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Mélanges in flysch-type formations: Reviewing geological constraints for a better understanding of complex formations with block-in-matrix fabric

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ABSTRACT

The geological term "mélange" is used to indicate a vast group of "chaotic rock" units with a block-in-matrix internal arrangement exhumed in orogenic belts. Geotechnically such units are often defined as "complex formations", and are commonly associated with flysch-type formations. Such units range from coherent, bedding-concordant broken-formations to fully disrupted, discordant block-in-matrix rock assemblages. Mélanges derive from the progressive disruption and mixing of flysch-type successions from their earliest phases of development to their complete lithification and exhumation. They are the product of sedimentary (submarine mass transport), tectonic (thrust-related shearing) and mud-diapiric (fluid/gas driven remobilization of mud/shales) processes. Throughout a review of geological data, we show that the different intrinsic anatomical features and relationships with the host rocks shown by these various units allow differential internal anisotropy of the lithological properties, and, depending on their origin, size and distribution, they can variably influence the overall mechanical behavior of the host flysch-type formation. The review of geological data thus provides useful observations to distinguish different types of "complex formations" and block-in-matrix rocks with different geotechnical and mechanical characteristics, and then potentially suggesting the application of different rock or soil mechanics procedures.

1. Introduction

The mechanical behavior of geological rock mixtures composed of fragmented competent lithologies surrounded by weak matrix is highly heterogeneous and a full geotechnical characterization of all types of "chaotic" geological masses is currently missing. Although some studies on the overall strength properties of block-in-matrix materials by in-situ testing have been carried out(Coli et al., 2008, 2011), researches focused mostly on investigating empirical relationships by implementing physical models (Lindquist and Goodman, 1994; Sonmez et al., 2004; Afifipour and Moarefvand, 2014; Kalender et al., 2014). Other studies instead, selected agglomerate rocks, detailing for example the strength contrast between volcanic rock blocks and weak tuff matrix (Sonmez et al., 2006; Sonmez et al., 2016). Based on the studies in literature, block-in-matrix bodies can be classified into two main groups, welded and unwelded, depending on the mechanical contrast between block and matrix at their contacts (mainly in terms of cohesion and friction; e. g. Medley and Zekkos, 2011). Besides, based on these results, numerical approaches were also used to evaluate overall strength of block-in-matrix materials and "structurally complex formations" (e.g. Barbero et al., 2012 and Napoli et al., 2018a).

The geotechnical term "structurally complex formation" (see Esu, 1977) describes different types of homogeneous ("Group A") and heterogeneous ("Groups B and C") rock units with different geotechnical complexities depending on their internal organization, composition and stress history. Part of "Group B" and the "Group C" show an apparently chaotic structure due to the complete dismemberment and transposition of an original coherent bedding. Following Esu (1977), several Authors investigated the geotechnical characteristics of the different types of heterogeneous complex formations and their internal "chaotic" fabric (see, e.g., D'Elia et al., 1998; Marinos and Hoek, 2001; Medley, 2001; Gokceoglu and Zorlu, 2004; Sonmez et al., 2004; Wakabayashi and Medley, 2004; Barla and Perello, 2014; Kalender et al., 2014; Marinos et al., 2019; Napoli et al., 2018b, 2020). As a general consideration, classical soil or rock mechanics procedures can be hardly applied in the geotechnical characterization of such complex formations, causing a high complexity in terms of predictability and reliability of any geotechnical model. This is because the classic geotechnical and geomechanical characterizations consider the internal "chaotic" arrangement of most complex formations as "unstructured and unpredictable" with an apparently random distributions of blocks in a matrix, without taking into account the entire geological background. Considering the latter, dedicated papers clearly document that different types of "chaotic" rock units (or mélange, the more widely used geological term, see below) exist and show different internal organizations (e.g., Raymond, 1984; Cowan, 1985; Pini, 1999; Festa et al., 2019 and reference therein), suggesting their potentially different geotechnical and mechanical properties.

In the geotechnical literature, classic flysch units, represented by well-bedded turbidite sequences, are usually found in close association with the complex formations (e.g., Marinos et al., 2019 and reference therein). Genetic relationships among them were inferred already at the end of the 19th century. In fact, flysch-type turbiditic successions (either siliciclastic and carbonatoclastic) sometimes appear pervasively disrupted and folded, with this progressive deformation ultimately ending in isolated, single bed chunks or fragments (i.e., blocks), or entire bed packages (megablocks, olistoliths, floaters), enclosed in a matrix of highly deformed fine-grained material. A characteristic block-in-matrix fabric is therefore common in these units, along with a mesoscopic to microscopic scaly fabric (see Mutti et al., 2009 and references therein).

This type of complex formation shows a marked contrast with the classic flysch units and was called "*wildflysch*" by early Alpine geologists (Kaufmann, 1886). On the same line, the block-in-clayey-matrix complex formations of the Apennines were classically termed from geologists as "*Argille scagliose*", "*Argille Varicolori*" and "*Argille brecciate*" (see, e.g., Ogniben, 1953; Selli, 1962; Lentini, 1979) or defined and mapped as "Chaotic Complex" (see, e.g., Abbate and Sagri, 1970; Boccaletti and Coli, 1982), while the highly deformed rock units underlying the far-travelled Helminthoid Flysch units of the Western Alps and Apennines were collectively named 'basal complexes', the latter showing different degrees of stratal disruption up to "chaotic" rocks (see discussions in Mutti et al., 2009; Camerlenghi and Pini, 2009 and further references therein).

In this paper we present a review from the geological point of view of different flysch-associated complex formations, observed in notable examples of the Northern Apennines, Pyrenees and Dinarides, documenting that they show different internal block-in-matrix arrangements according to the different processes/mechanisms of their formation. Our results show that this geological-based distinction and the recognition of different, diagnostic, block-in-matrix arrangement may thus provide useful information to take into account for planning the geotechnical characterization of different flysch-type "complex formations" and related possible practical implementation.

2. Geological versus geotechnical terminology and their link

The geotechnical term "heterogeneous complex formations" (see Esu, 1977) corresponds to the general geological term "chaotic rock units". Both these terms identify different degrees of disrupted units which have in common a block-in-matrix fabric with hard/competent blocks embedded in a softest/weakest matrix. The term block-in-matrix fabric, firstly proposed in the geological literature (see Berkland et al., 1972; Silver and Beutner, 1980; Raymond, 1984) was later adopted in the geotechnical literature with the term "bimrocks" (block-in-matrix rocks;Medley (1994). The term "bimsoils" (block-in-matrix soil) was later proposed in the engineering literature to differentiate those units with blocks embedded in a soil-like matrix (e.g., Medley and Goodman, 1994). These terms have been formalized to encompass a vast range of geological rock masses characterized by an internal "chaotic" arrangement, including "complex formations", "chaotic rock units", "block-in-matrix" units, but also conglomerates, breccias, coarse pyroclastic deposits, glacial tillites and fault rocks. They were originally intended to provide a focus on the geotechnical properties to meet engineers' standards, at the expenses of the intrinsic geological information, often considered as complementary. However, the use of these general, non-geological terms comprise the description of a wide range of block-in-matrix fabrics which are not geologically comparable one to each other and, importantly, show very different and not-comparable internal block-in-matrix organization and, therefore, different geotechnical characteristics. Therefore, the use of a correct geological terminology, aimed to distinguish and identify different types of chaotic rock units, does not represent a mere academic exercise but it is useful to indicate different "complex formations" with different internal organization and then, likely different geotechnical characteristics, mainly due to the various intrinsic orientation of the consequent mechanical anisotropies (see below).

From the geological point of view, the term *mélange* has been increasingly preferred to identify mappable geological units (at 1:25.000 scale) composed by block-in-matrix rocks characterized by the occurrence of "exotic" lithologies (Fig. 1). In particular, the term "exotic" is used to define elements "foreign" with respect to the matrix, indicating blocks/clasts not sourced from the surrounding lithological units (e.g., different lithological and/or mineralogical composition, lithification/compaction degree, metamorphic degree, etc.), whereas the term "native" is used to indicate "intraformational" elements originated from the disruption of the country rocks (Fig. 1). The matrix is formally defined as "deformed" or "fragmented", resulting from the interaction and superposition of different deformation processes (see, among many others, Hsü, 1968, Hsü, 1974; Cloos, 1982; Raymond, 1984; Cowan, 1985; Pini, 1999; Vannucchi and Bettelli, 2002; Festa et al., 2012, 2019).

