Transect)* runs from Mercallo dei Sassi to the locality of Oca (town of Lisanza), and comprises three conglomerate beds. In the last transect, the lowermost of those beds is located where Malusà et al. (2016) collected sample CVL1. Lithologies have been classified into tonalite, granite, quartzite, gneiss, micaschist, amphibolite, mafic/ultramafic and limestone clasts. 10 samples were collected and cut into standard thin sections for further detailed petrographical characterization, whereas 4 samples were collected for mineralogical characterization through X-Ray powder diffraction (XRD), for a total amount of 14 analysed samples.

## 4. Petrography of gravel-sized detritus within the central and western sectors of the Como Conglomerate

### *4.1. Central Sector*

Field-based clast counts show that all conglomerate beds are composed of plutono-metamorphic gravel, with an ephemeral contribution of volcanic lithologies in three beds, and limestones in a single bed at the top of the Valmorea Transect. Plutonic lithotypes comprise tonalite clasts and rare granite clasts. Metamorphic detritus is generally represented by gneissic clasts and quartzites, with subordinate amphibolites, metabasite detritus and rare micaschists. The metabasite detritus is represented by serpentine clasts that show fine-grained serpentinites, with little or no planar anisotropies, and interpenetrating to interlocking non-pseudomorphic textures (Fig. 5A and B). Relic pseudomorphs of olivine and pyroxene could not be detected. The mineralogical composition, as observed in thin section and through XRD analysis, is characterized by one or sometimes two generations of serpentine (mainly antigorite and minor lizardite), with smaller amounts of clinochlore and traces of tremolite – actinolite amphiboles in acicular clusters. Some specimens also contain traces of talc and carbonate minerals (dolomite). The main opaque mineral is magnetite, sometimes with small amounts of chromite. Volcanic clasts are porphyritic dacites, characterized of pluricentimetric zoned, weathered plagioclase, amphibole, and minor quartz embedded in a microcrystalline groundmass (Fig. 5C). Limestone clasts are characterized by the abundant presence of nummulites and are associated with the Eocene Ternate-Travedona Formation (Fig. 5D).

In the Valmorea Transect, the lowermost conglomerate bed is composed of tonalite clasts, with subordinate metamorphic fragments (quartzites, gneissic clasts and amphibolites) and rare volcanic clasts (Fig. 3B). The middle conglomerate bed comprises a higher proportion of metamorphic (quarzites and gneissic clasts) than tonalite clasts, whereas the uppermost conglomerate bed is largely composed of tonalite clasts with subordinate metamorphic (quartzite and gneissic clasts) and limestone clasts (Fig. 6A).

In the Rodero Transect, the lowermost count shows a rough prevalence of metamorphic detritus over plutonic detritus, with few volcanic clasts. Metamorphic clasts are here quartzite, gneissic clasts, and rare micaschists. Tonalite clasts totally represent the plutonic fraction. Upward, the plutonic signal becomes preponderant, with the net increase of tonalite clasts and the appearance of few granite clasts. Although decreased, metamorphic lithotypes become more differentiated, including also amphibolites and ultramafic (serpentinite-type) clasts from the second half of the sequence (Figs. 5A, 5B, 6B and 6C).

#### 4.1.1. Occurrence of granodiorite detritus

Few megaboulders of granodiorite and gneiss were encountered in a single paraconglomerate bed within the second half of the Rodero Transect (Fig. 6D). In the Valmorea Transect, few boulders of granodiorite, less than 30 cm in diameter, have been observed in a single bed in the middle part of the sequence.

### 4.2. Western sector

To the west, field-based clast counts show a typified pattern for the Como Conglomerate: a VOCA in the lowermost clast-count, predominantly composed of metamorphic lithotypes, with inputs of sedimentary (Fig. 6E), volcanic and plutonic detritus, that pass upwards into a CMA, where tonalite and minor granodiorite detritus dominates over other lithologies, whereas the sedimentary signature disappears. Mafic detritus, composed of fine-grained, foliated, slightly metamorphosed diorite (Fig. 6F), as well as phengite-bearing gneissic clasts (Fig. 6G) are observed.

