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# Detrital signatures of impending collision: The deep-water record of the Upper Cretaceous Bordighera Sandstone and its basal complex (Ligurian Alps, Italy)

**Pierre Mueller[1]*, Antonio Langone[2], Marco Patacci[3], Andrea Di Giulio[1]**

[1]. Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia, Pavia, Italy.

[2]. CNR – Istituto di Geoscienze e Georisorse, Unità di Pavia, Via Ferrata 1, 27100 Pavia, Italy

[3]. Turbidites Research Group, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK.

*Corresponding author; Email-address: pierre.mueller01@universitadipavia.it (P. Mueller)

## Abstract

Despite intensive research efforts and significant advances in the understanding of subduction and obduction processes that affected several units which at the present day compose the Western Alps, the paleogeographic evolution of the Alpine Tethys represents a debated topic in Alpine geology. The role of the opposing continental margins (passive European margin and active Adriatic margin) as source regions for Cretaceous siliciclastic turbidites bordering the convergent system remains disputed. To address this question along the Ligurian Alps transect, a multi-proxy provenance analysis is applied to the two terrigenous superimposed units (Hauterivian-Campanian San Bartolomeo Fm. and Campanian-Maastrichtian Bordighera Sandstone) of the San Remo-Monte Saccarello Unit of the Western Ligurian Flysch complex. Petrographic analyses characterize the basal San Bartolomeo Fm. as quartz-rich mature sandstones. By contrast, the overlying Bordighera Sandstone represents texturally and compositionally immature first-cycle arkosic arenites. This change records the evolution of the sediment provenance from a stable craton into a continental basement uplift setting, reflecting erosion of granitoid plutons and the low-grade metamorphic basement. Geochronological data (U-Pb detrital zircon ages) indicate that virtually the same source terranes provided the source for both formations. The detrital age spectra display age peaks are compatible with well-documented magmatic and metamorphic pulses that affected the Southern Variscides in the Paleo-European margin. The strong

affinity of clastic detritus with the Paleo-European margin basement rocks underlines the importance of the lower plate passive continental margin in supplying sand-rich turbidite systems prior to the arrival of the passive margin in the subduction zone.

Keywords: Sandstone provenance; (U-Pb) detrital zircon chronology; Piedmont-Ligurian ocean; Tethyan continental margins; subduction; impending collision.

**1 Introduction**

The geodynamic evolution of the Western Tethys during the Alpine subduction remains debated, with various models emphasizing on opposite subduction polarities and the presence of continental fragments and their role in the context of the pre-collisional geodynamic evolution of the Piedmont-Ligurian oceanic domain (e.g., Froitzheim and Manatschal, 1996; Dal-Piaz et al., 2003; Froitzheim et al., 2008; Molli, 2008; Alvarez and Shimabukuro, 2009; Viti et al., 2009; Handy et al., 2010, 2014; Marroni et al., 2010; Molli and Malavieleille, 2011; Decarlis et al., 2013; Malusà et al., 2015; Lin et al., 2018). Owing to crustal shortening and subduction, oceanic units became displaced, so that the reconstruction of their original positions remains uncertain. To this end, Upper Cretaceous to Paleogene turbiditic sequences scraped off in front of the Alpine subduction zone provide key evidence for Alpine convergence, predating continental collision after the closure of the Piedmont-Ligurian ocean in the early Cenozoic (e.g., Lanteaume, 1962; Sagri and Marri, 1980; Caron et al., 1981). The detrital signatures of these pre-collisional sequences that crop out along the entire Alpine belt allow insights into the plate-tectonic setting of the continental areas bordering the ocean and providing the source of the clastic detritus (e.g., Valloni and Zuffa, 1984; Fontana et al., 1994; Bracciali et al., 2014).

According to classical provenance models, the relative proportions of distinct types of terrigenous sand grains mirror the nature of the parent rocks of the clastic detritus, and in turn also provide information of the geodynamic setting of source to sink systems (e.g., Dickinson and Suczek, 1979; Bhatia, 1983; Dickinson et al., 1983; Dickinson, 1985; Garzanti et al., 2007; 2014). Moreover, the relationship between hinterland tectonics and associated sediment dispersal pathways towards the final depositional environments of the siliciclastic detritus can be reconstructed. Even though sandstone petrography depicts the most feasible link to reconstruct hinterland tectonics, the quantification of detrital components does not provide insights into the age of the parent rocks and the thermal history they underwent (Fedo et al., 2003; Andersen, 2005; Najman, 2006). Accordingly, additional data are required to pass from a generic definition of the source region to a paleogeographic picture where those areas are regionally constrained. Provenance studies increasingly highlight the advantage of combining sandstone petrography with geo-thermochronological analysis of detrital minerals and hence elaborate a "multi-proxy" source discrimination (e.g., Dunkl et al., 2001; Dickinson and Gehrels, 2009; Beltrán-Triviño et al., 2013; Bracciali et al., 2014; Di Giulio et al., 2017).

Here we apply this approach to the San Remo-Monte Saccarello Unit, the stratigraphically oldest and tectonically topmost unit of the Western Ligurian Flysch cropping out in NW Italy. The unit is interpreted to represent trench-fill successions that were scraped off from their oceanic substratum and became incorporated into the Alpine accretionary prism along the Ligurian Alps transect (Di Giulio, 1992). An integrated sediment provenance analysis that comprises modal framework analysis, detrital zircon U-Pb geochronology and the study of sediment dispersal patterns of the two terrigenous members of the unit is undertaken. The results validate the debated hypothesis that the detrital source was provided by the passive European continental margin approaching the subduction zone instead of the active Adriatic margin. Additionally, they show that activation of the studied deep marine clastic systems records the arrival of a passive continental margin in the subduction zone, immediately predating the transition from an oceanic subduction setting to that of a continental collision zone.

## 2 Background tectonics and stratigraphy

### 2.1 Tectonics

The study addresses the structurally topmost unit of the Cretaceous-Paleocene Western Ligurian Helminthoid Flysch Complex of the Ligurian Alps (Fig. 1). The Helminthoid Flysch Nappe represents the uppermost part of the Upper Penninic Nappe pile. During the late Eocene-early Oligocene the Helminthoid Flysch Units of the Ligurian Alps were thrusted over the more proximal domains of the European foreland and at the present day rest on the Mesozoic Dauphinois-Provençal succession (e.g., Vanossi et al., 1986; Di Giulio, 1992; Seno et al., 2005; Maino et al., 2015). They represent the accretionary wedge formed by the cover of the Piedmont-Ligurian ocean that was scraped off along the Ligurian Alps transect of the Alpine subduction system (Lanteaume, 1962; Vanossi et al., 1986; Di Giulio, 1992). The Western Ligurian Flysch Complex comprises four main subduction flysch units that from oldest to youngest are: the San Remo-Monte Saccarello Unit, the Moglio-Testico Unit, the Borghetto d´Arroscia Unit, and the Colla Domenica-Leverone Unit. These units are divided by southward dipping thrusts and are tectonically arranged in inverted chronostratigraphic order, with the oldest unit resting on top of the nappe pile, following the typical tectonic inversion of accretionary wedges (Di Giulio, 1992; Gasinski et al., 1997). The three lowermost and younger units underwent multi-phase ductile-brittle deformation, whereas the oldest and topmost San Remo-Monte Saccarello Unit is characterized by a rather simple structural setting, with relatively large-scale, open SW-verging kink folds (e.g., Di Giulio, 1992; Seno et al., 2005; Maino and Seno, 2016).

### 2.2 Stratigraphy

The San Remo-Monte Saccarello Unit consists of calcareous and mixed siliciclastic-calcareous successions that were deposited in abyssal environments in the Piedmont-Ligurian oceanic basin (Sagri, 1984; Di Giulio, 1992). This basin represents a branch of the Western Tethys that developed between the European and the Adria continental margins as a result of sequential rifting and spreading stages from early to late Jurassic (e.g., Marroni and Pandolfi, 2007 and references therein). The San Remo-Monte Saccarello Unit is divided in three lithostratigraphic units (Fig. 2A, B). The base of the unit is made up of the San Bartolomeo Formation, a succession of laterally extensive, thin-bedded and very fine-grained turbidites. This unit is interpreted as representing the abyssal plain deposits which form the allochthonous "basal complex" of the overlying turbidites (Vanossi et al., 1986). Varicolored Mn-rich shales at the base of the unit are overlain by more sandy shales and thin-bedded turbiditic limestones with minor intercalations of fine-grained sandstones towards the top of the formation (Di Giulio and Galbiati, 1985). Based on foraminiferal faunas, the age of the San Bartolomeo Fm. can be constrained to late Hauterivian to Campanian (Cobianchi et al., 1991; Galbiati and Cobianchi, 1998). The San Bartolomeo Fm. reaches an overall thickness of 200 – 300 m (Giammarino et al., 2010) and is conformably superimposed by both the Bordighera Sandstone and the San Remo Flysch (Di Giulio, 1992). Owing to a scarcity of microfaunas, the depositional ages of these younger formations are not well defined but can be attributed to the Campanian-Maastrichtian (Di Giulio, 1992; Giammarino et al., 2010). The Bordighera Sandstone mainly consists of medium- to thick-bedded, microconglomeratic to medium-grained siliciclastic turbiditic beds and reaches a thickness of more than 250 m (Giammarino et al., 2010). A general south to north, proximal to distal facies trend defines the sand-rich turbidite system (Sagri, 1980; Mueller et al., 2017). The San Remo Flysch is primarily made up of medium- to thick-bedded, fine-grained calcareous turbiditic sediments and ranges in thickness between 100 m and 650 m (Giammarino et al., 2010). These formations are interpreted to have been deposited in an abyssal domain below the carbonate compensation depth, presumably in a trench environment (Sagri, 1980; Di Giulio, 1992).

## 3 Samples and methodology

The sampling strategy intended to provide full coverage of the vertical stratigraphic expression of the San Bartolomeo Fm. succession and of the Bordighera Sandstone turbidite system. Sample locations are illustrated in Fig. 2A. Twelve samples from the San Bartolomeo Fm. were acquired from outcrops located in immediate vicinity to the type locality in the Valle Argentina (Fig. 3A, B). Samples from two continuously exposed stratigraphic sections of the Bordighera Sandstones were selected: (i) nineteen samples from the Monte Frontè section (Fig. 3C), in the axial domain, and (ii) eleven samples from the

Cima di Velega section (Fig. 3D), representative of the more distal preserved part of the system (see Mueller et al., 2017). The two sampled sections of the Bordighera Sandstones were selected because they both include a stratigraphically conformable basal contact with the San Bartolomeo Formation. Subsequently, thin-sections of 42 medium- to very fine-grained rock samples were prepared and analyzed by optical microscopy.

Petrographic analysis was conducted by a standard point-counting at the optical microscope according to guidelines provided by Di Giulio and Valloni (1992), following the Gazzi-Dickinson approach in order to reduce bias in modal composition due to sample size effects (cf., Ingersoll et al., 1984; Dickinson, 1985). Modal analysis was performed by counting a minimum of 250 framework grains per thin-section under both plane-parallel polarized and cross-polarized light. Framework parameters and full modal analysis results are reported in Supplementary data file 1. The degree of grain roundness was evaluated by visual comparison of the counted grains. Compositional maturity of sandstones was appraised by calculating the maturity index (MI), i.e., the ratios of total quartz grains over the sum of all feldspar grains and lithic fragments: MI = $\frac{Q}{(F+L)}$ (Pettijohn, 1975).