On the other hand, the term “broken formation” is used to define a stratally-disrupted and fragmented rock unit (Fig. 1), still with a block-in-matrix fabric, but with no evidence of mixing and thus no occurrence of exotic blocks (Hsü, 1968; Cowan, 1985). Broken formations represent intermediate units recording a gradual transition from a bedded and coherent succession to a fully dismembered block-in-matrix fabric (see Fig. 1), and therefore they still maintain their original lithological, geometrical and chronological internal coherence (Hsü, 1968; Raymond, 1984; Cowan, 1985; Pini, 1999).

Such terms, mélanges and broken formations, should be used with a strictly descriptive meaning, implying no genetic connotation. Their block-in-matrix fabric can be achieved through different geological processes, such as tectonic, sedimentary or intrusive (i.e., mud/shales/salt diapirism) process of mixing and stratal disruption, acting from the early stages of plastic soft-sediment to the later stages of brittle and ductile deformation postdating lithification (see Festa et al., 2019 and references therein). Accordingly, these units can be distinguished in tectonic, sedimentary and mud-diapiric mélanges/broken formations based on their different internal block-in-matrix arrangement of mechanical discontinuities achieved during tectonic deformation, subaqueous sedimentary mass wasting, and mud/shale diapirism, respectively, and on their relationships with the host rock. The significance in geotechnical engineering of the different types of chaotic rock units, whose geological name identify different internal arrangement and mechanical properties, has been overlooked this far.

In this framework, tectonic mélanges and sedimentary mélanges represent block-in-matrix rock units characterized by stratal disruption and lithological mixing related to faulting-shearing processes, and by subaqueous depositional (gravitational) processes, respectively. Instead, in diapiric mélanges, fragmentation and mixing are achieved by mechanical abrasion of the host rock during the active intrusion of the matrix material (see, e.g., Higgins and Saunders, 1974; Deville, 2009; Festa et al., 2019). Along with flysch- (and molasse-) type bedded units, these three main types of mélange/broken formations are fundamental components of exhumed orogenic belts as they are ubiquitously represented in the Alpine-type foreland system, both spatially and temporally (Fig. 2).

Notably, the term “olistostrome” was classically and separately introduced (Flores, 1956, 1959) for block-in-shaly/clayey matrix rocks originated from subaqueous mass transport (i.e., downslope motion) processes (see, e.g., Hsü, 1974; Raymond, 1984; Cowan, 1985; Pini, 1999; Camerlenghi and Pini, 2009; Festa et al., 2016). In general, sedimentary mélanges (and olistostromes) are composite sedimentary bodies displaying complex internal and external structural relationships, developed during single or multiple subaqueous mass wasting events (sliding, slumping, debris flow, blocky flow), and as such, following stratigraphic principles of both superposition and crosscutting (see, e.g., Lucente and Pini, 2008; Festa et al., 2016; Ogata et al., 2020).

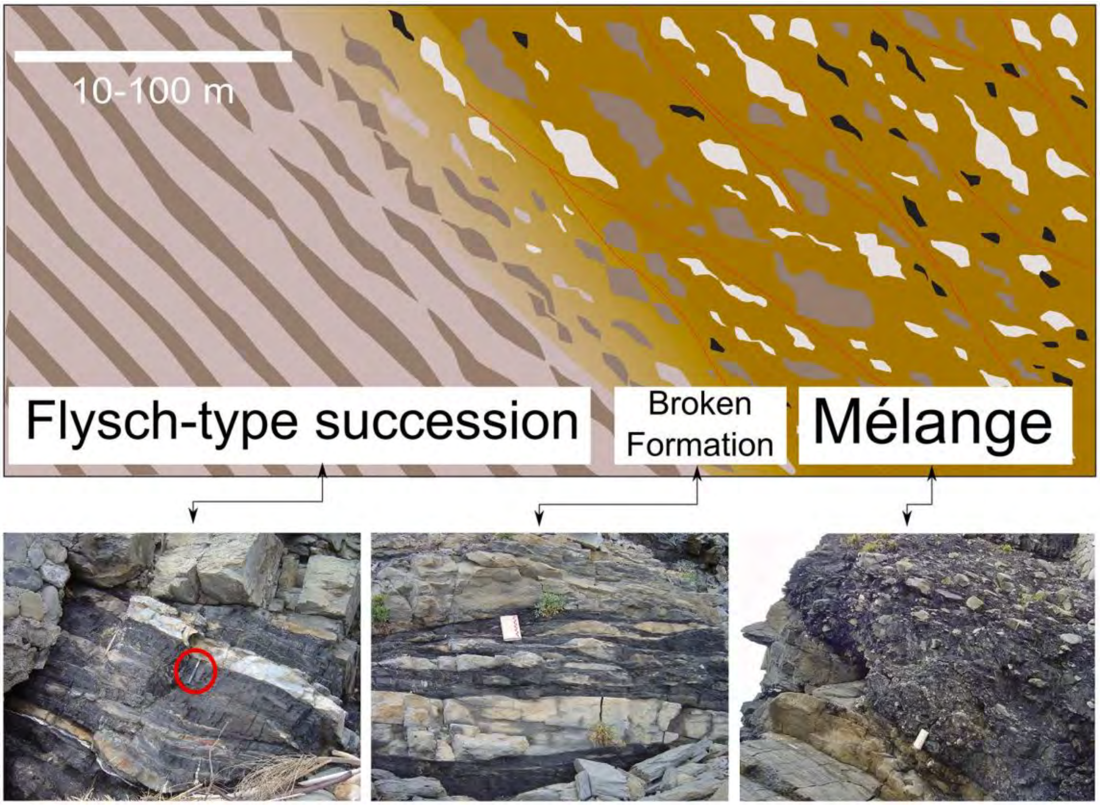

Fig. 1. Conceptual diagram showing a gradual transition from an undeformed, flysch-type lithology to a mélange (mixed rock) passing through a broken formation (un-mixed rock; modified from Festa et al., 2019). Outcrop examples are from the Eocene Canetolo Formation exhumed at the Cinque Terre, La Spezia (Northern Apennines, Italy).

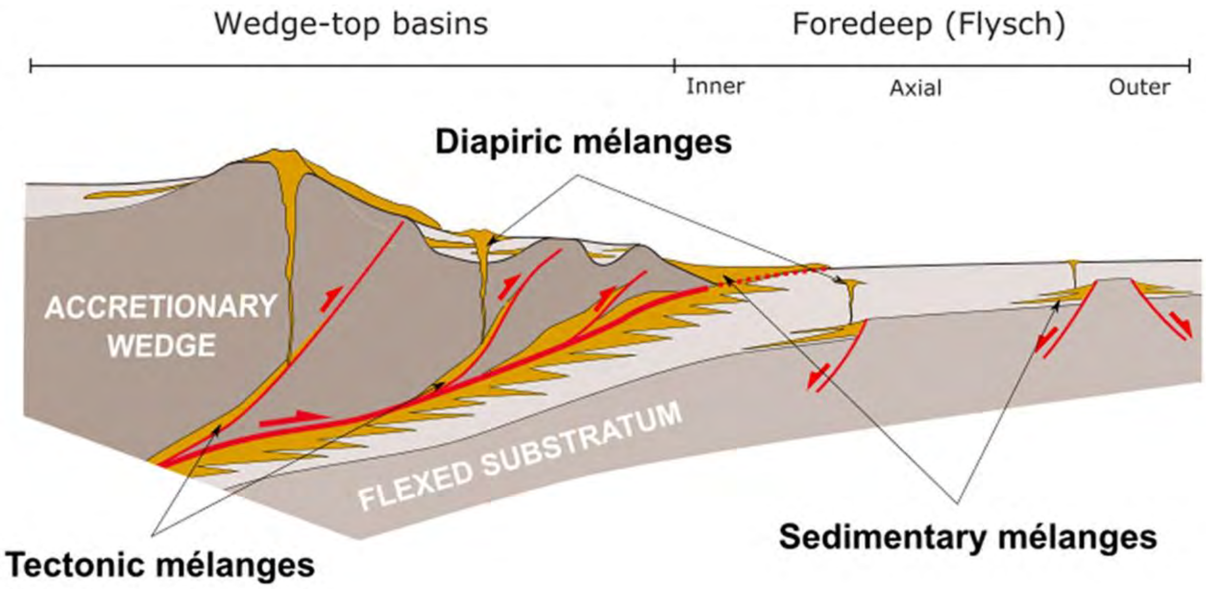

Fig. 2. Schematic cartoon illustrating a profile across an ideal Alpine-type foreland basin (flysch to molasse) with subdivision of the depositional settings and the typical localisation of sedimentary, tectonic and diapiric mélange units. Note the reworking and recycling of these processes and products through time (modified from Festa et al., 2019).

