Diagnostic features and field-criteria in recognition of tectonic, sedimentary and diapiric mélanges in orogenic belts and exhumed subduction-accretion complexes

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ABSTRACT

Multiple episodes of deformation during the tectonic evolution of orogenic belts and ancient subduction-accretion complexes cause obfuscation of primary block-in-matrix fabric of mélanges, and thereby making the recognition of their tectonic, sedimentary or diapiric origin difficult. Here we present a comprehensive overview and synthesis of a diverse set of field-based stratigraphic and structural criteria, which are at the base of geological mapping rules, to differentiate between various mélange types, developed by disparate geological processes and mechanisms. We first define the current concepts of mélange and mélange nomenclature, and describe the most diagnostic features of tectonic, sedimentary and diapiric mélanges at different scales. We discuss some of the main issues complicating the application of these diagnostic criteria, such as: (i) similarities between the block-in-matrix fabric of different mélange types formed in partially lithified sediments at shallow structural levels, (ii) transformation of fabric elements with increased depth due to tectonic reworking and recrystallization processes, (iii) significance of "exotic" versus "native" blocks in mélange matrix, and (iv) age relationships between blocks and matrix in a mélange. We introduce two additional criteria in approaching these complexities and in recognizing different processes of polygenetic mélanges formation in the field when primary diagnostic fabrics were reworked by multiple deformational events. These new criteria are based on (i) the coherence between lithological compositions of mélange components (blocks and matrix) and characteristics and tectonic evolution of the geodynamic setting of their formation ("tectonic environment criterion"), and (ii) specificity and kinematic coherence in the distribution of deformation between blocks and the matrix ("deformation criterion"). The discussed diagnostic criteria can be applied to all field-based investigations of mélanges and broken formations in orogenic belts and exhumed subduction-accretion complexes around the world, regardless of their location, age, and tectonic history.

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1. Introduction

1.1. The mélange problem in orogenic belts and exhumed subduction-accretion complexes

Since its first introduction in the geological literature nearly 100 years ago by Edward Greenly (1919), the term "*mélange*" has been used extensively to describe the occurrence of chaotic rock assemblages in orogenic belts and ancient subduction-accretion complexes. Details of the block-in-matrix fabric of mélanges reflect a close relationship between processes and mechanisms of their formation (e.g., Hsü, 1968; Berkland et al., 1972; Raymond, 1984, 2015; Cowan, 1985; Bettelli and Panini, 1987; Bettelli et al., 1996; Pini, 1999; Wakita, 2000, 2015; Bettelli and Vannucchi, 2003; Osozawa et al., 2011; Wakabayashi, 2011, 2017b; Festa et al., 2013; Balestro et al., 2015b; Ernst, 2016) and their tectonic settings of development (e.g., Suzuki, 1986; Camerlenghi and Pini, 2009; Festa et al., 2010a, 2010b, 2012, 2016). However, tectonic, sedimentary and diapiric processes at different stages of orogeny commonly disrupt and rework the primary structures, fabric elements and internal stratigraphy of mélanges (e.g., Hsü, 1968; Aalto, 1981; Cloos, 1984; Raymond, 1984; Cowan, 1985; Barber et al., 1986; Clennell, 1992; Festa et al., 2010a; Ernst, 2016; Wakabayashi, 2017a). Not surprisingly, then, contrasting interpretations and models have been proposed for mélanges and their origins (e.g., Cloos, 1982, 1986; Cloos and Shreve, 1988a, 1988b; Gerya et al., 2002; Erickson, 2011; Wakabayashi, 2015; Krohe, 2017). The main challenge in studies of mélanges is the recognition of their original, diagnostic block-in-matrix fabric elements, which provide critical clues for where and how these chaotic rock assemblages formed initially and what they tell us about the nature and interplay of different earth processes and mechanisms during their formation (e.g., Abbate et al., 1970; Cowan and Page, 1975; Aalto, 1981; Page and Suppe, 1981; Raymond, 1984, 2017; Cowan, 1985; Barber et al., 1986; Bettelli and Panini, 1989; Castellarin and Pini, 1987; Orange, 1990; Pini, 1999; Cowan and Pini, 2001; Panini et al., 2002; Bettelli et al., 2004; Festa et al., 2010a, 2013; Codegone et al., 2012a; Hajna et al., 2013; Balestro et al., 2015b; Raymond and Bero, 2015; Wakita, 2015; Ernst, 2016; Wakabayashi, 2011, 2017b; Yan et al., 2018). There is a need in the mélange literature to have systematic, process-oriented criteria to investigate different mélange types and their origin and unique block-in-matrix fabric structures that can be used effectively in the field.

1.2. Objectives of this study

The paper is aimed at streamlining a myriad of existing observations and interpretations from a large number of mélange occurrences around the world in order to have diagnostic field-criteria to recognize mélanges formed by different processes and mechanisms. We focus in this overview on recognizing and recording mélange structures following specific principles that are at the base of geological mapping rules, as well as of stratigraphic, structural and petrological principles, where possible (see, e.g., Hsü, 1974; Cowan, 1978, 1985; Aalto, 1981; Raymond, 1984, 2015, 2017; Pini, 1999; Panini et al., 2002; Bettelli et al., 2004; Cowan and Pini, 2001; Vannucchi and Bettelli, 2010, Festa, 2011; Festa et al., 2010a, 2012, 2013; Wakabayashi, 2011, 2015, 2017c). Our goal is also to make both the classic and modern concepts in the vast mélange literature accessible to those geoscientists, who are not intimately familiar with the debates and differences of opinion about mélange formation processes. In the first part of the paper (Section 2), we introduce the mélange terminology and define some of the most diagnostic features in differentiating various types of mélanges (tectonic, sedimentary and diapiric) at different scales (Section 3). In the second part of the paper (Section 4), we discuss the most common complications in recognizing different mélange types in orogenic belts and exhumed subduction–accretion complexes, which underwent multiple deformation events. We examine in this section how the primary block-in-matrix fabric of different mélange types that developed at shallow structural levels might have transformed into different structures (polygenetic mélanges) when involved and reworked in tectonic shear zones, including subduction plate interfaces at higher depths. We introduce in Section 5 the definition and discussion of two new additional and complementary criteria, which are necessary for a correct distinction of the different processes forming polygenetic mélanges. This synthesis provides selected field-criteria whose correct application is helpful to closely constrain with specific rules the nature of the different types of mélange and polygenetic mélange, their processes of formation and their mutual superposition as occurred during the tectonic and metamorphic evolution of orogenic belts and exhumed subduction-accretion complexes around the world, regardless of their location, age (including Precambrian and Phanerozoic belts), and tectonic history.

2. Mélange nomenclature and terminology: a simplest use of the term mélange

The term "mélange" (Greenly, 1919) is a descriptive and non-genetic term, defining a mappable (at 1:25,000 or smaller scale) body of internally disrupted and mixed rocks in a pervasively deformed matrix (Berkland et al., 1972; Wood, 1974; Silver and Beutner, 1980; Raymond, 1984; Cowan, 1985). This term must be used only when "exotic" blocks (with or without "native" blocks) occur within a matrix (Fig. 1), and is not restricted to any particular lithological units (e.g., Raymond, 1984).

The term "exotic", whose meaning largely changes on the basis of the background of geoscientists, the structural level and the tectonic setting investigated, and the nature (tectonic, sedimentary or intrusive) of mélanges (see, e.g., Hsü, 1968; Berkland et al., 1972; Raymond, 1984, 2017; Alonso et al., 2006; Festa et al., 2012), is here proposed to be used

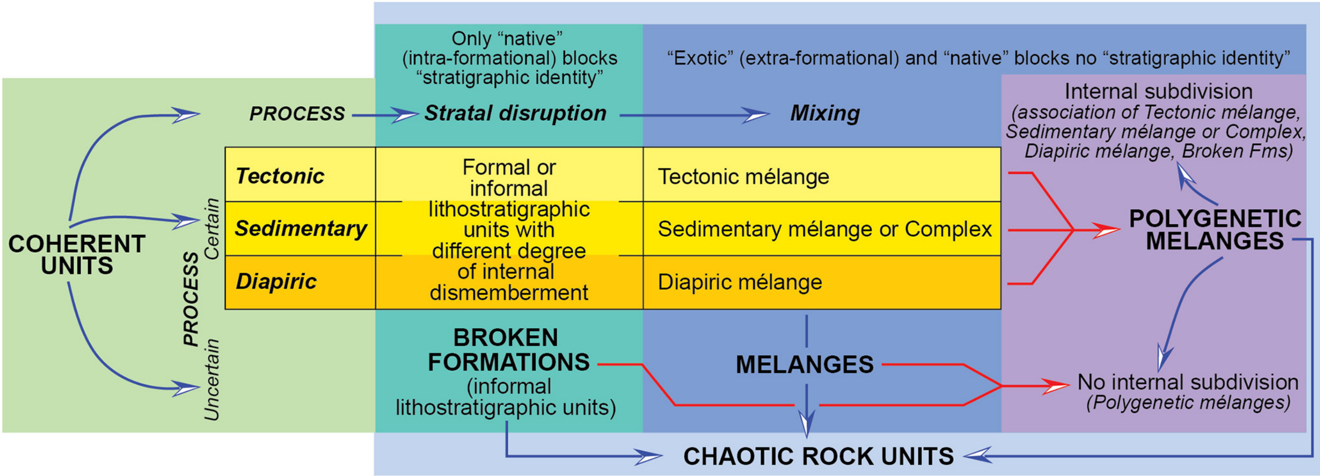


Fig. 1. Deterministic characters of mélanges and broken formations, based on the nature of blocks (native vs. exotic) and mechanism of formation (stratal disruption vs. mixing). Tectonic, sedimentary, and diapiric mélange types may be differentiated from generic mélanges, depending on the certain or uncertain nature of the formation process, respectively. Broken formations, which preserve their stratigraphic identity, can be indicated with formal or informal lithostratigraphic terms.
Modified from Raymond (1984), Bettelli et al. (2004), Vannucchi and Bettelli (2010), and Festa et al. (2012).

in a wide and simplest sense. This usage includes all types of blocks that are "foreign" with respect to the matrix of a mélange (see Hsü, 1968; Festa et al., 2012), regardless of whether they are of "extraformational" origin or of different metamorphic degrees (i.e., different P-T-t conditions), or derived from different tectonics units, paleogeographic domains and structural levels (Fig. 1). Thus, the term "exotic" indicates all those blocks/clasts whose source is not present in the surrounding lithological units within a mélange zone, and which are different from any lithology found in country rocks. On the contrary, the term "native" is used to indicate only "intraformational" blocks originated from the disruption of a primary lithostratigraphic unit (Fig. 1).

The matrix of a mélange is defined as "deformed" or "fragmented" (e.g., Silver and Beutner, 1980; Raymond, 1984), avoiding any specification on its origin (tectonic, sedimentary or diapiric). Independently from the tectonic, sedimentary or intrusive (i.e., diapiric) process of the mélange formation, mixing and stratal disruption (Fig. 1) are the two fundamental processes to include "exotic" and "native" blocks, respectively (Hsü, 1968; Silver and Beutner, 1980; Raymond, 1984; Festa et al., 2012).

Adjectives indicating the process of formation of the chaotic rock unit are used to distinguish tectonic, sedimentary and diapiric mélange types (Fig. 1). Thus, tectonic mélanges and sedimentary mélanges represent chaotic rock units, for which the incorporation and mixing of exotic blocks into the matrix occur by faulting – tectonic deformation processes, and by sedimentary (gravitational) processes, respectively (see below). In diapiric mélanges, the incorporation and mixing of exotic blocks into the matrix occur by mechanical wrenching of the host rocks during the upward rise of the (unconsolidated) matrix through the sedimentary column. However, in several cases, the diapiric-related mixing process reworks and reorganizes the primary block-in-matrix fabric of previously formed sedimentary or tectonic mélanges (see, e.g., Codegone et al., 2012a; Festa et al., 2013, 2015a, 2015b, 2015c).

The term "Broken formation" is used to define a disrupted rock unit (Fig. 1), with a block-in-matrix fabric, which contains no exotic blocks but only "native" components (Hsü, 1968). Here, stratal disruption and fragmentation occur without mixing (Hsü, 1968; Cowan, 1985). In fact, broken formations preserve their lithological and chronological identity (Fig. 1) being commonly characterized by a gradual transition from a bedded, and partially coherent, succession to a highly disrupted or dismembered (e.g., "dismembered units" of Raymond, 1984) block-in-matrix fabric (Hsü, 1968; Raymond, 1984; Cowan, 1985; Barnes and Korsch, 1991; Sunesson, 1993; De Libero, 1998; Pini, 1999), representing the intraformational equivalent of mélanges. Thus, broken formations can be indicated with formal (or informal) lithostratigraphic names (Fig. 1).

In a simplified use, mélanges and broken formations represent two end members in a wide range of chaotic rock assemblage occurrences, differing from each other in terms of the nature of their blocks (exotic and native vs. native) and the mechanisms of their formation (mixing plus stratal disruption vs. only stratal disruption).

In contrast to the mélange and broken formation nomenclature, the term "olistostrome" (Flores, 1955) has a genetic connotation, representing a counterpart of tectonic mélanges (i.e., olistostromal mélange or sedimentary mélange; see, e.g., Hsü, 1974; Raymond, 1984; Bettelli and Panini, 1985; Cowan, 1985; Pini, 1999; Camerlenghi and Pini, 2009; Festa et al., 2010a, 2012, 2014b), formed through sedimentary (i.e., downslope motion) processes. Thus, it is equivalent of the most general term "sedimentary mélange", which we prefer to be used to define mélanges formed by sedimentary (gravitational) processes (Fig. 1). It must not be confused with the term "non-metamorphic" mélange, which indicates a block-in-matrix unit made of only non-metamorphic rocks. Sedimentary mélanges are in general composite deposits displaying superposed structures and complex stratigraphic relationships that developed during multiple events and mass transport processes (sliding, slumping, debris flow, blocky flow, turbidity currents; see, e.g., Lucente and Pini, 2003, 2008; Pini et al., 2004; Festa et al., 2013, 2015c), which also follow stratigraphic principles of both superposition and crosscutting. For this reason, the term (sedimentary) "complex" is more appropriate than the terms sedimentary mélange and olistostrome (see Bettelli et al., 2004 and reference therein) in non-metamorphic successions (Fig. 1), representing a rock body of heterogeneous lithology, with or without deformation that hides stratigraphic relations among the different internal lithologies (see also Vannucchi and Bettelli, 2010; CCGG, 1992; Salvador, 1994). However, in all those cases in which superposition and cross-cutting relationships are not easy to be defined, as in metamorphic rocks, the general term sedimentary mélange is of easier application. This term also includes the term "allolistostrome" (Elter and Raggi, 1965), as it was proposed to define olistostromes containing both native (i.e., intraformational) and exotic (i.e., extraformational) blocks. The term "endolistostrome" (Elter and Raggi, 1965), which describes olistostromes containing only native blocks, is considered the equivalent sedimentary (gravitational) product of a broken formation (e.g., Raymond, 1984).

We use the term "polygenetic mélange" (Fig. 1) in reference to a mélange in which the primary block-in-matrix fabric (with exotic blocks)

Table 1
Diagnostic features of tectonic, sedimentary and diapiric mélanges from the map-scale to the meso-micro scale.
(Modified from Pini (1999) and Festa et al. (2013).)

