

THE SEDIMENTARY COVER OF THE ALPINE, CORSICAN, AND APENNINE OPHIOLITES: A CLUE TO THE PRE- AND SYN-CONVERGENCE HISTORY OF THE LIGURIAN-PIEDMONT OCEAN

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ABSTRACT

Remnants of the Ligurian-Piedmont Ocean are preserved within ophiolite successions of the Western Alps, Northern Apennines, and Alpine Corsica. By integrating sedimentological, structural, and metamorphic data from selected ophiolite sequences, we refine the stratigraphic architecture of the ophiolite sedimentary cover and reconstruct the basin evolution from the Middle Jurassic onward. Three major deposit types are recognized. (i) Pre-convergence pelagic deposits (Bajocian - Santonian), represented by the Monte Alpe Chert, Calpionella Limestone, and Palombini Shale Formations, are characterized by low sedimentation rates and basin-wide facies homogeneity, reflecting a long-lived period of tectonic quiescence after the end of the spreading phase. (ii) Syn-convergence basin-plain turbidites abruptly appeared during the Campanian stage, marking the onset of eastward subduction. (iii) Trench-related deposits of Maastrichtian-early Paleocene age consists of high-rate turbidites interbedded with mass-transport deposits, formed by interaction with the unstable slope of the accretionary wedge. Comparisons between units experiencing different metamorphic conditions reveal that the thickness and rheology of the sedimentary cover exert a first-order control on subduction processes. Variations between high- and low-grade metamorphic units reflect the influence of subducted bathymetric reliefs on the downward migration of the active décollement. Our findings outline the importance of integrated multidisciplinary approaches for reconstructing the evolution of ancient ocean basins worldwide.

INTRODUCTION

The Ligurian-Piedmont Ocean (LPO) is a narrow ocean basin which formed between the European and Adriatic continental margins during the Middle to Late Jurassic period. This ocean basin was gradually consumed by subduction from the Late Cretaceous to the early Cenozoic, and then completely closed during the Late Eocene to Early Oligocene continental collision (Elter and Pertusati, 1973; Polino et al., 1990; Bortolotti et al., 2001; Marroni et al., 2017; Barbero et al., 2020). Remnants of the LPO are preserved as deformed and metamorphosed fragments along the Apennine-Alpine belt exhumed from the subduction channel (Fig. 1), spanning over 1,000 km with good, continuous exposures. Analyzing these fragments can provide valuable insights into the characteristics of the oceanic crust and its associated sedimentary cover.

The characteristics of oceanic crust are well understood and have been outlined in several papers across the entire Apennine-Alpine belt, from the Central and Western Alps to the Northern Apennines and Corsica (Pognante et al., 1986; Lagabrielle and Cannat, 1990; Lagabrielle, 1990; Treves and Harper, 1994; Cannat et al., 1997; Marroni and Pandolfi, 2007; Montanini et al., 2008; Balestro et al., 2015a; Rampone et al., 2020; Festa et al., 2021). This crust shows the same features throughout the Apennine-Alpine belt and is interpreted as formed over a short period of time in an ultraslow spreading ridge. This ridge was characterized by a scarcity of magmatism and pervasive extensional tectonics, which led to large-scale exposures of the oceanic mantle and lower crust at the sea bottom. These exposures are covered by widespread ophiolitic breccia, which was intermingled with pillow lava basalt (Principi et al., 2004; Tartarotti et al., 2017; Festa et al., 2021).

The ophiolite sedimentary cover, which formed from the Late Jurassic period to the early Cenozoic era, has received less attention with only a few papers published on this topic (e.g., Principi et al., 2004; Tartarotti et al., 2021). However, this well-preserved sedimentary cover is present in several units as hemipelagic, turbidite and mass transport deposits, sometime of relevant thickness and with good exposures. Despite subduction-related metamorphism, it is still possible to fully reconstruct their sedimentary features as well as their age. These features allow for the reconstruction of a pelagic to proximal sedimentary sequence, shedding light on transition of an ocean basin from a long-lived stage of filling without active spreading-related tectonics, up to the onset of subduction and the subsequent complete closure. This paper provides detailed descriptions of several key areas (Fig. 1a, b) in the Western Alps, the Northern Apennines, and Corsica where the ophiolite sequences are exposed. Data from these areas will be compared to offer a fresh insight into the evolution of the ophiolite sedimentary cover from the Late Jurassic period to the early Cenozoic era. Finally, the reconstructed history of the ophiolite sedimentary cover will be considered in the context of the LPO's geodynamic evolution.

THE GEODYNAMIC HISTORY OF THE LIGURIAN-PIEDMONT OCEAN: STATE OF ART

The Ligurian-Piedmont Ocean was a narrow, east-west elongated oceanic area, the remnants of which are preserved today in a collisional belt (Fig. 1c) stretching from the Eastern and Western Alps to the Caribbean area, via Corsica, the Northern Apennines, Calabria, Northern Algeria and

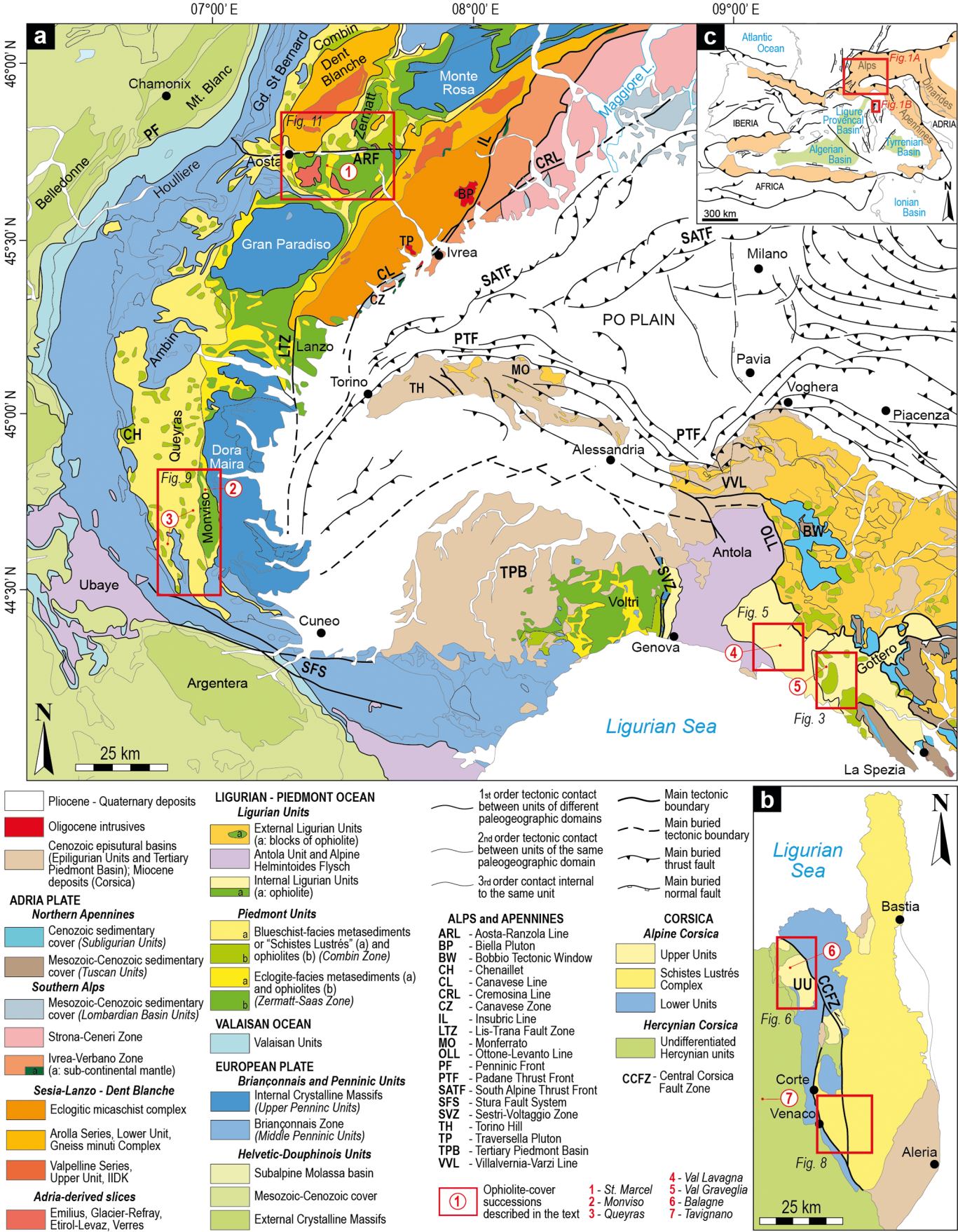


Fig. 1 - Tectonic map of (a) the Western Alps, the Northern Apennines (modified from Balestro et al., 2015a) and (b) Corsica (Di Rosa et al., 2025), showing the locations of the studied units discussed in the text (red circles and numbers). (c) - Index map, showing the Alps and the Apennines in their Mediterranean context.

Southern Spain (Savostin et al., 1986; Bortolotti and Principi, 2003; Handy et al., 2010; van Hinsbergen et al., 2020; Le Breton et al., 2021).

The formation and termination/demise of LPO occurred in several distinct stages over a period of more than 200 Ma, from the Triassic to the Eocene (Fig. 2). This history began with the rifting of a large continental domain, which initiate the formation of the oceanic crust, and growth of oceanic basin. It ended with the ocean's closure and subsequent collision, resulting in the formation of the present-day Alpine and Apennine belts, where oceanic fragments, i.e., the ophiolites, are amalgamated within continental units.

The rifting stage is preceded by the thinning of the post-Variscan orogenic lithosphere, which took place during the Permian and Triassic periods (Diella et al., 1992; Marotta et al., 2009). The thinning is accompanied by post-collisional magmatism, which is directly linked to the collapse of the post-Variscan collisional belt (Boscaini et al., 2020). The magmatism marks the transition to the rifting stage, which is considered to have begun in the Middle to Late Triassic pe-

riod (Dumont, 1988; Marroni and Pandolfi, 2007; Ribes et al., 2019), when rifting began with the widespread stretching of the continental crust of Europe due to pure shear-dominated extension (Marroni et al., 1988; Mohn et al., 2012; Masini et al., 2013). During the earliest part of the Jurassic period, the extension mechanism shifted towards localized lithospheric stretching by high-angle normal faults, which were concentrated in a few narrow areas (Mohn et al., 2012; Masini et al., 2013). This final step occurred in one of these areas during the Early to Middle Jurassic period (Fig. 2a), resulting from simple-shear-dominated lithospheric stretching via a westward-dipping detachment fault system (Lemoine et al., 1987; Manatschal, 2004; Marroni and Pandolfi, 2007; De Carlis et al., 2015). This step resulted in the formation of an embryonic oceanic area stretching from east to west, between the continental margins of the European and Afro-Arabian plates (including the Adria microplate) to the north and south, respectively. The main outcome of the final stage of rifting is the different configurations of the ocean-continent transition (OCT) on the two paired continental margins. On the

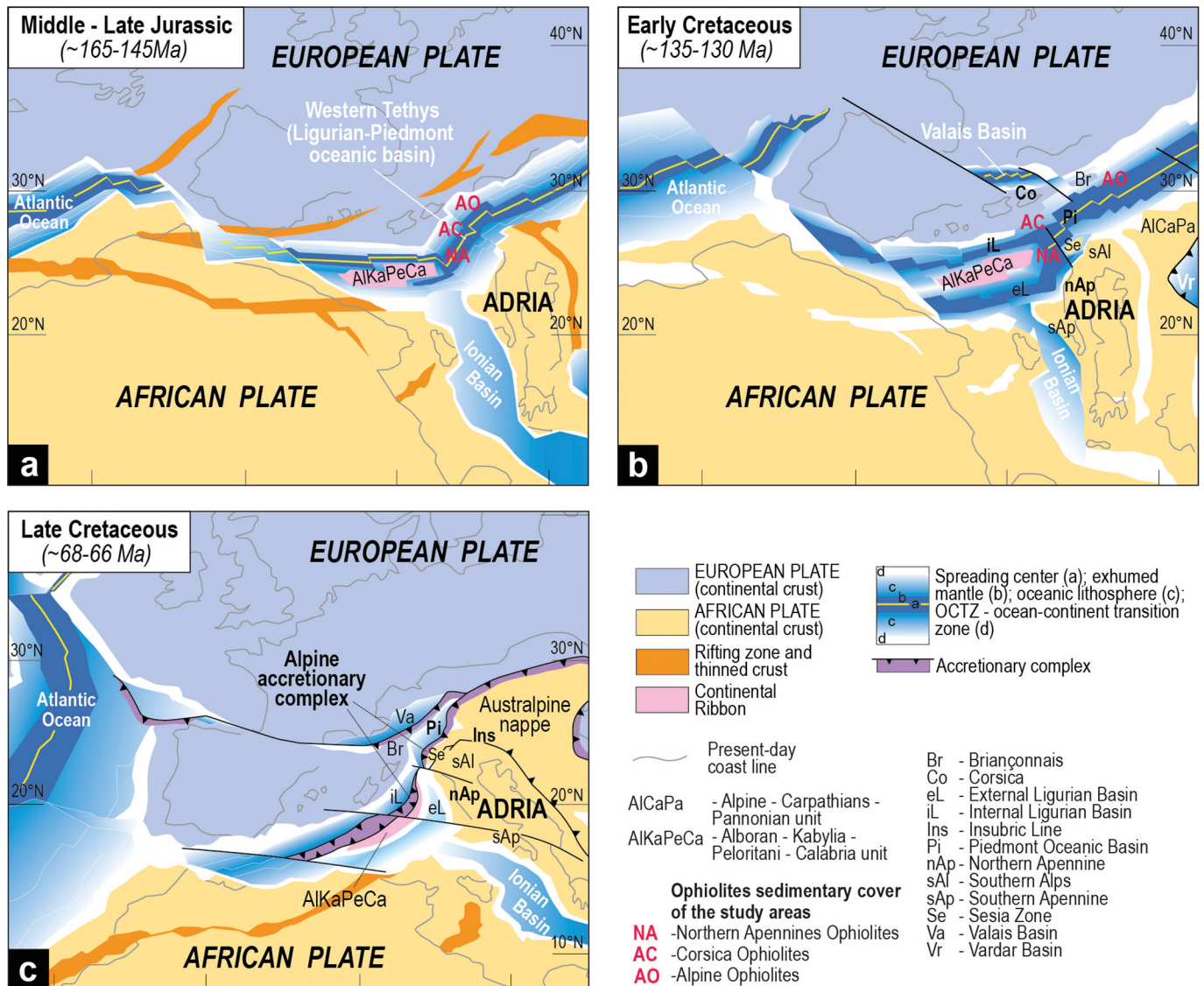


Fig. 2 - Paleogeographic reconstruction of the Western Tethyan realm (Ligurian-Piedmont Ocean) in the (a) Middle-Late Jurassic (modified from Stampfli and Kozur, 2006; Schettino and Turco, 2011), (b) Early Cretaceous (modified from Stampfli and Kozur, 2006; Schettino and Turco, 2011, and Le Breton et al., 2021), and (c) Late Cretaceous (modified from Michard et al., 2002; Stampfli and Kozur, 2006; Schettino and Turco, 2011; Marroni et al., 2017; Festa et al., 2020).