Z

3. Reappraising the block-in-matrix rocks tripartition

In block-in-matrix rocks (i.e., mélanges and broken formations), the dominant contribution by sedimentary, tectonic or diapiric processes (Fig. 3) can be discriminated in the field on the basis of different diagnostic meso- to map-scale, field-based structural-stratigraphic criteria (see, Festa et al., 2019 and references therein). Based on a review of our own data and those available worldwide from the literature, we use above all the mean aspect ratio (i.e., long axis/short axis) of clasts (< 1 m in diameter) and blocks (>1 m in diameter) to quantitatively compare the block-in-matrix fabric displayed by these different mélanges. As a result, block-in-matrix rocks formed by different processes are characterized by different diagnostic block-in-matrix arrangement, as described in the following.

3.1. Sedimentary mélanges

Sedimentary mélanges (or olistostromes), originated from submarine slope failures (see e.g. Ogata et al., 2020), show a highly disordered, and scale-invariant block-in-matrix fabric, contrasting with the generally more “ordered” internal structure of their tectonic counterparts (Fig. 3; see below). In these units, fragments of different size (from centimeters- to hundreds of meters), lithology, age and shape are randomly embedded within a fine-grained matrix (Fig. 4A, B, C). This internal arrangement outlines a homogeneous, isotropic texture from microscopic to cartographic scale. A distinctive element is the clastic (brecciated) matrix represented by an unsorted mixture consisting of angular- to rounded, sub-millimeters to millimeters particles of various composition (Abbate et al., 1970; Elter and Trevisan, 1973; Pini, 1999; Cowan and Pini, 2001; Vannucchi and Bettelli, 2010; Festa et al., 2016).

Blocks and clasts are typically polymictic and maintain the original fabric of source units (Fig. 4D): since sedimentary mélanges derive from slope failure and consequent mass transport processes, internal constituents may be sourced from lithologies having different ages and diagenetic/metamorphic grade, and thus different mechanical properties. The degree of mixing depends on the depth of the slope failure detachment, the physiography of the basin, the type of failure propagation (progressive vs. retrogressive, Masson et al., 2006), and the substrate erosion during the phases of transport and emplacement (see Ogata et al., 2019). These multi-sized blocks show mainly irregular to angular shapes, sometimes with overall tabular geometries defined by the internal layering of the involved bedsets. Overall, in sedimentary mélanges the aspect ratio of the internal blocks/clasts ranges between 1.4 and 2.5 (see Fig. 4E).

The basal contact of sedimentary mélanges can be either erosive or not, with spaced or crude scaly fabric, shear banding, and fluidal structures in the lower matrix interval (see, e.g., Pini, 1999; Ogata et al., 2012, Barbero et al., 2017). Such structures are commonly oriented at

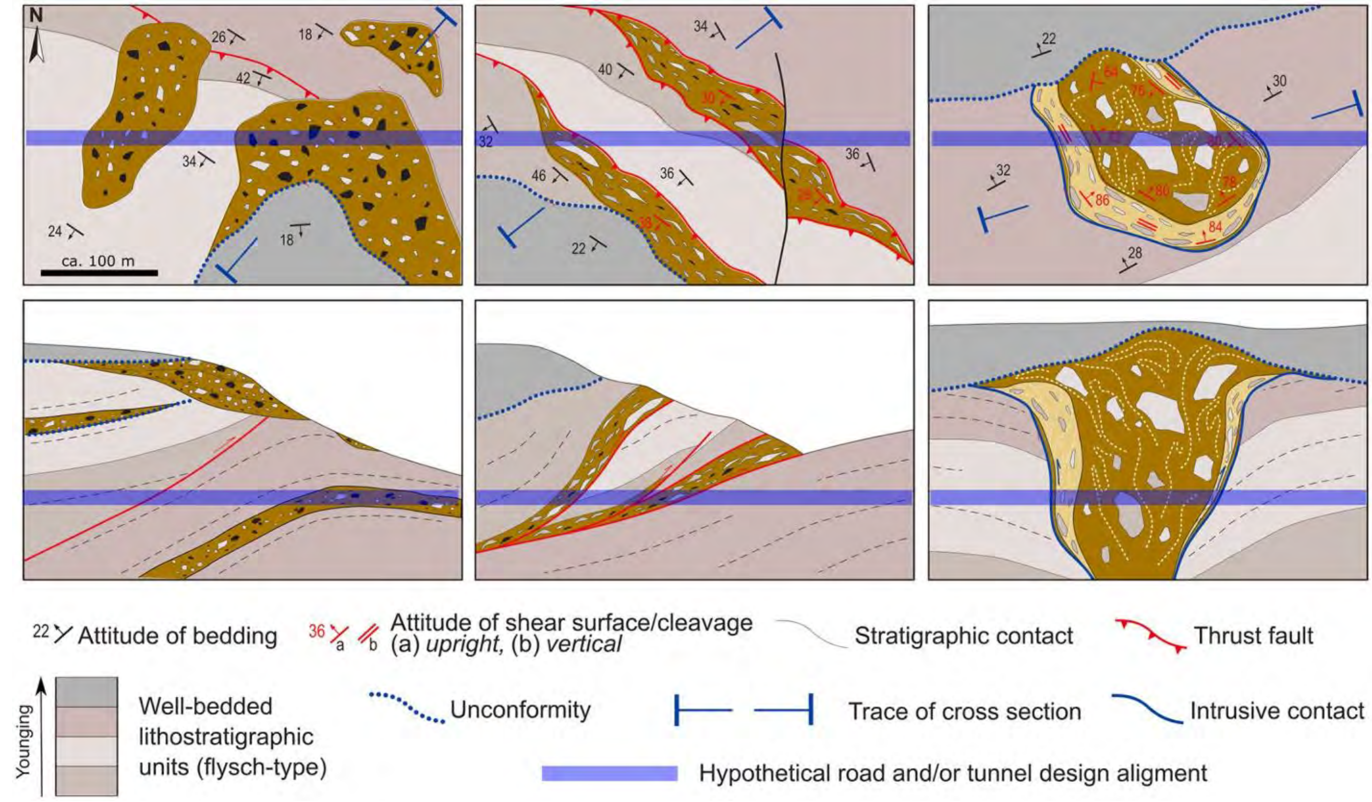

Fig. 3. Hypothetical map-view and cross-sectional representation of sedimentary, tectonic and diapiric mélanges and their relationship with the host formations as observed in the field.