		Sedimentary mélange	Tectonic mélange	Diapiric mélange
Processes of formation		Sedimentary (gravitational)	Tectonic	Diapiric
Map-scale features	General characteristic	Highly disordered block-in-matrix fabric (isotropic, scale independent –fractal- texture). Anisotropic block-in-matrix fabric marks the base of bodies	Structurally ordered block-in-matrix fabric consistent with regional stress (anisotropic texture). Commonly equivalent to mappable fault or shear zones	Internal structural zoning from margins to the core of diapiric body (from anisotropic to isotropic)
	Shape of chaotic unit	Map view: Irregular to sub-parallel to stratigraphic boundaries of coherent successions in which it is interbedded Section view: Lenticular at different scales (depending on body dimension)	Map view: From narrow and elongated to arcuate and lenticular; aligned to tectonic contacts Section view: Wedge-to lenticular shape	Map view: Circular to elliptical Section view: Conical to cylindrical
	Nature of bounding surface	Lower and upper depositional contacts as discontinuity surfaces and following the law of original continuity. Originally interbedded within coherent primary successions	At least one tectonic contact (i.e., fault, thrust, strike-slip fault). Not following the law of original continuity and stratal continuity	High angle intrusive contacts. Not following the law of original continuity and stratal continuity
Meso-scale features	Block-in-matrix fabric	Random distribution of blocks in a brecciated fine-grained matrix (e.g., shale, clay) and/or siliciclastic or ultramafic-rich arenitic-ruditic matrix. Fluidal fabric, faint scaly cleavage and alignment of blocks at the body bases (bases are therefore recognizable)	Structurally ordered fabric (mesoscopic ductile and brittle foliation, S-C and/or P-R shears, fracture systems and pinch and swell features by boudinage, folds) consistent with the regional tectonic stress, type and mechanism of deformation (brittle vs. plastic), rheological contrast, consolidation/lithification degree, strain rate, etc.	Zonation of deformation: - Core zone: plurimeters, irregular non-cylindrical folds with steeply dipping axes and irregular axial trends; - Marginal zone: pervasive vertical scaly fabric and fluidal features which wrap around the blocks
	Nature of blocks (and matrix)	Native (i.e., intra-formational) and exotic (i.e., extra-formational)		
	Shape of blocks	Angular to rounded and irregular to tabular (i.e. bed fragments) blocks with sharp and defined or diffused outlines depending on the rheology of the block (mean aspect ratio: 1.4–2.5)	From phacoidal and tabular to lenticular and sigmoidal shaped blocks (mean aspect ratio: 2.8–4.1)	- Core zone: irregular blocks (mean aspect ratio: 1.6–3.2) - Marginal zone: phacoidal blocks (mean aspect ratio: 2.9–3.8)
	Size of blocks	Centimeters to decimeters. Meters up to hundreds of meters blocks (olistoliths) and/or fragments of tectonic mélanges may occur	Decimeters to meters long. Tens of meters to hundreds of meters (tectonic slices) may occur	- Core zone: Several decimeters to tens of meters - Marginal zone: Centimeters to decimeters
Micro- to meso-scale features	Matrix fabric	From isotropic texture of unsorted liquefied/fluidized mixture of different grain-population of normal consolidated sediments to fluidal features of poorly consolidated ones. Fluidal features (banding) of the matrix, mostly at the base of the bodies.	Anisotropic texture with planar anisotropy defined by banding, scaly fabric, mesoscopic ductile features and foliation, anastomosing shear zones with S-C geometries, lenticular shaped micro-lithons. Occurrence of striation and systems of mineral-filled veins	Sub-vertical flow fabric. - Core zone: alignment of anasto-mosing and folded poorly--consolidated fine-grained sediments (irregular axial trends and steeply plunging axes); - Marginal zone: sub-vertical S-C fabric
	Clast arrangement	Random distribution of equidimensional, and angular- to rounded clasts. Close to the basal surface, elongated clasts are aligned to the sheared matrix	Alignment of elongated clasts to the S-C fabric and shear zones	- Core zone: Random distribution of irregular shaped clasts - Marginal zone: Alignment of elon-gated clasts to the fluidal fabric

is overprinted and reworked by the superposition of different processes (tectonic, sedimentary or diapiric). All different types of mélanges and broken formations, which differ from coherent successions or rock assemblages because of their block-in-matrix fabric, can be described in a broad sense as chaotic rock units or deposits (Fig. 1).

In the rest of this paper we use the term "subduction plate interface" to indicate the zone where shear deformation occurs dynamically between the downgoing and upper plates at convergent margins. According to direct observations of its internal features between zero and 15 km depths in modern and ancient subduction complexes, it is

Fig. 2. Cartoon showing the diagnostic features of tectonic, sedimentary and diapiric mélanges from the map-scale (map-view and section-view) to the meso-micro scale. *Sedimentary mélanges* are commonly characterized by: irregular shape that may overly one or more, older stratigraphic units in map view (A), and lenticular shape in section view (B); superposition of different mud/debris flow, each characterized by inverse grading of the largest blocks and a decimeters-thick basal shear zone at the meso-scale (C); random distribution of angular and irregular shaped clasts (isotropic texture) at the meso- to micro scale (D upper part); alignment of strongly elongated clasts parallel to the flow direction of the basal shear zone at the meso- to micro scale (D lower part). *Tectonic mélanges* commonly show: narrow and elongated to-arcuate shape aligned to the tectonic contacts in map view (E), and a wedge- to lenticular shape in section view (F); structurally ordered block-in-matrix fabric, which is consistent with the regional stress (anisotropic texture) at both the map- to meso-scale (G) and micro-scale (H); they may show an upward gradual transition to a broken formation (G left log) or may be bounded by lower and upper tectonic contacts (G right log). Note (G right log) the internal structural polarity marked by the distribution of exotic blocks wrenched from the hanging and footwall units, at the upper and lower bounding of the shear zone, respectively. *Diapiric mélanges* show a circular to elliptical and a conical to cylindrical shape in map- (I) and section- (L) view, respectively; at the meso- to map-scale they are characterized by the internal zoning of deformation; the core zone – CZ – is characterized by the random distribution of irregular shaped blocks, up to tens of meters in size, and by plurimeters non-cylindrical folds with steeply dipping axis and irregular axial trends (M); the marginal zone – MZ – is defined by a pervasive sub-vertical scaly fabric and fluidal features which wrap around phacoidal blocks elongated parallel to the intrusive contacts (M and N). See text and Table 1 for details. Map-scale details (i.e., A, B, E, F, I, L) are not to scale and represent simplified versions of field cases from Pini (1999), Cowan and Pini (2001), Dela Pierre et al. (2007), Festa (2011), Festa et al. (2013, 2015b). Meso-scale details in C, G and M show a potential range in the scale size to indicate the most common scale of observed examples (modified and or inspired from Festa et al., 2015b for G, and Dela Pierre et al., 2007, Festa, 2011 for M). Meso-scale close-ups in D, H and N are drawing from outcrop exposures in the (D) Northern Apennines (see Festa and Codegone, 2013), (H) San Simeon in Franciscan Complex (CA, USA), and Northern Apennines (see Festa et al., 2013).

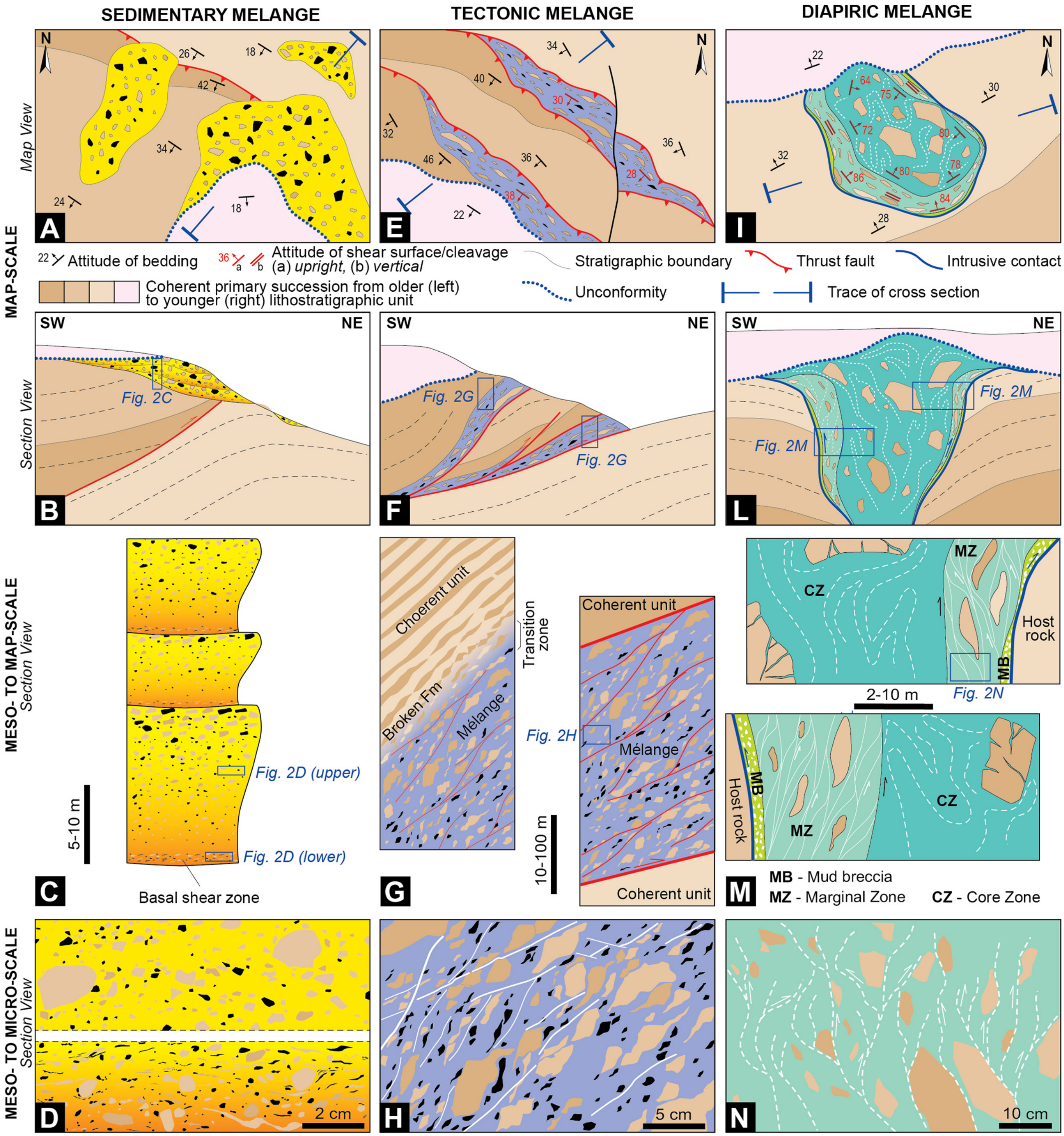
defined as an intensely sheared fault system, which is crosscut by sharp, discrete secondary faults within or along its edges (Rowe et al., 2013; see also Vannucchi et al., 2012).

3. Diagnostic features of different mélange types

Typical and well-preserved mélanges formed by tectonic, sedimentary or diapiric processes should be characterized by different diagnostic features sufficient to make a distinction (Hsü, 1974) through meso-to map-scale field-criteria. To be of large useful, their application needs to follow the normal rules of geological mapping and, where applicable, their close relation with stratigraphic principles.

3.1. Sedimentary mélanges

Independently on the scale of observation, the most visually striking characteristic of sedimentary mélanges is the highly disordered arrangement of the block-in-matrix fabric (Table 1) that strongly contrasts with the “structurally ordered” block-in-matrix fabric of tectonic mélanges (see below). As a general characteristic, blocks of different lithology, age, size (from centimeters-to hundreds of meters), and shape (irregular to equiangular, with sharp and defined or diffuse outlines, depending on the rheology of the block; e.g., Pini, 1999), float with a random distribution in a (finer grained) matrix (Fig. 2A–D). The random distribution of clasts defines an isotropic texture at the hand- sample scale that is invariable also at meso- and map-scale.



3.1.1. Meso-scale features

The matrix is commonly fine-grained (clay or shale) and characterized by an unsorted liquefied/fluidized mixture of different grain-size population. Clayey and shaly matrices shows an isotropic texture that is typical of mud breccias ("brecciated clays" of Ogniben, 1953, Beneo, 1956, Rigo de Righi, 1956, Abbate et al., 1970 and Elter and Trevisan, 1973; "brecciated or clastic matrix" of Swarbick and Naylor, 1980; Pini, 1999 and Cowan and Pini, 2001; "sedimentary breccias" of Vannucchi and Bettelli, 2010), consisting of angular-to rounded clasts, sub-millimeters to millimeters sized, of various composition (microclasts; Figs. 2D, 3A′ and Table 1). The presence of microclasts of claystone and shale is also typical. Sandstone matrix, matrix composed of ultramafic-rich arenites and rudites composed by serpentinite clasts, are also well documented in some mélange occurrences in exhumed accretionary complexes (e.g., Raymond and Bero, 2015; Wakabayashi, 2015, 2017a, 2017b).

Blocks are typically polymictic, both exotic (e.g., Beneo, 1956; Rigo de Righi, 1956; Abbate et al., 1970; Elter and Trevisan, 1973; Bettelli and Panini, 1985, 1987; MacPherson et al., 1990; Labaume, 1992; Pini, 1999) and native (e.g., Jacobacci, 1963; Abbate et al., 1970; Naylor, 1982; Codegone et al., 2012b), maintaining the original fabric of the protolith. Since sedimentary mélanges derive from slope failure and mass transport processes, blocks (and microclasts) may be sourced from different lithologies (e.g., sandstone-siltstone, limestone-marl, ophiolite, igneous-metamorphic rocks, etc.; Fig. 3A′, B, E), having different ages and lithification or metamorphic degrees, according to the stratigraphic level of the rupture surface, the geometry and morphology of the depositional basin, the mode of failure propagation (progressive vs. retrogressive), and the potential of substrate erosion during mass transport emplacement (see Pini et al., 2012; Ogata et al., 2014b). Larger blocks (up to hundreds of meters in size; Fig. 3E) may also be composed of fragments of tectonic mélanges or broken formations that preserve their internal block-in-matrix fabric and texture (i.e., boudinaged bed packages, and blocks in a shaly matrix), forming a chaotic assemblage which is, in part, well-comparable with the "*association of sedimentary breccias and non-metamorphic tectonites*" of Vannucchi and Bettelli (2010; see also Vannucchi and Bettelli, 2002; Bettelli and Vannucchi, 2003).

The shape of blocks is mainly irregular to angular but tabular single beds, and fragmented packs, in which the internal layering of blocks in truncated at the block margins by fractures, may also occur (Figs. 2C–D, 3A′, B–C). In general, at the mesoscale, the mean aspect ratio (long axis/short axis) of blocks embedded within sedimentary mélanges ranges between 1.4 and 2.5, based on our calculations of different representative examples around the world (Fig. 4A, D and Table 1).

Although the basal contact of sedimentary mélanges commonly corresponds to an erosive surface (see, e.g., Ogata et al., 2012, 2014b; Barbero et al., 2017; Tartarotti et al., 2017; Wakabayashi, 2017a), the matrix at the base of clayey and shaly sedimentary mélanges, may display spaced or faint scaly fabrics, banding, and fluidal structures. These structures are commonly oriented at low angles to the basal contact, and define a decimeter-to meter thick shear zone (Figs. 2C–D and 3A″; see Pini et al., 2012; Festa et al., 2013, 2015c). Close to the basal contacts, the poorly consolidated clasts are strongly elongated (Fig. 3A″) parallel to the flow direction (or direction of emplacement) while, a moderate flattening occurs in the orthogonal direction as it is related to syn-emplacement compaction (Abbate et al., 1981; Pini, 1999). Although these types of shear zone closely resemble those formed by tectonic processes, forming tectonic mélanges, they can be differentiated because of the occurrence of a gradual transition from the shear zone to a disorganized block-in-matrix fabric, with native and exotic blocks randomly distributed in a commonly brecciated matrix (Fig. 2C–D). In addition, the block-in-matrix fabric is characterized by a regular reduction of clast size (see Pini, 1999; Vannucchi and Bettelli, 2010; Festa, 2011; Festa et al., 2015c). Differently from tectonic mélanges (see below), the sheared matrix within the basal shear zone is commonly brecciated at mm to cm scales (Figs. 2D, 3A″).

