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Polygenetic mélanges: a glimpse on tectonic, sedimentary and diapiric recycling in convergent margins

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A significant part of mélanges recognized in exhumed convergent margins around the world has been recently documented to have chiefly originated from masse transport and subsurface remobilization and disruption (i.e. mélanges, from sedimentary and mud–serpentinite diapiric processes and from in situ fluidification–disruption). Tectonic and/or sedimentary processes occurring during subsequent multiple deformational events of convergent margin evolution commonly overprint and significantly rework the primary (sedimentary or diapiric) mélange fabric, forming polygenetic mélanges. This ultimately complicates their distinction from true tectonic mélanges, masking part of the recorded tectono-sedimentary evolution of the associated convergent margin. The contributions gathered in this thematic collection explore with different approaches (from field structural and stratigraphic observations to geophysical analyses) different types of polygenetic mélange, at various scales, around the world. These studies conclude that the understanding of this type of mélange may provide crucial insights for a more detailed interpretation of the evolution of ancient and modern convergent margins, and of processes and mechanisms triggering potential natural hazards (earthquakes and tsunamis). Case studies include the Apennines in the Central Mediterranean region, the Carpathians in Central Europe and the Nankai Prism in Japan.

Tectonic, sedimentary and (mud and serpentinite) diapiric processes form different types of mélange, each of which shows different diagnostic block-in-matrix fabric and composition according to their geodynamic setting of formation (Festa et al. 2010). During the multistage evolution of convergent margins, the alternation of these different processes, which commonly combine into complex interactions, overprints and reworks the primary (original) fabric of tectonic, sedimentary and (mud and serpentinite) diapiric mélanges (Fig. 1), forming polygenetic mélanges (e.g. Raymond 1984; Cowan 1985; Dilek et al. 2012; Festa et al. 2013, 2019b; Balestro et al. 2015; Platt 2015; Ernst 2016; Tartarotti et al. 2017).

Although various mutual interlinks between the different mélange-forming processes may occur (e.g. Camerlenghi & Pini 2009; Osozawa et al. 2009; Festa et al. 2012; Prohoroff et al. 2012; Moore et al. 2019; Raymond 2019), in most cases, tectonics represents the last and more pervasive overprinting process, conferring to polygenetic mélanges their typical block-in-matrix resemblance, sometimes virtually indistinguishable from that of true tectonic mélanges (Fig. 1). This resemblance is at the base of a long- lasting debate on the nature and mode of processes leading to the formation of block-in-matrix rock units, particularly in those sectors of well-preserved exhumed convergent margins such as the Western US Cordillera, the Circum-Pacific and the Circum-Mediterranean regions. The main aspect of the debate is whether the block-in- matrix arrangement of such exhumed chaotic rock units is the result of tectonic shearing and mixing alone, acting at different depths, or the product of tectonic reworking and 'recycling' of primary heterogeneous mass-transport deposits (i.e. sedimentary mélanges and olistostromes) or diapiric mélanges (e.g. Berkland et al. 1972; Hsü 1974; Raymond 1984, 2019; Cowan 1985; Barber et al. 1986; Pini 1999; Bettelli et al. 2004; Alonso et al. 2006; Festa et al. 2010, 2016; Wakabayashi 2011, 2019; Barber 2013; Balestro et al. 2015; Krohe 2017; Tartarotti et al. 2017).

To complicate this debate, evidence from explorations in trench systems and modern convergent margins documents that the different deformational processes affecting water-saturated and partially lithified sediments contribute to form a strong morpho- logical convergence of block-in-matrix fabrics between tectonic, sedimentary and diapiric products (e.g. Maltman 1994; Alonso et al. 2006; Ogata et al. 2014, 2020b; Festa et al. 2019c; Ogawa 2019). Regardless of the process of formation, different meso-scale features and structures (e.g. boudins, asymmetrical rootless folds, pseudo-SC structures, duplex types and imbricated structures, low- angle shear zones, etc.) form as a result of soft-sediment deformation in undrained, water-saturated and poorly consolidated to unconsolidated sediments (e.g. Maltman 1994; Ogata et al. 2016, 2019a, b; Ogawa 2019). The block-in-matrix arrangements of mélanges developed under these physical and mechanical conditions may thus appear highly similar in the field, creating confusion and uncertainty in their interpretation.

