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Tectonic significance of different block-in-matrix structures in exhumed convergent plate margins: examples from oceanic and continental HP rocks in Inner Western Alps (NW Italy)

[1]Gianni Balestro, [1*]Andrea Festa, and [2]Paola Tartarotti

[1]Dipartimento di Scienze della Terra, Università di Torino,
Via Valperga Caluso, 35, 10125 Torino, Italy
email: gianni.balestro@unito.it; andrea.festa@unito.it

[2]Dipartimento di Scienze della Terra, Università di Milano,
Via Mangiagalli, 34, 20133 Milano, Italy
email: paola.tartarotti@unimi.it

***Corresponding Author:**
Andrea Festa
email: andrea.festa@unito.it

Abstract
In the Inner Western Alps, three different types of block-in-matrix structures (BIMs) formed sequentially through time at a convergent plate margin. These show the superposition of progressive deformation from (i) subduction to eclogite facies depths, (ii) collision, accretion, and exhumation of oceanic crust, represented by the Monviso Meta-ophiolite Complex, to (iii) collision, accretion, and exhumation of the continental Dora Maira units. The Type 1 occurs in the metasedimentary cover of the Dora Maira Unit and consists of a map-scale broken formation with boudinaged "native" blocks of marble (Early Jurassic) in a calcschist matrix. It results from the tectonic overprinting of exhumation-related folding (D2-stage) on an earlier subduction-related dismembered succession (D1-stage). Type 1 also includes "non-mappable" BIMs with "exotic" blocks, resulting from the gravitational collapse of the Triassic carbonate platform of European Continental Margin, triggered by the Early Jurassic rifting. In the Monviso Meta-ophiolite Complex, Types 2 and 3 represent tectonically-induced broken and dismembered formations, respectively. They differ each other in the degree of stratal disruption of primary interbedded horizons of mafic metabreccia (Type 3) and mafic metasandstone (Types 2 and 3) sourced by the Late Jurassic – Early Cretaceous denudation of an oceanic core complex. Dismembered interbeds (Type 2) and isolated blocks were mixed together (Type 3) by the overlap of D2 tectonics and late-to post exhumation extensional shearing (D3-stage). Development of these types of BIMs may be common in many exhumed convergent plate margins, where severe tectonics and metamorphic recrystallization under high pressure conditions normally prevent the reconstruction of BIMs or mélange-forming processes. Our findings show that documenting the mode and time of the processes forming BIMs is highly relevant in order to reconstruct the oceanic seafloor morphology and composition of associated stratigraphic successions, and their control in the evolution of those convergent plate margins.

Key words: broken formation, mélange, meta-ophiolite, subduction, exhumation, Western Alps.

Introduction

Chaotic rock units with block-in-matrix structure (BIMs), commonly known as mélanges and broken formations, are one of the hallmarks of many exhumed convergent plate margins in both Circum-Pacific and Tethyan regions (e.g., Silver and Beutner 1980; Raymond 1984; Cowan 1985; Suzuki 1986; Kusky and Bradely 1999; Pini 1999; Alonso *et al.* 2006; Festa *et al.* 2010a; Wakabayashi and Dilek, 2011; Dilek *et al.* 2012; Wakabayashi 2012). They may commonly form at different tectonic settings and structural levels during the evolution of convergent plate margins, reflecting a close relationship between the active processes (tectonic, sedimentary and diapiric), the physical and mechanical conditions (e.g., water content, overpressure, strength of sediments, P-T conditions, etc.), and the strain rate (e.g., Hsü 1968; Raymond 1984; Cowan 1985; Cloos 1982; Cloos and Shreve 1988a, 1988b; Festa *et al.* 2012, 2014; Ukar and Cloos 2013; Wassmann and Stöckhert 2013). Hence, systematic and process-oriented, inter-disciplinary studies of chaotic rock units with block-in-matrix structure may provide much-needed information about convergent plate margin evolution (e.g., Dilek *et al.* 2012).

The relationships between the final block-in-matrix structure and process of their formation are, however, controversial in several cases because of their complex and seemingly chaotic nature (e.g., Silver and Beunter 1980; Cloos 1982; Raymond 1984; Cowan 1985; Pini 1999; Festa *et al.* 2010a; Wakabayashi 2012). In addition, the overlap of shearing, tectonic mixing, and metamorphic recrystallization may lead to the reworking and change of existing BIMs formed by original different processes (e.g., sedimentary or diapiric), and to the formation of polygenetic mélange types. As a matter of fact, BIMs formed by sedimentary processes may result very difficult to recognize-to non-distinguishable when placed, for example, in an accretionary wedge or in a subduction channel (e.g., Cowan and Page 1975; Cowan 1985; Dilek and Thy 2006; Burg *et al.* 2008; Cowan and Brandon 2011; Wakabayashi 2011, 2012; Prohoroff *et al.* 2012; Festa *et al.* 2013; Platt 2014) or after a complete cycle from subduction-to collision, exhumation and intra-continental deformation (e.g., Brandon 1989; Camerlenghi and Pini 2009; Codegone *et al.* 2012a; Dilek 2006; Osozawa *et al.* 2009, 2011; Festa *et al.* 2010b; Ogata *et al.* 2012). This is the case of different types of mélanges and block-in-matrix occurrences worldwide (e.g., see localities and references in Festa *et al.* 2010a, Wakabayashi and Dilek 2011; Dilek *et al.* 2012), where a long lived interesting debate has focused on the relative contribution of sedimentary, diapiric and tectonic processes in their formation. On the contrary, in the Western Alps a vivid debate on mélanges- and mélange-forming processes is still lacking probably because the severe tectonic shearing, folding, transposition, and strong metamorphic recrystallization under high pressure (HP)-to ultra-high pressure (UHP) conditions prevent useful information on the nature of sedimentary or diapiric origin. As for several other convergent margins worldwide, the distinction of different types of mélange and BIMs and the understanding of their processes of formation may thus provide new constraints to the geological evolution and documentation of the internal structure of Western Alps, which represent one of the most beautiful examples of exhumed convergent plate margin.

In this paper we describe, through multiscale, field- and laboratory-based structural studies (from geological map scale to mesoscale and microscope [thin-section] scale), three different types of BIMs which occur in the HP-Mesozoic metasedimentary cover successions of Inner Western Alps (Upper Pellice Valley) in Italy (Fig. 1). The latter represent an exhumed convergent plate margin, resulting from the tectonic imbrication of an oceanic subducted complex (Monviso Meta-ophiolite Complex; e.g., Castelli *et al.* 2014 and reference therein) or "serpentinite subduction channel" (e.g., Blake *et al.* 1995; Guillot *et al.* 2004, 2009), and a continental subducted unit (Dora Maira Unit; e.g., Sandrone *et al.* 1993 and reference therein). Our findings demonstrate that the three types of BIMs represent the product of progressive tectonically-induced stratal disruption of coherent and heterogeneous stratigraphic (or pseudostratigraphic) successions as originally deposited at shallow structural levels (i.e., broken formation *sensu* Hsü 1968 and dismembered formation *sensu* Raymond 1984) and not exclusively the product of deep-seated subduction-related processes. They result from the superposition of tectonics on earlier sedimentary processes occurred during different subsequent deformational stages, controlling a long-lived history from Early Jurassic preorogenic syn-sedimentary deformation, to Late Cretaceous – middle Eocene subduction (up to eclogite facies depth), and late Eocene – Oligocene collision and exhumation. Thereby, our data provide a significant and rare opportunity to reconstruct original stratigraphic successions, composition and morphology of both oceanic and passive margin seafloor in the exhumed HP metamorphosed convergent plate margins of Inner Western Alps, and better constrains the subsequent tectonic evolution.

2. Geological setting and mélanges and BIMs occurrences in the Inner Western Alps

The Western Alps (Fig. 1) resulted from convergence and subsequent collision between the Adria plate, the European continental margin and the interposed Ligurian-Piedmont oceanic basin (Ricou and Siddans 1986; Coward and Dietrich 1989; Laubscher 1991; Schmid and Kissling 2000). The axial sector of the Western Alps (Figs.1A and 1C) shows a double-verging structure and consists of a tectonic stack of different continental and oceanic tectonometamorphic units bounded by major orogen-scale faults (Platt *et al.* 1989; Polino *et al.* 1990; Lardeaux *et al.* 2006; Butler *et al*. 2013). In the inner sector of the Western Alps the Monviso Meta-ophiolite Complex, a major eclogitized remnant of the Ligurian-Piedmont oceanic lithosphere (Lombardo *et al.* 1978; Castelli *et al.* 2014), is tectonically superposed on the Dora Maira Unit (Figs. 1C and 1D) that was part of the European continental margin. To the West (Figs. 1C and 1D), the Monviso Meta-ophiolite Complex is, in turn, tectonically overlain by the Queyras Schistes Lustrés (Lemoine and Tricart 1986; Deville *et al.* 1992), that are interpreted as a fossil accretionary wedge where mafic and ultramafic blocks are embedded in blueschist- to greenschist-facies carbonate metasediments (Guillot *et al.* 2009). This present-day tectonic stack (Figs. 1C and 1D) resulted from three main geodynamic stages corresponding to (i) the Late Cretaceous to Eocene east-dipping subduction, (ii) the continental collision and west-verging accretion and (iii) the Oligocene-to Neogene deep crust/mantle indentation. The latter led to the doming of the Dora Maira Unit that in turn drove the final westward-tilting of the Monviso Meta-Ophiolite Complex and of the overlying Queyras Schistes Lustrés (Philippot 1990; Ballevre *et al.* 1990; Lardeaux *et al.* 2006; Schwartz *et al.* 2009).

The Dora Maira Unit consists of a Paleozoic basement unconformably overlain by a Mesozoic carbonate cover. The former consists of pre-Variscan sediments that were intruded by Upper Carboniferous granitoids and unconformably covered by Middle Carboniferous to Permian siliciclastic sediments (Vialon 1966; Wheeler 1991; Sandrone *et al.* 1993; Zechmeister *et al.* 2007; Compagnoni *et al.* 2012). The Mesozoic cover mainly consists of quartzite of presumed Early Triassic age, and Middle Triassic platform-derived metadolostone, passing upward to Upper Triassic - Lower Jurassic marble and calcschist with brecciated levels and olistoliths of Triassic age (Michard 1967; Marthaler *et al.* 1986; Philippot 1988). Alpine tectonics dismembered the Dora-Maira Unit into three superposed sub-units that were metamorphosed under different P-T peak conditions. They correspond to: *i*) the "Lower blueschist-facies sub-unit" (530–550° C and 6.0–7.5 kbar; Avigad *et al.* 2003), the "Upper eclogite-facies sub-unit" (515–525° C and 18–20 kbar; Gasco *et al.* 2011), and the tectonically interposed "coesite-bearing sub-unit" (730° C and 40-43 kbar; Castelli *et al.* 2007).

The Monviso Meta-ophiolite Complex derives from a mantle of likely lherzolitic origin that was intruded by Upper Jurassic gabbro (152 Ma, Lombardo *et al.* 2002; 163 Ma, Rubatto and Hermann 2003) and covered by tholeiitic basalt and Upper Jurassic to Cretaceous heterogeneous sediments (Lombardo *et al.* 1978, 2002; Balestro *et al.* 2011, 2013). Original ophiolite sequences were dismembered into different tectonic units that are interpreted as either (*i*) a fossilized serpentinite subduction channel wherein eclogite blocks were tectonically incorporated forming tectonic mélanges (Blake *et al.* 1995; Guillot *et al.* 2004), or (*ii*) an original almost continuous fragment of upper oceanic lithosphere, subducted at about 80 km-depth, and divided into different units by eclogite-facies shear zones (Angiboust *et al.* 2011). Different HP P-T peaks calculated for the lower tectonic units (580°C-19 kbar, Schwartz *et al.* 2000; 545°C-20 kbar, Castelli *et al.* 2002; 550°C-25 kbar, Groppo and Castelli 2010; 550°C-26 kbar, Angiboust *et al.* 2012b) and upper ones (480°C-22 kbar, Angiboust *et al.* 2012b), respectively, indicate that the Monviso Meta-ophiolite Complex was heterogeneously affected by eclogite-facies metamorphism.