## 5. Discussions

### 5.1. Detrital signatures of the Como Conglomerate

#### 5.1.1. Plutonic signature

The key signature is ascribed to the tonalite detritus that, together with the presence of granodiorite megaboulders, points to the Cenozoic magmatic body of the Bergell Pluton. This signature is in agreement with that proposed by Giger (1990), Oschidari (1991), and Bernoulli et al. (1993) who applied geochronological constraints on the same type of debris. Ephemeral granite signatures are less constrained. Similar lithologies were already documented by Di Capua et al. (2016) in the eastern part of the Gonfolite Lombarda and associated with the narrow area between the Bergell Pluton and the PFS, called the Bellinzona – Dascio Zone (Berger et al., 2005; Burri et al., 2005).

#### 5.1.2. Volcanic signature

Within the Como Conglomerate, there are two distinct volcanic signatures: the first one includes the Permian andesite, dacite and rhyolite clasts, likely derived from the Permian volcanic district running from the Sesia Valley to Lugano (Bakos et al., 1995; Cortesogno et al., 1998; Schaltegger and Brack, 2007), whereas the second one includes all the volcanic clasts that were dated as Oligocene in age by Giger (1991) and interpreted as being sourced from the Southalpine dykes or Lepontine volcanic cover (e.g., Carrapa and Di Giulio, 2001; Malusà et al., 2011; Di Capua et al., 2016). Although important in constraining the exhumation rate of the Lepontine Dome (Malusà et al., 2011), such a distinction is unremarkable for our purposes as the Permian volcanic district runs parallel to the hypothetical source area of the Cenozoic volcanic material along the PFS, and both were crosscut by the Alpine drainages supplying detritus to the Adriatic foredeep.

#### 5.1.3. Sedimentary signature

Variation in the amounts of sedimentary detritus within the Como Conglomerate has been commonly used to distinguish between the Villa Olmo Conglomerate and Camerlata Member (Bini et al., 2015 and ref. therein). Most of the sedimentary detritus within the Villa Olmo Conglomerate is derived from the Mesozoic sedimentary covers of the Southalpine domain. Among those formations, dolostones are a typical Triassic signature, because there are limited Jurassic and no Cretaceous dolostone sequences within this domain. Terrigenous fragments are mainly Permo-Triassic in age (e.g., Verrucano Lombardo, Servino and Bellano Formations – Sciunnach et al., 1996), with minor contribution from Upper Carboniferous to lower Permian (Ronchi et al., 2012) and Cretaceous sequences (e.g., Lombardian Flysch – Bersezio et al., 1993). Limestone detritus, when not specified like in the Lisanza well, have an ambiguous signature, as limestone sequences dominated the Lombardian stratigraphic record from the Triassic (e.g., Esino Limestones) to the Lower Cretaceous (e.g., Maiolica Formation) (Casati, 1978). On the contrary, Eo-Oligocene limestones were only derived from the carbonate platform, which previously fed the Ternate-Travedona Formation; this is widely documented in the eastern part of the Como Conglomerate (Carrapa and Di Giulio, 2001; Coletti et al., 2016; Di Capua et al., 2016).

#### *5.1.4.Metamorphic signature*

Metamorphic detritus within the Como Conglomerate often represents the largest signature, with this attributed to a Southalpine and Lepontine provenance in the eastern parts of the formation (e.g., Carrapa and Di Giulio, 2001). In its central side, provenance seems to be similar to that described in the literature, as shown by the near-identical field clast-counts. In the western side of the Como Conglomerate, the presence of high-pressure metamorphic rock detritus indicates that diluted inputs were also supplied from the Ivrea-Verbano or Sesia Lanzo Zone (e.g., Berger et al., 2012).