Sandstone petrography analysis was supplemented by U-Pb detrital zircon chronology (e.g., Fedo et al., 2003; Andersen, 2005; Dickinson and Gehrels, 2009). Six samples for detrital zircon age determinations were collected from stratigraphic intervals identical to those sampled for petrographic analysis (see Fig. 2B). Of these, three samples from different stratigraphic intervals of the San Bartolomeo Fm. were collected out of which only two yielded suitable quantities of detrital zircons. The other three samples come from the Bordighera Sandstone, one from the medial Monte Frontè section and two samples from the base and top of the more distal Cima di Velega section. The samples were processed for heavy mineral and detrital zircon separation by grinding, hydrodynamic procedures, magnetic isodynamic and heavy liquid separation (performed at the University of Padova). Separated zircons were hand-picked, placed into epoxy resin and polished to expose the zircon cores. For the purpose of revealing morphologies and internal structures of analyzed grains, micro-scale cathodoluminescence imaging was performed at the University of Genova and ENI SpA Laboratories.

U-Pb detrital zircon ages were determined at the LA-ICP-MS lab at the CNR - Istituto di Geoscienze e Georisorse, Unità di Pavia, Italy. Analytical procedures of detrital zircon U-Pb age determinations and analytical setups are presented in Supplementary data file 2. Only U-Pb ages with a discordance smaller than 10% were considered as reliable ($^{206}Pb/^{238}U$ ratios for grains younger and $^{206}Pb/^{207}Pb$ data for grains older than 1.2 Ga; cf., Gehrels et al., 2009). Discordant data were rejected. U-Pb precision estimations referred to in the text and figures are reported as 2σ values. Probability density plots (PDPs) and kernel density estimated (KDEs) were plotted with the DensityPlotter 8.1 software (Vermeesch, 2012). Statistical evaluation of detrital zircon age spectra similarities was conducted utilizing the DZStats 2.2 software (Saylor and Sundell, 2016).

## 4 Results from modal framework analysis

### 4.1 Detrital petrology of the San Bartolomeo Formation (basal complex)

Average grain size of the analyzed samples of the San Bartolomeo Formation ranges from very fine to fine sand. Sorting is predominantly well to moderate (Fig. 4A-C). Grains are typically sub-rounded to rounded (Fig. 4B). Sandstone grains are relatively loosely packed, with an average content of intergranular constituents (matrix and cements) of ca. 19% of total rock volume. Quartz represents the dominant constituent of the basal complex sands. Among the quartz grains, monocrystalline quartz is the by far most abundant quartz component (mean Qm/Qp ratio: 6.14). Alkali feldspar proportions are higher than those of plagioclase (mean P/K-ratio: 0.48). Lithic fragments occur in very small quantities, with metamorphic fragments slightly dominating over volcanic and sedimentary rock fragments. The samples show high compositional maturity, with maturity index values ranging from 1.46 to 3.73 (mean MI = 2.32). Accessory constituents are micas, siliciclastic mudclasts and heavy minerals, with zircons representing the most widespread heavy mineral variety.

### 4.2 Detrital petrology of the Bordighera Sandstone

The mean grain size of the analyzed Bordighera Sandstone samples is medium sand, associated with a poor degree of sorting. Framework grains are typically angular to sub-angular (Fig. 4D-F). Minor occurrences of sub-rounded grains are generally limited to samples of the uppermost parts of the stratigraphic sections. The samples are characterized by relatively loose packing as the average matrix content is 10% of total rock volume (see also Fig. 4D, E). Among the main framework components, detrital quartz grains make up the majority. Monocrystalline quartz dominates over polycrystalline quartz varieties (mean Qm/Qp ratio: 1.92). Polycrystalline quartz varieties exhibit both straight and sutured grain boundaries. Alkali feldspar concentrations exceed those of plagioclase (mean P/K-ratio: 0.56). Lithic fragments represent a recalculated average of 2%. Despite sedimentary, volcanic and metamorphic lithic fragments account for roughly equal shares, a dominance of metamorphic fragments is observable. Maturity index values vary between 0.6 and 1.37 (mean MI medial section: 1.08; mean MI distal section: 0.89). Among the accessory minerals, micas represent the most abundant constituent (mean share of 2.3% of total rock volume), with minor amounts of heavy minerals. Authigenic minerals are mainly represented by calcite cement which locally also fills the pore spaces derived from partial dissolution of altered plagioclase (Fig. 4F, G).

### 4.3 Interpretation of the detrital petrology data set

Modal framework compositions of both the San Bartolomeo basal complex and the Bordighera turbidite system suggest a continental block origin (Fig. 5A) according to the classical QtFL tectonic field discrimination plots (cf., Dickinson et al., 1983; Dickinson, 1985). The dominance of monocrystalline quartz over polycrystalline quartz varieties characterizing both units points towards dominantly plutonic parent rocks (e.g., Palomares and Arribas, 1993; Di Giulio et al., 1999; Datta, 2005). Minor proportions of polycrystalline quartz characterized by sutured domain boundaries and metamorphic lithic fragments indicate that – albeit to a lesser extent - low-grade metamorphic source rocks contributed to the clastic detritus (Das Gupta and Pickering, 2008). The fact that plagioclase is generally subordinate to alkali feldspar and the low percentages of micas further support the inferred dominant contribution from plutonic source rocks, specifically granitoids (e.g., Palomares and Arribas, 1993; McCann and Arbues, 2012). The QmPK ternary plots (Fig. 5B) reveal no major differences in feldspar varieties´ proportions between the two units. In contrast, the ratios between quartz and feldspar components show a significant up-section shift from the San Bartolomeo Formation to the Bordighera Sandstone (Figs 5A, 6). The San Bartolomeo Fm. samples are characterized by higher quartz proportions and a high degree of sorting, considerably differing from those of the Bordighera Sandstone:

Detrital petrology of the San Bartolomeo Formation samples allows their classification as quartz-rich sandstones to subarkoses (Folk, 1980), with an enhanced textural and compositional maturity (mean maturity index = 2.32; see Fig. 6). This mature character could reflect that these sediments experienced extended transport along continental surfaces characterized by low paleo-relief. The sediments were apparently subjected to prolonged exposure in depositional environments along their pathway from the source area to the final deep-marine sink (e.g., Boggs, 2009; Garzanti et al., 2014). Higher quartz contents in the San Bartolomeo Formation samples moreover imply intense weathering of the less stable grains along relatively low-relief continental land masses (Dickinson and Suczek, 1979).

By contrast, the Bordighera Sandstone samples show balanced proportions of quartz and feldspar and a scarcity of lithic fragments and can thus be classified as "classic" arkosic sandstones (Folk, 1980). Mainly angular to sub-angular grain morphologies and the poor degree of sorting reveal their textural immaturity. The relatively high feldspar content mirrors compositional immaturity (cf., Ghazi and Mountney, 2011). The lower maturity indexes of the Bordighera Sandstone samples (Monte Frontè section: MI = 1.08; Cima di Velega section: MI = 0.89; see Fig. 6), with respect to the underlying San Bartolomeo Fm., indicate shorter transport distances and rapid transportation rates, in a scenario in which sediments were almost directly shed into the deep-marine realm (cf., Zhang et al., 2016). Due to rapid denudation of the source area, no significant reworking that promoted unstable grains to dissolve occurred (e.g., Shanmugam and Moiola, 1988; Mattern, 2005). The observed low degree of both textural and compositional maturity would moreover suggest the dominance of physical weathering processes over chemical weathering (Diekmann and Wopfner, 1996). A first-cycle origin from crystalline source rocks can be inferred, as the greater abundance of chemically and mechanically less stable feldspar grains together with the negligible proportions of sedimentary rock fragments reasonably rule out a recycled provenance from quartz-rich clastic sediments (e.g., Dickinson et al., 1983; Johnsson et al., 1988; Di Giulio et al., 2003; Garzanti et al., 2006).

Summarizing, the bulk of the San Bartolomeo Fm. samples fit in the transitional continental-block provenance field, whereas the Bordighera Sandstone samples largely plot in the basement-uplift provenance field. Nonetheless, minor overlapping between the San Bartolomeo Fm. and the Bordighera Sandstone samples is evident in the provenance discrimination field (Fig. 5A) which would imply a somewhat gradual provenance evolution. Notably, the San Bartolomeo Fm. samples accounting for minor overlapping with the Bordighera Sandstone's compositional field were collected from the uppermost part of the formation. Consequently, a fundamentally inverse tectonic stability trend (i.e., from relatively stable to unstable source areas) in between the two units is recorded by detrital petrology (e.g., Dickinson et al., 1983; Garzanti et al., 2014). The possible interpretation of the observed detrital signature evolution is twofold: (1) a different source for clastic sediments forming respectively the San Bartolomeo Fm. and the Bordighera Sandstone, or (2) a common source for both formations that was subjected to a gradual change of regional tectonics resulting in differences in terms of weathering and the depositional setting of the two terrigenous formations. To solve this problem, and at the same time aiming to acquire more precise information about the possible source region for the studied units, U-Pb geochronological study of detrital zircons was undertaken.

## 5 Results from detrital zircon chronology

### 5.1 Age determinations and qualitative comparison of detrital age spectra

LA-ICP-MS age determinations of 108 single grains of the San Bartolomeo Fm. yielded 83 detrital ages (within ±10% of discordance). The analysis of 225 single grains of the Bordighera Sandstone yielded 186 concordant ages. Representative cathodoluminescence images are illustrated in Fig. 7, and full isotopic U-Pb analytical data is presented in Supplementary data file 3. Qualitative comparison of the obtained detrital spectra (normalized probability density plots in Fig. 8) reveals marked similarities in between the analyzed samples. For all the samples, > 85% of the ages younger than 1 Ga fall into the interval between 250 Ma and ca. 650 Ma. All detrital spectra display the most prominent broader peaks of Carboniferous ages around 360 Ma and 300 Ma which account for more than one third of all obtained ages. Additionally, there are significant populations of Silurian and Ordovician ages around 450 Ma and 480 Ma and one distinct Ediacaran peak around 560 Ma. Notably, narrow early- to mid-Permian peaks between ca. 270 Ma and 305 Ma are limited to samples SBF_4, CdV_1 and CdV_3. Significant Cambrian ages have only been determined in samples SBF_4 and CdV_1. Paleo- and Mesoproterozoic ages make up accessory peaks. With respect to their very broad distributions and the fact that these ages do not occur at a comparable magnitude than younger detrital ages, these old populations provide inadequate direct provenance information. The oldest dated grain corresponds to a $^{206}Pb/^{207}Pb$ crystallization age of 3028.5 ±49.9 Ma (SBF_4 sample), whereas the youngest grain reveals a reliable $^{206}Pb/^{238}U$ age of 259.4 ±5.2 Ma (CdV_3 sample).

**5.2 Statistical comparison of detrital age spectra**

For the purpose of providing a quantitative evaluation of whether the detrital age distributions of the samples from the two formations originated from the same parent rocks, a Kolmogorov-Smirnov test (K-S test) was conducted (e.g., Satkoski et al., 2013; Saylor and Sundell, 2016). In terms of detrital zircon age spectra analysis, the probability calculated (K-S test p-value) represents the probability that two or more randomly selected populations have originated from the same parent population. This degree of dissimilarity between compared age distributions is calculated by the maximum distance in between cumulative probability functions. KS-test p-values >0.05 confirm with a 95% confidence that the compared samples were derived from the same source (e.g., DeGraaff-Surpless et al., 2002; Dickinson and Gehrels, 2009; Satksoski et al., 2013). Cumulative probability functions are shown in Fig. 9A, and the results of the statistical evaluation of age spectra similarities (K-S test p-values) are shown in Fig. 9B. With the single exception of the direct comparison between the MF_1 and CdV_3 samples (p-value of 0.034), all combinations of detrital samples passed the K-S test p-value threshold. Accordingly, based on the integrated results from modal framework analysis and detrital geochronology, the inference is that the terrigenous successions were derived from the same source terrane.