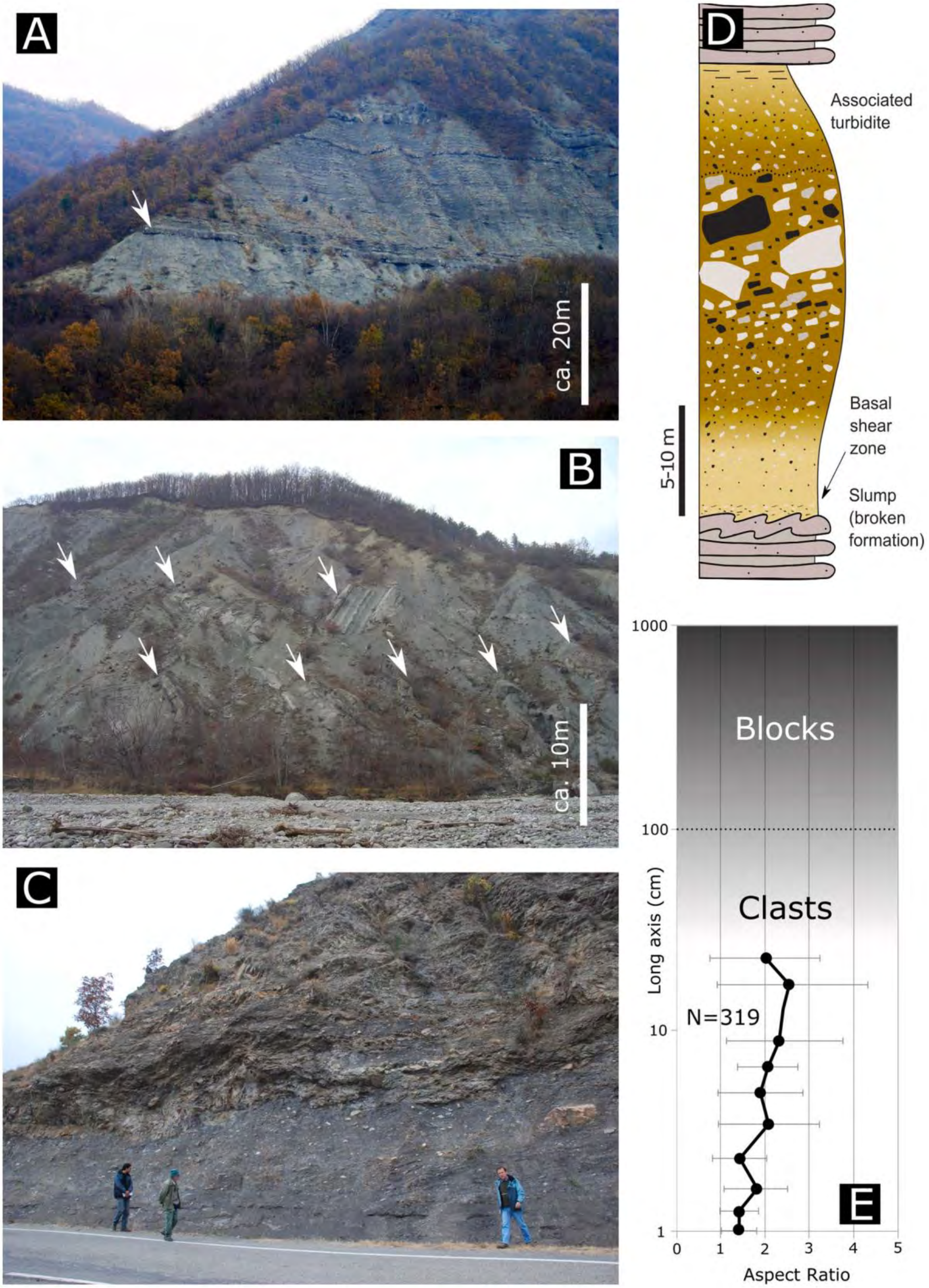

Fig. 4. Field examples of sedimentary mélanges (and olistostromes) with representation of their ideal anatomy and quantification of the block-in-matrix fabric in terms of clast/block aspect ratio. A. Blocky-flow deposit in wedge-top succession. Note the associated turbidite (white arrow) marking the top of the deposit (Early Oligocene Ranzano Formation of the Epiligurian Succession, Northern Apennines, Italy). B. Same unit as described in A. Tens-of-meters-sized blocks of deformed stratified are highlighted (white arrows). C. Typical appearance of an inner foredeep olistostrome with exotic clasts, in contact with the overlying fine-grained, stratified formation (thin-bedded turbidites: Early Oligocene Cervarola Formation, Northern Apennines, Italy). D. Synoptic stratigraphic log of a sedimentary mélange represented as a composite mass transport deposit (see Ogata et al., 2012), with labelling of the main internal components and structures. E. Aspect Ratio (long/short axis) vs. long axis diagram for the clasts comprising the matrix of sedimentary mélanges. The field labeled with "block" refers to out-sized slide blocks (i. e. olistholiths), reading out-of-scale values (up to kms across). Modified from Festa et al. (2019).

shear zone (see Ogata et al., 2014; Festa et al., 2016; Fig. 4D). Within this interval the poorly consolidated clasts are plastically deformed and strongly elongated according to the transport direction (Pini et al., 2012). At the same time a moderate flattening may occur orthogonally due to *syn*-emplacement compaction (Abbate et al., 1981). At micro-scopic scale, an alignment of clay minerals defines a weak scaly fabric in the basal shear zone, related to dewatering and subsequent pore collapse (e.g., Vannucchi and Bettelli, 2010), while a poorly compacted, open, edge-to-face texture of clay platelets is commonly observed in the rest of the unit (Pini, 1999).

The downward transition below the ductile shear zones (see Fig. 4D) can be gradual passing through a deformed substratum, that is folded and boudinaged beds up to broken formation, or a plastically brecciated fine-grained substratum with fluidal structures suggesting fluid over-pressure and in-situ hydraulic fracturing (Festa et al., 2015), or the transition is sharp coinciding with a single surface, which can be either non-erosive or erosive with scours (see, e.g., Abbate et al., 1970; Pini, 1999). The ductile shear zones make a progressive, upward transition into a disorganized block-in-matrix fabric (Fig. 4D), with the intra- and extra-basinal blocks distributed in the brecciated matrix are characterized by mechanical clast-size reduction (see Pini, 1999; Vannucchi and Bettelli, 2010).

Although as a mere concept, the aspect of the basal shear zone may resemble one of the typical characters of tectonic mélanges, the matrix of the basal shear zones of sedimentary mélanges is completely different, since it derives from the classic brecciated matrix of the sedimentary mélanges/olistostromes that has been highly sheared and flattened/ stretched.

The matrix is also observed to intrude clasts and blocks, forming clastic injections (Ogata et al., 2012). In this framework several generations of matrix may develop along with the downslope evolution of the sliding mass. These matrix phases are characterized by different sorting, textures, fabric and cementation, providing heterogeneous geotechnical characteristics varying laterally and vertically within the extent of the sedimentary mélange.

The mechanical (strength) contrast between blocks and matrix, which is an important geotechnical component of “structurally complex formations”, can be extremely heterogeneous within sedimentary mélanges and olistostromes, as they comprise resedimented products ranging from unconsolidated sediments to fully lithified rock aggregates. The volumetric amount of such components changes within the anatomy of a single sedimentary mélange, leading to highly variable geotechnical characteristics both vertically and laterally.

In terms of larger scale stratigraphic relationships, sedimentary mélanges are characterized by roughly lenticular shapes, unconformably overlying older stratigraphic (and tectonic) units (see Fig. 3). Such units are intercalated at different levels in bedded sedimentary successions, with lower and upper boundaries represented by unconformity (discontinuity) surfaces. The lower contacts commonly consist of irregular erosional surfaces with overall convex upward shape at tens-to- hundred meters across, and flat-ramp-flat geometries up to kilometers in scale. The upper contact is depositional and commonly conformable, separating the highly deformed material of the sedimentary mélange from the well-bedded overburden. The presence of meter/tens of meters thick packages of hemipelagites and/or very fine-grained turbidites atop the largest and thickest bodies is a common characteristic (see, e.g., Ogata et al., 2016; Tagliaferri and Tinterri, 2016), suggesting the accumulation of displaced masses changed the physiography of the basin for a long time.

In terms of size, sedimentary mélanges preserved in orogenic belts and exhumed subduction complexes are observed to spread over areas of several thousands of square kilometers (see, e.g., Burg et al., 2008; Alonso et al., 2015; Festa et al., 2016; Ogata et al., 2020), showing close similarities with the well-documented ones recorded in modern submarine settings by geophysical means (see, e.g., von Huene et al., 2004; Ogata et al., 2014; Moscardelli and Woods, 2016; Ogata et al., 2020).

3.2. *Tectonic mélanges*

In general, tectonic mélange are characterized by a “structurally ordered” block-in-matrix fabric (Figs. 3 and 5D) that strongly differs from the “disordered” one of sedimentary mélanges, nonetheless both have the same type of scale-invariant appearance (e.g., Pini, 1999). This structural arrangement is consistent with the orientation of the regional stress field and the general, large-scale tectonic setting in which the block-in-matrix fabric of tectonic mélanges is formed. These mélange units develop in response to different shearing processes acting in the zones of highest strain of faults (fault zone and shear zones) at different crustal levels, causing mechanical crushing of the country rock (hangingwall and footwall damage zones, see Chester and Logan, 1986), which is progressively incorporated and mixed in the core of fault (fault core, Chester and Logan, 1986). Notably, broken formation are the product of the damage zones and a true mélange only develop in the fault core (e.g., Cowan, 1985; Festa et al., 2012). Mélanges roughly bound the width of high strain areas of faults and shear zones, ranging from tens of meters to hundreds of meters in thickness (e.g., Ujiie, 2002; Festa et al., 2012).

