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Comparative analysis of the sedimentary cover units of the Jurassic Western Tethys ophiolites in the Northern Apennines and Western Alps (Italy): Processes of the formation of mass transport and chaotic deposits during seafloor spreading and subduction zone tectonics

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ABSTRACT

The Jurassic ophiolites in the Northern Apennines and the Western Alps represent fossil mid–ocean ridge (MOR) oceanic lithosphere that formed in the Mesozoic Ligurian–Piedmont Ocean Basin (LPOB). Their sedimentary covers include chaotic rock units containing ophiolite–derived material. The processes of formation and the lithostratigraphic position of these chaotic units in the Western Alps remain a matter of debate, unlike their counterparts in the Northern Apennines. This is because of pervasive tectonic deformation and high-pressure metamorphism that affected their internal structure during collisional tectonics. A comparative analysis of these chaotic units in both mountain belts reveals the nature of processes involved in their formation. Chaotic deposits of gravitational origin occur both below and above the extrusive sequences in the ophiolites. They represent syn-extensional, hyper-concentrated deposits associated with the seafloor spreading evolution of the LPOB lithosphere during Middle and Late Jurassic time. Mass transport deposits (MTDs) occur as intercalations within turbiditic sequences above the ophiolites. They represent syn–contractional submarine slides that occurred on frontal accretionary prism slopes during the Late Cretaceous–Paleocene closure of the LPOB. The results of our comparative analysis imply that: (1) the structure–stratigraphy of the chaotic deposits and MTDs of the Northern Apennines can be used as a proxy to better identify their metamorphosed and highly deformed counterparts in the Western Alps; (2) sedimentological processes associated with slow–spreading MOR tectonics and with accretionary prism development in convergent margin tectonics contributed to the sediment budgets of the cover sequences; and, (3) magmatic, tectonic and sedimentological processes that occurred during the formation of the Jurassic oceanic lithosphere and its sedimentary cover in the LPOB were remarkably uniform and synchronous.

Keywords: Mesozoic Ligurian–Piedmont Ocean; submarine chaotic rock units; submarine mass transport deposits; sedimentary cover of ophiolites; Western Alps; Internal Ligurian Units – Northern Apennines.

INTRODUCTION

Chaotic rock units (i.e., tectonic, sedimentary and diapiric mélanges, broken formations and polygenetic mélanges, see Festa et al., 2019b) containing fragments of an ophiolite represent the most significant component of the ocean-derived units preserved in Archean to Cenozoic collisional belts (e.g. Sample and Moore 1987; Orange 1990; Polat and Kerrich, 1999; Fitzherbert et al., 2005; Dilek, 2006; Yamamoto et al.2007; Federico et al., 2007; Festa et al., 2010, 2020c; Malatesta et al., 2012; Dilek et al., 2012; Balestro et al., 2015a, 2020; Ogawa et al., 2015; Ernst, 2016; Scarsi et al., 2018; Raymond, 2019; Roda et al., 2019; Wakabayashi, 2011; Hajná et al., 2019; Gao and Santosh, 2020; Palin et al., 2020; Žak et al., 2020; Barbero et al., 2021). Understanding the formation and emplacement of these chaotic deposits in space and time is significant for better constraining the nature, tempo and order of the magmatic, tectonic and sedimentological processes, which operated during the formation of ancient oceanic lithosphere and its sedimentary cover. Related data and observations can provide additional constraints for redefining the plate tectonic paradigm and fro developing a better understanding of the Earth systems.

In the Piedmont Zone of the Western Alps and in the Internal Ligurian Units of the Northern Apennines in Italy (Fig. 1), these types of chaotic rock units were derived from the deformation of the northern and southern parts of the Jurassic Ligurian-Piedmont oceanic rocks (Western Tethys), respectively (Marroni et al., 2017; Dilek and Furnes, 2019). In the Northern Apennines, the chaotic rock deposits show a very low–grade metamorphic overprint, allowing documentation in detail of their preserved diagnostic sedimentological features and their lithostratigraphic position. In turn, this knowledge allows interpretation of the chaotic rock masses as the products of different mass transport processes, which occurred during the Middle-Late Jurassic seafloor spreading of the Ligurian-Piedmont Ocean Basin (LPOB) lithosphere and the Late Cretaceous – Paleocene tectonic convergence between Europe and Adria (e.g., Fierro and Terranova 1963; Elter 1975; Abbate et al., 1970, 1980; Cortesogno et al., 1987; Marroni and Pandolfi, 2001; Bortolotti and Principi, 2003; Principi et al., 2004; Lamarche et al., 2008; Festa et al., 2018; Meneghini et al., 2020).

Conversely, in the Western Alps, the chaotic rock units containing ophiolite–derived material were affected by pervasive subduction- and exhumation-related deformation and high–pressure metamorphism. As a result, primary sedimentological features in these rock units are partially obscured or obliterated; lithostratigraphic position and evidence of tectonic versus sedimentary formational processes in their development, thus, remain matters of debate (see e.g., Balestro et al., 2015a, Tartarotti et al., 2017a; Roda et al., 2019 and references therein). This phenomenon complicates the detailed reconstruction of the syn-spreading to convergent stages of tectono-sedimentary evolution of the northern portion of the LPOB, as exposed in the Western Alps.

In this paper we define the original, oceanic sedimentary cover of the Jurassic ophiolites exposed in the Northern Apennines and the Western Alps (Italy), and document various chaotic rocks units preserved in these cover sequences. We compare and correlate both lithologically and chronologically these chaotic rock units and their stratigraphic positions in the Northern Apennines and the Western Alps (Fig. 1). We show that the well-known sedimentological-stratigraphical features of the chaotic deposits in the Northern Apennines can be used as a proxy allowing us to refine the tectonostratigraphy of their highly deformed and metamorphosed counterparts in the Western Alps. Our results indicate that the LPOB lithosphere underwent similar tectonic processes during the Jurassic seafloor spreading and Late Cretaceous–Early Paleocene closure phases of the ocean basin history throughout its entire length.

Nomenclature and terminology of chaotic rock units

In this paper we use the term *chaotic rock unit* as a general and descriptive, but not a genetic term, to describe different types of block-in-matrix rock assemblages. This term includes the entire range of chaotic rock mass occurrences, in which mélanges and broken formations represent two end members (see Festa et al., 2019b for details). Hence, chaotic rock units may represent a rock mass that can be formed by: (1) tectonic, sedimentary and/or diapiric processes; (2) both stratal disruption and/or mixing processes, and (3) superposition of exotic, native or mixed exotic – native blocks embedded in a matrix of various possible compositions. Chaotic rock units formed by sedimentary (gravitational) processes represent ancient submarine mass transport deposits (MTDs; see, e.g., Lucente and Pini, 2008; Ogata et al., 2012, 2020; Festa et al., 2016; Pini et al., 2020), commonly described as olistostromes (Flores, 1955; Elter and Trevisan, 1973; Pini, 1999) or sedimentary mélanges (e.g., Raymond, 1984; Bettelli and Panini, 1985, Bettelli et al., 2004; Festa et al., 2016) in orogenic belts and exhumed subduction – accretion complexes. We use the terms "mass transport deposit (MTD)" and "chaotic deposit" to denote two sedimentary (gravitational) chaotic rock unit types, which differ from each other in their matrix types. Chaotic deposits are characterized by a matrix- to clast-supported texture with a predominantly basic to ultrabasic sandy matrix, and more rarely by a hematitic to carbonaceous matrix, whereas MTDs have a shaly matrix. Note also that some of the described examples of chaotic deposits and MTDs consist of single layers. This prevents us from using the terms sedimentary mélange and olistostrome, as these occurrences are not mappable at 1:25,000, as required by the definition of the mélange term (e.g., Berkland et al., 1972; Wood, 1974; Silver and Beutner, 1980; Raymond, 1984; Cowan, 1985; Festa et al., 2019b).

GEODYNAMIC HISTORY OF THE LIGURIAN – PIEDMONT OCEAN BASIN (LPOB)

The Ligurian – Piedmont Ocean Basin (LPOB), which evolved between Europe and Adria, was a restricted, Red Sea – type ocean basin in the Mesozoic paleogeography of the Western Tethys (Fig. 2a; see, e.g., Dilek and Furnes, 2019 and references therein). It was connected with the Central Atlantic Ocean Basins to the west via a NW–SE–oriented transform fault system (Fig. 2a; Dercourt et al., 2000; Stampfli and Borel, 2002; Stampfli et al., 2002; Golonka, 2007; Schettino and Turco, 2011; Berra and Angiolini, 2014; Hosseinpour et al., 2016 and Dilek and Furnes, 2019). The opening of the LPOB is generally regarded as the result of rift–drift and seafloor spreading during Middle Triassic through Middle Jurassic time (Marroni et al., 1998; Müntener and Hermann, 2001; Whitmarsh et al., 2001; Capitanio and Goes, 2006; Montanini et al., 2006; Marroni and Pandolfi, 2007; Piccardo et al., 2014; Festa et al., 2020a). Initial lithospheric stretching and distributed extension was followed by strain localization and hyper-extension, which led to continental rifting and seafloor spreading (Lavier and Manatschal 2006; Péron-Pinvidic and Manatschal 2009; Mohn et al., 2012; Ribes et al., 2019). The resulting conjugate margins were asymmetric in their structural architecture with the European margin showing a narrow ocean-continent transition zone (OCTZ) marked by high-angle normal faults and the Adria margin characterized by a wider OCTZ (Fig. 2a), along which the subcontinental mantle and the lower continental crust were exhumed (Marroni and Pandolfi 2007; Saccani et al., 2015).

The oceanic lithosphere of the LPOB was unlike a typical Penrose–type oceanic lithosphere with a complete crustal pseudostratigraphy (or ocean plate stratigraphy, *sensu* Wakita, 2015) of a modern fast–spreading oceanic lithosphere (Anonymous, 1972; Dilek et al., 1998), rather it resembled a Hess–type oceanic lithosphere (Dilek and Furnes, 2011) that commonly develops at slow– to ultra slow–spreading mid–ocean ridge settings (Pognante et al., 1986; Lemoine et al., 1987, Lagabrielle and Cannat, 1990, Treves and Harper, 1994; Cannat, 1996, Cannat et al., 1997, Michard et al. 1996; Magde et al., 2000, Rabain et al., 2001; Balestro et al., 2015b; Rampone e al., 2020). The available paleontological data from chert deposits in the Ligurian ophiolites (Bill et al., 2001; Principi et al., 2004), as well as the radiometric dating results (Li et al., 2013; Tribuzio et al., 2016), indicate that seafloor spreading within the LPOB lasted for ~25 m.y. from Bajocian to Tithonian time. The seafloor spreading phased out and stopped at the beginning of the Early Cretaceous Epoch when the basin was about 600 to 700 km–wide (Abbate et al., 1980; Marroni and Pandolfi, 2007; Balestro et al., 2019). Throughout much of the Cretaceous Period the LPOB experienced deep-sea pelagic deposition without any tectonic or volcanic event interrupting this depositional record.

During Campanian time, the mode of sedimentation changed abruptly with the onset of deep-sea clastic sedimentation, which involved the deposition of a vast amount of siliciclastic and carbonate turbidites, whose sediments were derived from the European margin (Marroni and Perilli, 1990; Marroni et al., 1992; Principi et al., 2004). The onset of this extensive turbidite deposition episode is considered to be the beginning of a contractional deformation phase in the evolutionary history of the LPOB that led to its closure in the Cenozoic Era. The early Campanian time of the turbidite deposition coincides with the age of high–pressure metamorphism in the internal sectors of Western Alps (see, e.g., Manzotti et al., 2014 and reference therein) and in Corsica (e.g., Lahondère and Guerrot, 1997).

The initial stages of basin closure were facilitated by an intraoceanic subduction event, which resulted in the development of a subduction–accretion system (Fig. 2b). The position of this intraoceanic subduction within the LPOB is still a matter of debate. Recent geodynamic models place this subduction–accretion system close to or within the OCTZ along the Adria continental margin, with subduction beginning, in the Late Cretaceous Epoch (Manzotti et al., 2014; Marroni et al., 2017; Barbero et al., 2020; Festa et al., 2020a).

The accretionary wedge experienced slope instability due to subduction of an oceanic crust characterized by seamounts and a rough topography, probably inherited from the spreading phase (Marroni and Pandolfi, 2001; Marroni et al., 2017; Meneghini et al., 2020). The slope instability resulted in large submarine slides recorded as debris flows and slide deposits that were emplaced within or at the top of the trench turbidites (e.g., Pini, 1999; Festa et al., 2018; 2020b; Ogata et al., 2019; Meneghini et al., 2020 and references therein).