Further complications to this scenario are related to the fact that the abundance and size of (mud and serpentinite) diapiric and sedimentary mélanges in ancient convergent margins, as well as heterogeneous mass-transport deposits (MTDs) in modern ones, are poorly considered. Sedimentary mélanges and heterogeneous MTDs are described to reach >10 000 km^2 with a thickness ranging from hundreds of metres to about >1000 m (e.g. Woodcock 1979; Urgeles & Camerlenghi 2013; Festa et al. 2015,

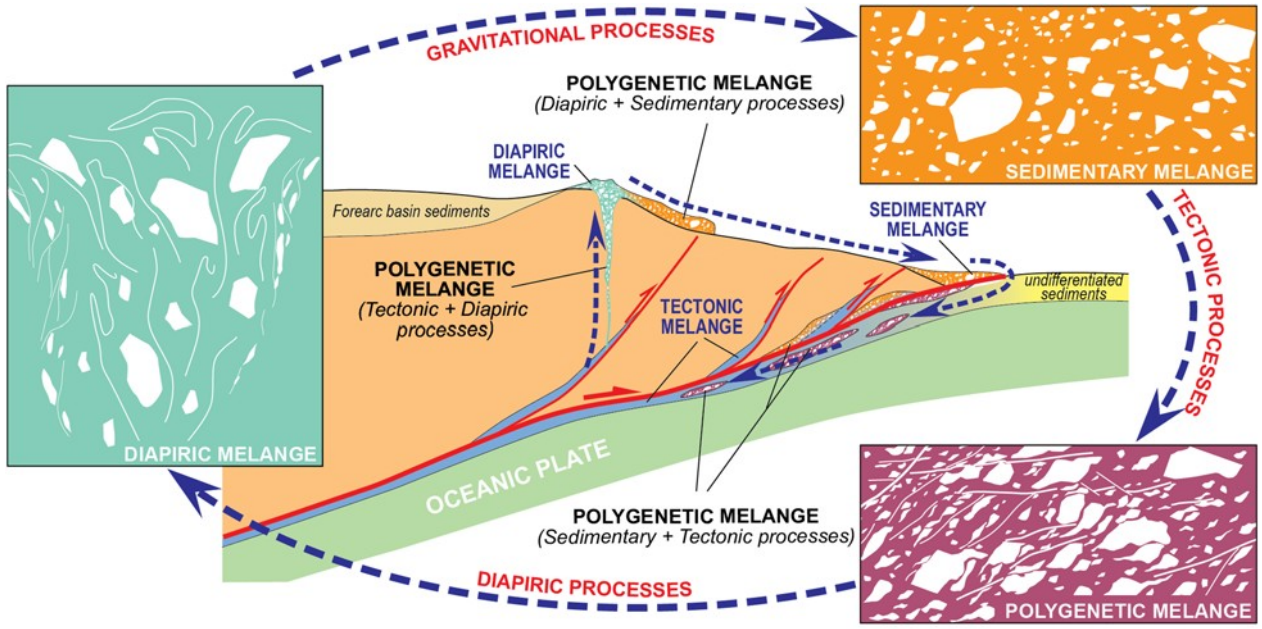

Fig. 1. Schematic illustration showing the interplay and superimposition of different mélange-forming processes during the tectonic evolution of a hypothetical convergent margin, and the consequent formation of different types of polygenetic mélange. The gravitational (sedimentary), tectonic and diapiric reworking of previously formed chaotic units with a block-in-matrix fabric (mass-transport deposits or sedimentary mélanges, tectonic mélanges, diapiric mélanges and/or broken formations) forms different types of polygenetic mélange. The internal fabric of the polygenetic mélange (purple box) shows that, commonly, the last and/or more pervasive process of deformation (i.e. tectonics in this example) masks the diagnostic block-in-matrix fabric of a previous one (i.e. gravitational process in this example).