In the Upper Pellice Valley (i.e. the central sector of the Dora Maira Unit and the northern sector of the Monviso Meta-ophiolite Complex), three main tectonometamorphic phases were recognized (named D1, D2 and D3, respectively; see Table 1 and Balestro *et al.* 2014). The D1 phase is coeval to the subduction-related eclogite-facies metamorphism, whose radiometric ages range from Paleocene to middle Eocene in the Monviso Meta-ophiolite Complex (Moniè and Philippot 1989; Duchene *et al.* 1997; Cliff *et al.* 1998; Rubatto and Hermann 2003). An HP P-T peak of 2.5-2.7 GPa for 550 – 570°C, compatible with the lawsonite-eclogite stability field, was estimated in the northern sector of the Monviso Meta-ophiolite Complex by Balestro *et al.* (2014). The D1 (Table 1) is recorded by an early foliation (S1) and related stretching lineation (L1), overprinting primary surfaces (i.e. S0 sedimentary bedding and magmatic foliation) in both the Dora Maira Unit and Monviso Meta-ophiolite Complex (Lardeaux *et al.* 1987; Philippot 1990). The D2 and D3 phases (Table 1) are coeval to the collision-related early exhumation and late exhumation, respectively (Ballevre *et al.* 1990; Philippot 1990). Since D3 roughly occurred between middle Oligocene to Miocene (Schwartz *et al.* 2009), D2 deformation can be referred to the late Eocene – early Oligocene, and is characterized by W- to SW-verging folds and thrusts along which the Monviso Meta-ophiolite Complex juxtaposed onto the Dora-Maira Unit. D2 folds developed an axial plane foliation (S2) that is characterized by a pervasive stretching lineation (L2). The S2 overprinted the S1, forming a composite (i.e. S1+S2) regional foliation that is coeval to the metamorphic re-equilibration of both the Dora-Maira and Monviso rocks. This re-equilibration was associated with a strong decompression and a weak cooling developed under epidote-blueschist to greenschist-facies transition (0.11-0.12 GPa for around 500° C; Balestro *et al.* 2014). The D3 phase developed conjugate transtensional faults that drove late-exhumation of the units and have been particularly related to the doming of the Dora Maira lower sub-unit (Philippot 1990; Ballevre *et al.* 1990; Schwartz *et al.* 2009). The doming was driven by deep crust/mantle indentation and caused the progressive westward tilting of the originally east-dipping tectonic stack up to the present-day setting (Figs. 1C and 1D). D3 faults are further crosscut by a network of transversal post-metamorphic faults that accommodate the ongoing orogenic extension ruled by isostatic forces (Sue *et al*. 2007; Perrone *et al.* 2011)

2.1. Block-in-matrix structures (BIMs) in the Inner Western Alps

Block-in-matrix rocks (or mélanges) recognized now and earlier in the Western Alps have origins attributed to different processes, mainly to deep-seated subduction-related processes and rarely to primary sedimentary ones. In the Monviso Meta-ophiolite Complex, exotic blocks of metabasite, metasediment and metagabbro embedded in a serpentinite matrix, were interpreted as a tectonic mélange formed in a "serpentinite subduction channel" (Blake *et al.* 1995; Guillot *et al.* 2004, 2009). Blocks record different P-T peak conditions (Blake *et al.* 1995; Schwartz *et al.* 2000, 2001) and derive from the subducting oceanic lithosphere but also from the above arc system (Hattori and Guillot 2007). The subduction channel is interpreted as a soft channel formed between the dry and rigid subducted oceanic lithosphere and mantle wedge (Guillot *et al.* 2009). Incorporation of exotic blocks was provided by low viscosity and density of serpentinite material, inducing the progressive exhumation of eclogite-facies material (Guillot *et al.* 2004). Similarly, a tectonic mélange related to subduction channel deformation has been described also southward in the Ligurian Alps (i.e the Voltri Massif; Federico *et al.* 2007). Differently, blocks and lenses of gabbro-derived eclogite breccias within a serpentinite shear zone were interpreted in the Monviso Meta-ophiolite Complex as the product of deformation related to "network widening" (Angiboust *et al.* 2011, 2012a) rather than "subduction mélanges" formed by extensive mixing along subduction channel.

The role of sedimentary (gravitational) processes forming BIMs was indirectly suggested by Lagabrielle (1994) in the Northern part of the Monviso Meta-ophiolite Complex. He observed an *"ophiolitic olistostrome with serpentinite matrix"* overlying *"chloritic and serpentinite-rich metabreccias"* (see Fig. 5 in Lagabrielle 1994), both strongly overprinted by deformation (i.e., *"sub-isoclinal hectometric reclined folds"*). BIMs of sedimentary origin were also described in the Mesozoic carbonate succession covering the Paleozoic basement of the Dora Maira Unit, wherein the Lower Jurassic carbonate metasediments host olistoliths of Triassic dolostone (Michard 1967).

Meta-ophiolite bodies, interpreted as oceanic-derived olistoliths (Guillot *et al.* 2009), were described in the Queyras Schistes Lustrés, too (e.g., Lemoine and Tricart 1986; Lagabrielle, 1994). They represent part of the exotic components embedded within a fossil accretionary wedge (Agard *et al.* 2009), consisting of metasediments scrapped off the underlying oceanic crust (or eroded from the upper plate). Thus, the Queyras Schistes Lustrés may be considered as a stack of different tectonostratigraphic units that preserve sedimentary-derived block-in-matrix structures and were stacked and refolded during early Alpine deformation (Lemoine and Tricart 1986).

3. Different types of BIMs in the Pellice Valley

In the Upper Pellice Valley (Inner Western Alps; Fig. 2A), on the basis of the block-in-matrix fabric, macro- and microstructural features (observed at various scales), and the nature and origin (i.e., “native” or “exotic”) of blocks included, we have differentiated three different types of BIMs within the metasedimentary cover successions of both the continental Dora-Maira Unit and Monviso Meta-ophiolite Complex (Table 2).

3.1. Type 1

The Type 1 block-in-matrix structure (Type 1 hereafter) characterizes the uppermost part of the Mesozoic metasedimentary succession of the Dora Maira Unit (Figs. 2A and 2B), which consists of about 300 meters thick calcschist. Type 1 shows the best exposures to the South of Alpe Giulian and North of Grange del Pis localities, in the footwall of the D2 thrust fault, tilted to SW by D3 deformation, and superposing the Monviso Meta-ophiolite Complex onto the Dora Maira Unit (Fig. 2). It consists of two different BIMs (Table 2) which occur at different scale: (i) mappable (Type 1a) marble blocks, tens-to hundreds of meters wide, enclosed in a calcschist matrix (Figs. 2A, 2B, 3A and 3B), and (ii) non-mappable (Type 1b) massive metadolostone clasts and blocks, centimeters-to decimeters wide, embedded within the matrix of Type 1a (Figs. 4B and 4C).

In Type 1a, the calcschist matrix mainly consists of calcite, white mica and quartz, whereas the marble blocks show a banded texture and are mainly made up of calcite, ankerite, dolomite, white mica, and quartz, with minor chlorite and opaque minerals. The blocks of Type 1a are tabular to elongated in shape along N-S cross sections, displaying a high aspect ratio (long axis/short axis; see Fig. 2B and Table 2) with long axis roughly parallel to the L1 stretching lineation, N-striking, and short axis perpendicular to the composite foliation (i.e., S1+S2), which plunges at low angle to WSW (Figs. 2B and 3B). The matrix mainly consists of homogeneous calcschist penetratively foliated by S2. The contact between blocks and matrix varies from sharp to transitional (Figs. 3C and 3D) at the outcrop-scale. Above the contact, the coarse- to fine-grained matrix is characterized by a decimeters to one meter thick fining-upward calcschist horizon that passes upward to medium –to fine-grained calcschist, in meters thick horizons, alternating with decimeters thick marble beds (Figs. 3C, 3D and 4A). The latters decrease upward both in frequency and thickness up to disappear. The marble and fine-grained calcschist represent excellent stratigraphic markers, outlining non-cylindrical, tight-to isoclinal W-verging D2 folds with N- and W-plunging fold axis, which also deform the contact with huge blocks. Hence, it is evident that isolate huge blocks, rounded to lenticular in shape (Fig. 3B), represent rootless and curved fold hinges. The described features and repetition of stratigraphic markers strongly support the folding of a primary stratigraphic succession, characterized by the gradual upward decrease of carbonate/dolomite component (Fig. 4A), and cannot solely reconcile with a lithological repetition related to tectonic stacking or transposition mechanisms. As commonly occur in unmetamorphosed block-in-matrix units, the local occurrence of a sharp contact between block and matrix is related to the overprinting of tectonics (i.e., the composite foliation S1+S2, in this case) onto the primary stratigraphic contact (S0) that was characterized by a strong competence contrast.

The Type 1b is a non-mappable chaotic rock body, hundreds of meters long and up to some meters thick, which is interbedded within the matrix of the Type 1a (Fig. 4A) and, particularly, within the alternating calcschist and marble beds, few to tens of meters above the contact with huge blocks of Type 1a. Blocks (and clasts) of Type 1b consist of massive metadolostone, angular to irregular in shape and centimeters-to about one meter wide, which are randomly distributed within the matrix (Fig. 4B and Table 2). The size of those blocks roughly decreases toward North from meters to centimeters, from Grange del Pis to Alpe Giulian localities, respectively (Fig. 2A). The metadolostone shows a granoblastic texture (Fig. 4D) and mainly consists of dolomite with minor white mica and chlorite, differing from the bonded texture of marble (Fig. 4C), which consists of calcite, ankerite, white mica and quartz, with minor chlorite and opaque minerals. Contacts between metadolostone blocks/clasts and matrix are sharp (Figs. 4B, 4C and 4D) and blocks locally cut the preserved original bedding of the matrix. The latter is locally outlined by alternating dark and light gray centimeters thick layers (i.e., S0; Fig. 4C), which are typical of some intervals recognized within the matrix of Type 1a. The above described block-in-matrix arrangement is locally overprinted by tectonics related to D2 as shown by wisp and tails structures, occurring at the termination of larger blocks, and lenticular to loosely elongated centimeters-scale clasts with long axis lying in the plane of the composite foliation (i.e., S1+S2) of the hosting matrix.

3.2. Type 2

The Type 2 block-in-matrix structure (Type 2 hereafter) occurs in the metasedimentary cover succession of the Monviso Meta-ophiolite Complex (East of the Colle del Baracun; Figs. 2A and 2B) that consists of medium-grained calcschist and fine-grained micaschist, locally alternating with decimeters to meters-thick horizons of mafic metabreccia and metagraywake, and fine-grained mafic metasandstone (Figs. 2A and 5). The most visual striking feature of Type 2 is the gradual and progressive degree of stratal disruption (Fig. 5A)

Progressive stratal disruption of mafic layers occurs from meso-to map-scale, defining two end-members which correspond to the primary coherent succession and isolated lenticular blocks of mafic metasandstone and metagraywake, respectively (Fig. 5 and Table 2). The isolated blocks are embedded within a calcschist matrix that includes detrital ophiolitic material (e.g. chromite crystals rimmed by Cr-rich white mica; Fig. 6A) which support primary sedimentary reworking resulted from submarine sediment transport. Preserved portions of the primary coherent succession are represented by the repeated folding of significant stratigraphic markers such as the decimeters to meters thick horizons of mafic metabreccia and metagraywake. The former is characterized by a fining-upward texture with irregular to angular-shaped, up to rounded, clasts of gabbroic composition (Fig. 6C), centimeters to decimeters sized, supported by angular –to irregularly shaped micro-clasts/grains. In thin section, the latters consist of omphacite and millimeters-sized fine grained aggregates of chlorite, Cr-rich white mica and epidote (pistacite) (Fig. 6D), embedded in a matrix of zoisite, light-green amphibole, epidote, albite, chlorite and sphene, and characterized by occurrences of quartz and white mica (Fig. 6E). Although metamorphism overprinted and deformed the primary texture, quartz and white mica, in association with the above described mineral assemblage, clearly support the detrital nature of these rocks. The primary texture (i.e. irregular to rounded shape of grains/micro-clasts) is mainly preserved in centimeters clasts as observed at the mesoscale (Fig. 6C), where metamorphic processes and recrystallization are not able to completely obliterate the original shape of wider detrital clasts. Laterally, the metabreccia horizons show a gradual transition (at tens to hundreds meters scale) to medium and fine-grained metagraywake with same composition and texture above described. The lateral decrease of clasts size and the transition from a brecciated texture to homogeneous fine-grained metagraywake roughly corresponds to the gradual decrease of thickness of these horizons, from 3-5 meters (e.g., Colle Mait del Pra) to decimeters (e.g., East of Colle del Baracun). In addition, homogeneous horizons of mafic metasandstone, decimeters to meters thick, also occur in the upper part of the succession (Fig. 5C) and locally embed levels of mafic metabreccia (Fig. 6B). The latter is characterized by irregular to angular-shaped clasts embedded in a fine-grained matrix. HP mineral assemblages are largely preserved both in clasts and matrix, and consist of omphacite and of garnet, and garnet, glaucophane, epidote and white mica, respectively (Fig. 6F).

Between the two end-members (i.e., the primary coherent succession and isolated lenticular blocks), different degrees of boudinage and pinch-and-swell structures occur (Figs. 5B and 6B, and Table 2). Boudinage is consistent with extension along long limbs of D2 folds with axial surfaces parallel to the S2 foliation (Figs. 2B and 6B). The latter is W-dipping and characterized by a SW-plunging L2 stretching lineation. Boudins formed in mafic metasandstone layers are connected to each other by narrow wisps and tails or result isolated at high degree of deformation (Fig. 5B). Highly stretched to lenticular boudins and blocks are associated with narrow (up to decimeters thick) and low angle D3 top to NNE shear zones (Fig. 5A), that cut the earlier D2 boudinage with only centimeters-to decimeters-scale displacements. Differently from mafic metasandstone, the more competent layers of mafic metabreccia and metagraywake show a lower degree of boudinage and extensional shearing (Fig. 6B).

3.3. Type 3

The Type 3 block-in-matrix structure (Type 3 hereafter) occurs to the West of Colle del Baracun (Figs. 2A and 2B) along a hundred of meters thick shear zone (Baracun shear zone hereafter), about NW-striking and SW-dipping. The latter is bounded by gently dipping, top to SW, D2 faults, which separate into two parts the original mantle (i.e. massive to mylonitic serpentinite)-cover (i.e., calcschist and ophiolite-derived metasediments) succession of the Monviso Meta-ophiolite Complex (see below) (Figs. 7A and 7B). The most visually striking characteristic of the Type 3 is the mixing of blocks of mafic metabreccia and metasandstone, rounded to lenticular in shape and ranging in size from decimeters-to several meters, which are embedded in a talc-and chlorite-schist matrix (Figs. 8A and 8B, and Table 2). The mafic metabreccia blocks (Fig. 8C) are made up of angular clasts, centimeters-to decimeters in size, which derive from Fe-Ti gabbro and likely from basalt (Figs. 8D and 8E). The texture ranges from clast-supported, showing a jigsaw-to crackle texture and the lack of sorting (Fig. 8D), to matrix-supported, consisting of fragments of larger clasts in a fine-grained matrix (Fig. 8E). At the micro-scale, the mafic metabreccia shows a matrix wrapping around angular to irregular-shaped clasts, and both in clasts and matrix the S1 foliation is defined by oriented blasts of garnet, omphacite and rutile (Fig. 9A). This eclogite-facies mineral assemblage is particularly well-preserved in the mafic metabreccia because of its primary composition and massive texture that preserve this rock both from high strain and blueschist- to greenschist-facies overprinting during D2 deformation.