### 5.3 Provenance significance of detrital age spectra and relation to potential source areas

With regards to the geochronologically well-defined geodynamic framework of Central and Western Europe (e.g., von Raumer et al., 2003; Linnemann et al., 2004; Dallagiovanna et al., 2009; Handy et al., 2010; Oggiano et al., 2010), the determined detrital zircon age spectra reveal several similarities with age peaks of geochronologically well-defined magmatic and metamorphic events that affected pre-Alpine basement successions. On that premise, the fit between clusters of detrital age populations and regional-scale geodynamic events provides further understanding of the regional paleogeography and the geodynamic setting of the sediment source. The peaks in the detrital zircon age spectra of the San Bartolomeo Fm. and the Bordighera Sandstone directly correspond to geological events recorded in pre-Alpine basement rocks. These age clusters embrace:

- **Ages older than 600 Ma**. This age group comprises Archean ages ranging from ca. 3 Ga to 2.55 Ga that are interpreted to reflect the first event of craton accretion (Cawood et al., 1999). Proterozoic ages spanning an interval from ca. 2000 Ma until 1600 Ma are interpreted as representing the assembly of Laurentia and accretion along its eastern margin (Cawood et al., 1999). Ages related to the assembly of the Rodinia supercontinent, the Greenville orogeny, span an interval from ca. 1200 Ma to 1000 Ma (Li et al., 2008; Meinhold et al., 2013), whereas ages ranging from 1 Ga to ca. 600 Ma can be assigned to the onset of the breakup of Rodinia. Magmatic activity related to preceding rifting occurred from ca. 850 to 750 Ma (e.g., von Raumer et al., 2014).
- **Ages related to the Pan-African / Cadomian orogenic cycles:** This age cluster comprises radiometric ages related to the Cadomian events. These widespread events occurred from ca. 600 Ma to 450 Ma (von Raumer et al., 2014) and represent a series of continental accretions at the margins of Gondwana which were to become involved into the formation of the

supercontinent Pangea. Extensive granitoid emplacement affected the pre-Variscan basement (Linnemann et al., 2008).

- **Ages related to Cambrian rifting stages** date from ca. 530-490 Ma. These crystallization ages are associated with magmatism at the onset of the collapse of the Cadomian orogeny that gave rise to multiple rifting and subduction episodes which marked the evolution of the Rheic ocean (Linnemann et al., 2004; Rossi et al., 2009; Maino et al., 2018). Stampfli et al. (2012) propose the drifting of pre-Variscan blocks away from Gondwana to form the European Hun terranes in the late Cambrian. The assemblage of these continental fragments was accompanied by magmatic pulses along the North African margin.
- **Ages related to Ordovician-Silurian magmatism**. Detrital ages ranging from ca. 490 to 440 Ma are assignable to the continuation of the collapse of the Cadomian orogeny that lead to the opening of the Paleo-Tethys rift and the progressive rifting of the Hun terrane in the Silurian (von Raumer et al., 2003). These early Paleozoic extensional tectonics gave rise to magmatic episodes that are documented to have extensively occurred along the Northern Gondwana margin. Magmatic activity is documented from Sardinia (Oggiano et al., 2010) as well as from the future External massifs (Argentera massif; cf., Rubatto et al., 2001, 2011). Gaggero et al. (2007) reported three distinct phases of magmatism in Sardinia that can be divided into events related to an early Ordovician rifting stage, Middle Ordovician arc volcanism and a late Ordovician to Silurian stage of volcanism resultant from continental drifting.
- **Ages representing events linked to the Variscan orogeny.** Ages spanning from ca. 390 to ca. 320 Ma are interpreted to reflect the continental collision of Gondwana, Laurussia and numerous microcontinental fragments in the Carboniferous. Related magmatic events represent the most widespread zircon age signature among both Tethyan margins (e.g., von Raumer et al., 2003; Beltrán-Triviño et al., 2013) and are represented by a series of granite emplacements (e.g., Calabria: Williams et al., 2012; Fornelli et al., 2016; Sardinia: Pavanetto et al., 2012; Corsica: Giacomini et al., 2006; Casini et al., 2012; Li et al., 2014; Ligurian Alps:

Dallagiovanna et al., 2009; Maino et al., 2012; Internal Western Alps massifs: Dora Maira: Sandrone et al., 1993; Manzotti et al., 2016; External massifs: Mont Blanc, Argentera: Ménot et al., 1994; Rubatto et al., 2001, 2011). Importantly, Variscan magmatic episodes are preferably recorded in the paleo-European basement in comparison to that of the Southern Alps (Linnemann et al., 2008; cf., Beltrán-Triviño et al., 2013).

- **Ages associated with post-Variscan magmatism** (ca. 300-280 Ma) are attributable to gravitational collapse of the thickened Variscan orogenic crust (McCann et al., 2006). Alternating transpressional and transtensional tectonic regimes promoted the development of continental basins in Central and Western Europe. Characteristic graben and half-graben structures are typically associated with syntectonic volcanic activity. Magmatic activity related to the initial orogen collapse is mostly documented from Calabria (Liotta et al., 2008), Sardinia (Ronca et al., 1999; Gaggero et al., 2017), and Corsica (Cabanis et al., 1990) as well as from the Southern Alps (e.g., Quick et al., 2009; Berra et al., 2014).
- **Ages attributed to mid-Permian to Lower Triassic magmatism** range from ca. 270 Ma to 240 Ma. Recent research documents a later stage of volcanism restricted to the Southern Alps (Beltrán-Triviño et al., 2013), Calabria (Fornelli et al., 2011), Sardinia and Corsica (Traversa et al., 2003; Gaggero et al., 2007), as well as to the Ligurian Alps (Dallagiovanna et al., 2009; Maino et al., 2012). These latter events are related to intense magmatic activity interpreted to reflect the onset of drifting since the Middle Triassic and might therewith epitomize the beginning of the Alpine cycle (cf., Beltrán-Triviño et al., 2013). It should be noted that these later-stage volcanic episodes can be separated from the post-Variscan magmatic events by a period of strike-slip activity and intermittent granite emplacement (cf., McCann et al., 2006).

## 6 Source area inference

Detrital modal assemblages of both the basal complex (San Bartolomeo Formation) and the coarse-clastic turbidite system (Bordighera Sandstone) indicate that predominantly upper crustal rocks – mainly granitoid plutons - provided the source rocks. Minor contributions by low-grade metamorphic rocks are recorded by very minor proportions of metamorphic lithic fragments. Owing to dissimilar architectures of the bounding margins of the Piedmont-Ligurian ocean, different levels of the continental crust were exposed (e.g., Müntener and Hermann, 2001; Bracciali et al., 2007; Malusà et al., 2015; Decarlis et al., 2017). According to Froitzheim and Manatschal (1996), the opening of the Piedmont-Ligurian ocean occurred in two stages. The initial rifting stage, assigned to the late Triassic to early Jurassic, was typified by the development of listric fault systems which represent symmetric lithosperic stretching. Contrastingly, in the early-middle Jurassic, lithosperic-scale detachment faults developed that facilitated passive asymmetric extension. The paleo-European margin comprised a crustal section mostly composed of granitoids and low-grade metamorphic rocks, whereas the Adriatic margin exposed a full crustal lithospheric section that also included high-grade metamorphic rocks (cf., Bracciali et al., 2007).

The sandstone detrital modes of the two successions reveal the dominance of plutonic constituents and for that reason suggest a paleo-European provenance. The integration of the results from detrital zircon chronology confirms the presumption that the paleo-European (i.e., the Northern Tethyan) margin provided the bulk of the clastic detritus. Essentially the dominant peaks related to the onset of the Variscan cycle that typify the detrital spectra allow to rule out a source terrane located in the Adriatic margin (cf., Bütler et al., 2011; Beltrán-Triviño et al., 2013). In particular, the distinct peaks of Mississippian ages (ca. 330 to 355 Ma) are absent in crystalline suites of the Adriatic margin (i.e., in the Sesia microfragment; e.g., Klötzli et al., 2014; Malusà et al., 2015). Moreover, the occurrence of Cambrian detrital zircons provides further evidence for a source terrane located in the European margin (Rossi et al., 2009; see also Thomas et al., 2010 and Fornelli et al., 2015 for discussions on European and "African" provenance signatures).

In combination with the prominent Carboniferous to lower Permian detrital age peaks, the data discussed above suggests that dominantly plutonic source terranes distributed along the margins of the composite crystalline Southern Variscan belt margins represent potential source areas. According to paleogeographic maps (e.g., von Raumer et al., 2002; Casini et al., 2015), the Variscan and pre-

Variscan continental basement assemblages of the Briançonnais, the Dora-Maira Massif (as part of the internal massifs of the proximal European margin), the Argentera Massif of the External Massifs, as well as the Corsica-Sardinia Batholith and the Calabrian granitoid massifs need to be taken into consideration. Although no paleocurrent indicators for the San Bartolomeo Fm. could be identified, analysis of paleocurrent indicators for the Bordighera Sandstones reveals a reasonably unidirectional (present-day) N-NE orientation of the main sediment flux. This is also confirmed by the distinct South-North directed facies trend characterizing the Bordighera Sandstone (see paleocurrent rose in Fig. 2A and Mueller et al., 2017, for details on facies distribution). Therefore, the source terrane must have been located in the SSW of the Bordighera turbidite system and candidate source areas can thus be narrowed to the Corsica-Sardinia block and the Calabrian massifs. Both terranes record geochronologically well-constrained evidence of magmatic and metamorphic pulses which are readily compatible with peaks of the detrital spectra (e.g., Giacomini et al., 2006, 2007; Gaggero et al., 2007, 2017; Liotta et al., 2008; Rossi et al., 2009; Oggiano et al., 2010; Casini et al., 2012; Pavanetto et al., 2012; Williams et al., 2012; Langone et al., 2014; Li et al., 2014; Fornelli et al, 2016). However, taking the abundant late Neoproterozoic ages of the detrital spectra into account, the Calabrian massifs can be ruled out, since the occurrence of late Ediacaran (pronounced peak around 650 Ma) magmatic activity or metamorphic phases have not been documented from Calabria (cf., Liotta et al., 2008; Williams et al., 2012; Fornelli et al., 2016). In particular, the marked similarity between Devonian to early Permian detrital zircon age peaks of the investigated sediments (see synthetic probability density plots of all obtained detrital ages in Fig 10) and pulses of crystallization ages that define the Sardo-Corsican batholiths (i.e., ca. 345-337 Ma "Durbachites" from NW Corsica of Paquette et al., 2003, and the ca. 325-285 Ma U2 and U3 suites of Casini et al., 2012, 2015) suggest that the Corsica-Sardinia block is the primary source area for both terrigenous formations of the San Remo-Monte Saccarello Unit. Such a scenario has previously been proposed solely based on paleocurrent analysis and observations on grain composition (e.g., Vanossi, 1965; Sestini, 1970; Sagri, 1980, 1984) and is herewith confirmed by means of coupling petrographic analysis with U-Pb detrital zircon chronology.

