



AperTO - Archivio Istituzionale Open Access dell'Università di Torino

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

This is the author's manuscript

Original Citation:

Availability:

This version is available http://hdl.handle.net/2318/1637837

since 2018-06-13T14:42:37Z

Published version:

DOI:10.1130/L605.1

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)





This is the author's final version of the contribution published as:

Paola Tartarotti1, *; Festa, Andrea; Benciolini, Luca; Balestro, Gianni. Record of Jurassic mass transport processes through the orogenic cycle: Understanding chaotic rock units in the high-pressure Zermatt-Saas ophiolite (Western Alps). LITHOSPHERE. 9 (3) pp: 399-407. DOI: 10.1130/L605.1

The publisher's version is available at: http://lithosphere.geoscienceworld.org/lookup/doi/10.1130/L605.1

When citing, please refer to the published version.

Link to this full text: http://hdl.handle.net/

This full text was downloaded from iris - AperTO: https://iris.unito.it/

1 Abstract (max. 200 parole)

2 The eclogite-facies Zermatt-Saas ophiolite in the western Alps includes a composite chaotic unit exposed in the Lake Miserin area located in the southern Aosta Valley region. The chaotic unit is 3 4 characterized by a block-in-matrix texture consisting of mafic/ultramafic clasts and blocks 5 embedded within a carbonate-rich matrix. This unit overlies massive serpentinite and 6 ophicarbonate rocks and is unconformably overlain by layered carbonate-rich calcschists. Despite 7 the effects of subduction and collision-related deformation and metamorphism, the internal 8 stratigraphy and architecture of the chaotic unit is recognizable and attributed to mass transport 9 processes, actingin the Jurassic Ligurian - Piedmont Ocean. This finding represents an exceptional 10 record of the pre-orogenic history of the Alpine ophiolites marked by different pulses of extensional 11 tectonics responsible of the rough seafloor topography characterized by structural highs exposed 12 to submarine erosion. The Jurassic tectono-stratigraphic setting here envisioned is closely 13 comparable with that observed in present-day "magma-poor" slow- and ultraslow-spreading ridges 14 characterized by mantle exposure along fault scarps which trigger mass transport deposits and turbiditic sedimentation. Our pre-orogenic reconstruction is significant in an eclogitized collisional 15 16 orogenic belt in which, chaotic rock units may be confused with the exclusive product of subduction-related tectonics, deleting the record of an important pre-orogenic history. 17

18

19

- 20
- 21
- Key words: Western Alps; ophiolite; syn-extension and post-extension sedimentary sequences,
 mélanges and broken formations; mass transport deposits.

25

26 INTRODUCTION

27

Jurassic Tethyan ophiolites emplaced in the Alpine orogen widely contributed to the 28 discussion on the ophiolite concept (see Lagabrielle, 2009 for a review). Although, in the last two 29 decades, the attention on Alpine ophiolites was mainly focused on the definition of their 30 31 subduction- and collision-related P-T-t trajectories, multidisciplinary field studies demonstrated that those ophiolite may preserve meaningful records of the pre-Alpine ocean-related history (e.g., 32 Balestro et al., 2015a; Festa et al., 2015), allowing to reconstruct the Jurassic tectonostratigraphic 33 architecture, which is comparable with that observed in present-day "magma-poor" slow- and 34 35 ultraslow-spreading ridges (e.g., Mével et al., 1991; Dick et al., 2003; Boschi et al., 2006; Escartin et al., 2008). 36

37 In this paper, we document the internal architecture of the Lake Miserin Ophiolite (LMO hereafter), which is part of the eclogite-facies Zermatt-Saas ophiolite (Western Alps). Detailed 38 39 stratigraphic and structural analysis of different block-in-matrix structures occurring in a composite 40 chaotic unit, allowed us documenting that, despite the overprint of subduction and collision-related deformation, exceptional records of intra-oceanic tectono-sedimentary processes are preserved as 41 42 the product of tectonically induced mass transport processes, which acted along the flanks of a 43 mantle structural high in the Jurassic Ligurian - Piedmont Ocean (JLPO herefater). The Jurassic tectono-stratigraphic setting which we reconstruct is closely comparable with those observed in 44 present-day "magma-poor" slow- and ultraslow-spreading ridges (e.g., Mével et al., 1991; Cannat, 45 1993; Dick et al., 2003; Boschi et al., 2006), providing profound implications in interpreting the 46 47 primary physiography and paleo-topography of the JLPO seafloor and in better understanding 48 present-day oceanic settings.