The massive mafic metasandstone blocks (Figs. 8F and 8G), medium-to coarse-grained, are locally alternating with calceschist and micaschist beds and embed rare and scattered distributed angular clasts of mafic composition, decimeters in size (Figs. 8G and 10A). The latter clasts are difficult to be explained as product of tectonic processes and likely result from gravitational-induced submarine processes.

In the footwall of main faults dissecting the Baracun shear zone, blocks have a lenticular to elongate shape, with a high aspect ratio (long axis/short axis; Table 2), and long axis aligned to the L2 lineation. Away from the main tectonic contacts, blocks show a progressive increase in size (from decimeters-to several meters), decrease of mixing of polymictic blocks, and change in shape (from elongated to rounded; see Figs. 8A and 8B). Huge blocks (i.e., up to several meters in size) are rounded in shape (i.e., very low aspect ratio; see Table 2), corresponding to rootless fold hinges of D2 non-cylindrical folds (Fig. 8C). Within the metasandsone blocks, the D2 phase folds earlier formed boudins and elongated blocks related to D1-layer parallel extension, as preserved at outcrop-scale (Figs. 8F and 8G). It is worth noting that in blocks of mafic metabreccia, the D2 phase folded an earlier foliation (i.e., S1) that, in turn, overprinted the brecciated texture of the blocks (Fig. 8D). At the micro-scale, the clast-matrix relations are not always easy to be observed because of the size of clasts. Nevertheless, matrix and micro-clasts, angular to irregular in shape, are commonly either foliated by the same eclogitic facies foliation (i.e., S1 in Fig. 9A), suggesting the earlier embedding of micro-clasts within the matrix, according to the meso-scale observations. In addition, the irregular shape of (micro)clasts at both the micro- and meso-scale cannot be exclusively explained as the product of strain and cataclasis, being more consistent with sedimentary processes (Figs. 8D, 8E, 10A and 10B). In spite of the mineralogical differences, this matrix can be compared in texture with the *"sedimentary serpentinite mélange"* matrix described by Wakabayshi (2012) in the Franciscan Complex.

The talc- and chlorite-schist matrix is characterized by a high degree of deformation, which is defined by the interlacing of centimeters-to decimeters long disjunctive D2 shear surfaces (Figs. 9C and 9D, and Table 2). The latters bound millimeters-to centimeters lozenge-shaped lenses, the surfaces of which are generally polished and smooth. Millimeters-to centimeters sized mafic clasts (i.e., same lithologies of larger blocks), irregular to elongate in shape, are highly mixed within the matrix (Figs. 9C and 9D). Elongated clasts are aligned parallel to the L2 lineation. Rounded to irregular shaped clasts rotated in the matrix develop sigma-type pressure shadows consistent to top to SW movements. Locally, isoclinally folded clasts occur with axial surfaces parallel to the D2 shear surfaces (Fig. 9D). The millimeters-to centimeters block-in-matrix structure and D2 shear surfaces are crosscut by D3 extensional shears with millimeters-to centimeters displacements (Figs. 9C and 9D).

The microscale fabric of the matrix shows the same block-in-matrix structure as observed at mesoscale. Thin sections show, in fact, the occurrence of clasts mainly made up of chlorite, in a matrix mainly consisting of talc, chlorite, light-green and green amphiboles (Figs. 9E and 9F). It is remarked that, differently from mafic massive blocks wherein D1-related HP mineral assemblages are well preserved, the talc-chlorite-rich matrix is characterized by a widespread blueschist- to greenschist-facies D2-related overprinting.

The mantle-cover succession of the Monviso Meta-ophiolite Complex, which is separated into two parts by the Baracun shear zone (Figs. 7A and 7B), consists of a massive mylonitic serpentinite basement overlain by homogeneous carbonate-rich calcschist, comparable with those of Type 2 (Fig. 7C). It is worth outlining that the latter are interbedded by decimeters to several meters thick horizons of mafic metabreccia and metasandstone of the same composition and texture (at both micro- and meso-scale) of those above described for isolated blocks embedded within Type 3 talc- and chlorite-schist matrix (Fig. 7C). To the South of Baracun shear zone, the mafic metabreccia horizon directly overlies the massive serpentinite (Figs. 7C, 10C and 10D) while toward north and, particularly, to the north of the Baracun shear zone it is interbedded within a northward thickening succession of calcschist alternating with decimeters thick micaschist beds (Fig. 7C). This succession gives rise to a wedge shaped body (Fig. 7C) that change in thickness laterally from zero (South) to tens of meters (North). Here, clasts of the mafic metabreccia horizons gradually change in size and shape toward north, ranging from decimeters to centimeters and angular/irregular (Fig. 8E and 10A) to roughly rounded (Fig. 10B), respectively. The increase in thickness of the calschist succession is also accompanied by the occurrence of horizons of massive mafic metasandstone, interbedded in different stratigraphic positions (Figs. 7C, 10C and 10D), both above and below the horizon of mafic metabreccia. These horizons show a northward decrease of thickness from meters to decimeters. The continuity of the mafic metabreccia and metasandstone horizons, as well as the lateral variation in both thickness and internal organization and texture (e.g., compare Figs. 8D, 8E, 10A and 10B), is well consistent with the characteristic of a preserved primary coherent sedimentary (or pseudosedimentary) succession deposited along the scarp of an exhumed mantle topographic high (Fig. 7C). On the contrary, it is difficult explaining those interbeds, their internal grading (e.g., Fig. 10B) and lateral textural variation as the product of tectonic stacking and/or tectono-metamorphic deformation.

4. Discussion

Our findings document the occurrence of three different types of BIMs in a sector of Inner Western Alps where the Dora Maira Unit (European continental margin) is tectonically overlain by the Monviso Meta-ophiolite Complex (eclogitized remnant of the subducted Mesozoic Ligurian – Piedmont ocean lithosphere). The occurrence of these three types of BIMs raises two important questions:

(i) how did the three different types of BIMs form?

(ii) what is their significance in the geological frame of this sector of Inner Western Alps?

4.1. Processes of formation of the BIMs

D2-deformation phase played the most significant role in the formation of all types of BIMs, whilst D1 and D3 contributed only to a minor extent or locally in the formation of Type 1 and Types 2 and 3, respectively (Fig. 11). In Type 1 and, particularly in Type 2, the D2 deformation phase is responsible for the progressive stratal disruption from a coherent primary (pseudo)stratigraphic succession to isolated blocks within a matrix. Thus, mappable blocks of marble, and mafic metabreccia and metagraywake of Type 1a and Type 2, respectively, represent “native” component with respect to the matrix (Table 2), dismembered by tectonics. On the contrary, the blocks of metadolostone of Type 1b, which differ in composition from blocks and interbeds of Type 1a (i.e., marble) and can be compared with the Triassic platform carbonate (meta)dolostone described to the south of the studied sector by Philippot (1988) and Michard (1967; see below), are “foreigner” with respect to the stratigraphic succession of Type 1a, thus representing “exotic” components (see Table 2).

Progressive layer-parallel extension and boudinage along long-limbs of tight to isoclinal, non-cylindrical, D2 folds, was favored by the competence contrast between calcschist matrix and interbedded layers (Fig. 11B). The size of isolated lenticular blocks (i.e., up to hundreds of meters in Type 1; up tens of meters in Type 2), as well as the thickness of strongly boudinated layers (i.e., up to tens of meters in Type 1a; decimeters to one meter in Type 2) is then constrained by the original thickness of the interbeds.

D1-deformation concurred significantly in earlier stratal disruption for Type 1, as shown by the map scale boudinage and layer-parallel extension along N-S direction (i.e., parallel with L1 stretching lineation) of the originally coherent and continuous marble succession (Fig. 2A; see also Fig. 11A). On the contrary, in other types of BIMs, the role of D1 is difficult to be detailed mainly because of the overprinting of later deformation (see below).

Extensional shearing related to D3-deformation played a minor role in the formation of block-in-matrix structures. In Type 1 formation, this role is negligible. In Type 2 it contributes in producing a weak asymmetry to (earlier) boudinated and lenticular shaped blocks by deforming them within narrow (decimeters to meters thick) and localized shear zones. However, D3-extensional shearing did not significantly reorganize the previously formed BIMs that, at the map-scale, mainly record the D2 deformation.

On the basis of all the above described characteristics, Types 1a and 2 represent two examples of broken formation (*sensu* Hsü 1968), retaining their overall stratigraphic identity of a primary coherent sedimentary succession (see below). They differ each other in the composition of incorporated blocks and degree of stratal disruption that is smaller in Type 1a with respect to Type 2 (Table 2). As D2-deformation played the most significant role in stratal disruption, both Types 1a and 2 mainly formed during early exhumation and building of the subducted units (Fig. 11B) even if earlier D1 boudinage and stratal dismemberment related to subduction processes are suggested for Type 1a. At the scale of the Alpine orogen, D2 phase controlled the West-verging tectonics accompanied by blueschist- to greenschist-facies metamorphic re-equilibration (Fig. 11B). Although the age of D2 is not well-constrained, it postdates the Paleocene to middle Eocene eclogite-facies metamorphism (Moniè and Philippot 1989; Duchene *et al.* 1997; Cliff *et al.* 1998; Rubatto and Hermann 2003) and predates the middle Oligocene to Miocene D3-deformation (Schwartz *et al.* 2009), likely occurring from about Late Eocene to Early Oligocene (Fig. 11B). The weak tectonic overprinting related to D3-extensional deformation occurred at shallower crustal level during the final exhumation of the Monviso Meta-ophiolite Complex and the Dora Maira Unit (Fig. 11C). Particularly, the D3-deformation has been related to the doming of the Dora Maira Unit driven by deep crust/mantle indentation (Philippot 1990; Bellevre *et al.* 1990; Schwartz *et al.* 2009).

Differently from Types 1 and 2, Type 3 is characterized by the mixing of polymictic blocks (i.e., mafic metabreccia and metasandstone), that are rounded to irregular and locally elongated to lenticular in shape, and incorporated within a highly sheared talc-and chlorite-schist matrix (Table 2). Apparently, Type 3 lacks of a stratigraphic identity, not preserving any trace of a primary coherent succession and original depositional contacts between blocks and matrix. This fabric was described as *“ophiolitic olistostrome with serpentinite matrix”* (see Fig. 5 in Lagabrielle 1994), strongly overprinted by tectonic deformation (i.e., *“sub-isoclinal hectometric reclined folds*”; Lagabrielle 1994).

Our structural observations show, however, that the rounded shape of blocks of mafic metabreccia and metasandstone in Type 3 (see Figs. 8A, 8C and 8F) represents the rootless hinge of D2 folds with axial surface parallel to the S2 foliation (Fig. 11B). Unravelling D3 and D2 deformation (see sequence from 11C to 11A in Fig. 11), blocks define different roughly tabular horizons, up to about one meter thick, which depict continuous stratigraphic horizons of mafic metabreccia and metasandstone interbedded at different levels within the talc- and chlorite-schist matrix (see also Fig. 12C). They correspond, and can be correlated, to the continuous horizons of same lithologies interbedded within the coherent metasedimentary succession to the North and South of the Baracun shear zone (see Figs. 7A and 7C). Here, in fact, a primary (pseudo)stratigraphic succession, increasing in thickness toward north, is preserved, showing also similar characteristics with that described for Type 2. This also suggests a gradual transition from the highly dismembered and mixed Type 3 to Type 2.

In Type 3, the role played by D1-deformation is not well constrained in detail because of the overprinting of later penetrative D2 and D3 deformation. Nonetheless, the occurrence of D1-boudins within mafic metasandstone blocks, suggest that stratal disruption of coherent and continuous horizons started earlier during subduction stage (see also Angiboust *et al.* 2012). According to our findings, however, D1-deformation did not contributed in mixing of polymictic blocks, which was favored by the overlap of D3 on D2 deformations (Figs. 11B and 11C). D2 deformation induced significant stratal disruption, as recorded at all scales, through repeated isoclinal folding, severe transposition, and tectonic shearing with a persistent localization of deformation within the low viscous talc-and chlorite-schist matrix. D3-deformation favored mixing processes by dissecting the earlier dismembered succession with extensional shearing concentrated within thin (centimeters-to decimeters thick) and penetrative shear zones (see Figs. 8B, 9C, 9D, and 11C). This allowed previously isolated blocks of different lithologies to be displaced in structural levels within the shear zone, favoring mixing of blocks (Fig. 11C). The isolated huge blocks of Type 3 represent, in fact, disrupted portions of primary continuous horizons of mafic metabreccia and metasandsone interbedded within the calcschist succession. Hence, they may be considered as “native” blocks as well as those of Type 2. Although mixing of rocks is included in the definition of mélange and addressed as one of the fundamental mélange-forming process (e.g., Hsü, 1968; Silver and Beutner 1980; Raymond 1984; Festa *et al.* 2012 and reference therein), the lacking of “exotic” blocks does not allow ascribing Type 3 to a “tectonic mélange”, but rather as a “dismembered formation or unit” (*sensu* Raymond 1984; see Table 2). The latter is characterized by an extremely high degree of internal dismemberment with respect to that observed in Type 1a and Type 2 broken formations, resulting from polyphasic tectonic deformation related to the superposition of D3 on D2 and D1 phases, occurred from the subduction stages, to exhumation stages of subducted units (Fig. 11). The final block-in-matrix structure is scale-invariant “structurally ordered” (*sensu* Festa, 2011), coherently with the stress field associated to the two last tectono-metamorphic phases (i.e., D2 and D3; see also Table 2). The same structural relationships are, in fact, observed at a smaller scale within the matrix.

4.2. Significance of blocks and BIMs in the geological frame of Inner Western Alps

In all the three types of BIMs, the internal structure of blocks is weakly deformed with respect to the matrix (see also Schwartz *et al.* 2001; Guillot *et al.* 2004, 2009), which commonly suffered a more pervasive foliation, recording a long lived history of tectono-metamorphic deformation. Hence, blocks better preserve the traces of the earlier deformation before the onset of Alpine tectono-metamorphic stages (Fig. 12).