#### *5.1.5.Mafic/Ultramafic signature*

The ultramafic signature represents a novelty within the Como Conglomerate. Although normally associated to the unroofing of the Penninic Nappes that run parallel beyond the PFS (e.g., von Eynatten, 2003), the signature does not show the typical high-grade mineral association of the Penninic Zone (e.g., titan-clinhumite, garnet) (e.g., Cavallo et al., 2004), or the olivine, pyroxene and quartz mineral assemblages of the Chiavenna ophiolite units (Huber and Marquer, 1998; Liati et al., 2003). On the contrary, similar mineralogical associations have been documented within the ultramafic rocks of the Strona-Ceneri Zone by Zurbriggen (2020), as well as in those of the Ivrea-Verbano Zone by Morishita et al. (2008) and Matysiak et al. (2015). All those potential sediment sources crop out in a narrow NE-SW trending area in the north-western part of the Lake Maggiore (Fig. 1).

The mafic rock types have a ubiquitous signature within the clast assemblages. Diorite material has been documented, and geochronologically constrained, by Giger and Hurdford (1989) within the Como Conglomerate, being from the Bergell Pluton. Alternatively (or additionally), fine-grained, slightly metamorphosed diorites appear in the Ivrea-Verbano Zone block, that outcrop along the western side of the Lake Maggiore, which were likely already exposed from the Oligocene times (e.g., Berger et al., 2012). The latter source area may be more likely, as large amounts of mafic material is found preserved in the western part of the Como Conglomerate.

### *5.2. Reconstructing paleo-drainages and their evolution across the Oligo-Miocene boundary*

Provenance relations are crucial to unravel central Alpine paleo-drainage configuration evolution through the Oligo-Miocene times. This palaeo-drainage system configuration is often described as a single-pattern model, connecting the Mera paleo-river and the western branch of the Lake of Como as paleo-canyon transferring detritus to the basin (e.g., Malusà et al., 2011). River displacement is thought to constrain the order of magnitude of PFS dextral displacement (Garzanti and Malusà, 2008).

The detrital components of the Chattian Villa Olmo Conglomerate provide important insights into the source-to-sink system at the time of deposition (Fig. 7A). Firstly, the Eo-Oligocene material derived from the Ternate-Travedona carbonate platform is only found from the Valmorea transect (central side of the Como Conglomerate) to the east. This point, together with a larger presence of Triassic dolostone and terrigenous detritus in the eastern side, indicates the presence of at least two separated drainage systems feeding the foredeep since the Chattian. The first system, which supplied the central-eastern part of the basin, probably ran southward through the Lake Lugano paleo-canyon, as testified by the presence of detritus composed of the Permian Volcanic sequences of the Lugano-Varese district deposited within the submarine fan (Fig. 7A) (Di Capua et al., 2016). The second drainage system passed through Lake Maggiore, where the Permian Volcanic sequences of the Sesia Valley, and the Upper Triassic to Cretaceous sequences of the Monte Nudo Basin favoured the accumulation of lithological assemblages recovered in the western side of the studied area, as well as in the Lisanza well. Considering the detrital zircon signatures of Malusà et al. (2016) within the Villa Olmo Conglomerate, as well as the proximal paleo-drainage patterns here proposed, an average dextral displacement of at least 30 km along the PFS is required to connect the paleo-Mera/paleo-Adda convergence to the head of the Lake of Lugano paleo-canyon. On the other hand, in agreement with the displacement order of $10^1$ km estimated by Garzanti and Malusà (2008), the paleo-Moesa/paleo-Ticino drainage system would require < 20 km lateral displacement to reconnect to the northernmost branch of Lake Maggiore. In this configuration, both paleo-drainage systems potentially contributed to the accumulation of the Villa Olmo Conglomerate. Comparable detrital zircon signatures (Malusà et al. 2016) indicate that both paleo-drainages were fed by similar terranes (e.g., Sesia-Margna Nappe) along and across the PFS. However, Cenozoic zircons are found in higher abundancies than in the eastern Villa Olmo Conglomerate, suggesting that volcanic detritus forms as a mixture of Oligocene and Permian lithologies. This is in contrast with the western Villa Olmo Conglomerate, where volcanic detritus was mainly derived from the Permian sequences of the Sesia area. In this scenario, the watershed between the two the paleo-drainage systems was constituted by the shallow levels of the Bergell Pluton (found as detritus by Giger and Hurford, 1989 in both depositional sequences) and of the southernmost border of the Lepontine Dome (Southern Steep Belt of Burri et al. (2005); found as detritus by Di Capua et al. (2016), against the hanging wall of the PFS.