## 7. Discussion

### 7.1 Comparison to proposed provenance models for flysch successions of the Piemont-Ligurian ocean

Numerous provenance studies addressed pre-collisional flysch successions of the Northern Apennines (e.g., Sagri and Marri, 1980; Valloni and Zuffa, 1984; Wildi, 1985, 1987; Rowan, 1990; Fontana et al., 1994; van de Kamp and Leake, 1995; Argnani et al., 2006; Bracciali et al., 2007). Flysch sedimentation occurred in two distinct paleogeographic domains, the Internal and the External Ligurian Units (Marroni et al., 2001). The Internal Ligurian Units represent a continuous succession ranging from the Jurassic ophiolites through Cretaceous and Paleocene turbidite successions, whereas in the External Ligurian Units the sedimentary succession became detached from their underlying oceanic crust substrate. Siliciclastic successions of the Internal Ligurian Units have generally been attributed to a European provenance (e.g., Fontana et al., 1994; Bracciali et al., 2007). By contrast, the External Ligurian Units have been interpreted as representing the distal Adriatic margin and the transition towards the Piemont-Ligurian ocean and are hence associated to an Adriatic provenance. Among the Upper Cretaceous to Paleocene Internal Ligurian successions, Valloni and Zuffa (1984) report quartzo-feldspathic arkoses from the "Arenarie Superiori" (i.e., the Gottero Sandstone) and the Monghidoro Formation which are defined by similar primary modal parameters to the ones documented in the present study (Gottero Sandstones: mean Qt51F39L10; Monghidoro Formation: mean Qt59F38L3). Supplementary petrographic studies by Van de Kamp and Leake (1995) and Pandolfi (1996) documented similar compositions (mean Qt42F55L3 and Qt50F33L17, respectively) for the Gottero Sandstone. These compositions are reasonably similar to the results derived from the Bordighera Sandstones (mean Qt49F48L3). Wildi (1985) defined a zircon-tourmaline-rutile dominated heavy mineral association as being characteristic for the Paleo-European margin and consequently claimed the European margin source for the Upper Cretaceous Flysch Units deposited in the Piemont-Ligurian ocean. Wildi (1987) also questioned the "passive" margin configuration of the European Tethyan margin and proposed a late Cretaceous inversion of the European margin that provided a Corsica-derived source for siliciclastic successions intercalated into Helminthoid Flysch sequences, among which the San Remo-Monte Saccarello Unit (i.e., the Bordighera Sandstone) was positioned.

Available datasets from recent studies on detrital zircon assemblages of Upper Penninic flysch successions (Chu et al., 2016; Lin et al., 2018) allow a comparison of the detrital suites of this study. No overlap can be identified with allochthonous successions of Internal Liguride affinity (e.g., Pandolfi et al., 2016; Marroni et al., 2017) which were incorporated into both the Piedmont Nappe and the Balagne Nappe (Fig. 11). In contrast, the qualitative comparison reveals a striking similarity with the Eocene Annunciata Fm. that is now overthrust onto Corsica (cf., Lin et al., 2018). Notably, the Annunciata Fm., although treated as allochthonous (Egal, 1992), has more recently been considered as having undergone minor displacement and being positioned in proximity to its original depositional location (cf. Marroni et al., 2001; Lin et al., 2018). In addition, the detrital chronology signature of the pre-collisional Upper Cretaceous Schistes Lustrès presented by Chu et al. (2016) displays strong similarities as the major detrital age population peaks around 330 Ma. Either way, based on the presence of Proterozoic age peaks, Chu et al. (2016) do not clearly assign the Schistes Lustrès to either a European or an Adriatic provenance, as these old detrital ages might reflect a complex inheritance of the detrital zircon grains or the detrital zircons could be polycyclic.

### 7.2 Control mechanism for re-activation of the paleo-European margin

The documentation of major sand supply from a source area located along the lower European plate requires an explanation. Evidence for emersion of the Sardo-Corsican block is provided by the presence of Albian bauxite deposits superimposing Oxfordian to Aptian shallow to transitional marine carbonates that imply subaerial exposure (Mameli et al., 2007). Mameli et al. (2007) follow the interpretation of a transpressive tectonic regime development suggested by Puigdefabregas and Souquet (1986) as the key control on continental block uplift. However, according to the observations presented in this study, the stratigraphic evolution linked to sediment maturity implies that the reactivation of the margin of the lower European plate occurred in a craton-ward prograding orientation.

According to our interpretation, the development of a flexural forebulge due to lithospheric flexure caused by the tectonic loading of the overthrust wedge is considered as better explaining the key tectonic control on re-activating the hyper-extended paleo-European margin (e.g., Stockmal et al., 1987; Barbieri et al., 2004). The craton-ward migration of its hinge line (e.g., DeCelles and Giles, 1996; Einsele, 2000) is mirrored by a gradual provenance evolution from the highly mature sediments of the San Bartolomeo Formation towards the highly immature Bordighera Sandstone (see conceptual models in Fig. 12) within a framework similar to the one proposed by Stockmal et al. (1987) for a passive continental margin arriving in a subduction zone.

Specifically, during the Hauterivian to Santonian, the craton-ward passing hinge line of the flexural bulge affected the distal European margin, and this is interpreted to have resulted in the tectonic instability along the shelfal areas of the passive margin, where terrigenous sediments were subjected to reworking processes before being re-sedimented into the trench. Such reworking can explain the textural maturity of the sediments of the San Bartolomeo Fm. Afterwards, during the Campanian to Maastrichtian, the NNW-prograding hinge line of the flexural bulge arrived in the hinterland part of the margin and triggered the uplift of crustal blocks promoting rapid sedimentation of the first-cycle coarse-clastic detritus of the Bordighera Sandstone into the trench.

The migration of the flexural bulge parallel to the Frontal Penninic Thrust can straightforwardly be integrated into paleogeographic and tectonic models that address the reconstruction of the evolution of the Western Alps. These models demonstrate that deformation and metamorphism stepwise migrated in a NW-ward directed orientation (e.g., Schmid et al. 1996; Lister et al., 2001; Rosenbaum and Lister 2005; Handy et al. 2010). However, it should be noted that the spatial and temporal magnitudes of the deformation remain poorly constrained (Lister et al., 2001; Ford et al., 2006). Based on tectonostratigraphic relationships of sedimentary cover successions of the Briançonnais domain, a flexural forebulge development has previously been proposed (Michard and Martinotti, 2002). Michard and Martinotti (2002) suggest that late Cretaceous to Eocene disconformities mirror the passage of a flexural bulge through the distal European margin and propose a bulge amplitude of ca. 800-1000 m which resulted in extensional faulting of the uplifted continental blocks and an enhanced sediment supply. Such a scenario can readily explain the reciprocal trend in sediment maturity from passive margin-fed quartz-rich sandstones of the basal complex towards the immature Bordighera Sandstone arkoses that is documented in this study.

## 8. Conclusions

The multi-proxy sediment provenance study of the two terrigenous members of the pre-collisional San Remo-Monte Saccarello Unit of the Western Ligurian Flysch complex gains a better understanding of the pre-collisional evolution of the Piedmont-Ligurian ocean and its bounding continental margins. The main conclusions are summarized as follows:

- Petrographic analyses of the terrigenous sediments reveal an upsection transition from mature, fine-grained, quartz-rich basin plain turbidite sandstones (San Bartolomeo Formation) towards first-cycle coarse-grained arkoses (Bordighera Sandstone). The onset of coarse-clastic sedimentation is interpreted to mark a substantial modification of the geodynamic regime. Increased sediment yield and sediment caliber result from the increased slope gradient caused by rapid basement uplift (Dickinson et al., 1983). Albeit the comparison of the textural character of the two members documents a marked difference in terms of sediment maturity, average modal framework compositions suggest a more gradual provenance evolution which is interpreted to mirror the exhumation of a crystalline basement terrane during the pre-collisional stage of the Alpine convergence.
- Geochronological data (U-Pb detrital zircon ages) provide evidence that, despite the observed compositional change, the terrigenous successions were derived from the same source

terrane. In combination with results from detrital petrography, these observations document that the source area underwent significant tectonic modification from a relatively stable craton to a basement uplift setting.

- Peaks in the detrital age spectra fit with well-documented magmatic and metamorphic pulses that affected the pre-Alpine basements and allow for the identification of the lower plate passive European continental margin as the primary source of the clastic detritus. More specifically, integrating geochronological ages with paleocurrent indicators shows that the proposed provenance from the Corsica-Sardinian block is confirmed.
- In the context of the Alpine subduction, this evidence argues for tectonic activity along the passive continental margin of the subducted plate that provided the major sand supply area for the clastic sediment delivered into the subduction zone.

  The craton-ward migration of the flexural bulge developed in response to the tectonic loading of the advancing Alpine accretionary wedge and explains the re-activation and tectonic inversion of the passive paleo-European margin. This implies that the detrital evolution documented in this work reflects the activation of the passive continental margin arriving in the subduction zone.

In a broad geodynamic context, based on the present study, we suggest that the tectonic inversion of a passive continental margin arriving in a subduction zone results in a recognizable petrographic signature in the detrital record of deep-sea sequences. Therefore, this signature provides a potential though often overlooked record of the imminent transition from subduction to collision of ancient collisional systems.

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Appendix

Appendix A: Full modal framework data

Appendix B: Methodology and analytical setup of detrital zircon chronology analysis

Appendix C: Full detrital zircon isotopic data

Appendix D: Zircon standard tables

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**Figure captions:**

**Fig. 1.** Simplified geological map of the Western Alps denoting the main paleogeographic units. Modified after Schmid et al. (2004) and Bousquet et al. (2008). Location of the study area is indicated in the black rectangle.

**Fig. 2. (**A) Geological map of the study area (box in Fig. 1). Modified after Lanteaume et al. (1990) and Di Giulio and Galbiati (1991). Rose diagram of palaocurrent measurements (n = 107) for the Bordighera Sandstone delineates the predominantly NNE-directed orientation of sediment flux. (B) Tentative chronostratigraphic framework of the San Remo-Monte-Saccarello Unit and approximate stratigraphic positions of the studied detrital zircon samples. Modified after Cobianchi et al. (1991), Galbiati and Cobianchi (1997) and Giammarino et al. (2010).

**Fig.3.** Outcrop examples of the stratigraphic members of the San Remo-Monte Saccarello Unit. (A) Sample location of the lowermost terrigenous lithozone of the San Bartolomeo Fm. (variegated shales with locally intercalated very fine-grained sandstones) at the type location north of the town of "Badalucco" (see also Fig. 2A). GPS 43°55'15.47"N, 7°50'31.79"E. (B) Sample location of the uppermost analyzed terrigenous lithozone of the San Bartolomeo Fm. (fine- to medium quartzarenites that exhibit normal grading) in the Valle Argentina. GPS 43°55'32.57"N, 7°50'35.75"E; (C) Panoramic view of the San Remo-Monte Saccarello Unit comprising the conformably superimposing San Bartolomeo Fm. (SBF), the Bordighera Sandstone (BGS) and the calcareous San Remo Flysch (SRF) cropping out in an anticlinal structure at sample location "Monte Frontè". Sampling location: GPS 44° 2'44.45"N, 7°45'10.48"E.  D) Outcrop image of the coarse-clastic Bordighera Sandstone at the distalmost sample location "Cima di Velega". GPS 44° 7'46.55"N, 7°40'33.45"E. Note that strata are overturned.

**Fig. 4.** Representative thin section microphotographs for samples of the San Bartolomeo Fm. (SBF; A-C) and the Bordighera Sandstone (BGS; D-I). (A) Typical appearance of relatively well-sorted, tightly packed SBF samples. Note the textural and compositional maturity of the sandstone. (B) Characteristic quartz-dominated nature of fine-grained SBF thin-sections. Note the sub-rounded to occasionally rounded grain shapes. (C) Uppermost SBF sample illustrating lithic fragment examples: chert fragment (Ls) and volcanic fragment (Lv). (D) Characteristic poorly mature BGS sample, showing poor degree of sorting, angular grains and an arkosic composition. (E) Typical constituents of the coarse detritus represented by monocrystalline quartz (Qm), alkali feldspar (K-F) and mica (m). (F) Typical alteration of plagioclase in association with monocrystalline quartz in tightly packed framework almost devoid of matrix. (G) Examples of lithic fragments: arkosic fragment (Ls) and volcanic fragment (Lv) in association with Qm and plagioclase (Plg). Note the abundant pinkish calcite cement (c_c). (H) Representative arkosic composition comprising quartz and feldspars (in granitic fragment), and low-grade metamorphic lithic grain (Lm). (I) Fine- and microcrystalline polycrystalline quartz grains (Qp) in metamorphic fragment in association with a chert sedimentary lithic fragment (Ls).

**Fig. 5.** Sandstone modal compositions of the San Bartolomeo Fm. and the Bordighera Sandstone. (A) QtFL modal analysis (cf., Dickinson et al., 1983) and (B) QmPK modal analysis ternary plots (cf., Dickinson and Suczek, 1979). Note the consistent dominance of K-feldspar over plagioclase in all the studied samples in the QmPK plots.

**Fig. 6.** Maturity indexes (whisker plots) for samples from the three analyzed sections. Monte Frontè = medial domain of the Bordighera Sandstone; Cima di Velega = distalmost domain of the Bordighera Sandstone.

**Fig. 7.** Cathodoluminescence images of representative detrital zircon grains from samples SBF_1 (A), SBF_4 (B), MF_1 (C), CdV_1 (D) and CdV_3 (E).

**Fig. 8.** Qualitative comparison of detrital age frequency distributions (probability density plots) of the analyzed samples for A) the time interval from 0-3500 Ma and B) for the time interval from 200-1200 Ma. Geological time-scale according to the International Commission on Stratigraphy.

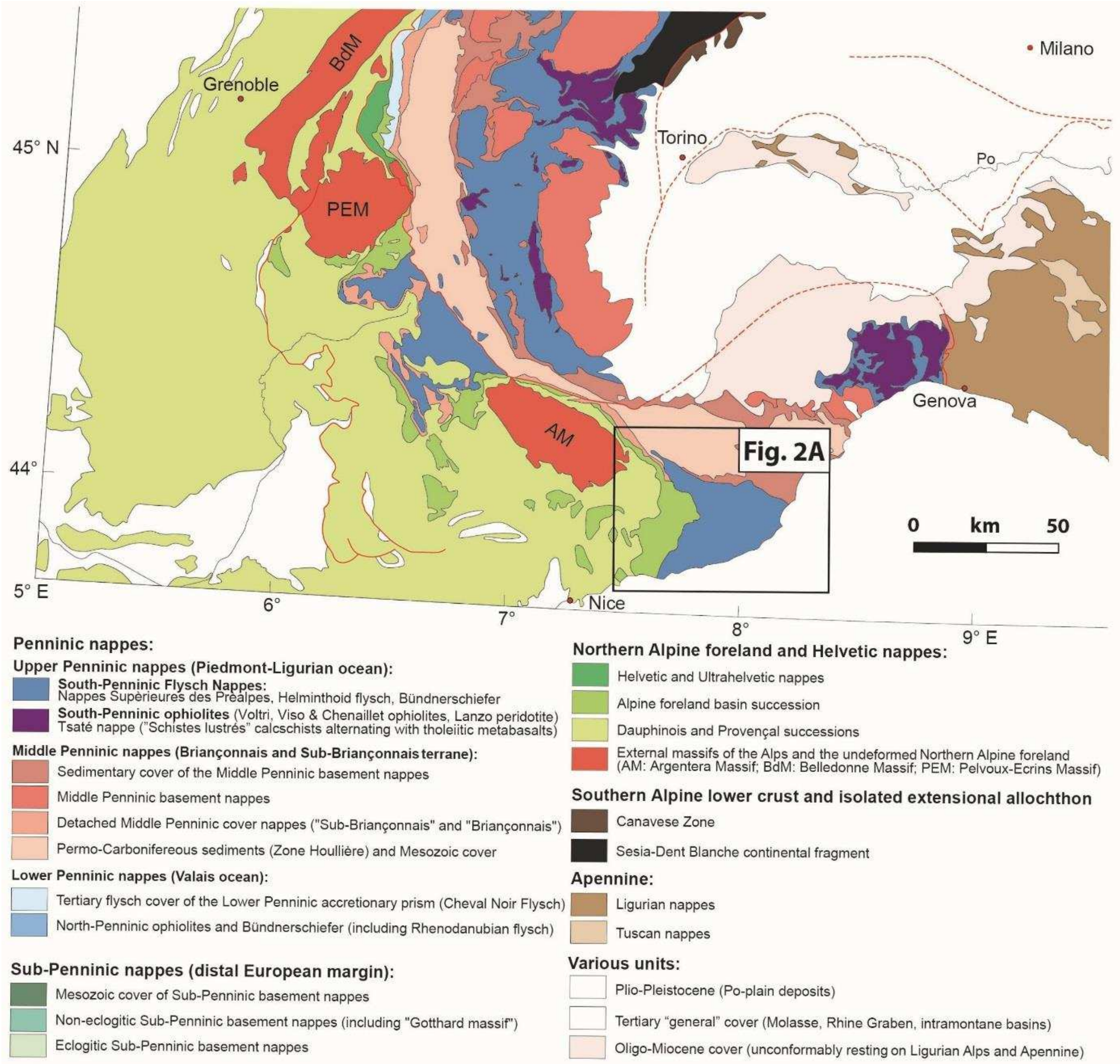
**Fig. 9. (**A) Qualitative confrontation of the detrital age spectra (cumulative distribution functions) for the time span from 0-3500 Ma and (B) Statistical evaluation of similarity (K-S test p-values) between the detrital samples cumulative distribution functions. Green-shaded boxes indicate p-values > 0.05, whereas red-shaded boxes indicate that confrontations did not pass the threshold value of 0.05.

**Fig. 10.** Histograms (bin size 5 Ma) and synthetic probability density curves of all concordant ages of samples of the Bordighera Sandstone (BGS) and the San Bartolomeo Fm. (SBF): (A) Age spectrum from 200 Ma to 800 Ma; (B) Age spectrum from 200 to 450 Ma.

**Fig. 11.** Kernel Density Estimation (KDE) plots of detrital zircon ages (200-1200 Ma) of the San Bartolomeo Fm. and the Bordighera Sandstone and of some published detrital zircon age data from Corsican (?) para-autochthonous flysch units (Eocene Annunciata flysch; samples 11CO68 and 11CO87 from Lin et al. (2017) and from the allochthonous successions of the Piedmont Nappe (Late Cretaceous Narbinco Fm. and Coniacian-Maastrichtian Tralonca Fm.) and the Albian-Cenomanian “Lydienne flysch” of the Balagne Nappe (Lin et al., 2018).

**Fig. 12.** Models for the evolution of the provenance of the investigated successions (not to scale), illustrating the effect of the inferred craton-ward (i.e., NNW-directed) shift of the flexural bulge hinge line. (A) During the Hauterivian to Santonian the flexural bulge was located in the extensive shelfal area of the distal European margin. (B) During the Campanian to Maastrichtian the flexural bulge arrived in the more proximal part of the margin. Resultant rapid uplift of crustal blocks promoted rapid sedimentation of the first-cycle Bordighera Sandstone arkoses which were shed into the trench without significant surface processes (physical and chemical) coming into effect.

Fig. 1



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Upper Penninic nappes (Piedmont-Ligurian ocean):
South-Penninic Flysch Nappes: Nappes Supérieures des Préalpes, Helminthoid flysch, Bündnerschiefer
South-Penninic ophiolites (Voltri, Viso & Chenaillet ophiolites, Lanzo peridotite) Tsaté nappe ("Schistes lustrés" calcschists alternating with tholeiitic metabasalts)
Middle Penninic nappes (Briançonnais and Sub-Briançonnais terrane):
Sedimentary cover of the Middle Penninic basement nappes
Middle Penninic basement nappes
Detached Middle Penninic cover nappes ("Sub-Briançonnais" and "Briançonnais")
Permo-Carboniferous sediments (Zone Houllière) and Mesozoic cover
Lower Penninic nappes (Valais ocean):
Tertiary flysch cover of the Lower Penninic accretionary prism (Cheval Noir Flysch)
North-Penninic ophiolites and Bündnerschiefer (including Rhenodanubian flysch)
Sub-Penninic nappes (distal European margin):
Mesozoic cover of Sub-Penninic basement nappes
Non-eclogitic Sub-Penninic basement nappes (including "Gotthard massif")
Eclogitic Sub-Penninic basement nappes
Northern Alpine foreland and Helvetic nappes:
Helvetic and Ultrahelvetic nappes
Alpine foreland basin succession
Dauphinois and Provençal successions
External massifs of the Alps and the undeformed Northern Alpine foreland (AM: Argentera Massif; BdM: Belledonne Massif; PEM: Pelvoux-Ecrins Massif)
Southern Alpine lower crust and isolated extensional allochthon
Canavese Zone
Sesia-Dent Blanche continental fragment
Apennine:
Ligurian nappes
Tuscan nappes
Various units:
Plio-Pleistocene (Po-plain deposits)
Tertiary "general" cover (Molasse, Rhine Graben, intramontane basins)
Oligo-Miocene cover (unconformably resting on Ligurian Alps and Apennine)

Fig. 2

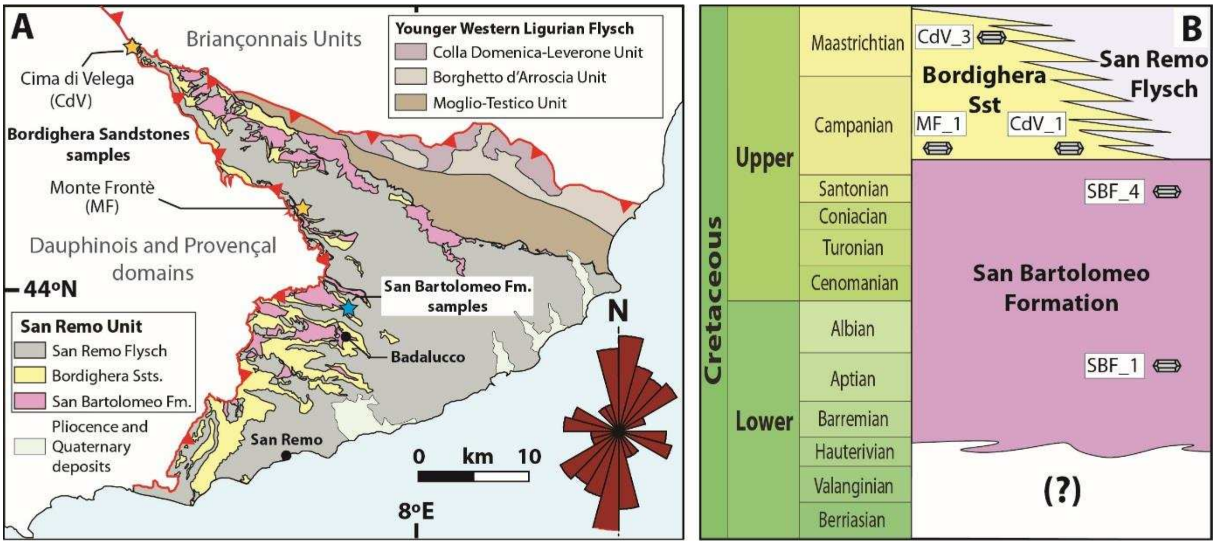

A
Briançonnais Units
Younger Western Ligurian Flysch
Colla Domenica-Leverone Unit
Borghetto d'Arroscia Unit
Moglio-Testico Unit
Cima di Velega
(CdV)
Bordighera Sandstones samples
Monte Frontè
(MF)
Dauphinois and Provençal domains
44°N
San Bartolomeo Fm. samples
San Remo Unit
San Remo Flysch
Bordighera Ssts.
San Bartolomeo Fm.
Pliocence and Quaternary deposits
Badalucco
San Remo
N
0 km 10
8°E
B
Cretaceous
Upper
Lower
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
CdV_3
Bordighera Sst
San Remo Flysch
MF_1
CdV_1
SBF_4
San Bartolomeo Formation
SBF_1
(?)

Fig. 3

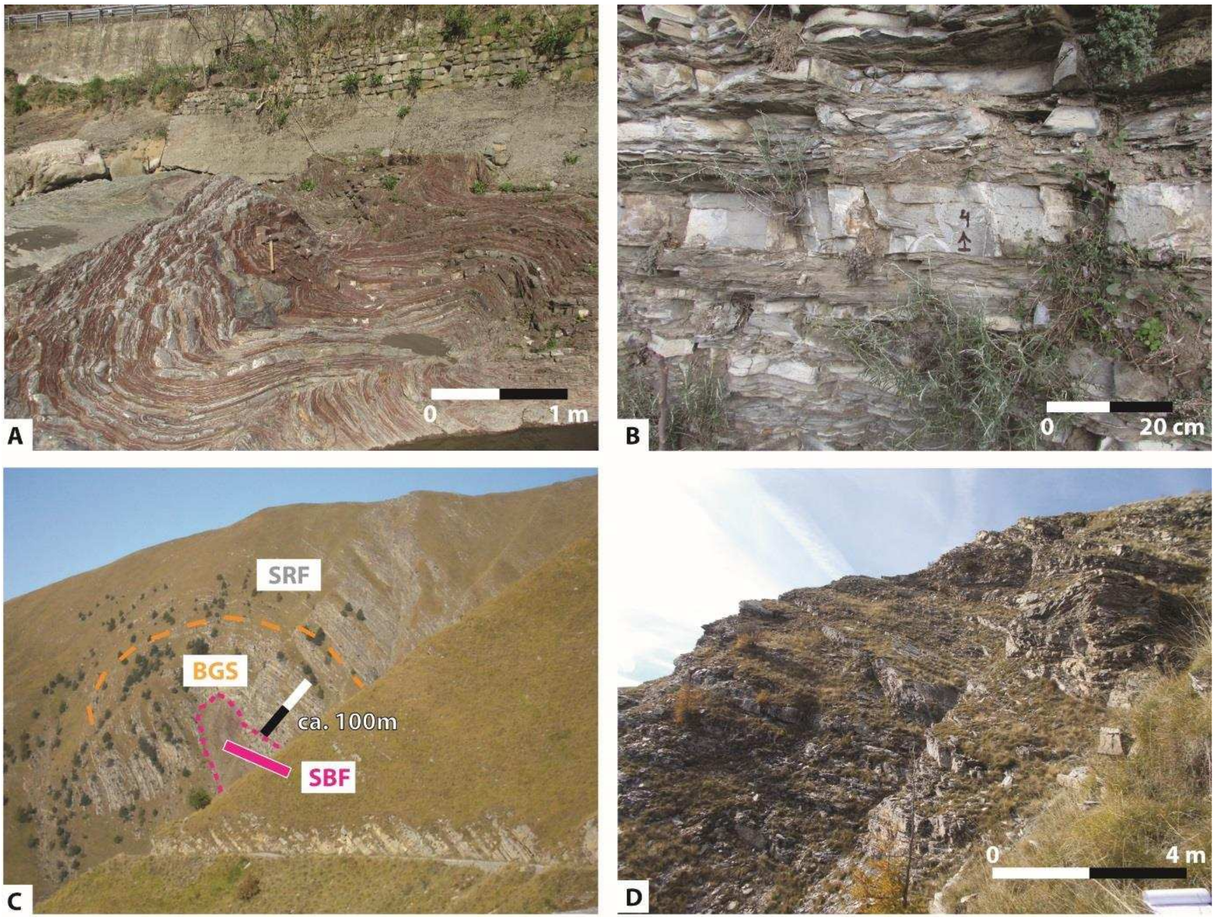


Fig. 4

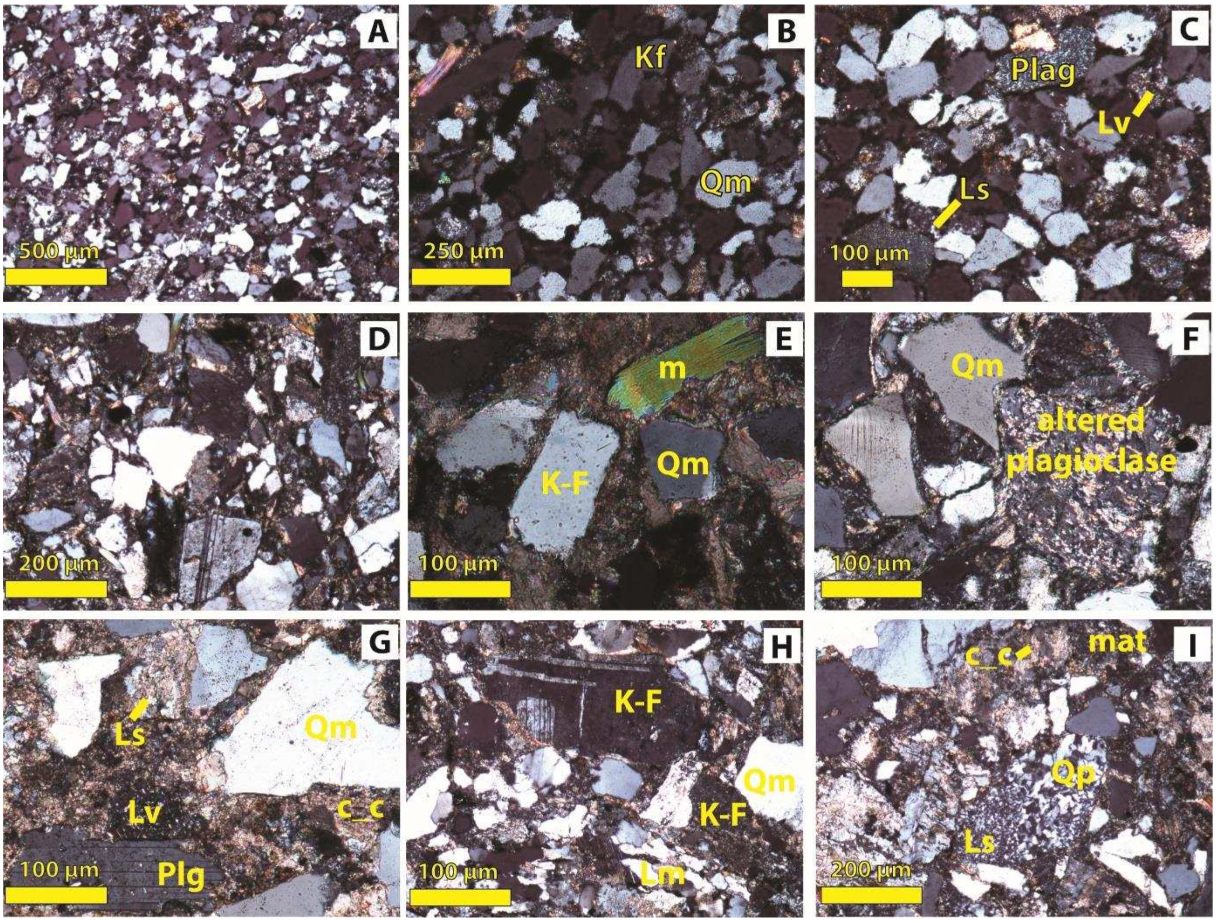

A
500 µm
B
Kf
Qm
250 µm
C
Plag
Lv
Ls
100 µm
D
200 µm
E
m
K-F
Qm
100 µm
F
Qm
altered plagioclase
100 µm
G
Ls
Qm
Lv
c_c
100 µm
Plg
H
K-F
Qm
K-F
100 µm
Lm
I
c_c
mat
Qp
Ls
200 µm

Fig. 5

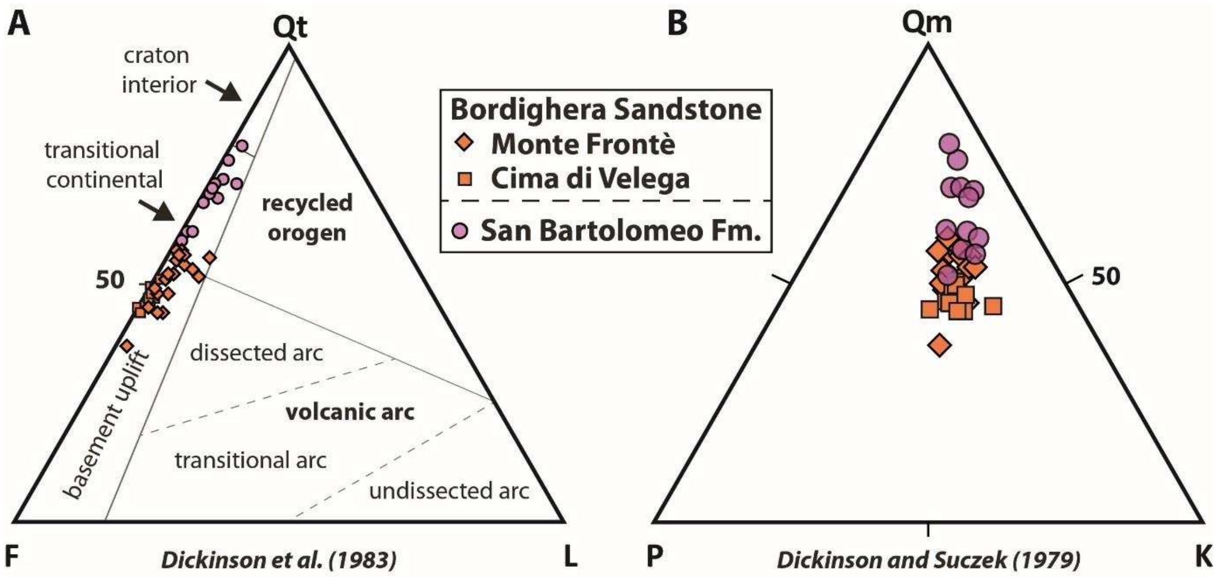

A
Qt
craton
interior
transitional
continental
recycled
orogen
50
dissected arc
volcanic arc
transitional arc
undissected arc
basement uplift
F
Dickinson et al. (1983)
L
B
Qm
Bordighera Sandstone
Monte Frontè
Cima di Velega
San Bartolomeo Fm.
50
P
Dickinson and Suczek (1979)
K