The Type 1b, which consists of “exotic” clasts and blocks of massive metadolostone embedded in a metasedimentary matrix, represents a non-mappable example of BIMs (“small-scale” mélange *sensu* Codegone *et al.* 2012b; “meso-scale” mélange *sensu* Bradley and Kusky, 1992) formed by sedimentary processes, associated with the gravitational collapse of the margin of carbonate platforms during and after rifting (i.e., “extensional-related mélange” *sensu* Festa *et al.* 2010a, 2012; see Table 2 and Fig. 12B). This is suggested by the dolomite-rich composition, which differs in composition and age with the pelagic matrix of Type 1a (see below), and by the angular to rounded shape of blocks, as well as their random distribution. Type 1b "exotic" clasts and blocks may record, therefore, the gravitational dismemberment of the Triassic platform triggered by the Early Jurassic extensional tectonics that affected its margin during rifting of the Ligurian – Piedmont Ocean (Figs. 12A and 12B). Large amounts of similar breccia that were generated by the collapse of the European margin during Early-Middle Jurassic time, are extensively described in other sector of the Western Alps, where poorly metamorphosed and deformed successions are exposed (e.g., Dallagiovanna and Lualdi 1986; Decarlis *et al.* 2013). In our case study, the small-size (up to one meter) of Triassic metadolostone blocks hosted in pelagic limestone suggest that the basin in which they emplaced was relatively distal to the source area. Metadolomitic units, interpreted as remnants of Triassic platforms, are exposed few tens of kilometers South of the studied sector (see, e.g., Michard 1967), showing a northward progressive thinning and dismembering towards the sector characterized by the Type 1 block-in-matrix structure (Balestro *et al.* 2013).

Differently from Type 1, the composition and internal texture of blocks and boudinated layers of Type 2 (i.e., the coarse- to medium-grained metasandstone and the fine-grained metabasite), are clearly of sedimentary origin and their internal characteristic texture (i.e., vertical grading) may be related to the deposition of sub-marine channelized turbidites supplied exclusively by a heterogeneous sequence of the Tethyan oceanic lithosphere (Fig. 12C; see also Table 2). The medium-to fine-grained texture of the mafic metasandstone suggests the emplacement in a relatively deep and distal sector of the oceanic basin, while the metabreccia and metagraywacke of gabbroic composition, passing laterally to metasandstone, represent more proximal deposition close to submarine escarpments. In Type 3 dismembered formation, the angular-to irregular shape of clasts of the mafic metabreccia with jigsaw-to crackle texture, the lack of sorting, and the matrix component produced exclusively by fragmentation of larger clasts, are consistent with a rapid deposition following mass-flow processes in an active tectonic environment (Fig. 12C). The direct overlap of a continuous horizon of metabreccia above a serpentinitic mantle to the South of the Baracun shear zone, and the northward thickening of the meta-sedimentary calcschist succession, interbedded by clastic to fine-grained horizons showing lateral and vertical texture grading, support the hypothesis that the ocean floor of the Jurassic Ligurian-Piedmont basin had an irregular topography. This is consistent with the occurrence of a topographic/structural high located to the South of Colle del Baracun, along which a heterogeneous oceanic lithosphere (i.e., serpentinized peridotite, and gabbro) was exposed along unstable escarpment (Fig. 12C).

Blocks of mafic metabreccia, similar to those embedded within the Type 3, have been already described in other sectors of the Monviso Meta-Ophiolite Complex (Angiboust *et al.* 2011) and recently interpreted by Angiboust (2012a) as the product of subduction-related earthquakes occurred at a depth of about 80 km. In our studied sector, however, the interpretation of a sedimentary origin for metabreccia is strongly supported by the occurrence of an early foliation (i.e., S1) overprinting a primary (i.e., stratigraphic) brecciated texture (Figs. 8D and 9A) that, importantly, needs to be considered in the general geological context, characterized in the Colle del Baracun sector by a deformed but partially preserved primary (pseudo) stratigraphic succession (see below). Since the S1 foliation developed under HP subduction-related metamorphic conditions (see Figs. 9A and 9B), and it is folded by D2 folds (Figs. 8C, 8D, 8G and 9E), it undoubtedly constrains that the brecciation process occurred before D1 deformation stage. In this context, it is important to outline that, in blocks/matrix pair from the Baracun shear zone (Type 3), the well-preserved D1-related eclogite-facies mineral assemblages within blocks of mafic metabreccia, and the widespread overprinting of the blueschist- to greenschist-facies mineral assemblages within the talc-chlorite-rich matrix, do not represent a contrasting metamorphic evolution but are due to contrasting metamorphic reactions controlled by deformation partitioning in the block-in-matrix assemblage. Because of their primary composition and massive texture, mafic blocks were relatively unaffected by high strain during D2-related deformation and metamorphic re-equilibration, that was mostly accommodated by the soft and more ductile matrix. In addition (or alternatively), the primary composition of the matrix produced by talc-amphibole-chlorite metasomatism played a significant role during the subsequent D1 and D2 tectono-metamorphic stages.

Hence, the nature, composition, and texture of the mafic metabreccia clasts (i.e., Fe-Ti gabbro and basalt) embedded within the talc-and chlorite-schist matrix are in agreement with our interpretation of a sub-marine environment characterized by local topographic/structural highs of a denudated mantle characterized by heterogeneous composition (Fig. 12C). This is also supported by the mixing of polygenetic micro-clasts within the talc- and chlorite-schist matrix, which needed sedimentary processes along an escarpment to be formed. Our reconstruction of the ocean floor well agrees with that proposed by other Authors for the Ligurian-Piedmont Ocean (Auzende *et al.* 1983; Lagabrielle *et al.* 1984; Lagabrielle and Cannat 1990; Lagabrielle 1994; Lagabrielle and Lemoine 1997; Balestro *et al.* 2014). These Authors also suggest a comparison with the unmetamorphosed sequence on top of the Northern Apennines ophiolites in Italy, and with the present-day slow-spreading axis of the Mid-Atlantic Ridge. Similar breccias have been, in fact, described in the Ligurian Units of the Northern Apennines, and interpreted as the product of submarine erosion of peridotite and gabbro exposed on the seafloor, originated during the opening of the Ligurian Ocean (i.e., the Tethyan Ocean) in the Late Jurassic – Early Cretaceous (Decandia and Elter 1972; Barrett and Spooner 1977; Bortolotti *et al.* 2001; Marroni and Pandolfi 2007). Similar breccias have been also sampled along the slow-spreading Mid-ocean ridge/transform system (e.g., Bonatti *et al.* 1971, 1974; Melson *et al.* 1978). Taking into consideration the Late Jurassic age of the gabbro intrusion in the Monviso Meta-ophiolite Complex (Lombardo *et al.* 1978; Rubatto and Hermann 2003), timing of gravitational denudation and downslope emplacement of mafic and ultramafic breccia and sandstone within calcschists of both Type 3 and Type 2 is consistent with the Late Jurassic – Early Cretaceous opening of the Ligurian Ocean. In addition to breccias, the talc-and chlorite-rich matrix of Type 3 shows close similarities with products of original hydrous mineral rich-levels associated with present-day submarine oceanic core complexes, which are exhumed along low-angle detachment faults during periods of pronounced tectonic extension and associated circulation of hydrothermal fluids (e.g., Escartin *et al.* 2003; Boschi *et al.* 2006a, 2006b; Cannat *et al.* 2009). Talc-amphibole-chlorite metasomatism characterizes rocks associated to those detachment faults, suggesting multiple phases of fluid infiltration and high strain deformation regime in limited domains (Boschi *et al.* 2006a). Talc may form at early stages of deformation, as soon as hydrothermal fluids interact with mantle rocks exposed on the seafloor, triggering metasomatic reactions. Dehydration of serpentinite to talc- and amphibole rich assemblage may occur simultaneously with deformation, producing rock weakening (e.g., Escartin *et al.* 2004; Boschi *et al.* 2006a) and localization of strain along faults that in turn, form tectonic escarpments along which gravitational denudation of exhumed rocks occurs. The association of mafic metabreccia and talc-and chlorite-schist in the Type 3 dismembered formation is thus well comparable with present-days active tectonic environment in slow-spreading oceanic settings. The contrasting rheology and competence between hard blocks of metabreccia and the soft, low viscous matrix represented favorable factors in forming a weak mechanical zone along which the later D2- and D3-deformation concentrated stratal disruption and mixing to form the Type 3 BIMs.

5. Conclusions

The detailed structural and stratigraphic analyses of BIMs occurrences within the meta-sedimentary cover of both the Monviso Meta-ophiolite Complex and Dora Maira Unit in the Inner Western Alps, allow us recognizing and distinguishing different examples of broken/dismembered formation, resulting from the progressive, tectonically-induced, stratal disruption of different originally coherent successions. This occurred progressively during subsequent deformational phases from deposition to subduction, up to collision, and exhumation. Importantly, our findings show that the nature and internal fabric of blocks record the result of superposition of tectonic deformation on -earlier sedimentary processes occurred during Early-to Late Jurassic time in different sectors of the Tethyan ocean (i.e., close to European passive margin and close to a mid-oceanic ridge). Except for the non-mappable Type 1b, which resulted from gravitational processes related to the collapse of the carbonate platform margin, all the others types of BIMs are the product of tectonic processes recording different degree of stratal dismemberment (Type 1a and Type 2) and mixing (Type 3). The nature and internal fabric of blocks incorporated within the BIMs suggest that those sectors were characterized by an irregular topography in which sedimentary (gravitational) processes concurred significantly in the denudation of topographic/structural highs, corresponding with a Triassic carbonate platform and an oceanic core complex in the Dora Maira Unit and Monviso Meta-ophiolite Complex, respectively.

Subduction-related deformation (D1) synchronous with the Paleocene to middle Eocene eclogite-facies metamorphism overprinted the primary and mostly coherent and heterogeneous stratigraphic successions. Since late Eocene, the successions were tectonically dismembered and disrupted by the exhumation phase (D2) that involved both the Dora Maira Unit and Monviso Meta-ophiolitic Complex, forming the different types of BIMs. Stratal disruption decreased in magnitude during late-to post metamorphic exhumation stage (D3; late Oligocene onward) related to the doming of the Dora Maira Unit, by deep crust/mantle indentation.

It is worth noting that the Type 3 BIMs shows internal features that are very similar to mélanges interpreted to form by tectonic processes in the deep structural levels of subduction channels. This brings up the potential value of discussing the predictions of subduction channel models for field relationships, and how those predictions are similar to or differ from the mélanges investigated in this study. Nonetheless, polymictic blocks (i.e., mafic metabreccia and metasandstone) within the talc-and chlorite-schist matrix represent, however, “native” components of dismembered primary stratigraphic successions instead of “exotic” blocks incorporated by return flow. Hence, although flow mélanges and return flow represent significant and common products and mechanisms in forming mélanges and BIMs in subduction settings, caution is needed in interpreting the nature and structural setting of processes forming block-in-matrix structures in HP-metamorphic orogens without a complete understanding of the true nature (i.e., “exotic” or “native”) of blocks, and reconstructing of the original coherent stratigraphic succession. Therefore, we suggest caution also in interpreting regional- scale reconstruction on metamorphosed exhumed convergent plate margins as Western Alps, based on discontinuous occurrence of BIMs. Without a detailed understanding of their nature, that is commonly polygenetic and polyphasic, different processes of formation may be easily confused each other with consequent wrong regional-scale interpretations and paleogeographic reconstructions.

In conclusion, our findings show that studying and documenting the mode and time of the processes forming BIMs is highly important and relevant in order to better understand the evolution of the Inner Western Alps, starting by the reconstruction of the oceanic seafloor morphology and composition of associated stratigraphic successions, and their control in the subsequent evolution of this convergent plate margin.

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Figure captions

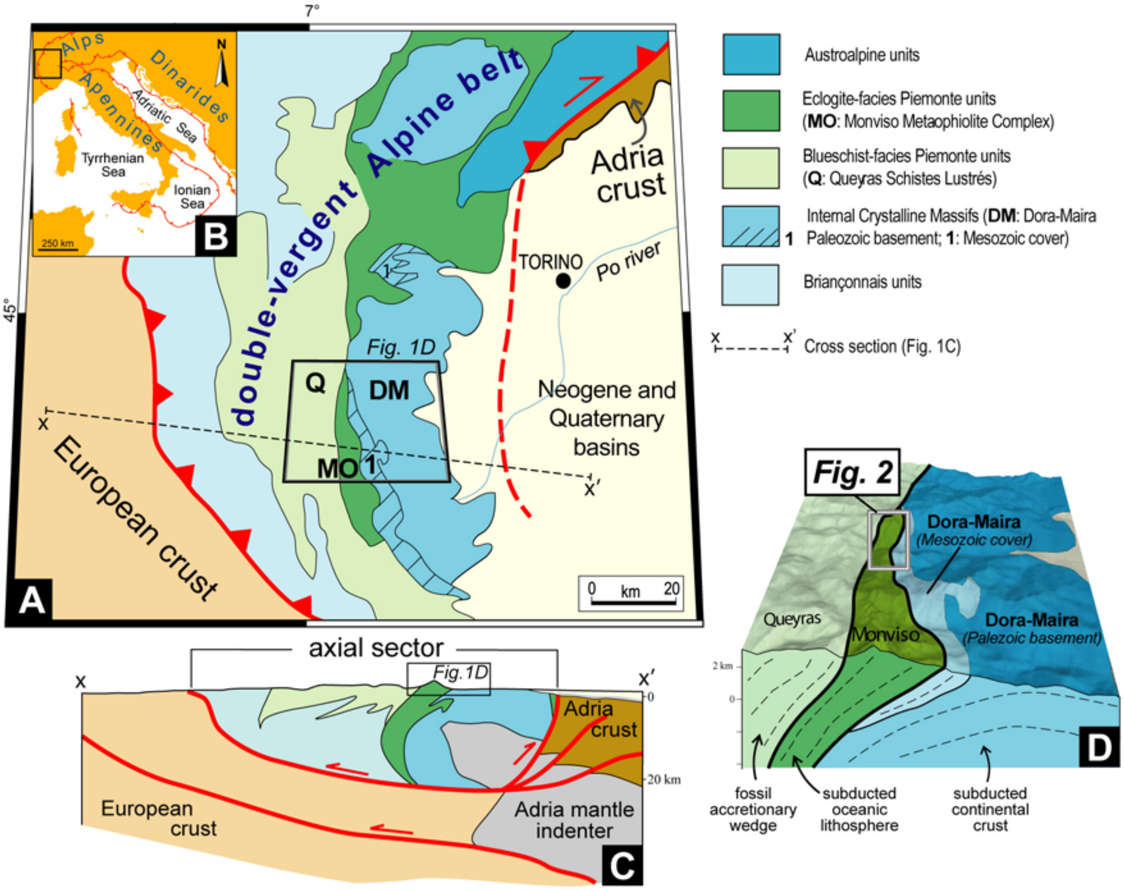

Figure 1 – (**A**) Structural sketch map of the Western Alps. (**B**) Location of Figure 1A (modified from Vezzani *et al.* 2010). (**C**) Geological cross section across the double verging axial sector of the Western Alps (modified from Lardeaux *et al.* 2006). Note the westward-tilting of the Monviso Meta-ophiolite Complex enlarged in Figure 1D. (**D**) 3D reconstruction of the Inner Western Alps in the Monviso sector, showing the tectonic imbrication of the Queyras Schistes Lustrés (i.e., ancient exhumed accretionary complex *sensu* Guillot *et al.* 2009), onto the Monviso Meta-ophiolite Complex (i.e., remnant of the Ligurian – Piedmont oceanic lithosphere or "serpentinite subduction channel" *sensu* Blake *et al.* 1995; Guillot *et al.* 2004) and the subducted Dora Maira Unit (i.e., European continental plate margin).