- 49
- 50

51 REGIONAL GEOLOGY

The Zermatt-Saas ophiolites (Bearth, 1967; see Martin et al., 1994 for a review) emplaced during the closure of a branch of the Jurassic Tethyan ocean (i.e., the JLPO), interposed between the European and African plates. They are tectonically stacked in the axial sector of the Western Alps (i.e. the Piedmont Zone; see e.g. Dal Piaz et al., 2003), resulting from deformation and metamorphism occurred during (i) Late Cretaceous to Middle Eocene SE-dipping subduction, (ii) Late Eocene–Early Oligocene collision and NW-verging accretion, and (iii) Oligocene to Neogene exhumation.

The LMO crops out in the southern sector of the Mount Avic ultramafic massif (Fig. 1). The latter 60 shows an early Alpine metamorphic overprint under eclogite-facies conditions, partially re-61 equilibrated under blueschists- to greenschists-facies conditions (e.g., Dal Piaz et al., 2010), and 62 63 consists of serpentinized metaperidotite intruded by Fe-Ti- and Mg-metagabbros, which are covered by different metasedimentary successions (Fontana et al., 2008; Panseri et al., 2008). The 64 northern sector of the Mount Avic ultramafic massif is particularly characterized by the occurrence 65 of (i) mafic/ultramafic metabreccia and meta-ophicalcite (Tartarotti et al., 1998; Dresnier, 1993), 66 67 documenting mantle sea-floor exhumation, and (ii) Mn ore deposits and Fe-Cu sulphide mineralizations. The latters were attributed to original hydrothermal vents (i.e. black smokers; 68 69 Martin et al., 2008; Tumiati et al., 2010), highlighting that mantle rocks were exhumed close to a 70 ridge center.

71

72

73 THE LAKE MISERIN OPHIOLITE (LMO)

74

The LMO consists of serpentinite followed, through a meta-ophicalcite horizon, by a Composite
Chaotic Unit (CCU hereafter) made of serpentinite blocks and disrupted metasandstone and
metabreccia horizons of ultramafic composition, embedded within a carbonate-rich matrix. A
Calcschist Unit directly overlies either the CCU, or the serpentinite and meta-ophicalcite (Figs. 2AC).

80 The serpentinite derives from peridotite of likely lherzolite composition. It consists of antigorite with mesh texture, Ti-clinohumite, oxides (Cr-Ni-rich magnetite, ilmenite, and chromite with Cr# ranging 81 82 between 60 and 80), and clinopyroxene with both magmatic augite (En₄₇₋₄₉, Wo₄₈₋₅₀, Fs₁₋₂) and metamorphic diopside/wollastonite (En_{45-48.} Wo₄₉₋₅₁, Fs₁₋₃) compositions. Upwards, the serpentinite 83 contains crosscutting sets of veins, up to 1-2 cm thick and filled with carbonate, antigorite, or talc, 84 which bound decimeter- to meter-sized "clasts" of massive serpentinite. Veined serpentinite are 85 86 covered by a meta-ophicalcite horizon (Fig. 3A), up to one meter thick and both are characterized by the occurrence of carbonate-rich nodules with a typical orange colored alteration coating. 87 The LMO was deformed during at least three superposed Alpine-related deformation phases 88 (named D1, D2 and D3). D1 is coeval to the subduction-related eclogite-facies metamorphism, and 89 90 developed the S1 foliation, which is parallel to the lithological contacts and overprinted the primary surfaces (i.e., the S0 sedimentary bedding). D2 is coeval to the collision-related blueschists- to 91 greenschists-facies re-equilibration, and is characterized by N-S trending isoclinal folds (Fig. 2D) 92 93 which pervasively deform the meta-ophiolite succession. D2 folds developed a W-NW-dipping axial 94 plane foliation (i.e. the S2) and are characterized by boudinage along long fold limbs. D3 is coeval to the exhumation stage and is characterized by NW-SE trending gentle folds (Fig. 3E) which 95 deform the previous D1+D2 structural architecture. 96

