# Record of Jurassic mass transport processes through the orogenic cycle: Understanding chaotic rock units in the high-pressure Zermatt-Saas ophiolite (Western Alps)

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## ABSTRACT

The eclogite facies Zermatt-Saas ophiolite in the Western Alps includes a composite chaotic unit exposed in the Lake Miserin area, in the southern Aosta Valley region. The chaotic unit is characterized by a block-in-matrix texture consisting of ultramafic clasts and blocks embedded within a carbonate matrix. This unit overlies massive serpentinite and ophicarbonate rocks and is unconformably overlain by layered calcschist. Despite the effects of subduction and collision-related deformation and metamorphism, the internal stratigraphy and architecture of the chaotic unit are recognizable and are attributed to different types of mass transport processes in the Jurassic Ligurian-Piedmont Ocean. This finding represents an exceptional record of the preorogenic history of the Alpine ophiolites, marked by different pulses of extensional tectonics responsible for the rough seafloor topography characterized by structural highs exposed to submarine erosion. The Jurassic tectonostratigraphic setting envisioned is comparable to that observed in present-day magma-poor slow- and ultraslow-spreading ridges, characterized by mantle exposure along fault scarps that trigger mass transport deposits and turbiditic sedimentation. Our preorogenic reconstruction is significant in an eclogitized collisional orogenic belt in which chaotic rock units may be confused with the exclusive product of subduction-related tectonics, thus obscuring the record of an important preorogenic history.

## INTRODUCTION

In most orogenic belts, the temporal and spatial distributions of different types of mass transport deposits (MTDs) commonly document different tectonic stages within the Wilson cycle evolution of oceanic basins, from the early stages of rift drift to later subduction, collision, and orogenic exhumation (Festa et al., 2016, and references therein). MTDs therefore represent fundamental markers of most of the tectonic events, and the documentation and understanding of their overall architecture, internal fabric, composition, and mechanisms of their downslope deformation and emplacement are relevant for better understanding the characteristics of depositional basins and the evolution of orogenic belts. However, in most orogenic belts and exhumed subduction-accretion complexes, a strong similitude of fabric exists between MTDs with a block-in-matrix fabric (i.e., olistostrome sensu Flores, 1955; sedimentary mélanges, e.g., see Raymond, 1984) and tectonic mélanges (e.g., Hsü, 1974; Raymond, 1984; Cowan, 1985; Bettelli and Panini, 1989; Pini, 1999; Festa et al., 2010, 2013; Dilek et al., 2012; Alonso et al., 2015; Balestro et al., 2015b; Platt, 2015; Wakabayashi, 2015). This similitude is the basis of a long-lasting debate on the processes of formation of chaotic rock units (i.e., tectonic versus gravitational), and is strongly amplified in metamorphic belts, where polyphase deformation and metamorphic recrystallization to

eclogitic conditions commonly rework and obscure the primary internal structure of chaotic rock units.

In the metaophiolite units of the Western Alps, different methodological approaches (e.g., structural, petrographic, stratigraphic) adopted in the interpretation of the nature of chaotic rock units and mélanges led to the definition of different tectonic models, which are still debated. For example, mélanges consisting of mafic blocks tectonically incorporated in a serpentinite matrix (i.e., the serpentinite mélange) were described by Guillot et al. (2004) and Federico et al. (2007) as remnants of an exhumed subduction channel (see also Blake and Jayko, 1990; Gerya et al., 2002; Guillot et al., 2009). However, tectonostratigraphic approaches interpreted the western Alpine ophiolitic mélanges as the product of inherited intraoceanic deformation (Balestro et al., 2015a; Lagabrielle et al., 2015), despite the reworking by Alpine subduction- and exhumation-related deformation. This has allowed the documentation of details on the preorogenic evolution of the high-pressure (HP) western Alpine metaophiolites, describing the exhumation of mantle rocks at the seafloor, the formation of chaotic rock units linked with oceanic detachment faults, and the emplacement of basaltic and sedimentary succession with strong lateral and vertical variations (e.g., Tricart and Lemoine, 1991; Festa et al., 2015a; Lagabrielle et al., 2015, and references therein). These different models may, however, not represent contrasting interpretations, but only different stages of a complex evolution from intraoceanic deformation to subduction and subsequent collision.

The application of the proper criteria to the study of mélange rock units together with detailed structural and stratigraphic analyses may provide

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new and useful information to better constrain the nature of these chaotic units, and consequently the evolution of metamorphic orogenic belts.

In this paper we document the internal structure of different block-in-matrix rock assemblages occurring in a chaotic rock unit in the Lake Miserin ophiolite (LMO), which is part of the eclogite facies Zermatt-Saas ophiolite (ZSO) (Western Alps; Fig. 1). The application of criteria adopted to identify mélange rock units (e.g., by Raymond, 1984; Cowan, 1985; Orange, 1990; Bettelli and Panini, 1989; Pini, 1999; Festa et al., 2010, 2012; Wakabayashi, 2015) allowed us to determine that the chaotic rock unit resulted from synextensional intraoceanic mass transport processes, the evidence of which is exceptionally well preserved in the deeply subducted ZSO. Stratigraphic and structural analyses further allow us to highlight that the chaotic rock unit is sealed by postextensional metasediments, and that, despite the polyphase Alpine deformation and metamorphism, a paleounconformity is, uncommonly, still recognizable. The overall architecture demonstrates that mass transport processes acted along the flanks of structural highs made of mantle rocks in the Jurassic Ligurian-Piedmont Ocean (JLPO), that are comparable with those observed in present-day magma-poor slow- and ultraslow-spreading ridges (Dick et al., 2003; Escartin et al., 2008).