2016; Moscardelli & Wood 2016; Ogata et al. 2020a, and references therein). Embedded lithified slide blocks (e.g. olistoliths) may be up to several kilometres in size (see, e.g. the Ruatoria Avalanche in New Zealand, Collot et al. 2001; Lewis et al. 2004; the Casanova Complex in the Italian Northern Apennines, Bertotti et al. 1986; Elter et al. 1991). Diapiric mélanges also have been documented to commonly reach several kilometres in size (e.g. Barber et al. 1986; Barber 2013), in a few cases extending to 30 km in diameter and about 2000 m in thickness as in the Mariana Trench (see, e.g. Maekawa et al. 1993; Fryer et al. 1999; Tamblyn et al. 2019), where blueschist exotic blocks, sourced from the subduction zone, are embedded within a serpentinite muddy matrix.

According to their documented size, the potential occurrence of sedimentary and (mud and serpentinite) diapiric mélanges, masked by the overprinting of tectonic processes, should thus be accurately taken into consideration in interpreting sectors characterized by large-scale mélange occurrences. In fact, after years of debate and controversies, it is now broadly documented and accepted that sedimentary and diapiric mélanges represent a consistent part of chaotic rock units (e.g. Barber et al. 1986; Bettelli & Panini 1989; Pini 1999; Bettelli et al. 2004; Camerlenghi & Pini 2009; Festa et al. 2010, 2016; Barber 2013; Ogata et al. 2014, 2016; Gawlick & Missoni 2019; Moore et al. 2019; Wakita 2019).

Within this complex scenario, it is evident that the study and understanding of the mode and time of polygenetic mélange formation is highly significant to better constrain interpretation of the evolution of convergent margins around the world. They record the superimposition of the different processes that acted during convergent margin evolution (Fig. 1).

In this thematic collection, we follow the most common mélange terminology used in the literature of chaotic rock units. To avoid confusion between contrasting terms proposed in this literature after the introduction of the geological term ‘mélange’ by Greenly (1919), we present in the following a streamlined usage of the complex, and sometimes unclear, mélange terminology. This is useful both to properly address the concepts expressed in the papers of this collection and to make this terminology accessible to all those geoscientists who are not intimately familiar with it. An extensive discussion on mélange terminology has been presented by Festa et al. (2019c).

Polygenetic mélanges and the mélange nomenclature

‘Mélange’ is a descriptive and non-genetic term, defining a mappable body (at 1:25 000 or smaller scale) of internally disrupted and mixed rocks, with ‘exotic’ lithologies included as discrete masses (i.e. blocks) in a pervasively deformed finer grained matrix, without restriction to any particular lithological unit (e.g. Berkland et al. 1972; Wood 1974; Silver & Beutner 1980; Raymond 1984; Cowan 1985). As stated above, different processes may lead to the formation of a mélange (Fig. 2): the adjectives ‘tectonic’, ‘sedimentary’ and ‘diapiric’ can therefore be used to indicate the interpreted origin of mélanges. The adjective ‘polygenetic’ on the other hand indicates mélange formed by the interplay and superimposition of tectonic, sedimentary and/or diapiric contributions (Fig. 2).