Fig. 6

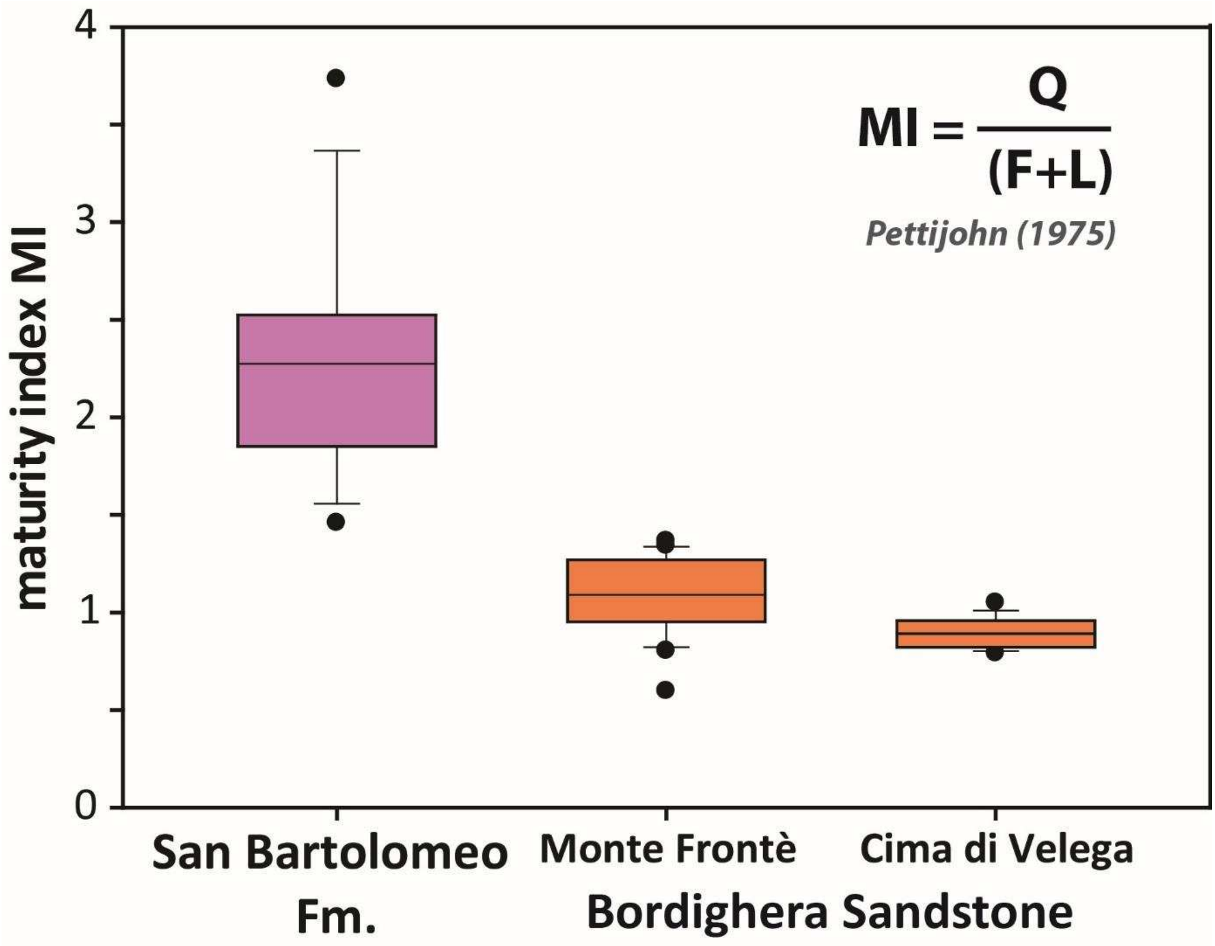

maturity index MI
4
3
2
1
0
MI = Q / (F+L)
Pettijohn (1975)
San Bartolomeo Fm.
Monte Frontè
Cima di Velega
Bordighera Sandstone

Fig. 7

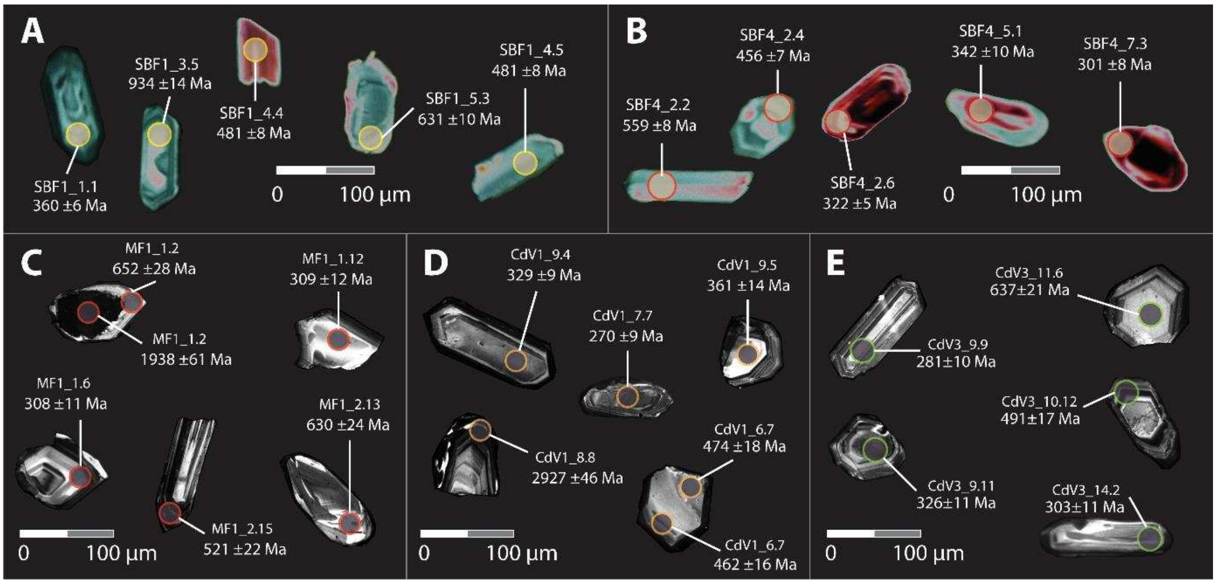

A
SBF1_3.5
934 ±14 Ma
SBF1_4.4
481 ±8 Ma
SBF1_5.3
631 ±10 Ma
SBF1_4.5
481 ±8 Ma
SBF1_1.1
360 ±6 Ma
0 100 µm
B
SBF4_2.4
456 ±7 Ma
SBF4_5.1
342 ±10 Ma
SBF4_7.3
301 ±8 Ma
SBF4_2.2
559 ±8 Ma
SBF4_2.6
322 ±5 Ma
0 100 µm
C
MF1_1.2
652 ±28 Ma
MF1_1.12
309 ±12 Ma
MF1_1.2
1938 ±61 Ma
MF1_1.6
308 ±11 Ma
MF1_2.13
630 ±24 Ma
MF1_2.15
521 ±22 Ma
0 100 µm
D
CdV1_9.4
329 ±9 Ma
CdV1_9.5
361 ±14 Ma
CdV1_7.7
270 ±9 Ma
CdV1_8.8
2927 ±46 Ma
CdV1_6.7
474 ±18 Ma
CdV1_6.7
462 ±16 Ma
0 100 µm
E
CdV3_11.6
637±21 Ma
CdV3_9.9
281±10 Ma
CdV3_10.12
491±17 Ma
CdV3_9.11
326±11 Ma
CdV3_14.2
303±11 Ma
0 100 µm

Fig. 8

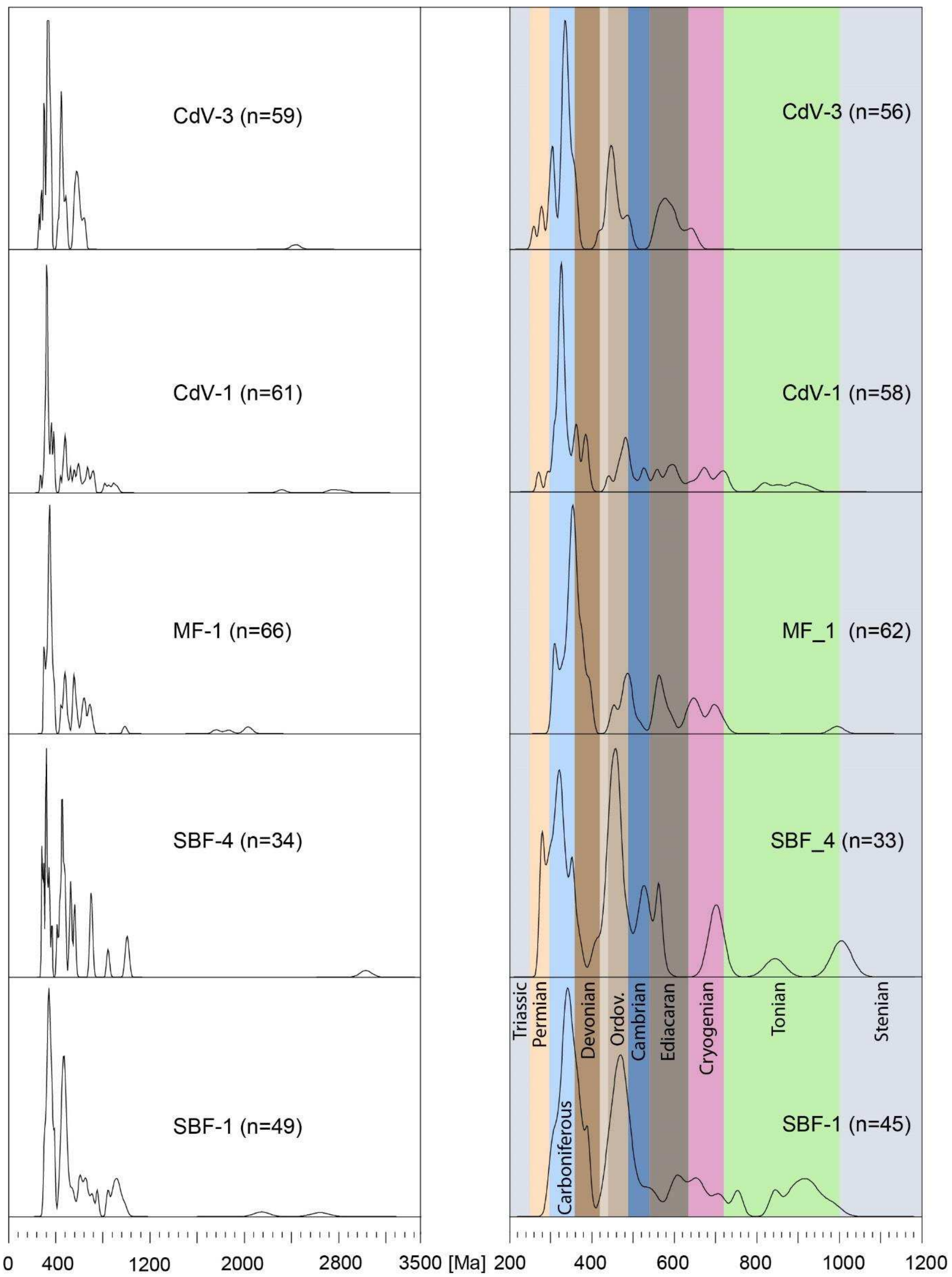
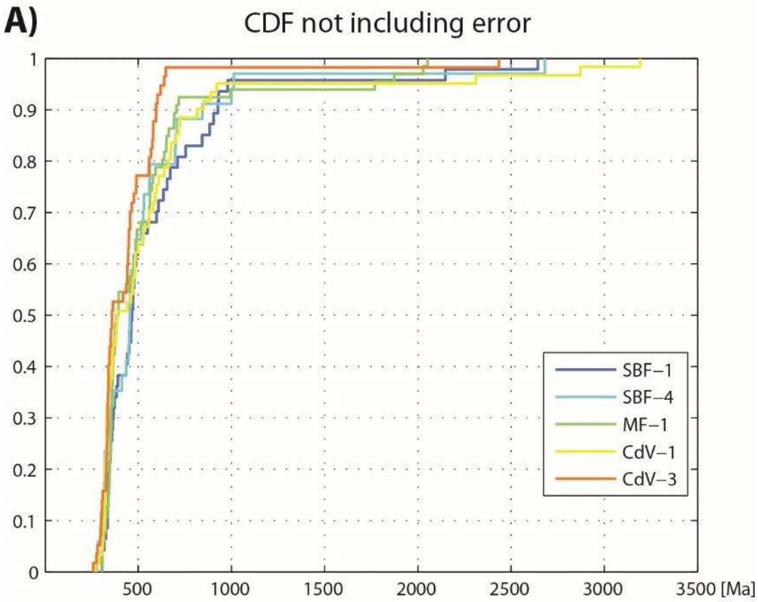