## REGIONAL GEOLOGY

The ZSO (Bearth, 1967; see Martin et al., 1994, for a review) was emplaced during the closure of a branch of the JLPO, which was interposed between the European and African plates, and was tectonically stacked within the western Alpine belt (i.e., the Piedmont Zone; e.g., see Dal Piaz et al., 2003). This was the result of deformation and metamorphism that occurred during (1) Late Cretaceous–middle Eocene southeast-dipping subduction, (2) late Eocene–early Oligocene collision and northwest-verging accretion, and (3) Oligocene–Neogene exhumation (e.g., Dal Piaz et al., 2001). The subduction history in the ZSO is recorded by high-pressure mineral assemblages (e.g., Ernst and Dal Piaz, 1978; Martin and Tartarotti, 1989; Li et al., 2004; Bucher et al., 2005; Angiboust et al., 2009; Angiboust and Agard, 2010) to ultrahigh-pressure mineral
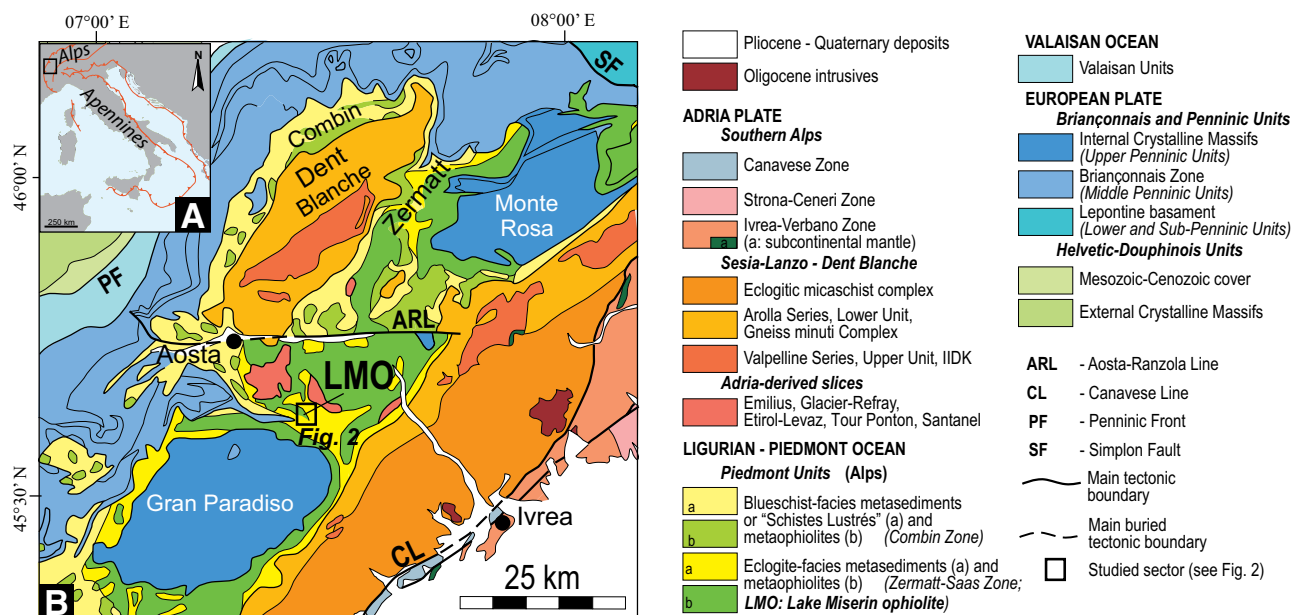
assemblages (e.g., Reinecke, 1991, 1998; Frezzotti et al., 2012, and references therein). The collision and exhumation paths were characterized by blueschist facies decompressional conditions (e.g., Barnicoat and Fry, 1986) and subsequent Barrovian greenschist facies overprint (e.g., Benciolini et al., 1988).
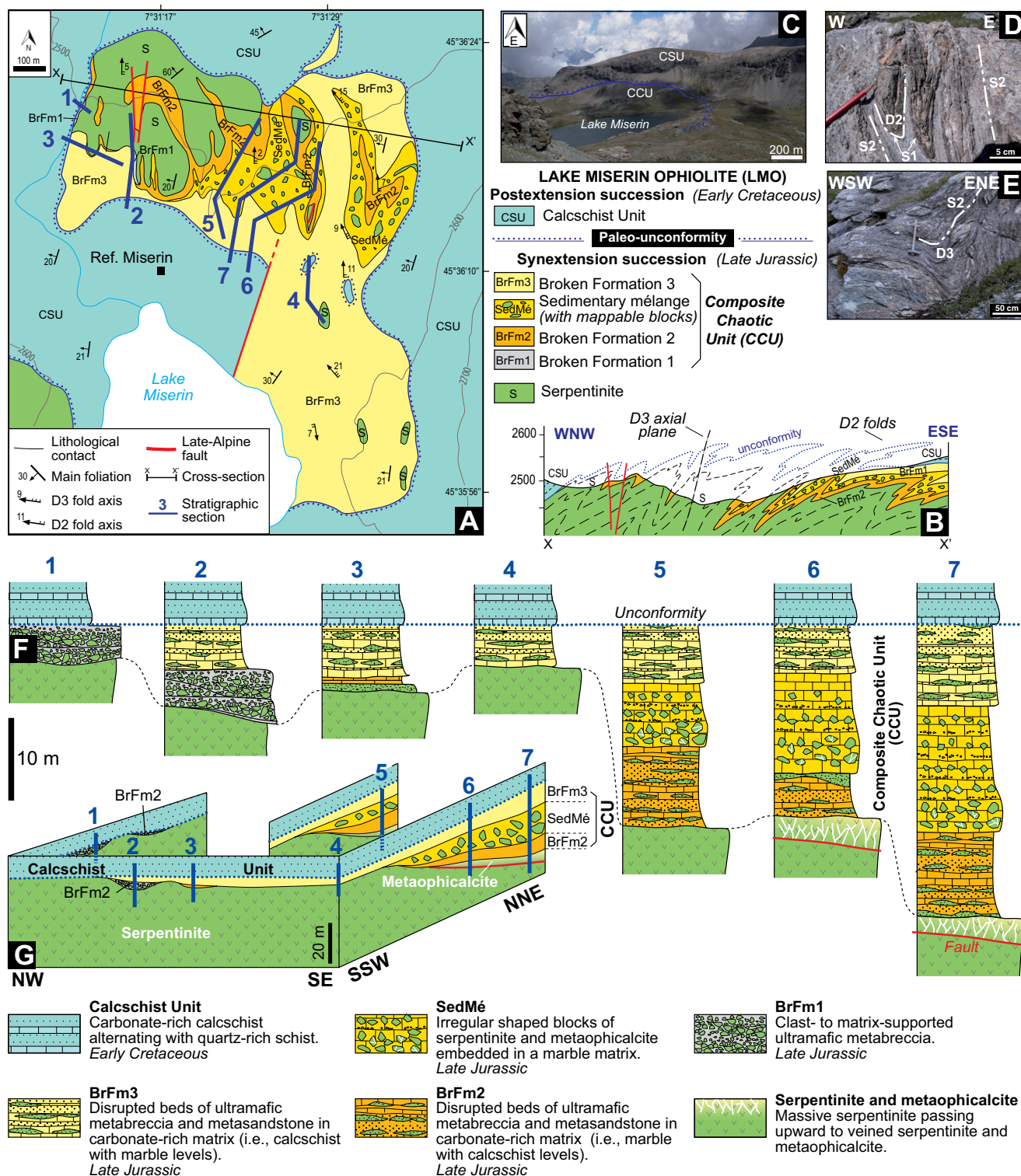
Based on scattered records of hydrothermal oceanic alteration (Cartwright and Barnicoat, 1999; Widmer et al., 2000; Martin et al., 2008) and geochemical mid-oceanic ridge basalt affinity (Bearth and Stern, 1979; Dal Piaz et al., 1981; Pfeifer et al., 1989), the ZSO was interpreted as consistent with a mid-ocean ridge setting of formation. However, the local occurrence and mixing and/or juxtaposition of oceanic- and continent-derived material and units allowed the different interpretation of the ZSO as either the remnant of an hyperextended continental margin in an ocean-continent transition zone (e.g., see Beltrando et al., 2014, and references therein) or the result of the Alpine tectonic juxtaposition between oceanic and continental margin units (e.g., Fassmer et al., 2016, and references therein).