97

98 The Composite Chaotic Unit (CCU)

The CCU corresponds to a wedge shaped unit in cross-section, which increases in thickness from zero to about 40 meters from WSW to ENE and N (Fig. 2), showing lateral and vertical change of facies of its block-in-matrix fabric. It consists of three types of broken formation (*sensu* Hsü, 1968), i.e., BrFm1, BrFm2 and BrFm3, and a sedimentary mélange (*sensu* Raymond, 1984 and Festa et al., 2012), i.e., SedMé. The contact between the different types of chaotic rock units is transitional and it does not show any traces of Alpine-related mylonitic deformation.

105

106 <u>Type 1 Broken Formation (BrFm1)</u>

The BrFm1 consists of different superposed bodies of ultramafic metabreccia, ranging in 107 thickness from 1 to 3 m (Figs. 2F-G), and characterized by an internal normal grading. Metabreccia 108 109 varies from clast- to matrix supported, with irregular to sub-rounded shaped clasts ranging in size from decimeters to centimeters (Fig. 3B). The matrix consists of a coarse-grained metasandstone 110 of the same composition of clasts. Rare elongated blocks, up to 50 cm long, are randomly 111 distributed within the metabreccia. The BrFm1 shows a lenticular shape at scale of hundreds of 112 113 meters with a maximum thickness of about 15 m (Figs. 2F-G). The contact with serpentinite is 114 sharp, locally corresponding to a decimeters thick layer of coarse -to medium-grained metasandstone of ultramafic composition. 115

116

117 <u>Type 2 Broken Formation (BrFm2)</u>

The BrFm2 consists of disrupted horizons, decimeters in thickness, of clast-to matrix 118 supported metabreccia and coarse-grained metasandstone embedded in a carbonate-rich matrix 119 (Fig. 3C), which gradually passes upward from calcschist to whitish marble. It crops out in the 120 121 eastern and northeastern sectors of the studied area, showing a wedge-like shape varying from zero to about 15 m in thickness from SSW to NNE (Figs. 2F-G), and resting directly onto the meta-122 ophicalcite horizon through a sharp contact marked by a centimeters-thick calcschist horizon. 123 Disrupted horizons of detrital ultramafic metabreccia are prevalent in the basal part, and show an 124 125 internal normal grading marked by angular to irregular shaped clasts, up to centimeters in size, 126 passing upward to metasandstone. Those horizons are boudinated at meters scale as a result of 127 D2 deformation (Fig. 3C). The marble matrix prevails in the upper part, showing a transitional 128 contact with the above SedMé unit.

129

130 <u>Sedimentary mélange (SedMé)</u>

The SedMè is characterized by a block-in-matrix fabric (Figs. 3D-E) with mainly rounded to irregular and equiangular exotic blocks of massive to veined-serpentinite and meta-ophicalcite, decimeters to one meter in size, embedded within a whitish marble matrix. Carbonate veins, decimeters long and up to 1-2 cm thick, are bounded within the blocks and does not cross the

matrix (Fig. 3E). Blocks are randomly distributed within the matrix (see Figs. 3D-E) and only rare 135 elongated shaped blocks are aligned to the S2 foliation. The matrix commonly includes 136 137 centimeters-thick horizons of metabreccia of ultramafic composition, which are characterized by angular or sub-angular clasts of serpentinite (Fig. 3F). The entire detrital horizons are foliated (S1-138 S2) and folded (D2), constraining the brecciation process as having occurred before the D1 139 deformation stage (i.e., before the subduction-related deformation stage; Fig. 3G). In the upper 140 141 part of the unit, blocks decrease in size (i.e., up to decimeters) and the matrix is gradually interfingered by centimeters thick levels of calcschist, which marks the transition to the above 142 BrFm3. The SedMé shows a wedge-like shaped geometry ranging in thickness from few meters to 143 15-20 meters, from SW to NE (Figs. 2F-G). In the southwestern sector, it directly overlies the 144 145 massive serpentinite and the meta-ophicalcite.

146

147 Type 3 Broken Formation (BrFm3)

The BrFm3 represents the uppermost part of the CCU. It shows similar characteristics to BrFm2, consisting of a calcschist and marble matrix, embedding disrupted horizons and bed fragments, decimeters to meters long and up to decimeters thick, of medium-grained metasandstone of ultramafic composition (Fig. 3H). The elongated to sigmoidal shape of blocks, is consistent with D2-related boudinage. This unit, which shows an average thickness of about 10 m, decreases in thickness toward WNW where it directly overlies the BrFm1 and it is followed upward by the Calcschist Unit (Figs. 2F-G).

155

156 Calcschist Unit

The CCU and underlying massive serpentinite are unconformably overlain by layered carbonate-rich calcschist (Fig. 2), devoid of any ophiolite-derived detrital material, and alternating with levels of quartz-rich schist. The basal contact between this succession and the underlying lithostratrigraphic units is sharp and corresponds to a depositional surface as inferred form the lack of any mylonitic structure associated with it (Fig. 3I). The unconformable contact at the base of

162 calcschist is folded together with the units below due to the superposition of D2- and D3-related163 folding (Fig. 2B).

164

165

THE LAKE MISERIN OPHIOLITE AS A PRODUCT OF JURASSIC MASS TRANSPORT PROCESSES

168

We interpret the LMO as a remnant of an intra-oceanic structural high of the JLPO 169 lithosphere and the CCU as the product of downslope mass transport processes related to 170 Jurassic extensional tectonics. By unravelling the Alpine deformation in the CCU, it is possible to 171 understand its significance in the context of extensional tectonics leading to mantle exhumation in 172 the JLPO. The chaotic block-in-matrix arrangement of BrFm2 and BrFm3, is related to the tectonic 173 dismemberment of their primary stratigraphic organization by means of the D1- and D2 Alpine 174 deformation, whereas the BrFm1 and SedMé fabric was acquired by mass-transport processes 175 176 acted at the time of Jurassic extensional tectonics.

177 The BrFm2 and BrFm3 consist of calcschist with disrupted horizons of metasandstone and metabreccia of ultramafic composition which represent native components (i.e., turbiditic horizons) 178 179 with respect to the carbonate-rich matrix (e.g., Balestro et al., 2015b). The BrFm1, which consists 180 of blocks and matrix of the same composition, corresponds to a "serpentinite matrix broken 181 formation", being composed of only native components, but showing strong analogies with 182 "serpentinite matrix mélanges" described in the Franciscan Complex and US-Western Cordillera (e.g., Wakabayashi, 2015 and reference therein). The block-in-matrix arrangement of the SedMé 183 represents the emplacement of exotic components with respect to the carbonate matrix. The 184 185 random distribution of blocks suggests an original emplacement through gravitational processes (see below), rather than tectonic slicing. The occurrence of carbonatic veins, which are bounded 186 within the same blocks, also constrains their exotic nature, sourced from the primary ophicalcite 187 horizon. 188

190 The Composite Chaotic Unit: a record of tectono-sedimentary processes

The wedge-shaped architecture of the CCU, its internal fabric and subdivision, and the 191 192 nature of the contacts with the underlying serpentinite suggest tectonically induced mass transport sedimentation spatially and temporally associated with extensional deformation and erosion along 193 an intra-oceanic bathymetric high (Figs. 4A-D). The vertical and lateral organization of the BrFm2, 194 which consists of a wedge-shaped fining-upward succession of alternating 195 196 metabreccia/metasandstone horizons of ultramafic composition and calcschist passing upward to marble, represents the deposition of channelized turbidites. The prevalent occurrence of 197 brecciated horizons alternating with calcschist in the lower part of this succession suggests 198 199 proximal deposition close to a submarine escarpment with high depositional energy, recording a 200 first extensional stage of mantle denudation (Fig. 4A). The upward gradual increasing of the 201 carbonate component within the matrix and decreasing of grain size within the ultramafic detrital horizons, are consistent with the progressive decrease of depositional energy, suggesting in turn a 202 decrease of tectonic activity and/or deepening of the relative sea level. 203

204 The block-in-matrix arrangement of the SedMé, with serpentinite blocks embedded within a carbonate matrix, records a new significant pulse of extensional tectonics (Fig. 4B). The random 205 distribution of blocks within the matrix and the occurrence of carbonate veins confined only within 206 207 the blocks, suggests their collapse from bathymetric/structural highs exposing both serpentinized 208 peridotite and ophicalcite. The upward decrease of blocks size up to the gradual transition to 209 BrFm3, is consistent with the gruadual decrease in magnitude of this tectonic activity. BrFm3 records a new turbititic input (Fig. 4C). Its direct superposition onto the BrFm1 (Fig. 3B) and locally 210 211 onto the serpentinite suggests that the BrFm1 was originally located on a topographic high mainly 212 consisting of mantle rocks exposed to in situ mechanical fracturing and erosion, thus representing 213 part of the source area for the ultramafic detrital components interfingered within the CCU (Figs. 214 4B-C).

The wedge shape of the CCU, which thickens toward ENE, is consistent with the vertical change of facies of each single unit and with a paleo-escarpment probably dipping toward the same direction (at present-day coordinates).

The unconformable deposition of the Calscschist Unit (Fig. 4D), overlying both the CCU and 218 the serpentinite, represents a post-extensional succession that was deformed and folded during 219 220 Alpine tectonic stages, together with the underlying sequence. Ophiolitic-detrital material is lacking and the occurrence of quartz-rich schist records an input of continental-derived sediments within 221 222 the basin, which is thus filled by distal mixed siliciclastic-carbonatic turbidites reworking a passive margin source area. This depositional stage, which coincides with significant terrigenous input into 223 224 the basin, is well comparable with Early Cretaceous post-extensional deposits preserved in the unmetamorphosed Ligurian Units in the Northern Apennines (e.g., Decandia and Elter, 1972). 225

226

227 The Lake Miserin ophiolite and the physiography of the Jurassic Ligurian – Piedmont

228 seafloor

Pre-orogenic reconstruction of the LMO implies tectonic denudation of mantle rocks at the 229 seafloor of the JLPO, as it has been widely documented in modern slow- and ultraslow-spreading 230 ridges (e.g., Mével et al., 1991; Dick et al., 2003; Escartin et al., 2008). Meta-ophicalcite records 231 232 the early history of lithospheric mantle exumation by extensional tectonics, and of concurrent hydrothermal fluids circulation on the JLPO seafloor. Brecciation and mass transport deposits 233 recorded in the CCU are evidence of tectonically-induced sedimentation during the mature stage of 234 235 ocean opening, thus representing syn-extensional (i.e., syn-rift) deposits. Similar serpentinite 236 breccias have been observed in serpentinite bodies of the Atlantic ocean exposed along the western median valley wall of the MARK (Mid Atlantic Ridge-Kane fracture zone) area. 237 Submersible diving on Alvin (Karson et al., 1987) and Nautile (Mével et al., 1991) reveal that this 238 239 region is characterized by active faulting and mass wasting dominated by extensive debris slide 240 deposits (see also Karson and Lawrence, 1997): along steep fault scarps foliated serpentinites are 241 directly overlain by coarse, clast-supported breccia consisting of angular cobbles of foliated 242 serpentinite in a matrix of consolidated carbonate. Furthermore, in the median valley wall of the 243 MARK area, mass transport processes has produced rock deposits with angular shapes, similar to those found in our broken formations. In our model, the serpentinite breccia of BrFm1 could have 244 been reactivated by normal faults (as suggested for the MARK area; see Karson and Lawrence, 245

1997) providing the source material delivered to breccia of BrFm2, BrFm3 and SedMé.