The frequency and/or location of extra-formational, “exotic” blocks largely depend on the “maturity” of the tectonic mélange, which relates to the efficiency of tectonic mixing. This depends, in turn, on the tectonic environment and the rheology reached at local crustal PT conditions. The initial deformation stages are characterized by a poor mixing together with a structural order defined by the distribution of ripped-up, extra-formational blocks and clasts concentrated at the margins of the fault/shear zone (Fig. 5D). This internal arrangement testifies a close lithological correspondence with the hangingwall and footwall sections, which is gradually obliterated by the progressively higher strain and efficiency of mixing processes going from this marginal (transitional) zones into the interior of the body (core zone).

Notably, the relationships between block shapes and size distributions, and their total volume with respect to the matrix provide useful information to reconstruct the bulk viscosity and overall rheology of the shear zone (Grigull et al., 2012). The sequential development of sigmoidal tectonic slices (“horses”) in duplex systems, of imbricated thrust systems, thrust splays and/or out-of-sequence thrusts (Kimura and Hori, 1993; Kimura and Mukai, 1991; Wakita, 2012; Escuder- Viruete and Baumgartner, 2014), increase the number of faults/shear zones and, thus, extend the total volume of disrupted and mixed rocks. The gross size of exhumed tectonic mélanges is in agreement with direct measurements of the thickness (i.e., up to hundreds of meters) of shear zones associated with subduction plate interfaces and thrust splays down to 15 km depth, as recorded in modern and ancient convergent margins (see Rowe et al., 2013).

The thickest and widely distributed examples of tectonically-related “chaotic” complexes (extending for several tens/hundreds of square kilometers, as in the examples of the Apennines of Italy) seem to be actually made of broken formations (see Pini, 1999; Cowan and Pini, 2001; Bettelli and Vannucchi, 2003; see, e.g., Fig. 5A and B), with the “real” tectonic mélanges localised within relatively thinner high strain intervals along faults putting in contact different units of broken formations (see Pini, 1999; Cowan and Pini, 2001; Festa et al., 2019).

The size and shape of clasts and blocks, and their arrangement within the mélange and broken formation matrix depend on the types of deformation mechanism (e.g., brittle versus ductile), rheological properties, burial conditions (e.g., fluid pressure, pressure, temperature, mineral transformation), the degrees of consolidation, compaction and lithification, and strain rates. For instance, heterogeneous flattening in poorly consolidated sediments under prevailing coaxial strain develop pinch-and-swell structures and either asymmetric or symmetric boudinage (Fig. 5A, B, C) defining sigmoidal or lens-shaped blocks (e.g.,

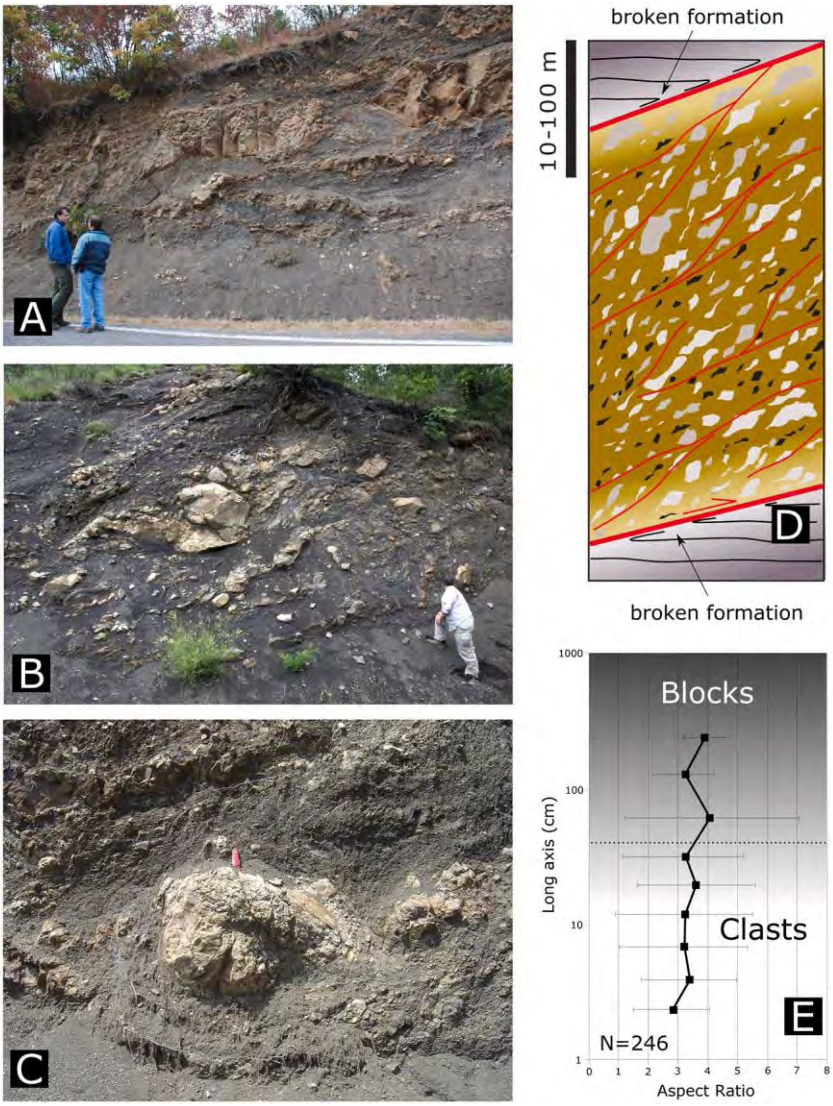

Fig. 5. Field examples of tectonic mélanges with representation of their ideal anatomy and quantification of the block-in-matrix fabric in terms of clast/block aspect ratio. A. Phacoidal- and lozenge-shaped blocks in scaly fabric matrix. Note the strong preferential alignment of the elements. B. Typical block-in-matrix fabric with sigma-shaped clasts and blocks. C. Detail showing the geometric relationships between indurated blocks and scaly fabric matrix. A, B and C are from the Early Miocene Cervarola Formation (Northern Apennines, Italy). D. Synoptic profile across an hypothetical tectonic melange with labelling of the main internal components and structures. E. Aspect Ratio (long/short axis) vs. long axis diagram for the clasts and blocks comprising tectonic mélanges. Modified from Festa et al. (2019).

Harris et al., 1998; Ujiie, 2002; Festa et al., 2012). This is typical of the deformation ahead and below of principal thrust faults (see, Fisher and Byrne, 1987; Kimura and Mukai, 1991; Meneghini et al., 2009). The more competent the involved beds, the more symmetrical boudinage structure may develop, consequently to the formation of conjugated shear sets. In this framework, tectonic mixing of internal components is mainly controlled by simple shearing.

The lateral continuity of originally layered sediments may be preserved for several meters although the strong transposition by isoclinal folding with eventual detachment of fold hinges (e.g., Pini, 1999; Vannucchi and Bettelli, 2002; Bettelli and Vannucchi, 2003). Moreover, as evidence of progressive deformation, stacking and piling up of boudinaged layers by subsequent thrusting may also occur (Pini, 1999; Cowan and Pini, 2001.

In relatively more competent sediments, with varying mechanical contrast between blocks and matrix, a sequential process of (micro) fracturing, cataclastic banding, and Riedel-type shearing (Tchalenko and Ambraseys, 1970) can further increase the boudinage with a higher fragmentation of the internal components (Kimura et al., 2012).

In lithified carbonate rocks, brittle deformation could occur from the relatively early stages of burial and diagenesis, with the development of Riedel-type shears (R and P planes; Tchalenko and Ambraseys, 1970) kinematically associated with a sigmoidal-shaped pressure solution cleavage (see. e.g., Castellarin et al., 1986; Pini, 1999) causing multi-scale pinch-and-swell of beds (see Fig. 5D). The lenticular to sigmoidal shape of clasts and blocks also relates to slicing and mechanical crushing of the hanging and footwall rocks of the shear zone (e.g., Pettinga, 1982; Cowan, 1985; Byrne, 1984; Ogawa, 1998; Fergusson and Frikken, 2003).