The LMO (Fig. 1), including the chaotic rock units, occurs in the southern sector of the ZSO (the Mount Avic ultramafic massif; e.g., Dal Piaz et al., 2010, and references therein), which consists of serpentinized metaperidotite with relict oceanic textures (Fontana et al., 2008, 2015; Panseri et al., 2008), that was intruded by Fe-Ti and Mg metagabbros. To the north of the LMO (north of Mount Avic), the ZSO is characterized by the occurrence of mafic and/or ultramafic metabreccia and metaophicalcite (Driesner, 1993; Tartarotti et al., 1998) documenting mantle seafloor exhumation, and Mn ore deposits and Fe-Cu sulfide mineralization attributed to oceanic hydrothermal vents (Martin et al., 2008; Tumiati et al., 2010).

## LMO

The LMO consists of serpentinite stratigraphically overlain, through a metaophicalcite horizon, by a composite chaotic unit (CCU) made of serpentinite blocks and disrupted metasandstone and metabreccia horizons with ultramafic composition, embedded within a carbonate-rich matrix. A calcschist unit (CSU) directly overlies either the CCU or the serpentinite and metaophicalcite (Figs. 2A–2C).



Figure 1. (A) Geographic location of the study area. (B) Tectonic map of the northwestern Alps (modified after Balestro et al., 2015a) and location of the study area (LMO–Lake Miserin ophiolite).

Figure 2. (A) Geological map of the Lake Miserin ophiolite (LMO). (B) Cross section of the LMO. (C) The panoramic view of the unconformable contact (dotted blue line) of the calcschist unit (CSU) above the composite chaotic unit (CCU). (D) D2 isoclinal folds deforming S1 foliation (here defined by the serpentinite metasandstone-calcschist contact). (E) D3 gentle folds folding the S2 foliation. (F) Stratigraphic columns. (G) The three-dimensional correlation of the stratigraphic columns in F, showing the relationships between the ophiolite basement and the different rock types within the CCU.