The term ‘exotic’ includes all types of block that are ‘foreign’ (i.e. from an ‘extraformational’ origin to different metamorphic degrees) with respect to the matrix (Hsü 1968; Festa et al. 2012). ‘Exotic’ are all those blocks or clasts whose source is not present in the surrounding lithological units within a mélange zone, and that are different from any lithology found in country rocks (for a complete discussion see Festa et al. 2019c). When blocks within a chaotic rock unit originated only from the disruption of a primary lithostratigraphic unit (i.e. ‘native’ blocks of ‘intraformational’ origin), this unit is named a ‘broken formation’ (sensu Hsü 1968; Fig. 2). This latter term defines a disrupted rock unit, with a block-in-matrix fabric, that contains no ‘exotic’ blocks but only ‘native’ components (Hsü 1968). As opposed to a mélange, a broken formation preserves lithological and chronological identity (Fig. 2), being commonly characterized by a gradual transition from a bedded and/or coherent primary succession to a highly disrupted or

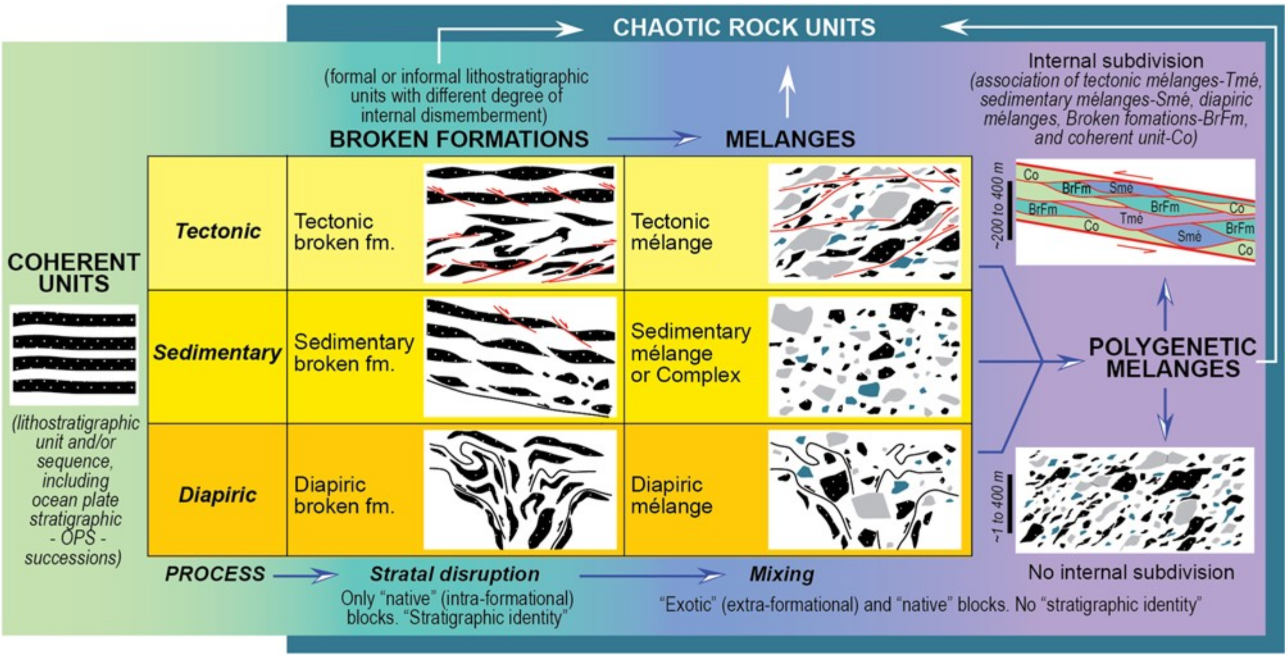

Fig. 2. Schematic illustration showing the transition from a coherent, pristine lithostratigraphic unit (or sequence) to a polygenetic mélange. Different mechanisms (stratal disruption v. mixing) and nature of blocks (native v. exotic) concur to form different types of broken formation and mélange according to different forming processes (tectonic, sedimentary and diapiric). Polygenetic mélanges represent the product of the interplay and superimposition of different processes. In contrast to mélanges, broken formations preserve their stratigraphic identity, representing formal or informal lithostratigraphic units.