Elongated shape of the blocks may also change to oblate, up to spherical (e.g., Kimura et al., 2012), along with increasing P-T conditions during progressive involvement into deeper shear zones (i.e., "flow mélanges" of Cloos, 1982). Overall, the mean aspect ratio (long axis/ short axis) of the blocks belonging to tectonic mélanges ranges between 2.8 and 4.1 (see Fig. 5E).

In tectonic mélanges the matrix typically shows a well pronounced mesoscopic foliation characterized by spaced, disjunctive, and anastomosing planar features (Raymond, 1975; Lundberg and Moore, 1986) organized in a pervasive spacing of anastomosing and polished/striated surfaces (scaly fabric, see, e.g., Pini, 1999, Vannucchi and Bettelli, 2002, 2010; Bettelli and Vannucchi, 2003; Vannucchi et al., 2003). The spacing in particular is highly variable ranging from sub-millimeter in mechanically weak, foliated rocks (e.g., shale, serpentinite), to tens of meters in more competent, unfoliated lithologies, such limestones (Cowan, 1982; Byrne, 1984; Ujiie, 2002; Vannucchi and Bettelli, 2010).

Embedded within this scaly fabric matrix, sigmoidal and lenticular bed fragments millimeters to centimeters in size can also be found, showing their long-axis aligned to the main shear surfaces as already observed for larger clasts and blocks. Along with the scaly fabric, this structural arrangement defines a general planar anisotropy, which is the mesoscopic tectonic foliation imprinted by the (paleo)tectonic regional stress field (e.g., Vannucchi and Bettelli, 2010).

In a geotechnical framework, the properties of the scaly fabric developed within the matrix play a fundamental role in controlling the anisotropy of the mechanical weakness, which is usually parallel to the scaly fabric trend (Esu, 1977).

At smaller scale, single mappable units of tectonic mélanges commonly appear bow- to lens-shaped (see Fig. 3), depending on the tectonic setting (e.g., contractional, transcurrent), and more generally on the regional stress field. Poor (lateral) stratal continuity and (vertical) ordered superposition characterise the tectonic mélanges (Hsü, 1968). Mélanges formed in compressional settings are deformed according to regimes of thrust tectonics, with geometrical relationships dictated by in- or out-of-sequence propagation. In particular, out-of-sequence thrusting splitting up pre-existing tectonic stacks (e.g., thrust splays, duplex) can efficiently achieve a lithological mixing of blocks. On the other hand, tectonic mélanges associated to transcurrent settings and therefore related to strike-slip stress regimes are put in contact with tectonic units of different ages and nature, according to the overall kinematics of the associated fault zone.

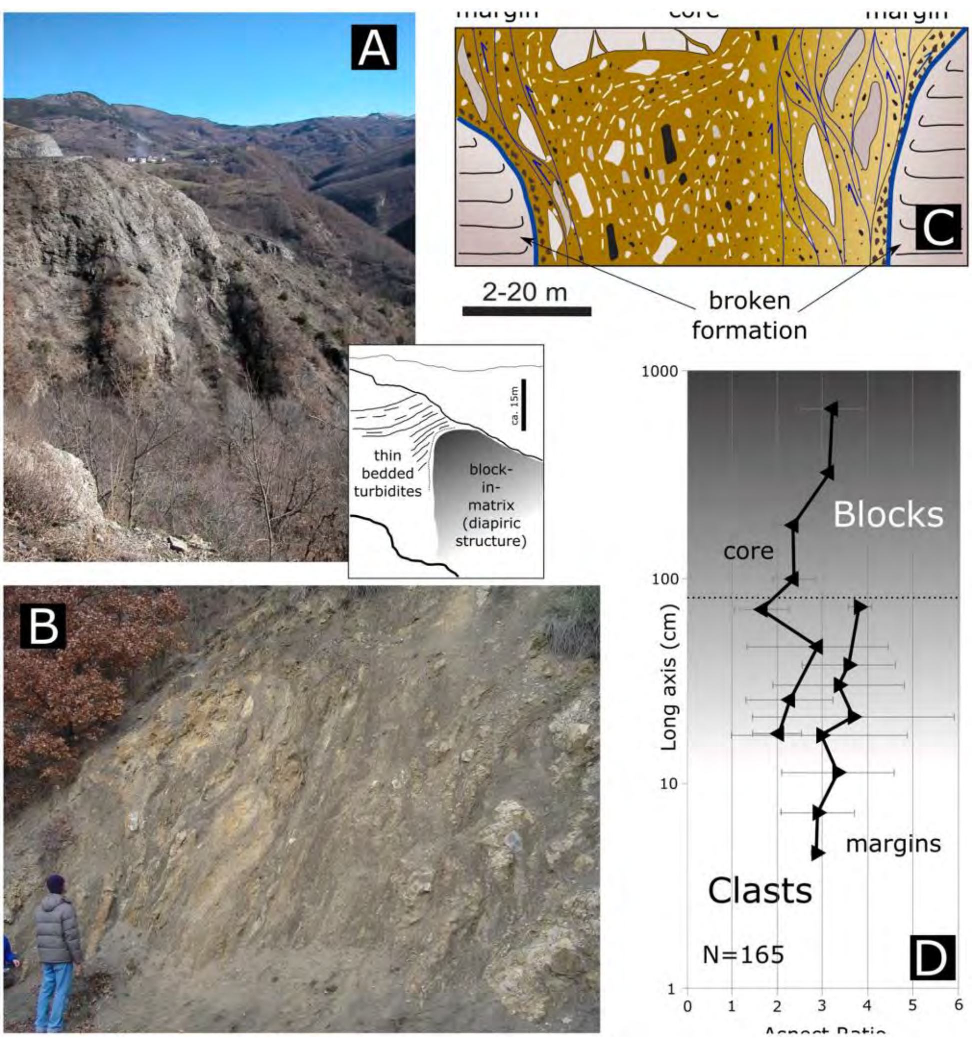

Fig. 6. Field examples of diapiric mélanges with representation of their ideal anatomy and quantification of the block-in-matrix fabric in terms of clast/block aspect ratio. A. Lateral-vertical geometrical relationships between sub-horizontal, well-bedded and fine grained turbidite secession and a block-in-matrix body characterized by a dome shape (see interpretation in small inset) B. Mesoscale appearance of the block-in-matrix body shown in A. Note the "fluidal" appearance and the complex folding. A and B are from the Early Miocene Cervarola Formation (Northern Apennines, Italy). C. Synoptic cross- section outlying the anatomy of an hypothetical diapiric mélange with labelling of the main internal components and structures. D. Aspect Ratio (long/short axis) vs. long axis diagram for the clasts and blocks comprising diapiric mélanges. Modified from Festa et al. (2019).

Their upper and lower boundaries can be either tectonic contacts or be present only at the base (thrust tectonics) or at one side (strike-slip tectonics), with an outward gradual transition to a broken formation and/or to a bedded flysch-type succession (see, e.g., Codegone et al., 2012).

3.3. *Diapiric mélanges*

The distribution of the block-in-matrix fabric in diapiric mélanges (Figs. 3, 6A, B) is strikingly different from the other sedimentary and tectonic counterparts (see above), with an internal architecture defined by a litho-structural zoning, from the margins to the core of the diapiric body (Barber et al., 1986; Barber and Brown, 1988; Orange, 1990; Festa, 2011; Codegone et al., 2012). This internal configuration is mainly due to the combination of fluid overpressure, density disequilibrium, inverted buoyancy, hydrofracturing processes, progressive incorporation of wall rock material and liquidization (i.e., liquefaction + fluid-isation; Allen, 1982). The deformation process is therefore inferred to be related to different states of subsurface flow, consolidation degree and rheological contrast between both the flysch-type layers of the host stratigraphic succession and the diapiric matrix (see, e.g., Pini, 1999; Festa et al., 2012).

In close proximity to the intrusive contacts, a marginal/transitional zone is commonly present, in which the block-in-matrix fabric show sub-vertical foliation with mainly phacoidal- to tabular-shaped blocks, dispersed in a fine-grained (shaly or clay/silty) matrix with pervasive anastomosing mm-to cm-scale scaly fabric (Fig. 6C) (Brown and Orange, 1993). Simple shear-related structures (S-C, Riedel; see above) indicate a relative movement of the diapiric body (e.g., Orange, 1990; Festa, 2011). Accordingly, to the overall size of the unit, elongated blocks, ranging in size from decimeters to meters, appear to be clustered close to the contacts due to a velocity gradient in the matrix causing shear localisation in these marginal/transitional zones (e.g., Orange, 1990; Festa, 2011). In terms of mean aspect ratio of blocks (see above), the marginal zone ranges between 2.9 and 3.8 (see Fig. 6D), showing similarities with tectonic mélanges (i.g. shear-induced fabric). Mechanical fragmentation (ductile and/or brittle, depending on the overall lithification contrast) and block size reduction may lead to the creation of millimeters- to centimeters-sized elongated and stretched clasts, spread along the shear zones, outlining disaggregation (particulate flow) and cataclastic bands, wisp and tail features and pseudo-pressure shadows. Blocks commonly show fluid overpressure and hydraulic fracturing features (millimeters to several centimeters-sized) represented by injections of fine-grained matrix with a millimeter- to centimeter-sized scaly fabric aligned to the walls (see Clennell, 1992; Codegone et al., 2012).

The intensity of the scaly fabric and shear zones, along with the preferential elongation of the major axes of blocks and clasts gradually increase from the interior (i.e., core) to the margins. In the center of a diapiric body blocks and clasts are larger (up to tens of meters in size) and appear commonly angular to sub-angular, matrix-supported, with patchy clustering (e.g., Kopf, 2002; Clennell, 1992; Festa et al., 2019). In this core zone the mean aspect ratio of the blocks (see above) ranges from 1.6 to 3.2 (Orange, 1990; Festa et al., 2019). Moreover, these elements are randomly distributed within a non-foliated matrix, commonly preserving highly asymmetrical and disharmonic folds.

As for sedimentary mélanges (see above), there is a theoretical limit for the size (up to thousands of meters across) and number of undissociated blocks that can be carried and sustained in the diapiric flow, which is dictated by the density and viscosity contrast between matrix and blocks, and the deformation rates beside the driving fluid overpressure (e.g., Clennell, 1992; Fryer et al., 1999; Barber, 2013).

In some cases, a relatively thin halo (up to decimeters thick) made up by mud breccias with fluidal features oriented parallel to the main walls of the diapir body, is observed to separate the sheared marginal/transitional zone from the pristine host rocks (see Festa, 2011).

At smaller (i.e., cartographic) scales, the intrusive contacts bounding a diapiric mélange show ellipsoidal and lenticular geometries in plan view /see Fig. 3), and variable angles (usually high) with respect to the overall layering of the host succession, which is typically younger than or coeval to the matrix material (e.g., Clennell, 1992; Kopf, 2002; Festa, 2011; Codegone et al., 2012).

The overall size of entire diapiric bodies spans from tens of meters up to tens of kilometers in longest dimension (e.g., Clennell, 1992; Kopf, 2002; Codegone et al., 2012; Barber, 2013; Maekawa et al., 1993; Fryer et al., 1999). In longitudinal profiles, their boundaries usually appear as high-angle intrusive contacts converging downward into a typical “inverted cone”-type shape (or “Christmas tree”-like in case of surface extrusion and outward fringing of mudflow lobes, see, e.g., Deville, 2009).

4. Discussion

In the last decades many efforts have been made in order to provide reliable geotechnical characterization of block-in-matrix rocks. Through implementation of analogue and numerical modelling (Barbero et al., 2012), as well as experimental petrophysical testing of manufactured (Afifipour and Moarefvand, 2014; Kalender et al., 2014) and natural block-in-matrix rocks (Sonmez et al., 2006; Coli et al., 2011), crucial findings on their mechanical response have been made, identifying and quantifying parameters such as the volumetric rock proportion (VBP), block count (Bc) and the related tortuosity of failure surfaces (Lindquist, 1994; Lindquist and Goodman, 1994; Wakabayashi and Medley, 2004; Sonmez et al., 2016). Nonetheless, “chaotic” rock complexes and especially block-in-matrix rocks are routinely modelled as intrinsically heterogeneous, but at the same time somewhat isotropic, following the pre concept ofunstructured and “unpredictable” media, being considered as massive assemblages of fine-grained (i.e., concrete-like) matrix material with randomly distributed multi-sized blocks.

On the contrary, geological observations clearly show that different types of complex formations with different and diagnostic block-in-matrix internal organizations occur representing the product of different deformational processes that occur in different geological environment (Fig. 3). These different diagnostic block-in-matrix fabrics are repetitive at different scales and can be predictable at least in part when geological observations and identification of processes of their formation are correctly applied. In fact, due to the different internal and external structural-stratigraphic attributes contrasting with the surrounding well-bedded country rocks, sedimentary, tectonic and diapiric mélanges strongly influence the general mechanical behavior of the host flysch-type successions, at the different scales and with different modes, depending on their different block-in-matrix arrangement (i.e., degree of anisotropy). While sedimentary and tectonic mélanges appear clearly separated by the amount of preferentially directed strain recorded by the block-in-matrix fabric (see Fig. 3), diapiric ones show mixed characteristics, conforming to the former and latter in terms of core and marginal zones, respectively (see Figs. 4, 5, 6).

In this framework, the main pre-conditioning factors controlling such a behavior are: 1) the different arrangement and characteristics of their boundaries, showing varying relationships (e.g., cut-off angles, transitional vs sharp contacts) with respect to the flysch-like host formation, 2) the shape, size and internal distribution of clasts/blocks, 3) the state of deformation of the matrix (e.g. scaly vs massive fabric), 4) the amount of lithological mixing (i.e. compositional differences be- tween clasts/blocks and matrix) defining the rheological/mechanical contrast between components, and 5) the different internal distribution and lateral-vertical variations of the block-in-matrix fabric features (e.g. volumetric block proportion). These characteristics vary accordingly to the different characteristics of the associated mélange type as depicted in Fig. 3, and more specifically in Fig. 7. In fact, beside the differential mechanical anisotropy intrinsically due to various mélanges anatomies, their differently oriented external contacts provide, for example,