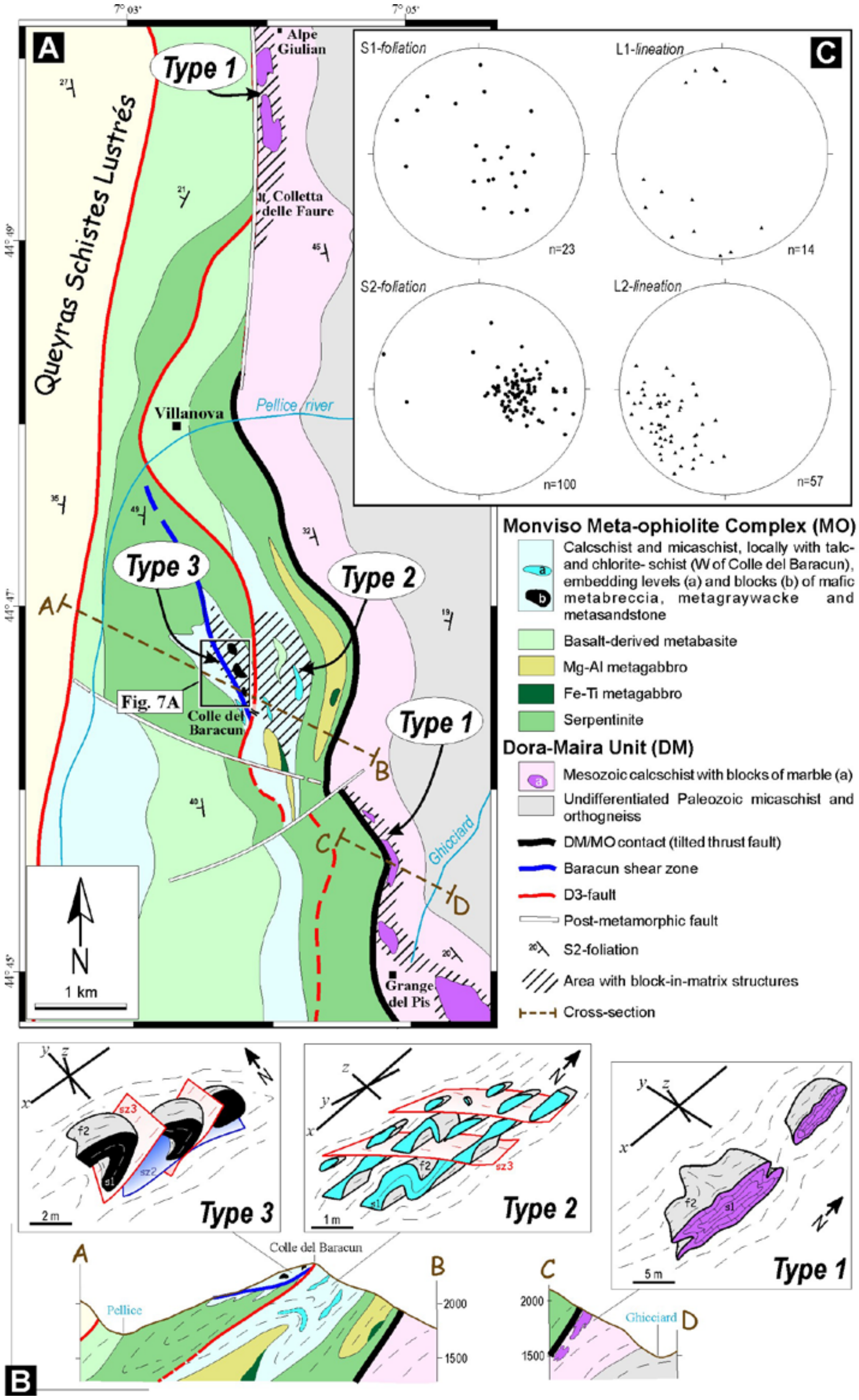

Figure 2 – (**A**) Simplified geological-structural map of the study area (location in Fig. 1D), showing the distribution and structural relationships between different block-in-matrix structures. (**B**) Geological cross-section (trace in Fig. 2A). The three close-ups illustrate the block-in-matrix arrangement of each type of chaotic rock structure (Types 1, 2 and 3) and the distribution of long (x), intermediate (y), and short (z) axes of blocks: s1) foliation related to D1-stage, f2) fold related to D2-stage, sz2) shear zone related to D2-stage, sz3) shear zone related to D3-stage. Note in the Type 2 the progressive stratal disruption from coherent beds to the block-in-matrix fabric. (**C**) Stereographic projections (Schmidt net, lower hemisphere) of D1 –and D2-related structural data from Dora Maira Unit and Monviso Meta-ophiolite Complex.

Table 1. Summary of the deformation history in the study area

	D1-phase	D2-phase	D3-phase
Structures	S1-foliation L1-stretching lineation	S2-foliation L2-stretching lineation Tight to isoclinal folds Shear zones	Shear zones Faults
Kinematic	Top to N (?)	W- to SW-verging fold and thrusts	Conjugate top to SW and NE extensional shearing
Age and metamorphic conditions	Paleocene to Middle Eocene eclogite-facies metamorphism	late Eocene to early Oligocene blueschist- to greenschist-facies metamorphism	middle Oligocene to Miocene (not metamorphic)
Regional event	Plate convergence, subduction	Continental collision, early exhumation	Deep mantle-crust indentation, late exhumation

Table 2. Diagnostic structural features of block-in-matrix structures

		Type 1		Type 2	Type 3
		Type 1a	***Type 1b***		
BLOCKS	**Nature and lithology**	Native blocks (pelagic marble)	Exotic blocks/clasts (metadolostone)	Native blocks (mafic metasandstone, metagraywake and metabreccia)	Native blocks (mafic metabreccia and metasandstone)
	Shape	Tabular to lenticular (high aspect ratio)	Angular to rounded (very low aspect ratio)	Lenticular and boudinated (high aspect ratio)	Rounded (low aspect ratio) and rarely elongated (high aspect ratio)
	Nature of bounding surface	Lower and upper depositional contacts			Tectonic contacts
MATRIX	**Lithology**	Homogeneous calcschist alternating with marble beds	Homogeneous calcschist alternating with marble beds	Calcschist	Talc-and chlorite-schist
	Fabric	Penetrative S2-foliation on homogeneous calcschist	Well bedded marble alternating with calcschist, overprinted by S1 and S2	Penetrative S2-foliation locally overprinted by D3-extensional shear zones.	Structurally ordered fabric with elongated clasts aligned to S2 shears. Occurrence of striation.
Block-in-matrix fabric		Progressive dismemberment from continuous layering to boudinage, up to isolated block	Random dismemberment of exotic blocks/clasts within the matrix	Progressive dismemberment from continuous layering to boudinage, up to isolated blocks	Mixing of polymictic blocks with structurally ordered fabric
Process of formation		Tectonics (D1 + D2) D2 played the most prominent role.	Sedimentary (gravitational) overprinted by later tectonics (D1 + D2)	Tectonics (D2 + D3) D2 played the most prominent role.	Tectonics (D1 + D2 + D3) D2 played the most prominent role
Classification of block-in-matrix fabric		Broken formation	“Non-mappable” sedimentary mélange	Broken formation	Dismembered formation
Pre-deformation setting of deposition		Slope to basin in a passive margin setting	Gravitational collapse of platform margin	Slope of oceanic core complex to oceanic basin	Slope of oceanic core complex

Table 2 – Diagnostic structural features of the block-in-matrix structures

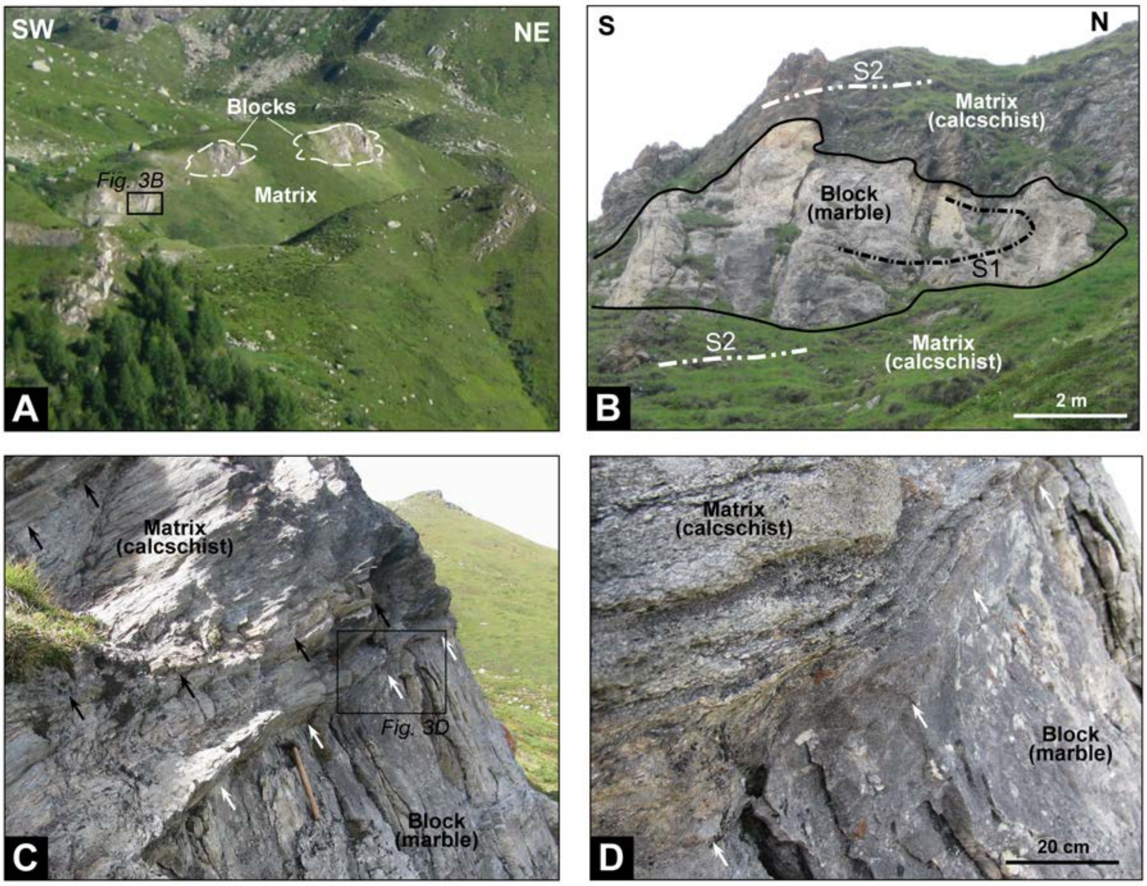

Figure 3 – *Type 1 block-in-matrix structures:* (**A**) Panoramic view of tabular to elongated blocks of marble, tens of meters in size, enveloped within a matrix consisting of homogeneous calcschist (Type 1a). Note the high aspect ratio (long axis/short axis) of blocks (Alpe Giulian). (**B**) Close-up of Figure 3A, showing an isolated block of marble, tens on meters long and elongated in shape, enveloped within the calcschist matrix which is foliated by S2 (white dashed line). The composite foliation (S0+S1; black dashed line) is preserved within the block. (**C**) Transitional contact (white arrows) between the marble block and the calcschist matrix alternating with decimeters thick layers of marble (black arrows). (**D**) Close-up of Figure 3C, showing the transitional contact between marble (block) and calcschist (matrix). Note that, close to the contact, the marble is interlayered by calcschist beds, centimeters thick, which increase in thickness upward up to pass to the coarse-grained homogeneous calcschist matrix. This gradual transition is well consistent with a primary stratigraphic contact (S0), locally overprinted by the composite foliation (i.e., S1+S2).