It is not uncommon to observe in the whole chaotic body the alignment of clay minerals defining a weak scaly fabric as it is related to dewatering and subsequent pore collapse (e.g., Vannucchi and Bettelli, 2010). This is a distinctive character of the basal shear zone, since a poorly compacted, open, edge to face texture of the clay platelets characterizes the rest of the body (Pini, 1999). The matrix also fills the interstices within large blocks and/or separates those, forming clastic injections (i.e., sedimentary dykes) which may intrude discrete slide elements (Ogata et al., 2012; Pini et al., 2012). Liquefaction features commonly occur outlining the rapidity of mass-transport deformation processes under undrained conditions (Allen, 1982; Ogata et al., 2012; Pini et al., 2012).

3.1.2. Map-scale features

In map-view, sedimentary mélanges show an irregular shape that unconformably overlies one or more, older stratigraphic units and/or tectonic units (Figs. 2A–B, 3D and Table 1). They are intercalated within a sedimentary unit or sedimentary succession, bounded by lower and upper depositional contacts as discontinuity surfaces (e.g., Flores, 1959; Hsü, 1968, 1974; Abbate et al., 1970, 1981; Elter and Trevisan, 1973; Cowan, 1978, 1985; Castellarin et al., 1986; Bettelli and Panini, 1989, 1992; Pini, 1999; Cowan and Pini, 2001; Dela Pierre et al., 2007; Festa, 2011; Remitti et al., 2007, 2011; Codegone et al., 2012a, 2012b),

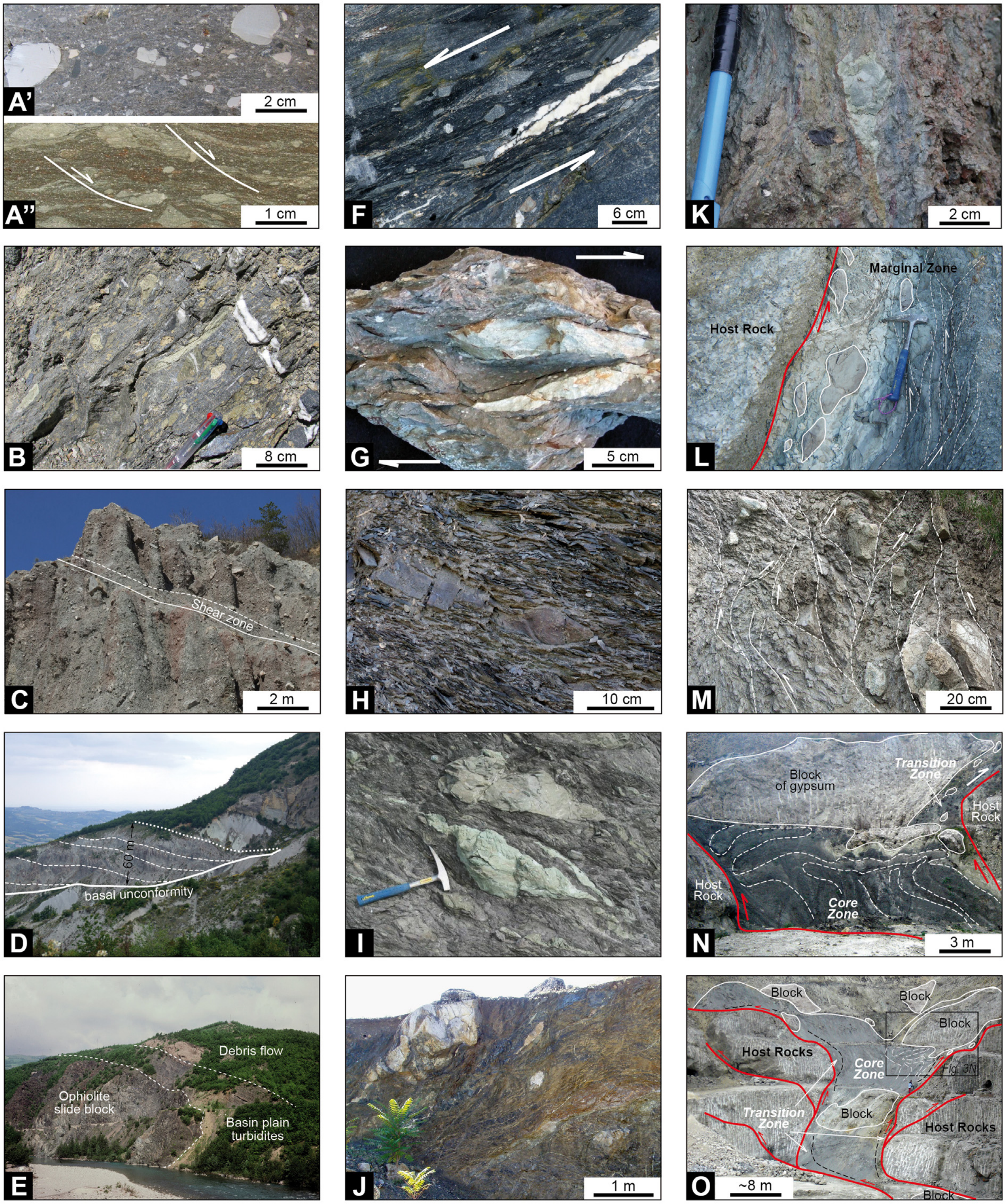
Fig. 3. Field example of diagnostic features of sedimentary (A–E), tectonic (F–J) and diapiric (K–O) mélanges at different scales. *Sedimentary mélanges*: close-ups of polished surfaces of hand samples showing (A′) the isotropic texture of the brecciated shaly matrix, and (A″) the extensionally sheared layers of the basal shear zone with planar anisotropy crosscut by low-angle extensional shear surface (R shear: white lines) (Northern Apennines, Italy; modified from Festa and Codegone, 2013); (B) highly disordered block-in-matrix fabric of trench-related debris flow with variably shaped blocks (equidimensional, tabular, phacoidal, and irregular) of metavolcanic and metagraywacke rocks (Panoche Road, Franciscan Complex, California; see Wakabayashi, 2012); (C) internal arrangement of a sedimentary mélange (Northern Apennines, Italy, modified from Festa et al., 2015c), showing the superposition (and amalgamation) of two single mud/debris flows characterized by inverse grading of blocks. A decimeters-thick shear zone (white lines) bounds at the base the upper mud/debris flow; (D) panoramic view of an epi-nappe sedimentary mélange (see Table 2), emplaced within the late Oligocene–early Miocene wedge-top basin succession atop of the Ligurian Units (Northern Apennines, Italy; modified from Festa et al., 2015b, 2015c). White dashed lines show the stack of different debris flow deposits, each up to tens of meters thick; the white dotted line indicate the unconformable overlain of the coherent hemipelagic sediments; (E) overturned succession showing a large ophiolitic block (several hundreds of meters wide) embedded in a turbiditic sequence (Upper Cretaceous Casanova Complex, Northern Apennines, Italy; courtesy of E. Mutti). *Tectonic mélanges*: (F) Close-up of narrow, anastomosing and coalescent shear zone including exotic blocks of sandstone and mudstone in a shaly limestone matrix (Taconic mélange) (Hoosic River at Schaghticoke Gorge, eastern NY, Central Appalachians – USA; modified from Festa et al., 2012); (G) close-up of hand sample showing whitish limestone and sandstone lenticular blocks embedded within a shaly matrix deformed by layer-parallel extensional fabric with pinch-and-swell structures and boudinage (Mt. Frentani mélange sensu Vezzani et al., 2010, Central Apennines, Italy). (H) Scaly fabric in the Middle Ordovician Taconian Flysch (Taconic mélange sensu Kidd et al., 1995; Northern Appalachians, NY-USA; modified from Festa et al., 2010a); (I) phacoidal exotic blocks in a sheared matrix (Franciscan Complex, CA-USA). Hammer for scale; (J) phacoidal Upper Triassic pelagic limestone blocks in a heterogeneous and variously deformed matrix composed of shale, mudstone, and sandstone in the Jurassic-Cretaceous Avdella mélange (Pindos Mountains, Northern Greece). *Diapiric mélanges*: (K) Close-up of elongated calcareous marly block aligned parallel to the subvertical flow fabric of the varicolored shaly matrix at the marginal zone of the diapiric body (Northern Apennines, Italy; modified from Festa et al., 2013); (L) close-up of the marginal zone, showing a sub-vertical shear zone (white dashed lines), enveloping phacoidal hard blocks aligned parallel to the intrusive contact (red line) (Northern Apennines, Italy; modified from Festa, 2011); (M) phacoidal and (rarely) tabular limestone and sandstone blocks aligned parallel to the subvertical fluidal fabric (dashed white lines) of the shaly matrix within the marginal zone (Northern Apennines, Italy; modified from Festa et al., 2013); (N) huge gypsum block enveloped within a marly matrix at the core zone of a diapiric body (Northern Apennines, Italy; modified from Festa, 2011). Note the strongly asymmetric folds (white dashed lines) with irregular axial trends and steeply dipping, plunging axes within the marly matrix. Red lines represent intrusive contacts; (O) panoramic view of the diapiric mélange of N, showing the internal zoning of deformation and the block-in-matrix arrangement (Northern Apennines, Italy).

and follow the law of original continuity (Figs. 2A, 3D and Table 1). They, hence, represent sedimentary deposits or complexes. The nature of the lower depositional contact commonly consists of an irregular erosional surface that defines a lenticular shape at tens-to-hundred meters in scale, up to kilometers (Figs. 2B, 3D). The erosional nature of the contacts is highlighted by erosional scours, ranging in size from tens of centimeters to meters (Pini, 1999). The upper depositional contact is commonly conformable, separating the sedimentary mélange from the well-bedded upper succession (Figs. 2B, 3D and Table 1).

Regarding the size, during last decades, sedimentary mélanges preserved in orogenic belts and exhumed subduction complexes are mapped to reach up to several thousands of kilometers square (see, e.g., Burg et al., 2008; Alonso et al., 2015; Festa et al., 2015c, 2016 for a complete review), showing close similarities in size with those documented in modern submarine settings (see, e.g., von Huene et al., 1989, 2004; Collot et al., 2001; Geersen et al., 2011; Urgeles and Camerlenghi, 2013; Ogata et al., 2014a; Moscardelli and Woods, 2016; Festa et al., 2018; Artoni et al., 2019).

3.2. Tectonic mélanges

A distinctive feature of tectonic mélanges is the scale-independent repetition of a "structurally ordered" block-in-matrix fabric (e.g. Pini, 1999; Festa, 2011) that is consistent with the regional stress field and that strongly contrasts with the "disordered" fabric of sedimentary mélanges (Fig. 2E, F and Table 1). This is closely related to the fact that the



block-in-matrix fabric of tectonic mélanges forms within strain localized (mappable) fault/shear zones which involve displacement parallel to their bounding walls and gradually tend to grow in both width, length and displacement accumulation. In fact, tectonic mélanges can be considered structurally equivalent to mappable fault or shear zones (Figs. 2E–H, 3G–J), ranging from tens of meters to hundreds of meters in with (e.g., Coleman, 1971; Cowan, 1974; Festa et al., 2010a, 2012) in which different types of tectonic processes and mechanisms (e.g., offscraping, underplating, sinking of roof thrust rocks, and tectonic slicing) cause mechanical crushing of the bounding rock units (e.g., hangingwall and footwall rocks). The latter then become progressively incorporated and mixed as exotic blocks (Fig. 2G), with native blocks disrupted by the originally coherent succession (e.g., Cowan, 1974, 1985; Barnes and Korsch, 1991; Onishi and Kimura, 1995; Ogawa, 1998; Cowan and Pini, 2001; Bettelli and Vannucchi, 2003; Federico et al., 2007; Meneghini et al., 2009; Festa et al., 2012; Kimura et al., 2012; Malatesta et al., 2012; Roda et al., 2018).

The observed limited size of "true" tectonic mélanges (i.e., up to hundreds of meters in thickness) is in agreement with direct measurements of the thickness of shear zones associated with subduction plate interfaces between zero and 15 km depth in modern and ancient convergent margins (see Rowe et al., 2013). Studies of the most notable examples of mélanges around the world (see Festa et al., 2010a) have shown that most of the thicker (up to kilometers) "tectonic mélange" occurrences commonly consist of broken formations (i.e., without "exotic" blocks included) and/or polygenetic mélanges. It appears that tectonic events do not facilitate the most efficient mélange forming processes, at least at shallow structural levels (see also Festa et al., 2012 for further details).

3.2.1. Meso-scale features

The shape of both exotic and native blocks and their arrangement within a mélange matrix vary depending on the types and mechanisms of deformation (brittle versus plastic deformation mechanism), rheological properties of rocks, physical factors acting at different structural levels (e.g., fluid pressure, pressure, temperature, mineral transformation), consolidation and lithification degrees, and strain rates. For example, heterogeneous flattening in all directions forms pinch-and-swell structures and irregular boudinage that define ellipsoidal-shaped blocks in unconsolidated or loosely consolidated sediments under coaxial strain (e.g., Harris et al., 1998; Ujiie, 2002; Festa et al., 2012). With increased consolidation or within more competent layers, a symmetrical boudinage structure may develop by the formation of conjugate extensional features. However, tectonic mixing of exotic and native blocks is mainly controlled by a component of simple shear. Non-coaxial strain forms regular boudinage characterized by lozenge- to sigmoidal-shaped blocks. In case of deformation of originally layered sediments, they may preserve their continuity for several meters (e.g., Pini, 1999; Pini et al., 2004), resulting highly transposed by isoclinal folding (e.g., Bailey et al., 1964; Fergusson, 1985; Bettelli and Vannucchi, 2003; Bero, 2014) with unrooted fold hinges. Stacking by thrusting of already boudinaged layers may also occur, indicating different steps of a progressive deformation (Pini, 1999; Cowan and Pini, 2001).

In lithified sediments, boudinage may also develop as a result of a sequential process of cataclasis, fracturing and Riedel shearing (Kimura et al., 2012). In carbonate rocks experiencing brittle deformation conditions, R and P shear planes crosscut (see Tchalenko and Ambraseys, 1970) and form sigmoidal shaped pressure solution cleavage (see. e.g., Castellarin et al., 1986; Pini, 1999), causing internal and pinch-and-swell boudinage of beds. Separation of blocks commonly occurs in correspondence of mineral-filled veins (see, e.g., Needham, 1995) in brittle to brittle-ductile conditions. Lenticular to sigmoidal shape of blocks is also strictly related to slicing and mechanical crushing of the hanging- and footwall rocks of the fault or shear zone (Fig. 3G, I, J; e.g., Cowan, 1974, 1985; Pettinga, 1982; Byrne, 1984; Bosworth, 1989; Brown and Behrmann, 1990; Barnes and Korsch, 1991; Onishi and Kimura, 1995; Ogawa, 1998). In this case, blocks may consist of both single lithologies or sliced originally coherent successions, up to hundreds of meters wide (e.g., Pettinga, 1982; Fergusson and Frikken, 2003).

The degree of boudinage, slicing or fragmentation may change as a function of block aspect ratios (e.g., Needham, 1995) and the elongated shape of blocks may also change to oblate, up to spherical (e.g., Kimura et al., 2012), with the increase of P-T conditions during progressive involvement into deep shear zones (i.e., "flow mélanges" of Cloos, 1982). In general, the mean aspect ratio (long axis/short axis) of the blocks embedded within tectonic mélanges ranges between 2.8 and 4.1 (Fig. 4B, D and Table 1), as calculated at the mesoscale on different representative examples worldwide (see also Orange, 1990 and Festa et al., 2013 for local examples). Calculation on the relationships between blocks shape and size distribution, and the total blocks volume fraction in a matrix may, in fact, provide useful information on the influence of blocks on the bulk viscosity of the shear zone of the subduction plate interface (Grigull et al., 2012). The distribution and/or concentration of exotic blocks within the fault/shear zone forming the tectonic mélange, also depends on its maturity, which is in turn related to the magnitude of tectonic mixing and the internal viscosity. In the early stage of formation, characterized by a low-magnitude of mixing, chaotic rock assemblages may preserve an internal structural polarity marked by the distribution of exotic blocks which are concentrated at the bounding of the shear zone (Fig. 2G). This distribution also preserves a good lithological correspondence with that of the hanging wall and footwall rock source, which gradually disappears with an increase of shear strain and the magnitude of mixing processes.

Matrix of tectonic mélanges is commonly characterized by a typical scaly fabric formed by anastomosing polished surfaces, mm to cm spacing (Bianconi, 1840; Penta, 1950; Pini, 1992, 1999, Vannucchi and Bettelli, 2002, 2010; Bettelli and Vannucchi, 2003) and arranged in anastomosing shear zones with S-C geometries (Fig. 3H and Table 1). This kind of fabric may be regarded as a scaly cleavage characterized by spaced, disjunctive, and anastomosing features (Hsü, 1974; Cowan, 1974, 1982; Raymond, 1975; Lundberg and Moore, 1986; Vannucchi et al., 2003). The cleavage spacing ranges from sub-millimeter, in foliated rocks as shale and serpentinite, up to tens of meters in unfoliated ones, such as limestone (Cowan, 1982; Byrne, 1984; Lundberg and Moore, 1986; Moore et al., 1986; Brown and Behrmann, 1990; Ujiie, 2002; Vannucchi and Bettelli, 2010). The scaly fabric may contain millimeter-to centimeter sized elongated and lenticular bed fragments, that, as the larger blocks, show the long-axis aligned sub-parallel to the main shear surfaces (Fig. 3H). Bed fragments and scaly fabric define a planar anisotropy that represents a tectonic bedding or mesoscopic foliation (e.g., Vannucchi and Bettelli, 2010) well consistent with both the inferred tectonic stress and regional stress field (Figs. 2H and 3H-I). The superposition of more stages of progressive deformations and/or the changes in tectonic stress field can cause the deformation of the scaly fabric into S-C-like structures (Dellisanti et al., 2008) by subsequent generations of shear planes, rotated and/or folded (see e.g., Moore et al., 1986; Pini, 1999).

3.2.2. Map-scale features

In map-view, tectonic mélanges commonly define arcuate-to lenticular shape at different scales, according to the contractional or transcurrent nature of the bounding faults, respectively, and the regional stress field (Fig. 2E, F and Table 1; e.g., Festa, 2011). On the contrary of sedimentary mélanges, the mapping of tectonic mélanges "*cannot be based upon a presumption of stratal continuity*", and its stratigraphy "*cannot be established on a presumption of normal superposition*" (Hsü, 1968). Mélanges formed under contractional stress regime follow the rules of thrust tectonics being superposed onto different units (including mélange units), according to the in- or out-of-sequence propagation. On the contrary, mélanges associated with strike-slip stress regime are juxtaposed to tectonic units of different ages and nature,

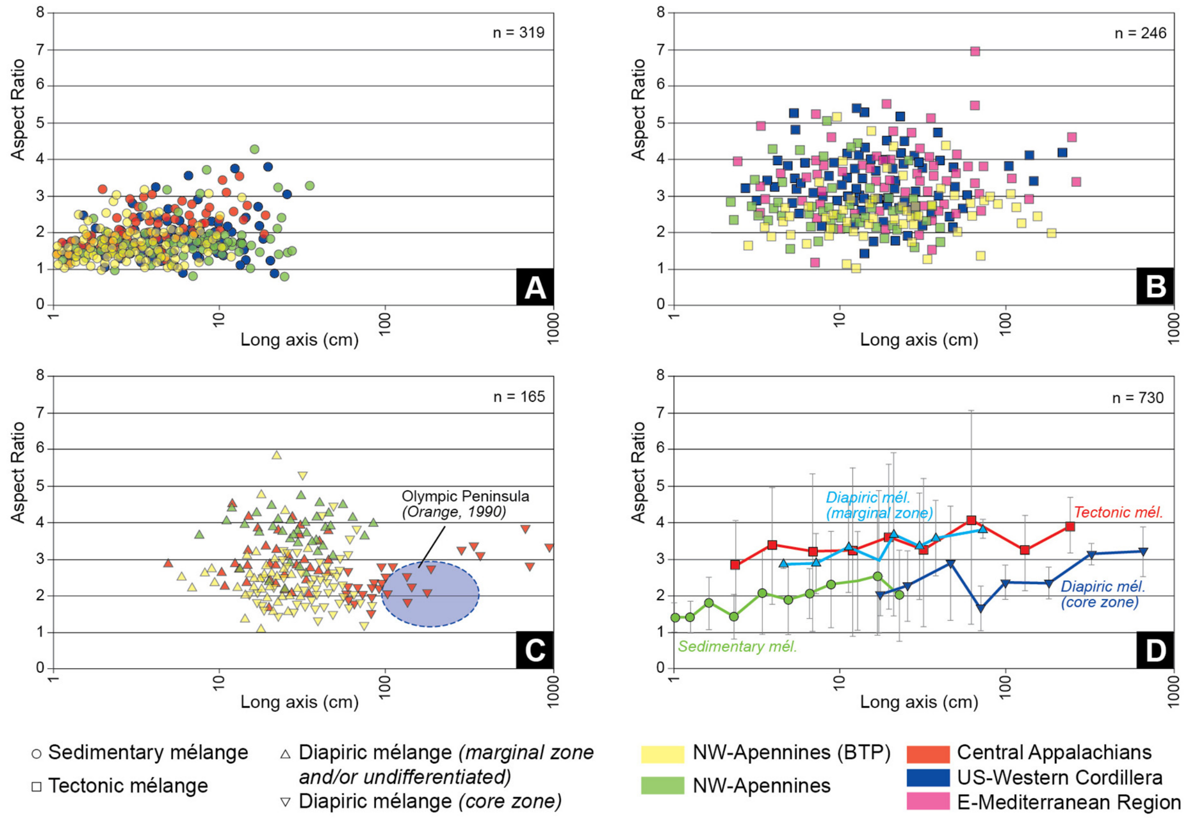


Fig. 4. Diagrams showing different (meso-scale) organizational types of the blocks fabric in sedimentary (A), tectonic (B), and diapiric (C) mélanges, and their comparison (D), in terms of aspect ratio (block long axis/short axis) vs. block long axis. Data are plotted as means with 95% error bars indicated. Data from Northern Apennines (BTP – Tertiary Piedmont Basin) and Olympic Peninsula (i.e., Hoh accretionary complex, WA-USA) are from Festa et al. (2013) and Orange (1990), respectively.

depending on the kinematic of the fault and displacement entity. Out-of-sequence thrusting cutting at high angle dipping, already stacked, thrust units (and horses of duplexes) may result in the more efficient way to realize mixing of different structural units. Tectonic mélanges may also be bounded by tectonic contacts only at the base (in case of contractional tectonics; see Fig. 2F, G) or on one single side (in case of strike-slip tectonics), showing an upward gradual transition to a broken formation and/or to a primary/coherent succession (Fig. 2F, G), far away from the tectonic contact (see, e.g., Codegone et al., 2012a, 2012b; Festa et al., 2013).

3.3. Diapiric mélanges

The most visual striking of diapiric mélanges is the distribution of the block-in-matrix fabric, showing internal structural zoning from the margins to the core of a diapir (Fig. 2I, L and Table 1; e.g., Orange, 1990; Dela Pierre et al., 2007; Festa, 2011; Codegone et al., 2012a, 2012b). The final internal organization of a block-in-matrix fabric of diapiric mélanges mainly depends on the combination of hydrofracturing processes, progressive incorporation of wall rock material and flow, consolidation degree and rheological contrast between both the layers of the stratigraphic succession and the diapiric matrix and hosting rocks (see, e.g., Pini, 1999; Festa et al., 2012).

3.3.1. Meso-scale features

Adjacent to intrusive contacts, the block-in-matrix fabric of a marginal zone is commonly characterized by a sub-vertical foliated block-in-matrix fabric with mainly phacoidal to tabular blocks, encapsulated within a fine-grained (shaly or clay) matrix. The latter displays a pervasive anastomosing scaly fabric, showing mm- to cm-scale spacing (Figs. 2I–N, 3L–M and Table 1). The matrix, is commonly deformed by S-C shear zones that indicate upward rise movements and, opposite sense of movement on the opposite margins of the diapir (e.g., Orange, 1990; Festa, 2011).

Phacoidal to tabular blocks, ranging in size from decimeters to meters depending on the size of a diapir, show an increase in clustering at diapir's contacts due to an increased pervasiveness of shearing in the matrix (Figs. 2M, N and 3L–M; e.g., Orange, 1990; Festa, 2011). In general, the mean aspect ratio (long axis/short axis) of blocks embedded within a diapir's marginal zone ranges between 2.9 and 3.8 (Fig. 4C, D and Table 1), as observed at mesoscale in different representative examples worldwide (see also Festa et al., 2013 for local examples). Millimeters- to centimeters-long, broken and disaggregated hard clasts are spread along the shear zones and depict wisp and tail features (Fig. 3K; see Festa, 2011; Codegone et al., 2012a, 2012b; Festa et al., 2013). Blocks commonly show hydraulic features (millimeters- to several centimeters-wide) filled by injections of fine-grained sediments with a mm- to cm-sized scaly fabric that is parallel to fracture margins (Figs. 2M, N and 3L–N). Shear fracturing and cataclasis may also occur but they are limited to lithified or partially-lithified rocks close to diapir margins. Deformation of unlithified sediments is, on the contrary, mainly restricted into particulate flow structures (Clennell, 1992).

Pervasiveness of a scaly fabric and S-C shear zones, as well as the clustering of the long axes of blocks gradually decrease toward the center of a diapiric body (i.e., the core zone). Here, blocks are commonly angular and loosely clustered, and are larger in size, up to tens of meters (Figs. 2I–N, 3N–O; e.g., Kopf, 2002, Clennell, 1992; Dela Pierre et al., 2007; Festa, 2011, Codegone et al., 2012b; Festa et al., 2013). The main aspect ratio of such blocks (long axis/short axis) ranges from 1.6 to 3.2 in the core zone of different diapirs in NW Italy (Festa et al., 2013) and in the Olympic Peninsula in Washington, USA (Orange, 1990), respectively (Fig. 4C, D and Table 1). Blocks are randomly distributed within a non-foliated matrix, which commonly preserves highly asymmetrical folds (Figs. 2I–M, 3N and Table 1) with irregularly oriented axial trends and steeply plunging axes (Codegone et al., 2012b; Festa et al., 2012). The size of blocks that can be carried in the diapiric flow may have a theoretical limit. If blocks in a diapiric flow are not particularly dense, the matrix is very viscous or the diapiric emplacement is relatively rapid, their size may be rather large (e.g., Clennell, 1992). The size and number of blocks entrained in a diapir may hence be controlled by the buoyancy theories of diapiric bodies (e.g., Clennell, 1992). The nature of blocks encased within a diapiric matrix varies depending on the nature of surrounding rocks. Commonly, blocks wrenched out from country rocks are exotic with respect to matrix material and may include both sedimentary and metamorphic rocks (e.g., Barber et al., 1986, Barber and Brown, 1988; Maekawa et al., 1993; Fryer et al., 1999; Barber, 2013). The source material for matrix is an unlithified fine-grained sediment (mud, shale, serpentinite mud) rarely having a coarse-grained texture, and may contain rare lithified beds, which get commonly broken-up during diapiric movement.

In some cases, a thin collar (up to few decimeters thick) of mud breccias with sub-vertical fluidal features separates the sheared marginal zone of a diapir from surrounding rocks (Fig. 2L–M; see Festa et al., 2005; Dela Pierre et al., 2007; Festa, 2011). These features indicate the occurrence of overpressure conditions during which low-viscous and quasi-fluid material may facilitate the upward rise of the more viscous diapiric body.

3.3.2. Map-scale features

In map-view, intrusive contacts of a diapiric mélange show rounded or ellipsoidal and lenticular geometries (e.g., Barber et al., 1986; Barber and Brown, 1988; Clennell, 1992; Kopf, 2002; Festa, 2011; Codegone et al., 2012a, 2012b) and juxtapose the diapiric body against host rocks at high angles (Fig. 2I, L and Table 1). Surrounding lithologies are commonly younger than or coeval in age with respect to rock units in blocks included in the diapir matrix. The diameter of diapirs ranges in size from tens of meters to few kilometers (e.g., Clennell, 1992; Kopf, 2002; Codegone et al., 2012a, 2012b; Barber, 2013), and up to tens of kilometers as described in the Mariana subduction zone (Maekawa et al., 1993; Fryer et al., 1999). In cross section, these diapiric bodies are bounded by sharp and commonly high-angle intrusive contacts that converge downward, defining a typical cone-shape diapirs (Fig. 2L).

Diapiric mélanges may also be spatially associated with transpressional faults (e.g., Festa et al., 2005, 2010a; Dela Pierre et al., 2007; Festa, 2011). In such cases these diapiric mélanges may look similar in map view to tectonic mélanges produced by strike-slip tectonics. However, the opposite sense of shear along the opposite margins of a diapiric mélange (Fig. 2M and Table 1) is a key factor in distinguishing intrusive contacts from tectonic ones (Orange, 1990; Festa et al., 2005; Dela Pierre et al., 2007; Festa, 2011; Codegone et al., 2012a, 2012b).

4. Complications in orogenic belts and exhumed subduction-accretion complexes

Careful application of the above listed diagnostic criteria is fundamental for differentiating mélange types formed by different processes (tectonic, sedimentary, and diapiric). However, it is well known that in ancient orogenic belts and exhumed subduction-accretion complexes with a record of multiple deformation events, pre-existing primary diagnostic features are commonly overprinted and significantly reworked by tectonic processes and/or masked by metamorphic recrystallization. This tectonic and/or metamorphic overprint commonly leads to the formation of "polygenetic mélanges", whose primary forming processes may be difficult to recognize in the field (e.g., Cowan and Page, 1975; Aalto, 1981; Page and Suppe, 1981; Raymond, 1984, 2015; Cowan, 1985; Codegone et al., 2012a; Dilek et al., 2012; Festa et al., 2013, 2016; Hajna et al., 2013; Raymond and Bero, 2015; Wakabayashi, 2015; Ernst, 2016). Therefore, we need additional criteria for their correct recognition and interpretation. We will introduce them in Section 5 after the analysis and discussion of the main complications, which commonly hamper the distinction of processes of polygenetic mélange formation.

4.1. Convergence of block-in-matrix fabrics at shallow structural levels

Explorations in trenches and modern submarine accretionary prisms have shown that orogenesis and related deformation processes commence at convergent margins long before plate collisions, affecting wet and only partially lithified material (Lundberg and Moore, 1986; Moore et al., 1988; Brown and Behrmann, 1990; Vannucchi and Maltman, 2000; see also Maltman, 1994; Anma et al., 2011; Kawamura et al., 2011; Ogawa et al., 2011). Shortly after deposition, sediments may start undergoing deformation due to the interplay between gravitational forces and tectonic stress, during the progressive burial (Maltman, 1994; Kawamura et al., 2011; Fig. 5D–E). Processes of burial, dewatering and tectonism intricately overlap, contributing to form an overlapping zone at shallow structural levels, where the block-in-matrix fabrics of tectonic and sedimentary mélanges, as well as of diapiric ones, show a strong convergence of fabric (Fig. 5; e.g., Maltman, 1994; Alonso et al., 2006, 2008; Festa et al., 2012, 2013; Ogata et al., 2016). Regardless of the nature of processes of their formation, a series of asymmetrical structures of various scales, such as boudinage, asymmetric rootless folds, pseudo-S-C structures, duplex types and imbricated structures, and low-angle shear zones (Maltman, 1994; Alonso et al., 2006, 2008, 2015; Pini et al., 2012; Ogata et al., 2014b, 2016; Festa et al., 2016) form as a result of soft-sediment deformation in undrained, water-saturated, and poorly- to unconsolidated sediments (Figs. 5 and 6). Thus, the internal structure and block-in-matrix arrangement of different types of mélanges developed under these physical and mechanical conditions may appear highly similar in the field (Figs. 5 and 6).

The key question to consider regarding the significance of mélanges in orogenic belts (see Alonso et al., 2006) and exhumed subduction-accretion complexes is whether their block-in-matrix fabric formed along shear zones (i.e., within or at the base of a convergent margin or along the subduction plate interface), incorporating hard block components or slices as the result of tectonic brecciation, offscraping and/or underplating mechanisms (e.g., Bailey and McCallien, 1950; Merla, 1952; Vollmer and Bosworth, 1984; Bosworth, 1989), or whether it derives from denudation of moving nappes or frontal erosion of non-accretionary margins as gravity mass transport deposits detached from their toe (e.g., Signorini, 1940; Abbate and Bortolotti, 1961; Page, 1962; Elter and Trevisan, 1973; Page and Suppe, 1981; Alonso et al., 2006, 2008, 2015; Camerlenghi and Pini, 2009; Festa et al., 2010a, 2015c, 2018). Processes of tectonic reworking at higher depths in subduction-accretion complexes, as recorded in polygenetic mélanges, further complicate our interpretations of the origin of primary block-in-matrix fabrics in mélanges.

4.2. Transformation with depth and the limit of distinction between different mélange types

Primary diagnostic features of the block-in-matrix fabric in each specific mélange type (tectonic, sedimentary or diapiric) become tectonically reworked and/or overprinted by metamorphic recrystallization following their incorporation within a shear zone. Although this problem is well known, particularly for those mélange occurrences within exhumed and/or metamorphosed subduction plate interfaces and accretionary wedges (e.g., the Franciscan Complex, see Berkland et al., 1972; Silver and Beutner, 1980; Raymond, 1984, 2015, 2017; Cowan, 1985; Platt, 2015; Raymond and Bero, 2015; Ukar and Cloos, 2015; Krohe, 2017; Wakabayashi, 2011, 2015, 2017b), the mode of transformation and downdip reworking of a primary block-in-matrix fabric has been rarely described in the literature.

Festa et al. (2018) have discussed that an irregular block-in-matrix fabric of a sedimentary mélange (i.e., heterogeneous mass transport

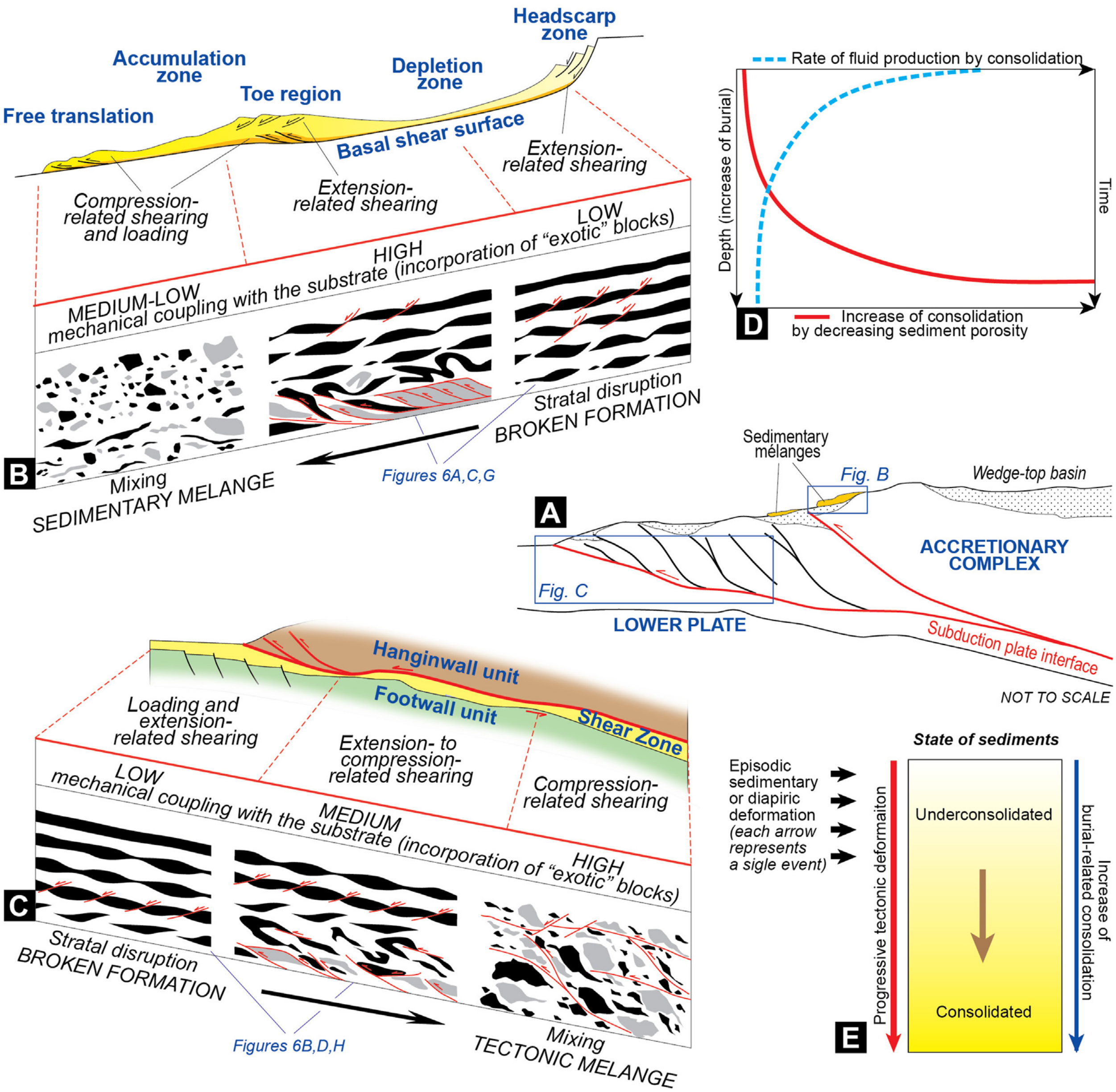


Fig. 5. Cartoon showing the convergence of block-in-matrix fabric between sedimentary (B) and tectonic (C) mélanges in unconsolidated- to poorly-consolidated sediments within a convergent margin (A); see text for explanation. (D) Schematic diagram showing the progressive increase of the consolidation degree (and decrease of fluid production) with depth. Note that consolidation is time dependent. Modified after Collison (1994), Brown (1994), and Festa et al. (2012). (E) Schematic diagram, showing a conceptual difference between depositionally (gravitational), diapirically and tectonically induced deformation with respect to the consolidation. Sedimentary and diapiric chaotic bodies may record only instantaneous and episodic events that punctuate the consolidation history, whereas tectonic chaotic bodies may record different stages of deformation that persist through time and different degrees of consolidation and lithification.
Modified after Byrne (1994) and Festa et al. (2012).

deposits) that was incorporated into and reworked within a tectonic shear zone of a subduction plate interface at depths, corresponding to T > 150 °C (>~5 km of vertical burial), closely resembles a "structural ordered" block-in-matrix fabric of tectonic mélanges (Fig. 7). Primary diagnostic features of the block-in-matrix fabric of sedimentary mélanges, defined by random distribution of blocks within a brecciated matrix may display geological evidence of the initial stages of reworking at depths corresponding to T ~ 60°–80 °C (~2 to ~3 km of vertical burial) (Fig. 7A). Tabular and elongated clasts start to show a preferred alignment along planes of flattening, whereas rounded to irregularly shaped clasts preserve their random distribution within the matrix, which is similar to the primary one (Festa et al., 2018). After progressive reworking and reshaping of block-in-matrix that keeps pace with increased tectonic shearing (Fig. 7C), competent blocks and clasts become strongly elongated at depths corresponding to T > 150 °C (>~5 km of vertical burial) (Fig. 7D and E). They acquire phacoidal shape fabric, pinch-and-swell and symmetrical-asymmetrical boudinage structures, extensional veining and shearing, brecciation of tails and necks of blocks, and pressure shadows (Fig. 7D and E; e.g., Pini et al., 2012; Platt, 2015; Festa et al., 2016, 2018; Mittempergher et al., 2018).

Stratigraphic boundaries of sedimentary mélanges may also become obliterated and reactivated by tectonic shearing as pre-existing weakness surfaces. Structural depths corresponding to T > 150 °C (>~5 km of vertical burial) in subduction-accretion complexes represent a down-section limit, below which the distinction between different types of mélanges becomes more challenging. This problem gets bigger with increased depth and with the inception of metamorphic recrystallization. Tectonic juxtaposition and distribution of metamorphic blocks, which largely

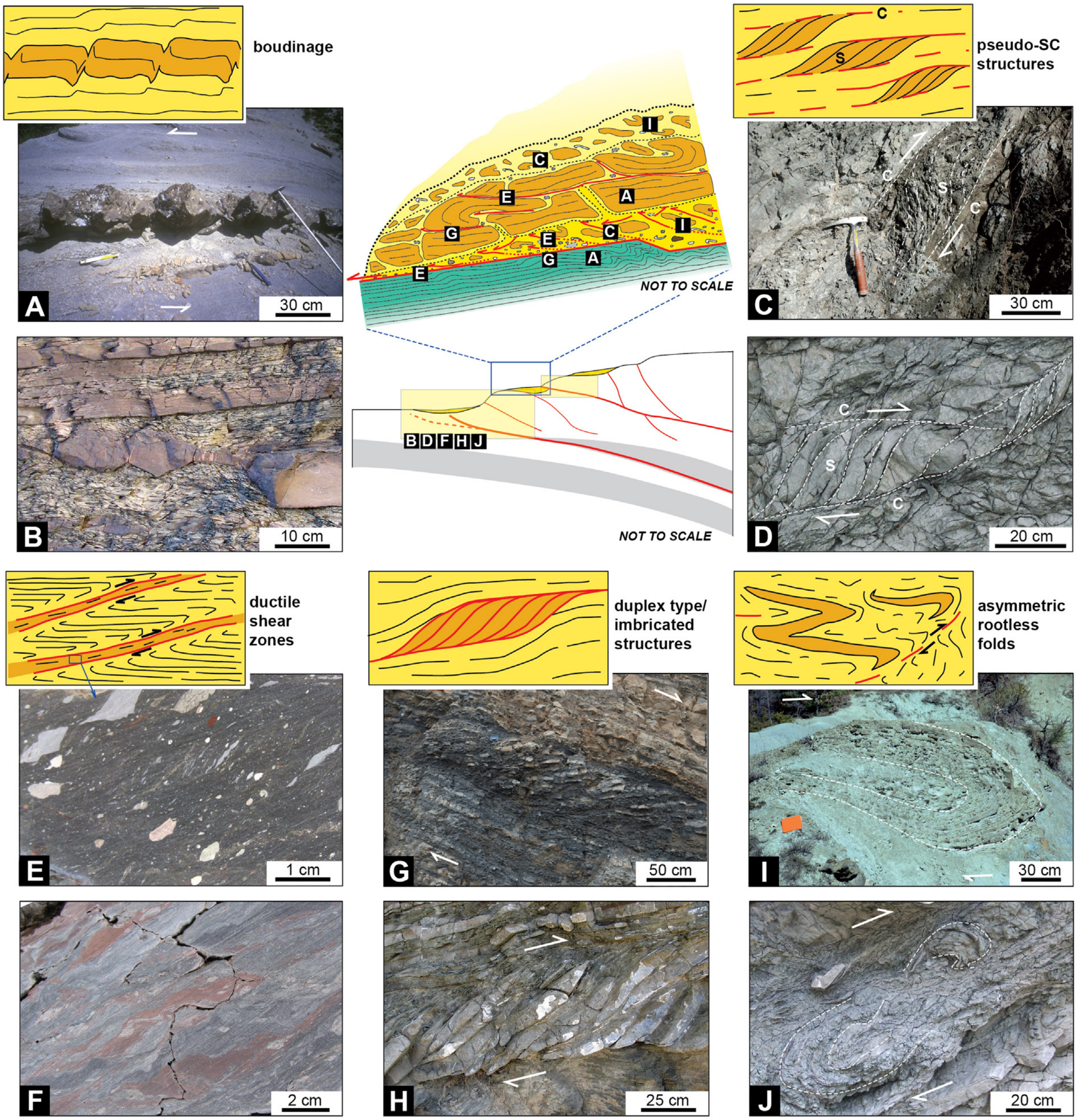


Fig. 6. Simplified cartoons of ductile and brittle–ductile deformation fabrics as discussed in the text and field photographs depicting some of the most representative examples of these structures for both sedimentary mélanges (A, C, E, G, I) and tectonic mélanges (B, D, F, H, J). Note the close convergence of fabric between sedimentary and tectonic-related features. The cartoons in the center of the figure display the location of these deformational fabrics in both the frontal wedge of a convergent margin and within a mass transport deposit with main internal subdivisions, facies associations, and mesoscale structures of the evolving slide body.
Modified from Ogata et al. (2014b).

vary in their peak metamorphic pressure and temperature conditions may lead to different interpretations such as potential products of continuous return-flow along a subduction channel (e.g., Cloos, 1982, 1986; Cloos and Shreve, 1988a, 1988b; Gerya et al., 2002; Federico et al., 2007; Blanco-Quintero et al., 2011; Ukar and Cloos, 2015) or tectonic reworking of sedimentary mélanges (e.g., Erickson, 2011; Wakabayashi, 2015, 2017a, 2017c; Platt, 2015; Krohe, 2017 and references therein). These complications in the recognition of different types of polygenetic mélanges stem in part from our poor understanding of the nature and origin of blocks embedded in them.

4.3. Significance of blocks: exotic or native?

The blocks content and their nature (i.e., “exotic” or “native” blocks) have been used in literature to define and characterize different types of mélange. However, the above listed evidences of the tectonic (and/or metamorphic) transformation and downdip reworking of the primary block-in-matrix fabric, clearly outline that the interpretation of their primary forming process based on only the content and nature of blocks (i.e., “exotic” or “native” blocks) is a difficult task, and caution is needed (see, e.g., Raymond, 1984 for a complete discussion; see also Cowan, 1985; Festa et al., 2012, 2016; Platt, 2015; Raymond, 2017; Wakabayashi, 2017c).

The terms “exotic” and “native” blocks may be ambiguous (see, e.g., Raymond, 1984, 2017; Camerlenghi and Pini, 2009; Festa et al., 2012 for a complete discussion), particularly in metamorphic rock units in which the distinction between blocks disrupted from a primary coherent sequence and “exotic” blocks, which are “foreigners” (i.e., sourced from different tectonics units, paleogeographic-geodynamic domains and structural levels) with respect to the matrix,

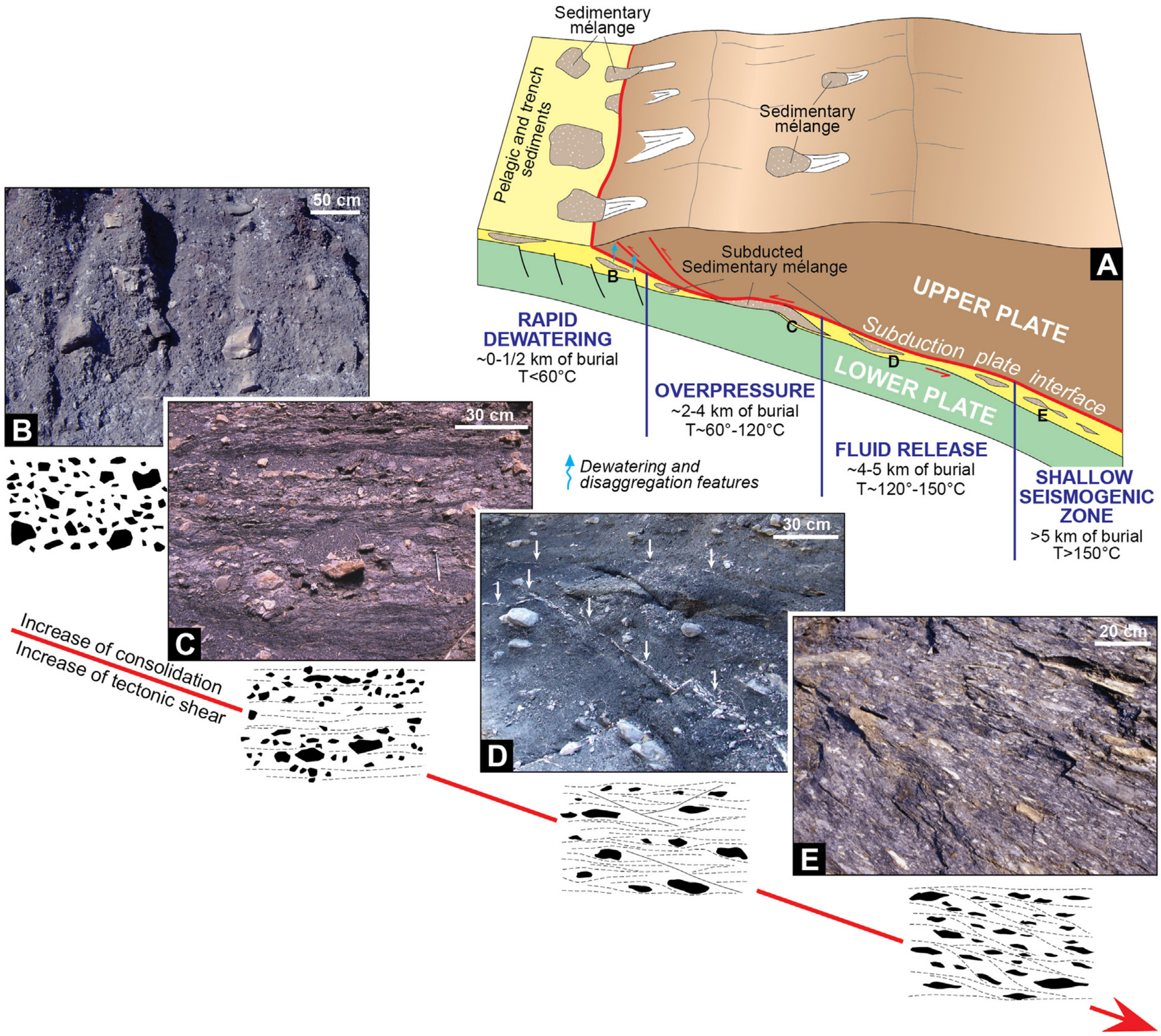


Fig. 7. (A) Conceptual model based on geophysical and geological observations from modern and ancient convergent margins depicting mass transport deposits (i.e., sedimentary mélanges) with variable sizes (from small- to giant) situated within a subduction plate interface (modified from Vannucchi et al., 2012; Festa et al., 2018). (B through E) Field photographs from the Northern Apennines (Italy) and related cartoons of each block-in-matrix fabric, showing the transformation with depth, increase of consolidation and tectonic shear (red arrow), of the block-in-matrix fabric of subducted sedimentary mélanges within the subduction plate interface, from the frontal thrust zone (B) to the up–dip limit of a shallow seismogenic zone (E) (modified from Festa et al., 2018). Note that the block-in-matrix fabric in (E) closely resembles the "structural ordered" block-in-matrix fabric of tectonic mélanges.

is commonly problematic. Consequently, the interpretation of the nature of a mélange based on the attribution of these terms may be incorrect. For example, phacoidal blocks of metabasite embedded within a calcschist matrix, showing the same P-T metamorphic peak, may represent both the inclusion of exotic blocks coming from a different geodynamic or tectonic setting, and the product of stratal disruption of primary pelagic sediments, alternating with lava flows (see, e.g., Raymond, 1984; Balestro et al., 2015b). In this latter case, blocks should be considered "native" components in origin, possibly representing the results of a strong boudinage process or of severe folding and transposition within the same lithostratigraphic unit (see, e.g., Balestro et al., 2015a; Tartarotti et al., 2017). Similar cases are well-documented for different types of ophiolitic mélanges (e.g., Saleeby, 1984; Suzuki, 1986; Wakabayashi, 2015, 2017a, 2017c).

Further complications also depend on the degree of heterogeneity of the primary lithostratigraphic units involved in tectonic processes forming chaotic rock units (Fig. 8). An increasing number of studies show that varied stratigraphic or primary rock assemblages can be progressively deformed into block-in-matrix units, giving a wider potential variety of native blocks (e.g., see Wakabayashi, 2015, 2017c; see also Balestro et al., 2015a; Wakita, 2015; Tartarotti et al., 2017). This is the case for OPS (Ocean Plate Stratigraphy) mélanges (see Wakita, 2015), which result from the fragmentation, disruption and/or mixing of different types of primary heterogeneous lithostratigraphic successions, forming an OPS without inclusion of other ("exotic") components (Fig. 8). Wakita (2015) documented that each of the three different types of OPS stratigraphy intervals forms a corresponding type of mélange (i.e., turbidite type, sandstone-chert type, and limestone-basalt type), notwithstanding they derived from different sectors of the OPS (Fig. 8). This depends on the stratigraphic and structural level sampled by the décollement/shear zone surface and the occurrence or not of mixing process. Considering the heterogeneity of the primary OPS stratigraphy, Wakabayashi (2015, 2017a, 2017c) has suggested that the OPS-related chaotic rock units correspond to broken formations (with only native blocks) rather than mélanges. In addition, an imbricated OPS stratigraphy is no longer expected to consist entirely of clasts of basalt and chert (and/or limestone); serpentinite clasts derived from oceanic core complexes and fracture zone – spreading center intersections may also become an integral part of OPS. Consequently, OPS combinations include serpentinite-basalt-chert (plus or minus clastics), and even serpentinite-clastics, as well as serpentinite-(mafic plutonics)-basalt-chert-clastics. Thus, a final block-in-matrix assemblage may consist of serpentinite

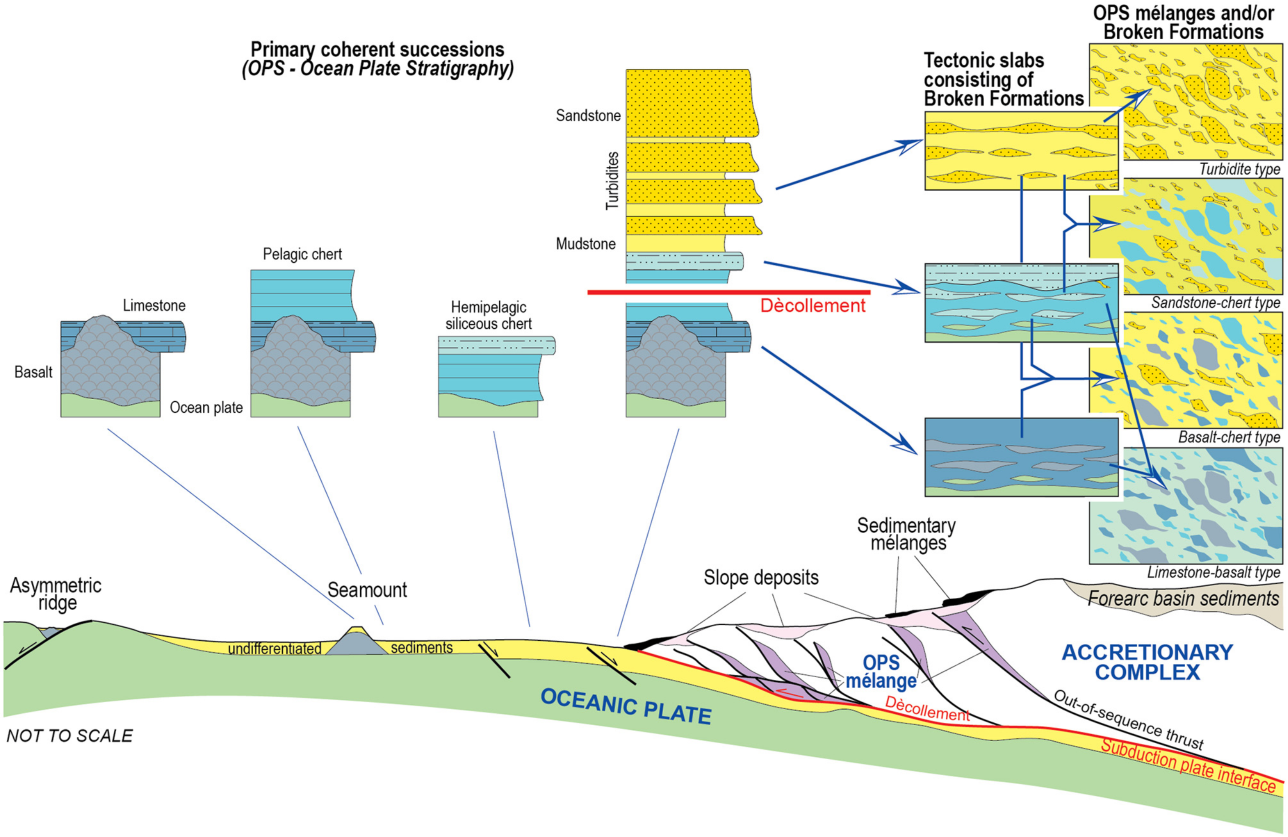


Fig. 8. Conceptual model of the formation of OPS mélanges through subduction and accretion of an oceanic plate stratigraphy (OPS) at convergent margins (modified from Wakita, 2015). The OPS is gradually disrupted and fragmented to firstly form a broken formation (early stages of deformation) and then broken formations and/or mélanges with the increasing of tectonic deformation, and depending of the portion of OPS involved in the deformation and the degree of mixing (see text for details). Note that mélanges formed only with the contribution of mixing processes.

matrix with "native" blocks of clastics, chert, limestone, basalt, etc. as well as siliciclastic matrix with all of the above as "native" blocks (see Wakabayashi, 2015, 2017a, 2017c for a complete discussion). The variety of potential "native" blocks becomes larger when we consider the heterogeneous rock assemblages of oceanic lithosphere (Dilek et al., 1990; Dilek and Robinson, 2003; Dilek and Furnes, 2011, 2014). On the contrary, Raymond (2017) considers blocks of chert and basalt within an OPS chaotic rock unit to be exotic elements, as well, if they occur in either a serpentinite or a mud- to sand-matrix (see also Erikson, 2011). He outlines that an OPS is arguably not a formation in the traditional sense nor do the basalt, peridotite, chert, and overlying sandstones of an OPS all form in the same environments under the same conditions. If blocks of these lithologies are mixed with a matrix dominated by one or two of the others (e.g. sandstone-shale, mudstone or serpentinite matrix) that formed in a different environment than blocks, the latter must be exotic and the OPS block-in-matrix fabric is a mélange.

In light of these contrasting interpretations, our revised simplified use of the term "exotic" (see Section 2; i.e., "*all those foreign blocks/clasts whose source is not present in the bounding units of mélange zone and/or differ from any lithology found in the units flanking it*") together with the statement that "mixing" is a fundamental process to form mélanges, may thus be useful to differentiate broken formations from mélanges in OPS and other similar cases.

A large part of OPS chaotic rock units, developed during early stages of deformation represent broken formations formed by progressive disruption and dismemberment of a primary heterogeneous succession formed in the same environment (e.g., alternating pelagic sediments and basalts or sandstones and marls/clays; see Fig. 8). During early stages of deformation, stratal disruption and fragmentation represent the main processes of deformation. The latter preserves the primary lithological and chronological identity between the components involved in the deformation, being commonly characterized by a gradual transition from a bedded, and partially coherent, succession to a highly disrupted or dismembered one with no mixing. In most of these cases, the mixing is only apparent as due to primary heterogeneity of the disrupted sequence (e.g., alternating pelagic sediments and basalts) and/or to the superposition of two different previously formed broken formations (last right column of Fig. 8). Only with the increase of deformation and the onset of accretionary processes, components formed in different environments (e.g., mantle rocks and sediments) can be mixed together forming mélanges, in agreement with Raymond (2017). Similar observations exist for mélanges formed by reworking parts of rifted continental margins and ocean floor successions during subduction and continental collision stages (e.g., Dilek and Eddy, 1992; Dilek and Rowland, 1993; Dilek et al., 1999; Shallo and Dilek, 2003; Bortolotti et al., 2013; Balestro et al., 2015a; Tartarotti et al., 2017; Roda et al., 2018). This is not a simply terminological debate but it has a primary geological importance in distinguishing very different processes and mechanisms of mélange formation (e.g., mixing vs. stratal disruption), which commonly are associated with very different strain magnitude. They provide significant constraints to a better understanding of both the tectonic setting in which mélanges formed and the tectonic evolution of orogenic belts and exhumed subduction-accretion complexes in which they occur. Thus, caution is needed in interpreting the "native" or "exotic" nature of blocks within chaotic rock units. The most obvious exotic blocks are commonly those that have undergone higher-grade metamorphism than the matrix (see, e.g., Cowan, 1978; Cloos, 1982; Ukar, 2012; Wakabayashi, 2015) while, on the contrary, several chaotic rock units commonly described as mélanges (e.g., some chaotic rock units in the Shimanto Belt or in the Western Alps) are broken formations.

4.4. Age relationships between blocks and the matrix

In sedimentary mélanges, the age of the matrix is younger than that of “exotic” hard blocks incorporated from the substrate during downslope movement, and only “native” blocks or components may have the same age of the matrix. On the contrary, in tectonic and diapiric mélanges, the age of the matrix can be indifferently older or younger (and coeval) of that of the younger “exotic” block, depending on the stratigraphic and structural level sampled within the architecture of the orogenic belt and subduction-accretion complex. In fact, although in most of the cases the upward rise of diapiric bodies pierces successions with a normal attitude (e.g., Maekawa et al., 1993; Fryer et al., 1999; Dela Pierre et al., 2007; Festa, 2011), it is not uncommon that they crosscut a structural edifice formed by the tectonic superposition and imbrication of different tectonic units having different ages and consolidation degree of sediments, including those older than the intrusive matrix (e.g., Barber et al., 1986; Codegone et al., 2012a, 2012b; Barber, 2013; Festa et al., 2013). Similarly, the matrix of tectonic mélanges may indifferently incorporate younger or older blocks, depending on the stratigraphic and structural level sampled by the shear zone through the tectonic pile (see, e.g., Festa et al., 2013), the in- or out-sequence of thrusting propagation, and the geodynamic setting (e.g., accretionary margins, non-accretionary margins, strike-slip tectonics, etc.).