From ca. 26 Ma (Camerlata Member; Fig. 7B), the in-bringing of younger deeper tonalites and granodiorites next to the old shallow tonalites testifies that different crustal levels of the Bergell Pluton went juxtaposed at the surface, largely as a direct consequence of an eastward tilting of the plutonic complex (Rosenberg and Heller, 1997). The tilting is corroborated by calculated paleodepths at which the exposed plutonic levels were emplaced during the Oligocene (e.g., Malusà et al., 2011; Gianola et al., 2014). This tilting is also coeval with the timing of the Lepontine Dome exhumation climax and the west-ward migration of the Adriatic indenter (Garzanti and Malusà, 2008; Malusà et al., 2016). This major tectonic event progressively generated a major reorganization of paleodrainage systems across the Chattian – Aquitanian boundary. This reorganization is recognizable within the composition of the lithological associations that characterize the Camerlata Member. At a higher level, there is a net contrast between the local persistence of mafic detritus only within the western side of the member and presence of tonalite and granodiorite gravel in both sides. This testifies the presence of a local source on the west drained by the Lake of Maggiore paleo-canyons, next to a common source located in the center of the Lepontine Dome, which provided the plutonic detritus. At a more local level, the upper part of the central-eastern Camerlata Member comprises beds including either tonalite or granodiorite detritus, as well as a double signature of detrital zircon data, one typical of the central-western side of the Lepontine Dome and the other typical of the central-eastern side of it (Malusà et al., 2016). This points to a sedimentary system with multiple sourcing areas, one rooted within the central-eastern side of the Lepontine Dome that provided plutonic detritus, and the other with a longer pathway crosscutting the central-western part of the Dome that provide large volumes of metamorphic detritus next to the plutonic one. Therefore, it is envisaged that the paleo-Ticino/paleo-Moesa drainage system shifted to east and started to feed both canyons. Paleo-Moesa, which crosscuts the central-eastern Lepontine dome, contributed with the large amount of plutonic detritus to both sides of the Camerlata Member, whereas paleo-Ticino sourced material into the central-western part of the Lepontine Dome.

Mafic detritus was likely supplied to the paleo-Ticino/Lake Maggiore system by a local source located in the north-western part of the Lake Maggiore. This interpretation is further supported by the south-westward rotation of the Ivrea-Verbano and Sesia-Lanzo blocks (Berger et al., 2012; Zanoni et al., 2020; Scaramuzzo et al., 2022). This sediment source signature is also observed in the central part of the Camerlata Member (Rodero Transect) at around 24 Ma.

To the east, the absence of a paleo-Adda zircon signature indicates the likely disconnection of this paleo-river to the Camerlata Member sediment sink, leaving mainly granodiorite-rooted paleo-Mera to occasionally supply detritus. The progradation of the submarine system of the Fornaci Marls and Briosco Sandstones in the Brianza area (between Milan and the Lake of Como), which contains the Adda sand petrofacies (Fellin et al., 2005; Sciunnach, 2014; Bini et al., 2015), supports a hypothesis of the Lower (?) Aquitanian shift of the river from the Lake of Lugano to the Lake of Como paleo-canyon head.

During the Aquitanian (Fig. 7C), the uplift of the Southalpine nappes due to the Lombardic tectonic event (e.g., Sciunnach, 2014; Scaramuzzo et al., 2022) triggered the final disconnection of the palaeodrainage systems from Lake of Lugano, whereas the paleo-Mera reached its modern-day position, reconnecting with the paleo-Adda at the head of the Lake of Como (*cfr* Fig. 1).