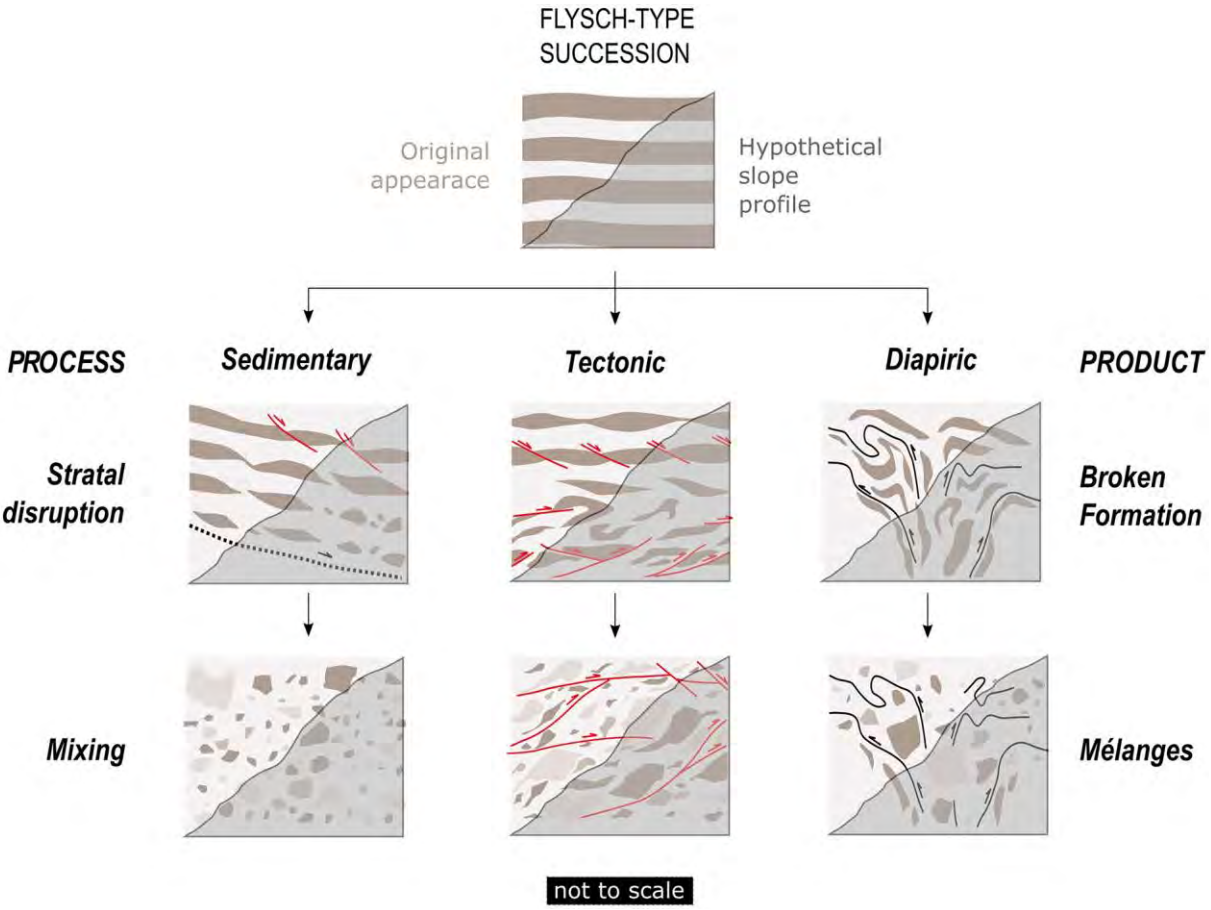

Fig. 7. Flow diagram summarising the progressive deformation from a flysch-type "protolith" to sedimentary, tectonic and diapiric block-in-matrix fabric units in terms of processes (stratal disruption vs. mixing) and products (broken formation vs. mélange).

mechanically weak boundaries for later strain localisation (and therefore representing weak zones prone to be reactivated by landsliding), and preferential meso-scale fracture-related permeability due to planar discontinuities (e.g., scaly fabric), which are expected to deeply influence the overall petrophysical and physicochemical architecture (e.g. by localised weathering/alteration). A compilation of the geotechnically relevant features displayed by these different mélanges is provided in Table 1.

Slope stability is variably affected by the occurrence of these units, mainly depending on the spatial arrangement of these internal and external mechanical discontinuities with respect to the overall slope gradient and topography (e.g., direction of valleys and hill ridges). Among the most representative showcase examples of such scenarios are those related to the mining operations threatened by the differential anisotropic slope instability due to the depositional architecture of sedimentary megabreccia bodies in flysch-type country rocks such as the Paleocene-Eocene megabeds in NW Slovenia (see Pogačnik et al., 2014).

Notably, apart from the strong morphological convergence of the final mélange appearance, reworking and recycling by consequent interacting processes is also common, such as diapiric bodies originating from buried MTDs or olistostromes, and their subsequent tectonìc shearing (see Fig. 1). This polyphased deformation history leads to the genesis of “polygenetic” mélanges, further complicating the overall scenario (Festa et al., 2019).

5. Conclusions

Despite the long-lasting debate focusing on mélanges with a block-in-matrix fabric, the correct recognition and interpretation of the origin and processes of formation of “chaotic” rock complexes related to flysch-type lithologies are usually overlooked, despite the practical implications described this far.

In fact, confusion still lingers among the vast majority of geoscientists about the correct interpretation of “chaotic” rock units leading to the consequent lack of knowledge needed for correct reconstruction of the tectonic evolution of orogenic belts and exhumed subduction-accretion complexes in which geotechnically heterogeneous flysch-type rocks and stiff clays are exhumed.

In this review we document that different types of mélanges (i.e., complex formations) associated with flysch formations, show different internal block-in-matrix arrangements according to the tectonic, sedimentary or diapiric processes of their formation and related deformation mechanisms. These different and diagnostic block-in-matrix fabrics have significant implication of mechanical properties of “complex formations” (e.g., orientation of the scaly fabric and other structural discontinuities) and their geotechnical characterization, according for instance to their different degree of anisotropy and block/matrix ratio. Using geological observations, correct interpretations on the nature of mélanges/complex formations can be outlined, with important benefits in terms of predictability and reliability of any geological and geotechnical model. In particular, some key points have to be addressed when dealing with “chaotic” block-in-matrix rock complexes:

- the logical lithological coherence of components (i.e., blocks vs. matrix) - the associated geodynamic setting of their formation and the associated tectonic history
- the specificity and kinematic consistency in the deformation between blocks and the matrix.

According to these concepts, it is deemed essential to develop a baseline geological constraints backed up by multidisciplinary (e.g. structural, stratigraphic, petrographic, paleontological, geophysical, geotechnical) studies and a reappraisal of high-resolution geological mapping (see also Şengör, 2014; Festa et al., 2019) to correctly implement practical studies and realistic models dealing with the different types of block-in-matrix rock units (mélanges and broken formations) associated to flysch-type formations around the world, regardless of their location, age, and tectonic history.

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Table 1
Main geological attributes and relevant geotechnical implications for sedimentary, tectonic and diapiric mélanges.

Mélange types		Sedimentary	Tectonic	Diapiric
Block-in-matrix features		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 local to regional tectonic stress (anisotropic texture). Commonly equivalent to mappable fault or shear zones	Internal structural zoning from margins to core of diapiric body (from anisotropic to isotropic)
Bounding contacts and general shape		Map view: Irregular to sub-parallel contacts to stratigraphic boundaries of the host successions. Section view: Lenticular at different scales. Lower and upper depositional contacts as discontinuity (unconformity) surfaces and following original continuity. Originally interbedded within coherent primary successions	Map view: From narrow and elongated to arcuate and lenticular; aligned to tectonic contacts and lineaments. Section view: Wedge- to lenticular shape. At least one tectonic contact (i.e., fault, thrust, strike-slip fault). Not following the original stratal continuity	High to low angle intrusive contacts. Not following the original stratal continuity
Block/matrix contacts		High to low contrast (welding) depending on the consolidation state of the lithologies involved in the mass transport event and differential diagenesis/ compaction	High to low contrast (welding) depending on the consolidation state of the lithologies involved in the tectonic shear zone and differential mineralization	High to low contrast (welding) depending on the consolidation state of the intruded lithologies and source formation
Block proportions		Variable according to the stratigraphy of the deposit (mass transport facis)	Variable according to the structural order of the unit (thrust sequence, shear zone architecture)	Variable according to zonation of deformation: lower in marginal zones, higher in core zones
Matrix	Lihologies	Random distribution of blocks in a brecciated fine-grained matrix (e.g., shale, clay, marl), siliciclastic or carbonate (but also metamorphic/ igneous) arenitic-ruditic matrix.	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 to local 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
	Fabric and texture	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.	Sub-vertical flow fabric. Core zone: alignment of anastomosing and folded poorly-consolidated fine-grained sediments (irregular axial trends and steeply plunging axes). Marginal zone: sub-vertical S-C fabric
	Internal arrangement and discontinuities	Random distribution of equidimensional, and angular- to rounded clasts. Close to the basal surface, elongated clasts are aligned to the sheared matrix. Fluidal fabric, faint scaly cleavage and alignment of blocks at the body bases	Alignment of elongated clasts to the S-C fabric and shear zones. Occurrence of striation and systems of mineral-filled veins	Core zone: Random distribution of irregular shaped clasts. Marginal zone: Alignment of elongated clasts to the fluidal fabric
Blocks	Lithologies	Native (i.e., intra-formational) and exotic (i.e., extra-formational) depending on the depositional environment; sedimentary with original stratigraphy	Native (i.e., intra-formational) and exotic (i. e., extra-formational) depending on the involved tectonic-stratigraphic units;	Native (i.e., intra-formational) and exotic (i. e., extra-formational) depending on the source and the host formations
	Shape/aspect ratio	Angular to rounded and irregular to tabular (i.e. bedded) 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)

(*continued on next page*)

.

Table 1 (*continued*)

	Mélange types		
	Sedimentary	Tectonic	Diapiric
Long axis orientation	Parallel to bedding and elogated along the direction of flow	Parallel to bouding faults and elongated along the direction of tectonic shearing	Core zone: no preferred orientation. Marginal zone: parallel to boundig intrusive contacts and elongated along the direction of flow
Size/ dimensions	Centimeters to decimeters (clasts). 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

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