The recognition, for the first time in this sector of the Western Alps of the unconformable 247 248 deposition of the post-extensional Calcschist Unit, sealing the syn-extensional LMO architecture, is well comparable with the Valanginian-early Aptian post-rift siliciclastic rocks interfingering with 249 carbonate-rich turbiditic deposits in the Deep Galicia margin (Winterer et al., 1988), which 250 represents an excellent modern analogue for the post-extensional succession that we describe 251 252 from the LMO. The close similarity with the Early Cretaceous post-extensional calcschist in other Alpine (Festa et al., 2015) and Northern Apennines (e.g., Decandia and Elter, 1972) ophiolites, 253 marks the critical timing of the final opening stages of the JLPO. 254

Our results have thus profound implications for the physiography and geodynamics of the JLPO: the occurrence of pre-orogenic, syn-extensional deposits indicate that the seafloor of the JLPO should have been characterized by regions of active faulting responsible for the formation of a rugged seafloor topography exposed to widespread gravitational processes (Fig. 4E. Furthermore, the occurrence of paleo-hydrothermal vents in the ultramafic massif (i.e. the Mount Avic) which includes the LMO, highlights that mantle rocks were exhumed close to a ridge center (Fig. 4E).

- 262

263 CONCLUSIONS

264

Our findings document, in the eclogitized Zermatt-Saas ophiolite, exceptionally preserved 265 records of mass transport deposits and turbiditic sedimentation, which formed by intra-oceanic 266 267 tectono-sedimentary processes during the Late Jurassic syn-rift stages of the Ligurian – Piedmont 268 oceanic basin. The understanding of the meaning of each type of chaotic rock unit within the LMO 269 allowed us to detail the role played by different pulses of extensional tectonics associated with 270 mantle exhumation and their control of sedimentation. This is significant to be reconstructed in an 271 eclogitized collisional orogenic belt in which, the occurrence of chaotic rock units may be commonly confused and interpreted as the exclusive product of subduction-related tectonics, 272 deleting the record of an important pre-orogenic history. Significant for our interpretation resulted 273

the detailed analysis of block-in-matrix structures in the CCU, which allowed unraveling Alpine
deformation and reconstructing pre-Alpine history.

276

277

278 **REFERENCES**

- Balestro, G., Festa, A., Dilek, Y., and Tartarotti, P., 2015a, Pre-Alpine extensional tectonics of a
 peridotite-localized oceanic core complex in the Late Jurassic, high-pressure Monviso.
 Episodes, v.38(4), p.266-282.
- Balestro, G., Festa, A., and Tartarotti, P., 2015b, Tectonic significance of different block-in-matrix
 structures in exhumed convergent plate margins: Examples from oceanic and continental
 HP rocks in inner western Alps (northwest Italy): International Geology Review, v.57(5–8),
 p.581–605.
- Boschi, C., Früh-Green, G.L., and Delacour, A., 2006, Mass transfer and fluid flow during
 detachment faulting and development of an oceanic core complex, Atlantis Massif (MAR
 30°N): Geochemistry, Gephysics, Geosystem, v.7, doi: 10.1029/2005GC001074.
- Bearth, P., 1967, Die Ophiolithe der Zone von Zermatt-Saas Fee. Beiträge zur Geologischen Karte
 der Schweiz, Neue Folge, 132, 130 pp.
- Dal Piaz, G.V., Bistacchi, A., and Massironi, M., 2003, Geological outline of the Alps: Episodes,
 v.26, p.175–180.
- Dal Piaz, G.V., Pennacchioni, G., Tartarotti, P., Carraro, F, Gianotti, F., Monopoli, B., G., Schiavo,
 A., 2010, Carta Geologica d'Italia alla scala 1:50.000, Foglio 091 "Chatillon" con Note
 Illustrative, Ed. ISPRA.
- Decandia, F.A., and Elter, P., 1972, La "zona" ofiolitifera del Bracco nel settore compreso fra
 Levanto e la Val Graveglia (Appennino Ligure): Memorie della Societa Geologica Italiana,
 XI, p.503–530.
- Dick, H.J.B., Lin, J., and Schouten, H., 2003, An ultraslow-spreading class of ocean ridge: Nature,
 v. 426, p.405-412.

Driesner, T., 1993, Aspects of petrographical, structural and stable isotope geochemical evolution
 of ophicarbonate breccias from ocean floor to subduction and uplift; an example from
 Chatillon, Middle Aosta Valley, Italian Alps: Schweiz. Mineral. Petrogr. Mitt., v.73(1), p.69 84.

305 Escartin, J., and Canales, J.P., 2011, Detachments in oceanic lithosphere: Deformation,

- 306 magmatism, fluid flow and ecosystems: Eos, Transactions, American Geophysical Union,
 307 v.92, pp.31.
- Escartin, J., Smith, D.K, Cann, J., Schouten, H., Langmuir, C.H., and Escrig, S., 2008, Central role
 of detachment faults in accretion of slow-spreading oceanic lithosphere: Nature, v.455,
 doi: 10.1038/nature07333.
- Festa, A., Dilek, Y., Pini, G.A., Codegone, G., and Ogata, K., 2012, Mechanisms and processes of
 stratal disruption and mixing in the development of mélange and broken formations:
 Refining and classifying mélanges: Tectonophysics, v.568-569, p.7-24.
- Festa, A., Balestro, G., Dilek, Y., and Tartarotti, P., 2015, A Jurassic oceanic core complex in the high-pressure Monviso ophiolite (western Alps, NW Italy): Lithosphere, v. 7, p.646-652.
- Fontana, E., Panseri, M., and Tartarotti, P., 2008, Oceanic relict textures in the Mount Avic
 serpentinites, Western Alps: Ofioliti, v. 33(2), p.105-118.
- Hsü, K. J., 1974, Melanges and their distinction from olistostromes: SEPM Spec. Publ., v.19, p.
 319 321-333.

Karson, J.A., Thompson, G., Humphris, S.E., Edmond, J.M., Bryan, W.B., Brown, J.R., Winters,

A.T., Pockalny, R.A., Campbell, A.C., Klinkhammer, G., Palmer, M.R., Kinzler, R.J., and Sulanowska, M.M., 1987, Along axis variations in seafloor spreading in the MARK area: Nature, v.328, p.681-685.

- 324 Karson, J.A. and Lawrence, R. M., 1997, Tectonic setting of serpentinite exposures on the
- Western median valley wall of the MARK area in the vicinity of Site 920, In: Karson, J.A.,
- 326 Cannat, M., Miller, D.J., and Elthon, D. (Eds.), Proceedings of the Ocean Drilling Program,

327 Scientific Results, v.153, p.5-21.

Lagabrielle, Y., 2009, Mantle exhumation and lithosphere spreading: An historical perspective from

- investigations in the oceans and in the Alps-Apennines ophiolites: Italian Journal of
 Geosciences, v.128 (2), p.279-293.
- Martin, S., Tartarotti, P., and Dal Piaz, G.V., 1994, The Mesozoic ophiolites of the Alps: a review:
 Boll. Geofisica Teoria e Applicata, v.36, p.175-219.
- Martin, S., Rebay, G., Kienast, J.-R., and Mével, C., 2008, An eclogitised oceanic palaeo-
- hydrothermal field from the St. Marcel valley (Italian Western Alps): Ofioliti, v.33(1), p.4963.
- Mével, C., Cannat, M., Gente, P., Marion, E., Auzende, J.-M. and Karson, J.A., 1991,
- Emplacement of deep crustal and mantle rocks on the west median valley wall of the MARL area (MAR, 23°N): Tectonophysics, v.190, p.31-53.
- Panseri, M., Fontana, E., and Tartarotti, P., 2008, Evolution of rodingitic dykes: metasomatism and
 metamorphism in the Mount Avic serpentinites (Alpine ophiolites, southern Aosta valley):
 Ofioliti, v.33 (2), p.165-185.
- Raymond, L.A., 1984, Classification of melanges, Geol. Soc. Am. Special Paper n. 198, p. 7-20.
- 343 Tartarotti, P., Benciolini, L., and Monopoli, B., 1998, Brecce serpentinitiche nel massiccio
- ultrabasico del Monte Avic (Falda Ofiolitica Piemontese): possibile evidenze di erosione
 sottomarina: Atti Tic. Sc. Terra, v.7, p.73-86.
- Tumiati, S., Martin, S., Godard, G., 2010, Hydrothermal origin of manganese in the high-pressure
 ophiolite metasediments of Praborna ore deposit (Aosta Valley, Western Alps). European
 Journal of Mineralogy, v.22, p.577–594
- Wakabayashi, J., 2015, Anatomy of a subduction complex: architecture of the Franciscan
 Complex, California, at multiple length and time scales: International Geology Review,
 v.57, p.669-743.
- Winterer, E.L., Gee, J.S., and Van Waasbergen, R.J., 1988, The source area for Lower
- 353 Cretaceous clastic sediments of the Galicia Margin: geology and tectonic and erosional 354 history, *in* Boillot, G., Winterer, E.L., et al., Proc. ODP, Scientific Results, v.103: College 355 Station, TX (Ocean Drilling Pro-gram), p.697-732.
- 356