A criterion based on the relationships between the ages of blocks and the matrix is a difficult application to polygenetic mélanges as well as in metamorphic belts in which the age of the different components is difficult to constrain. However, a criterion based on the coherence in age between the matrix and the tectonic history of the embedding “exotic” blocks has been proposed in subduction channel environments for discriminating processes characterized by the juxtaposition of blocks with different P-T metamorphic peaks and P-T-t paths within a matrix (see Krohe, 2017). Accordingly (see Krohe, 2017), (i) the protolith age of the matrix of tectonic mélanges should be older that the higher P-T metamorphic peak of blocks included, and (ii) if the tectonic mélange contains a mixing of blocks of different ages and P-T metamorphic peaks, the matrix should also be mixed and potentially portions of the matrix, which record the same age of the higher P-T metamorphic peak of the older block, should be present. In our opinion, these assumptions may be useful only in specific cases and/or assuming a specific model of deformation within the subduction plate interface. The above evidences that the matrix of tectonic mélanges may be indifferently older or younger of “exotic” blocks depending on the stratigraphic and structural level sampled by the shear zone and the characteristic of the tectonic environment, suggest to use this criterion with caution.

5. Criteria helpful to differentiate the nature of polygenetic mélanges

According to the above considerations (Section 4), it is unquestionable that a distinction of mélanges based on their primary block-in-matrix fabric alone (Section 3), is commonly highly complicated in ancient orogenic belts and exhumed subduction-accretion complexes, where most of mélanges are actually polygenetic. Thus, in addition to the above listed criteria (i.e., the diagnostic features of the different mélange types), two main complementary criteria are proposed in the following. Importantly, these criteria alone are not always strictly discriminatory, therefore they should be used in combination to support and complement the basic ones.

5.1. The deformation criterion: coherence in the distribution of deformation between blocks and the matrix

A primary formed tectonic mélange it commonly characterized (Fig. 9) by (i) a kinematic coherence between the distribution of deformation in the matrix and the mechanism of formation of its block-in-matrix fabric, and (ii) a kinematic coherence between the magnitude of the distributed deformation in the matrix and the degree of transport and juxtaposition of “exotic” blocks with different paths (including P-T-t paths) against each other, from tens of meters to kilometers distances along the shear/fault zone. Similar observations constrain diapiric mélanges. On the contrary, in sedimentary mélanges deformation of the matrix is not required and/or is completely different from that of tectonic mélanges (Fig. 9). When a distributed deformation is present, its magnitude is not coherent with the degree of juxtaposition of several “exotic” blocks incorporated during downslope movement (Fig. 9). These observations are highly significant in considering polygenetic mélanges formed by tectonic reworking of the diagnostic block-in-matrix fabric of primary mélanges (tectonic, sedimentary and diapiric) within shear/fault zones (Fig. 9C–D).

Field data from exhumed convergent margins and direct measurements in modern submarine ones, show that shear is commonly localized on multiple, often simultaneous, active adjacent fault strands (Fig. 9B), implying non-viscous rheology at a local scale, and isolating poorly- to not-reworked deformed domains (e.g., Fagereng and Sibson, 2010; Vannucchi et al., 2012; Rowe et al., 2013; Krohe, 2017; Mittempergher et al., 2018). These isolated domains, commonly preserve remnants of relatively poorly- to not-reworked block-in-matrix fabrics, which are diagnostic of different primary processes of mélange formation (Fig. 9C–D), independently on the tectonic environment of deformation and, in some cases, on the P-T metamorphic conditions of recrystallization. For example, although strongly deformed and reworked after a complete orogenic cycle from subduction to collision and exhumation, notable occurrences of primary sedimentary mélanges isolated within the eclogite-facies Western Alpine ophiolite are documented (see, e.g., Balestro et al., 2015a; Tartarotti et al., 2017). Similarly, relatively undeformed domains preserving sedimentary (e.g., Aalto, 1981, 2014; Wakabayashi, 2012, 2015; Prohoroff et al., 2012; Raymond and Bero, 2015; Raymond, 2015, 2017) or diapiric (e.g., Becker and Cloos, 1985; Hitz and Wakabayashi, 2012; Ogawa et al., 2015; Wakabayashi, 2015) mélanges are documented within the subduction-related rock assemblages of the Franciscan Complex in California.

The record of these domains may vary in both scale and size depending on the physical and mechanical characteristics of the shear zone in which primary mélanges are incorporated, the degree of compositional heterogeneity, variations of fluids content and pressure during deformation, and strain rate. Polygenetic mélanges associated with shear/fault zones, then result in the mixing and/or juxtaposition of larger coherent domains (i.e., non-chaotic rock units or layered primary successions) and smaller reworked mélanges (Fig. 9C and D; see, e.g., Remitti et al., 2007; Vannucchi et al., 2012). The component of continuous deformation within the matrix may be not large enough for mingling of different “exotic” blocks as the deformation is commonly localized along thin domains of high shear and fluid flow (e.g., Bebout and Penniston-Dorland, 2016; Krohe, 2017), such as, for example, metasomatic rims of blocks and the immediately adjoining sediments.

On field, examples of this repartition of deformation with consequent preservation of both poorly- to un-deformed domains and/or the diagnostic fabric of primary mélanges, are documented at different scales (Fig. 9C–G), ranging from meso- (e.g., Fisher and Byrne, 1987; Moore and Byrne, 1987; Meneghini et al., 2009; Codegone et al., 2012b) to map-scale mélanges. The latters formed by the superposition and mixing of both “coherent” successions/rock units and different types of “chaotic” units (i.e., primary tectonic, sedimentary and/or diapiric mélanges; see, e.g., Pini, 1999; Remitti et al., 2007, 2007, 2011; Codegone et al., 2012a, 2012b; Festa et al., 2010b, 2013, 2014a, 2015c; Wakabayashi, 2012, 2015, 2017c; Festa and Codegone, 2013; Balestro et al., 2015b; Raymond, 2015, 2017; Barbero et al., 2017; Roda et al., 2018).

The nature of the contact between "chaotic" and "coherent" domains may vary from sharp to transitional (Fig. 9D–G), depending on the structural level in which tectonic deformation localized (e.g., Festa

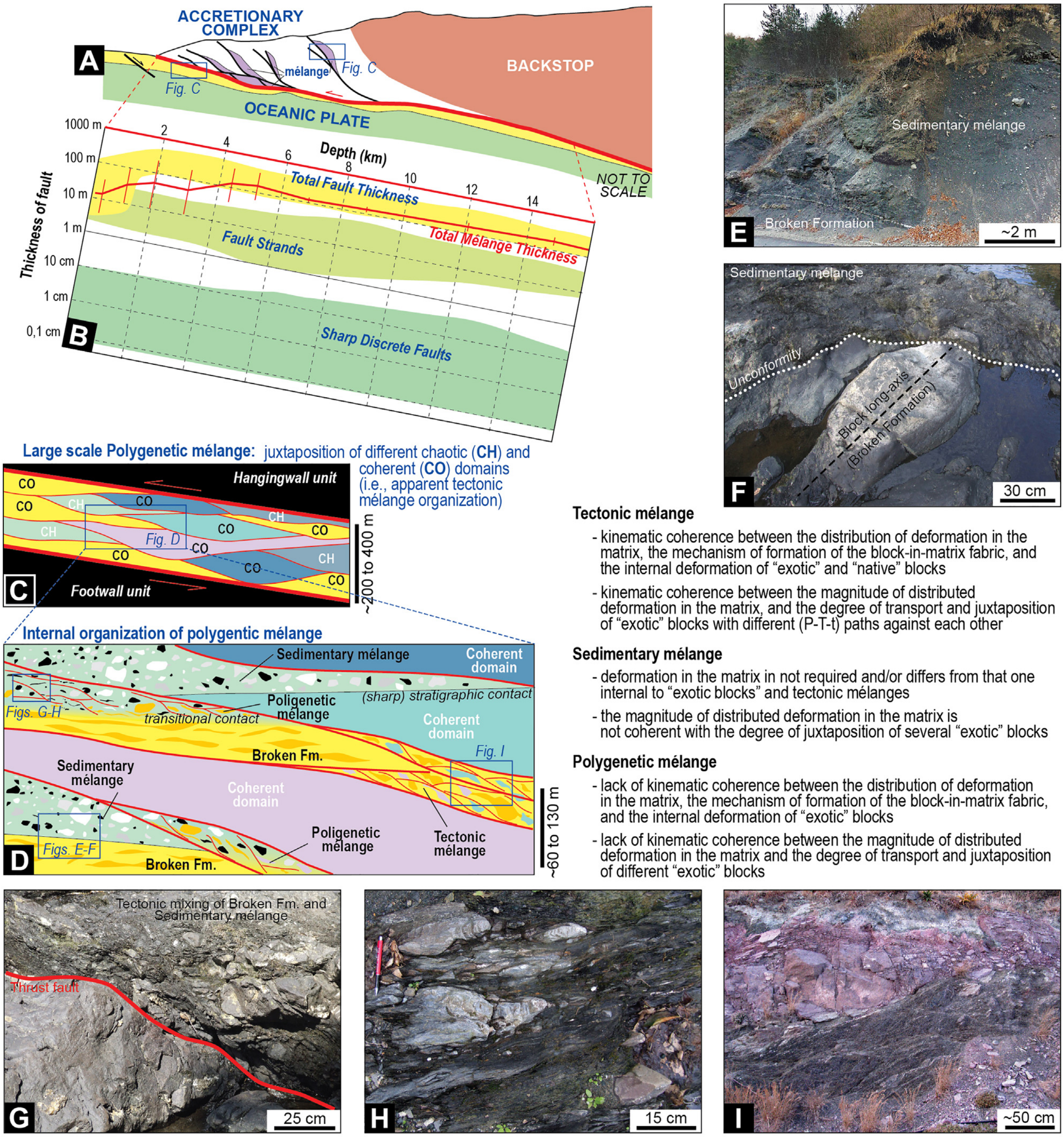


Fig. 9. Conceptual model showing different arrangements of distribution of deformation in polygenetic mélanges, and synthesis of the characteristics of primary formed tectonic, sedimentary, and diapiric mélanges. (A) Tectonic mélanges represent the product of mappable shear zones, and their field-observed limited size (i.e., tens to hundreds of meters in thickness) well agrees with direct measurements of the thickness of shear zones associated at subduction plate interfaces between zero and 15 km depth in modern and ancient convergent margins (B, modified from Rowe et al., 2013). (C) Polygenetic mélanges associated with shear/fault zones commonly result in the mixing and/or juxtaposition of larger coherent domains (i.e., non-chaotic rock units or layered primary successions), smaller reworked mélanges of different origin (sedimentary, diapiric and/or tectonic), and broken formations, forming in an "apparent" tectonic mélange organization. (D) Depending on the magnitude of deformation and mixing, and the repartition of deformation, poorly- to un-deformed domains of primary sedimentary, diapiric and/or tectonic mélanges may be preserved at different scales. The nature of the contact between the different domains may vary from sharp to transitional, depending on the structural level in which tectonic deformation localized as also shown in the photographs: transitional (E) and sharp (F) contacts between sedimentary and tectonic mélanges in the Northern Apennines (Italy) and at the Poetstenkill Gorge in the Northern Appalachians (NY-USA), respectively; (G and H) close-ups views of polygenetic mélanges formed by tectonic reworking of previously formed sedimentary mélanges at Poetstenkill Gorge and Hoosic River (Northern Appalachians, NY–USA); (I) structurally ordered block-in-matrix fabric of tectonic mélange (Arvi Unit, South Crete, Greece).

et al., 2013). Thus, detailed meso-scale field observations on deformational characteristics of the matrix and their kinematic coherence with both the mechanism of formation of the block-in-matrix fabric, and the type and degree of internal deformation of "exotic" and "native" blocks, are essential. They allow to distinguish between the typical internal organization of polygenetic mélanges (i.e., mixing of reworked domains and primary chaotic domains) and the only apparent chaotic morphology of complex shear zones (compare Fig. 9C and D). This morphology is closely related to the variation from smooth to chaotic flow of the material incorporated within the shear/fault zone which can produce morphologies, ranging from anastomosing and bifurcating localized stand faults to the chaotic deformation typical of mélanges (see, e.g., Vannucchi et al., 2012).

Although out of the aim of the paper, similar considerations are possible (and should be supported) at the micro-scale through specific analyses (e.g., microstructural, magnetic rock fabric, etc.; see, e.g., Osozawa et al., 2009; Yamamoto et al., 2012; Wassmann and Stöckhert, 2012, 2013; Wakabayashi, 2017a, 2017c). For example, it is well documented that the microfabric of mélanges matrix is commonly characterized by low deformation magnitude and inhomogeneous, continuous and discontinuous deformation with near undeformed layers alternating with highly-deformed ones (see, e.g., Krohe, 2017; Mittempergher et al., 2018).

If we consider that the internal morphology documented from a large number of observations from modern and ancient shear zones in ancient orogenic belts and exhumed subduction-accretion complexes shows a localized distribution of deformation, the "deformation criterion" may provide useful constraints also to discriminate the nature of complex mélange and/or polygenetic mélange occurrences. Among others, this is the case of the Franciscan Complex where blocks with different P-T metamorphic peaks and P-T-paths are embedded in a poorly- to non-metamorphic matrix. The apparent diversity of structural deformation and P-T metamorphic peaks conditions and P-T-t paths observed at small length scales could be related to different factors if supported by the "deformation criterion". For example, this diversity of structural deformation may depend on the localization of fluid infiltration in domains where dissolution precipitation reactions occurred (see Krohe, 2017). The preservation of domains recording large volumes of older, metastable mineral assemblages may depend on the slowness of element transport by solid-state diffusion, which is inefficient to promote high P-T metamorphic peaks at given temperature and time scale (Krohe, 2017; see also Austrheim, 1987; Jamtveit et al., 1990; John and Schenk, 2003; Putnis and John, 2010). Depending of fluid infiltration, hydration at lower pressure, along the retrogressive P-T path, may also erase these different mineral assemblage only in same places (Krohe, 2017). Thus, the application of the "deformation criteria" to complex cases as the Franciscan Complex and subduction plate interfaces in general, may provide some useful constraints to distinguish between processes of mélange formation. For example, Krohe (2017) suggested that (i) the magnitude of distributed deformation of the matrix is too low to have caused juxtaposition of blocks different in P-T metamorphic paths against each other from km-scale vertical distances, (ii) deformation of the matrix occurred during a second loop of high-P metamorphism postdating creation and ascent of the "exotic" blocks, and (iii) the counterclockwise P-T-t paths of "exotic" blocks predated the deposition of the bulk of the metasediments constituting the matrix.

All these considerations and evidences suggest that, at least locally, the juxtaposition of blocks and/or coherent domains with different P-T-t paths within a subduction plate interface may be related to the activity of narrow (up to few tens of meters) shear/fault zones formed by localization of deformation rather than by "return flow" in a viscous matrix (see Vannucchi et al., 2012; Krohe, 2017 for details). The mixing of these blocks may locally be explained as the juxtaposition of remnants of different (monogenetic) mélanges products (i.e., sedimentary, tectonic, diapiric mélanges and, possibly, remnants of "flow" mélanges), through localized multiple and often simultaneous, active adjacent fault strands. For a complete discussion we remand to the comparison of, e.g., Cloos, 1982, 1986; Cloos and Shreve, 1988a, 1988b; Gerya et al., 2002; Ukar, 2012; Ukar and Cloos, 2015 and, e.g., Wakabayashi, 2011, 2012, 2015; Vannucchi et al., 2012; Platt, 2015; Krohe, 2017; Raymond, 2017.