### *5.3. Implications on post-collisional tectonics*

#### *5.3.1. Implications on the dextral displacement of the PFS*

From west to east, different constraints have been used to quantify the order of dextral displacement along the PFS during the Oligo-Miocene times (see Schmidt et al., 1989; Müller et al., 2001; Garzanti and Malusà, 2008). In this work, it has been postulated that along the Tonale between the Lakes Maggiore and of Como the PFS experienced a displacement of around 20 km, according to Garzanti and Malusà (2008). In particular, the displacement that resulted in the eastward shift of the northernmost part of the Ticino-Moesa drainage systems seems to be less than that of the displacement of the Mera-Adda drainage system. This is based on the comparison between the new reconstruction provided in this study, and the modern configuration of both drainages. The first and westernmost drainage run almost N-S until reaching the PFS, then turns to the west for 13 km, before connecting with the modern Lake Maggiore. The second drainage runs N-S until reaching the PFS, where their confluence shifts for around 30 km from the head of the Lake of Lugano. In addition, the modern distance between the Mera and the Adda rivers is around 60 km due to the interposition of the Malenco Unit between their thalwegs. Provenance constraints in this study, which are also supported in the work of Sciunnach et al. (2014) and Bini et al. (2015) on the Briosco Sandstones, and thermochronological constraints on the Alpine bedrock of the Malenco Nappe (Price et al., 2018), indicate that this distance has increased progressively from the Miocene (after 20 Ma), after the complete exhumation of the Malenco Unit. This implies that the dextral displacement of the PFS along the Tonale branch increases from the west (ca. 10 – 20 km; Garzanti and Malusà, 2008) to the east (ca. 60 km; Schmidt et al., 1989).

#### *5.3.2. Implications on the post-depositional history of the Gonfolite Lombarda Group*

The interpreted provenance of the sediments observed and characterised in this study does not match that of the previous palaeo-current observations of Gelati et al. (1988), whose measured trends are southwestward in the eastern part of the Como Conglomerate and south to southeastward from the eastern to the central part of the formation. This inconsistency demonstrates that the entire stack of the Gonfolite Lombarda Group was not only backthrust towards the northeast after its emplacement (Bernoulli et al., 1989; Cardinetti et al., 2005), but also rotated clockwise of ca. 40°. This rotation resulted in the disarticulation of the submarine deposits from the drainage systems, which prevented for many years a complete reconstruction of the connections delivering sediments from the Alpine chain to the Adriatic Foredeep.

## 6. Conclusion

Vertical exhumation processes are generally considered as the fundamental player in building orogenic belt architectures, as well as in providing large amounts of sediments to peripheral basins.

This work reassesses the evolution of the Oligo-Miocene paleo-drainage systems that transferred sediment from the growing Alpine belt to the Adriatic Foredeep. It describes and discusses the importance of the lateral displacement along the PFS and the structures significance in the basins sedimentary fill. Integrating large volumes of detrital constraints in the literature with new field- and laboratory-based data, a model on the changes of paleo-drainage systems has been built. This model considers the Adriatic Foredeep basin as being fed by at least two different fluvial drainage systems, one running through Lake Maggiore, the other through Lake of Lugano. Changes in lithology and detrital geochronology compositions from the eastern to the western sides of the Como Conglomerate not only reflect the progressive exhumation of the Lepontine Dome, but also the influence of the connection and disconnection of the paleo-drainage systems to the paleo-canyons feeding basinally-located submarine systems. Unravelling the paleo-drainage system configuration that crosscut the Alpine belt during the Oligo-Miocene times has important implications both in terms of constraining the dextral displacement of the PFS, which probably increased eastward from ca. 20 km to ca. 60 km along the Tonale branch, and as in determining the post-depositional evolution of the Gonfolite Lombarda Group, which was not only backthrusted, but also rotated clockwise of ca. 40°.

The results of this study show how strike-slip movements, triggered by deep geodynamic modifications such as a continental indentation, are as fundamental as vertical exhumation processes in the delivery of sediments from sourcing areas to basins. Such kinds of surface processes are important to understand because they shape the drainage pathways over time, influencing the types and distribution of sediment lithofacies associations or architectures within deep-water sedimentary systems.