CdV-3 (n=59)
CdV-1 (n=61)
MF-1 (n=66)
SBF-4 (n=34)
SBF-1 (n=49)
CdV-3 (n=56)
CdV-1 (n=58)
MF_1 (n=62)
SBF_4 (n=33)
SBF-1 (n=45)
Triassic
Permian
Carboniferous
Devonian
Ordov.
Cambrian
Ediacaran
Cryogenian
Tonian
Stenian
0
400
1200
2000
2800
3500 [Ma]
200
400
600
800
1000
1200

Fig. 9

A)




B)

**K-S test p value**

| | SBF-1 | SBF-4 | MF-1 | CdV-1 | CdV-3 |
|---|---|---|---|---|---|
| **SBF-1** | 1 | 0.506075 | 0.429343 | 0.073544 | 0.058132 |
| **SBF-4** | 0.506075 | 1 | 0.340518 | 0.63103 | 0.199757 |
| **MF-1** | 0.429343 | 0.340518 | 1 | 0.10868 | 0.033701 |
| **CdV-1** | 0.073544 | 0.63103 | 0.10868 | 1 | 0.186431 |
| **CdV-3** | 0.058132 | 0.199757 | 0.033701 | 0.186431 | 1 |

Fig. 10

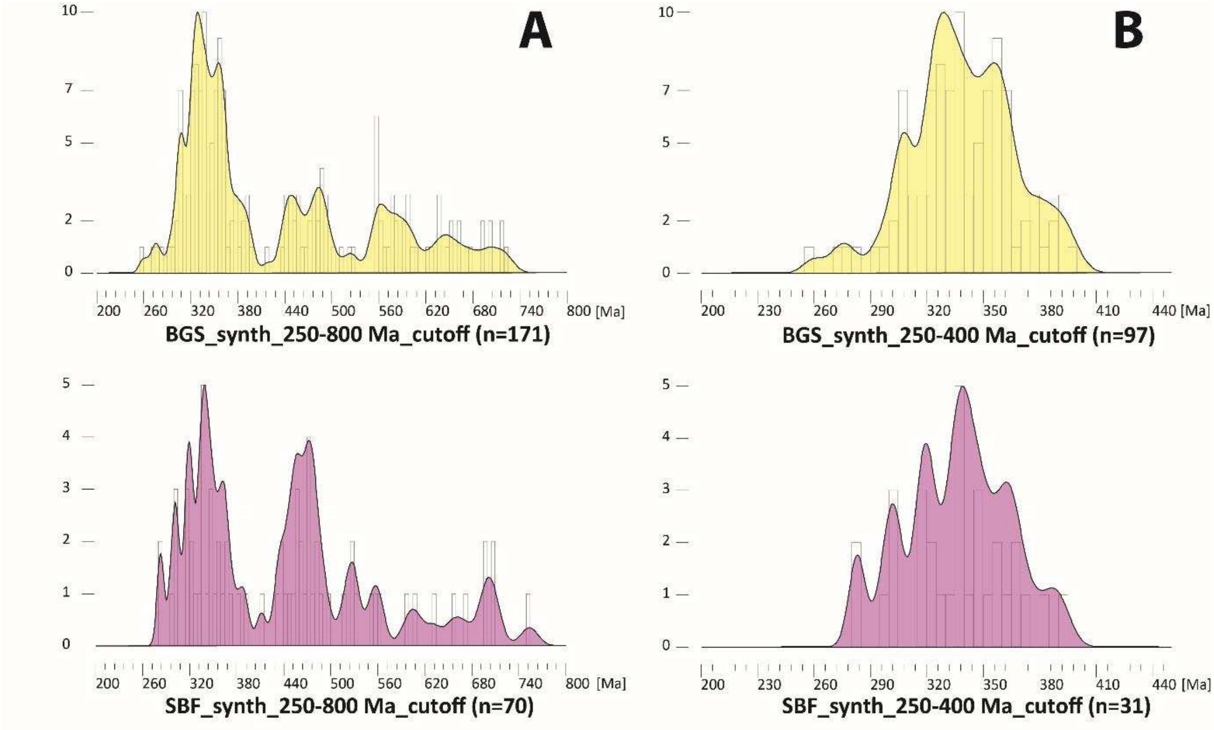

A
B
BGS_synth_250-800 Ma_cutoff (n=171)
BGS_synth_250-400 Ma_cutoff (n=97)
SBF_synth_250-800 Ma_cutoff (n=70)
SBF_synth_250-400 Ma_cutoff (n=31)
[Ma]

Fig. 11

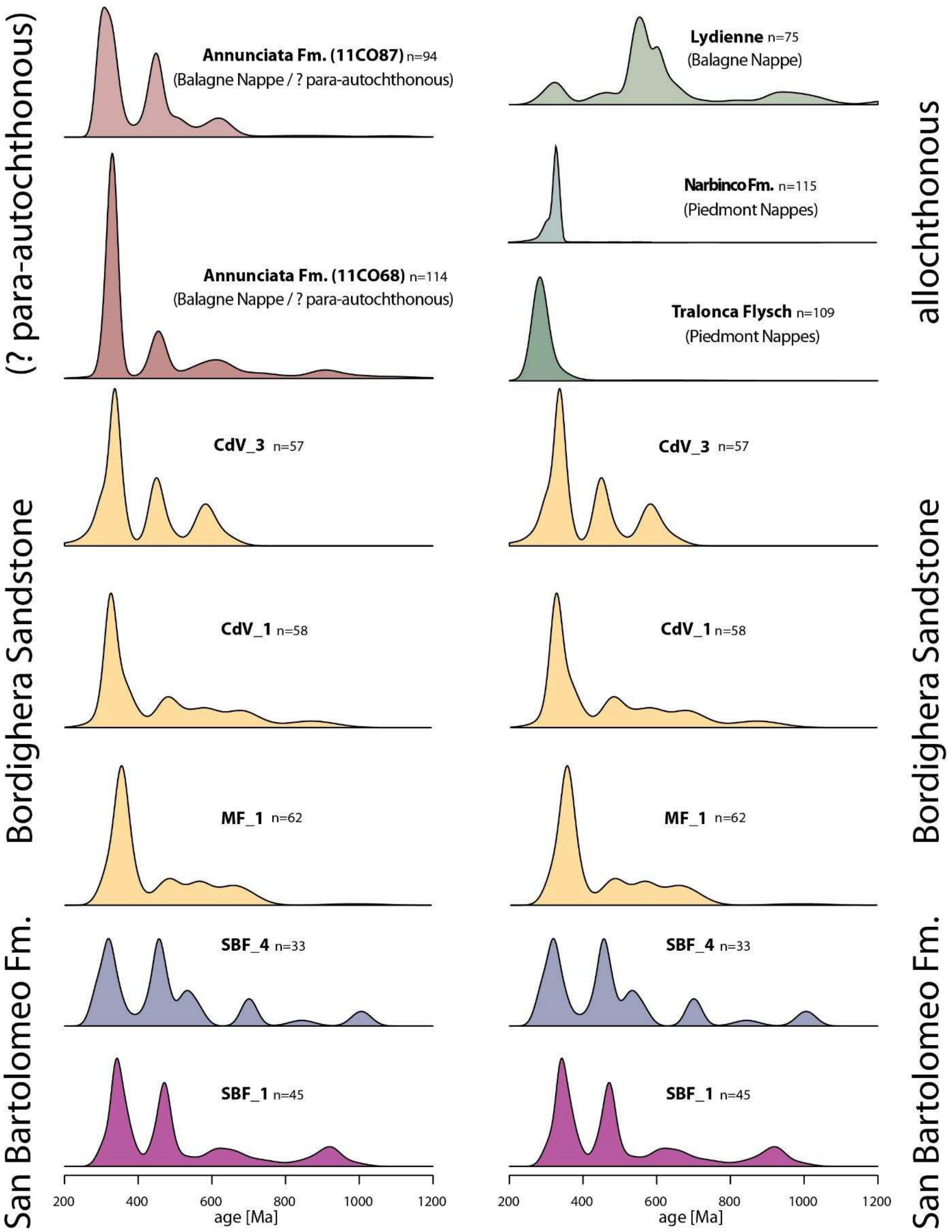
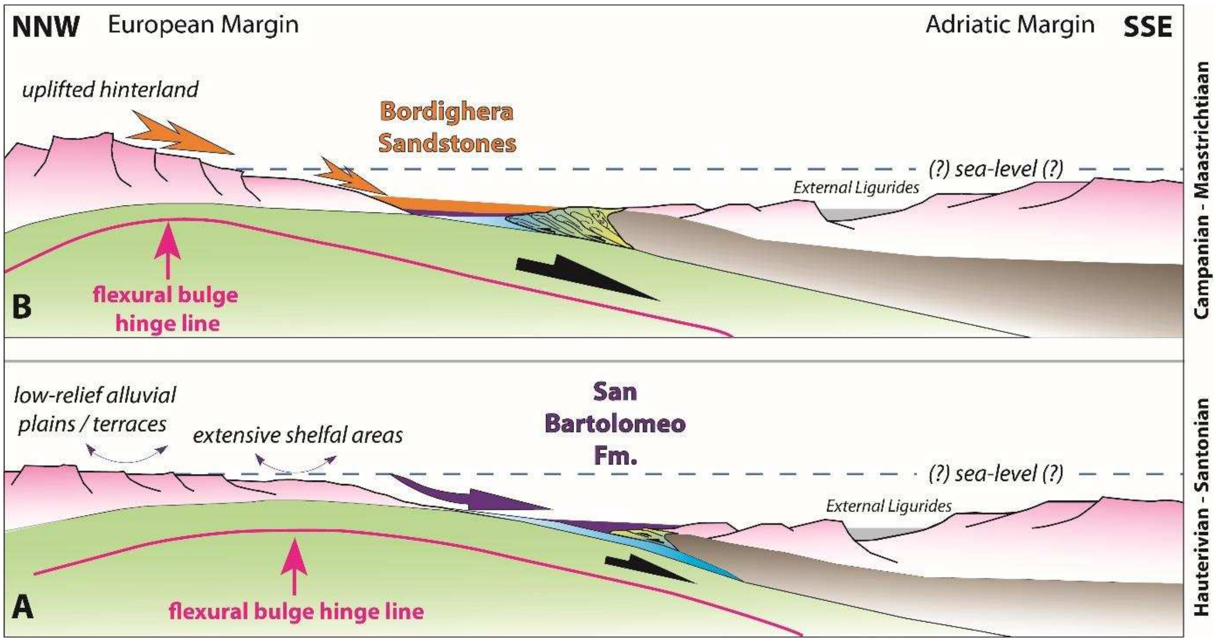

(? para-autochthonous)
Annunciata Fm. (11CO87) n=94
(Balagne Nappe / ? para-autochthonous)
Annunciata Fm. (11CO68) n=114
(Balagne Nappe / ? para-autochthonous)
Lydienne n=75
(Balagne Nappe)
Narbinco Fm. n=115
(Piedmont Nappes)
Tralonca Flysch n=109
(Piedmont Nappes)
allochthonous
Bordighera Sandstone
CdV_3 n=57
CdV_1 n=58
MF_1 n=62
San Bartolomeo Fm.
SBF_4 n=33
SBF_1 n=45
200
400
600
800
1000
1200
age [Ma]

Fig. 12



NNW
European Margin
Adriatic Margin
SSE
uplifted hinterland
Bordighera Sandstones
(?) sea-level (?)
External Ligurides
flexural bulge hinge line
B
Campanian - Maastrichtiaan
low-relief alluvial plains / terraces
extensive shelfal areas
San Bartolomeo Fm.
(?) sea-level (?)
External Ligurides
A
flexural bulge hinge line
Hauterivian - Santonian