5.2. The tectonic environment criterion: lithostratigraphic and geodynamic coherence between blocks and the matrix

The application of the above criteria to differentiate the process/es of formation of polygenetic mélanges, together with the observation of diagnostic features of each type of mélange, need to be linked together by the "tectonic environment criterion". This criterion states that the blocks and matrix composition and nature should be compatible with the tectonic environment of mélange formation and occurrence (Table 2).

Complications in distinguishing different mélange types after their tectonic reworking may be overcome taking in consideration that it exists a specific genetic relationship between the nature of both blocks and of the matrix, and the geodynamic setting of mélange formation. This has been well documented on a complete review of most of all notable examples of mélanges throughout the world (Table 2; see Festa et al., 2010a). For example, sedimentary mélanges formed in passive margins during rifting (Type 1 mélange of Festa et al., 2010a, 2012) are characterized by blocks of intrabacinal composition (i.e., olistoliths), commonly consisting of already cemented carbonate platform margins, embedded within a matrix of prevalent pelagic limestone (e.g., Castellarin, 1972; Bosellini et al., 1977; Rast and Kohles, 1986; Bailey et al., 1989; Channell et al., 1992; Mandl, 2000; Bernoulli, 2001; Ortner, 2001; Amerman et al., 2009; Festa et al., 2016; see Table 2). On the contrary, in sedimentary mélanges formed at the ocean-continent transition (OCT; see Type 2 mélange of Festa et al., 2010a, 2012), blocks may vary in composition from fine-grained carbonate, siliciclastic turbidite, and/or chaotic brecciated (i.e., matrix supported) masses (e.g., Festa et al., 2016; see also Smith et al., 1979; Naylor, 1982; Dilek and Rowland, 1993; De Libero, 1998; Shallo and Dilek, 2003; Pini et al., 2004; Alonso et al., 2008; see Table 2). The matrix is commonly brecciated with angular to sub-rounded clasts of the same composition of blocks, embedded in fine-grained sediments (clay or shale). In oceanic realm, blocks mainly consist of collapsed mantle rocks, basalts and related sedimentary cover, which are embedded in a brecciated matrix (debris flow deposit). The latter commonly consists of clast- to matrix-supported angular clasts of mafic-to ultramafic-rocks and fragments of the oceanic sedimentary cover in pelagic limestone and/or medium- to coarse-grained sandstone with ophiolite-derived detrital material (e.g., Decandia and Elter, 1972; Saleeby, 1979; Lagabrielle, 1994; Bortolotti et al., 2001; Clerc et al., 2012; Balestro et al., 2014, 2015a, 2015b; Festa et al., 2015a; Tartarotti et al., 2017).

Sedimentary mélanges formed in association with the evolution of convergent margins and subduction zones (Type 4 of Festa et al., 2010a) differ from the above listed ones (Table 2). Generally, they are characterized by different degrees of stratal disruption, related to the consolidation state at time of the slope failure and the final run-out distance of slide masses. Blocks and clasts within the matrix, include deformed sediments and both native and exotic rocks of different ages that are generally older and more consolidated than intrabacinal components sourced from the accretionary wedge-front and/or wedge-top basins. Importantly, blocks locally preserve and display an internal fabric and/or traces of older tectonic deformation, which occurred before and/or during subduction-accretion and/or exhumation stages. The matrix varies from shale and generally fine-grained sediments, to medium- to coarse-grained sandstones.

Several others significant differences in the composition of blocks and the matrix, and their genetic relationships with the geodynamic setting of mélanges formation can be outlined for each specific geodynamic setting, ranging from extensional tectonics, passive margin evolution, strike-slip tectonics, subduction zones, collisional tectonics, and intracontinental deformation (Table 2). We remand to Camerlenghi and Pini (2009), Festa et al. (2010a, 2010b, 2012, 2016) for a complete review. Thus, in general, these specific compositional and genetic differences show that the application of the "tectonic environment criterion" is of great helpful to correctly constrain the nature of those (polygenetic) mélanges whose primary internal fabric was reworked during the evolution of orogenic belts and exhumed subduction complexes. This has been documented, for example, in the Franciscan Complex (see, e.g., Raymond and Bero, 2015). Here, the occurrence of sandstone matrix mélanges rather than shale matrix ones, indicates that gravitational processes, which formed sedimentary mélanges,

Table 2
Relationships between types of mélanges and the geodynamic environment of their formation (modified after Festa et al., 2010a, 2012, 2016). Acronyms are listed at the bottom of the table.

Types of mélange related to:	Geodynamic environment	Processes	Triggering mechanisms	Products	Mesoscale characteristics	Minor products
Passive margin						
Collapse of platform margins	Passive margins (during and after rifting)	MTP (debris avalanches/flows, etc.)	Tectonic	MTD (megabreccias, breccias, olistolith fields, debrites, slide blocks, etc.)	Chaotic angular clasts (cm to >10 m) in fine-grained (pelitic) matrix	In situ fluidization: mud diapirs?
Mass-transport deposits at the ocean-continent transition (OCT)	Ocean-continent transition (OCT)	SSD and MTP with related progressive deformation from slumping to debris flows, to gravitational sliding	Tectonic, sedimentary	MTD, sedimentary mélanges with continent rock olistoliths (10–100 m to several km slide blocks) in a matrix of oceanic sediments	Chaotic monomictic to polymictic brecciated (matrix-supported) masses (including native, extra-basinal and/or exotic blocks of both oceanic and continental origin)	
Intra-oceanic setting						
Sedimentary	Oceanic realm (mid-oceanic ridge, seamounts, oceanic core complexes)	MTP (debris flows and avalanches, slumps, slides, etc.)	Tectonic	MTD (megabreccias, breccias, olistolith fields, debrites, slide blocks, etc.)	Chaotic angular clasts (cm to >5 m) in fine-grained pelagic matrix and/or ultramafic rich-sandstone	
Tectonic		TSD and/or tectonic mixing along detachment faults		BrFm; mélanges (exotic blocks wrenched along detachment faults)	Structurally ordered BIM fabric (commonly ultramafic rich matrix)	
Strike-slip tectonics and transform setting	Different types of collision	TSD: fault-to fold-related, fluidization (overprinting previous mass-wasting-related deformation)	Tectonic	BrFm; mélanges (exotic blocks being commonly recycled from other previously formed mélanges)	Structurally ordered BIM fabric (parallel orientation of blocks and matrix features – i.e. pseudo-bedding)	MTD *s.l.*; mud diapirs *s.l.*
Convergent margins and oceanic crust subduction						
Mass-transport deposits at the wedge and retro-wedge front	Subduction (at the front of the wedge and retro-wedge) and fore-arc basins	MTP (debris flows and avalanches, slumps, slides, etc.)	Tectonic, sedimentary	MTD, BrFm, sedimentary mélanges (olistoliths, olistolith fields and swarm, slide blocks)	Chaotic BIM fabric (from matrix-supported cm-to m in size blocks to clast supported >10 m blocks and olistoliths)	Mud and serpentinite diapirs and mud volcanoes
Broken fms and tectonic mélanges	Subduction (at the base of the wedge) and subduction plate interface	TSD: fault-to fold-related, fluidization (overprinting previous mass-wasting-related deformation); tectonic mixing	Tectonic	BrFm; mélanges (exotic blocks being recycled from other previously formed mélanges or formed by subduction processes)	Structurally ordered BIM fabric (parallel orientation of BIM features – i.e. pseudo-bedding)	
Obduction-related setting						
Sedimentary	Obduction settings (from intra-oceanic to marginal stage)	MTP (debris flows and avalanches, slumps, slides, etc.)	Tectonic, sedimentary	MTD, BrFm, sedimentary mélanges (olistoliths, olistolith fields, slide blocks, breccias, debrites)	Chaotic BIM fabric (including native, extra-basinal and/or exotic blocks)	
Tectonic and/or tectono-sedimentary		TSD: fault-to fold-related, fluidization (overprinting previous mass-wasting-related deformation)	Tectonic	Mélanges (exotic blocks being commonly recycled from other previously formed sedimentary mélanges); BrFm	Structurally ordered BIM fabric (polymictic blocks of oceanic and continental origin)	
Collision and intracontinental deformation						
Sub-nappe						
Precursory olistostromes	At the base or at the front of intra-continental thrust sheets or nappes	MTP (debris flows and avalanches, slumps, slides, etc.)	Tectonic, sedimentary	MTD, sedimentary mélanges (olistoliths, olistolith fields and swarm, slide blocks)	Chaotic BIM fabric (from matrix-supported cm-to m in size blocks to clast supported >10 m blocks and olistoliths)	Mud diapirs and mud volcanoes
Olistostromal carpet		TSD: fault-to fold-related, fluidization (overprinting previous mass-wasting-related deformation)		Mélanges (exotic blocks being commonly recycled from other previously formed sedimentary mélanges); BrFm	Chaotic BIM fabric overprinted by tectonic deformation and shearing	
Tectonic			Tectonic		Structurally ordered BIM fabric	
Intra-nappe						
Sedimentary	Within intra-continental thrust sheets or nappes	MTP (debris flows and avalanches, slumps, slides, etc.)	Tectonic, sedimentary	MTD, sedim. mélanges (olistoliths, olistolith fields and swarm, slide blocks)	Chaotic BIM fabric (blocks of intra-basinal origin)	Mud diapirs and mud volcanoes
Tectonic and/or tectono-sedimentary		TSD: fault-to fold-related, fluidization (overprinting previous mass-wasting-related deformation)	Tectonic	BrFm; mélanges (exotic blocks being commonly recycled from other previously formed sedimentary mélanges)	Structurally ordered BIM fabric (parallel orientation of blocks and matrix features – i.e. pseudo-bedding)	
Epi-nappe						
Sedimentary	A top of intra-continental thrust sheets or nappes (e.g. piggy back, top thrust	MTP (debris flows and avalanches, slumps, slides, etc.)	Tectonic, sedimentary	MTD, sedimentary mélanges (olistoliths, olistolith fields and swarm, slide blocks)	Chaotic BIM fabric (originated from the succession tectonically imbricated in the thrust-sheet)	Mud diapirs and mud volcanoes
Tectono-sedimentary		TSD (overprinting previous	Tectonic, sedimentary	BrFm; mélanges (exotic blocks being commonly	Structurally ordered BIM fabric	MTD *s.l.*, mud diapirs

Table 2 (*continued*)

Types of mélange related to:	Geodynamic environment	Processes	Triggering mechanisms	Products	Mesoscale characteristics	Minor products
	basins)	mass-wasting-related deformation)		recycled from other previously formed sedimentary mélanges)		*s.l.*
Diapiric		Extrusion of non-to poorly consolidated sediments	Tectonic, sedimentary	Mud diapirs and mud volcanoes	Zonation of deformation from core to margins	MTD *s.l.*, *s.l.*

BIM – block-in-matrix; BrFm – broken formation; MTD – mass-transport deposits; MTP – mass-transport processes; SSD – soft sediment deformation; TSD – tectonic stratal disruption.

contributed to the formation of at least part of the Franciscan Complex (Aalto, 1981, 2014; Raymond and Bero, 2015 and reference therein). The occurrence within these sedimentary mélanges of well-bedded huge olistoliths ("floaters"), such as slide blocks composed of specific turbidite facies and grain-flow deposits, embedded in a sandstone matrix, are stratigraphically and sedimentologically consistent with parts of the lower slope-base of slope sedimentary successions, arguing against tectonic origins in a subduction channel (see Raymond and Bero, 2015 for details).

Other lines of evidences outline, for example, that not all the rocks forming the different part of the subduction complex may be incorporated within the shear zone at the subduction plate interface, providing indirect constraints to the process of their formation. For example, MacPherson et al. (1990) and Wakabayashi (2015) interpreted in the Franciscan Complex that the occurrence within the subduction complex mélanges of blocks of upper crustal rocks of the upper plate, represents the product of sedimentary mélanges rather than of tectonic ones. The primary structural position of such rocks (i.e., upper plate), suggests they cannot be incorporated into the shear zone of the subduction plate interface by tectonics (slicing or faulting) because the zone of slicing in such a shear zone would be well below the level in which such rocks occur. On the contrary, rocks of the subduction complex that were initially on the subducted plate can be transferred to the upper plate as a result of subduction-accretion processes and/or the migration of the shear zone of the subduction plate interface.

The "tectonic environment criterion", therefore represents (see Table 2) the most important one in strongly constraining the nature of polygenetic mélanges. However, it requires a very deep and detailed knowledge of the regional geology and tectono-stratigraphic (and/or metamorphic) evolution of the sector in which mélanges occur. To this aim it is essential, and cannot be renounced to constrain multidisciplinary analytical studies (e.g. structural, stratigraphic, petrological) on new detailed geological maps (see also Şengör, 2014; Balestro et al., 2018; Festa et al., 2019), if we aim to really understand their tectonometamorphic evolution, and better constrain paleogeographic reconstructions.

6. Concluding remarks

Most of all papers focusing on mélanges, indirectly suggested specific criteria supporting the interpretation of both the origin and processes of formation of described mélanges. However, after 100 years from the inception of the term mélange in geology (see Greenly, 1919), these specific, and in several cases, local criteria are still not completely acknowledged by the majority of geoscientists and confusion exits in the correct interpretation of chaotic rock units with consequent uncompleted reconstruction of the tectonic evolution of orogenic belts and exhumed subduction-accretion complexes in which mélanges occur.

After several years of study on most of all notable examples of mélanges throughout the world, we have defined and streamlined for the first time in this paper the most useful diagnostic criteria to differentiate on-field different types of mélange. We dedicated particular attention to complications occuring in orogenic belts and exhumed subduction-accretion complexes, where the primary fabric of the mélange is commonly reworked by tectonic processes (i.e., polygenetic mélanges).

The novelty and significance of these criteria is that they all follow specific principles that are at the base of geological mapping rules, as well as of stratigraphic principles, and structural geology and petrological constraints, where possible (see also, e.g., Hsü, 1974; Cowan, 1978, 1985; Aalto, 1981; Raymond, 1984, 2015; Pini, 1999; Panini et al., 2002; Bettelli et al., 2004; Cowan and Pini, 2004; Vannucchi and Bettelli, 2010, Festa, 2011; Festa et al., 2010a, 2012, 2013). Thus, together with a semplified use of the mélange terminology, they can be successfully applied on-field in way to constrain with specific rules and principles the interpretation on the nature of mélanges. Importantly, considering the complexity of the problem, none of criteria proposed works alone but, on the contrary, they need to be supported each other's, having particular attention in considering (i) the coherence between lithological compositions of mélange components (i.e., blocks and the matrix) and characteristics and tectonic evolution of the geodynamic setting of their formation (the "tectonic environment criterion"), and (ii) the specificity and kinematic coherence in the deformation between blocks and the matrix (the "deformation criterion").

Considering the importance of the "tectonic environment criterion", a detailed knowledge of the regional geology of the studied sector and its tectono-stratigraphic (and/or metamorphic) evolution is mandatory, if we aim to correctly interpret the nature of mélanges. Thus, it is essential, and we cannot renounce, to constrain our multidisciplinary analytical studies (e.g. structural, stratigraphic, petrological) on new detailed geological mapping (see also Şengör, 2014; Balestro et al., 2018; Festa et al., 2019).

We envision this overview as a useful field-guide for students and researchers in the broad field of geosciences who are not intimately familiar with mélanges, mélange terminology and inherent problems with complex internal structures and superposed origins of mélanges. We are confident that the streamlined terminology and criteria for recognizing different mélange types as we introduce in this synthesis can be successfully applied in all field-based investigations of mélanges, broken formations and exhumed subduction-accretion complexes around the world, regardless of their location, age, and tectonic history.

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