dismembered block-in-matrix fabric (Hsü 1968; Raymond 1984; Cowan 1985; Barnes & Korsch 1991; Sunesson 1993; Pini 1999; Festa et al. 2012). Therefore, regardless of the process, the progressive disruption of a coherent lithostratigraphic unit or sequence first forms a broken formation (Fig. 2), which represents a formal or informal disrupted lithostratigraphic unit with a block-in-matrix fabric, without 'exotic' blocks included. Only with the contribution of mixing processes can 'exotic' blocks be embedded within a matrix and mixed with 'native' ones to form a mélange (Fig. 2). The latter does not preserve a 'stratigraphic identity'. Tectonic, sedimentary and diapiric processes can form different types of broken formation and mélange. The combination and interplay of two or more of these processes, as well as that of different deformational stages, form a polygenetic mélange (Fig. 2; see, e.g. Raymond 1984; Pini 1999; Bettelli & Vannucchi 2003; Codegone et al. 2012; Ogata et al. 2012a; Balestro et al. 2015; Tartarotti et al. 2017; Roda et al. 2019).

In contrast to the term 'mélange', 'olistostrome' (Flores 1955), which is widely used in chaotic rocks literature, has a genetic connotation, being synonymous with a sedimentary mélange in a broad sense. It includes the terms 'endolistostrome' and 'allolistostrome' (Elter & Raggi 1965), which describe chaotic rock units formed by sedimentary (gravitational) processes (i.e. MTDs and complexes), embedding 'native' and 'exotic and native' blocks, respectively. Therefore, 'endolistostrome' is synonymous with sedimentary broken formation, whereas 'allolistostrome' is synonymous with sedimentary mélange (Raymond 1984; Festa et al. 2019c). Sedimentary mélanges and broken formations that formed as a result of sedimentary mass-transport or mass-wasting processes preserved in exhumed convergent margins represent the ancient counterpart of modern MTDs (Lucente & Pini 2008; Ogata et al. 2012b). The latter are commonly characterized by great internal heterogeneity and deformation, representing the product of single or multiple, and superimposed depositional events (Ogata et al. 2014, 2019a, 2020a; Della Valle et al. 2015; Festa et al. 2016; Pini et al. 2020).

All the different types of mélange and broken formation, which differ from coherent successions or rock sequences because of their block-in-matrix fabric, can be described as 'chaotic rock units' or deposits or complexes (Fig. 2).

Scope of the thematic collection

The papers in this thematic collection are subdivided into three main threads: (1) the significance of polygenetic mélanges in the evolution of convergent margins; (2) analytical methods; (3) mélanges and seismicity. The geographical locations of the case studies covered in this thematic collection are shown in Figure 3.

The first thread presents field-case studies from exhumed convergent margins in the Alps–Apennines junction sector in the Central Mediterranean region (Barbero et al. 2019; Festa et al. 2019a; Meneghini et al. 2019), and in the Polish Outer Carpathians in Central Europe (Siemińska et al. 2019). These papers (Fig. 3) document how the study of polygenetic mélanges and the understanding of their temporal–spatial evolution and processes of formation provide new constraints on the multistage tectono-stratigraphic evolution of the associated convergent margins. Relationships of these mélange-forming processes with global climate changes are also documented.

Papers in the second part of this collection (Kuranaga et al. 2019; Marzec et al. 2019) show results from the application of different geophysical methods (i.e. anisotropy of magnetic susceptibility (AMS), and seismic and acoustic imagery) in the recognition and distinction of diagnostic features of mélanges formed at different scales during the evolution of modern and ancient convergent margins. Case studies include the Nankai Prism offshore of Japan and the Polish Carpathians in Central Europe (Fig. 3).

The last paper (Cerchiari et al. 2020), forming the third part of the thematic collection, documents the importance of detailed structural analyses in an exhumed analogue of a subduction megathrust zone, located at the base of a polygenetic mélange zone in the Northern Apennines of Italy (Fig. 3). This study allows us to better constrain the seismic behaviour of megathrust shear zones, comparable with those in modern subduction settings, which are commonly responsible for high-magnitude earthquakes.

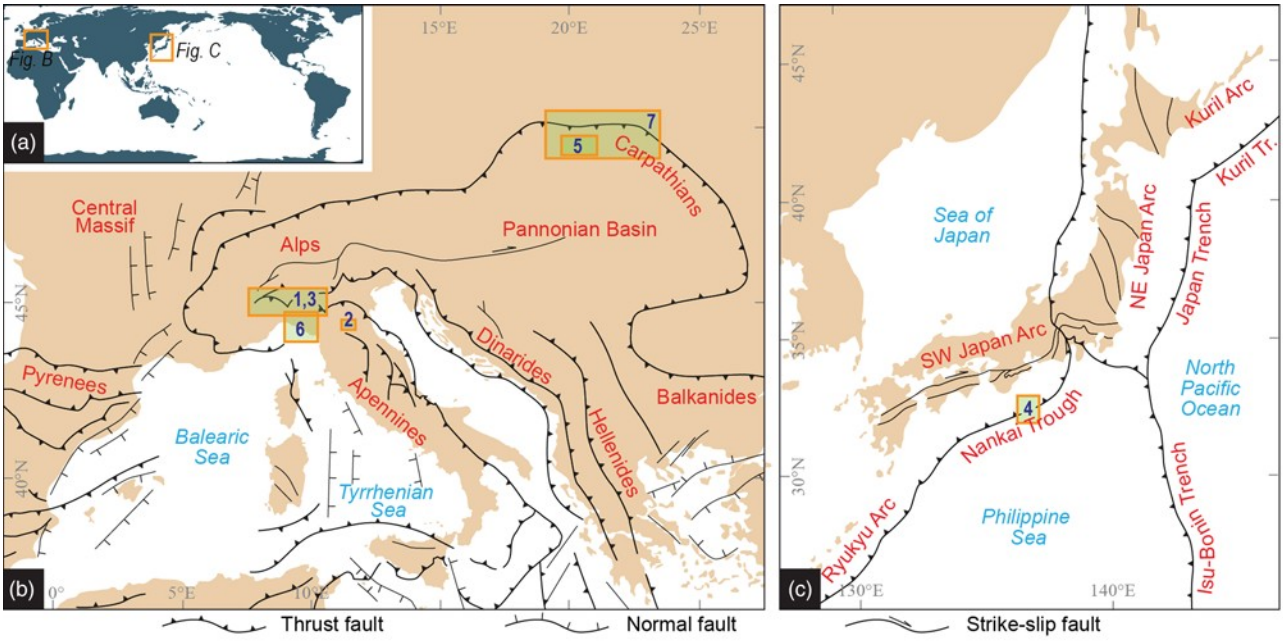

Fig. 3. World map (a) showing sectors covered by the case studies presented in this thematic collection in the Central Mediterranean Region–Central Europe (b) and offshore Japan (c). Each case study is marked by an orange box and a number: (1) Barbero et al. (2019); (2) Cerchiari et al. (2020); (3) Festa et al. (2019a); (4) Kuranaga et al. (2019); (5) Marzec et al. (2019); (6) Meneghini et al. (2019); (7) Siemińska et al. (2019).

As a whole, the papers collected in this issue provide a modern analytical dataset on different types of polygenetic mélange, representing useful case studies to be applied to different convergent margin settings around the world, where multistage deformation masked and reworked the primary fabric of sedimentary and diapiric products, independently of their age.