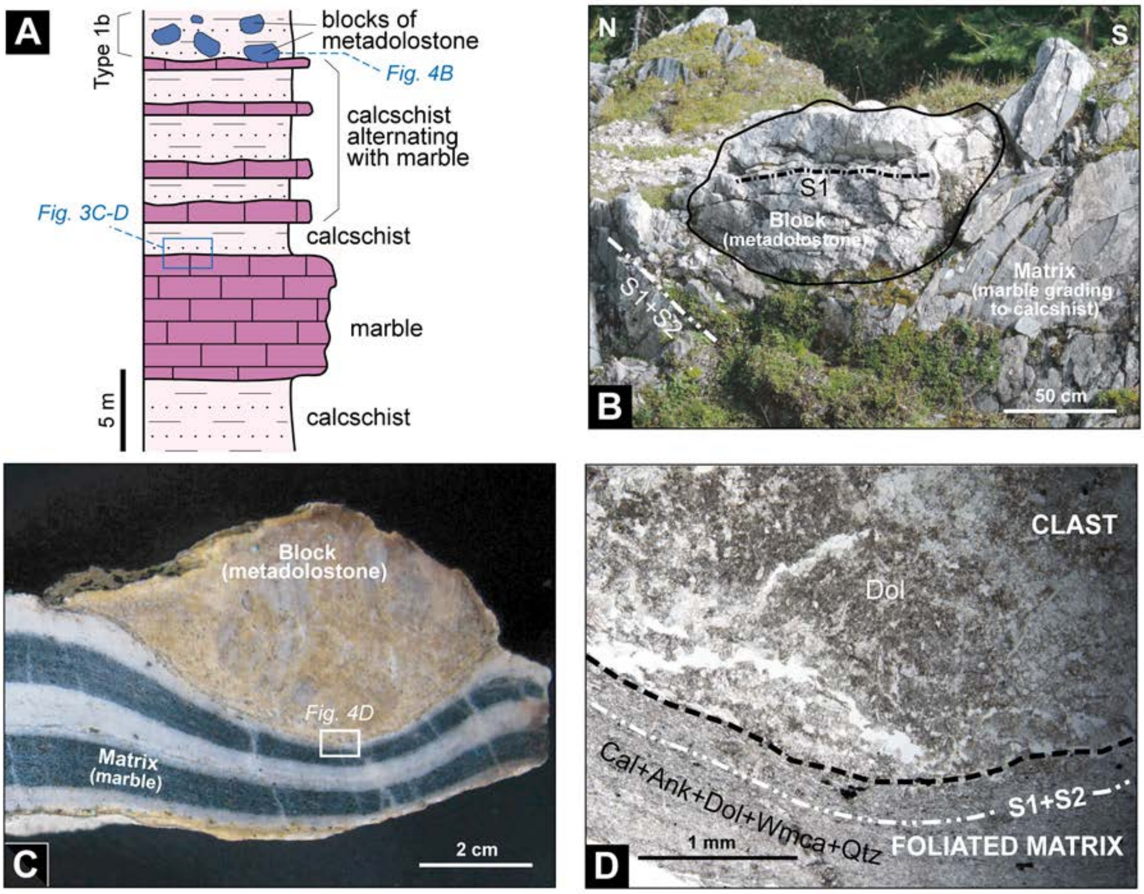

Figure 4 – (**A**) Stratigraphic column of the Alpe Giulian sector where Type 1 block-in-matrix structure occurs. Note the gradual upward decrease in both frequency and thickness of marble succession and beds. Blocks of metadolostone, forming Type 1b, are randomly distributed in the upper part of the succession. The location of the examples shown in Figures 3C, 3D and 4B is shown. (**B**) Irregular shaped block of massive metadolostone (Type 1b), about one meter in size, encased within the matrix of Type 1a, which consists of alternating marble and calcschist beds (Colletta delle Faure), as shown in the stratigraphic column of Figure 4A. The S1 foliation (black dashed line) is preserved only within the metadolostone block, showing an angle with the composite S1+S2 foliation (white dashed line) of the matrix. (**C**) Detail of the block-in-matrix structure of Type 1b: polished surface of hand sample with an elongated block of massive metadolostone embedded within a highly stretched matrix characterized by alternating black and white levels of marble (Colletta delle Faure). (**D**) Close-up of Figure 4C: photomicrograph (plan light), showing the clast/matrix relation (dashed black line) in Type 1b. The massive clast shows a granoblastic texture and mainly consists of dolomite, whereas the pervasively foliated fine-grained matrix mainly consists of calcite, ankerite, dolomite, white mica, quartz. Mineral abbreviations according to Siivola and Schmid (2007) in all photomicrographs.

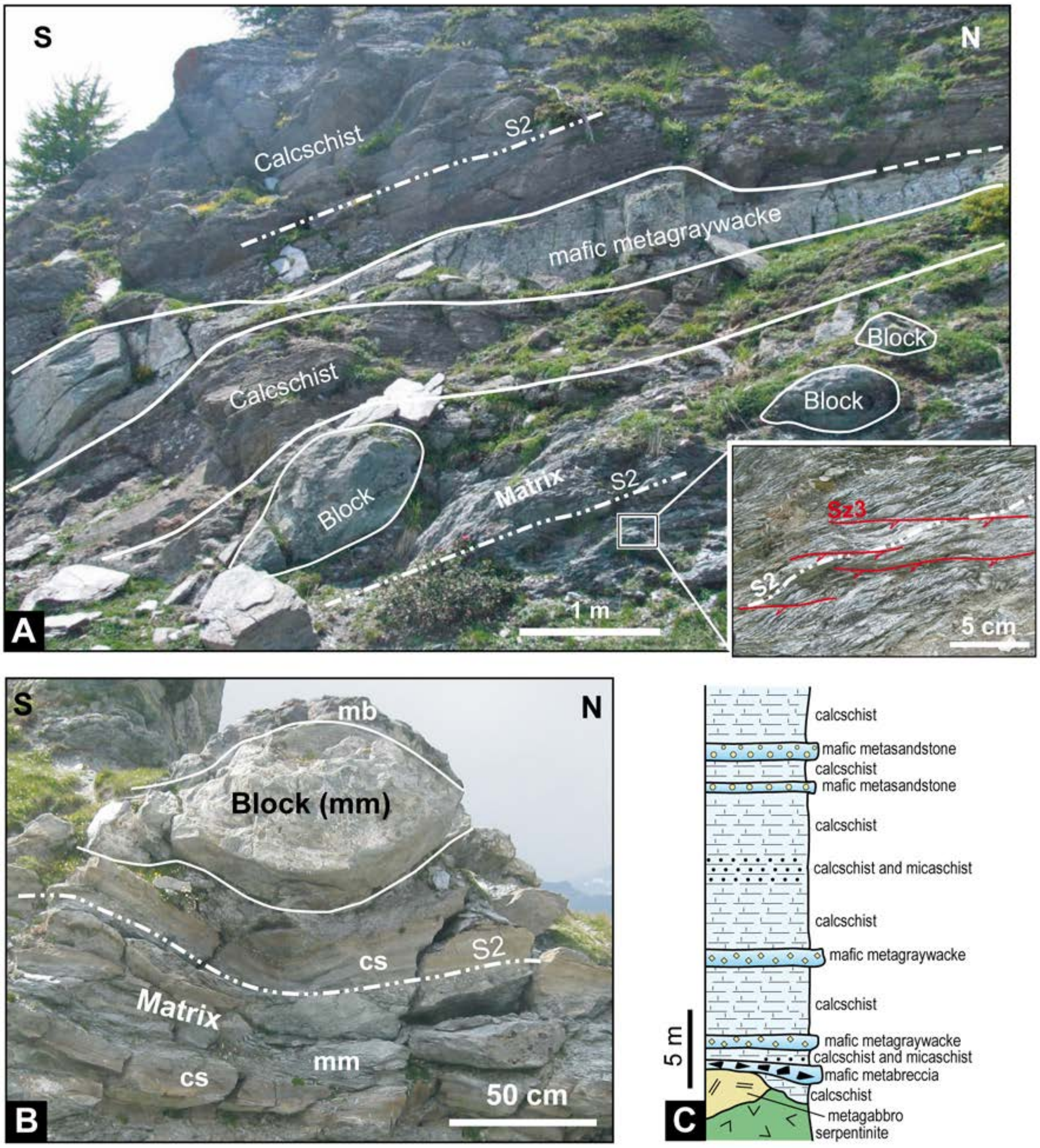

Figure 5 – *Type 2 block-in-matrix structures:* (**A**) Progressive stratal disruption (i.e., from top to bottom of the photograph) of the primary coherent succession made up of calcschist alternating with horizons of mafic metagraywake and metasandstone. Layer-parallel extension and boudinage affect the mafic metagraywake while higher degree of layer-parallel extension isolates lenticular blocks or boudins of mafic metasandstone (East of Colle del Baracun). Lenticular blocks show high aspect ratio (long axis/short axis) with long axis roughly parallel to the S2 (dashed white line). The close-up shows D3 shears (Sz3; red line) dissecting the S2 (dashed white line). Red arrows indicate the dip of D3 extensional shears. (**B**) Close-up of an isolated lenticular block of mafic metasandstone (mm) and mafic metabreccia (mb) embedded within a matrix of calcschist (cs), alternating with levels of mafic metasandstone (Colle del Baracun). The block derives from the progressive dismemberment of the original coherent succession that is still preserved in the same sector, as shown in the column of Figure 5C. (**C**) Stratigraphic column of the eastern sector of the Colle del Baracun where Type 2 occurs.

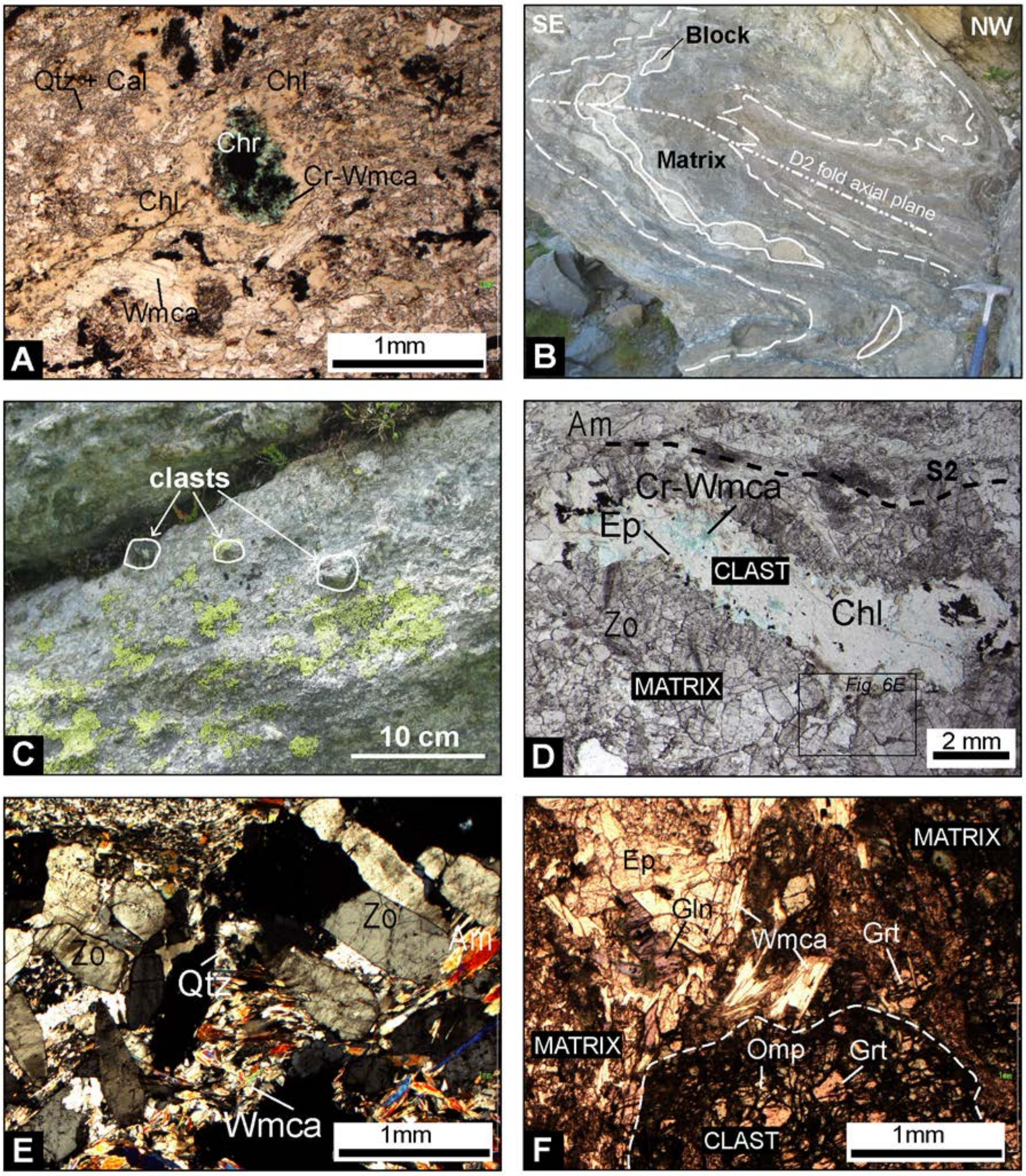

Figure 6 – *Type 2 block-in-matrix structures:* (**A**) Photomicrograph of calcschist (Colle del Baracun) including detrital ophiolitic material represented in this case by chromite crystals rimmed by Cr-rich white mica (fuchsite). Plain light. (**B**) Progressive boudinage of a mafic metabreccia level, decimeters thick, interbedded within a mafic metasandstone matrix. Note that boudinage defines a planar alignment in cross-sections and consists with extensional shearing along long limbs of D2 folds with axial surface parallel to the S2 foliation (Colle del Baracun). Hammer for scale. (**C**) Close-up of a mafic metabreccia horizon, showing irregular to rounded-shaped clasts of gabbroic composition, centimeters in size, in a matrix of rounded to angular micro-clasts of the same composition (East of Colle del Baracun). (**D**) Photomicrograph of mafic metagraywake of Figure 6C, showing the clast/matrix textural relationship. The irregular shaped clast consists of fine-grained chlorite, Cr-rich white mica (fuchsite) and epidote (pistacite). The inset shows the location of Figure 6E. Plain light. (**E**) Close-up view of the matrix near the clast contact (see Figure 6D), consisting of zoisite, light-green amphibole, quartz and white mica. Crossed nicols. (**F**) Photomicrograph showing the clast/matrix relation of the mafic metabreccia level of Figure 6B: clast and matrix mainly consist of omphacite and garnet, and garnet, glaucophane, epidote and white mica, respectively. Crossed nicols. Mineral abbreviations according to Siivola and Schmid (2007) in all photomicrographs.

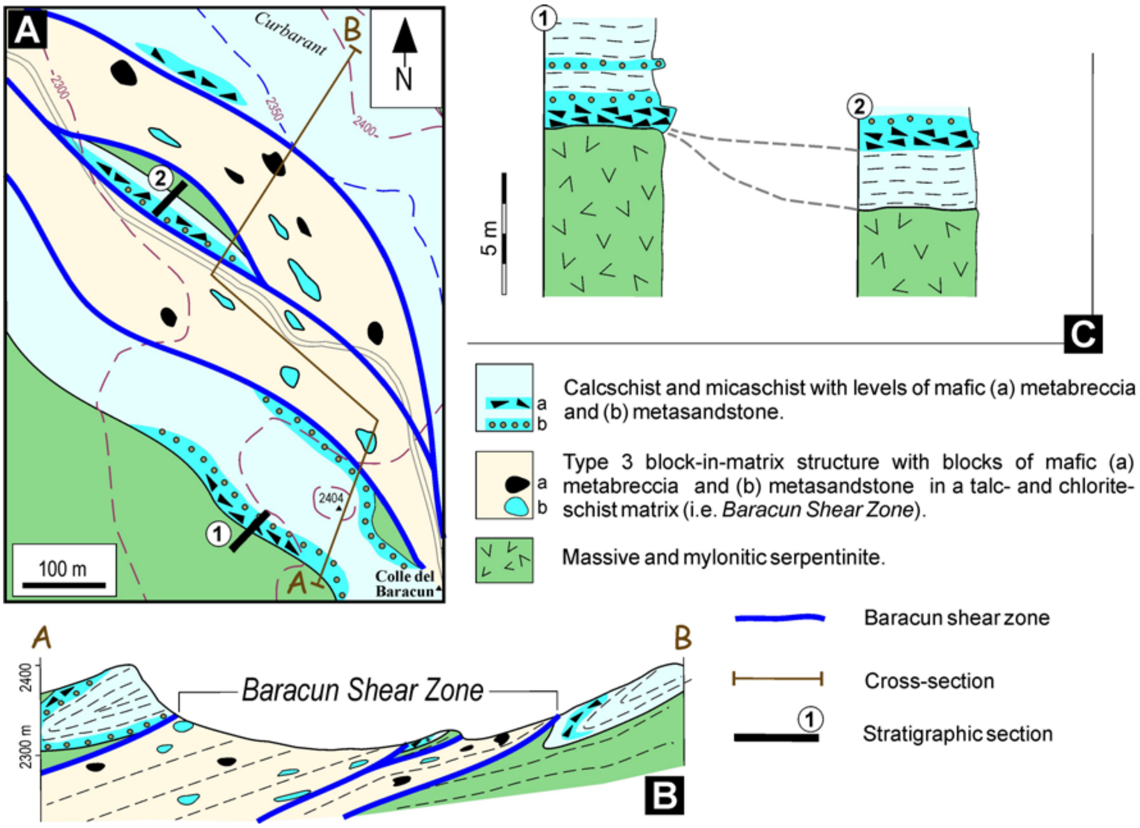

Figure 7– (**A**) Simplified geological map of the Baracun Shear Zone (location in Fig. 2A), showing the distribution of polymictic blocks of Type 3 within the talc-and chlorite-schist matrix. Note that, outside of the Baracun Shear Zone, continuous horizons of same composition of blocks are interbedded within the original coherent succession (see also stratigraphic columns in Fig. 7C). (**B**) Geological cross-section (trace in Fig. 7A). (**C**) Stratigraphic columns of the Colle del Baracun sector (traces are shown by the thick black line in Fig. 7A), showing the northward increase in thickness of the metasedimentary succession interbedded by the mafic metabreccia and metasandsone horizons, which represent continuous stratigraphic markers. Dashed gray lines correlate the mafic metabreccia horizon and the top of serpentinite across the Colle del Baracun sector.

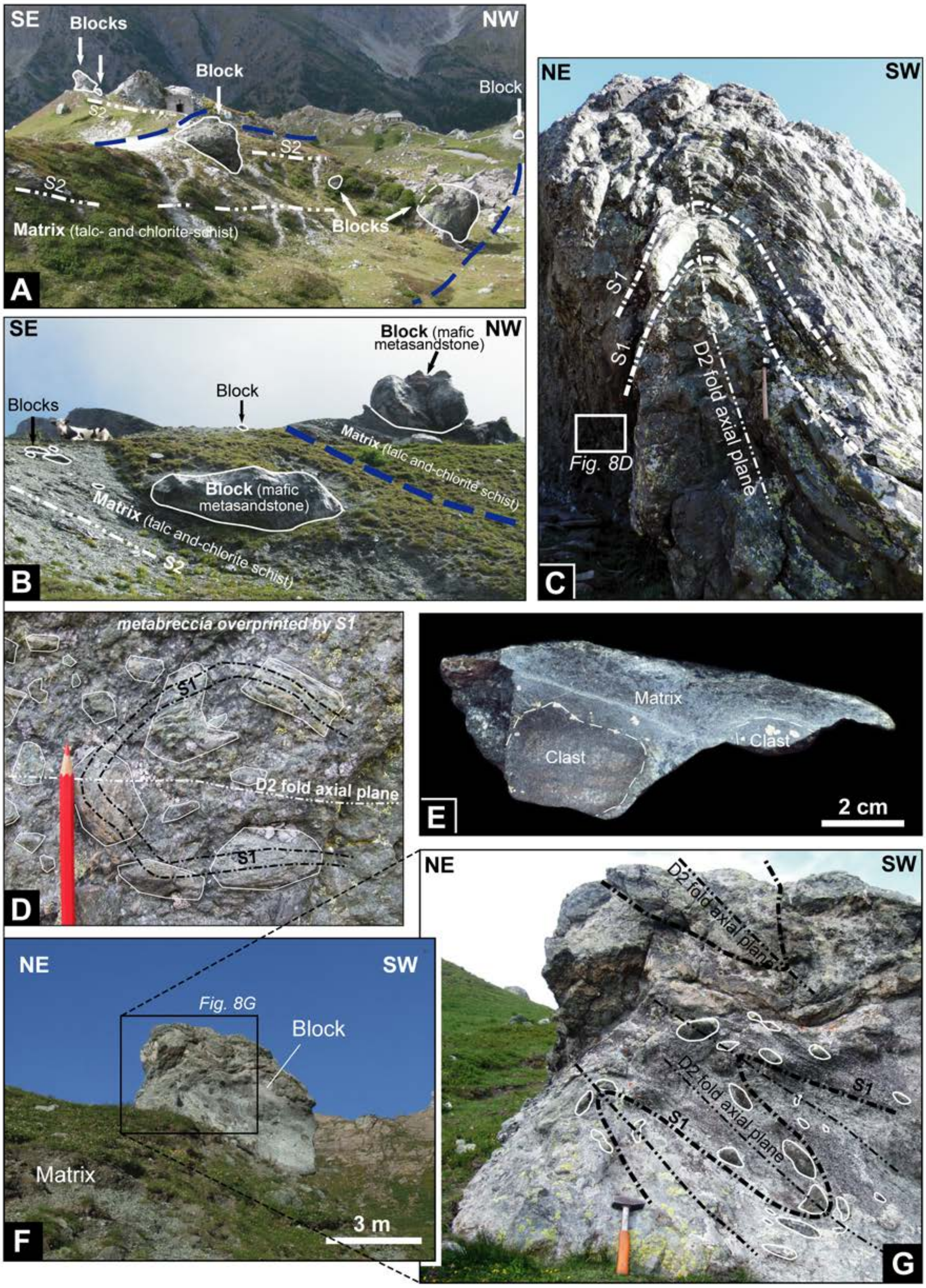

Figure 8 – *Type 3 block-in-matrix structures* at Colle del Baracun: (**A**) Panoramic view of the Type 3 block-in-matrix structure, showing rounded to elongated polymictic blocks (mafic metabreccia and metasandstone), decimeters to several meters in size, enveloped within a talc-and chlorite-schist matrix. Blocks are aligned (see Fig. 8B) to the D2 faults (dashed blue lines) bounding the Baracun Shear Zone. (**B**) Elongated block of metasandstone with high aspect ratio (long axis/short axis). Note that the blocks show a lenticular and irregular shape in the footwall and hanging wall of the D2 fault (dashed blue line), respectively. (**C**) Detail of one of the rounded blocks of mafic metabreccia, showing that its shape corresponds to the fold hinge of a D2

non-cylindrical fold which deformed an earlier foliation (S1). (**D**) Close-up of the brecciated texture of the mafic metabreccia block of Fig. 8C. The clast-supported metabreccia consists of centimeters sized irregularly shaped clasts, deriving from Fe-Ti gabbro and likely from basalt, and show a jigsaw texture characterized by the lack of sorting. Importantly, an earlier foliation (S1) that is folded by D2 deformation overprints the brecciated texture of the block. (**E**) Polished sample of mafic metabreccia, showing irregular –to roughly rounded clasts of irregularly distributed within a fine-grained matrix. (**F**) Panoramic view of a block of mafic metasandstone embedded in the talc-and chlorite-schist matrix. (**G**) Close-up of Figure 8F, showing the high degree of boudinage and layer-parallel extension acted by D1 deformation on original coherent horizons of mafic sandstone (now elongated blocks outlined by the white lines). D2 deformation folded the S1 (thick dashed black lines) and contributed in increasing the stratal disruption and boudinage along the fold limbs.

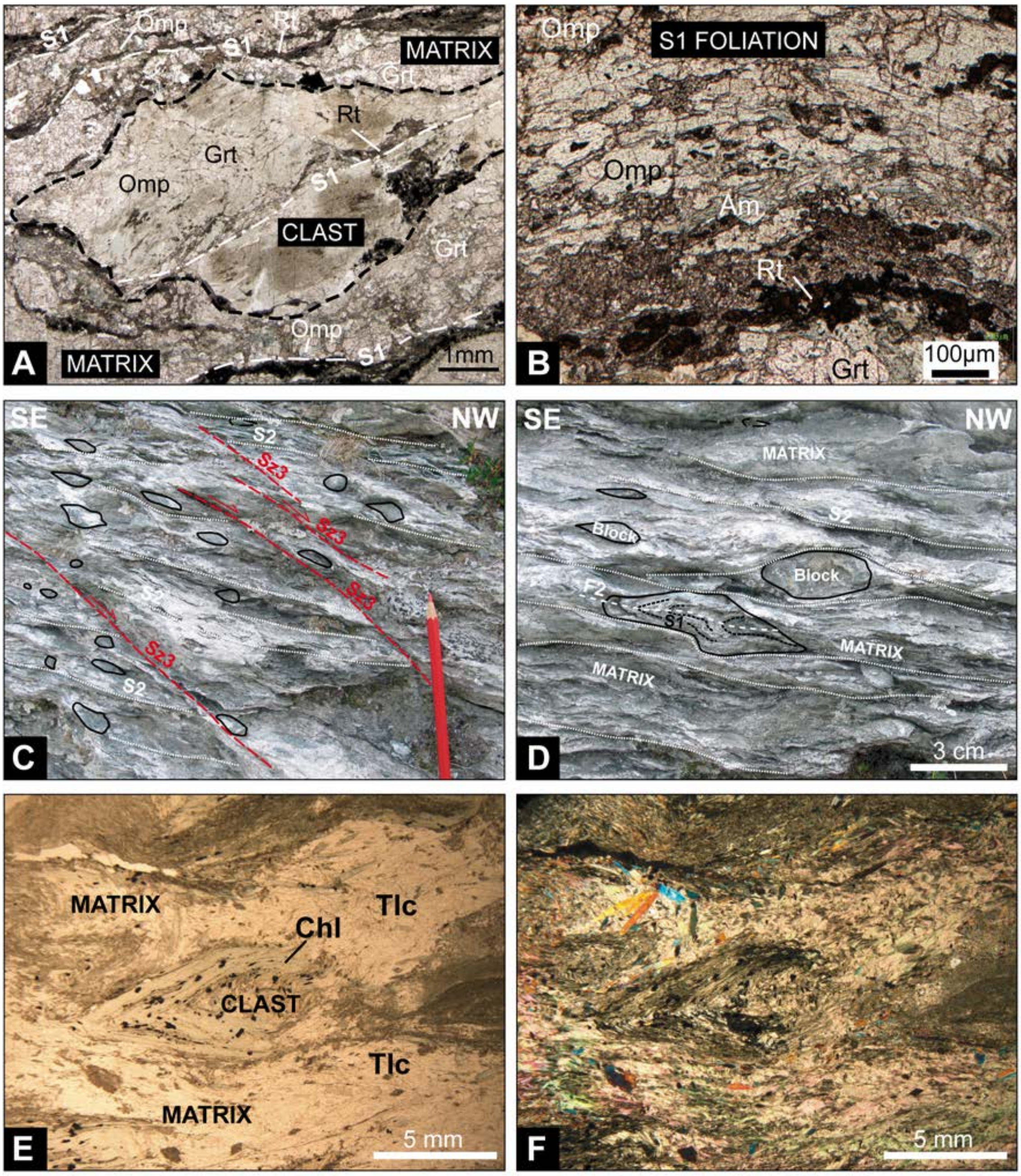

Figure 9 – *Type 3 block-in-matrix structures* at Colle del Baracun: (**A**) Photomicrograph showing the clast/matrix relation within the mafic metabreccia of Figure 8D. Note that the both the matrix and the irregular shaped clast are affected by the S1 foliation (dashed white line) defined by eclogite-facies mineral

assemblage (i.e., garnet, omphacite and rutile). (**B**) Photomicrograph showing the eclogite-facies mineral assemblage (i.e. garnet, omphacite and rutile) that define the S1 foliation (dashed white line) within the mafic metabreccia of Figure 8D. Plain light. (**C**) Typical aspect of the block-in-matrix fabric of the talc-and chlorite-schist matrix including elongated to rounded clasts of mafic metastandstone (black lines), centimeters in size, with long axis aligned to S2-foliation. Note that the extensional shears related to D3-deformation (Sz3, dashed red lines) dissect the S2-foliation (S2, dotted white lines). (**D**) Close-up of the talc-and chlorite-schist matrix, showing elongated to lenticular blocks (black line) of mafic metasandstone with long axis aligned to S2-foliation (dotted white line). Note that one on the blocks preserves an earlier foliation (S1, dashed black line) folded by D2 (dashed white line). (**E-F**) Photomicrographs of the talc- and chlorite-schist matrix (note the scale invariance of tectonic structures with respect to Fig. 9D): (**E**) Clast mainly made up of chlorite, in a matrix mainly consisting of talc. Plain light; (**F**) same picture at crossed nicols. Mineral abbreviations according to Siivola and Schmid (2007) in all photomicrographs.

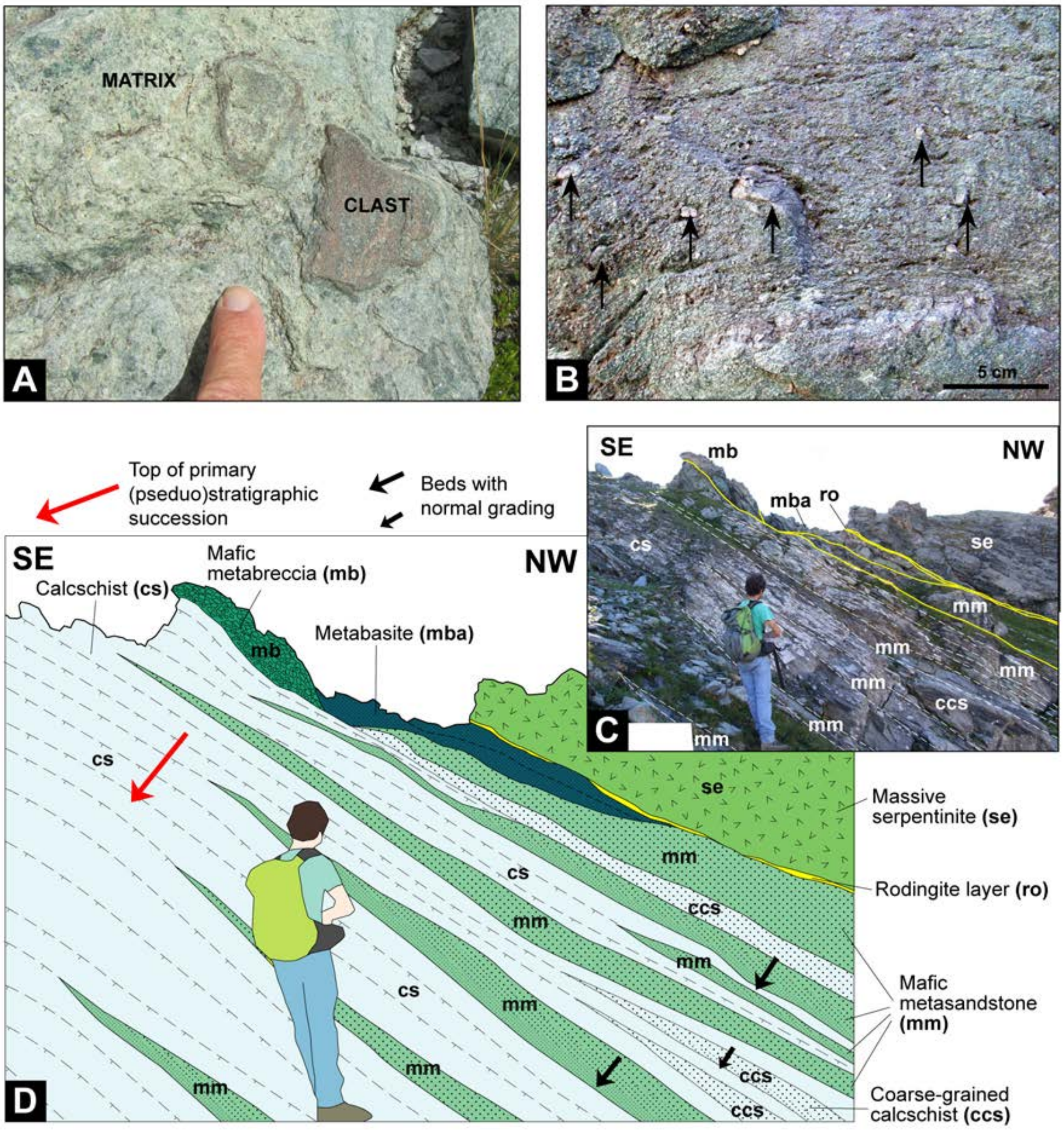

Figure 10 – *Type 3 block-in-matrix structures* at Colle del Baracun: (**A**) Detail of a block of mafic metasandsone showing an isolated irregular shaped clast of Fe-Ti metagabbro embedded in the medium-to coarse grained mafic matrix. Finger as scale. (**B**) Close-up of the detrital texture of the matrix-supported mafic metabreccia horizons. Note the rounded shape of clasts (black arrows) and the fining-upward grading.

(**C**) Panoramic view and line drawing (**D**) of the preserved overturned mantle-cover succession cropping out south of Colle del Baracun (E. Scaramuzzo for scale). The metasedimentary succession is interbedded by mafic metabreccia and different, normal graded layers (black arrows), of mafic metasandstone and coarse-grained calscshist which represent same lithologies of blocks of Type 3. The characteristics of this succession are well consistent with a preserved primary coherent (pseudo)sedimentary succession deposited on an exhumed serpentinitic mantle. Part of this succession is schematized in the stratigraphic column 1 of Figure 7C.

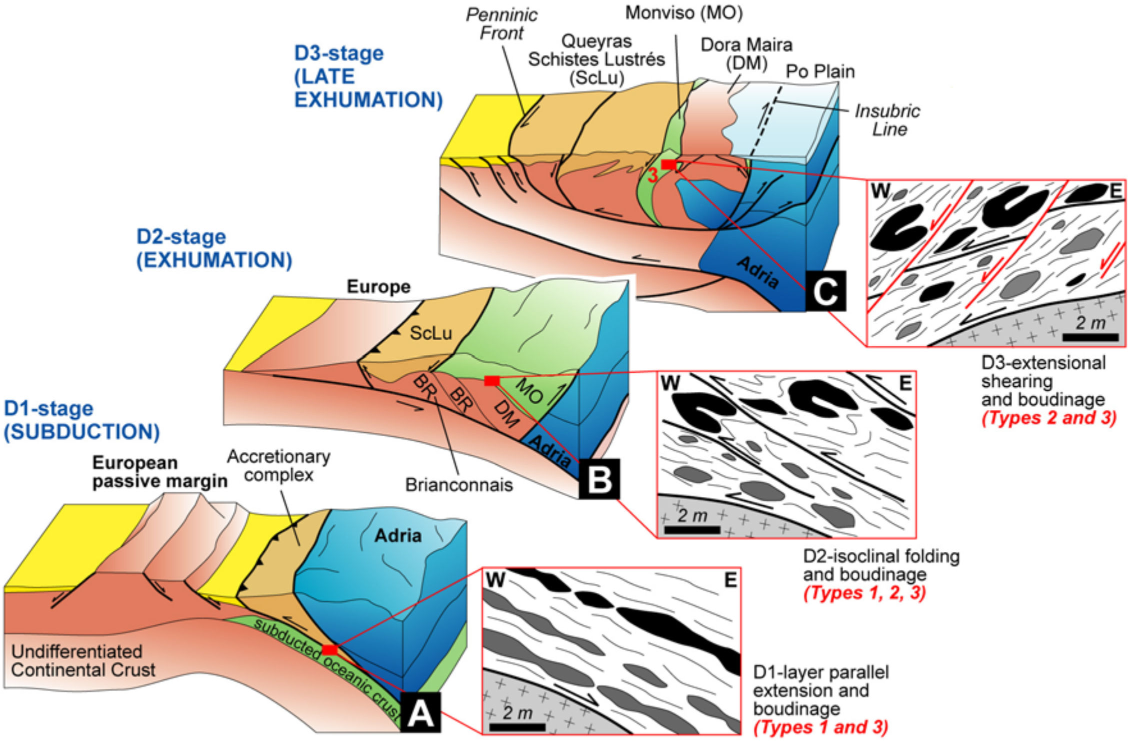

Figure 11 –Cartoons showing the different stages and geodynamic environments, and the progressive stratal disruption of the original non-metamorphic succession, forming the different types of BIMs (see text for detailed explanation): (**A**) D1 stage related to subduction (Paleocene – middle Eocene) contributed to layer-parallel extension and boudinage of Types 1 and 3 which, on the contrary, are not preserved in Type 2 probably because of the overprinting of later deformation; (**B**) D2 stage related to continental collision and exhumation (late Eocene – early Oligocene; modified from Agard *et al.* 2002) played the most significant role in stratal disruption of all the types of BIMs. Isoclinal folding and boudinage of fold limbs occurred during this stage up to isolate lenticular to elongated blocks (Types 1 and 2) and rounded blocks, corresponding to D2-related fold hinges (Type 3); (**C**) D3 stage related to late exhumation (middle Oligocene – Miocene; modified from Lardeaux *et al.* 2006) and doming of the Dora Maira Unit contributed to an higher degree of stratal disruption (Type 2) up to mixing of polymictic blocks (Type 3). In Type 3, D3-related extensional shearing favored mixing processes by dissecting the earlier dismembered succession and allowing previously isolated blocks of different lithologies (mafic metabreccia and metasandstone) to shift among structural levels within the Baracun Shear Zone.

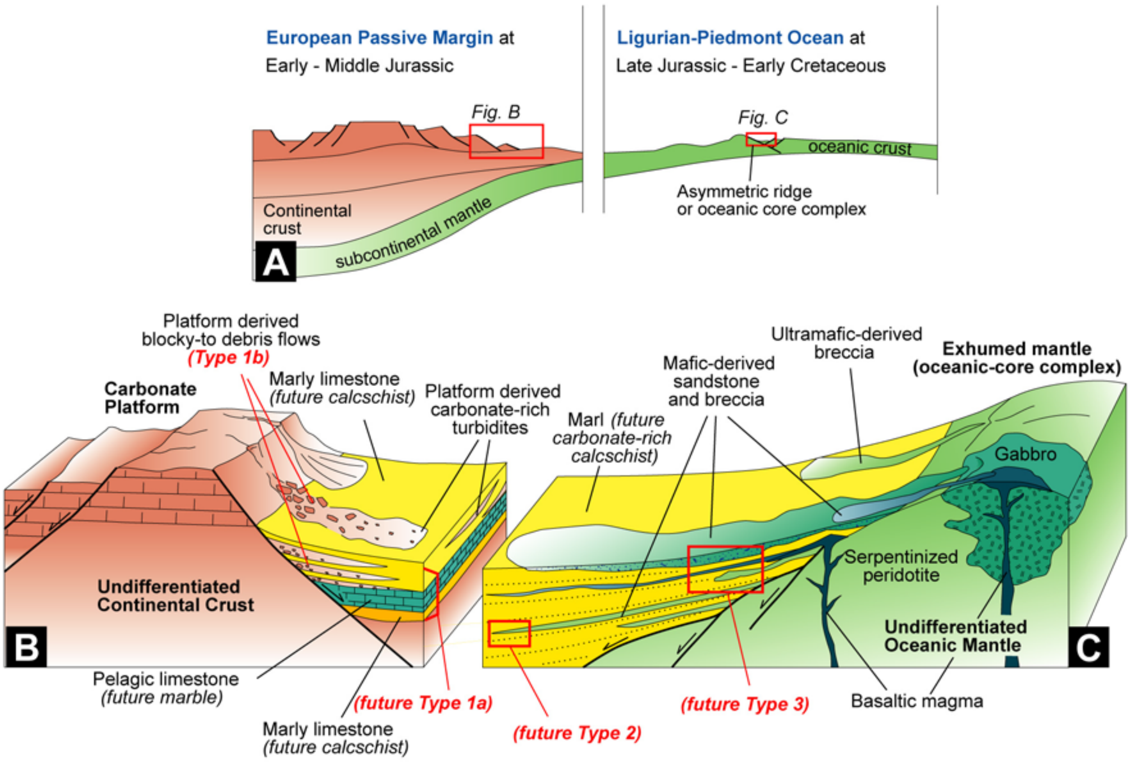

Figure 12 – (**A**) Cartoons showing the geodynamic environments in which protoliths of the different BIMs formed at different times (see text for details): (**B**) Collapse of platform margins of the European passive margin (i.e., Dora Maira Unit) at Early Jurassic time, accompanying the rifting stage. Blocks of Triassic platform-derived dolomite (present-day massive metadolostone) gravitationally emplaced via block-to debris flows within an Early Jurassic pelagic matrix (present-days marble alternating with calcscshist), forming the Type 1b. These non-mappable BIMs of sedimentary origin emplaced within a basinal succession (i.e., marls in yellow and orange color, and pelagic limestone in blue color), which represents the original stratigraphic succession progressively dismembered during subduction to collisional stages (see Figs. 11A-C) to form the Type 1a broken formation. (**C**) Denudation of an oceanic core complex of the Ligurian – Piedmont Ocean at Late Jurassic – Early Cretaceous time. Channelized turbiditic bodies (present-day mafic metasandstone) and breccias (present-day mafic metabreccia) horizons supplied from a heterogeneous sequence of the Tethyan oceanic lithosphere were emplaced at different stratigraphic levels within the slope-to basin succession. The progressive stratal disruption and tectonic mixing of the heterogeneous stratigraphic succession that occurred from subduction to collisional stages (see Figs 11A-C) formed the Type 2 broken formation and Type 3 dismembered formation, respectively.