European side, the OCT zone is clearly defined, with an exposure of upper continental crust rocks. In contrast, the OCT on the Adriatic side consists of a large area with extensive exposure of exhumed subcontinental lithospheric mantle and lower continental crust rocks, both of which are covered by extensional allochthons made up of upper continental crust rocks (Marroni et al., 1988; Froitzheim and Eberli, 1990; Lagabriele, 1990; Froitzheim and Manatschal, 1996; Masini et al., 2013; Ribes et al., 2019). In the reconstruction proposed by Marroni et al. (2017) and Festa et al. (2020), the Adriatic margin comprises a continental ribbon that separates the LPO from a basin with an extremely thin continental crust, which transitions southward into a wide oceanic area. Figure 2a shows this ribbon as the northernmost edge of the AlKaPeCa domain. The onset of spreading is constrained to the Middle Jurassic (Bajocian stage) by U-Pb zircon geochronology (De Togni et al., 2024), and to the Middle Jurassic (latest Bajocian-early Bathonian, Chiari et al., 2000) and Middle-Late Jurassic (middle Bathonian-late Oxfordian stages) (Bill et al., 2001) by radiolarian dating in the Northern Apennines and the Alps, respectively. The youngest U/Pb zircon dating in Alpine and Apennine belt span from Kimmeridgian to Tithonian stages (Late Jurassic, De Togni et al., 2024). These data suggest that spreading magmatism spanned a period of about 20–25 Ma, from 170–165 Ma to 150–145 Ma. Additionally, the characteristics of the ophiolite sequence clearly indicate that a magma-poor, ultra-slow mid-ocean ridge system developed throughout the spreading phase of the LPO (Lagabriele and Cannat, 1990; Treves and Harper, 1994; Marroni and Pandolfi, 2007; Balestro et al., 2019; Festa et al., 2021). Seafloor spreading in the LPO is estimated to have occurred at an average rate of approximately 2 cm/yr, consistent with spreading rates documented for the Central and North Atlantic during the Early to Late Jurassic (e.g., Savostin et al., 1986; Rosenbaum et al., 2002; Handy et al., 2010). When combined with the inferred duration of spreading, this rate suggests that the LPO was relatively narrow and likely did not exceed approximately 400–500 km in width. Subsequently (Fig. 2b), and until the earlier part of Late Cretaceous period, the sedimentation features within the LPO suggest a long-lived period without evidence of extensional or contractional tectonics (Festa et al., 2021). The successions sedimented during this period consist of hemipelagic deposits interspersed with fine-grained, distal carbonate and siliciclastic turbidites without any coarse-grained clastic levels (Decandia and Elter, 1972; Marroni, 1991; Principi et al., 2004). This scenario changed abruptly in the Santonian-Campanian period (Fig. 2c) when a major reorganization of the plates occurred. This reorganization primarily involved a shift in convergence from east-west to north-south between the Afro-Arabian and European plates (Savostin et al., 1986; Dewey et al., 1989; Van Hinsbergen et al., 2020). This shift resulted in east-dipping subduction, which began within the Adria continental margin (Manzotti et al., 2014; Festa et al., 2020) or within its OCT (Marroni et al., 2017) at the northern and southern rims of the LPO, respectively. This tectonic event was marked by the onset of turbiditic sedimentation within the LPO, supplied by detritus derived from the European continental shelf (Marroni et al., 1992). First, the thinned continental margin and the oceanic lithosphere of the Adria Plate were involved in the subduction, followed by the LPO from the Cretaceous-Cenozoic boundary (Manzotti et al., 2014; Marroni et al., 2017; Festa et al., 2020). The subduction zone was characterized by the development of a double-verging accretionary wedge (Fig. 2c), in which slices of oceanic lithosphere were progressively

accreted and deformed under high-pressure, metamorphic conditions (Dal Piaz et al., 1990; Di Giulio, 1992; Marroni et al., 2004; Zanchetta et al., 2012; Agard, 2021; Herviou et al., 2022). Continued convergence led to the progressive consumption of the oceanic lithosphere and ultimately resulted in the involvement of the thinned European continental margin in the subduction processes. The continental collision began when the thickest continental lithosphere of the European plate entered the subduction zone (Bellahsen et al., 2014; Rosenbaum and Lister, 2005; Dielforder et al., 2016), and throughout the Middle to Late Eocene time resulted in the formation of a Late Eocene collisional belt (Trumpy, 1975). The structures of this belt are subsequently sealed by Late Eocene to Early Oligocene wedge-top basins (i.e., the Tertiary Piedmont Basin *Auct.*, the Epiligurian Units *Auct.*, and the Ranzano-Bismantova Basin *Auct.*; Gelati et al., 1998; Elter et al., 2003; Carrapa et al., 2004; Maino et al., 2013).

DESCRIPTION OF OPHIOLITE SEDIMENTARY COVER IN SELECTED AREAS FROM THE NORTHERN APENNINES

The ophiolites of the Northern Apennines (Fig. 1a) belong to the Internal Ligurian Units, which represent deformed oceanic fragments derived from the interior of the southern LPO (Marroni et al., 2017). These units are exposed at the top of the tectonic stack of the Northern Apennine collisional belt. The Internal Ligurian Units have been thrust over the External Ligurian, Subligurian and Tuscan Units, which represent slices detached from the Adria continental margin and its transition to the LPO (Abbate et al., 1970; Elter et al., 1998; Conti et al., 2020). During the closure of the Ligurian-Piedmont basin, the Internal Ligurian Units underwent underplating and exhumation within the accretionary wedge that formed during the Late Cretaceous-Early Cenozoic. Underplating-related metamorphism developed under pressure and temperature conditions pertaining to prehnite-pumpellyite and the low blueschist metamorphic facies. This feature enabled the primary sedimentary characteristics of the ophiolite sedimentary cover to be well-preserved.

Two different areas, i.e., the Graveglia and Lavagna Valleys, have been selected to describe this sedimentary cover.

The Bracco-Val Graveglia Unit in the Graveglia Valley

In Graveglia Valley of the Ligurian Apennine (Fig. 3a), the Bracco-Val Graveglia Unit is characterized by an ophiolite sequence and the lower part of its sedimentary cover (Fig. 3b), consisting of Monte Alpe Chert, Calpionella Limestone and Palombini Shale Fms. (Decandia and Elter, 1972; Borolotti and Principi, 2003). The Bracco-Val Graveglia Unit is affected by two main deformation phases (Hoogerduijn Strating and Van Wamel, 1989; Marroni et al., 2004). The D₁ phase rested in map- to meso-scale isoclinal folds with ophiolites in their core, which were later deformed by close, east-verging folds during the subsequent D₂ phase. The metamorphism associated with the D₁ phase is characterized by P-T conditions pertaining to prehnite-pumpellyite facies (Sanità et al., 2024). Despite the polyphase folding, low-grade metamorphism has allowed the stratigraphic and sedimentological features of the sedimentary cover to be well preserved. The deposits overlying the Palombini Shale Fm. were probably detached during the D₁ phase and, as consequence, are not exposed in the Bracco-Val Graveglia Unit.

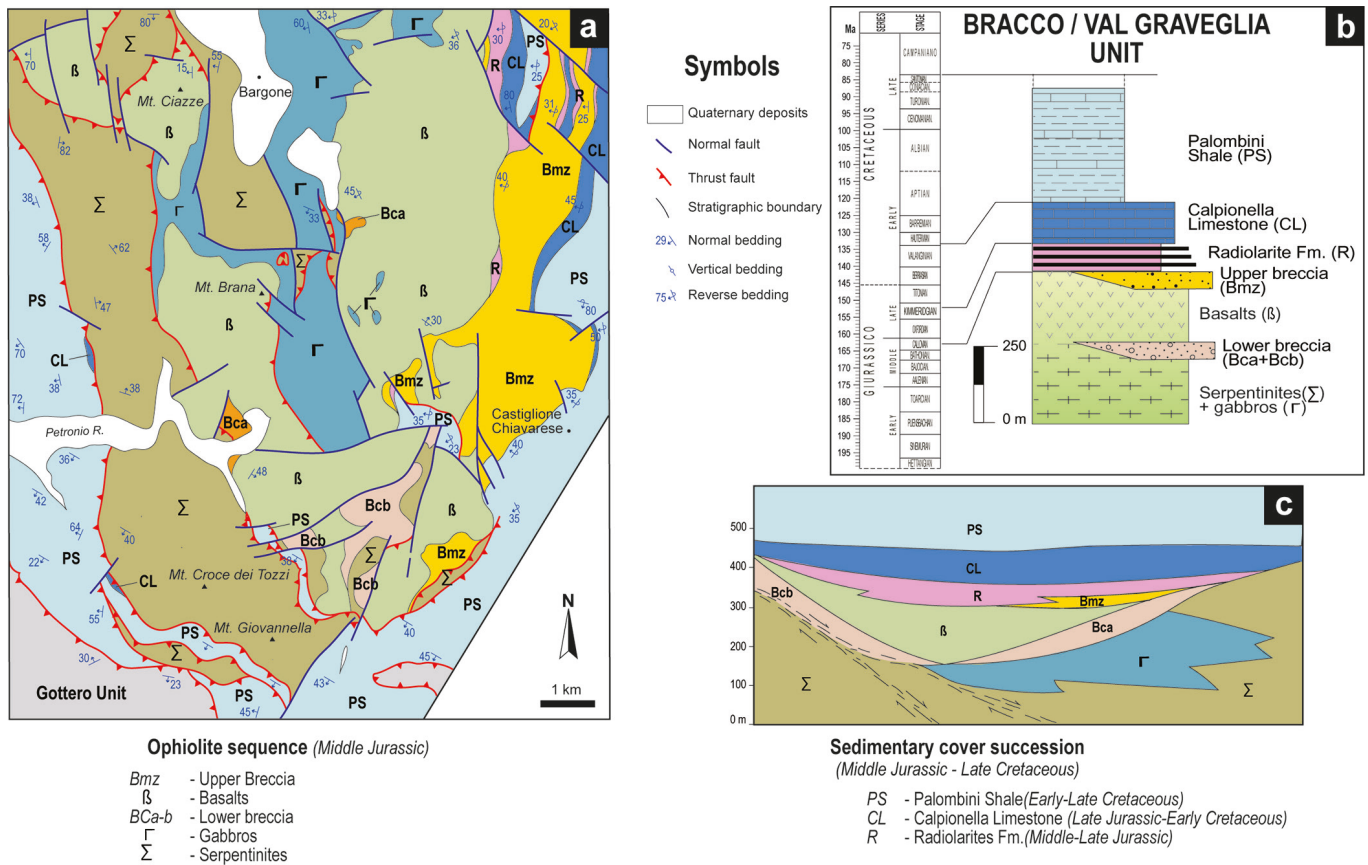


Fig. 3 - (a) Geological map of the southern area of the Graveglia Valley (modified from Bortolotti and Principi, 2003). (b) Log section of the Bracco-Val Graveglia Unit in the Graveglia Valley. (c) Reconstruction of the relationships between the ophiolite sequence and the sedimentary cover.

Ophiolite sequence

The ophiolite sequence, which shows the maximum thickness observed in the Internal Ligurian Units, includes a basement consisting of mantle peridotite intruded by bodies of gabbro. This basement is covered by lower ophiolitic breccia (Monte Capra and Case Boeno Breccia; Festa et al., 2021), which are in turn overlain by pillow-lava basalt grading upward to pillow-lava breccia (Fig. 3c). A discontinuous level of upper ophiolitic breccia (Monte Zenone and Monte Bianco Breccia; Festa et al., 2021) occurs at the top of the pillow-lava basalt and breccia, reaching a maximum thickness of 150 meters. The transition from the Monte Alpe Chert Fm. to the Monte Zenone Breccia is marked by a layer of gabbro breccia, 20 to 30 meters thick, with a red siliceous mudstone matrix. When the upper ophiolitic breccia is absent, the transition from the pillow-lava breccia to the Monte Alpe Chert Fm. is characterized by 1- to 3-meter-thick level of pillow fragments set in a siliceous mudstone. This level shows a transition to a 10-meter-thick layer of well-bedded siliceous mudstone ranging in color from dark grey to reddish. This level is characterized by manganese-rich layers forming banded ore, which is evidence of widespread hydrothermal activity on the seafloor during sedimentation (Cortesogno et al., 1975). In some outcrops (e.g., Ponte Lagoscuro in Graveglia Valley), the basal part of the Monte Alpe Chert Fm. comprises levels of fine-grained breccia, up to 1 m thick, consisting of gabbro fragments (Fig. 4a). This breccia level can be correlated to the Monte Zenone Breccia cropping out south of Graveglia Valley. The main body of the Monte Alpe Chert Fm. consists of a monotonous sequence of very thin to thin beds of radiolarite

and siliceous mudstone. The radiolarite beds exhibit parallel lamination and sometimes a graded bedding. In thick radiolarite beds, the base consists of large radiolarian fragments associated with quartz and chlorite mineral fragments (Barrett, 1982). These beds are interpreted as turbidite deposits derived from oceanic structural highs and subsequently redeposited in small basins bounded by normal faults formed during ridge-related tectonic activity responsible for the development of these structural highs. The Monte Alpe Chert Fm. is characterized by a lower section in which beds of siliceous mudstone and radiolarite alternate, whereas in the upper part, siliceous mudstones largely prevail (Barrett, 1982; Aiello, 1994). The thickness of this formation ranges from 50 to 150 meters (Aiello, 1994; Chiari et al., 2000) but the estimate of the real thickness is hampered by the occurrence of D_1 phase isoclinal folds. In the Graveglia Valley, the age of this formation is Middle Callovian-Early Oxfordian to Tithonian (Chiari et al., 2000). However, in the Monte Bianco area, the base of the Monte Alpe Chert Fm. is attributed to the Late Bajocian-Early Callovian (Chiari et al., 2000). These data suggest that the base of this formation is diachronous over short distances.

Pre-convergence pelagic deposits

The transition from the Monte Alpe Chert Fm. to Calpionella Limestone Fm. occurs through 10- to 20-meter-thick level in which the siliceous mudstone alternates with cherty limestone beds. The Calpionella Limestone Fm. consists of a succession of beds of fine-grained cherty limestone, ranging from thick to very thick, which are interlayered with very thin layers of siliceous, CaCO_3 -free shale (Fig. 4b). The limestone

beds are almost completely made up of nannofossils. The very thick beds generally consist of amalgamated limestone layers. Based on the occurrence of parallel and convolute laminations, as well as fine-grained calcarenite at the base of the thickest beds, the limestone beds are interpreted as carbonate turbidites (Decandia and Elter, 1972; Andri and Fanucci, 1975; Principi et al., 2004). In the calcarenite at the base of a very thick bed of cherty limestone, fragments of oolite-bearing limestone have been found, suggesting that the carbonate turbidites originated from a continental margin (Decandia and Elter, 1972). The siliceous shale is instead interpreted as hemipelagic deposits (Marroni and Perilli, 1996). The thickness of this succession varies from a few meters to a maximum of 150 meters (Decandia and Elter, 1972; Bortolotti and Principi, 2004). In the Graveglia Valley, the age of this formation ranges from Late Tithonian to Early Valanginian (Cobianchi and Villa, 1992; Cobianchi et al., 1994).

The transition to the Palombini Shale Fm. occurs through a progressive increase in the thickness of the siliceous shale, accompanied by a decrease in the frequency of limestone beds. The lower section of this formation is exposed in the Graveglia Valley, while the upper part was detached during subduction-related tectonics (Marroni et al., 2004).

The Palombini Shale Fm. (Fig. 4c) consists of a monotonous alternation of medium-to-very-thick beds of CaCO_3 -free siliceous shale and medium-to-thick beds of limestone, as well as thin beds of siliciclastic siltstone and fine-grained sandstone (Decandia and Elter, 1972; Principi et al., 2004). As with the Calpionella Limestone Fm., the limestone beds of the Palombini Shale Fm. can be interpreted as carbonate turbidites due to the presence of graded bedding, flute casts, and parallel and convolute laminations. Fine-grained calcarenite bearing fragments of oolite and peloid-bearing limestone have been found at the base of the thicker limestone beds. The CaCO_3 -free siliceous shale beds are devoid of any sedimentary structures and are interpreted as hemipelagic deposits. The shale consists of flakes of white mica, chlorite, quartz, albite, and small amounts of titanite and K-feldspar (Sanità et al., 2025). In the Palombini Shale Fm., siliciclastic turbidites consisting of medium to thin layers of siltstone and fine-grained arenite, as well as shale, are common. The arenite contains single-crystalline quartz grains, with minor amounts of feldspar and phyllosilicate minerals. No recognizable lithic fragments are present, nor are there any fragments of ophiolites or carbonate rocks. The age of the Palombini Shale Fm. in the Graveglia Valley section has been determined as late Valanginian - Early Aptian by Cobianchi and Villa (1992).