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**Figure Captions**

Figure 1: Geological map of the Central Alps, redrawn from Tremolada et al. (2010) and Scaramuzzo et al. (2022).

Figure 2: modern drainage configuration of the study area, depicting the actual position of the Gonfolite Lombarda Group wedge with respect to potential source rivers and paleo-canyons. Geology of the Eo-Oligocene sequences are redrawn from Gelati et al. (1988) and Di Giulio et al. (2001).

Figure 3: General stratigraphy of the a) Sesto Calende, b) Como and c) Briosco areas. TT: Ternate – Travedona Formation; CH: Chiasso Formation; CG: Como Conglomerate – VO: Villa Olmo Conglomerate and CM – Camerlata Member; PR: Prestino Mudstones; FR: Fornaci Marls. CLV1, CLG3, CLG4 and VOA: locations of detrital geochronology samples of Malusà et al. (2016). CGL1a and CGL1b, VO3a and VO3a, VO2: locations of detrital geochronology samples of Lu et al. (2019). Blue stars: field-based clast counts of Carrapa and Di Giulio (2001). Green star: fieldwork clast counts of Di Capua et al. (2016).

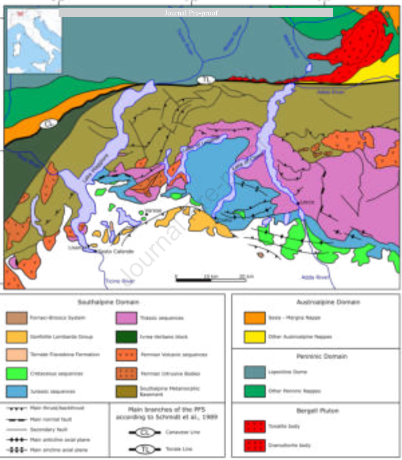
Figure 4: A) Simplified geological map depicting the Ternate – Travedona Formation and the lower Formations of the Gonfolite Lombarda Group. VT: Valmorea transect (1 to 3); RT: Rodero Transect (1 to 4); MT: Mercallo Transect (1 to 3). Counts numbers are in stratigraphic order (from the lowermost at the bottom to the uppermost on top). Satellite photo from Google Maps. B) Results of the field clast-counts in stratigraphic order, from the lowermost count at the bottom to the uppermost count on top for each transect. Colour legend is depicted.

Figure 5: A) Polarized light micrograph (crossed polars) of a fine-grained serpentinite with non-pseudomorphic texture. B) Polarized light micrograph (crossed polars) of a serpentinite with traces of tremolite-actinolite and carbonates (mainly dolomite). C) Polarized light micrograph of a dacite clast, showing strongly weathered plagioclase minerals (red stars) and amphibole minerals (light blue stars) within a

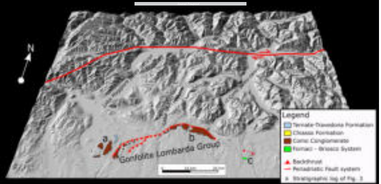
devitrified, microcrystalline groundmass. D) Polarized light micrograph (parallel polars) of a limestone clast of the Ternate-Travedona Formation, collected in the uppermost bed of the Valmorea Transect.

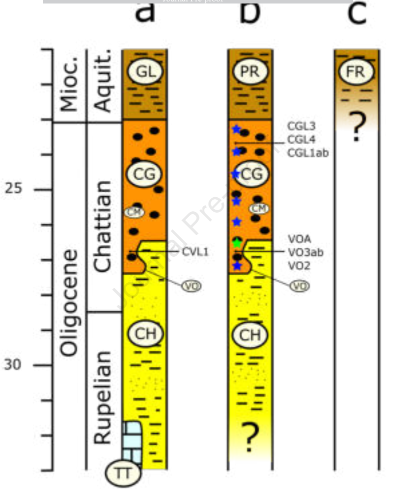
Figure 6: A) field photo of the uppermost conglomerate of the Valmorea Transect. Red circles include limestone clasts. B) field photo of the uppermost conglomerate of the Rodero Transect, with serpentine clasts are in red circles. C) Close-view photo of the previous conglomerate body, where serpentinite clasts (S) have been identified with tonalite (T) and volcanic (V) clasts among the others. D) Megaboulder of granodiorite in a paraconglomerate bed of the Rodero Transect. E) Limestone clast in a basal conglomerate bed of the Marcallo Transect, corresponding to CVL1 sample of Malusà et al. (2016). F) Foliated sample of diorite and (G) sample of phengite-bearing gneiss of the Marcallo Transect.