The serpentinite derives from peridotite and consists of antigorite with mesh texture, Ti clinohumite, oxides (Cr-Ni–rich magnetite, ilmenite, and chromite with Cr# ranging between 60 and 80), and diopside with relict augite composition (enstatite$_{47-49}$-ferrosilite$_{1-2}$-wollastonite$_{48-50}$). Upward the serpentinite is covered by a metaophicalcite horizon as thick as 1 m characterized by sets of veins to 1–2 cm thick filled with carbonate, antigorite, or talc, which bound decimeter- to meter-sized clasts of massive serpentinite (Fig. 3A).

The LMO was deformed during at least three superposed Alpine-related deformation phases (D1, D2, D3). D1 is coeval to the subduction-related eclogite facies metamorphism, and developed the S1 foliation, which is parallel to the lithological contacts and overprinted the primary surfaces (i.e., the S0 sedimentary bedding). D2 is coeval to the collision-related

blueschist to greenschist facies reequilibration, and is characterized by north-south–trending isoclinal folds (Fig. 2D) that pervasively deform the metaophiolite succession. D2 folds developed a west-northwest–dipping axial plane foliation (the S2) and are characterized by boudinage along long fold limbs. D3 is coeval to the exhumation stage and is characterized by northwest-southeast–trending gentle folds (Fig. 2E) that deform the previous D1 + D2 structural architecture.

## CCU

The CCU corresponds to a wedge-shaped unit in cross section, which shows a thickness of ~40 m and tapers out from east-northeast and north to
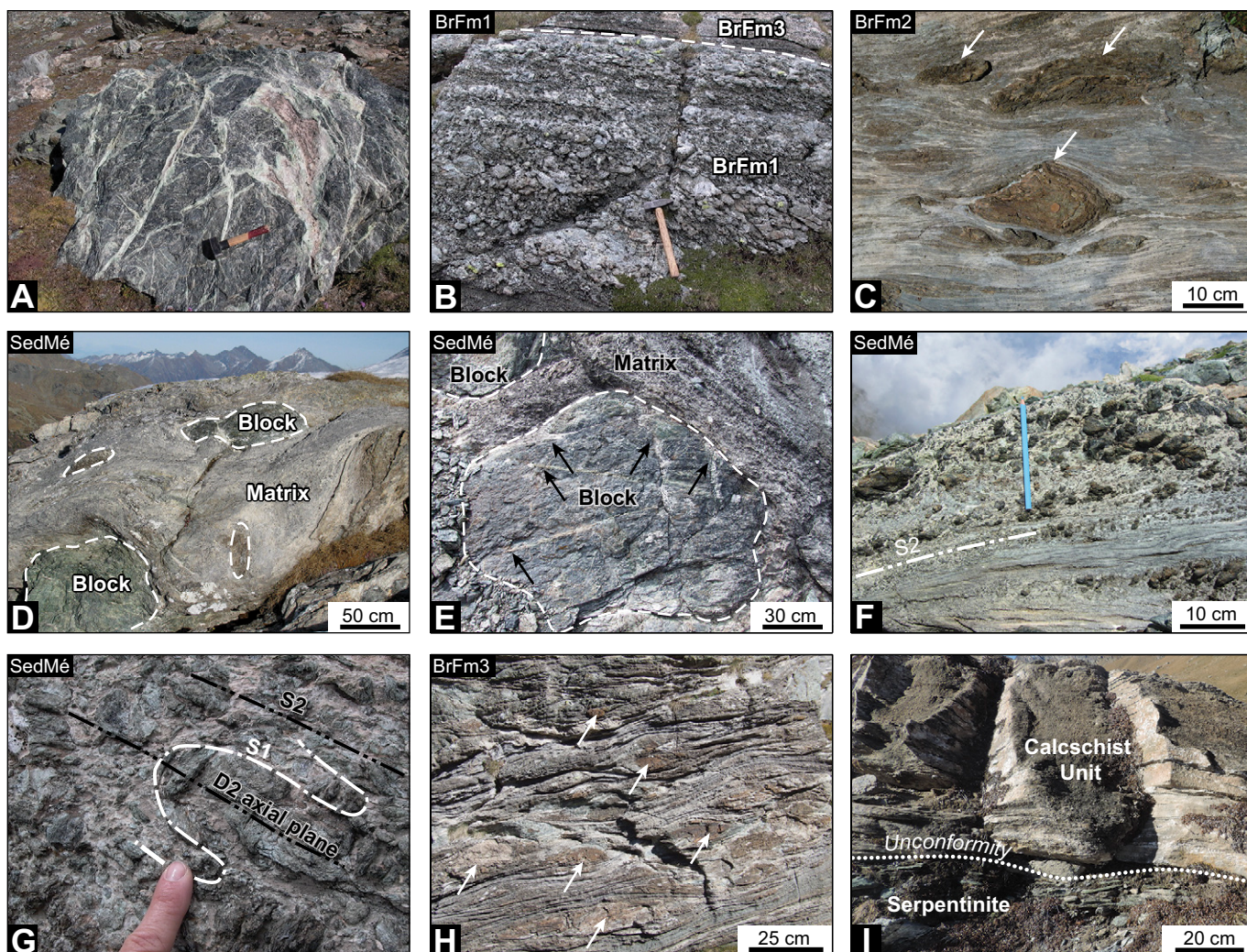


Figure 3. View of the Lake Miserin ophiolite (LMO) and composite chaotic unit (CCU). (A) Close-up view of the metaophicalcite horizon. Hammer used for scale is 30 cm long. (B) BrFm1 (broken formation) consisting of alternating clast- to matrix-supported ultramafic metabreccia horizons, followed by the BrFm3. (C) Close-up view of the BrFm2, showing disrupted and boudinaged horizons of metasandstone with ultramafic composition (arrows) embedded in a sheared carbonate-rich matrix to form the block-in-matrix arrangement. (D) Block-in-matrix fabric of the SedMé (sedimentary mélange and/or olistostrome) with decimeters- to meters-wide exotic blocks of serpentinite (dashed white line), randomly distributed within a whitish marble matrix. (E) Close-up view of isolated blocks of metaophicalcite with carbonate veins (arrows), decimeters long and 1–2 cm thick, in the SedMé. Note that veins do not cross the hosting whitish marble matrix. (F) Close-up view of the SedMé consisting of horizons of ultramafic metabreccia with angular clasts of serpentinite embedded within the marble matrix. (G) Close-up view of foliated (S2; dashed black line) ultramafic metabreccia in the SedMé showing centimeter-sized, irregularly shaped clasts that mark the relict S1 foliation (dashed white line) deformed by D2 folds. (H) Disrupted horizons and bed fragments of ultramafic composition (arrows) embedded within a matrix of alternating calcschist and marble beds of BrFm3. (I) Unconformable contact (dotted line) of the CSU above the serpentinite.

west and south (Fig. 2), showing lateral and vertical changes in the facies of its block-in-matrix fabric. It consists of three types of broken formation (sensu Hsü, 1968), BrFm1, BrFm2, and BrFm3, and a sedimentary mélange/olistostrome (sensu Raymond, 1984; Festa et al., 2012, 2015b), called here SedMé. The contact between the different types of chaotic rock units is transitional and does not show any traces of Alpine-related mylonitic deformation, even if folded and deformed by the Alpine tectonics. In the following, we refer to mélange as a body of mixed rocks, containing both exotic (i.e., extraformational origin) and native (i.e., intra-formational origin) components in a pervasively deformed matrix (see Raymond, 1984; Festa et al., 2012). We refer to broken formations (sensu Hsü, 1968) as stratally disrupted units that preserve the lithological and chronological identity, and contain only native components.

### BrFm1

The BrFm1 consists of different superposed bodies of ultramafic metabreccia ranging in thickness from 1 to 3 m (Figs. 2F, 2G), and is characterized by internal grading. Metabreccia varies from clast supported to matrix supported, with irregular to subrounded clasts ranging in size from decimeters to centimeters (Fig. 3B). The matrix consists of a coarse-grained metasandstone of the same composition as clasts. Rare elongated blocks as much as 50 cm long are randomly distributed within the metabreccia. The BrFm1 shows a lenticular shape at a scale of hundreds of meters with a maximum thickness of ~15 m (Figs. 2F, 2G). The contact with serpentinite is sharp, locally corresponding to a decimeter-thick layer of coarse- to medium-grained metasandstone with ultramafic composition. In the western sector of the area, the BrFm1 is directly overlain with a sharp contact by the CSU (see following) while southward, it gradually passes to the BrFm3 via the gradual increases of the carbonate component in the metasandstone.

### BrFm2

The BrFm2 consists of decimeters-thick disrupted horizons, clast supported and matrix supported, metabreccia, and coarse-grained metasandstone embedded in a carbonate-rich matrix (Fig. 3C), which gradually passes upward from calcschist to whitish marble. It crops out in the northern sectors of the study area (Fig. 2A), showing a wedge-like shape varying from zero to ~15 m in thickness from south-southwest to north-northeast (Figs. 2F, 2G), and directly overlies the metaophicalcite horizon through a sharp contact marked by a centimeters-thick calcschist horizon. Disrupted horizons of detrital ultramafic metabreccia are prevalent in the basal part, and show an internal grading marked by angular to irregularly shaped clasts, to centimeters in size, passing to metasandstone. Those horizons are asymmetrically to symmetrically boudinaged at the scale of meters and define a planar alignment that is consistent with extensional shearing associated with D2 deformation (Fig. 3C). Elongated blocks show a medium to high aspect ratio (i.e., long axis/short axis), with the long axis aligned in a north-south direction, and an irregular flat to ellipsoidal shape corresponding to different degrees of extensional shearing of the primary bedding plane, coherent with the D2 deformation. The marble matrix prevails in the upper part, showing a transitional contact with the overlying SedMé unit.