Sedimentation history

Overall, the Calpionella Limestone and Palombini Shale Fms. are the result of sedimentation in a basin plain over oceanic crust, where distal carbonate and siliciclastic turbidites were deposited alongside hemipelagic shales. According to Marroni (1994), the sedimentation rate of both the Calpionella Limestone and the Palombini Shale Fms. is very low, in the order of less than 100 meters per million years, as calculated from lithified sections (Fig. 5c). It is important to note that the presence of ophiolite bodies within the Palombini Shale Fm. in the Graveglia Valley should be interpreted as slices along tectonic surfaces, given the presence of shear zones at their boundaries and the absence of sedimentary breccias around these bodies. This interpretation is confirmed by the absence of ophiolitic detritus in the lithotypes from the Calpionella Limestone and Palombini Shale Fms.

The Gottero Unit in the Lavagna Valley

In the southern Lavagna Valley of the Ligurian Apennine, between the Ramaceto and Capenardo mountains, the upper part of the ophiolite sedimentary cover belonging to the Gottero Unit is clearly visible (Fig. 5a). The Gottero Unit is the most deformed and metamorphic of the Internal Ligurian Units, comprising only a sedimentary sequence (Fig. 5b). In fact, the Gottero Unit is detached at the upper level of the Palombini Shale Fm., including only the youngest part of this formation topped by the Mangesiferi Shale, Monte Verzi, Zonati, Monte Gottero and Bocco Shales Fms. (Decandia and Elter, 1972; Casella and Terranova, 1963; van Zupthen et al., 1985; Marroni, 1994). The deformation phases identified in the Bracco-Val Graveglia Unit have also been recognized with the same features in the Gottero Unit (Marroni, 1994; Meneghini et al., 2007), although in this unit the metamorphic peak developed under low-grade blueschist facies (Meneghini et al., 2024; Sanità et al., 2024).

Pre-convergence pelagic deposits

In the Lavagna Valley, the youngest section of the Palombini Shale Fm. exhibits characteristics similar to those of the formation exposed in the Graveglia Valley. Close to the stratigraphic transition to the Mangesiferi Shale Fm., however, this formation is characterized by carbonate turbidites, with layers of limestone associated with marlstone. Similarly, the thickness of the siliceous shales increases significantly. At the top of the upper section a nannofossil association of Late Santonian was reported by Marroni and Perilli (1990).

Syn-convergence deposits

The Palombini Shale Fm. shows a gradual transition to the Mangesiferi Shale Fm., which is about 400 meters thick. The lower part of the succession consists of thin to medium turbiditic layers of fine and very fine-grained sandstone, which gradually change to predominantly dark, Mn-rich shale (Fig. 4d). The middle and upper parts of the formation are characterized by a gradual increase in sandstone thickness and grain size, up to the medium-coarse range, along with a corresponding decrease in the thickness of the shale layers. The sandstone fraction of these siliciclastic layers can be classified as arkose or subarkose (Fig. 5c). The Mangesiferi Shale Fm. is interpreted as Late Santonian to Early Campanian in age (Marroni and Perilli, 1990).

At the top of the Mangesiferi Shale Fm., the Monte Verzi Fm. crops out at a thickness of approximately 400 meters. The stratigraphic succession of the Monte Verzi Fm. is characterized by two different types of turbidite layers: one with a siliciclastic composition and the other with a calcareous-marly composition. The typical lithofacies results from the interaction of these two types of layers. The siliciclastic turbidite consists of thin to thick layers of fine- to medium-grained sandstone and shale, whereas the carbonate turbidites have a sandstone base that grades upwards to marlstone. The sandstone in the Monte Verzi Fm. can also be classified as arkose or subarkose (Fig. 5c). This formation is entirely Early Campanian in age (Marroni and Perilli, 1990).

Both the Mangesiferi Shale and the Monte Verzi Fms. are interpreted as prograding basin-floor fans on the oceanic crust. The siliciclastic turbidites of these deposits were supplied by the European continental shelf. Marroni et al. (1992, 2017) interpreted the sedimentation of these deposits as a response to the onset of subduction in the Ligurian-Piedmont Ocean.

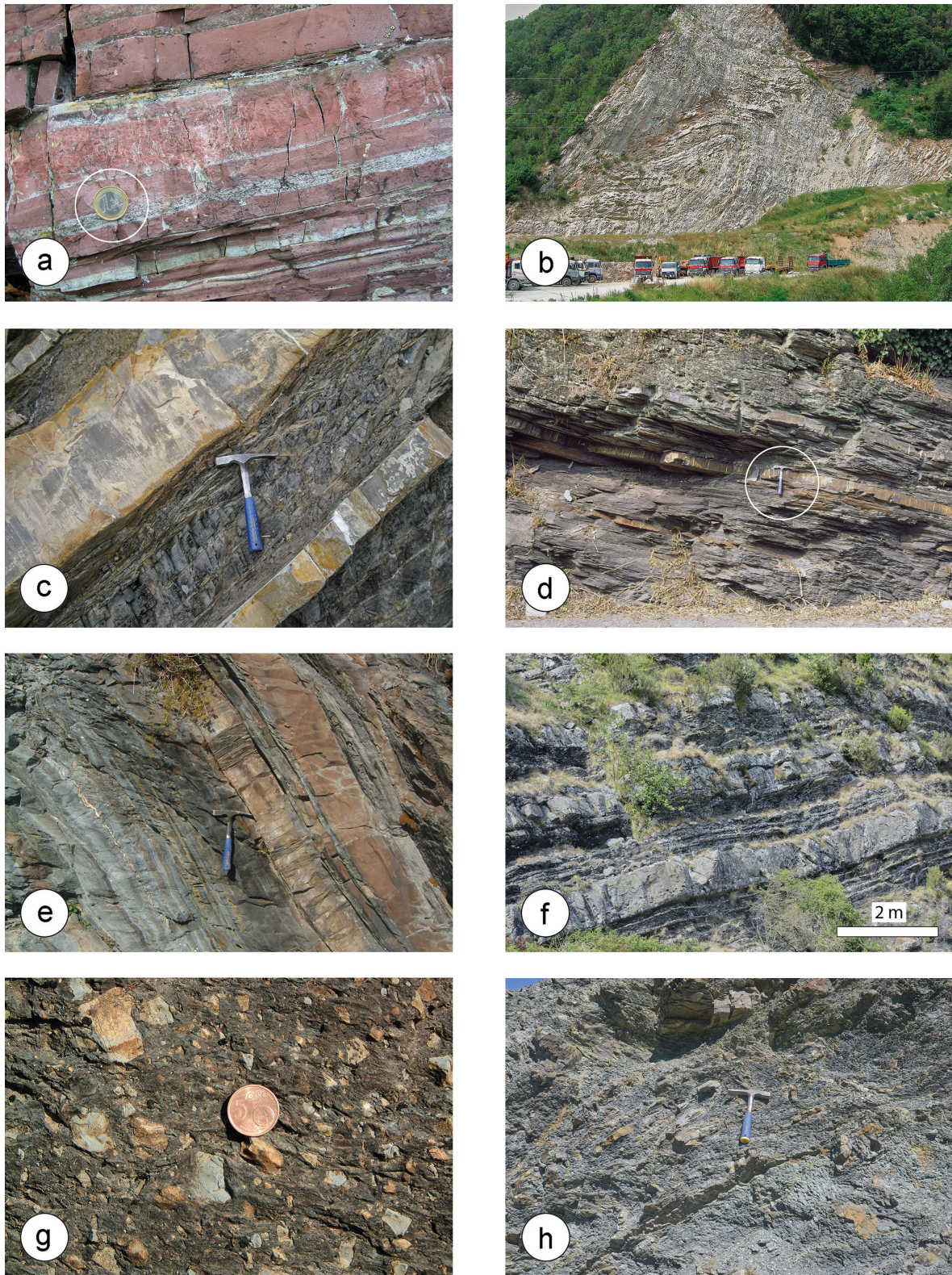


Fig. 4 - Field images of the different lithologies of ophiolite sedimentary cover from Bracco-Val Graveglia and Gottero Units. (a) A detail of the Monte Alpe Chert Fm. characterized by thin levels of ophiolite-bearing rudites interspersed within the radiolarite, 44°20'45"N, 9°27'31"E. (b) Outcrop of the Calpionella Limestone Fm. characterized by a fold that affected a sequence of thick to very thick beds of limestone, 44°20'11"N, 9°26'3"E. (c) Outcrop of Palombini Shale Fm. showing a typical alternance of beds of CaCO_3 -free siliceous shale and limestone, 44°20'53"N, 9°27'50"E. (d) Field occurrence of the lower part of the Mangesiferi Shale Fm. consisting of dark, Mn-rich shales and fine-grained arenite, 44°24'41"N, 9°13'23"E. (e) Outcrop of Zonati Shale Fm. consisting of fine and very fine-grained sandstone, that grade up to siltstone and shale, 44°27'40"N, 9°20'6"E. (f) Field occurrence of the Monte Gottero Fm. characterized by thick to very thick beds of coarse-grained sandstone grading upwards to thin beds of siltstone and shale, 44°25'20"N, 9°18'24"E. (g) A detail of a debris flow deposit intercalated within the Zonati Shale Fm. The debris flow deposit consists of a pebbly mudstone with cm-sized angular fragments of limestone from Palombini Shale and Calpionella Limestone Fms. set in a shaly matrix, 44°27'38"N, 9°20'3"E. (h) Field occurrence of the Bocco Shale Fm. In this picture a monomict pebbly mudstone derived from the Zonati Shale Fm is shown, 44°25'21"N, 44°25'21"E.

The transition from the Monte Verzi Fm. to the overlying Zonati Shale Fm. is sharp. The Zonati Shale Fm. is approximately 400 meters thick and consists of thin-bedded siliciclastic turbidites (Fig. 4e). These turbidites have layers that rarely exceed 50 cm in thickness and are characterized by fine or very fine grain size of the sandstone, that grade up to siltstone and shale. According to Marroni and Perilli (1990) the Zonati Shale Fm. is Late Campanian-Early Maastrichtian in age.

The transition to the Monte Gottero Fm. is foreshadowed by several intercalations of medium-thick beds of sandstone at the top of the Zonati Shale Fm. The Monte Gottero Fm. consists of a succession of siliciclastic turbidites up to 1,000 meters thick, consisting of thick to very thick beds of coarse-grained sandstone and thin beds of siltstone and shale (Fig. 4f). The sandstone can be classified as arkoses (Fig. 5c), with a composition like that of the underlying formations. The framework contains quartz and feldspar fragments, as well as smaller amounts of granitoid rock fragments and low-grade metamorphic rocks, acid volcanics and rare carbonate fragments from the platform (oolitic and peloid grainstone). At the top of this formation both foraminifera (Passerini and Pirini, 1964) and nannofossils (Marroni and Perilli, 1990) of Early Paleocene have been found. The age of the Monte Gottero Fm. is therefore regarded as late Maastrichtian to Early Paleocene.

The Zonati Shale and Monte Gottero Fms. are considered as belonging to the same deep-water depositional system,

which encompasses a variety of facies and sub-environments, including proximal channels, unconfined proximal and distal lobes, and deposits from the confined basin plain. This system is the result of the sedimentation process in an extensive, prograding basin-floor fan. It records the transition from a relatively unconfined setting to a progressively more confined basin (Fonnesu and Felletti, 2019). This evolution has been regarded by Nilsen and Abbate (1983) as indicative of an origin of these deposits in a subduction-related trench.

An important characteristic of the Zonati Shale and the Monte Gottero Fms. is the occurrence of mass transport deposits, which, in some areas, have a volume equivalent to that of siliciclastic turbidites. These deposits can be classified into two types, which are both recognized at different levels within the Zonati Shale and the Monte Gottero Fms. The first type consists of varicolored, Mn-rich shales that have been affected by syn-sedimentary deformation, which indicates that they were deposited as mudflows. The second type consists of pebbly mudstone containing mm to m-sized limestone clasts derived from the Calpionella Limestone and Palombini Shale Fms., set in a shaly matrix (Fig. 4g). These features suggest that these deposits originated from debris flows. Both mud-flow and debris flow deposits are interpreted as supplied by the frontal part of an accretionary wedge by several events of landslides triggered by a frontal erosion event at the prism base (Marroni and Pandolfi, 2001; Meneghini et al., 2020; Sanità et al., 2025). These deposits are regarded as the precursor of the topmost formation of the Gottero Unit, i.e., the

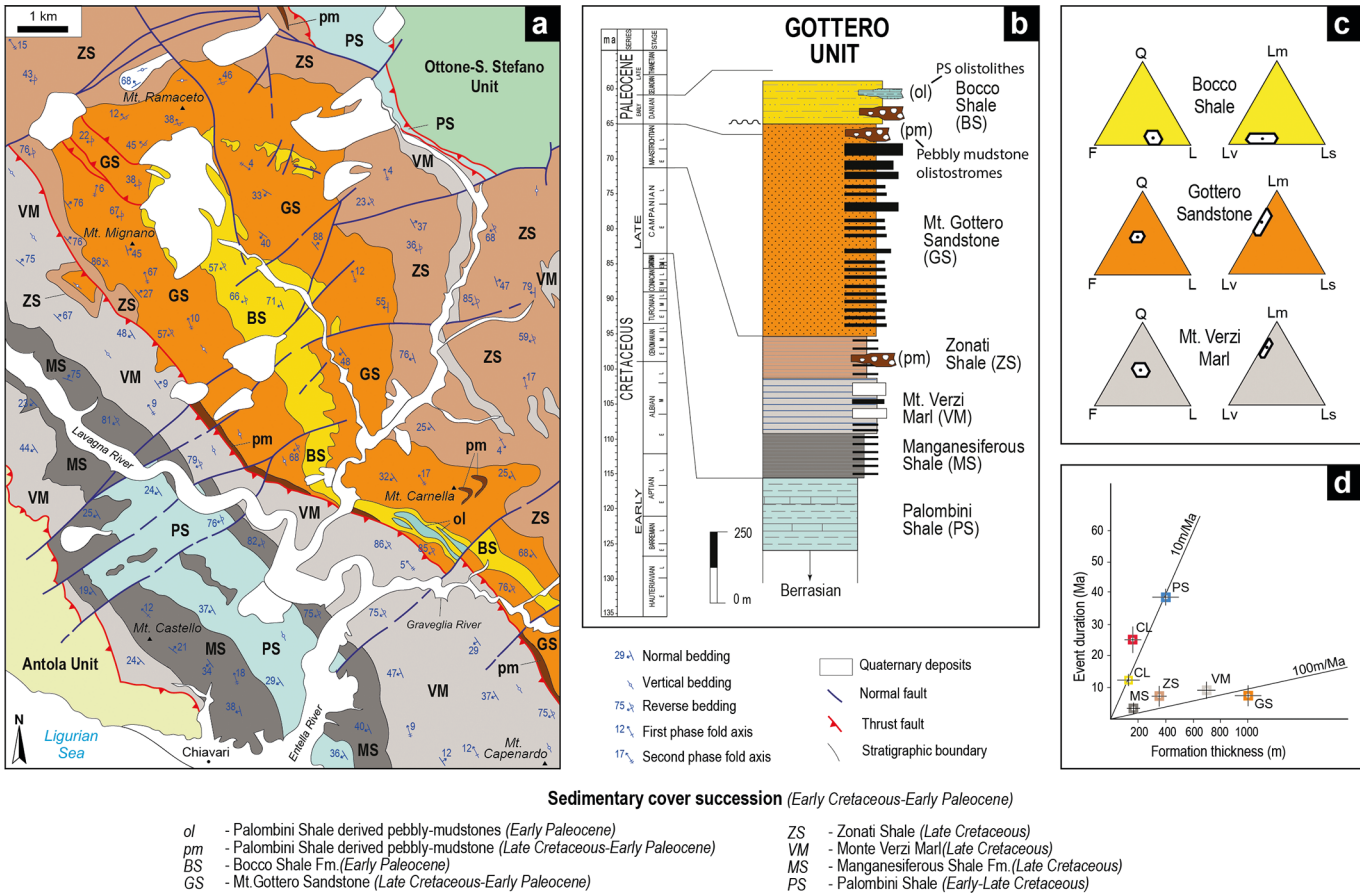


Fig. 5 - (a) Geological map of the southern area of the Lavagna Valley. (b) A stratigraphic columnar section of the Gottero Unit in the the Lavagna Valley. (c) Ternary diagrams of the arenite composition in the Monte Verzi, Monte Gottero and Bocco Shale Fms. (d) Diagram showing the different sedimentation rates for lithified sections calculated for all the formations of the ophiolite sedimentary cover from the Internal Ligurian Units

Bocco Shale Fm. also known as Giaiette shales or Colli-Tavarone Fm. (Decandia and Elter, 1972; Pertusati, 1972; Marroni and Meccheri, 1992). This formation comprises an assemblage of lenticular bodies of varicoloured shales and pebbly mudstones (Fig. 4h), interspersed with siliciclastic turbidites (Meneghini et al., 2020; Sanità et al., 2025). The turbidites consist of thin to medium beds of fine- and very fine-grained sandstone, siltstone, and dark shale. The sandstone can be classified as arkose, like those found in the Zonati Shale and the Monte Gottero Formation. The varicoloured shales and siliciclastic turbidites make up most of the sediment, while the pebbly mudstones are less voluminous. Polymictic pebbly mudstone where clasts of limestone are associated with clasts of ophiolite can also be found in the Bocco Shale Fm. Additionally, slide blocks of Palombini Shale, Zonati Shale and Monte Gottero Fms. have been mapped (Marroni et al., 1988). The relationships of the Bocco shale Fm. with the underlying formations are marked by an angular unconformity which has been identified in several sections of the Lavagna Valley (Pertusati, 1972; Pandolfi, 1997; Fonnesu and Felletti, 2019). The Bocco Shale Fm. can be up to 300 meters thick. Its age, as determined by foraminifera and nannofossils, is Early Paleocene (Passerini and Pirini, 1964; Marroni and Perilli, 1990).

Sedimentation history

Overall, the Zonati Shale, Gottero Sandstone and Bocco Shale Fms. can be considered trench deposits. They originated in a confined, tectonic-controlled basin where siliciclastic turbidites from the European continental shelf interacted with mass gravity deposits from the accretionary wedge during the Maastrichtian-Paleocene period.

DESCRIPTION OF OPHIOLITE SEDIMENTARY COVER IN SELECTED AREAS FROM ALPINE CORSICA

On Corsica Island, remnants of the oceanic crust of the LPO are preserved within the Alpine Corsica domain (Fig. 1b). This domain is thrust over the Hercynian Corsica, a domain only locally affected by Alpine deformation. The Alpine Corsica domain consists of three stacked tectonic units that crop out on the north-western side of the island. The lowermost stack comprises the Lower Units, which consist of slices of the thinned Europe continental margin that were involved in subduction during the Early Cenozoic (Bezert and Caby, 1988; Egal and Caron, 1988; Di Rosa et al., 2023). These units consist of a pre-Carboniferous basement intruded by Late Carboniferous-Early Permian granitoid. Both are unconformably topped by Permian metavolcanics and by two metasedimentary cycles of Mesozoic and Cenozoic age, each bounded by angular unconformities (Bezert and Caby 1988; Malasoma and Marroni, 2007; Maggi et al., 2012; Frassi et al., 2023). The Lower Units are capped by the Schistes Lustrés Complex, a stack of oceanic and continental units derived from the LPO and its transition to the European continental margin. The oceanic units are represented by metaophiolites and metasediments, both deformed during underthrusting in an east-dipping subduction zone and affected by a metamorphism developed at P-T conditions pertaining to blueschist and eclogite metamorphic facies (Caron and Péquignot, 1986; Caron, 1994; Lahondère and Guerrot, 1997; Vitale Brovarone and Herwatz, 2013). By contrast, continental units are represented by slices of the upper continental crust, primarily metagranitoids, with rare remnants of their sedimen-

tary cover (Vitale Brovarone et al., 2011; Meresse et al., 2012). Also, the continental slices are deformed and affected by HP metamorphism ranging from blueschist to eclogite facies (Lahondère, 1988). The Schistes Lustrés Complex is in turn topped by the Upper Units made up of weakly metamorphosed oceanic fragments characterized by Middle to Upper Jurassic ophiolite sequence and its Upper Jurassic-Upper Cretaceous sedimentary cover (Durand-Delga et al., 1997; Marroni and Pandolfi, 2003; Pandolfi et al., 2016).

The Balagne Nappe in the Balagne area

In the Upper Units of Alpine Corsica, the Balagne Nappe (Fig. 6a) consists of ophiolites and related sedimentary cover, which are well exposed in the Balagne area (Nardi et al., 1978; Rossi et al., 2001; Marroni and Pandolfi, 2003; Rossi et al., 2009). The Balagne Nappe consists of three tectonic units, the Toccone, Alturaja and Navaccia Units. The Navaccia Unit is in turn subdivided into different subunits by Marroni and Pandolfi (2003). In addition, Pandolfi et al. (2016) state that the Bas-Ostriconi Unit should be included within the Balagne Nappe. The Balagne Nappe underwent deformation during a polyphase history comprising three phases. The D₁ phase is characterized by non-cylindrical, tight to isoclinal folds that formed under prehnite-pumpellyite facies conditions (Di Rosa et al., 2025). At the map scale, the west verging D₁ folds expose ophiolites at their cores. The subsequent D₂ and D₃ phases developed during the exhumation of the Balagne Nappe.

Ophiolite sequence

A synthetic log of the ophiolite sequence and its sedimentary cover has been reconstructed by combining information from the various units and sub-units of the Balagne Nappe (Fig. 6b). The ophiolite sequence comprises a basement of mantle peridotite and gabbro, which is covered by a thin layer of ophiolitic breccia topped in turn by a thick level of pillow-lava basalt. The geochemistry of the basalt indicates that it was emplaced during the initial stage of oceanic spreading (Venturelli et al., 1979; Saccani et al., 2008). This interpretation is supported by the intercalation of siltstone and fine-grained arenite within the pillow lava sequence (Fig. 6, Piana di Castifao Sandstone of Durand-Delga et al., 1997; Rossi et al., 2009). The arenite contains fragments of micaschist, rhyolite, basalt, and Jurassic limestone, as well as zircons originating from the calc-alkaline granitoid of Hercynian Corsica.

The pillow-lava basalt is characterized by a transition from a level of pillow breccia to sedimentary cover consisting of Chert, Calpionella Limestone and San Martino Fms. However, a polymictic conglomerate occurs between the pillow-lava basalt and the Chert Fm. The conglomerate consists of pebbles, up to 1 meter large, of granitoids, acidic volcanic rocks, metamorphic pebbles, and carbonate platform derived limestone. Furthermore, soft clasts of red chert and siliceous shale can be found amongst the pebbles. The Chert Fm. consists of a sequence of thin and very thin layers of siliceous mudstone and radiolarite, with thin layers of limestone and marlstone intercalated at its top. The Chert Fm. is approximately 20 meters thick and ranges in age from the Middle-Late Callovian to the Early Kimmeridgian (De Wever et al., 1987).

Pre-convergence pelagic deposits

A 10-metre-thick sequence of alternating layers of siliceous mudstone and limestone ranging in age from late Kimmeridgian to Tithonian marks the gradual transition to the

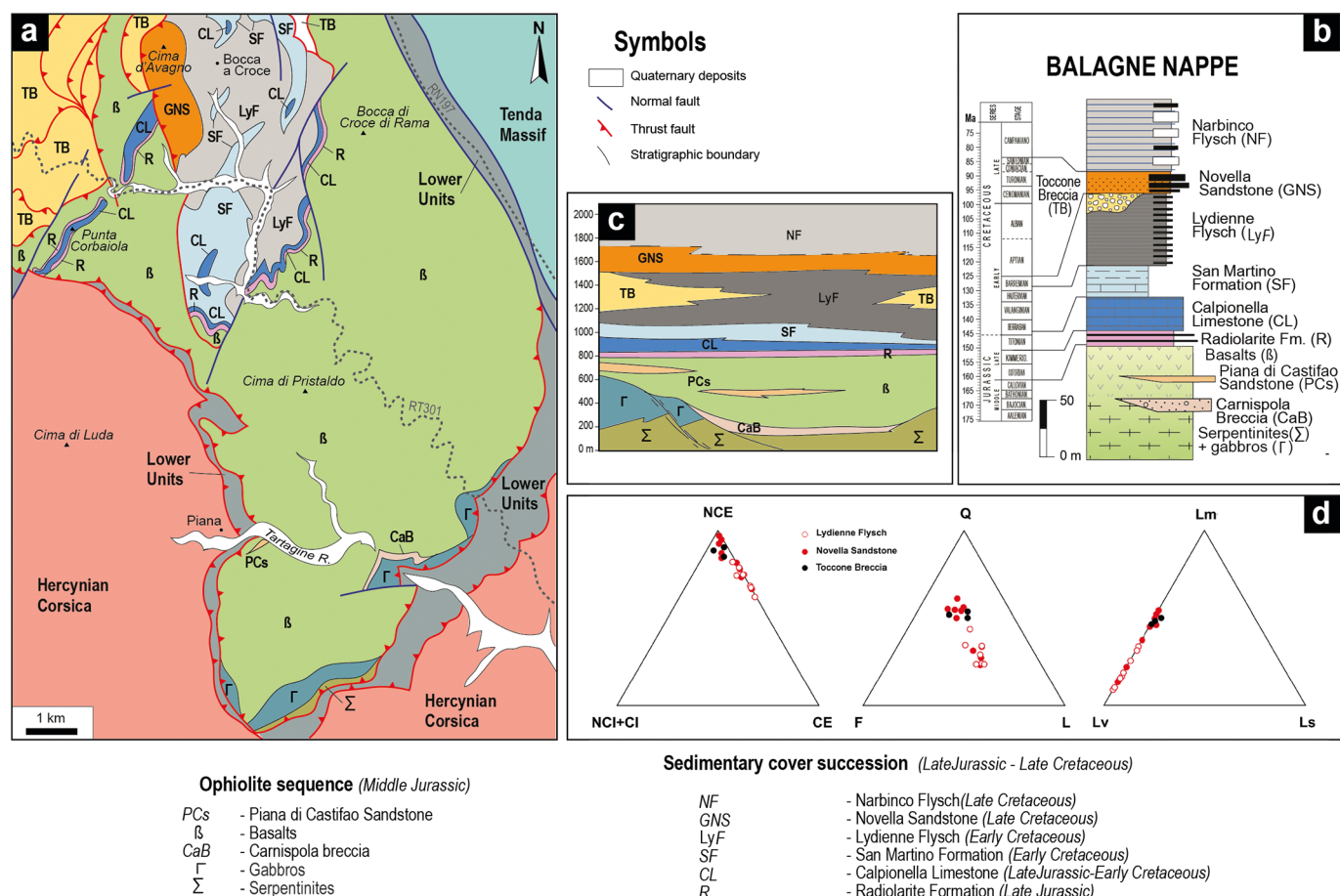


Fig. 6 - (a) Geological map of the southern area of the Balagne area (modified from Rossi et al., 2001). (b) A reconstructed stratigraphic columnar section of the Balagne Nappe in the Balagne area. (c) Alongside a reconstruction of the relationships between the ophiolites and the sediments. (d) The ternary diagrams of the arenite composition in the Lydienne Flysch, Novella Sandstone and Narbinco Flysch.

Calpionella Limestone Fm. (Fig. 7a). This formation, which is Tithonian-Early Berriasian in age (Marroni et al., 2000), consists of medium to thick layers of limestone and marlstone characterized by coarse-grained bases where continental-derived fragments of rhyolite, granitoid, micaschist and amphibolite have been found (Pybernés et al., 2001). The Calpionella Limestone Fm. grades upwards into the San Martino Fm. This formation ranges in age from the Early Berriasian to the Early Barremian (Marroni et al., 2000) and is characterized by a succession of thin to medium layers of CaCO_3 -free shale, which alternate with carbonate turbidite (Fig. 7b). The carbonate turbidite consists of medium-sized limestone beds, sometimes with a coarse-grained arenitic base. The San Martino Fm. grades up to the Lydienne Flysch Fm. that consists of thin-bedded turbidite ranging from medium-grained arenite and siltstone interbedded with lenticular coarse-grained beds showing a mixed siliciclastic-carbonate composition (Fig. 7c). The Lydienne Flysch Fm. is Late Hauterivian/Early Barremian to early Turonian in age (Marino et al., 1995; Marroni et al., 2000). The arenite from the San Martino and Lydienne Flysch Fms. can be classified as arkose, and their composition suggests a source on the European continental margin. Overall, the San Martino and Lydienne flysch Fms. can be correlated with the Palombini Shale Fm. of the Northern Apennines (Marroni and Pandolfi, 2003). In the Toccone Unit, the Lydienne Flysch Fm. is heteropic to the Toccone Breccia Fm. that consists of thick, generally amalgamated

beds of polymictic breccia (Fig. 7d) showing the same composition of the arenite of Lydienne Flysch Fm.

Syn-convergence deposits

The Lydienne Flysch Fm. is overlain by the Novella Sandstone Fm., which is made up of thick to very thick beds of sandstone that are generally amalgamated or separated by thin levels of shale. The age of the Novella Sandstone Formation is still undetermined. The few nannofossils identified in this formation suggest an age no older than the Late Cenomanian stage (Marino et al., 1995). According to Pandolfi et al. (2016), the Narbinco Flysch Fm., which occurs in a separate tectonic unit, represents the youngest deposit belonging to the ophiolite sedimentary cover. This Campanian formation (Marino et al., 1995) consists of medium to thick beds of carbonate turbidite made up of fine-grained rudite and medium- to coarse-grained arenite, which are capped by thick marlstone or calcareous marlstone. Rossi et al. (2009) have reported intercalations of polymictic conglomerate, known as Cima Lo Caigo Conglomerate (Pandolfi et al., 2016), at the base of the Narbinco Flysch Formation. The arenite and conglomerate have the same composition as the Lydienne Flysch, Toccone Breccia, and Novella Sandstone Fms.

Sedimentation history

The most impressive feature of the Balagne Nappe succession is then the occurrence of terrigenous debris interbed-

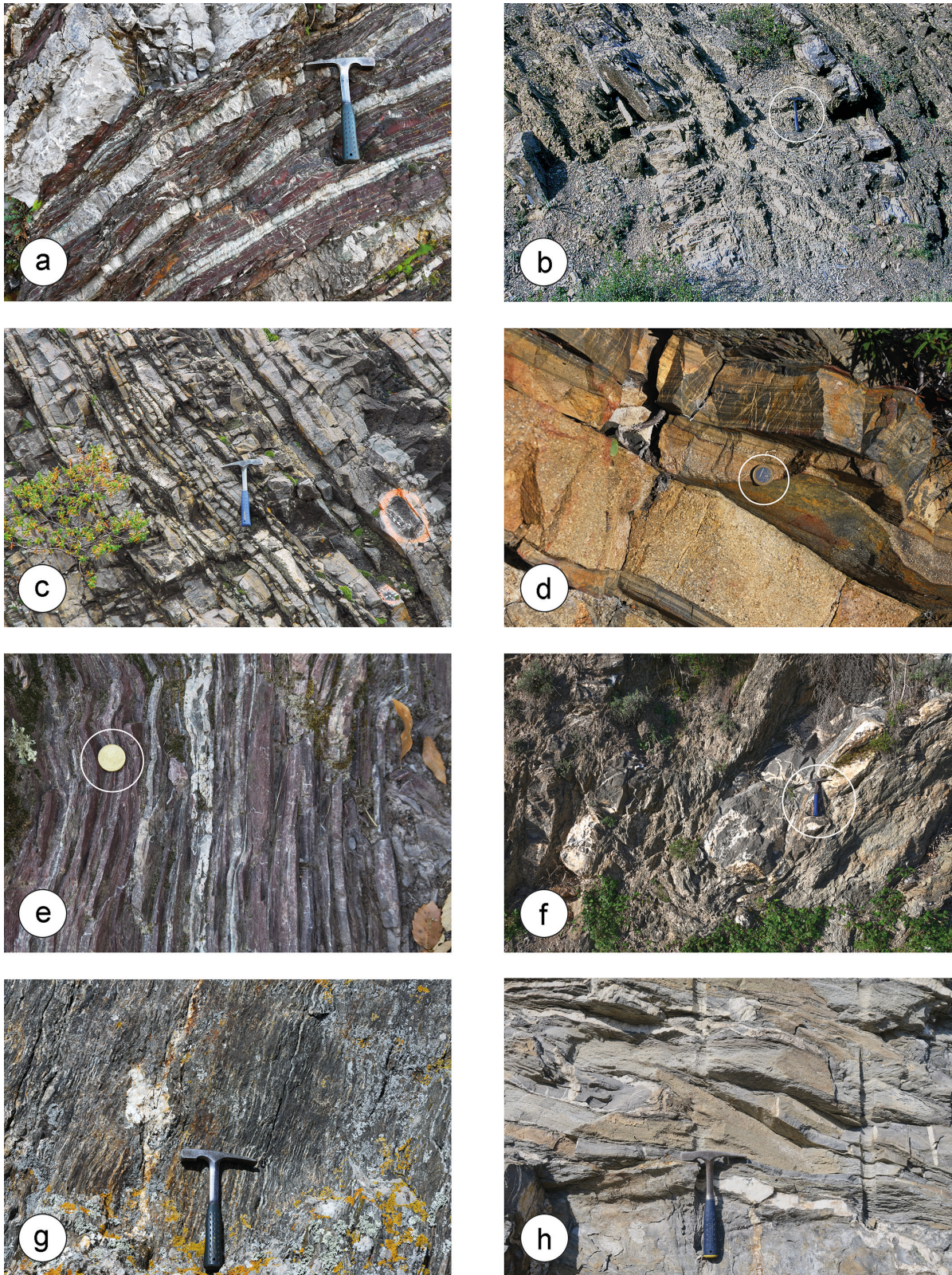


Fig. 7 - Field images of the different lithologies of the ophiolite sedimentary cover from Balagne Nappe and Inzecca Unit. (a) A detail of the transition between the Radiolarite and Calpionella Limestone Fms. characterized by alternating beds of radiolarite and limestone, 42°34'47"N, 9°4'38"E. (b) Outcrop of the San Martino Fm. showing a typical alternance of beds of CaCO_3 -free siliceous shale and beds of limestone, 42°34'7"N, 9°7'21"E. (c) Outcrop of Lydienne Flysch Fm. consisting of thin-bedded beds of medium-grained arenite and siltstone, 42°33'49"N, 9°7'23"E. (d) Field occurrence of the Toccone Breccia Fm. close to the transition to the Lydienne Flysch Fm. This transition is represented by thick to very thick beds of polymictic microbreccia and thin beds of shales, 42°33'59"N, 9°14'55"E. (e) The typical appearance of metaradiolarite, consisting of thin beds of metachert and siliceous shale, 42°10'10"N, 9°14'38"E. (f) Outcrop of the Erbasolo Fm. where a boudinaged layers of fine-grained marble are interspersed in the schist, 42°15'54"N, 9°11'35"E. (g) A detail of the Petraggiolo Fm. showing the foliated, very thin layers of fine-grained quartzite alternating with layers of black shale, 42°13'29"N, 9°11'41"E. (h) Field occurrence of the Bagliacone Fm. In this picture the Bagliacone Fm. is represented by strongly deformed medium- to fine-grained metasandstone and very thin layers of shale, 42°13'30"N, 9°12'16"E.

ded throughout the stratigraphic column (Fig. 6c), from the Jurassic basalt (Rossi et al., 2009) to the Narbinco Flysch Fm. (Pandolfi et al., 2016). This feature indicate that the ophiolite sequence and its sedimentary cover preserved in the Balagne Nappe was located close to the European continental margin (Durand Delga, 1984; Marroni and Pandolfi, 2003; Rossi et al., 2009; Pandolfi et al., 2016).

The Inzecca Unit in the Tavignano Valley

The Inzecca Unit, which belongs to Schistes Lustrés Complex, is well exposed in the Tavignano Valley (Fig. 8a), about 2 km south of Corte. This unit represents a fragment of the LPO that has been strongly deformed and metamorphosed under blueschist facies P-T conditions (Caron, 1977; Garfagnoli et al., 2009; De Cesari et al., 2025). This fragment includes an ophiolite sequence and its sedimentary cover (Fig. 8b), both of which are still well preserved despite having undergone high-pressure metamorphism (Amaudric du Chafaut et al., 1972). The deformation history of the Inzecca Unit has been outlined by De Cesari et al. (2025). According to these authors, the deformation history includes four phases, from D₁ to D₄ phases. The D₁ phase and the associated HP metamorphic imprint (Fig. 8c) emerged during the coherent underplating of the Inzecca Unit into the Alpine accretionary wedge (De Cesari et al., 2025). The subsequent D₂, D₃ and D₄ phases are related to the progressive exhumation of the Inzecca Unit under decreasing P conditions.

While the lithostratigraphy of the ophiolite sequence has been well studied (Ohnenstetter, 1979; Padoa, 1999; Guelfi et al., 2025), less attention has been devoted to the sedimentary cover, until the recent work by De Cesari et al. (2025), where the setting of the sedimentary cover has been fully redefined.

Ophiolite sequence

The proposed reconstructions for the Inzecca Unit (Fig. 8b) suggest that the ophiolite sequence comprised a basement of mantle peridotite, which were likely intruded by small metagabbro bodies (e.g., Guelfi et al., 2025). This basement was locally exposed on the seafloor, as evidenced by the presence of opihalcite. The opihalcite was partly covered by ophiolite-bearing breccia, which were in turn covered by a sequence of massive, pillow-lava, and pillow-breccia metabasalt. This sequence was finally intruded by plagiogranite of Late Jurassic age (Ohnenstetter et al., 1981; Li et al., 2015; Guelfi et al., 2025). The basalt is topped by a thin, discontinuous layer of radiolarite, consisting of thin beds of chert and siliceous shale (Fig. 7e).

Pre-convergence pelagic deposits

The metaradiolarite grades upwards into the Erbajolo Fm., which is correlated with the Palombini Shale Fm. of the Internal Ligurian Apennines (Caron, 1977; Durand Delga, 1984; De Cesari et al., 2025). There is no evidence of a level corresponding to the Calpionella Limestone Fm. between the metaradiolarite and the Erbajolo Fm.

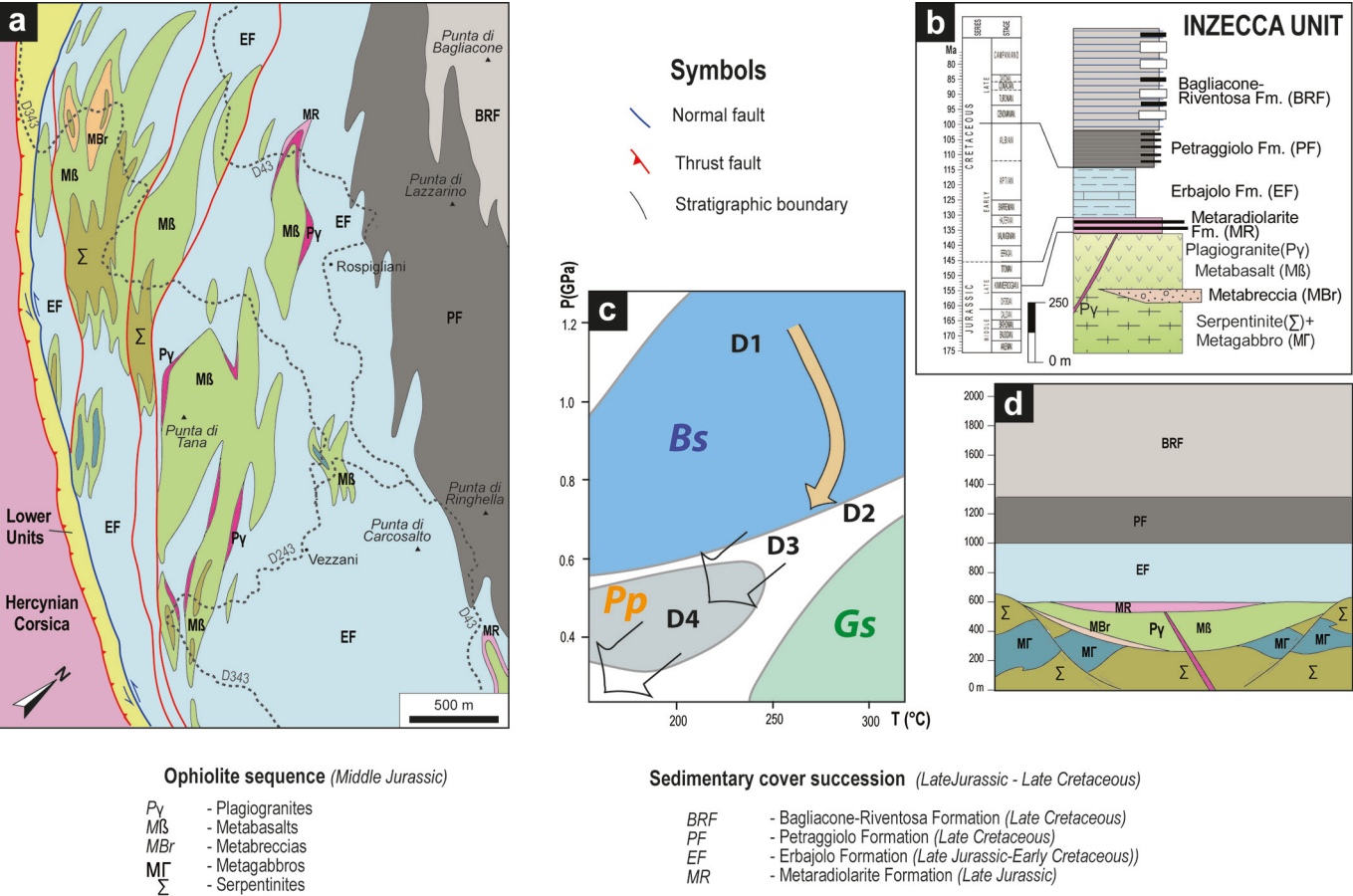


Fig. 8 - (a) Geological map of the Inzecca Unit in the Tavignano Valley, south of Venaco Village (modified from Guelfi et al., 2026). (b) A reconstructed stratigraphic columnar section of the Inzecca Unit in the Tavignano Valley. (c) P-T path of the Inzecca Unit (modified from Guelfi et al., 2026) and, below, the reconstruction of the relationships between the ophiolite sequence and its sedimentary cover.

The Erbasolo Fm. (Fig. 7f) consists of thick layers of schist alternating with strongly boudinaged, thin to medium layers of fine-grained marble (Caron, 1977; Amaudric du Chaffaut et al., 1972; De Cesari et al., 2025). The formation is about 400 m thick. The presence of rare sedimentary structures such as graded bedding and laminations indicates that the protoliths of the marble are carbonate turbidites. No fossils have been found in this formation, but Caron (1977) and Durand-Delga (1984) inferred an Early Cretaceous age.

Syn-convergence deposits

According to De Cesari et al. (2025), the Erbasolo Formation is overlain by the Petraggiolo Formation, which is about 300 meters thick and consists of thin layers of fine-grained quartzite alternating with thick layers of black shale (Fig. 7g). Graded bedding is rarely evident in fine-grained quartzites. In this section, the fine-grained quartzite mainly consists of quartz, with minor fragments of plagioclase and K-feldspar. There are also minor fragments of phyllosilicates, whereas no lithic or ophiolite fragments are present. According to Amaudric du Chaffaut et al. (1972), the transition from the Erbasolo Fm. to the Petraggiolo Fm. occurs through a 150-200 m thick level, in which the layers of marble progressively disappear, being substituted by layers of fine-grained quartzites.

The Petraggiolo Fm. shows a gradual transition to the Bagliaccone-Riventosa Fm. (Amaudric du Chaffaut et al., 1972; De Cesari et al., 2025). This transition occurs within a 100-150 meters thick interval, where the layers of black shale become thinner and the fine-grained quartzites are progressively replaced by metasandstone. This Bagliaccone-Riventosa Fm. is represented by a succession, 700-800 m thick, of medium- to fine-grained metasandstone alternating with very thin layers of shale (Fig. 7h). In the metasandstone, the only relic of the sedimentary structures is the graded bedding, which is clearly visible in several outcrops. This finding suggests that the metasandstone can be interpreted as turbidites. Where the layers are thicker, the metasandstone exhibits a coarse-grained base consisting of millimeter- to centimeter-sized fragments of magmatic, metamorphic, and sedimentary rocks, with the latter prevailing. In thin section, the metasandstone is characterized mainly by the widespread presence of mono- and polycrystalline quartz, plagioclase, and K-feldspar. Lithic fragments include acidic volcanic rocks such as rhyolites and dacites, but granitoids, carbonate and dolostone rocks are also common. Ophiolite-derived fragments are never observed. The protoliths of the metasandstone were probably an arenite with sublitharenite and subarkose compositions. Unfortunately, strong metamorphic recrystallisation has prevented any fossil preservation. De Cesari et al. (2025) have proposed a Late Cretaceous age for both the Petraggiolo and Bagliaccone-Riventosa Fms.

Sedimentation history

Overall, the sedimentary cover of the Inzecca Unit is one of the few examples where a thick sequence of siliciclastic and mixed turbidites is preserved above the basin plain deposits of the metaradiolarite and the Erbasolo Fm.

DESCRIPTION OF OPHIOLITE SEDIMENTARY COVER IN SELECTED AREAS FROM WESTERN ALPS

The Western Alpine Ophiolites, preserved as remnants of the LPO stacked within the axial sector of the Alpine belt

(Fig. 1a; Dal Piaz et al., 2003; Schmid et al., 2004), consist of several tectonic units interposed between continental-margin units, derived from both the European and Adriatic plates (Rosenbaum and Lister, 2005; Handy et al., 2010). These ophiolites were subducted to depths of up to 100 km and metamorphosed under high- to ultrahigh-pressure conditions during the Late Paleocene-Middle Eocene (Agard, 2021, and references therein). The Western Alpine Ophiolites (i.e., the Piedmont Zone; Martin et al., 1994), have traditionally been divided into Zermatt-Saas and Combin-type units (Bearth, 1967). The Zermatt-Saas type units (i) crop out in the inner part of the axial belt (i.e., the Internal Piedmont Zone), (ii) experienced eclogite-facies P-T peak conditions, and (iii) consist of meta-ophiolite overlain by a thin oceanic metasedimentary cover (Balestro et al., 2019; Herviou et al., 2022). In contrast, the Combin-type units (i) crop out in the external part of the axial belt (i.e., the External Piedmont Zone), (ii) record predominantly blueschist-facies peak P-T conditions, and (iii) consist of oceanic metasediments embedding meta-ophiolite bodies (Tricart and Lemoine, 1991; Agard et al., 2001; Lagabriele et al., 2015).

To describe the oceanic metasedimentary cover, three different areas have been selected from the Zermatt-Saas-type, Monviso and St. Marcel Valley metaophiolite complexes, and from the Combin-type Queyras Schistes Lustrés complex.

The Monviso Ophiolite between the Po and Pellice valleys

The Monviso ophiolite represents a major remnant of the LPO (Fig. 1a, 9a). It extends for about 35 km from North to South in the Cottian Alps (Rolfo et al., 2015) and consists of a meta-ophiolite succession with minor metasedimentary units (Lombardo et al., 1978). The Monviso ophiolite is tectonically juxtaposed against the Dora-Maira continental margin unit and is, in turn, overlain by the Queyras Schistes Lustrés Complex (Ballèvre et al. 1990; Philippot, 1990; Lardeaux et al., 2006; Balestro et al., 2022). It records quartz-eclogite to coesite-eclogite-facies peak P-T conditions (Schwartz et al., 2000; Groppo and Castelli, 2010; Angiboust et al., 2012; Balestro et al., 2014; Ghignone et al., 2023), and its present-day structural architecture reflects three major tectonic stages (i.e., D₁, D₂ and D₃; Balestro et al., 2018). D₁ deformation was characterized by stretching and shearing during Paleocene - Middle Eocene subduction. The Late Eocene-Early Oligocene D₂ event produced W-verging accretion through non-cylindrical folding associated with shearing (Balestro et al., 2013; Angiboust and Glodny, 2020). Finally, Late Oligocene - Neogene D₃ deformation resulted in extensional westward tilting of the Monviso ophiolite (Tricart et al., 2004; Balestro et al., 2015b).

The Monviso ophiolite is dissected by a major shear zone, which separates serpentinite with metagabbro bodies in the footwall from metabasalt and metasedimentary rocks in the hanging wall (Fig. 9a). This structure, which records a polyphasic evolution from the pre-orogenic stage to the subduction, collisional, and exhumational stages (see Balestro et al., 2015b, 2018), also preserves remnants of a fossil intraoceanic detachment fault (i.e., the Baracun Shear Zone) related to Late Jurassic oceanic core complex (Festa et al., 2015).

Ophiolite sequence

The metagabbro, dated to the Middle Jurassic (Rubatto and Hermann, 2003), locally hosts Late Jurassic metaplagiogranite dykes (Lombardo et al., 2002). The metabasalt

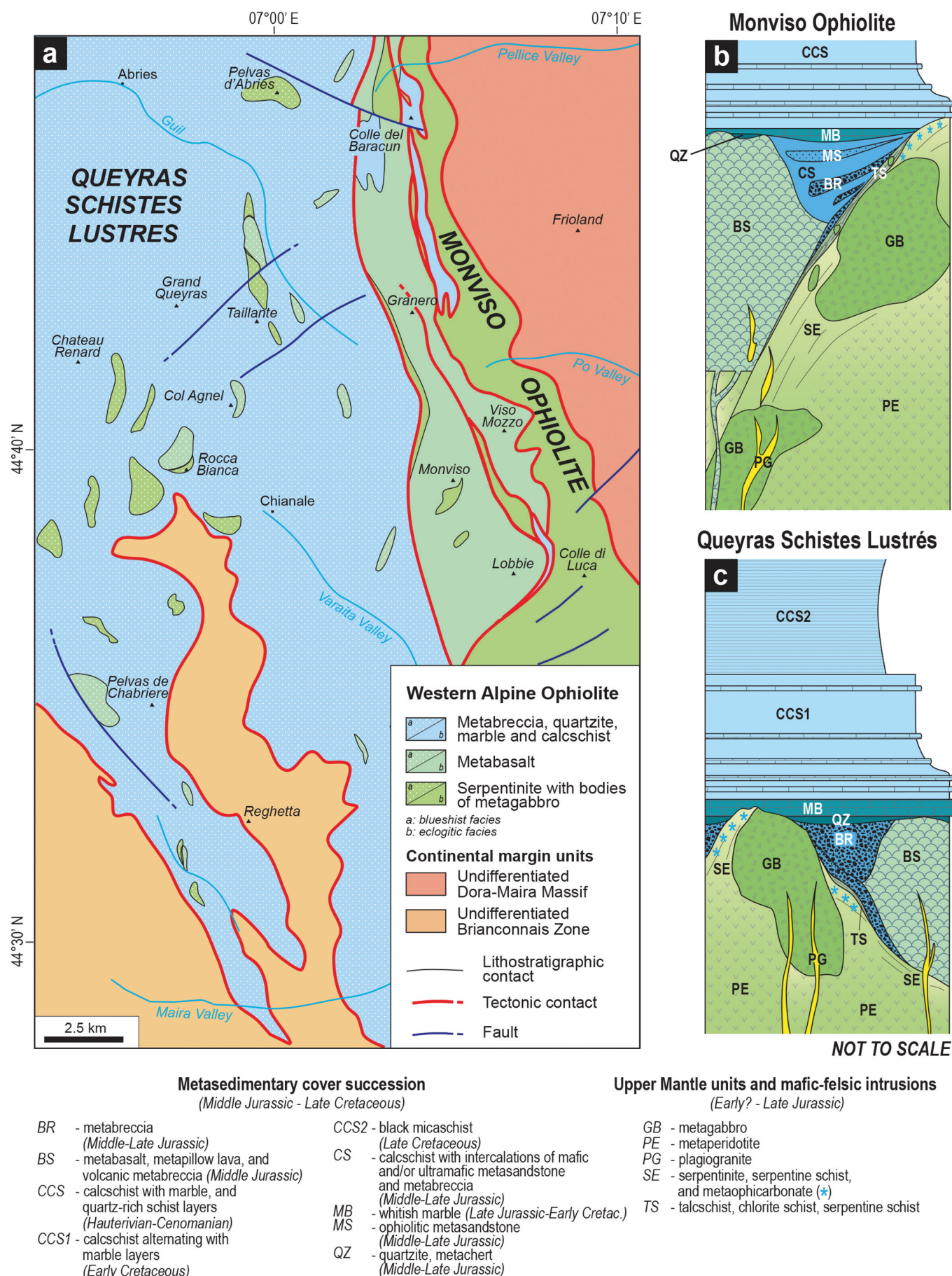


Fig. 9 - (a) Geological map of the study area in the Western Alps, showing the tectonic relationships between the Monviso ophiolite, the Queyras Schistes Lustrés, and the continental margin units of Europe (modified from Kerckhove et al., 1979; Balestro et al., 2011, 2013, 2019). Stratigraphic columnar section of (b) the Monviso ophiolite and (c) the Queyras Schistes Lustrés in the Upper Maira Valley (modified from Balestro et al., 2019), depicting the lateral and vertical relations between the metasedimentary ophiolite cover succession and the exhumed upper mantle rocks.

preserves relics of pillow lava and breccia textures, and locally shows lateral contacts with metasandstone and metabreccia containing gabbroic clasts (Balestro et al., 2015b).

Metasedimentary rocks covering the meta-ophiolite succession are relatively more abundant in the central-northern sector of the Monviso ophiolite, between the Po and Pellice valleys (Lagabriele, 1994; Balestro et al., 2011). They consist of quartzite, marble, and calcschist (Fig. 9b). The quartzite is up to one metre in thickness and forms a discontinuous horizon, stratigraphically overlying the metabasalt (Fig. 10a) and, locally, serpentinitized mantle rocks. It is whitish to greenish grey in colour, fine-grained, and mainly composed of quartz, white mica of phengite composition and garnet, with subordinate epidote, chlorite, amphibole and ankerite. The quartzite is correlated with the Monte Alpe Chert Fm. of the Internal Ligurian Units, although the original siliceous sediments appear to have been much thinner in the Monviso ophiolite, likely or at least in part due to tectonic stretching.

Pre-convergence pelagic deposits

Up-section, the metasedimentary cover continues with white marble, which may overlie the quartzite (Fig. 10b) or rest directly on the metabasalt quartzite (Fig. 9b). This carbonate-rich rock is discontinuous and has a thickness similar to that of the quartzite. It is whitish, fine-grained, and composed primarily of calcite, with minor white-mica, dolomite, quartz, and chlorite. The marble derives from thin limestone layers interpretable as equivalents of the Late Tithonian - Early Valanginian Calpionella Limestone Fm. of the Internal Ligurian Units.

The succession is capped by calcschist, up to several tens of meters thick, overlying the marble (Fig. 10b) or resting directly on the meta-ophiolite where marble or quartzite are absent (Fig. 9b). The calcschist shows alternating carbonate-rich and carbonate-poor layers (Fig. 10c), locally interbedded with quartz-schist layers that are up to several centimetres thick, suggesting turbidite sedimentation in a basin plain setting above oceanic crust. Carbonate minerals are dominated by calcite, with minor dolomite and ankerite. The mineral assemblage also includes quartz, white mica and chlorite, with local occurrence of epidote, chloritoid, and garnet. Locally (i.e., Colle del Baracun), the calcschist directly overlies the meta-ophiolite and shows a reduced thickness of about 20 metres. In this area, sub-millimetric aggregates of calcite and Fe-oxides preserve outlines resembling planktonic foraminiferal sections (Tartarotti et al., 2021), comparable to other occurrences reported from the Western Alps (Lemoine et al., 1984; Marthaler et al., 1986) and Corsica (Meresse et al., 2012) and referred to the Albian-Cenomanian period. This evidence suggests that the calcschists were locally deposited on structural highs inherited from the Jurassic rifting stage (Festa et al., 2015; Balestro et al., 2019). Overall, the calcschist succession can be correlated with the Lower Cretaceous Palombini Shale Fm. of the Internal Ligurian Units, with foraminiferal occurrences indicating a locally extended age up to Cenomanian period.

The St. Marcel Valley Ophiolite

The St. Marcel Valley is a dextral tributary of the Aosta Valley (Figs. 1, 11a) and represents one of the best areas of the northwestern Alps where both the metaophiolite basement and its metasedimentary cover are well exposed. These are tectonically overthrust by the Mount Emilius continental unit of the Austroalpine domain (Dal Piaz et al., 2001).

Ophiolite sequence

The St. Marcel Ophiolite is comparable to the Zermatt-Saas unit. It mainly consists of eclogite-facies Fe-Ti and Mg-metagabbro, garnet-lawsonite (now pseudomorphosed)-bearing glaucophanite enclosing eclogite boudins (metabasalt), garnet-chloritoid-glaucophane-chlorite-bearing schist, and minor talcschist. Metabasalt hosts a Fe-Cu sulphide-bearing mineralization and a Mn-ore attributable to oceanic hydrothermal vents (Martin et al., 2008; Tumiati et al., 2010, 2015).

The present-day structural setting of the St. Marcel Ophiolite results from three main superposed ductile deformation events. The tectono-metamorphic framework is best preserved in the northern part of the valley, where the main foliation at the outcrop scale is defined by high-pressure minerals (glaucophane, garnet, omphacite and rutile), as in most parts of the Zermatt-Saas unit (Dal Piaz and Ernst, 1978). The eclogitic imprint recorded by this metaophiolite is of Eocene age (47-42 Ma; Dal Piaz et al., 2001; Dragovic et al., 2020) and characterized by $T = 550 \pm 60$ °C and $P = 2.1 \pm 0.3$ GPa (Martin and Tartarotti, 1989; Martin et al., 2008).

Pre-convergence pelagic deposits

The St. Marcel Valley Ophiolite is overlain by a metasedimentary succession mainly consisting of manganiferous quartzite (Fig. 10d), fine-grained impure marble, and flysch-type calcschist (Fig. 10e), comparable to the Palombini Shale Fm. of the Northern Apennines, although affected by HP metamorphic imprint (Fig. 11b). The best-preserved metasedimentary successions occur along the eastern side of the valley, on the Mount Roux-Mont de Corquet ridge (Tartarotti et al., 2017). Their thickness is highly variable due to difference in the degree of tectonic Alpine deformation. In a reconstructed stratigraphy (from bottom to top), the successions (Fig. 11b) consists of: (i) micaceous quartzites, generally lying directly on the metaophiolite basement, made of quartz, white mica, garnet, clinozoisite; (ii) impure marble composed of calcite, polycrystalline quartz, white mica, garnet, zoisite; (iii) manganiferous quartzites made of quartz, garnet, tourmaline, white mica, chlorite, piemontite, braunite; and (iv) carbonate-rich micaceous quartzites alternating with fine-grained pale-grey marble.

In the southern part of the valley, the quartzite levels are enriched in quartz-chloritoid-rich micaschist, which can reach several tens of meters in thickness.

This sequence is overlain by calcschist with a typical flysch-like appearance, consisting of siliceous marly limestone alternating with shaly beds (carbonate, polycrystalline quartz, white mica, garnet), and minor quartz-carbonate-rich micaschist and micaceous quartzite (Fig. 11b). Mafic layers or boudins may also occur within the calcschist, whose thickness may reach several tens of meters. The St. Marcel Valley Ophiolite is well known for the occurrence of Mn-rich as well as Cu-Fe sulphide-rich mineralizations showing an HP mineral assemblage. The close association of metabasalt with such mineralizations makes these metaophiolites almost unique among the eclogite-facies Alpine metaophiolite complexes.

The coexistence in the St. Marcel Valley of both a quartzite-marble-calcschist type metasedimentary succession and of Cu-Fe sulphide mineralizations and Mn-rich deposit, interpreted as palaeo-hydrothermal fields of the LPO (Martin et al., 2008; Tumiati et al., 2005; Nimis et al., 2018), suggests that the metasedimentary succession represents a pelagic sequence deposited in proximity to hydrothermal vent systems (Tartarotti et al., 2021).

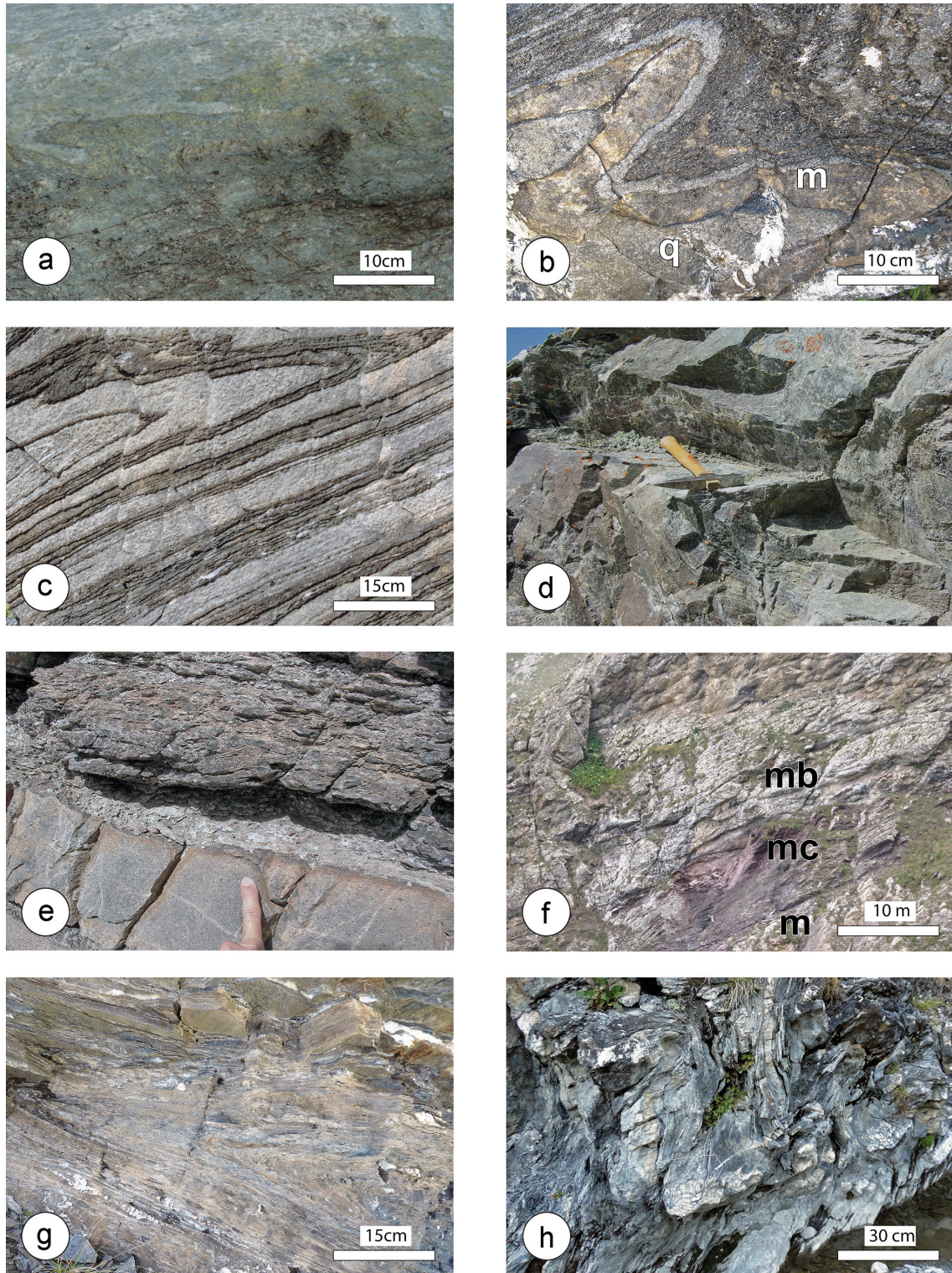


Fig. 10 - Field images of the different lithologies forming the metasedimentary cover of the Western Alpine Ophiolite. (a) Detail of a rugged primary contact between greenish basalt-derived metabasite (lower part) and whitish quartzite (upper part) (Monviso Ophiolite, Pellice river, north of Colle del Baracun, 44°47'58"N, 7°2'36"E). (b) Folded contacts between quartzite (q), yellowish marble (m) and calcschist with layers of quartz-rich schist (Monviso Ophiolite, Colle del Baracun, 44°46'25"N, 7°3'50"E). (c) Close up view of folded calcschist with alternating carbonate-rich and carbonate-poor layers (Monviso Ophiolite, Colle del Baracun, 44°46'26"N, 7°3'48"E). (d) Folded contact between manganiferous violet quartzite (lower part) and grey-green micaceous quartzite (upper part) (Zermatt-Saas ophiolite, eastern side of the St. Marcel Valley, near Mount Courquet, 45°41'09"N, 7°28'06"E). (e) Detail of calcschist with alternating impure marble (lower part) and carbonate-rich micaschist (upper part), showing cm-sized pseudomorphs replacing former lawsonite (black rectangular portions) and lesser garnet (black rounded portions) (Zermatt-Saas ophiolite, eastern side of the St. Marcel Valley, near Mount Roux, 45°41'41"N, 7°27'48"E). (f) Overtaken primary contacts between metabasalt preserving relicts of pillow textures (mb), reddish to violet metachert (mc) and whitish marble (m) (Queyras Schistes Lustrés, Mollasco Valley, Traversiera, 44°31'50"N, 6°57'9"E). (g) Detail of folded calcschist with alternating carbonate-rich and carbonate-poor layers (Queyras Schistes Lustrés, Mollasco Valley, near Traversiera, 44°31'30"N, 6°57'20"E). (h) Folded dark grey micaschist with layers of brownish siliceous metasandstone (Queyras Schistes Lustrés, Mollasco River, 44°30'57"N, 6°58'24"E).

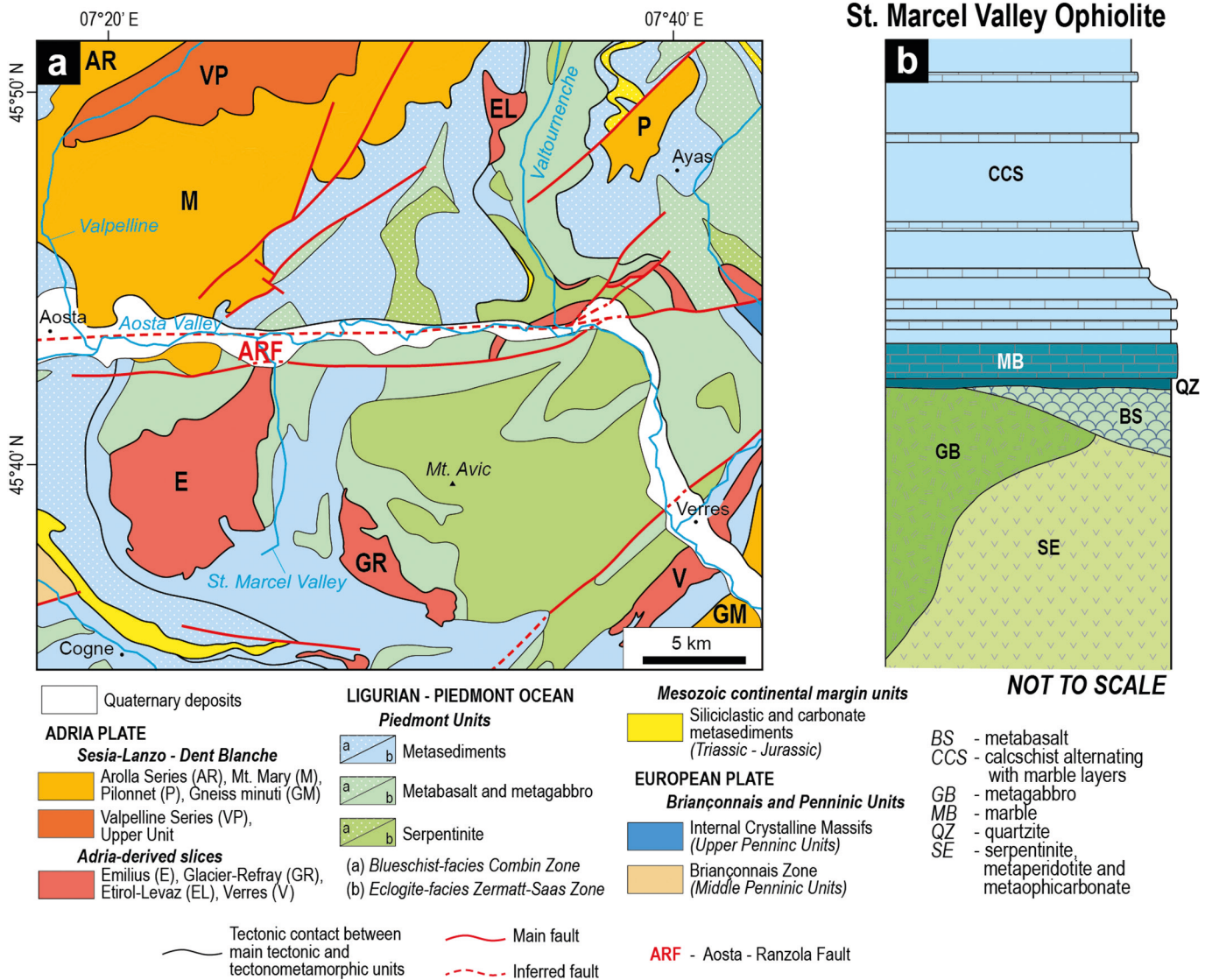


Fig. 11 - (a) Geological map of the study area in the Aosta Valley in the Western Alps, showing the tectonic relationships between the Zermatt-Saas ophiolite, the Combin Units, and the continental margin units of Europe and Adria (modified from Beltrando et al., 2014). (b and c) Stratigraphic columnar section of the St. Marcel metaophiolite (modified from Tartarotti et al., 2021), depicting the lateral and vertical relations between the metasedimentary ophiolite cover succession and the exhumed upper mantle rocks.

The Queyras Schistes Lustrés in the Upper Maira Valley

The Queyras Schistes Lustrés (Fig. 1a, 9a) form part of a complex consisting of several tectonic units whose P-T metamorphic peaks decrease structurally upward, from high-temperature ($P = 1.7\text{--}2.2$ GPa, $T = 415\text{--}475^\circ\text{C}$) to low-temperature ($P = 1.2\text{--}1.9$ GPa, $T = 320\text{--}400^\circ\text{C}$) blueschist-facies conditions (Vitale Brovarone et al., 2014; Agard, 2021; Herviou et al., 2022). The diachronous subduction of these units is recorded by metamorphic peak ages ranging from c. 40 Ma to c. 60 Ma (Agard et al., 2002; Ghignone et al., 2021; Gyomlai et al., 2023). The Queyras Schistes Lustrés were initially deformed during a subduction-related D_1 phase and subsequently involved in multistage folding and shearing of the nappe stack (i.e., D_2 to D_4 phases) (Caby, 1973; Caron et al., 1973; Tricart and Schwartz, 2006; Remitti et al., 2026). In the Cottian Alps and Queyras regions, the Schistes Lustrés tectonically overlie several units, including the Monviso Ophiolite and the Briançonnais continental-margin units (Lefèvre and Michard, 1976; Michard et al., 2004; Ballevre et al., 2020).

Ophiolite sequence

The Queyras Schistes Lustrés consists of Upper Jurassic to Cretaceous oceanic metasediments (Fig. 9a) embedding ophiolite bodies that range from a few meters to several kilometers in size (Tricart and Lemoine, 1991). Within these bodies, different portions of meta-ophiolite successions are preserved, including serpentinized metaperidotite, metagabbro, meta-ophicalcite, metabasalt and ophiolitic metabreccia (Caby et al., 1987; Tricart and Lemoine, 1983; Le Mer et al., 1986; Pinet et al., 1989). Structures interpreted as remnants of oceanic core complexes have also been documented (Lagabrielle et al., 2015). The oceanic metasediments overlying the meta-ophiolite blocks and slices are well exposed in the upper Maira Valley (Fig. 9a). The base of the metasedimentary succession consists of metaradiolarite and phylladic quartz-rich schist, which occur as discontinuous horizons a few meters thick and rest stratigraphically on both metabasalt (Fig. 10f) and mantle rocks (Fig. 9c). These siliceous metasediments are very fine grained and greenish to reddish in color, consisting of quartz with minor Fe- and Mn-oxides, white mica, and epidote. They

preserve radiolarian relics originally dated as Late Oxfordian–Early Kimmeridgian (Schaaf et al., 1985), later revised as Late Bathonian–Early Callovian (De Wever et al., 1987).

Pre-convergence pelagic deposits

In a correlation effort of these metasediments with the sedimentary cover of the Northern Apennines, the metaradiolarite and phylladic quartz-rich schist are comparable with the Monte Alpe Chert Fm., and are stratigraphically overlain by whitish marble (Fig. 10f) that can be correlated with the Calpionella Limestone Fm. (Fig. 9c). This marble unit is up to several meters thick, fine to medium grained, and composed mainly of calcite, with minor ankerite, quartz, white mica, and oxides.

Up-section, the succession continues with several hundred meters of carbonate rich-calcschist (i.e., Replatte Fm. of Lemoine, 1971), characterized by interlayered carbonate-poor beds (Fig. 10g). The calcschist is brownish grey in colour and fine grained, and consists of calcite, quartz, white mica of phengite composition, and graphite. The mineral assemblage may locally include lawsonite and carpholite (Goffè and Chopin, 1986). This calcschist can be correlated with the Palombini Shale Fm. of the Northern Apennines and is interpreted as deriving from Lower (to Upper?) Cretaceous carbonate turbidites and hemipelagic deposits.

Syn-convergence deposits

The oceanic metasedimentary cover is capped by up to a few tens of meters of micaschist (Fig. 9c; i.e., Roche Noire Fm.; Tricart, 1973). This unit is typically blackish in colour, very fine grained, and locally interlayered with several centimetre thick beds of brownish siliceous metasandstone (Fig. 10h). The micaschist consists of quartz, white mica, chlorite, graphite, and albite, and is commonly cut by networks of quartz and calcite veins. It likely represents the metamorphic equivalent of the Late Santonian – Early Campanian Mangesiferi Shale Fm. of the Northern Apennines.

DISCUSSION

A fresh perspective on the ophiolite sedimentary cover

Comparison of data from key selected areas in the Western Alps, the Northern Apennines and Alpine Corsica (Fig. 1a,b) allows a refined subdivision of the succession of the ophiolite sedimentary cover that integrates all available lithostratigraphic constraints, including lithological, sedimentological, petrographic, and paleontological data. The oldest and lowest parts of this succession correspond to the classical trilogy of the Monte Alpe Chert, the Calpionella Limestone and the Palombini Shale Fms. (Fig. 12). This trilogy is particularly well-preserved in both low-grade and high-grade metamorphic units. Following metamorphic overprinting, the Palombini Shale Fm. commonly occurs as a thick sequence of poorly differentiated calcschist referred to by various names, ranging from the general calcschist term in many sectors of the high-grade metamorphic units of the Western Alps, to specific formational names such as the Erbajolo Fm. in Alpine Corsica (Durand-Delga, 1984) or Replatte Fm. in the low-grade metamorphic units of the Queyras Schistes Lustrés (Lemoine, 1971).

All formations of this trilogy are characterized by low sedimentation rates. These deep-sea pelagic deposits consist of hemipelagic shales interbedded with fine-grained siliciclastic and carbonate turbidites. Detrital zircon U/Pb geochronology indicates that the siliciclastic turbidites were sourced from the Africa plate margin (Jacobs et al., 2025). All units were de-

posited below the calcite compensation depth. Sedimentation spanned from the Middle Jurassic (Bajocian to Bathonian) to the Late Cretaceous (Santonian), recording a long-lasting interval of tectonic quiescence during which the LPO shows no evidence of syn-tectonic and/or spreading sedimentation. Evidence of the variable thickness and incomplete succession of first-type deposits across the studied sectors (see also Principi et al., 2004) suggests that their deposition ultimately sealed the complex, articulated tectono-stratigraphic architecture that was inherited during Jurassic rifting. This sedimentation process persisted in some areas until the lower part of the Late Cretaceous period, and effectively homogenized the physiography of the LPO (see, for example, Festa et al., 2015; Balestro et al., 2019).

This first type of deposit is abruptly replaced across the entire ocean basin in the Campanian, by high-rate sedimentation of carbonate and siliciclastic turbidites (Fig. 12). This transition appears to have occurred nearly synchronous throughout the basin (Marroni et al., 2017). These second-type deposits are mainly preserved in low-grade metamorphic units, such as the Gottero Unit, but also occur in higher-grade metamorphic units, such as the Inzecca Unit in Alpine Corsica. All the data, including the petrography of the sandstone and the detrital zircon U/Pb geochronology, indicate that these turbidites were sourced from the European continental shelf, implying a significant shift in provenance of siliciclastic turbidites between the first and second deposit types. Overall, the second-type deposits are interpreted to record the onset of eastward subduction and the related uplift of the continental shelf of the lower European plate (Marroni et al., 1992). In the Internal Ligurian Units, these deposits, which include the Mangesiferi Shale and Monte Verzi Fms., span the Early to Late Campanian (Marroni and Perilli, 1990). Many of the dark, massive schist occurring above calcschist in the high-pressure units of the Western Alps likely derived from sediments analogous to those of the Mangesiferi Shale Fm., as suggested for example for the micaschist of the Roche Noire Fm. of the Queyras Schistes Lustrés. Similarly, the metamorphic Petraggiolo and Bagliaccone Riventosa Fms. of the Inzecca Units in Alpine Corsica probably correspond to the Mangesiferi Shale and Monte Verzi Fms. of the Internal Ligurian Units in the Northern Apennines.

A third type of deposit is represented by high-rate siliciclastic turbidites intercalated with mass-transport deposits (MTDs), which locally prevail in the succession (Fig. 12). The best example occurs in the Bocca Shale Fm. of the Internal Ligurian Units. According to Meneghini et al. (2020), Festa et al. (2021) and Sanità et al. (2025), these deposits formed in a trench environment, where siliciclastic turbidites derived from the approaching European continental shelf interacted with MTDs sourced from the unstable slope of the accretionary wedge. This interpretation is supported by the presence of clasts of ophiolites and their sedimentary cover within the MTDs, whereas the siliciclastic turbidites contain no fragments of ocean-derived material. The transition from the second to the third type of deposit is broadly synchronous across the ocean basin and depends on the timing of the approach of the oceanic domain to the accretionary wedge.

In summary, we propose a new subdivision of the ophiolite sedimentary cover into three types of deposits, arranged from bottom to top: i) pre-convergence pelagic deposits, ii) syn-convergence basin-plain turbidites, and iii) trench deposits. Each type reflects a distinct geodynamic setting, ranging from pre-convergence oceanic-basin plain environments to the subduction-zone trench.

	Bracco / Val Graveglia Unit BVG	Balagne Nappe BLG	Gottero Unit GTT	Inzecca Unit INZ	Queyras Schistes Lustrès QU	St. Marcel Valley Ophiolite SMO	Monviso Ophiolite MO	
Early Paleocene			BS					Trench-Lower slope deposits
Late Cretaceous- Early Paleocene			GS					SYN-CONVERGENCE DEPOSITS BASIN- PLAIN TURBIDITES AND TRENCH DEPOSITS
Late Cretaceous			ZS					
		NF	VM	BRF				
		GNS	MS	PF	CCS2			
Early-Late Cretaceous			PS					PRE-CONVERGENCE HEMIPELAGIC DEPOSITS
		LF+TB		EF	CCS1		CCS	
	PS	SF						
Early Cretaceous	CC	CC			MB	MB	MB	Limestones and marbles
Middle-Late Jurassic	R	R		MR	QZ	QZ	QZ	Radiolarites and quartzites
Middle Jurassic	Bmz							Upper breccias
	B	B		MB	BS	BS	BS	Basalts and metabasalts
	Bca+Bcb	CaB		Mbr	BR		BR	Lower breccias
	Σ+ Γ	Σ+ Γ		GB+SE	GB+SE	GB+SE	GB+SE	Mantle and lower crust (Serpentinites and Gabbros)

Ophiolite sequences: Σ+ Γ gabbros and serpentinites, GB+SE metagabbros and serpentinites, Bca+Bcb+CaB Lower breccia, Mbr and BR Lower metabreccia, B basalts, MB+BS Metabasalts, Bmz Upper breccia, R Radiolarites Formation, MR Metaradiolarites, QZ quartzite. **Pre-convergence pelagic deposits:** CC Calpionella limestone, MB Marble, PS Palombini Shale, SF San Martino Formation, EF Erabajolo Formation, CCS Calcschist, CCS1 Calcschist and marble. **Syn-convergence deposits:** MS Manganiferous Shale, VM Monte Verzi Marl, ZS Zonati Shale, LF+TB Lydienne Flysch and Toccone Breccia, GNS Novella Sandstone, PF Petraggiolo Formation, CCS2 Black Micaschist, NF Narbinco Flysch, BRF Bagliacone-Riventosa Formation, GS Gottero Sandstone, BS Bocco Shale.

Fig. 12 - Chronostratigraphic framework of the studied successions highlighting correlations among formations of the Northern Apennines, Western Alps, and Alpine Corsica based on lithostratigraphy and age.

Hints for the pre-convergence architecture of the Ligurian-Piedmont Ocean (LPO)

The pre-convergence architecture of the LPO can be re-constructed by comparing deep-sea pelagic deposits (i.e., the pre-convergence type pelagic deposits) preserved in both low- and high-grade metamorphic ophiolite units from the Western Alps, the Northern Apennines, and Alpine Corsica. These deposits sedimented before any convergence-related deformation within the ocean basin and therefore provide a snapshot of the original oceanic setting. Field evidence indicates that pelagic sedimentation occurred across a rugged seafloor morphology, which was inherited from extensional tectonics during phases of ultra-slow seafloor spreading. This interpretation is supported by both the occurrence of variable thicknesses and locally incomplete stratigraphic successions of the pre-convergence pelagic deposits, as well as by the presence of coarse-grained arenite-bearing ophiolite fragments in their lower part. For example, in the Monviso ophiolite, a very thin pelagic succession, such as the Palombini Shale Fm., rests in stratigraphic contact (i.e., lack of significant tectonic shearing) on exhumed mantle rocks, and its lower portion contains Albian-Cenomanian planktonic Foraminifera (see Tartarotti et al., 2021). These features suggest deposition on a structural high inherited from the Jurassic rifting stage, which may have persisted until the earlier Late Cretaceous, although minor later reactivations cannot be excluded (see, e.g., Festa et al., 2015, and Balestro et al., 2019 for details). This interpretation is further supported by the observation that the pre-convergence pelagic succession thickens away from the structural mantle high, grading into a complete succession (i.e., equivalent to Monte Alpe Chert, Calpionella Limestone and Palombini Shale Fms.), similar to that preserved in the Zermatt-Saas ophiolite of the St. Marcel Valley. The characteristics of this complete cover succession document deposition in a basin-plain setting. Additional evidence comes from the occurrence of coarse-grained arenite-bearing ophiolite clasts in the lower part of the Monte Alpe

Chert Fm., and from local pinch-outs of this formation and of the Calpionella Limestone Fm., features that outline the role of pre-convergence pelagic sedimentation in progressively sealing and homogenizing the rugged seafloor morphology inherited from the Jurassic rifting, as also documented in several Northern Apennine (Cortesogno et al., 1987; Principi et al., 2004; Marroni and Meccheri, 1993) and Western Alpine (Festa et al., 2015; Tartarotti et al., 2017, 2019; Balestro et al., 2019, 2025; De Togni et al., 2024) sections. This picture is consistent with the stratigraphic relationships between the ophicalcites, and the Palombini Shale Fm. observed at the top of oceanic mantle reliefs in the Bracco area, eastern Liguria (Decandia and Elter, 1972). The regional unconformity beneath the pre-convergence pelagic succession thus marks the temporal transition from lithosphere-scale extension associated with rifting and upper mantle exhumation to a prolonged period of both tectonic quiescence and very low sedimentation rate during which predominantly pelagic sedimentation took place in and across the LPO (Marroni et al., 2017; Balestro et al., 2019). This situation represents evidence that oceanic spreading has ceased and convergence has not yet begun.

The Palombini Shale Fm., which spans a long period from the Late Valanginian to the Santonian, displays remarkably similar characteristics throughout most oceanic sequences, regardless of metamorphic grade. The sole significant exception occurs in the Balagne nappe of Alpine Corsica, where the ophiolites and their sedimentary cover include continental, coarse-grained deposits. The composition of the coarse-grained arenite and conglomerate indicates a source area from the European continental margin, suggesting that this ophiolite sequence was located close to the European continental shelf, close enough for coarse debris to prograde directly onto the oceanic crust. This picture aligns very well with the proposed reconstruction of the rifting processes that led to opening of the LPO (Marroni et al., 1998; Di Rosa et al., 2023). The final stage of rifting is in fact interpreted as marked by asymmetric extension accommodated by a lithospheric detachment fault. The detachment created a faulted

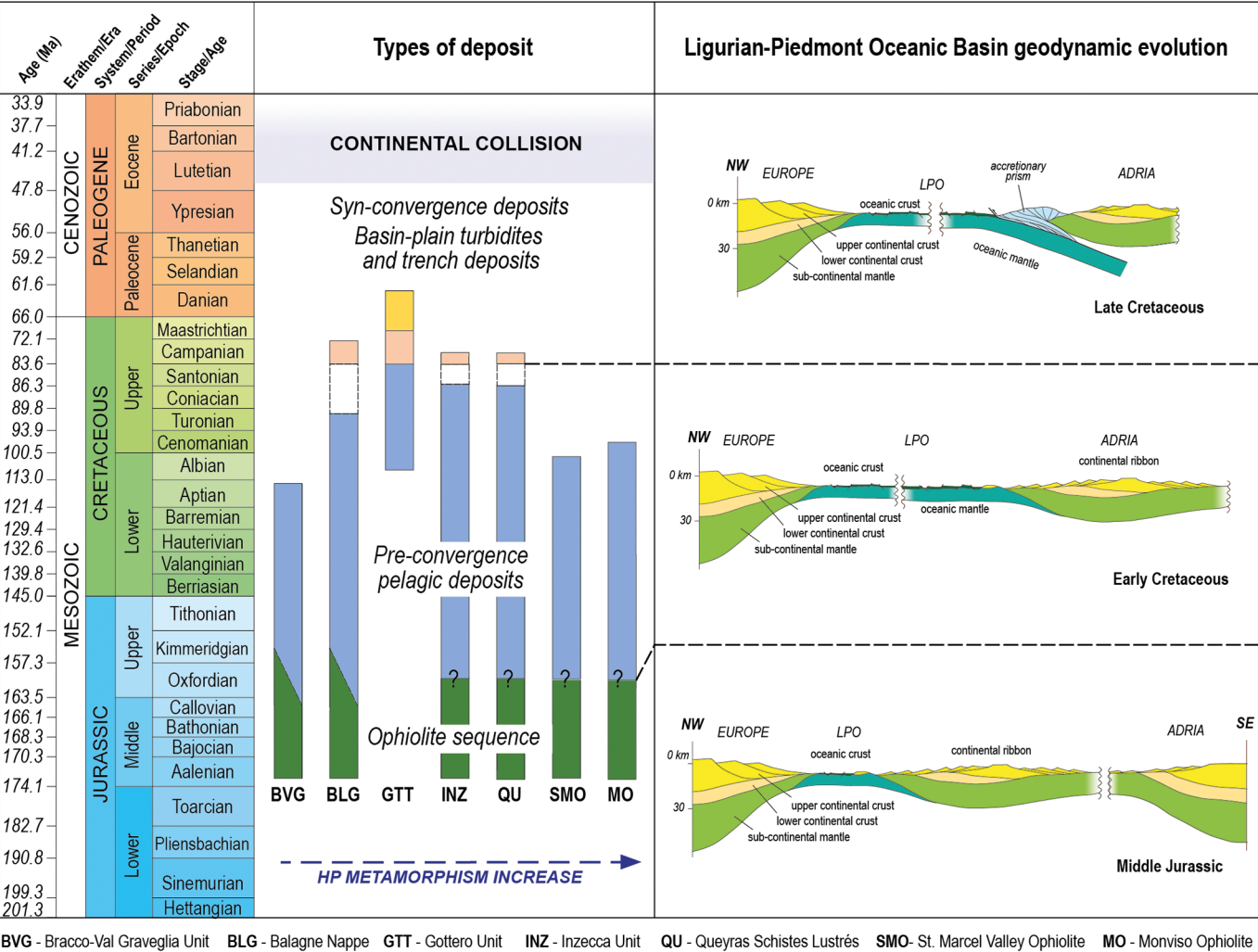


Fig. 13 - Sketch illustrating the types of deposits in the ophiolite sedimentary cover from the Western Alps, the Northern Apennines and the Alpine Corsica, and their correlation with the geodynamic evolution of the Ligurian-Piedmont oceanic basin (redrawn from Marroni et al., 2017). The stratigraphic logs are organized according to their P-T conditions of the metamorphic peak acquired during underplating onto the Alpine accretionary prism.

continental margin toward the Europe plate, made up of an upper continental crust domain with a narrow ocean-continent transition (OCT). In contrast and according to the reconstruction by Marroni and Pandolfi (2007), the hyperextended margin facing the Adria plate is characterized by exhumed subcontinental mantle peridotite and lower continental crust overlain by extensional allochthons derived from the upper continental crust. The association was subsequently covered by pillow-lava basalt and by the same sedimentary cover succession that draped the oceanic crust, namely the Monte Alpe Chert, Calpionella Limestone, and Palombini Shale Fms., all of which lack coarse-grained deposits sourced from the Adria continental margin (Bertotti et al., 1986; Elter et al., 1991; Casnedi et al., 1993; Barbero et al., 2020). Figure 12 illustrates the proposed reconstruction, depicting the LPO as a system with paired OCTs that retain contrasting architectures inherited from the Jurassic rifting phase.

A selected sampling of the ophiolite sedimentary cover during subduction

Analyses of the ophiolite sedimentary cover in the various metamorphic units, ranging from prehnite-pumpellyite

to eclogite facies, provides key insights into accretionary processes active within the subduction zone. Although these units record metamorphism at different depths, they all developed under a cold geothermal gradient of approximately 10-20°C/km, typical of subduction zones (Peacock, 1996; Gerya et al., 2002; Syracuse et al., 2010). Within this setting, slices of ophiolite and their sedimentary cover are progressively detached from the downgoing oceanic plate and accreted to the growing accretionary wedge. This transfer may occur either at the frontal accretionary wedge or along its base (Scholl et al., 1980; Moore, 1989; Meneghini et al., 2009; Ellis et al., 1999; Nirta et al., 2024; Sanità et al., 2025). Frontal accretion involves deformation at very shallow levels with no metamorphic overprint, whereas basal accretion occurs at greater depth and is associated with high-pressure metamorphism. Underplating is controlled by the downward migration of the decollement zone, located at the base of the plate interface (see Agard et al., 2018 cum biblio). Accreted slices may then be deformed through coherent underplating, producing folds and foliation, or through diffuse underplating, which results in tectonic mélanges with a block-in-matrix fabric (Moore and Sample, 1986; Meneghini et al., 2009; Menant et al., 2019; Ruh, 2020; Nirta et al., 2024; Remitti et al., 2024,

2026). These processes may operate within the same accretionary wedge at different times or in distinct regions along the subduction interface.

All described ophiolite-bearing units exhibit deformation consistent with coherent underplating at different depths, accompanied by significant accretion of both sediments and ophiolitic material. Three lines of evidence clarify the underplating mechanisms involved.

First, the significant thickness of sedimentary deposits that accumulated in the LPO during the pre- and syn-convergence stages strongly influenced the style of underplating. A sediment-rich oceanic lithosphere favors coherent underplating during subduction (see also Geersen et al., 2020 and references therein), as shown in the Kodiak accretionary wedge (Meneghini et al., 2009).

Second, the abundant incorporation of ophiolite slices at both shallow and deep structural levels is a distinctive feature of the Alpine accretionary wedge. By contrast, most modern and ancient subduction zones contain very little to no ophiolite material, that is in general limited to the basal section (Westbrook et al., 1982; Schlüter et al., 2002; Deville, 2023). The lithosphere of the LPO formed at an ultra-slow spreading ridge, where extensional tectonics and pervasive serpentinization of exhumed mantle peridotite generated multiple weakness surfaces. These surfaces facilitated repeated detachment of oceanic crust slices during underplating (see also Nirta et al., 2024 and references therein).

Third, the thickness and completeness of the preserved sedimentary cover vary systematically among units with different metamorphic imprint. High-grade metamorphic units typically preserve only a thin remnant of pre-convergence pelagic deposits. In contrast, low-grade metamorphic units retain the full range of deposits, ranging from pre-convergence pelagic sediments to syn-convergence basin-plain turbidites and trench deposits. In this context, the Palombini Shale Fm., owing to its high shale content, acted as the main detachment horizon. Nonetheless, exceptions occur. The Bracco-Val Graveglia Unit, for example, lacks both syn-convergence basin-plain turbidites and trench deposits and preserves only pre-convergence pelagic deposits. Conversely, the Inzecca Unit in Alpine Corsica, despite its blueschist-facies metamorphic overprint, retains both pre- and syn-convergence deposits. Similarly, the eclogite-facies Zermatt-type units of the Western Alps (see, for example, the Monviso and the St. Marcel ophiolites) are dominated by pre-convergence metasedimentary successions and typically lack syn-convergence basin-plain turbidites. In contrast, these turbiditic deposits are commonly preserved in the blueschist-facies Combin-type units, extending from the Queyras Schistes Lustrés in upper Maira Valley to Susa Valley and the Combin Unit in the Aosta Valley. This contrast may reflect the morphological relief of the subducted oceanic lithosphere. When such relief is not detached, they represent an obstacle to the downward progradation of the decollement zone. These asperities can inhibit shallow accretion of syn-convergence basin plain turbidites and trench deposits, promoting their underthrusting to greater depth where underplating takes place.

CONCLUSIONS

Our review and the new data on the ophiolite cover successions in the Western Alps, the Northern Apennines and the Alpine Corsica provide an exceptional tool for reconstruct-

ing the sedimentary and tectonic evolution of the LPO. Integrating lithostratigraphic, sedimentological, petrographic, and geochronological data from these exhumed sectors of the LPO reveals a coherent basin-scale tectono-stratigraphic evolution, extending from Middle Jurassic rifting to final ocean closure during Alpine-Apennine subduction. This evolution is recorded by the stratigraphic and sedimentological characteristics of three sedimentary endmembers. Long-lived, pre-convergence pelagic deposits, consisting in Monte Alpe Chert, Calpionella Limestone and Palombini Shale Fm., record uniformly low sedimentation rates and basin-wide facies homogeneity from the Bajocian to the Santonian. These deposits were abruptly replaced in the Campanian by syn-convergence turbidites derived from the rising European continental margin, marking the onset of eastward-directed subduction. Approaching the trench, these turbidites interfingered with mass-transport deposits (MTDs) sourced from the episodic collapses of the developing accretionary wedge, forming a third deposit type that documents the formation of trench environments.

Our regional-scale analysis of the ophiolite cover successions also provides a better constrain of the pre-convergence architecture of the LPO. Variable thicknesses, coarse ophiolite-bearing arenite and local stratigraphic pinch-outs document that pelagic sedimentation draped a rugged, fault-controlled seafloor inherited from the Jurassic ultra-slow spreading stage. The widespread uniformity of the Palombini Shale Fm. throughout the Northern Apennines, Western Alps, and Alpine Corsica, contrasted with coarse continental detritus restricted to the Balagne nappe, supports an asymmetric rift configuration with a narrow, fault-bounded OCT on the European margin and a hyperextended, mantle-dominated margin facing Adria.

Finally, the thickness and mechanical properties (i.e., the mechanical stratigraphy) of the ophiolite sedimentary cover of the LPO exerted a first-order control on subsequent subduction and accretion processes which led to the formation of the Alpine-Apennine accretionary complex. A sediment-rich incoming lower plate favored coherent underplating, while the presence of serpentinized mantle and inherited extensional structures promoted repeated detachment of oceanic slices. Differences in the successions preserved between high- and low-grade metamorphic units reflect how subducted relief influenced the downward migration of the active decollement, determining whether syn-convergence and trench deposits were accreted at shallow levels or underplated at greater depth.

In conclusion, our findings show that the sedimentary cover of the LPO preserves a uniquely continuous record of the transition from ocean opening to convergence, early subduction, and accretionary wedge growth. They outline the importance of combining sedimentological, structural, and metamorphic observations to unravel the evolution of ancient ocean basins and their subsequent subduction-related evolution.

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