357

358 FIGURE CAPTIONS

359

Figure 1. Geographic location of the study area (A) and tectonic map of the Northwestern Alps (B)
 (modified after Balestro et al., 2015).

362

Figure 2. Geological map (A) and cross section (B) of the LMO. Photographs showing: the panoramic view of the unconformable contact (dotted blue line) of the Calcschist Unit (CSU) above the Composite Chaotic Complex (CCU) (C); D2 isoclinal folds deforming S1 foliation (defined by the serpentinite metarenite/calcschist contact) (D); D3 gentle folds ondulating the S2 foliation (E). Stratigraphic columns (F) and their three-dimensional correlation (G), showing the relationships between the ophiolite basement and the different types of chaotic rock units within the CCU.

369

Figure 3. View of the LMO and CCU: (A) Close up view of the meta-ophicalcite horizon consisting 370 371 of serpentinite crosscutted by sets of veins, cm-thick, of carbonate, antigorite, or talc; (B) BrFm1 consisting of alternating clast- to matrix-supported ultramafic metabreccia horizons, followed by the 372 BrFm3; (C) Close-up view of the BrFm2, showing disrupted and boudinated horizons of ultramafic 373 374 metasandstone (arrows) embedded in a sheared carbonate-rich matrix to form the block-in-matrix 375 arrangement; (D) Block-in-matrix fabric of the SedMé with dm- to meters wide "exotic" blocks of 376 serpentinite (dashed white line), randomly distributed within a whitish marble matrix; (E) Close-up view of isolated blocks of ophicalcite with carbonate veins (arrows), decimeters long and 1-2 cm 377 thick, in the SedMé. Note that veins are bounded within the blocks and do not cross the hosting 378 whitish marble matrix; (F) Close-up view of the SedMé consisting of horizons of ultramafic 379 380 metabreccia with angular clasts of serpentinite embedded within the marble matrix. (G) Close-up 381 view of foliated (S2; dashed black line) ultramafic metabreccia in SedMé showing centimeter-sized. irregularly shaped clasts which mark the relict S1 foliation (dashed white line) deformed by D2 382 383 folds; (H) Disrupted horizons and bed fragments of ultramafic composition (arrows) embedded

- 384 within a matrix of alternating calcschist and marble beds of BrFm3; (I) Unconformable contact
- 385 (dotted line) of the Calcschist Unit above the serpentinite.
- 386
- 387 Figure 4. Cartoon showing different stages (A-D) of syn- to post-extensional intra-oceanic tectono-
- 388 sedimentary evolution of the CCU in Late Jurassic Early Cretaceous time, and interpreted three-
- 389 dimensional intra-oceanic reconstruction of the physiography of the studied sector of the Ligurian-
- 390 Piedmont Ocean in Late Jurassic time (E) (inspired and modified from Escartin and Canales,
- 391 **2011**).
- 392



Fig 1 - Tartarotti et al.



Fig 2 - Tartarotti et al.



Fig. 3 - Tartarotti et al.



Fig. 4 - Tartarotti et al.