During the convergence, the LPOB lithosphere was subducted largely into the mantle or was locally accreted at the base or in front of an accretionary wedge (Fig. 2b). Thus, several segments of the LPOB that were accreted at different depths are found today as tectonic thrust sheets of ophiolites in the Western Alps and the Northern Apennines. These units were affected by pervasive deformation associated with subduction-related metamorphism ranging from very low-grade to blueschist and eclogite facies (Goffè et al., 2003), similar to that typically described in many exhumed, sediment-dominated accretionary prisms (Ernst, 1970, 1971, 2015; Miyashiro, 1973; Raymond, 1973; More and Sample, 1986; Meneghini et al., 2009; Plunder et al., 2015). In the Northern Apennines the ophiolite units were subducted to shallow levels (maximum of 25 km depth; Marroni et al., 2017), whereas in the Western Alps they were subducted to depths ranging from 30 km to 90 km (e.g. Handy et al., 2010; Roda et al., 2020 and reference therein) and were metamorphosed under peak P-T conditions during latest Cretaceous(?) to middle Eocene time (e.g. Rosenbaum and Lister 2005; Zanoni et al., 2016; Rebay et al., 2018; Luoni et al., 2020 and references therein).

The deformation characteristics of these units indicate an accretion by coherent underplating during east–dipping and low–rate subduction dominated by a high sediment budget. The deformation history and the related metamorphism testify not only to the accretion phases, but also to the exhumation history of these units (Polino et al. 1990; Butler et al. 2013; Roda et al., 2020; Luoni et al., 2020). Ophiolite units detached from the subducting slab were uplifted to shallow crustal levels and rapidly exhumed before the early Oligocene. This inference is supported by the occurrence of continental conglomerates in the Tertiary Piedmont Basin (Fig. 1), which represents a wide episutural basin overlying the metamorphosed ophiolites both in the Western Alps and in the Northern Apennines (Federico et al., 2015; Barbero et al., 2020; Festa et al., 2013, 2020b). During and after middle Eocene time, the Jurassic ophiolites underwent continental collision tectonics and deformation both in the Western Alps and the Northern Apennines and were involved in nappe and overthrust development and large–scale isoclinal and recumbent folding.

In summary, the LPOB developed during three main stages. The first stage involved continental rifting and seafloor spreading in Middle to Late Jurassic time (Fig. 2a). During the second stage, between the Berriasian and the Santonian ages, it experienced tectonic quiescence and extensive pelagic deposition. During the third stage, starting in the Campanian age, the LPOB underwent intraoceanic subduction, basin closure, and continental collision.

OPHIOLITE AND SEDIMENTARY COVER RECORD IN THE NORTHERN APENNINES

In the Internal Ligurian Units (Fig. 1), a series of tectonostratigraphic units occurs in thrust sheets. These thrust sheets extend from southern Tuscany to the city of Genova, in the north, where they are in contact with eclogitic oceanic rocks of the Voltri Group, assigned to the Western Alps (Fig. 1). These tectonostratigraphic units show pervasive deformation structures that are spatially and temporally associated with a metamorphic overprint, decreasing in grade from the structurally lowermost units to those lying on top of the tectonic pile (Leoni et al. 1996; Ellero et al. 2001). The lowermost units (Cravasco-Voltaggio and Mt. Figogna Units) are affected by low-grade blueschist facies metamorphism, whereas the uppermost ones (Gottero, Bracco-Val Graveglia, Colli-Tavarone, Portello, Vermallo and Due Ponti units) display mineral phases and textures suggesting very low-grade metamorphic conditions, ranging from upper anchizone to epizone conditions (Leoni et al. 1996; Crispini and Capponi 2001; Ellero et al. 2001).

The Internal Ligurian Units, regardless of the degree of metamorphism or deformation, display a stratigraphic succession that reflects the inferred three stages of development of the LPOB. This succession includes a ~1–km–thick ophiolite sequence and a ~4–km–thick sedimentary cover, which includes two lithologically and compositionally different parts with different geodynamic significance (Decandia and Elter, 1972, Abbate et al., 1980; Treves 1984; Marroni and Perilli 1990; Marroni et al. 1992; Abbate et al. 1994).

First Stage: Formation of the oceanic lithosphere and its oldest sedimentary cover

The Middle to Late Jurassic ophiolite sequence formed during the first stage in a slow- to ultraslow-spreading ridge environment, where magma supply was limited and tectonic (amagmatic) extension processes, producing high– to low–angle normal faults, were dominant (e.g., Lagabrielle and Cannat, 1990, Treves and Harper, 1994; Marroni and Pandolfi, 2007; Rampone et al., 2020). Tectonic extension in the absence of a steady–state magma supply resulted in the exhumation of upper mantle peridotites, which underwent widespread serpentinization, and in the formation of sags and structural highs, creating a rugged seafloor bathymetry (e.g., Principi et al., 2004; and reference therein).

Exhumed serpentinized peridotites were intruded by gabbroic stocks and plutons and were covered by volcanic and sedimentary rocks, composed of basaltic pillow-lavas and sills, radiolarian cherts and ophiolitic breccias. Basaltic lavas and sills have MORB-type geochemical signatures (e.g., Renna et al., 2018). Ophiolitic breccias represent chaotic deposits accumulated in half-grabens and tectonic sags developed in the hanging walls of normal faults (e.g., Elter 1975; Bortolotti and Principi, 2003; Principi et al., 2004). They are subdivided into several types according to their clast compositions, which reflect the source lithology and their lithostratigraphic position below or above the basaltic carapace of the ophiolite (Elter 1975; Cortesogno et al., 1987; Bortolotti and Principi, 2003; Principi et al., 2004).

Second Stage: Formation of deep-sea pelagic sedimentary cover

The ophiolite sequence is overlain by Callovian-Santonian deep-sea pelagic sedimentary rocks deposited during the second stage, which lasted nearly 80 m.y. The pelagic deposits include Middle Callovian to Early Berriasian cherts and fine-grained, carbonaceous turbidites that are composed of the Late Berriasian-Valanginian Calpionella Limestone and the Valanginian-Santonian Palombini Shale. All these deposits were the products of a low sedimentation rate in a deep–marine environment (Marroni and Perilli, 1990; Marroni et al., 2004).

Third Stage: Deposition of turbidites in a closing ocean basin

The deep–marine pelagic rocks are conformably overlain by a Lower Campanian–Lower Paleocene, thick turbidite sequence, the deposition of which started contemporaneously with the onset of subduction within the LPOB. The lower part of this sequence consists of carbonaceous and siliciclastic turbidites (i.e., the Val Lavagna Shale Group, which includes the lower Campanian Manganesiferi Shale, the lower to upper Campanian Monte Verzi Marl, and the lower Campanian to lower Maastrichtian Zonati Shale). These fine–grained rocks reflect a high sedimentation rate within a shrinking basin following the onset of intra–basin subduction. They grade stratigraphically upwards into the lower Maastrichtian to lower Paleocene sandstone (i.e., the Gottero Sandstone). Arenites in siliciclastic turbidites represent arkosic–subarkosic rocks, whose clast compositions are compatible with lithologies constituting the upper part of the rifted European margin. Hence, it is widely accepted that the provenance of the turbiditic sequence above the ophiolite was the passive continental margin of Europe (Valloni and Zuffa, 1984; Van de Kamp and Leake, 1995; Pandolfi, 1997; Marroni and Pandolfi, 2001). These turbiditic sequences (i.e., Zonati Shale and the Gottero Sandstone) were deposited in submarine fans adjacent to the European passive continental margin (Abbate and Sagri, 1982; Nielsen and Abbate, 1983; Fonnesu and Felletti, 2019). The stratigraphically upper parts of this submarine fan sequence contain MTDs consisting of debris flow deposits, which include reworked clasts derived from an oceanic lithosphere and its sedimentary cover.

The youngest deposit of the Internal Ligurian Units consists of an MTD, represented by the Lower Paleocene Bocco Shale, also known as the Colli-Tavarone and Lavagnola Formations (Marroni et al., 2017). The Bocco Shale rests unconformably on top of all the older formations and consists of thin-bedded turbidites, and slide and debris flow deposits. Clasts and materials of these deposits were derived from an oceanic mantle and its sedimentary cover (Marroni and Pandolfi, 2001; Marroni et al., 2017; Meneghini et al., 2020).

DIAGNOSTIC FEATURES AND DEPOSITIONAL MECHANISMS OF CHAOTIC DEPOSITS AND MTDs IN THE NORTHERN APENNINES

The sedimentary cover units of the Internal Ligurian ophiolites in the Northern Apennines include two distinctive chaotic rock unit types of gravitational origin with specific age spans corresponding to different phases in the evolutionary history of the LPOB. The oldest (Middle to Upper Jurassic) chaotic rock units developed during the seafloor spreading and hence the opening phase of the LPOB. We refer to these deposits as syn–extensional chaotic deposits in the rest of the paper. The youngest, Upper Cretaceous–Lower Paleocene chaotic rock units formed during the convergence and closure phase of the LPOB. We refer to these deposits as syn–contractional mass–transport deposits (MTDs) in the rest of the paper. In both the opening and the closing phases, accumulation of chaotic deposits and MTDs over a recently formed oceanic lithosphere was a tectonically induced depositional event.

Syn–Extensional Chaotic Deposits

The syn-extensional sedimentary chaotic rocks are well exposed in the Val Graveglia and the Bracco Massif (see 11 and 12 of Fig. 1, also see Fig. 3), both of which are located in the eastern Liguria region, between the cities of Genova and La Spezia. These chaotic deposits are designated as the lower and upper ophiolitic breccias on the basis of their stratigraphic position below or above the basaltic lava flows, respectively (Figs. 3A and 3E; Principi et al., 2004); their clasts were sourced from an entirely local provenance. These ophiolitic breccias represent one specific type of a syn-extensional chaotic deposit. The lower ophiolitic breccias rest directly on serpentinized peridotites or gabbros, and they are overlain by basaltic flows or cherts. The upper ophiolitic breccias occur between the base of the basaltic lava flows and on top of the cherts. The ages of the lower and upper breccias are poorly constrained due to the low resolution of radiolarian assemblages in their matrix material. The available biostratigraphic data indicate an age of the ophiolitic breccias and the associated basaltic flows spanning from Upper Bajocian to Lower Callovian (Chiari et al., 2000, and reference therein).

Syn-extensional lower ophiolitic breccias. The lower ophiolitic breccias include the Levanto, Framura, Casa Boeno and Monte Capra Breccias (Principi et al., 2004, and references therein). The first three overlie the serpentinized peridotites, whereas the last breccia covers the gabbro. The lithological composition of these breccias reflects the substrate on which they rest. The Levanto Breccia (ophicalcites *s.s.*) is a tectonic-hydrothermal breccia, which occurs above the serpentinized upper mantle rocks (Figs. 3E and 3F). It marks a cataclastic shear zone composed of fragmented serpentinites crosscut by a network of veins, filled with sparry calcite, talc and locally by smaller serpentinite fragments. This cataclastic shear zone marks an oceanic detachment fault zone, which was exposed on the LPOB seafloor (Treves and Harper, 1994).

The overlying Framura Breccia consists mainly of reworked Levanto Breccia material (Abbate et al., 1980; Cortesogno et al., 1987), and is composed of a coarse-grained breccia containing mostly serpentinite and rare gabbro clasts in a hematitic matrix (Fig. 3G and H). The Case Boeno Breccia (Cortesogno et al., 1987; Principi et al., 2004) is a monogenic breccia consisting of serpentinite clasts in a scarce, serpentinite–sand matrix. The Case Boeno Breccia locally includes large serpentinite blocks, up to several metres wide. As with the Framura Breccia, the Case Boeno Breccia also lies stratigraphically on top of the serpentinized peridotites. Overlying the gabbro intrusions, the Monte Capra Breccia represents a clast-supported polymictic breccia (Fig. 3B) with clasts of Fe-gabbro, Fe-basalt, plagiogranite, and serpentinite in a scarce sandy matrix (Bortolotti and Principi, 2003; Principi et al., 2004). The existence of Fe-basalt and Fe-gabbro clasts is unique to the lower ophiolitic breccias.

Syn-extensional upper ophiolitic breccias. The syn-extensional upper ophiolite breccias (Figs. 3A and 3E) include the Movea, Mt. Zenone, and Mt. Bianco Breccias (Principi et al., 2004, and references therein). The Movea Breccia is a polymictic breccia mainly containing clasts of foliated gabbro with minor amounts of pillow basalt, gabbro, and serpentinite clasts within a chloritized sandy matrix (Bortolotti and Principi, 2003; Principi et al., 2004). The Movea Breccia grades upward into the Mt. Zenone Breccia (Figs. 3C and 3F), which is a monomictic breccia showing only clasts of foliated gabbro in a sandy matrix composed of gabbro fragments. In contrast, the Mt. Bianco Breccia consists of serpentinite and ophicalcite clasts within an abundant sparry calcite matrix (Bortolotti and Principi, 2003; Principi et al., 2004).

Both the syn-extensional lower and upper ophiolitic breccias are characterized by comparable sedimentological features: they all have a clast-supported texture with angular or sub-angular clasts. The matrix has the same lithological composition as the main clast types. The maximum clast-size ranges from gravel to boulder. Beds are lenticular in shape, and their thicknesses range from 1 m up to 20 m. Bed bottoms display planar to erosive surfaces. The erosional nature of the basal contact is suggested by common bottom bedset scours and diffuse, amalgamated beds. A faint internal organization is locally present, and grading is roughly developed. Bed–cap, if not eroded, is characterized by a cm- to dm-thick, coarse-grained and laminated sandstone and siltstone beds composed of ophiolitic material. The downcurrent evolution of the turbidity current depositional events can produce poorly developed ophiolitic sandstones characterized by F5-F6 turbidite facies of Mutti (1992), capped by F9b siltstone beds. These beds are commonly preserved in the lower part of the chert layers. The clastic sediments can be interpreted to have been formed either as hyperconcentrated flow-derived deposits (Costa, 1988) or, alternatively, as the downcurrent evolutionary products of cohesive debris flows that trasformed into hyperconcentrated flows (F2 and F3 facies of Mutti, 1992).

Clasts of the lower ophiolitic breccias were mainly derived from reworking of the lower and upper crustal sections of the Jurassic oceanic lithosphere within the basin that had undergone ocean floor metamorphism. Stratigraphically higher up into the upper ophiolitic breccias, debris deposits derived from the upper oceanic crustal subunits and even from oceanic siliceous sedimentary rocks become predominant. We summarize the thickness and other sedimentological features of these syn-extensional chaotic deposits in Figs. 3A and 3E.

Syn-Contractional Mass Transport Deposits (MTDs)

Syn-contractional MTDs, which are well exposed in the eastern Liguria region between the cities of Genova and La Spezia (see 9 and 10 of Fig. 1, also see Fig. 3), developed by submarine mass transport mechanisms and are subdivided on the basis of their spatial relationships with the turbiditic deposits (Figs. 4A, B). Some of these MTDs occur as intercalations in the turbiditic deposits of the Val Lavagna Shale Group, whereas others overlie this lithostratigraphic unit and contain minor siliciclastic turbidites (Fig. 4C). All clastic materials for these turbiditic deposits were derived from the continental margin of Europe (Marroni and Pandolfi, 2001; Prinicipi et al., 2004; Marroni et al., 2017; Fonnesu and Felletti, 2019; Meneghini et al., 2020).

The MTDs intercalated within the turbiditic deposits of the Val Lavagna Shale Group consist of several mappable bodies of predominantly monomictic, pebbly-mudstones and, locally of varicolored mudflow-derived deposits. Their ages range from Lower Maastrichtian to Lower Paleocene. The predominantly monomictic pebbly-mudstones also include gravel to boulder-sized clasts embedded in a muddy–silty matrix (Fig. 4D). The clast composition is dominated by calcilutites derived from the Palombini Shale, but clasts of fine-grained arenites also exist. The matrix is composed of arenitic to rudistic clasts of carbonate-free mudrock, mainly derived from hemipelagic shales (Fig. 4D). The thickness of beds ranges from a few centimeters to several meters (cf. Olistostroma di Passo della Forcella, Fierro and Terranova 1963). The bed shape is lenticular, and erosional features are present at the bases of beds. The internal organization in the beds is faint to absent. The pebbly mudstone deposits represent cohesive debris flows (cf. olistostrome of Abbate et al., 1970 and F1and F2 facies of Mutti, 1992).

Varicolored shale beds also occur in the upper stratigraphic levels of the Gottero Sandstone (see Fig. 4). Their bed thickness ranges from a few meters to more than 20 meters. Bed shape in shale is lenticular and no erosional features are present at bed bases. These deposits were derived from mud flow processes probably related to submarine landslides originated from a steep slope draped by fine-grained sediments.

The MTDs overlying the turbiditic sequences are represented by the lower Paleocene Bocco Shale (Cf. Colli/Tavarone Formation, Giaiette Shale, Lavagnola Formation) (Figs. 4B, 4C, 4E-G). The Bocco Shale unconformably rests on the underlying formations of the Internal Ligurian Units, mainly the Palombini Shale and the Gottero Sandstone (Decandia and Elter, 1972; Marroni and Pandolfi, 2001; Marroni et al., 2017; Meneghini et al., 2020). Clasts within the Bocco Shale were derived from two main facies groups (Marroni and Pandolfi, 2001). The first group is composed of various rock blocks in a matrix of pebbly-mudstone, mudstone, clast-supported breccias, and very coarse- to coarse-grained turbidites. The second group consists of fine-grained, thinly bedded siliciclastic turbidite clasts. We summarize the thicknesses and stratigraphic features of these MTDs in Figure 4C.

Deposits containing the first facies group include MTDs that originated from reworking of an ophiolite sequence and its sedimentary cover (Lamarche et al. 2008; Festa et al. 2016). The block-in-matrix character is displayed by blocks of different sizes (ranging from 1 to 50 m) embedded in a shale–dominated matrix. Blocks are surrounded by syn-sedimentary deformation structures and by slide-block-derived, monomictic pebbly mudstone and pebbly sandstone. Locally, blocks are missing from the beds and such interbeds are mud-flow-derived mudstone. Pebble-bearing beds range from pebbly mudstones to mud- to clast-supported conglomerates and/or breccias (pebbly mudstone, pebbly sandstone and orthoconglomerate), all interpreted as cohesive debris flow-derived deposits (sensu Mutti 1992). Blocks were derived entirely from reworked ophiolitic subunits (serpentinized peridotites, basaltic lavas, and rare gabbros) and from the Upper Jurassic–Lower Paleocene sedimentary cover of the ophiolite (chert, Calpionella Limestone, Palombini Shale, Val Lavagna Shale, and Gottero Sandstone). The matrix also includes arenitic to ruditic clasts, originated from reworked hemipelagic pelites of the Palombini and Val Lavagna Shales.

Deposits containing the first facies group are associated with dm- to m-thick beds of polymictic, clast-supported and poorly sorted conglomerates. These conglomerates, which show the same clast composition as the pebbly mudstones, represent the down-current evolution of cohesive debris flows into hyperconcentrated flows (F2 and F3 facies of Mutti 1992). Cohesive debris flow- and hyperconcentrated flow-derived deposits are associated with subordinate, coarse-grained high-density turbidity current deposits. These facies are locally associated with thin Bouma base-missing beds (F5 + F9 facies of Mutti 1992). Arenite framework composition analyses performed on three samples from F5 beds, collected from the Bocco Shale in the Gottero Sandstone indicate a litharenitic composition. This framework is characterized by fragments of basalt, serpentinite, chert and Calpionella-bearing limestone (Meneghini et al., 2020). Similarly, pebbles in F1, F2 and F3 beds show the same composition as recognized in the slide-blocks and arenites. These data and observations collectively point to a source area characterized by reworking of ophiolites and related sedimentary cover within the Internal Ligurian tectonostratigraphy (Marroni and Pandolfi, 2001; Meneghini et al., 2020).

Clasts of the second facies group consist of thinly bedded turbidites and mudstones, the most common facies association recognized in the Bocco Shale. The thinly bedded turbidites consists of alternations of fine- to medium-grained siliciclastic arenites with carbonate-free mudstones. Sand to shale ratio in this facies group is generally >1. Arenite beds show moderate lateral continuity. Stratigraphic and sedimentological features of deposits of the second facies group point to low-density turbidity currents as the main depositional agent. Thick packages of thinly bedded turbidites were affected by widespread syn-sedimentary deformation due to slumping and submarine mass-wasting. These processes were responsible for the formation of meso-scale angular unconformities (more than 30°) among different packages of beds. The inferred processes and their manifestations suggest their development on a steep and unstable submarine slope. Thin–bedded turbidites grade into thick packages of varicolored carbonate-free mudstones, which are intensively bioturbated. These mudstones are also characterized by the presence of lenticular, thin beds of siltstones and fine–grained arenites. Bioturbation affected both the arenites and mudstones. The Bocco Shale likely originated from multiple submarine – slide events developed on an accretionary wedge slope (Figs. 4A, 4B), which was covered with thinly bedded turbidites near a lower–trench environment (Marroni and Pandolfi 2001; Meneghini et al., 2020).

OPHIOLITE AND SEDIMENTARY COVER RECORD IN THE WESTERN ALPS

Several examples of chaotic rock units composed of reworked ophiolitic material are preserved in the sedimentary cover of the Jurassic ophiolites (i.e., the Zermatt-Saas Zone, Monviso and Queyras Complexes) in the Piedmont Zone of the Western Alps (Elter, 1971; Tartarotti et al., 1998, 2017a; Dal Piaz et al., 2003; Balestro et al., 2015a; Corno et al., 2021). These ophiolites display strong deformation fabrics and variable, high to ultrahigh–pressure metamorphic overprints (i.e., eclogite- to blueschist-facies; Fig. 1). Prior to their emplacement and during their subduction, these ophiolites were stretched and sheared but not significantly dismembered, at least locally. They were further deformed during their exhumation, although they mostly remained as coherent slices of a metamorphosed oceanic lithosphere. This exhumation-related deformation produced NW- to W-vergent folding and shearing, coeval with greenschist-facies metamorphism of all ophiolitic subunits.

The Zermatt-Saas ophiolite (Fig. 1) is a large remnant of the Jurassic oceanic lithosphere, extending for about 60 km along-strike. It was metamorphosed under eclogite- and coesite-eclogite facies conditions as a result of its subduction (e.g., Groppo et al., 2009; Frezzotti et al., 2011; Luoni et al., 2018). The Zermatt-Saas ophiolite consists of serpentinized metaperidotites (Li et al., 2004; Rebay et al., 2012; Fontana et al., 2008) with Middle to Late Jurassic metagabbros intruded into the metaperidotites (Bearth, 1967; Rubatto et al., 1998; Zanoni et al., 2016). Peridotite host rocks and their gabbroic intrusive bodies were exhumed on the seafloor as a result of amagmatic extensional tectonics during the opening of the LPOB. Ophicalcite and ultramafic breccia deposits formed during this phase, directly overlying the exhumed peridotite and gabbro bodies on the seafloor (Driesner, 1993; Tartarotti et al., 1998, 2021). The upper part of the Zermatt-Saas ophiolite includes discontinuous metabasaltic lava flows that locally show well preserved pillow structures (Bucher et al., 2005) and a thin metasedimentary cover made of Mn-rich chert, marble and calcschist (Dal Piaz and Ernst, 1978; Bearth and Schwander, 1981; Tartarotti et al., 2017b, 2021).

The Monviso ophiolite (Fig. 1), which is several–km–thick, extends for about 35 km from N to S, and tectonically overlies the Dora-Maira continental margin unit (Groppo et al., 2019; Balestro et al., 2020). Similar to the Zermatt-Saas ophiolite, it was metamorphosed under eclogite facies conditions (Lombardo et al. 1978; Schwartz et al., 2000; Groppo and Castelli, 2010; Angiboust et al., 2012; Balestro et al., 2014, 2018). The Monviso ophiolite contains a major shear zone (i.e., Baracun Shear Zone of Festa et al., 2015) that separates massive serpentinite and metagabbro outcrops in its footwall from pillow metabasalts and metasedimentary rocks within its hanging wall. This shear zone has been interpreted as a fossil intraoceanic detachment fault with a Late Jurassic oceanic core complex developed in its footwall (Balestro et al., 2015b). Protoliths of the serpentinite are lherzolite and harzburgite, which were intruded by numerous stocks and dikes of Middle Jurassic gabbro (Rubatto and Hermann, 2003) and some Late Jurassic plagiogranite (Lombardo et al., 2002).

Metasedimentary rocks in the cover of the Monviso ophiolite make up two different sequences. The structurally and stratigraphically lower sequence rests below or is intercalated with metabasaltic lava flows that display relict pillow lava structures and volcanic breccia textures. This lower sedimentary sequence includes calcschist interbedded with metasandstone and metabreccia units, whose clasts are gabbroic rocks (Balestro et al., 2011). The upper sedimentary sequence unconformably overlies serpentinite, metagabbro, metabasalt and ophiolitic metabreccias, and consists of thin metaquartzite, white marble and calcschist. These rocks in the upper sequence lack any ophiolite-derived material (Balestro et al., 2019).

The Queyras ophiolite tectonically overlies the Monviso ophiolite along an N-striking fault (Fig. 1). Its subunits display blueschist-facies metamorphic overprint (e.g., Vitale Brovarone et al., 2014), the degree of which decreases structurally up-section throughout the ophiolite (Lagabrielle and Polino, 1988). Similar to the Monviso ophiolite, the Queyras ophiolite also includes a fossil intraoceanic detachment fault with an oceanic core complex in its footwall (Lagabrielle et al., 2015). The sedimentary cover consists of calcschist characterized by the occurrence of blocks of serpentinized metaperidotite, metagabbro, metabasalt and mafic-ultramafic metabreccias (Tricart and Lemoine, 1991) ranging in thickness from a few metres to a few km (Schistes Lustrés *Auct*.; Lemoine and Tricart, 1986; Tricart and Schwartz, 2006). Larger blocks locally preserve a mantle-cover succession with mantle rocks overlain by metachert, up to a few meters thick, locally containing Middle Bathonian to Late Oxfordian radiolarians (Cordey et al., 2012, and reference therein), and by several meters of white marble, which has been correlated with the Calpionella limestone of the Northern Apennines (Principi et al., 2004). The calcschist sequence includes a lower member (Replatte Formation of Lemoine 1971), mainly consisting of carbonate-rich calcschist, a middle member (Roche Noire Formation of Tricart, 1973) composed of black micaschist, and an upper member (Gondran Flysch of Lemoine, 1971), consisting of alternating layers of calcschist and metasandstone. The sedimentological features of the Gondran Flysch and the black shales at its base are correlative with the turbiditic deposits of the Val Lavagna Group–Gottero Sandstone in the Internal Ligurian Units.

METAMORPHOSED CHAOTIC ROCK UNITS IN THE WESTERN ALPS

Notable examples of chaotic rock units with fragments of ophiolitic material occur in the metasedimentary covers of the Jurassic ophiolites in the Western Alps. These ophiolites and related metasedimentary covers were deformed during two main tectono-metamorphic phases (named D1 and D2), which are correlated to subduction and continental collision-related tectonics, respectively. The D1 developed an early foliation (S1) coeval with high-pressure metamorphism. The D2 was the main phase of folding and thrusting and developed a new foliation (S2) coeval with greenschist-facies metamorphic re-equilibration. Although these sedimentary cover units experienced alpine tectonic deformation and metamorphic recrystallization, they locally preserve lithostratigraphic and sedimentological features (Fig. 5B) that are well preserved in low – strain domains, where primary textures are deformed and overprinted by metamorphic foliation but not transposed and obscured (see also Balestro et al., 2015a; Tartarotti et al., 2017a for details). Here we discuss such rocks in the eclogite-facies (Zermatt-Saas and Monviso) and blueschist–facies (Queyras) cover rocks of the ophiolites and, we categorize them as syn-extensional chaotic deposits and syn-contractional MTDs of the Western Alps.

Syn–Extensional Chaotic Deposits

Below, we subdivide and categorize the Western Alpine metamorphosed counterparts of the Northern Apennine syn-extensional chaotic deposits. The metabreccias are divided into lower and upper ophiolitic metabreccias on the basis of their lithostratigraphic position below or above the base of basaltic lava flows, respectively.

Syn-extensional lower ophiolitic metabreccias. In both the eclogite-facies and blueschist-facies metaophiolites in the Western Alps, the structurally uppermost part of the exposed serpentinized metaperidotites contains a dense network of meters– to several tens of meters–thick carbonate–rich veins, forming metaophicarbonates (metaophicalcite *Auct.*, see OC1 of Lemoine et al., 1987) (e.g., Lagabrielle and Polino, 1985; Lemoine et al., 1987; Tricart and Lamoine, 1991; Driesner, 1993; Lagabrielle, 1994; Tartarotti et al., 1998, 2017a; Dal Piaz, 1999; Balestro et al., 2019, and reference therein). Similar to the Levanto Breccia in the Northern Apennines, the Western Alpine metaophicarbonates are characterized by a complex network of veins filled with carbonate minerals, antigorite, and/or talc (e.g., Lemoine et al., 1987; Tricart and Lemoine, 1991; Dresnier, 1993; Lafay et al., 2017; Tartarotti et al., 2017a). These veins surround dm- to m-sized, angular to rounded fragments of massive serpentinite. Complex crosscutting relationships between different generations of carbonate veins, the infilling and episodic growth of calcite fibers, and the pervasive replacement of serpentinite by carbonate minerals indicate repeated episodes of cracking–fracturing of peridotites and fluid–peridotite interactions during their development. These metaophicarbonate veins were the manifestations of both brittle failure and hydrothermal fluid circulation within the upper mantle peridotites, as these rocks were undergoing exhumation and extensional faulting in Middle to Late Jurassic time.

As is the case in the Northern Apennines, the top of the metaophicarbonate unit in the Western Alps is extensively reworked, forming discontinuous layers of a clast-supported metabreccia. For example, in the Lake Miserin area (see 3 of Fig. 1, also see Figs. 3 and 5A) in the Zermatt-Saas ophiolite (see Tartarotti et al., 2017a, 2019), the metaophicarbonate is overlain by a predominantly clast–supported metabreccia ("BrFm1" and "BrFm2" of Tartarotti et al., 2017a). Clasts are angular- to sub-angular in shape, made of serpentinite and metaophicarbonate, and range in size from cm to dm (Fig. 5C). The scarce matrix in this metabreccia consists of a coarse-grained metasandstone, including serpentinite and metaophicarbonate derived sediments.

The bottom of this clast-supported metabreccia corresponds to an erosional surface, marked by a dm-thick layer of coarse- to medium-grained metasandstone composed of peridotite-derived sediments. The whole metabreccia unit shows a lenticular shape at a scale of hundreds of meters and a maximum thickness of about 15 m (Fig. 5A; see Tartarotti et al., 2017a for details). This metabreccia gradually passes upward into a chaotic rock unit ("sedimentary mélange" of Tartarotti et al., 2017a), which consists of serpentinite and ophicarbonate blocks in a carbonate (now marble) matrix (see the section on Syn-extensional upper ophiolitic metabreccias below). This marble is unconformably overlain by a post-extensional calcschist unit (Fig. 5A), which is devoid of any ophiolite-derived material. In terms of its stratigraphic–structural position above the ophiolite and its compositional makeup and sedimentological characteristics, this calcschist unit correlates with the

Lower Cretaceous post-extensional deposits in the Northern Apennines (see Tartarotti et al., 2017a, 2019).

In the Mt. Avic ultramafic massif of the Zermatt-Saas ophiolite in the Western Alps (see 2 of Fig. 1, see Fontana et al., 2008, 2015; Panseri et al., 2008), prevalently monomictic clast-supported metabreccias with poorly sorted angular clasts of serpentinite are embedded in a carbonate matrix (Figs. 5A, 5F; see Tartarotti et al., 1998). Locally, mm– to cm–long mafic clasts derived from a gabbro source also occur, forming a polymictic-type metabreccia. Structurally, these metabreccias generally occur on top of the serpentinite and Mg-Al metagabbro units, and below a metabasaltic lava sequence.

In the Queyras ophiolite in the Western Alps, different types of poorly-sorted, clast-supported metabreccia (i.e., the OC2 of Lemoine et al., 1987) range from monomictic–type with cm–long, sub-angular clasts made only of serpentinite (e.g., Pic Cascavelier section, see Tricart and Lemoine, 1983, 1991; Caby et al., 1987; Lemoine and Tricart, 1986) or metagabbro (e.g., Crete Mouloun section, Le Mer et al., 1986), to polymictic–type metabreccia (see 6, 7 and 8 of Figs. 1 and 5I, 5G) with clasts of both serpentinite and metagabbro (see Le Mer et al., 1986; Lemoine et al., 1987; Balestro et al., 2019, and reference therein). These metabreccias are laterally discontinuous in exposure and range from a few cm to several tens of meters in thickness. Large blocks (olistoliths), up to tens of meters wide, locally occur (Tricart and Lemoine, 1983) in a sandy matrix with grains of mixed mafic rock and carbonate composition. The structural position of both monomictic and polymictic metabreccias (Fig. 5I) is commonly above the exhumed serpentinite and metagabbro and below the metabasaltic lava sequence (metapillow lavas and basaltic metabreccias).

In the Monviso ophiolite in the Western Alps (see 5 of Fig. 1), a sedimentary sequence, consisting of calcschist interbedded with mafic metasandstone and matrix-supported metabreccia layers, onlaps a fossil detachment fault and its footwall units (Fig. 6A). The footwall of this detachment fault zone is made of serpentinized metaperidotites, intruded by Mg-Al and Fe-Ti gabbro plutons and stocks. The mafic–ultramafic part of the Monviso ophiolite has been interpreted as an exhumed oceanic core complex (OCC; see Balestro et al., 2015a, 2019; Festa et al., 2015). The matrix-supported metabreccia includes poorly sorted sub-angular to angular clasts of metagabbro (Figs. 6B-D) and laterally grades, at a scale of tens of meters, into coarse-grained metasandstone of the same composition, locally with a fining-upward texture (Fig. 6E). The thickness of these syn-extensional metasedimentary rocks shows significant lateral variations, ranging from several centimeters to about 70 meters, and generally tapers out toward an association of talcschist and serpentine–schist containing blocks of highly sheared metagabbro. These intensely foliated talcschist and serpentine–schist units correspond to an intra-oceanic detachment fault zone (i.e., the Baracun Shear Zone of Festa et al., 2015). The shear zone is unconformably overlain by post-extensional white marble and carbonate-rich calcschist (Fig. 6A), devoid of any ophiolite-derived material. The white marble and calcschist correspond to the Upper Jurassic-Lower Cretaceous Calpionella Limestone and the Early Cretaceous Palombini Shale of the Internal Ligurian Units in the Northern Apennines, respectively (see Balestro et al., 2015a, 2019; Festa et al., 2015).

Syn-extensional upper ophiolitic metabreccias. The most notable examples of monomictic basaltic metabreccia and polymictic-metabreccia, correlating lithologically and stratigraphically with the upper ophiolitic breccias in the Northern Apennines, are best preserved in the Queyras ophiolite (e.g., Caby et al., 1971, 1987; Tricart and Lemoine, 1983, 1991; Le Mer et al., 1986; Saby, 1986; Pinet et al., 1989). The metabreccias in the Queyras ophiolite are stratigraphically situated between the base of the pillow metabasalt sequence and the first post-extensional sedimentary units (i.e., metachert and white marble; see Fig. 5I).

The monomictic metabreccia consists only of angular to sub-angular clasts, up to 30 cm–long, of metabasalt that are embedded within a sandy matrix composed of fragments of metabasalt and/or metahyaloclastite (see, e.g., the Crete Mouloun and Pic Marcel sections in Le Mer et al., 1986 and Tricart and Lemoine, 1983, respectively. See 6 and 7 of Fig. 1). Although this monomictic metabreccia commonly overlies the metabasaltic pillow lava sequence (e.g, Crete Mouloun), it locally occurs both at the base of (e.g., Pic Marcel) and/or interfingered with these metabasaltic lava flows (e.g., Tricart and Lemoine, 1983).

Polymictic metabreccia with cm- to dm-long clasts of massive and variolitic metabasaltic lavas, metagabbro, and quartzo-feldspathic rocks (plagiogranite) occur both at the base (e.g., Pic Marcel, see Tricart and Lemoine, 1983) and at the top (e.g., Crete Mouloun, see Le Mer et al., 1986) of the metamorphosed pillow lava sequence. The matrix of this metabreccia is sandstone, which is composed of fragments of the same compositions as the clasts.

All these different types of metabreccias have a poorly sorted, clast-supported texture with angular to sub-angular clasts. Stratigraphically upward, they grade into a matrix-supported metabreccia and coarse-grained metasandstone with well–preserved incipient layers of different compositions (see also Tricart and Lemoine, 1983). The bottoms of these metabreccia layers are commonly lenticular and erosional.

The occurrence of metabreccias in a stratigraphic position comparable to the one of the upper ophiolitic metabreccias of the Appennines is rare in the Monviso and Zermatt Saas ophiolites in the Western Alps. There are, however, two examples of possible upper ophiolitic metabreccias in the Zermatt-Saas ophiolite. The first one is part of the Garten Formation (i.e., the Rifelberg-Garten mélange or Palon de Resey mélange; see Dal Piaz, 1965, 1992; 2004; Bearth, 1967; Dal Piaz and Ernst, 1978; Campari et al., 2004; Dal Piaz et al., 2015; Gusmeo et al., 2018), which crops out discontinuously from the Cime Bianche ridge to the highest Ayas Valley (see 1 of Fig. 1; see Dal Piaz, 1992; Dal Piaz et al., 2015 for details). The Garten Formation consists of a chaotic rock unit, meters– to tens of meters–thick, with rounded to elongated clasts (cm to dm in size) of fine-grained metabasalt (metamorphosed to eclogite and glaucophanite), serpentinite and marble (Gusmeo et al., 2018), embedded in a matrix of alternating layers of micaschist and calcschist (Figs. 6F-H). This formation represents the superposition of different individual deposits, each a few decimeters to nearly one meter in thickness (Fig. 6F). The largest clasts occur in the lower part of the beds and "float" in a fully mixed and crudely graded matrix, made of calcschist (Figs. 6G, 6H). The stratigraphic position of this formation is at the base of metabasaltic lava flows with locally well – preserved pillow structures (Fig. 6I; see Dal Piaz, 1965, 2004). It is, however, important not to confuse the above-described chaotic deposit with the larger part of the Garten Formation that corresponds to a typical "broken formation" (*sensu* Hsü, 1968), resulting from layer-parallel tectonic extension of alternating micaschist and metabasite layers and boudinage formation.

In the Lake Miserin sedimentary cover sequence of the Zermatt-Saas ophiolite (Fig. 1), the lower ophiolitic metabreccia is overlain by a chaotic rock unit characterized by a block-in-matrix fabric with rounded to irregular–shaped blocks (dm- to a meter-wide) of massive to veined serpentinite and metaophicarbonate embedded in a white marble matrix (Figs. 5A, 5E). Blocks are randomly distributed within the matrix, except where elongated and deformed blocks are aligned with the regional tectonic foliation (Tartarotti et al., 2019). The matrix is commonly interbedded with cm- to dm-thick layers of metabreccia, with clasts angular to sub-angular clasts of serpentinite (Fig. 5E).

Syn-contractional mass–transport deposits (MTDs)

The identification of possible counterparts of the syn-contractional mass–transport deposits of the Northern Apennines in the metasedimentary cover of the ophiolites in the Western Alps is not easy. The gravity-induced MTDs, composed of material derived from both a continental margin and the ophiolites, are lacking in the Zermatt-Saas and Monviso ophiolites, but they occur in the Lago Nero Unit of the Queyras ophiolite (see 4 of Fig. 1). The Lago Nero Unit includes a thick metasedimentary sequence, starting at the bottom with a radiolarite member, topped by a limestone member and the Replatte Formation (Lemoine et al., 1970; Polino, 1984; Barfety et al., 1995; Burroni et al., 2003). The Replatte Formation contains alternating layers of thick calcschist and thin marble. It grades stratigraphically upwards into both a thin unit of grey to black schists and to the Gondran

Flysch, composed of alternating layers of calcschist and metasandstone (Fig. 5I). The Gondran Flysch represents thinly bedded turbidites with minor occurrences of thick and coarse–grained, terrigenous metasandstone. Petrographic analysis of the terrigenous metasandstone indicates an arkosic composition, made predominantly of quartz, feldspar and minor lithic fragments. The metasedimentary cover sequence of the Lago Nero Unit stratigraphically is capped by the Rocher Renard Complex (Fig. 5I; Barfety et al., 1995; Burroni et al., 2003). The Rocher Renard Complex consists of homogeneous dark schists, locally containing metre- to decametre-size blocks composed mainly of limestone and chert, with local occurrences of metabasalt, metaophicalcite, serpentinite and metagabbro (Figs. 5H, 5I).

DISCUSSION: THE CHAOTIC DEPOSITS AND MTDs OF THE NORTHERN APENNINES AS A PROXY FOR METAMORPHOSED COUNTERPARTS IN THE WESTERN ALPS

Our detailed description of chaotic rock units and MTDs indicates that different ophiolite units in the Northern Apennines and the Western Alps correlate well, both chronologically and stratigraphically (Table 1). These correlations suggest that the diagnostic features of the chaotic deposits and MTDs in the Internal Ligurian Units can be used as a proxy for better definition of the tectonostratigraphy of their highly deformed and metamorphosed counterparts in the Western Alps. The strong similarities between these chaotic deposits and MTDs within the epi–ophiolitic sequences in both orogenic belts, allows reconstructing: (i) the pre-orogenic primary lithostratigraphy and sedimentological features of the Western Alpine occurrences, (ii) the processes and mechansims of Western Alpine rock formation and, (iii) the characteristics of the depositional or geodynamic settings of rock body origins. Our findings also indicate that the LPOB lithosphere underwent similar tectonic processes during the Jurassic seafloor spreading and Late Cretaceous – Early Paleocene closure phases of the ocean basin throughout its entire length (Fig. 7).

Processes of formation of chaotic deposits and MTDs in the Western Alps from seafloor spreading to subduction

Although they experienced severe tectonic deformation and metamorphic recrystallization, the described examples of chaotic rock units in the Western Alps locally preserve lithostratigraphic and sedimentological features (see also Balestro et al., 2015a; Tartarotti et al., 2017a for details) that are comparable with those of the little metamorphosed Internal Ligurian Units in the Northern Apennines. The oldest syn-extensional chaotic deposits (the lower ophiolitic metabreccias) of the Western Alps preserve remnants of sedimentological features and internal organization that are diagnostic of different products formed by the downcurrent transformation of cohesive flows through progressive mixing with ambient fluids (F2 facies of Mutti, 1992). In different sections of the Queyras (see Pic Cascavelier and Crete Mouloun) and Zermatt-Saas (see Lake Miserin and Mt. Avic) ophiolites, the faint internal structure of the clast-supported breccia, such as the lack of a well-defined grading, the scarcity of lamination, and the absence of any pelagic interbeds, suggest rapid deposition through cohesive debris flows or hyperconcentrated flows. In these processes, the larger clasts float in a mixed and crudely graded matrix, which was probably composed of mud and mafic and/or ultramafic sand and gravel, with largest clasts occurring in the lower part of the bed. In some cases, such as for the lower ophiolitic metabreccia unit in the Monviso ophiolite, the occurrence of a poorly sorted, coarse-grained sandstone, grading laterally into a coarse-grained sandstone with a fining-upward texture, suggests that these deposits represent the products of downslope transformation of a hyperconcentrated flow into a high-density and supercritical turbidity current, and locally a low-density one, possibly corresponding to a gravity transformation from F4-F5 to F7 facies of Mutti (1992).

The characteristics of the matrix-supported metabreccia and coarse-grained metasandstone of the youngest syn-extensional upper ophiolitic metabreccias of Pic Marcel and Crete Mouloun in the Queyras suggest that they represent the products of hyperconcentrated flows. These products result from downslope transformation of cohesive-flow (F2 and F3 facies of Mutti, 1992), which changes laterally and upward into gravelly, high-to low-density turbidity currents (F4-F5 and F7 facies of Mutti, 1992). This is similar to the examples interpreted for the Monviso ophiolite.

Our documented sedimentological features of part of the Garten Formation and of the upper ophiolitic metabreccias of the Lake Miserin in the Zermatt-Saas ophiolites confirm that they represent the products of submarine mass transport processes, as suggested by Bearth (1963) and Dal Piaz (1965), and by Tartarotti et al (2017a, 2019), respectively. We have observed that the sedimentary fabric elements of these metabreccias are consistent with the deposition from either hyperconcentrated flows (F2 of Mutti et al.,1992) or generally high–density turbidity currents (F4-F5 of Mutti et al., 1992) that resulted from downslope transformation of closure flows through progressive mixing with ambient fluids.

The sedimentological features of the syn-contractional MTD of the Lago Nero Unit (i.e., the Rocher Renard Complex) in the Western Alps (i.e., prevailing shaly matrix and the occurrence of angular blocks of ophiolitic material and sedimentary rocks) and its stratigraphic position correlate well with the Bocco Shale in the Northern Apennines (Table 1; Burroni et al., 2003). Similarly, its sedimentological features fit well with those of the product of multiple submarine cohesive debris flows evolving down-current to hyperconcentrated turbidity deposits that were emplaced on an accretionary wedge slope.

Comparison between chaotic deposits and MTDs in the Northern Apennines and the Western Alps

The documented similarities of the sedimentological features and internal organization of the syn-extensional chaotic deposits in both the orogenic belts is consistent with their formation through deposition of small volumes of poorly consolidated material accumulated in the hanging walls of submarine normal faults and fault escarpments. These deposits formed above detachment faults and oceanic core complexes (Fig. 7A) during the Jurassic seafloor spreading (e.g., Tricart and Lemoine, 1983, 1991; Caby et al., 1987; Lemoine and Tricart, 1986; Dilek and Eddy, 1992; Tartarotti et al., 1998, 2017a; Dilek and Thy, 1998; Principi et al., 2004; Lagabrielle, 2009; Balestro et al., 2015a, 2019 and reference therein). The occurrence of these deposits in two different specific tectonostratigraphic positions (below or above the basaltic pillow lava flows; Figs. 3, 5, 6) in both the Northern Apennines and the Western Alps, suggests that their formation occurred in two distinct events of extensional tectonics during a continuum of syn-spreading deformation. Moreover, the chaotic deposits in the different sectors of the Jurassic LPOB (i.e., Western Alps and Northern Apennine) show the same features and the same lithological composition of clasts (Table 1), strongly indicating that the oceanic basin developed with the same features and in a similar basin floor architecture during its entire history and along its entire length (Fig. 7a). It is, however, necessary to use caution in the attempt to correlate the chaotic deposits related to syn-spreading extensional tectonics, and to discriminate between the lower and upper ophiolitic metabreccias in the metamorphosed Western Alps. This is because their correlation is hampered where the oceanic crust stratigraphy is incomplete such that extrusive rocks are missing, or when a diagnostic clast composition is not recognizable within gravitationally induced chaotic deposits.

Independent of the type of breccia (lower or upper), the composition of clasts depends on the nature of the source area and its location with respect to the site of deposition. In these cases, our findings show that the diagnostic sedimentological features of the non- to poorly metamorphosed syn-extensional ophiolitic breccias of the Northern Apennines may represent a proxy of comparison, providing useful constraints for the interpretation of the metamorphosed Alpine breccias. For example, although basalt flows are not observed and basalt clasts are lacking, the upper ophiolitic metabreccias of the Lake Miserin (i.e., the "Sedimentary mélange" of Tartatotti et al., 2017a) are comparable with the syn-extensional upper ophiolitic Monte Bianco breccias of the Northern Apennines, whose stratigraphic position is well defined. They show the same sedimentological features and composition of both clasts and the matrix (see Table 1). This correlation is further supported by field-evidence, showing that the Lake Miserin upper breccia is deposited above the lower ophiolitic metabreccia of the same sequence and it is covered by mixed siliciclastic-carbonaceous sediments, corresponding to the Lower Cretaceous post-spreading deposits in the Northern Apennines (see Tartarotti et al., 2017a for details). Therefore, although caution is necessary in interpreting chaotic deposits in the highly deformed and metamorphosed Western Alpine units, the use of the Northern Apennines examples may represent a useful proxy for better interpretation of their metamorphosed counterparts, which were deposited during the Jurassic syn-spreading tectonics of the LPOB.

The syn-contractional MTDs with ophiolitic material that are widespread in the Internal Ligurian Units of the Northern Apennines have been also identified in the Western Alps, as detected in the Lago Nero Unit of the Queyras ophiolite. In both orogenic belts, the sedimentological features and internal organization of these deposits suggest they originated by several events of tectonic erosion at the front of the accretionary wedge (Fig. 7b), which developed in the Late Cretaceous in response to the development of an east-dipping subduction of the LPOB lithosphere close to or within the thinned Adria margin (Marroni et al., 2017 and reference therein). These events of frontal tectonic erosion were induced by underthrusting of the seafloor morphological relief inherited from the previous Jurassic syn-spreading tectonics (Fig. 7b; Marroni and Pandolfi, 2001; Burroni et al., 2003; Meneghini et al., 2020). The subduction of morphological relief commonly produces the uplift of the lower slope of the frontal wedge, its collapse and the subsequent downslope mobility of wide MTDs and their emplacement in the lower plate and/or in the trench (Fig. 7b; e.g., von Huene and Lallemand, 1990; von Huene et al., 2004; Kawamura et al., 2009; Remitti et al., 2011; Festa et al., 2018; Geersen et al., 2020; Meneghini et al., 2020; Ogata et al., 2020).

During the Late Cretaceous – Early Paleocene convergent stage of the LPOB, these ophiolitic MTDs, mainly consisting of pebbly mudstones and slides (Lamarche et al. 2008; Festa et al. 2016), interfingered with thin bedded, siliciclastic turbidites supplied by the European continental margin, as was the case in the Rocher Renard Complex in the Lago Nero Unit (Queyras ophiolite; see also Burroni et al., 2003) and the Bocco Shale in the Northern Apennines (see also Marroni and Pandolfi, 2001; Meneghini et al., 2020). Therefore, syn-contractional MTDs in both transects of the convergence system can be regarded as formed by similar processes widespread along the entire width of the oceanic basin. In the Western Alps, however, the occurrence of syn-contractional MTDs are restricted to the units subducted at moderate depths (i.e., those affected by blueschist-facies P-T metamorphic peak), and they are not observed in the deeper eclogite-facies units. It is hard to discriminate whether the absence of these deposits in higher grade units is simply due to failure to recognize them in the field, if these deposits were not preserved, or they did not form at all. An explanation for the occurrence of syn-contractional MTDs only in the units accreted at shallow to moderate depths could be that frontal tectonic erosion was active in a restricted time span, probably in the Late Maastrichtian-Early Paleocene, when most of the eclogite facies units were already underthrust at depth in the subduction zone. On the other hand, underplating at shallow to moderate depths, especially in sediment-dominated systems, generally involves preferential removal of the sedimentary cover from the upper part of an oceanic lithosphere (Meneghini et al., 2009 and reference therein). This phenomenon occurs when the downgoing plate reaches a depth consistent with the development of eclogite-facies metamorphism (Moore and Sample, 1986). In this framework, the lack of syn-contractional ophiolitic MTDs in the eclogite-facies units of the Western Alps could be also explained by selective removal of these deposits during progressive subduction underthrusting.

CONCLUDING REMARKS

In this comparative analysis, we have examined the occurrence and the internal structure of different types of chaotic rock units with ophiolitic material in the Internal Ligurian Units of the Northern Apennines and in the Piedmont Zone of the Western Alps. Our findings document that the internal structure-stratigraphy and sedimentological characteristics of the chaotic deposits and MTDs in the Northern Apennines can be used as a proxy to identify the nature and processes of formation of their highly deformed and metamorphosed counterparts in the Western Alps. The chaotic deposits and MTDs in the Western Alps are commonly confused with tectonically produced rocks asemblages and tectonic mélanges. We have shown in this study that the MTDs in the Western Alps consist of two different types of chaotic deposits of gravitational origin, formed by different submarine mechanisms, and that they occur in different tectonostratigraphic positions within the epi-ophiolitic sedimentary cover. The oldest chaotic deposits occur both below and above the extrusive sequences in the ophiolites, representing syn-extensional, hyper-concentrated deposits associated with the seafloor spreading evolution of the LPOB lithosphere during the Middle-Late Jurassic. The youngest chaotic deposits consist of MTDs, which occur as intercalations within turbiditic sequences above the ophiolites, representing syn–contractional submarine slides. The slides occurred on frontal accretionary prism slopes during the Late Cretaceous–Paleocene closure of the LPOB.

This comparative study provides important clues for the contextual framework of the definition of magmatic, tectonic, and sedimentary processes, which occurred throughout the formation of the Jurassic oceanic lithosphere and its sedimentary cover in the LPOB (Western Tethys), and during the subsequent Late Cretaceous–Paleocene convergent margin tectonics. These processes were remarkably uniform and synchronous as shown by the occurrence of comparable chaotic deposits and MTDs characterized by the same features and the same lithological compositions of clasts. Our data and observations indicate that the LPOB developed with the same features and in a similar basin floor architecture during its entire history and along its entire length.

The results and the geological implications of this comparative study are not limited only to the Western Alpine orogenic belt. The diagnostic features of the different types of chaotic rock units described in this study can also help in distinguishing among those similar units that extensively occur in many Precambrian to Cenozoic orogenic belts, where the overprint of tectonic and metamorphic processes obscured their primary features and the modes of formation. Their detailed lithological, structural and chronological correlations along and across the orogenic belts should provide additional constraints for reconstruction of the magmatic, tectonic and sedimentary evolution of ocean basins, and for the subsequent convergent margin evolution. Therefore, detailed, multidisciplinary studies of chaotic rock units are an integral part of systematic investigations of the temporal evolution of different stages of orogenic buildup, from continental rifting and seafloor spreading to subduction, and crustal exhumation. Such studies and their results have contributed significantly to further refining the plate tectonics paradigm since the mid-1960s.

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FIGURE AND TABLE CAPTIONS

Figure 1. A- Tectonic map of the Western Alps and the Northern Apennines, showing the distribution of different lithospheric plates and ocean basins that were involved in the evolution of the orogenic belts in this region (modified from Balestro et al., 2015). Locations of the major chaotic rock units and MTDs discussed in the text are also shown in red circles and numbers. B- Index map, showing the Alps and the Apennines in their Mediterranean context.

Figure 2. Paleogeographic reconstruction of the Western Tethyan realm (Ligurian-Piedmont Ocean Basin) in the (**A**) Middle Jurassic (modified from Sampfli and Kozur, 2006; Schettino and Turco, 2011) and (**B**) late Maastrichtian (modified from Michard et al., 2002; Sampfli and Kozur, 2006; Schettino and Turco, 2011; Marroni et al., 2017; Festa et al., 2020).

Figure 3. Stratigraphic columnar sections and outcrop photos showing the sedimentary and structural features of the syn-extensional, lower and upper ophiolitic breccias of the Internal Ligurian Units in the Graveglia (**A**) and Bracco (**E**) sections (Northern Apennines). (**B**) Polymictic clasts composed of Fe-gabbro, Fe-basalt, plagiogranite, and serpentinite units in a scarce sandy matrix of the Monte Capra Breccia (lower ophiolitic breccia). Hammer for scale; (**C**) Close-up view of subrounded clasts of Mg-gabbros in the Monte Zenone Breccia (upper ophiolitic breccias) and their stratigraphic relationships (**D**) with Radiolarian cherts. Hammer for scale; (**F**) close-up view of the ophicalcite texture of the Levanto Breccia; (**G**) close-up view of the Framura Breccia (lower ophiolitic breccia) showing serpentinite clasts in a serpentinite-derived matrix. Coin for scale; (**H**) Panoramic view displaying the relationships between the lower ophiolitic breccia (Levanto Breccia) and massive basalts. The stratigraphic relationships are highlighted by ophiolitic sandstones.

Figure 4. Inferred tectonic settings for the emplacement of the syn-contractional MTDs in the Northern Apennines: (**A**) General; (**B**) In detail. (**C**) Representative stratigraphic columnar sections (with scale). (**D**) Close-up view of the cohesive debris flows in the Val Lavagna Shale Group (i.e., "Olistostroma del Passo della Forcella", showing angular to subangular clasts of calcilutites embedded in a muddy-silty matrix. Coin for scale; (**E**) stratigraphic contact (white arrows) between the Bocco Shale (BS) and the Val Lavagna Shale (VLS) in the Portello Unit. Coin for scale; (**F**) Panoramic, and (**G**) Detail view of the Bocco Shale (early Paleocene), showing angular to subangular clasts of calcilutite in muddy-silty, foliated matrix. Hammer for scale.

Figure 5. (**A**) Representative stratigraphic sections, depicting the distribution of the lower and upper syn-extensional ophiolitic metabreccias within the Zermatt-Saas ophiolites in the sector between the Lake Miserin (modified from Tartarotti et al., 2017) and Mt. Avic. (**B**) Field evidence of the superposition of two tectono-metamorphic stages (D1 and D2) of the Alpine deformation onto the eclogite-facies ophiolite metabreccias of the Lake Miserin (Zermatt-Saas ophiolites). Note that the orientation of irregularly shaped clasts, centimeter in size, marks the relict of S1 foliation (dashed yellow line) which is deformed by D2 folds (dashed white lines indicate S2 foliation and D2 fold axial plane; see Tartarotti et al., 2017a for details). (**C**) Field occurrence of lower ophiolite metabreccias (Zermatt-Saas ophiolites) in the Lake Miserin area, showing alternating layers of different sized clast-supported metabreccias, made of angular clasts of serpentinized metaperidotite and metaophicarbonate. Field book for scale; (**D** and **E**) Different close-up views of the Lake Miserin Sedimentary mélange (syn-extensional upper ophiolitic metabreccias; Zermatt-Saas ophiolites), showing angular to sub-rounded clasts of serpentinized metaperidotite in a carbonate-rich (marble) matrix. Dashed white line indicates the S2 foliation. Pencil for scale; (**F**) Close-up view of the Mt. Avic lower ophiolitic metabreccias (Zermatt-Saas ophiolites), showing angular shaped clasts of serpentinized metaperidotite and metaophicarbonate in a mixed carbonate-ultramafic metasandstone matrix. (**G**) Close-up view of the polymictic syn-extensional upper ophiolitic metabreccias

(blueschist facies) of the Queyras ophiolite, showing angular clasts of serpentinized metaperidotite and metagabbros in a calcschist matrix; (**H**) Close-up view of the syn-contractional MTDs of the Rocher Renard Complex (Lower Paleocene?), showing rounded clasts of serpentinized metaperidotite and marble in a metapelite matrix. Camera cap for scale; (**I**) Stratigraphic columnar section of the Queyras ophiolite (modified from Balestro et al., 2019), depicting the stratigraphic position of the lower and upper syn-extensional ophiolitic metabreccias, and syn-contractional MTDs.

Figure 6. (**A**) Stratigraphic columnar section of the Monviso ophiolite (modified from Balestro et al., 2019), depicting the lateral and vertical relations between the syn-extensional chaotic deposits, the exhumed upper mantle rocks and the sedimentary succession. (**B**, **C** and **D**) Various close-up views of angular to irregular – shaped clasts of gabbro in a coarse-grained matrix of mafic-metasandstone (lower syn-extensional ophiolitic metabreccias), and line drawing (**E**) of the overturned peridotite – cover succession relationship, cropping out at Colle del Baracun (Monviso ophiolite); notice the stratigraphic position of mafic metabreccias and metasandstones within the calcschist sequence (modified from Balestro et al., 2015a) (**F**) Panoramic view of the Garten Formation (syn-extensional upper ophiolitic metabreccias) to the East of Cime Bianche (Aosta Valley), showing intercalations of hyperconcentrated deposits (dashed white lines), decimeters to one meters thick, in a calcschist matrix. Dashed black line indicates the S2 foliation. Backpack for scale. (**G** and **H**) Close-up views of the internal arrangement of the Garten Formation, showing rounded to elongated shaped clasts of metabasalt in a coarse-grained calcschist matrix. (**I**) Interpreted stratigraphic sections, depicting the distribution of the syn-extensional upper ophiolitic metabreccias of the Garten Formation in the Zermatt-Saas ophiolite sequence of the Cime Bianche sector.

Table 1. Comparison among syn-extensional lower and upper ophiolitic breccias and syn-contractional MTDs of the Internal Ligurian Units of Northern Apennines and Western Alps.

Figure 7. Interpretative block diagrams depicting the geodynamic and tectono-stratigraphic depositional setting for syn-extensional, lower and upper ophiolitic breccias and syn-contractional MTDs during: (**A**) The Middle–Late Jurassic seafloor spreading, and (**B**) Late Cretaceous – Paleocene convergence tectonic stages of the evolution of the Western Tethyan realm (Ligurian – Piemont Ocean Basin), respectively.

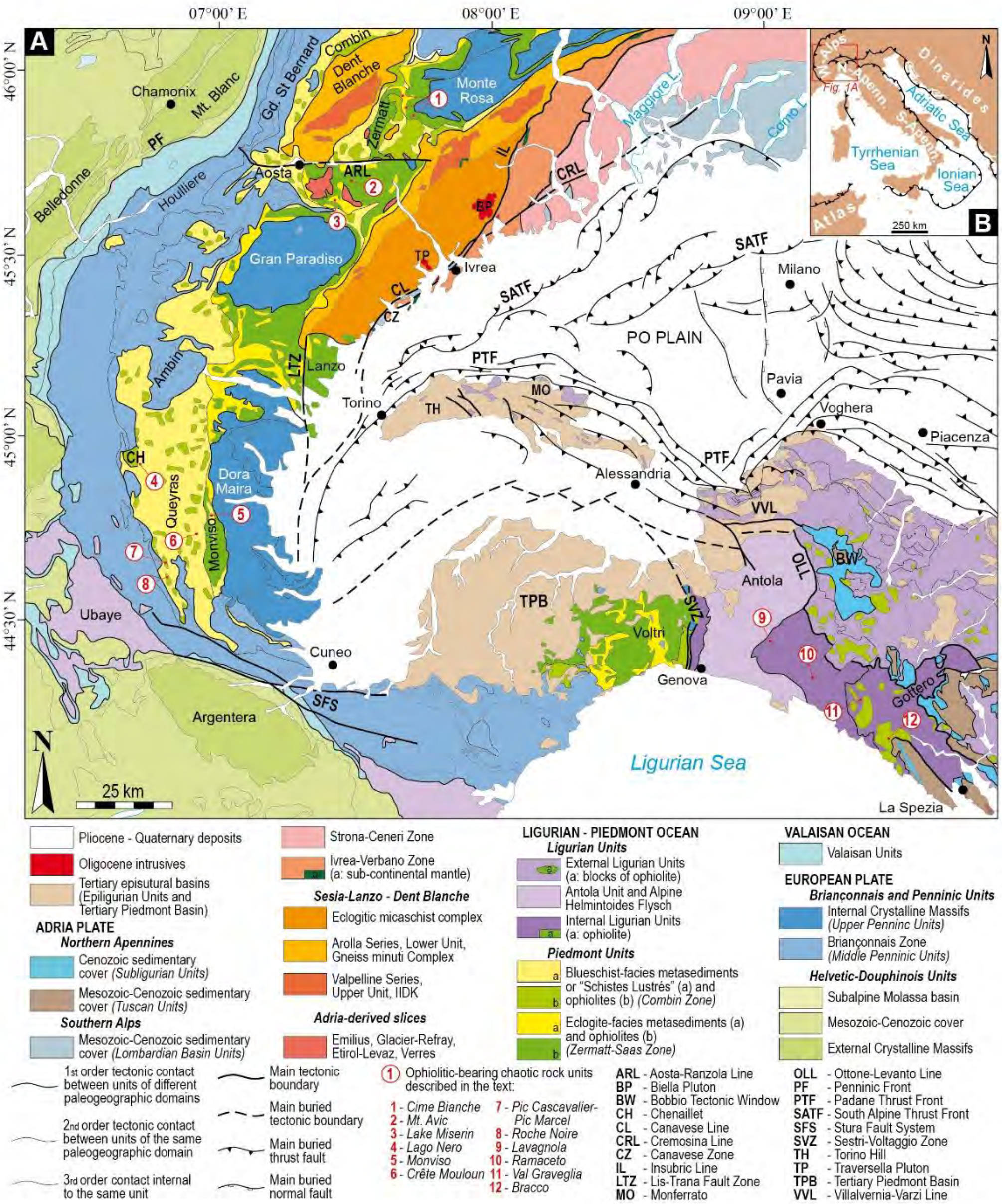
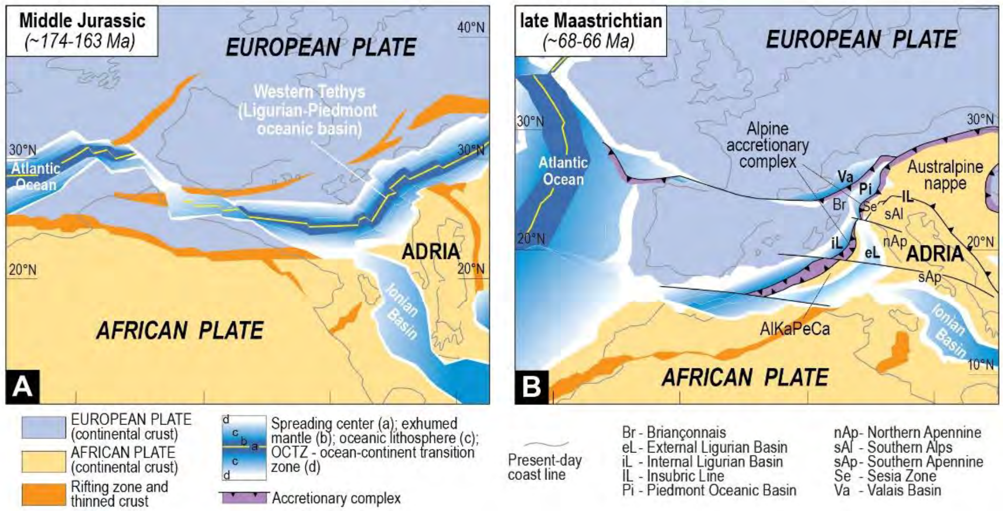


Figure 1 - *Festa et al.* (width 170 mm)



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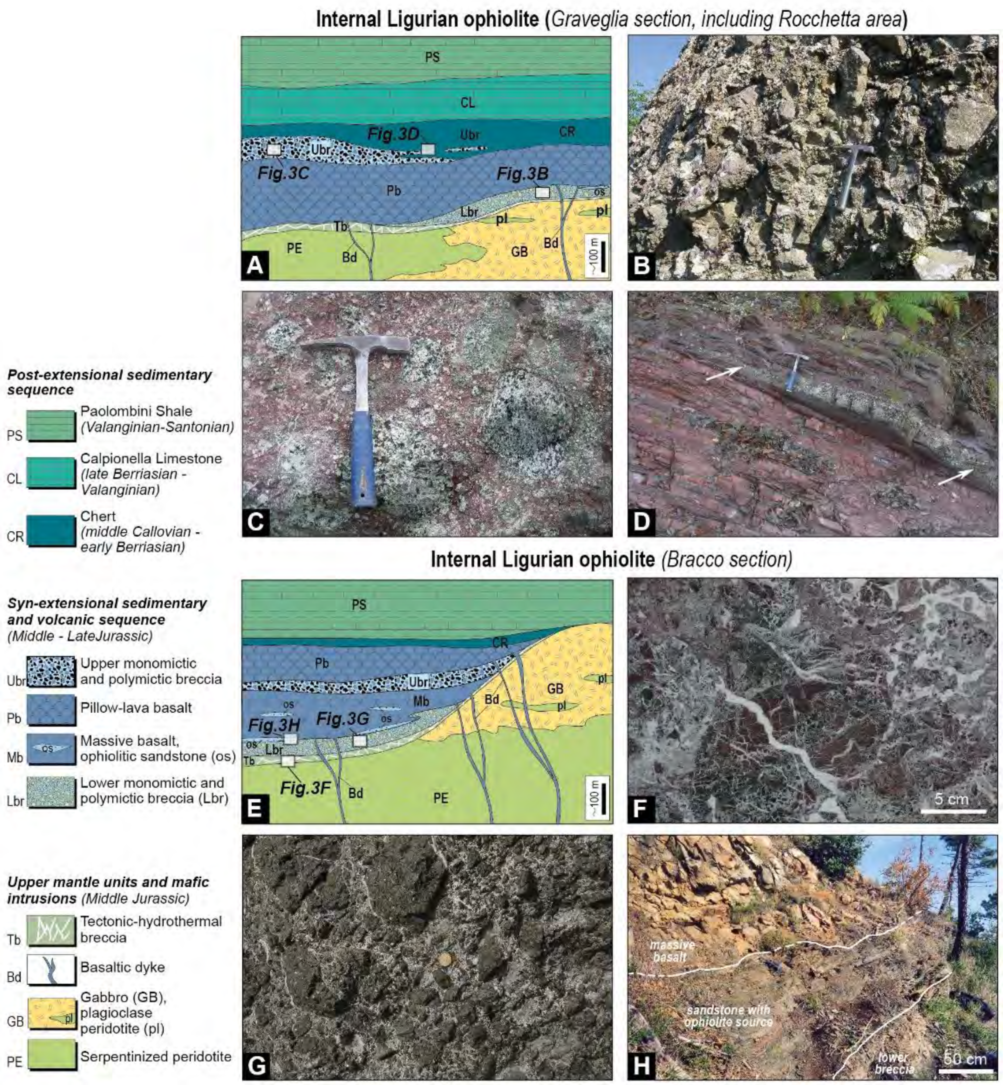

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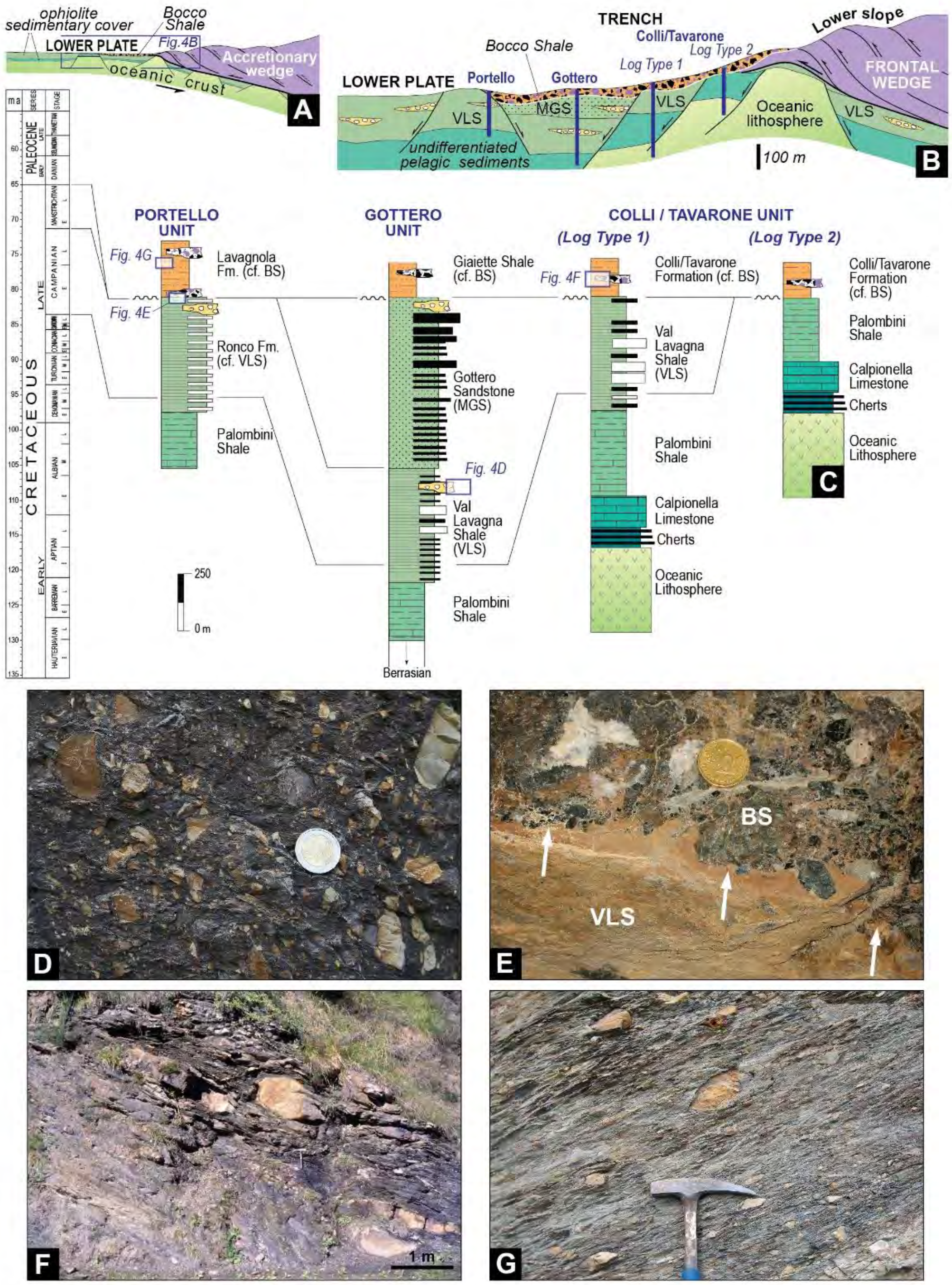

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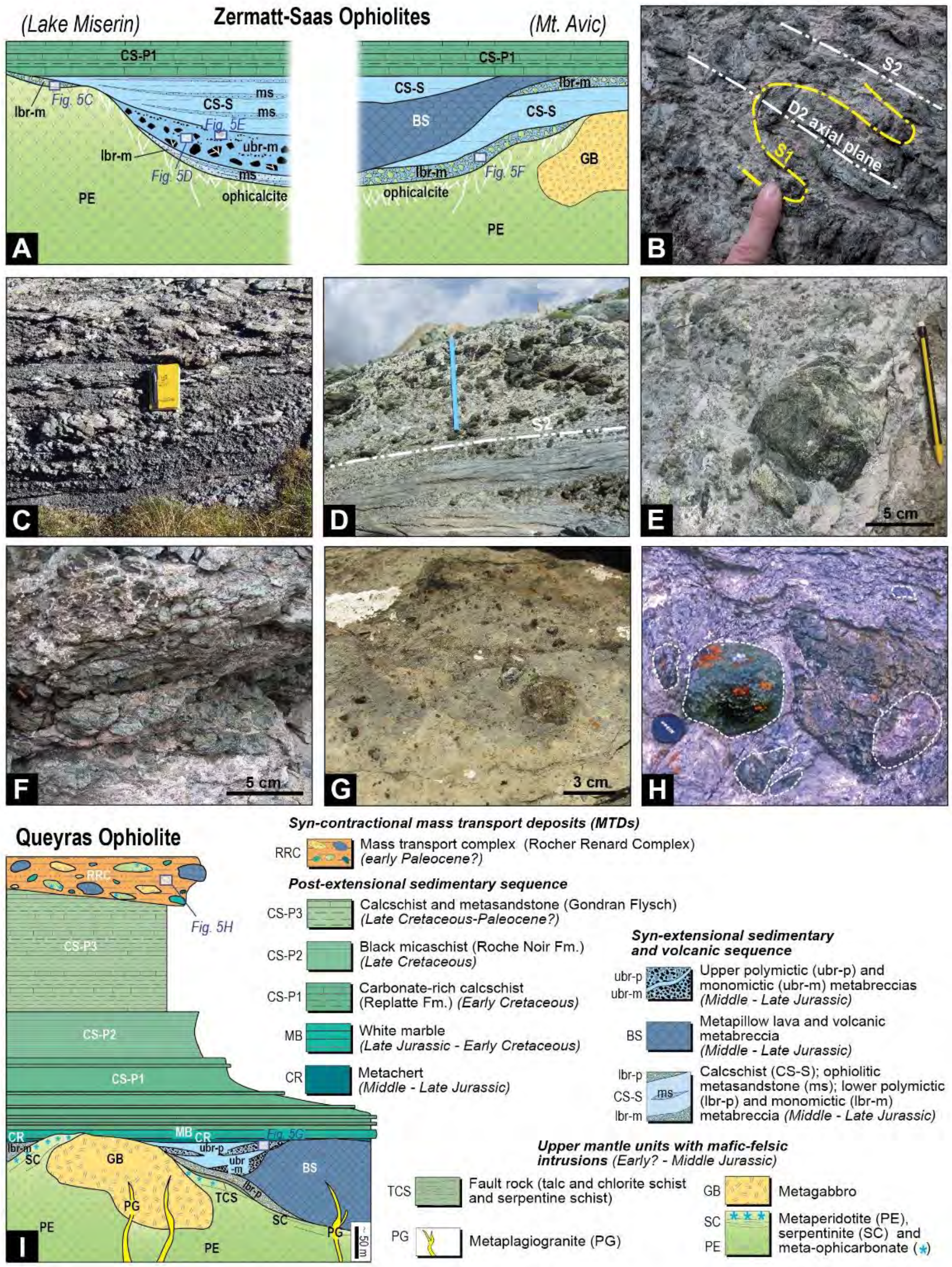

Figure 5 - *Festa et al.* (width 170 mm)

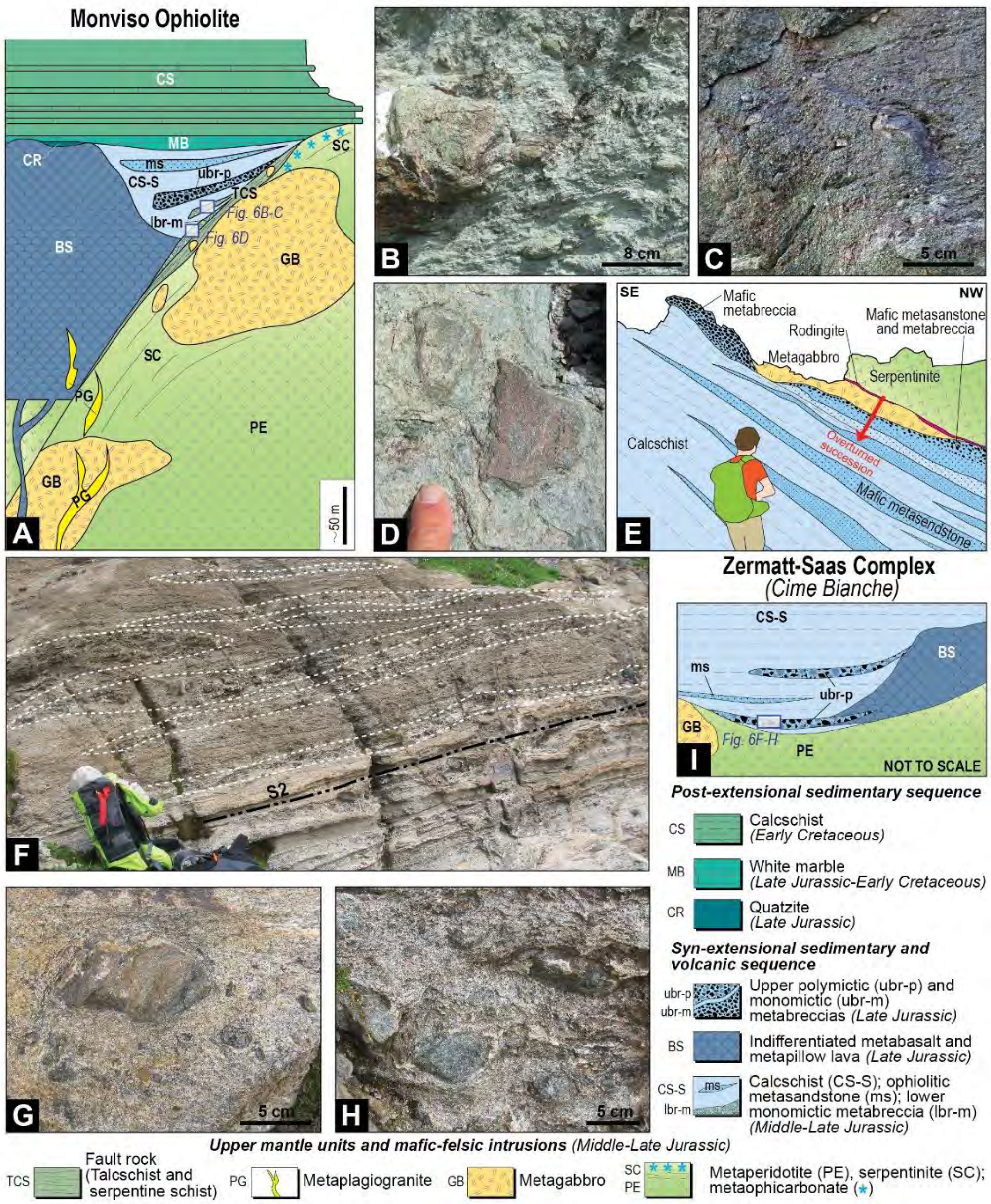

Figure 6 - *Festa et al.* (width 170 mm)

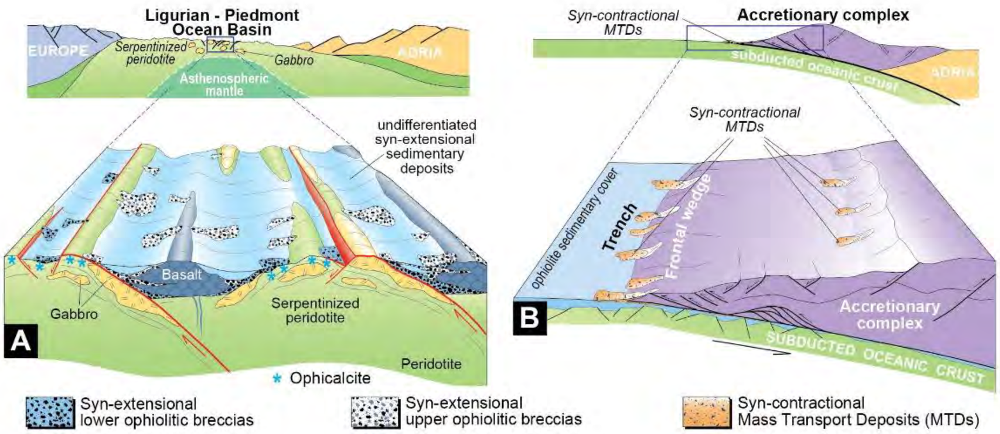

Figure 7 - *Festa et al.* (width 170 mm)

		Name	Texture	Matrix	**Clasts** (in abundance order)	Clasts size	Stratigraphic position	Age
NORTHERN APENNINE	Lower breccias	Levanto Breccia (ophicalcite)	cataclastic	no-matrix	serpentinized peridotite, gabbro, foliated gabbro	cm-m	- Bottom: mantle peridotite - Top: ophiolite-bearing sandstones and basalt	Middle to Late Jurassic
		Framura Breccia	clast-supported	hematitic	ophicalcite, serpentinized peridotite, gabbro	dm-m	- Bottom: Framura Breccia - Top: Basalt flow/Cherts(?)	Middle to Late Jurassic
		Case Boeno Breccia	clast-supported	sandy	serpentinized peridotite, ophicalcite, gabbro	cm-m	- Bottom: mantle peridotite and gabbro - Top: pillow lava basalt	Middle to Late Jurassic
		Monte Capra Breccia	clast-supported	sandy	Fe-gabbro, Fe-basalt, plagiogranite, serpentinite, ophicalcite	cm-m	- Bottom: mantle peridotite and gabbro - Top: pillow lava basalt	Middle to Late Jurassic
	Upper breccias	Movea Breccia	clast-supported	sandy	Mg-gabbro, Mg-basalt, serpentinite, ophicalcite,	cm-m	- Bottom: pillow lava basalt - Top: Monte Zenone Breccia	Late Jurassic
		Monte Zenone	clast-supported	sandy	Mg-gabbro	cm-m	- Bottom: pillow lava basalt - Top: chert	Late Jurassic
		Monte Bianco	clast-supported	sparry	ophicalcite, serpentinized peridotite	cm-m	- Bottom: mantle peridotite - Top: Chert	Late Jurassic
	MTDs	Forcella Breccia	matrix-supported	shaly	limestone, marl, fine-grained arenite	cm-m	Inside the Zonati Shale and Gottero Sandstone	Maastrichtian to Early Paleocene
		Bocco Shale	matrix-supported	shaly	limestone, arenite, marl, basalt, gabbro, serpentinite, chert	cm-dam	Unconformbly on: Palombini Shale, Manganesiferous Shale, Verzi Marl, Zonati Shale and Gottero Sandstone	Early Paleocene
WESTERN ALPS	Lower breccias	Meta-ophicarbonate	cataclastic to hydrofract,	no-matrix	serpentinite	cm-m	- Bottom: mantle peridotite - Top: ophiolite-bearing metabreccia and metasandstone	Middle to Late(?) Jurassic
		Lake Miserin and Mt. Avic metabreccia	clast- to matrix-supported	mixed ultramafic-carbonate (calcschist) to carbonate (marble)	meta-ophicarbonate, serpentinite	cm-dm	- Bottom: ophicarbonate and peridotite - Top: sedimentary mélange (Lake Miserin) and basalt (Mt. Avic)	Middle to Late Jurassic
		Queyras lower mono- and polymictic-metabreccia	clast-supported	mixed mafic-carbonate (calcschist)	- Monomictic: serpentinite, meta-ophicarbonate or metagabbro - Polymictic: serpentinite and metagabbro	cm-dm (rarely m)	- Bottom: mantle peridotite or gabbro or shear zones - Top: basalt sequence or calcschist	Middle to Late Jurassic
		Monviso metabreccia and metasandstone	matrix-supported	mafic metasandstone	metagabbro	cm-dm	- Bottom: Mg-Al metagabbro in the footwall of an extensional detachment fault - Top: post-extensional carbonate-rich metasediment	Middle to Late Jurassic
	Upper breccias	Lake Miserin sedimentary mélange	matrix-supported	carbonate (marble)	massive serpentinite and veined serpentinite (meta-ophicarbonate)	dm-m	- Bottom: Lake Miserin lower metabreccia - Top: post-extensional calcschist	Middle(?) to Late Jurassic
		Queyras upper mono- and polymicitic metabreccia	clast- to matrix-supported	metasandstone (same composition of clasts)	- Monomictic: metabasalt - Polymictic: metabasalt, metagabbro, ingneous quartz-feldspatic rocks (plagiogranite?)	cm-dm	- Bottom (or inside to): metabasalt and meta-pillow lava basalt - Top: post-extensional metasediment (metaradiolarite or marble)	Late Jurassic
		Garten Formation	clast- to matrix-supported	micaschist and calcschist	Metabasalt, serpentinite and marble	cm-dm	Inside the base of metabasite or (locally) within calcschist	Late(?) Jurassic
	MTDs	Rocher Renard Complex	matrix-supported	shaly	metabasalt, meta-ophicarbonate, serpentinite, metagabbro, metalimestone, metachert)	cm-dam	- Bottom: Gondrand Flysch - Top: ?	Maastrichtian to Early Paleocene

Table 1 – *Festa et al.*