### SedMé

The SedMé shows a wedge-like shaped geometry ranging in thickness from few meters to 15–20 m, oriented from southwest to north-east (Figs. 2F, 2G). In the northwestern sector, it directly overlies the massive serpentinite and the metaophicalcite. It is characterized by a block-in-matrix fabric (Figs. 3D, 3E) with mainly rounded to irregular and equiangular exotic blocks of massive to veined serpentinite and metaophicalcite, decimeters to 1 m in size, embedded within a whitish marble matrix. The blocks show a low aspect ratio (i.e., main aspect ratio of 1.0–1.6). Carbonate veins, decimeters long and as much as 1–2 cm thick, are bounded within the blocks and do not cross the matrix (Fig. 3E). Blocks are randomly distributed within the matrix and only rare elongate blocks are aligned with the S2 foliation. The matrix commonly includes centimeters-thick horizons of metabreccia consisting of angular or subangular clasts of serpentinite (Fig. 3F). These horizons are foliated (S1, S2) and folded (D2), constraining the brecciation process as having occurred before the D1 deformation stage (i.e., before the subduction-related deformation stage; Fig. 3G). In the upper part of the unit, blocks decrease in size (to decimeters) and the matrix is gradually interfingered with centimeters-thick levels of calcschist that mark the transition to the overlying BrFm3.

### BrFm3

The BrFm3 represents the uppermost part of the CCU. It has characteristics similar to those of the BrFm2, and consists of a calcschist and marble matrix, embedded disrupted horizons and bed fragments, decimeters to meters long and to decimeters thick, of medium-grained metasandstone with ultramafic composition (Fig. 3H). The elongated to sigmoidal shapes of blocks are consistent with D2-related boudinage. The mean aspect ratio of blocks is medium to high (as for the BrFm2). This unit, which has an average thickness of ~10 m, decreases in thickness toward the west-northwest, where it directly overlies the BrFm1 and/or the serpentinite, and it is followed upward by the CSU (Figs. 2F, 2G).

### CSU

The different units of the CCU and underlying massive serpentinite are unconformably overlain by layered carbonate-rich calcschist (CSU, Fig. 2) that is devoid of any ophiolite-derived detrital material and alternates with levels of quartz-rich schist. The basal contact is sharp and corresponds to a depositional surface as inferred from the lack of any associated mylonitic structure (Fig. 3I). The unconformable contact at the base of the CSU is folded together with the units below due to the superposition of D2- and D3-related folding (Fig. 2B).

### LMO AS A PRODUCT OF JURASSIC MASS TRANSPORT PROCESSES

Although the Alpine subduction to collisional processes and metamorphism strongly deformed the primary structural tectono-sedimentary setting (e.g., Gerya et al., 2002), our tectonostratigraphic reconstruction documents that in this sector of the ZSO, the inherited intraoceanic architecture is well preserved in the LMO. Direct application of the criteria used to identify mélange rock units allowed us to interpret the tectonic significance of the CCU. We infer that the BrFm1 and SedMé fabrics formed by a close association of intraoceanic tectonics and mass transport processes acting at the time of Jurassic extensional tectonics, whereas the chaotic block-in-matrix arrangement of BrFm2 and BrFm3 is related to the tectonic dismemberment of their primary stratigraphic organization by means of the Alpine D1 and D2 deformations.

The BrFm1, which consists of blocks and matrix with similar compositions, corresponds to a serpentinite matrix broken formation, composed of only native components. The latter were disrupted in situ by extensional

tectonics and related mechanical fracturing of the mantle rocks that were exhumed to the seafloor and subsequently reworked by mass transport processes with a limited run-out distance of downslope transport.

The block-in-matrix arrangement of the SedMé represents the emplacement of exotic components with respect to the carbonate matrix. The random distribution of rounded to irregularly shaped blocks (i.e., low aspect ratio) suggests an original emplacement through gravitational processes (see following) rather than tectonic slicing. The occurrence of carbonatic veins, which are within the same blocks, also constrains their exotic nature, sourced from the primary ophicalcite horizon. The characteristics of this sedimentary mélange correspond to the passive margin olistostrome type of Festa et al. (2016) that formed in intraoceanic settings.

The BrFm2 and BrFm3 consist of calcschist with disrupted horizons of metasandstone and metabreccia with an ultramafic composition that represent native components (i.e., turbiditic horizons) with respect to the carbonate-rich matrix (e.g., Balestro et al., 2015b).

### CCU: A Record of Tectono-Sedimentary Processes

The wedge-shaped architecture of the CCU, its internal fabric, composition, and subdivision, and the nature of the contacts with the underlying serpentinite and the overlying unconformable CSU, suggest different mechanisms of tectonically induced mass transport sedimentation spatially and temporally associated with extensional deformation and erosion along an intraoceanic bathymetric high (Figs. 4A–4D). The vertical and lateral organization of the BrFm2 represents the deposition of channelized turbidites. The occurrence of brecciated horizons alternating with calcschist in the lower part of this succession suggests proximal deposition close to a submarine escarpment with high depositional energy, recording a first extensional stage of mantle denudation (Fig. 4A). The gradual upward increasing of the carbonate component within the matrix and decreasing of grain size within the ultramafic detrital horizons are consistent with the progressive decrease of depositional energy, suggesting in turn a decrease of tectonic activity and/or deepening of the relative sea level. However, the occurrence of turbidites with lithics of only ultramafic composition within the middle to upper part of the BrFm2 clearly shows that their source area and the depositional setting of this part of the ZSO were not influenced by material coming from the erosion of continental margin rocks.

The block-in-matrix arrangement of the SedMé, with serpentinite blocks embedded within a carbonate matrix, records a main and abrupt pulse of extensional tectonics (Fig. 4B). The random distribution of blocks within the matrix and the occurrence of carbonate veins confined within the blocks suggest their collapse from bathymetric and/or structural highs, exposing both serpentinized peridotite and ophicalcite. The upward
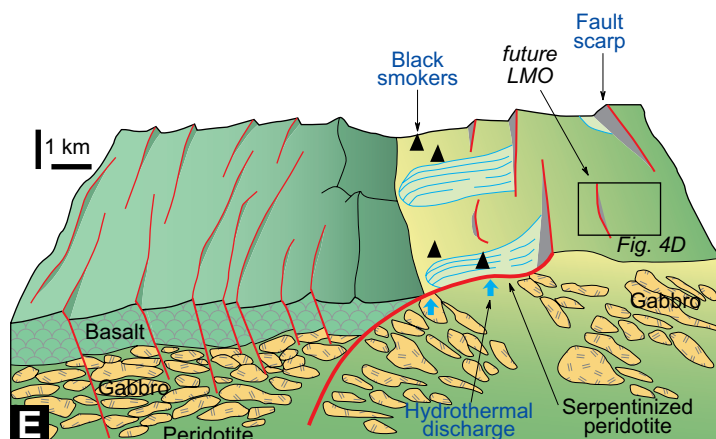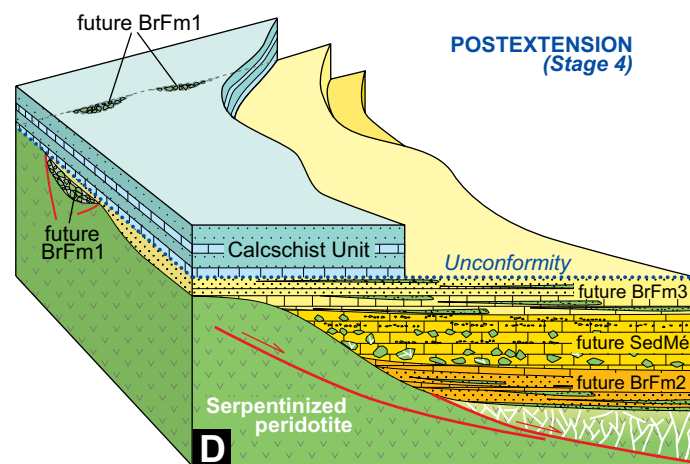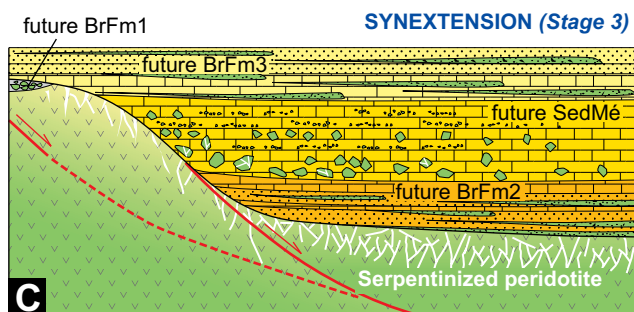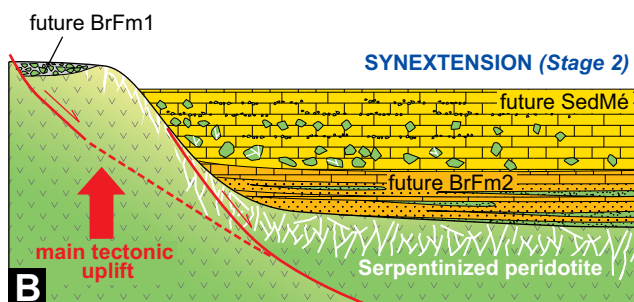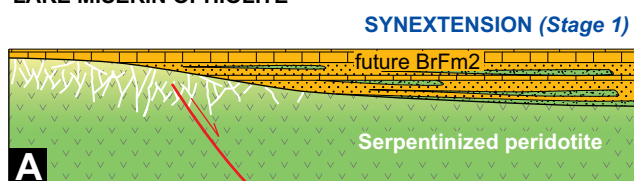


Figure 4. (A–D) Different stages of synextensional to postextensional tectono-sedimentary evolution of the composite chaotic unit (CCU) in Late Jurassic–Early Cretaceous time. BrFm—broken formation; SedMé—sedimentary mélange and/or olistostrome. (E) Interpreted three-dimensional reconstructions of the physiography of the studied sector of the Lake Miserin ophiolite (LMO) in Late Jurassic time (inspired and modified from Escartin and Canales, 2011).

decrease of block size to the gradual transition to BrFm3 is consistent with the gradual decrease in magnitude of the tectonic activity.

BrFm3 records a new turbiditic input (Fig. 4C), comparable in both composition and interpretation to that described here for BrFm2. Its direct superposition onto the BrFm1 (see Fig. 3B) and locally onto the serpentinite suggests that the BrFm1 was originally located on a topographic high mainly consisting of mantle rocks exposed to in situ mechanical fracturing and erosion, thus representing part of the source area for the ultramafic detrital components interfingered within the CCU (Figs. 4B, 4C).

The wedge shape of the CCU is consistent with the vertical change of facies of each single unit and with a paleoescarpment probably dipping east-northeast (present-day coordinates).

The unconformable deposition of the CSU (Fig. 4D), overlying both the CCU and the serpentinite, represents a postextensional succession that was deformed during Alpine tectonic stages, together with the underlying sequence. Ophiolitic detrital material is lacking and the occurrence of quartz-rich schist records an input of continent-derived sediments within the basin, which was thus filled by distal mixed siliciclastic-carbonatic turbidites reworking a passive margin source area. This depositional stage, which coincides with significant terrigenous input into the basin, is comparable to Early Cretaceous postextensional deposits preserved in the unmetamorphosed Ligurian units in the northern Apennines (e.g., Decandia and Elter, 1972).

### LMO and the Jurassic Ligurian-Piedmont Seafloor

Preorogenic reconstruction of the LMO implies tectonic denudation of lithospheric mantle at the seafloor of the JLPO, as it has been documented in modern slow- and ultraslow-spreading ridges (e.g., Cannat, 1993; Dick et al., 2003; Escartin et al., 2008) and inferred for some areas of the Alps and Apennines (e.g., Tricart and Lemoine, 1991; Lagabrielle, 2009; Tartarotti et al., 2011; Sansone et al., 2012; Beltrando et al., 2014; Balestro et al., 2015a). Metaophicalcite records the early history of mantle exhumation by extensional tectonics and concurrent hydrothermal fluid circulation on the seafloor. Brecciation and MTDs recorded in the CCU are evidence of tectonically induced sedimentation, thus representing synextensional (synrift) deposits. Similar serpentinite breccias have been observed in the Atlantic Ocean, along the western median valley wall of the MARK (Mid Atlantic Ridge–Kane Fracture Zone) area. Submersible diving on *Alvin* (Karson et al., 1987) and *Nautile* (Mével et al., 1991) reveals that this region is characterized by active faulting and mass wasting dominated by extensive debris-slide deposits (Karson and Lawrence, 1997). Along steep fault scarps, foliated serpentinites are directly overlain by coarse, clast-supported breccia consisting of angular cobbles of foliated serpentinite in a matrix of consolidated carbonate. Furthermore, in the median valley wall of the MARK area, mass transport processes have produced rock deposits with angular shapes (see Karson and Lawrence, 1997), similar to those found in our CCU. In our model, the serpentinite breccia of BrFm1 could have been reactivated by normal faults, providing the source material delivered to clastic material and blocks of the SedMé. Similar, but much farther away, structural highs of mantle rocks represented the source material for the turbiditic intercalation within the BrFm2 and BrFm3, suggesting that the turbiditic deposition within this part of the ZSO was not contaminated by material sourced from continental margins.

The recognition of the unconformable deposition of the postextensional CSU, sealing the synextensional LMO architecture, is comparable with the Valanginian–early Aptian postrift siliciclastic rocks interfingering with carbonate-rich turbiditic deposits in the well-documented deep Galicia margin (e.g., Winterer et al., 1988). The similarity to the Early Cretaceous postextensional calcschist in other Alpine (Festa et al., 2015a)

and northern Apennines (e.g., Decandia and Elter, 1972) ophiolites marks the critical timing of the final opening stages of the JLPO.

Our results have profound implications for the physiography and geodynamics of the JLPO: the occurrence of preorogenic, synextensional deposits indicates that the seafloor of the JLPO should have been characterized by regions of active faulting responsible for the formation of a rugged seafloor topography exposed to widespread gravitational processes (Fig. 4E). The composition of detrital material within the different units of the CCU, which is exclusively of ultramafic composition and lacks any continental-derived material, may suggest that in Late Jurassic time the LMO was located far from the continental margin, i.e., at the time of mantle exhumation and synextensional (i.e., synrift) deposition. Therefore, this evidence may suggest that the LMO represents a depositional setting located in the oceanward part of an ocean-continent transition setting, protected by the deposition of continental derived material, or an embryonic oceanic basin far from the continental margins. Although it is not within the scope of this work, the latter interpretation seems to better agree with (1) the geochemical and isotopic data from this region (e.g., see Cartwright and Barnicoat, 1999; Widmer et al., 2000; Martin et al., 2008), (2) the recent interpretation of the contact between ZSOs and continental units (i.e., Etirol-Levaz slice) as a product of the Alpine tectonics (e.g., Fassmer et al., 2016), and (3) the lack of any kind of continental-derived material within the CCU.

### CONCLUSIONS

Our findings document an exceptionally preserved record of MTDs and turbiditic sedimentation in the deeply subducted ZSO, which formed by intraoceanic tectono-sedimentary processes during the Late Jurassic synrift stages of the LPO basin. The understanding of the meaning of each type of chaotic rock unit within the LMO, as well as the recognition of a paleounconformity, allow us to detail the role played by different pulses of extensional tectonics associated with mantle exhumation and their control on sedimentation. This reconstruction as an eclogitized collisional orogenic belt is significant, because the occurrence of chaotic rock units may be commonly confused and interpreted as the exclusive product of subduction-related tectonics, obscuring the record of an important preorogenic history. In particular, in orogenic belts such as the Western Alps, in which subduction tectonics represent an efficient mechanism of rock mixing (e.g., see Cloos, 1982; Federico et al., 2007; Festa et al., 2012; Platt, 2015; Raymond and Bero, 2015; Wakabayashi, 2015; Ukar and Cloos, 2016), the application of criteria derived from the study of mélange rock units represents a useful methodology not only to discriminate the process (i.e., gravitational versus tectonics) for the mixing of oceanic and continental blocks, but also to provide complementary data to better constrain paleogeographic reconstructions.

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