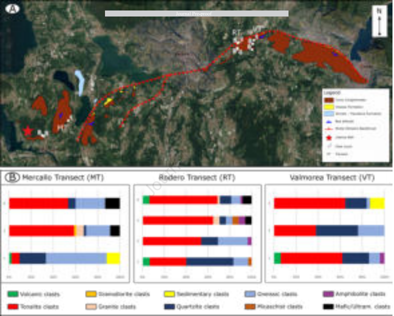
Figure 7: A) Drainage patterns during the Lower Chattian time. LC: position of river confluences in the Lower Chattian. B) Drainage patterns during the Upper Chattian (around 26 Ma) LC: position of river confluences in the Lower Chattian. UP: position of river confluences in the Upper Chattian. C) Drainage patterns during the Upper Aquitanian (ca. 23 Ma). LC: position of river confluences in the Lower Chattian. UP: position of river confluences in the Upper Chattian. O/M: position of river confluences at the Oligocene/Miocene boundary.

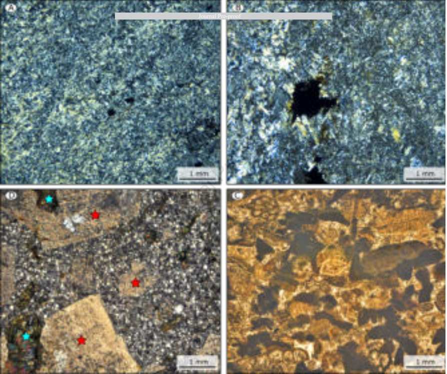


TL
CL
Ticino River
Adda River
Southalpine Domain
Triassic sequences
Cretaceous sequences
Jurassic sequences
Permian Volcanic sequences
Permian Intrusive Bodies
Southalpine Metamorphic Basement
Austroalpine Domain
Sesia - Margna Nappe
Other Austroalpine Nappes
Penninic Domain
Lepontine Dome
Other Penninic Nappes
Bergell Pluton
Tonalite body
Granodiorite body
Main normal fault
Secondary fault
Main branches of the PFS according to Schmidt et al., 1989
Canavese Line
Tonale Line


N
a
b
c
Gonfolite Lombarda Group
Legend
Ternate-Travedona Formation
Chiasso Formation
Como Conglomerate
Fornaci – Briosco System
Backthrust
Periadriatic Fault system
Stratigraphic log of Fig. 3


a
b
c
Mioc.
Aquit.
Oligocene
Chattian
Rupelian
25
30
GL
PR
FR
?
CG
CM
CVL1
VO
CH
TT
CGL3
CGL4
CGL1ab
VOA
VO3ab
VO2


A
N
RT
MT
Legend
B
Mercallo Transect (MT)
Rodero Transect (RT)
Valmorea Transect (VT)
Volcanic clasts
Tonalite clasts
Granodiorite clasts
Granite clasts
Sedimentary clasts
Quartzite clasts
Gneissic clasts
Micaschist clasts
Amphibolite clasts
Mafic/Ultram. clasts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B
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C
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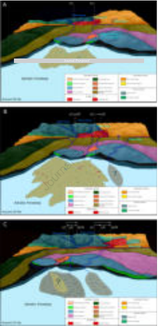

***Highlights***

- Revised and new data redefine provenance of Oligo-Miocene Alpine detritus
- New provenance constrains morphogenic evolution of river catchments
- Paleocurrents and provenance constrain post-sedimentary history of sequences

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: