1	Recycling of heterogeneous material in the subduction factory: evidence
2	from the sedimentary mélange of the Internal Ligurian Units, Italy
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14 Abstract

15 In the Northern Apennine (Italy), the Internal Ligurian Units consist of Middle-Late 16 Jurassic ophiolites covered by thick sedimentary deposits whose top is represented by 17 the Early Palaeocene Bocco Shale. This formation is characterized by mass-transport 18 deposits (MTDs) interlayered with thin-bedded siliciclastic turbidites. The 19 sedimentological and structural features of these MTDs reveal a long-lived history of 20 recycling of heterogenous material in a subduction setting. This history started with 21 the frontal accretion of a fragment of oceanic crust into an accretionary prism whose 22 lower slope was subsequently affected by tectonic erosion and consequent instability, 23 leading to MTDs production and transfer of relevant volume of material to the lower 24 plate. These MTDs were subsequently underthrust and then again transferred to the 25 base of the accretionary prism by coherent underplating, before their exhumation up 26 to the surface. The Bocco Shale is thus representative of a subduction setting, where 27 both accretionary and erosive events occurred, depending on changing boundary 28 conditions. The reconstructed history for the Bocco Shale indicate that the 29 sedimentary and gravitational processes both at prism front and on the prism slope, 30 possibly induced by alternating accretion and erosion events, are the most efficient 31 mechanisms of lithological mixing and recycling in subduction margins. 32

34 Introduction

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36 Subduction zones are restless centrifuges of material continuously reshaping the 37 Earth's surface. Mass and fluids are transferred along and across subduction zones in 38 time and space, at scales ranging from that of a seismic event to millions of years, and 39 from the micro-scale to hundreds of km. This material recycling controls the 40 distribution of chemical elements and heat, and the mechanical properties of 41 sediments and rocks, making subduction zones one of the most dynamic systems on 42 Earth: subduction zones host devastating earthquakes across the first tens of km, and 43 disastrous volcanic eruptions deeper down, thus exerting a fundamental control on 44 our environment and on climate.

45 In this system, the plate interface can be imagined as a tectonic-scale conveyor belt 46 through which sediments, rocks and fluids move from the trench down to ca. 100 km 47 along an ever-increasing pressure-temperature-stress regime. Some material will be 48 conveyed at depth, and some will be recycled up to the surface by accretion and 49 exhumation. Previously accreted material can be then put back into the system after 50 remobilization and transport due to slope failure and gravitational deformation from 51 the trench and prism slopes (Festa et al., 2018 and its Fig. 2). Therefore, mechanically 52 and lithologically diverse materials are continuously mixed at trenches and along the 53 plate interface, contributing to the complex nature, structure and properties of the 54 interface itself.

55 There is a growing body of evidence that subduction of heterogeneous material with 56 strong competency contrast and variable incompetent/competent ratio, such as 57 chaotic deposits and sedimentary/tectonic mélanges, can explain the variability of slip 58 style and seismic character observed in subduction zones from creeping to seismic slip 59 thorugh tremors, slow slip events, low frequency earthquakes (Fagereng & Sibson, 60 2010; Skarbek et al., 2012; Wang & Bilek, 2014). Although this documented tight 61 relationship, the lithology, size, geometry and mechanical properties of the plate 62 interface, and how they evolve with depth and through time, are largely undefined 63 (Agard et al., 2018; Festa et al., 2018). The various sedimentary and tectonic processes 64 forming mélanges or, more generally, block-in-matrix fabric, are the most efficient 65 processes contributing to the lithological, mechanical, and frictional heterogeneity of the material entering trenches and moving along the plate interface in subduction zones (Festa et al., 2010; Pini et al., 2012; Festa et al., 2019 and references therein). More over, the frequent polygenetic nature (i.e. reworking by superposition of different, sedimentary, tectonic or diapiric processes, see Festa et al., 2019 for a comprehensive review) of chaotic rock units in exhumed accretionary complexes demonstrate their power in recycling and mixing rocks with different composition and rheology.

73 In this paper we examine the sedimentological and structural features of the chaotic 74 tectonic- and gravity-controlled deposits of the Bocco Shale (Internal Ligurian Units of 75 the Northern Apennine of Italy) to reconstruct their complex trajectories along and 76 across the plate interface during the building of Northern Apennine wedge. Although 77 now cropping out as a deformed sedimentary mélange (Marroni & Pandolfi, 1996; 78 2001; Marroni et al., 2017), the reported multidisciplinary analysis of the 79 sedimentologic, structural, metamorphic and petrographic features of the Bocco Shale 80 mélange reveal a complex history of re-mobilization and recycling of heterogeneous 81 material, from sediments and rocks derived from the lower plate and the flanks of the 82 accretionary prism, to metamorphosed, already accreted material from the prism 83 interior.

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86 **Geological framework**

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The Internal Ligurian Units represent the exhumed accretionary prism of the late Cretaceous to present Northern Apennine collisional belt (Fig. 1) that formed during subduction and closure of the Ligure-Piemontese oceanic basin developed between the Adria and Europe plates (Marroni et al, 2010; Molli & Malavieille, 2011, Argnani; 2012; Marroni et al., 2017). These units are thrust over the External Ligurian Units, interpreted as representative of the ocean-continent transition at the Adria margin, (Marroni & Tribuzio, 1996; Marroni et al., 1998).

95 The northernmost sector of the Northern Apennine belt, where both the Internal and 96 External Ligurian units are exposed, developed through two diachronous subduction 97 events, informally referred to as "Alpine" event (Late Cretaceous-Middle Eocene east-

98 dipping subduction of the Ligure-Piemontese oceanic basin below the Adria Plate) and 99 "Apennines" event (Late Eocene to present west dipping subduction developing in this 100 area through the Late Eocene-Early Oligocene continental collision between the 101 Europe and Adria plates) (Doglioni, 1991; Marroni et al, 2010; Molli & Malavieille, 102 2011, Marroni et al., 2017). The structures of the "Alpine" event are sealed by the 103 sedimentary deposits of the episutural Epimesoalpine Basin, whose succession starts 104 in the studied area with Late Eocene deep-water deposits (cf. Monte Piano Marls) 105 unconformably topped by Early Oligocene shallow-water conglomerates (e.g. Val 106 Borbera Conglomerate and Persi Formation, see Mutti et al., 1995; Di Biase et al., 107 1997).

108 The Internal Ligurian Units are arranged in a stack of tectonic units cropping out 109 extensively from the town of Genova, where they are in contact with the ocean-110 derived, eclogitic units of the Voltri Group, belonging to the Western Alps, to southern 111 Tuscany (Fig. 1). The units are arranged classically, with a decrease in metamorphic 112 grade from the structurally lowermost units to those lying on top of the tectonic pile 113 (Leoni et al., 1996; Ellero et al., 2001). Particularly, metamorphic assemblages are 114 indicative of the low-grade blueschist facies for the lowermost Cravasco/Voltaggio and 115 Mt. Figogna units and range to the very low-grade metamorphic conditions (Gottero, 116 Bracco-Val Graveglia and Colli/Tavarone units) and to immediately below the 117 anchizone-epizone transition (Portello, Vermallo and Due Ponti units) (Fig. 2, Leoni et 118 al., 1996; Crispini & Capponi, 2001; Ellero et al., 2001).

119 The units ascribable to the Internal Ligurian Units, no matter the degree of 120 metamorphism or deformation, share a systematic, ocean-derived stratigraphic 121 sequence (Fig. 3), (Treves, 1984; Marroni & Perilli; 1990; Marroni et al., 1992; Abbate 122 et al., 1994), with a MORB-type geochemical signature (Renna et al., 2018). The 123 sequence can be schematized as: (i) an ophiolite sequence comprising mantle 124 Iherzolite, a gabbroic complex and a volcano-sedimentary complex of pillow-lavas, 125 basaltic flows and ophiolite breccias, interpreted as originated in an ultraslow-126 spreading ridge; (ii) a Callovian-Santonian thick sequence of hemipelagic deposits 127 tapering the oceanic rocks (Diaspri, Calcari a Calpionelle and Argille a Palombini 128 formations). An early Campanian- Early Paleocene thick turbiditic succession, covers 129 indifferently all the Ligure-Piemontese oceanic-derived rocks, and comprises the Val 130 Lavagna Shale Group, consisting of the Manganesiferi Shale, Monte Verzi Marl, Zonati 131 Shale formations, that grades upward to the Gottero Sandstone. The age of the oldest 132 turbidite sedimentation, together with the Late Cretaceous to Early Tertiary age of 133 metamorphism in the western side of the Northern Apennine, as well as in Corsica 134 (Malavieille et al., 1998; Marroni et al., 2010; Molli & Malavieille, 2011), point to the 135 early Campanian as the onset of subduction, closure of the Ligure-Piemontese ocean, 136 and building of an accretionary prism (Fig. 4). This evolution is recorded in the entire 137 pre-Oligocene sequence of the Internal Ligurian Units by a multi-stage deformation 138 history similar to that typically described in many exhumed sediment-dominated 139 accretionary prisms (Moore, 1984; Wakabayashi, 1992; Meneghini et al., 2009; Plunder 140 et al., 2015; Schmidt & Platt, 2018). The metamorphic conditions estimated for the 141 Internal Ligurian Units indicate accretion at intermediate to shallow levels (Marroni et 142 al., 2017 for a review).

The youngest deposits of the Internal Ligurian Units are the Early Paleocene Bocco Shale that lies unconformably on top of all the older formations in the Gottero, Portello and Colli/Tavarone units (Fig. 3). These chaotic deposits are the object of this study and comprise thin-bedded turbidites, slide and debris flow, and mass transport deposits reworking an oceanic lithosphere and its sedimentary cover (Marroni & Pandolfi, 2001; Marroni et al., 2017)

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151 Sedimentary architecture of the Bocco Shale

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In order to better describe the sedimentary architecture of the Bocco Shale two points
must be preliminarily introduced: the relationships between this formation and its
substratum, and the stratigraphic features of the different lithologies recognized inside
the Bocco Shale.

157 Despite the complex deformation history, which will be described in detail in the next 158 sections, the Bocco Shale preserves exceptionally most sedimentary structures, as well 159 as the primary stratigraphic relationships with the underlying successions.

160 In the Portello, Gottero and Colli/Tavarone units the Bocco Shale (Figs. 2, 3, including 161 the local names assigned to the Bocco Shale) shows stratigraphic unconformable relationships with the succession below, regardless the contact is with the turbidite systems on top of the oceanic sequence, or the hemipelagic cover of the ophiolites. In the early 70's, Pertusati (1972) described already a "regional unconformity" of the Bocco Shale on all the turbidite covers of the Ligure-Piemontese oceanic lithosphere (Fig. 2).

167 Marroni and Pandolfi (2001) report well-preserved angular unconformity as well as 168 erosive relationships between the Bocco Shale and its substrate in several outcrops of 169 the Gottero Unit. Here the authors describe a deep erosive tabular scour into the 170 turbiditic formation of the Gottero Sandstone, as well as angular unconformity 171 relationships in the Colli/Tavarone Unit among Palombini Shale-Val Lavagna Shale 172 Group, and the Bocco Shale, in this units named the Colli/Tavarone Formation (Figs. 5, 173 6a). Moreover, the Bocco Shale of the Portello Unit (cf. Lavagnola Fm., Marroni et al. 174 2017 and reference therein) is a clast-supported ophiolite-bearing breccia (F3 facies of 175 Mutti, 1992) that preserves primary erosive relationships with the Ronco Fm. (cf. 176 Zonati Shale) below (Fig. 6b).

This chapter is dedicated to a description of the sedimentary and compositional features of these deposits that is crucial to the understanding of the history of remobilization and recycling that the Bocco Shale holds. The Bocco Shale can be described as made by two main facies groups (Marroni & Pandolfi, 2001):

(i) slide-blocks (Fig. 5a) in a matrix of pebbly-mudstones (Fig. 5b), mudstones, clastsupported breccias, very coarse- and coarse-grained turbidites;

(ii) fine-grained thin-bedded siliciclastic turbidites and their reworking products bysubmarine landslides .

(i) The deposits of the first facies group include mass-transport deposits (MTDs), in its
generic meaning of a geological material that has been rapidly remobilized and redeposited on the seafloor as a result of slope failure, gravitational deformation or
tectonic activity in the form of downslope mass movements and flows (Lamarche et
al., 2008; Festa et al., 2018). These deposits rework an ophiolite basement and its
related sedimentary cover.

The "slide-block-in-matrix" facies is composed of slide-blocks (olistoliths *Auctt*.) of different size (ranging from 1m up to 50m) set in a shaly-dominated matrix. An emplacement due to submarine landslides for these blocks is suggested by syn194 sedimentary deformation structures recognized in the sediment around the blocks and 195 by slide-block-derived monomictic pebbly-mudstones and pebbly-sandstones found 196 around several slide-blocks. The Palombini Shale-derived slide-blocks (Fig. 5a) can be 197 often referred to a submarine landslides-derived sedimentary broken-formation sensu 198 Abbate et al. (1980). Locally, this facies lacks any blocks and the deposit can be 199 described as a mud-flow-derived mudstone. The slide-blocks derive exclusively from 200 the Internal Ligurian Units and rework a Jurassic ophiolite basement (serpentinized 201 mantle peridotites, MOR basalts and rare gabbros) and the related Late Jurassic-Early 202 Paleocene sedimentary cover (Cherts, Calpionella Limestone, Palombini Shale, Val 203 Lavagna Shale and Gottero Sandstone).

204 The pebbly-mudstones (Fig. 5b) and clast-supported breccias (Fig. 6b) are quite 205 common in the Bocco Shale. They are generally associated with the slide-blocks facies 206 and range from mud- to clast-supported conglomerates and/or breccias (pebbly-207 mudstones, pebbly-sandstones and orthoconglomerates) and derive from debris flows 208 and high-density turbidity currents. The commonest facies is represented by prevalent 209 monomict pebbly-mudstones (cf. olistostrome of Abbate et al. 1970 and F1 facies of 210 Mutti, 1992) in which pebble- to boulder-sized clasts are enclosed into a predominant 211 muddy matrix. The matrix is composed of arenitic to ruditic soft clasts mainly 212 reworking the hemipelagic pelites of the Palombini Shale and Val Lavagna Shale (Fig. 213 7a-b). Arenitic to boulder-sized clasts of calcilutites derived from the Palombini Shale 214 are the most common kind of recognized clasts, but ophiolite-derived clasts 215 (serpentinites, basalts, gabbros and radiolarites) can be also recognized (Fig. 6b). These 216 sediments can be interpreted as cohesive debris flow-derived deposits (sensu Mutti, 217 1992) and they are associated with decimeters to meters thick polymictic, clast-218 supported and poorly sorted conglomerates. These sediments were interpreted as the 219 down-current evolution of cohesive debris flows into hyperconcentrated flows (F2 and 220 F3 facies of Mutti, 1992). As seen for the slide-blocks deposits above, basalts, 221 serpentinites, gabbros, radiolarites, Calpionella-bearing limestones and siliciclastic 222 sandstones and siltstones define the composition.

Cohesive debris flow and hyperconcentrated flow derived deposits are found
associated with subordinate coarse-grained high-density turbidity current deposits.
These facies are sometimes associated with thin Bouma base-missing beds (F5+F9)

226 facies of Mutti, 1992). Arenites framework composition analyses performed on three 227 samples from F5 beds collected from Bocco Shale in the Gottero Unit point to a 228 lithoarenitic composition characterized by rock fragments such as basalts, 229 serpentinites, cherts and Calpionella-bearing limestones (Fig. 7c). Similarly, the 230 pebbles from F1, F2 and F3 beds show the same composition recognized in the slide 231 blocks and arenites. These data point to a source area characterized by reworking of 232 ophiolites and related sedimentary cover belonging to the Internal Ligurian successions 233 (Marroni & Pandolfi, 2001).

234 (ii) The thin-bedded turbidites of the second group are a widespread facies recognized 235 in the Bocco Shale. The turbidites are characterized by thin- to medium- bedded 236 alternations of fine- to medium-grained siliciclastic arenites with carbonate-free 237 mudstones, and a sand/shale ratio generally >1 (Fig. 5c). The arenites are 238 characterized by moderate lateral continuity. Td-e and subordinately Tc-e base-missing 239 Bouma sequences are commonly observed in this facies, which is typically 240 characterized by an internal organization dominated by traction plus fall-out structures 241 (Fig. 7d) such us plain lamina, ripples, climbing ripples and convolute laminations. The 242 stratigraphic and sedimentological features of these deposits point to low-density 243 turbidity currents as the main type of genetic flow (F9b Facies of Mutti, 1992).

As suggested by Marroni & Pandolfi (2001) the thick packages of thin-bedded turbidites are affected by intensive syn-sedimentary deformation due to slumping and submarine landslides (Fig. 7e). These processes are responsible for the diffuse mesoscale angular unconformities (more than 30°) among different packages of beds and testify the deposition along a steep and unstable slope.

249 The medium-grained arenites show a siliciclastic framework composition characterized 250 by prevalent monocrystalline quartz and feldspar fragments (from subarkose to arkose 251 composition, Fig. 7f). Subordinate lithic fragments are represented by granitoids and 252 very low-grade metamorphic rocks such as micaschists and gneisses. Ophiolite-derived 253 rock fragments are lacking. As suggested by Marroni et al. (2017) the framework 254 composition of these arenites is comparable to that of the Gottero Sandstone. One of 255 the main differences between the two groups of deposits consists in the diverse 256 nature and internal organization of the pelitic grain-size. In the first group it is 257 characterized by a complete internal disorganization (Figs. 7a, b) that suggest a mass dominate processes. Often the matrix of the pebbly-mudstone consists of a intrarenite (*sensu* Zuffa, 1980) in which fragments of arenitic size soft clast derived from the reworking of pelites from both the thin-bedded turbidites (Fig. 7e) and the turbidite cover of the oceanic sequence (Palombini Shale, Val Lavagna Shale and Gottero Sandstone). In the thin-bedded turbidites facies the pelites are always well organized and often characterized by lamina-set (Fig. 7d, e) that suggest the dominance of selective processes rather than mass-transport.

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267 Geological evidence of the multiple paths to build the Bocco Shale deposits

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The described facies association in the Bocco Shale preserves evidence of a long-lived history of re-mobilization and recycling of heterogenous material during subduction. In this paragraph we intend to show of how the tectonic processes during the evolution of this subduction system interacted with the sedimentary processes to contribute to continuous mobilization and circulation of diverse material across and along the plate interface.

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Frontal accretion: evidence of clasts deformation before their incorporation in the Bocco Shale

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279 The petrographical analysis of the MTD in the Bocco Shale shows that the carbonate 280 clasts of the MTD are typically characterized by en-echelon calcite veins clearly 281 truncated at the contact of the matrix (Fig. 8a). Some of these veins show irregular 282 boundaries and bear flakes of their walls, suggesting their origin in unconsolidated 283 sediments. Therefore, the clasts were subject to lithification, hydrofracture and 284 deformation before their inclusion in the MTD. Fragments of these calcite veins are 285 also found as isolated clasts in the MTD matrix. In addition, several clasts are crosscut 286 by a network of joints that seem to be developed before their inclusion in the MTD, 287 suggesting, that clasts with different degree of consolidation and deformation were 288 incorporated in the MTD.

In the pebbly-mudstones, the matrix at microscale can be described as a lithic wake composed of flakes of shales with different texture and colour surrounded by a shaly matrix. The shale clasts all have an elongated shape and no matter the different colour they commonly show a rough planar anisotropy defined by aligned phyllosilicate mineral: this anisotropy is interrupted at the contact with the matrix. These features seem to be indicative of clasts lithification before their inclusion in the matrix.

As a whole, the carbonate and shaly fragments were variably lithified and deformedbefore the inclusion in the MTD.

Re-mobilization of material from the prism slope

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300 The evidence of a re-mobilization of material already accreted at the prism of the 301 Ligure-Piemontese subduction system is testified by the occurrence of MTDs in the 302 Bocco Shale. The large amount of MTDs such as slide-blocks, pebbly-mudstones, 303 mudstones, clast-supported breccias, very coarse- and coarse-grained turbidites 304 clearly indicate a sedimentation resulting from collapse of a topographic relief able to 305 supply such an heterogeneous material. These proximal deposits interfered and 306 partially reworked the distal sediments represented by the fine-grained thin-bedded 307 siliciclastic turbidites supplied by the continental margin. In addition, the nannofossils 308 assemblage across the entire succession (Marroni & Perilli, 1990; Marroni et al., 1992) 309 indicates a very short deposition time for the Bocco Shale, suggesting that the Bocco 310 Shale deposited during a very fast sedimentary event. The arising picture is a sudden 311 and fast event of a proximal sedimentation of the MTDs in a basin bounded by a 312 topographic relief under collapse, i.e. the source area of these deposits. Even if totally 313 destroyed and not longer observable, this source area can be regarded as 314 corresponding to the lower slope of an accretionary prism, coherently with the 315 composition of the MTDs. We will propose the possible geodynamic significance of this 316 event in the discussion section.

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318 **Coherent underplating record: the D1 phase in the Bocco Shale**

320 The structural history of the entire sequence of the Internal Ligurian Units is classically 321 described as multi-stage (Marroni et al, 2004, Meneghini et al., 2009), and the first 322 step is documented by the D1 phase, which is a composite deformation stage 323 developed in the frame of a non-coaxial progressive deformation (see D1a, D1b and 324 D1c sub-phases of Marroni et al., 2004). The D1a sub-phase includes the development 325 of layer-parallel veins of calcites. Veins develop extensively in the turbidite facies of 326 the Bocco Shale, along bedding, at the boundary between the shaly and sandy interval, 327 i.e. along strong competency contrast directions. Calcite infilling is blocky and coarse 328 grained with a dirty appearance due to the occurrence of flakes of shales, suggesting 329 formation in partly lithified hosts (Marroni et al, 2004; Meneghini et al., 2007; 2009). 330 These veins as well as the primary sedimentary fabrics S0 are deformed by the 331 pervasive structures of the sub-phase D1b that include F1 isoclinal to subisoclinal folds 332 and the associated S1 foliation (Fig. 8b, and see Pertusati & Horremberger, 1975; van 333 Zutphen et al., 1985; Van Wamel 1987; Thio & van Wamel, 1990; Marroni & Pandolfi, 334 1996; Marroni et al, 2004; Meneghini et al., 2007). F1 folds commonly have thickened 335 hinge and boudinaged limbs in the Bocco Shale facies with strong competence contrast 336 such as the turbidites, and show a strong re-orientation of the A1 axis on their axial 337 plane, suggesting high value of simple shear during the D1 phase. The S1 axial plane 338 foliation is a slaty cleavage in the shales and a disjunctive cleavage in the limestone 339 and sandstones. The slaty cleavage is generally at low-angle to the bedding where 340 present, whereas in the pebbly-mudstones is recognized as a continuous anastomosing 341 foliation wrapping around the clasts. In thin section, the slaty cleavage consists of 342 aligned, inequant phyllosilicates and elongate quartz-albite-mica aggregates showing 343 the effects of the deformation, mainly consisting of pressure-solution parallel to the 344 slaty cleavage domains. Along the S1 foliation the recrystallization of quartz + calcite + 345 albite + chlorite + white mica + Fe-oxides assemblages can be observed in the shales. 346 This assemblage can be referred to a very low-grade metamorphism characterized by P 347 ranging from 3 to 4 kbars and T ranging from 160 to 285°C; representing the peak 348 metamorphic conditions in the Bocco Shale in all the different units (Leoni et al., 1996; 349 Ellero et al., 2001). The last step of the D1 phase is represented by the D1c sub-phase 350 featuring meter-thick, localized shear zones marked by foliated cataclasites that are 351 parallel or sub-parallel to the S1 foliation (Fig. 8c, and see Marroni et al., 2004; 352 Meneghini et al., 2007). Cataclasites at micro-scale typically show S-C fabric defined by 353 thin layers of very fine-grained, mica-rich material, which enclose ribbons of elongated 354 grains displaying often relicts of S1 foliation. These regional-scale thrusts are 355 responsible for the present-day imbrication of the Internal Ligurian Units.

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357 Exhumation path of the Bocco Shale: the D2 phase

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359 The following D2 tectonic stage is also described in terms of a progressive deformation 360 summarized in two sub-phases, both developed at shallow structural levels (Marroni et 361 al., 2004). The D2a sub-phase is characterized by open to close, parallel F2 folds with 362 subhorizontal axial plane and rounded hinges (Pertusati & Horremberger, 1975; van 363 Zutphen et al., 1985; Van Wamel 1987; Thio & van Wamel, 1990; Marroni & Pandolfi, 364 1996; Marroni et al, 2004; Meneghini et al., 2009). These folds show a well-developed 365 axial plane foliation, classified in the shales as a zonal to discrete crenulation cleavage 366 (Fig. 8d). The F2 folds appear everywhere associated to low-angle, brittle shear zones 367 showing normal sense of shear. The D2b sub-phase is represented by high-angle 368 normal faults (Marroni & Pandolfi, 1996; Marroni et al, 2004; Meneghini et al., 2009).

369 The undeformed Early Oligocene conglomerates, belonging to the Epimesoalpine 370 succession sealing unconformably all the Ligurian Units, bear in their basal levels 371 several clasts derived from all the Internal Ligurian Units formations, including the 372 Bocco Shale (Di Biase et al., 2007; Marroni et al., 2017). Interestingly, these clasts bear 373 evidence of deformation that can be referred to the D1 and D2 phases: clasts 374 deformed by F2 folds or clasts showing the interference of two foliations (Fig. 9) are 375 quite commonly observed and described in literature (Di Biase et al., 1997). The D2 376 phase thus represents the deformation acquired during the transition of the Bocco 377 Shale from the maximum burial depth up to its exposure at the surfaces, where it 378 supplied the clastic material for the Epimesoalpine basin.

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381 Discussion

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383 A summary of the history preserved in the Bocco Shale

385 The most peculiar sedimentary feature of the Bocco Shale is the close association of 386 different sedimentary facies ranging from slide-blocks in matrix, pebbly-mudstones, 387 clast-supported breccias, very coarse and coarse grained turbidites up to thin-bedded 388 turbidites and mudstones. The second prominent characteristic of the Bocco Shale is 389 the polymictic nature and the provenance of its debris (Fig. 10): while the thin-bedded 390 turbidite facies is mainly alimented by an upper continental crust, i.e. the same source 391 area that produce the turbidite sedimentary cover of the Internal Ligurian Units (e.g. 392 Val Lavagna Shale and Gottero Sandstone), the coarse-grained facies reworks all the 393 lithologies that form the Internal Ligurian oceanic lithosphere from ocean-derived 394 mantle rocks up to the Gottero Sandstone. This facies association is hardly explainable 395 within a classical deep-sea turbidite system sensu Mutti & Ricci Lucchi, (1972), and its 396 origin is rather related to a strongly confined sedimentary basin supplied by both sides 397 of the trench from two different source areas (the lower plate sediments and rocks 398 and the upper plate/accretionary prism, Fig. 10). These deposits also record a complex 399 interaction between sedimentary/gravitational processes and tectonic processes, as 400 demonstrated by the sequence of tectonic and sedimentary events depicted in the 401 previous sections, that allows depicting multiple paths of materials flow now 402 preserved as components of the Bocco Shale deposits and responsible for the 403 sedimentological and compositions heterogeneity (Figs. 10, 11).

404 This history of recycling starts with the transfer from the lower plate to the front of the 405 accretionary prism of slices of the oceanic crust and its sedimentary cover, eventually 406 associated with portion of the distal thin-bedded turbidites already deposited in the 407 confined trench. As postulated by Lundberg & Moore, (1986); Moore et al., (1988) Brown & Behrmann, (1990), Clift & Vannucchi (2004), Vannucchi & Bettelli, (2002), 408 409 Ogawa et al. (2011) and many others, the transfer of material at shallow structural 410 level, i.e. accreted at the non-subducted part of the prism, before the subduction inlet, 411 is defined as frontal accretion and occur by offscraping of poorly consolidated deposits 412 that undergo subsequently a weak deformation accompanied with progressive 413 lithification and dewatering, while they are structured in a thrusts and folds system 414 with consistent vergence toward the lower plate (step 1 of Fig. 11). The record of this 415 deformation in materials at different degrees of lithification is now preserved in the

416 clasts of the Bocco Shale MTDs and pebbly-mudstones, such as: the evidence in the 417 clasts of fluid flow (dewatering) in partly lithified sediments, the joints in already 418 lithified rocks, and the heterogeneous matrix of the pebbly-mudstones. Therefore, 419 after frontal accretion, this weakly deformed material must have been re-mobilized 420 again to the trench/lower slope transition (Figs. 4 and 5) by mass-transport 421 sedimentary processes to form the MTDs of the Bocco Shale (Marroni & Pandolfi, 422 2001; Marroni et al., 2017). An event of frontal tectonic erosion is considered as the 423 most probable candidate for the triggering of these processes (Marroni & Pandolfi, 424 2001; Marroni et al., 2017). In fact, according to what proposed in literature (von 425 Huene & Scholl, 1991; Clift & Vannucchi, 2004), tectonic erosion is commonly 426 associated with the collapse of the lower slope of the accretionary prism as a 427 consequence of its deformation and uplift (von Huene and Scholl, 1991; Clift & 428 Vannucchi, 2004). The collapse includes the large removal of material from the lower 429 slope and reworking as MTDs and sedimentation on the lower plate (Step 2 of Fig. 11). 430 Unstable lower slopes in prisms are typical of margins with subduction of oceanic 431 crusts with rough topographies, because of dense systems of seamounts (i.e. 432 Lamarche et al., 2008; Mountjoy et al., 2009; Moscardelli & Woods, 2016), or because 433 of highly faulted oceanic basins: subduction of rough topographic reliefs can produce 434 the sudden uplift of the lower slope of the accretionary prism. Due to its origin in a 435 slow-spreading ridge, the oceanic sequence of Internal Ligurian Units is, as a matter of 436 fact, typically described as characterized by pervasive Jurassic faulting (Fig. 11, see also 437 Abbate et al., 1980; Marroni & Pandolfi, 2007).

438 Subsequently, the Bocco Shale is underthrust at depth along the subduction zone. This 439 underthrusting is associated with dewatering during lithification that in the Bocco 440 Shale turbidite facies, as well as in the entire Internal Ligurian Units succession, is 441 recorded by the bedding-parallel veins (sub-phase D1a interpreted as early 442 hydrofractures induced by fluid escape (Vrolijk 1987; Moore & Vrojlik., 1992; Fisher, 443 1996; Meneghini & Moore, 2007; Meneghini et al., 2009). At about 10-12 km, the 444 Bocco Shale is transferred at the base the accretionary prism (Step 3 of Fig. 11) 445 through the sequences of pervasive non-coaxial deformation of the D1 phase (Marroni 446 & Pandolfi, 1996; Marroni et al, 2004; Meneghini et al., 2007; 2009, Marroni et al., 447 2017).

448 The development of the D1b folds during the metamorphic climax, the development of 449 the S1 continuous foliation, and the occurrence of metamorphic mineral assemblages 450 that suggest deformation at moderately shallow levels ranging 10-12 kilometers 451 (Marroni & Pandolfi, 1996; Marroni et al., 2004; Meneghini et al., 2009) testify 452 accretion by coherent underplating, i.e. addition of discrete tectonic slices to the base 453 of the prism through down-stepping of the roof-décollement of the system (Moore & 454 Sample, 1986; Wakabayashi, 1992; Plunder et al., 2015; Schmidt & Platt, 2018). Then, 455 the imbrication at the base of the prism, recorded by the cataclastic shear zones at the 456 end of the D1 phase (sub-phase D1c, Marroni et al., 2004), produced a thickening of 457 the accretionary prism and, consequently, a first exhumation event of the accreted 458 material, as described in several analogical models (Gutscher et al., 1996; 1998).

459 After the coherent underplating, the Bocco Shale underwent final exhumation up to 460 the surface (Step 4 of Fig. 11), where it became a source of clasts for the Early 461 Oligocene conglomerates of the Epimesoalpine Basin (Step 5 of Fig. 11, see Di Biase et 462 al., 1997). This exhumation is accomplished by the development of the D2 phase 463 deformations, that can be likely regarded as developed during an extensional tectonics 464 (Hoogerduijn Strating, 1994; Marroni & Pandolfi, 1996; Marroni et al., 2004), 465 experienced by the accretionary prism to accommodate the thickening caused by 466 continuous underplating, as predicted by Platt's model (1993). Accordingly, the 467 features of the D2a folds, such as their subhorizontal axial plane and their close 468 association with low-angle normal faults, indicate a development during vertical 469 shortening. This exhumation represents the last step experienced by the Bocco Shale 470 before their involvement in the Miocene tectonics connected with the building of the 471 Northern Apennine belt.

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473 **Comparison with active margins and exhumed complexes**

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The present day subduction zones have been classified in accretionary and erosive types (e.g. Clift & Vannucchi (2004), depending on the material balance over a given time span. The accretionary types is characterized by trench retreating from a fixed point on the forearc, resulting in a subduction setting generally dominated by large volumes of trench-fill turbidites that allow the development of voluminous 480 accretionary prism. In contrast, the non-accretionary types show a trench advancing to 481 a fixed point with trenches almost devoid of turbidite infillings and, consequently, 482 poorly developed accretionary prisms. The latters, which account for 75% of the global 483 length of oceanic trenches (Clift & Vannucchi, 2004; Stern, 2011; von Huene & Scholl, 484 1993), are characterized by removal of the accreted crustal rocks at the front and/or at 485 the base of the accretionary prism and/or from the overlying plate (von Huene & 486 Lallemand, 1990; von Huene & Scholl, 1993; Lallemand et al., 1994). Subduction 487 erosion seems to be promoted by the underthrusting of high topographic reliefs on the 488 subducting plate, as ridges, seamounts or fracture zones, because of their impact on 489 the accretionary prism (e.g., Kukowski & Oncken, 2006; Wipf et al., 2008; Stern, 2011; 490 Vannucchi et al., 2016). The increase of data about fossil and present day examples 491 indicates that also intermediate types of margin occur, where the material balance 492 depends on the sequence of accretionary and erosive events, and suggesting that a 493 single margin can evolve through time between these two different end-members, 494 depending on changing boundary conditions of the system, such as geometry and 495 properties of the entering plate (e.g. Meneghini et al., 2009; Hajná et al., 2014; Ueda 496 et al., 2018).

497 Regardless of where we are in this classification between end-members, chaotic 498 deposits are ubiquitous in exhumed and active subduction margins (Festa et al., 2018). 499 For instance, since subduction erosion hardly leaves traces in the rock record, several 500 fossil margins have been interpreted as dominantly non-accretionary on the base of 501 the widespread occurrence of MTDs (Okamura, 1991; Oncken, 1998; Vannucchi et al., 502 2006; Amato et al., 2013; Ueda et al., 2018). Hajná et al., (2014), for example, 503 described a fossil accretionary prism characterized by alternating coherent and 504 mélange units, and interpreted it as the result of repeating cycles of frontal accretion 505 interrupted by frontal tectonic erosion due to the subduction of trench-parallel 506 topographic highs. Moreover, fossil and recent examples of events of seamount 507 subduction resulting in prism deformation and production of large volumes of MTDs 508 are also reported in literature (e.g. Lallemand & Le Pichon, 1987; Ballance et al., 1989; 509 Robertson, 1998; Collot et al., 2001; Lamarche et al., 2008; Mountjoy et al., 2009; 510 Pedley et al., 2010; Vannucchi et al., 2016; Moscardelli & Woods, 2016).

511 The Bocco Shale is a chaotic deposit characterized by wide compositional and facies 512 variability. As reconstructed through steps in Fig. 11, this complex deposit is 513 characterized by trench-confined distal thin-bedded turbidites draping the slope base 514 of the accretionary prism, and fed by the continental margin, that were repeatedly re-515 worked with proximal coarse-grained facies during MTD-forming processes at the 516 lower slope-trench boundary. These proximal deposits were alimented by the ocean-517 derived material already accreted to the prism and recording the complex history from 518 its deposition of exhumation at shallow levels. The actual evolution of margins such as 519 the Hikurangi of New Zealand, central and Northeast Japan, all share these same 520 characteristics, together with several other examples from ancient complexes 521 (Lamarche et a., 2008, Mountjoy et al., 2009; Yamamoto et al., 2009; Pini et al., 2012; 522 Festa et al., 2013; 2015; Zyabrev, 2015; Moscardelli & Woods, 2016; Ueda et al., 2018). 523 For the Bocco Shale, similarly to what cited above, these chaotic deposits allowed 524 formulating a hypothesis of events of frontal tectonic erosion, giving rise to transient 525 instability of the prism (Okamura, 1991; Oncken, 1998; Vannucchi et al., 2006; Amato 526 et al., 2013; Ueda et al., 2018).

527 In summary, the Bocco Shale and all these cited studies are only a few examples of a 528 much larger number of margins testifying that accretionary prisms are dynamic and 529 unstable settings, no matter their size and the dominance of the accretionary or 530 erosive character. The Bocco Shale records an extremely complex interplay between 531 sedimentary/gravitational and tectonic processes in which the typical, gravitation-532 induced trench sedimentation is punctuated with events of chaotic, mass-533 remobilization, possibly induced by tectonic processes. Thanks to the low-grade of 534 metamorphism and the good level or preservation of even delicate structures, these 535 chaotic deposits allow deciphering in detail the history of their clastic fraction before it 536 was incorporated in the deposit, making the Bocco Shale an exceptional case study for 537 the reconstruction of the accretionary prism dynamic. Particularly, the reconstructed 538 history of material recycling in the Bocco Shale indicate that the sedimentary and 539 gravitational processes related to prism dynamics and instability are the most efficient 540 mechanism of lithological mixing in subduction margins, that need to be considered 541 and reconstructed in detail when evaluating mass and fluid flow. As said, these 542 processes primarily control the degree of heterogeneity of material entering the plate

interface, which in turn influence strongly the mechanic and seismic character and
evolution of the plate interface, and their definition and characterization if therefore
crucial for our understanding and forecast of the plate interface slip behaviour through
space and time.

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549 **Conclusions**

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551 We can summarize the main results of this study as follows:

552 - The Bocco Shale is a chaotic deposit characterized by wide compositional and facies

variability with trench-confined distal thin-bedded turbidites repeatedly re-worked by

554 MTD-forming processes at the lower slope-trench boundary.

555 - The described facies association in the Bocco Shale preserves evidence of a long-lived

history of re-mobilization and recycling of heterogenous material during subduction.

557 - The low-grade of metamorphism and the good level or preservation of the Bocco558 Shale chaotic deposits allow deciphering in detail the history of their formation,

559 making the Bocco Shale an exceptional case study.

The Bocco Shale records a complex interplay between sedimentary/gravitational and
 tectonic processes in which the typical, gravitation-induced trench sedimentation is
 punctuated with events of chaotic, mass-remobilization, possibly induced by tectonic
 processes as frontat tectonic erosion.

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Fig. 1. a) Overview of the collisional belts surrounding the Mediterranean Sea; b) tectonic sketch map of the Northern Apennines; c) regional cross section through the Ligurian Northern Apennines showing the main relationships between the different tectono-stratigraphic groups of units, representative of different paleogeographic domains. The Internal Ligurian Units are indicated (Modified from Marroni et al. 2017).

Fig. 2. Simplified stratigraphic columns of the Internal Ligurian tectonic units whose
successions feature the Bocco Shale as closing formation. In the figure the local names
of the Bocco Shale formation are also indicated.

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914 Fig. 3. Synthetic stratigraphic log of the Internal Ligurian Units showing the lithologies 915 and the depositional environment of the main formations constituting the 916 sedimentary succession. OPH, ophiolite sequence; CH, cherts; CL, Calpionella 917 Limestone; PS, Palombini Shale; Val Lavagna Shale Group including: MS, 918 Manganesiferous Shale; MV, Monte Verzi Marls; ZS, Zonati Shale (corresponding to the 919 Ronco and Canale formations); GS, Gottero Sandstone; BS, Bocco Shale (including also 920 Colli/Tavarone Formation, and Lavagnola Formation); a, debris flow and arenites in the 921 Zonati Shale, cf. olistostroma del Passo della Forcella; b, ophiolite-bearing lithoarenites 922 in the Gottero Sandstone. (Modified from Marroni et al. 2017).

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Fig. 4. Paleotectonic reconstruction of the Ligure-Piemontese oceanic basin and its
transition to the Europe and Adria continental margins during the Late Cretaceous
subduction. Explanation: IL, Internal Ligurian Domain; EL, External Ligurian Domain;
SBL, Subligurian Domain. (Modified from Marroni et al., 2010).

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Fig. 5. Cross section of the Colli/Tavarone Formation (= Bocco Shale) in the
Colli/Tavarone Unit outcropping in the Vara Valley, showing the angular unconformity
between the Colli/Tavarone Formation and its substratum, represented here by the
Val Lavagna Shale and Palombini Shale. The Colli/Tavarone Formation is overthrust by
the Bracco-Val Graveglia Unit, as visible on top of the cross section (PS, Palombini
Shale; VLS, Val Lavagna Shale; TBT, thin-bedded turbidite facies (Bocco Shale).

a) "slide-block-in-matrix" facies with clasts reworking the Palombini Shale ; b) cohesive
debris flow (F1 facies of Mutti, 1992) from the Bocco Shale; c) thin-bedded turbidites
facies (TBT) from the Bocco Shale.

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939 Fig. 6. Field-scale primary relationships between Bocco Shale and the sedimentary 940 cover of Internal Ligurian Units. a) Angular relationships between Bocco Shale and 941 Palombini Shale (Colli/Tavarone Unit, Vara Valley). A pebbly-mudstone, consisting of 942 reworked calcilutites boulders, pebbles and slide-blocks derived from Palombini Shale 943 unconformably overlies a substratum made up of Palombini Shale. The bedding 944 surface for Palombini Shale (S0 PS) and Bocco Shale (S0 BS) are indicated. Modified 945 from Marroni and Pandolfi (2001); b) stratigraphic relationships between Ronco 946 Formation (= Val Lavagna Shale) and the ophiolite-bearing breccia belonging to 947 Lavagnola Formation (= Bocco Shale, cf. Fig.2) formed by a quasi-monogenic 948 serpentinite clast-supported breccia.

949

950 Fig. 7. Microscopic-scale sedimentary features of the Bocco Shale:

951 a-b) photomicrographs of the pebbly-mudstone matrix showing its characteristic 952 intrarenitic aspect made by muddy and silty soft clasts. c) Ophiolite-bearing 953 lithoarenites from Bocco Shale (serp, serpentinite fragment; bas, basalt fragment; 954 arrow indicate picotite crystals in serpentinite fragment); d) photomicrograph of thin-955 bedded turbidite facies (TBT). The not-reworked aspect of these sediments is indicated 956 by the lamina (arrows); e) TBT clast reworked in the matrix of a pebbly-mudstone. 957 These clasts show often a "soft clast" appearence (arrow); f) petrofacies of a rare 958 medium- to coarse-grained arenite from the TBT facies. The arkose composition is 959 comparable with the Zonati Shale and Gottero Sandstone framework composition (see 960 also fig.10).

961

962 Fig. 8. Microscopic-scale structural features of the Bocco Shale formation:

963 a) close-up of a micritic clast (reworked from the Palombini Shale, ps) showing 964 evidence of a pre-Bocco Shale deformation. White arrow indicate a pre-clast-fracture 965 calcite veins. Black arrow, instead, indicate a post Bocco Shale calcite veins affecting 966 both clast and matrix (m); b) flattening of the soft-clasts in the Bocco Shale matrix. The 967 main S1 foliation parallel to the soft-clast flattening is indicated (S0=S1); c) D1 phase-968 related shear zone developed in the reworked-matrix of Bocco Shale. The shear sense 969 is indicated; d) effect of the D1 and D2 phases on the Bocco-Shale matrix formed by 970 both fine grained arenites and silty soft-clasts. The S1 and S2 foliations crosscut both 971 soft-clasts and matrix.

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Fig. 9. Field and microscopic evidence of a polyphase deformation history recognized
in the clasts (derived from the Internal Ligurian Units) forming the Early Oligocene Val
Borbera and Persi formations (Tertiary Piemontese Basin).

a) clast of folded metapelite from the Persi Formation.; b) two foliations (S1 and S2)
recognized inside a clast of Val Lavagna Shale forming the framework of the Val
Borbera Conglomerate.

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980 Fig. 10. 3D paleotectonic reconstruction of the Ligure-Piemontese oceanic domain 981 during the oceanic lithosphere subduction and sedimentation of the Bocco Shale. The 982 scheme proposes a sediments dispersal pattern that take into account the two main 983 source areas that feed the Bocco Shale: the Europe continental margin and the 984 accretionary prism. The framework composition of the different source areas can be 985 inferred from the triangular diagrams. Q-F-L and Lm-Lv-Ls triangular diagrams from 986 Valloni & Zuffa (1984), Van de Kamp & Leake (1995), Pandolfi (199) and Marroni & 987 Pandolfi (2001).

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Fig. 11. 2D paleotectonic reconstruction of the Bocco Shale tectono-depositional environment. The thick red lines schematize the recycling processes that characterized the lower slope-trench boundary during evolution of subduction. The boxed numbers represent the steps described in the text. The framework composition of the different formations and lithofacies is indicated in the right side of the column using Q-F-L and Lm-Lv-Ls triangular diagrams. Diagrams built after data of this study (see also Pandolfi, [1997]) and data from Valloni & Zuffa, [1984]; Van de Kamp & Leake, [1995]; Marroni 8 Pandolfi [2001]. The inferred paleogeographic position of the units of figure 2c is9 indicated.





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figure 5

