Significance of polygenetic mélanges in the evolution of convergent margins

Different types of mélange form at different structural positions and different depths during the evolution of a convergent margin (Fig. 1). Submarine mass-transport processes generating sedimentary mélanges (or olistostromes) result from slope instability in the trench–inner slope, and in the upper parts of frontal wedges (e.g. Lallemand et al. 1990; von Huene et al. 2000; Collot et al. 2001; Sage et al. 2006; Remitti et al. 2011; Geersen et al. 2013; Festa et al. 2015; Ogata et al. 2020a). Tectonic processes forming highly sheared, disrupted and fragmented broken formations and tectonic mélanges mainly occur along the basal décollement (i.e. the subduction plate interface) in accretionary and non-accretionary margins, and within shear zones in collisional belts (e.g. Cloos 1982; Moore & Byrne 1987; Ujiie 2002; Kitamura et al. 2005; Federico et al. 2007; Remitti et al. 2007; Grigull et al. 2012; Mittempergher et al. 2018; Saccani et al. 2018; Friedel et al. 2019; Fuentes et al. 2019; Lacombe et al. 2019; Roda et al. 2019; Ukar & Cloos 2019; Ghignone et al. 2020; Pirnia et al. 2020). Shale and mud diapiric processes, forming diapiric mélanges, lead to the ascent of overpressured fluids that migrate along the basal décollement and are ultimately channelled along megasplay faults (e.g. Brown & Westbrook 1988; Moore & Vrolijk 1992; Kopf 2002; Camerlenghi & Pini 2009; Codegone et al. 2012; Barber 2013; Moore et al. 2019). However, after tectonic reworking (and/or metamorphic recrystallization), the structural position of these different mélange types is commonly changed, and the recognition of the different processes that formed the polygenetic mélange is difficult but highly important for a better understanding of the tectonic and geodynamic history of the setting of their formation.

Siemińska and others (Siemińska et al. 2019) describe previously unknown aspects and a detailed tectonostratigraphic evolution of the Outer West Carpathians orogen, distinguishing sedimentary and diapiric mélanges within the poorly known chaotic rock units in the Skrzydlna area (Fig. 3). The diagnostic block-in-matrix fabric features of the studied sedimentary mélange (olistostrome), which is late Oligocene in age, suggest mechanisms of emplacement through non-cohesive debris flows and high-density turbidity currents. Vertical facies variations, and the growth of strata associated with progressive unconformities, document uplift of the source area (i.e. the Silesian Ridge) and seafloor (i.e. the Dukla Basin) deformation. The sedimentary mélange and the overlying turbidite succession form a retrogressive sequence interpreted as a submarine canyon infill, grading into a confined submarine fan.

The analysed diapiric mélange, previously interpreted as a tectonic or gravitational chaotic product, is distinguished on the basis of contact relationships with the host deposits, and internal zoning of deformation. Such internal distribution, from the margin to the core of an intrusive unit, is a diagnostic feature of many diapiric mélange bodies around the world (for details see, e.g. Orange 1990; Festa 2011; Codegone et al. 2012; Festa et al. 2013, 2019c), being related to differences in the velocity gradient (from margin to interior) of the ascent of poorly consolidated to unconsolidated material, acting as a viscous fluid.

In the Outer West Carpathians, several lines of evidence, showing that the main part of the diapiric material is composed of Early to Late Cretaceous rock fragments not belonging to the host rock succession (i.e. the Dukla Basin), suggest a source from a previously disrupted tectonic unit formed during the contractional stage of the Carpathian orogenic wedge. These findings indicate that sedimentary and diapiric mélanges represent two different stages of tectonic evolution of the Outer West Carpathian orogen. The Oligocene age of the sedimentary mélange corresponds to the growth of the accretionary wedge, whereas the Miocene age of the diapiric mélange postdates the continuing thrusting.

Interestingly, the formation of the diapiric mélange occurred in association with a strike-slip fault zone, as also documented in other orogens (see, e.g. Dela Pierre et al. 2007; Festa 2011). This suggests a specific role of strike-slip tectonics in the rise of diapiric material during late intra-collisional deformation stages of convergent margin evolution, or during a rapid temporal shift of the orientation of stress axes.

On the basis of diagnostic features of mélanges and broken formations, Barbero and others (Barbero et al. 2019) differentiate three tectonostratigraphic units within the undifferentiated chaotic Ligurian Units of the Western Alps–Apennines junction (i.e. Torino Hill and Monferrato sectors; see Fig. 3). The internal stratigraphy of the studied chaotic units records deposition in an ocean–continent transition (OCT) zone between the northern termination of the Jurassic Ligurian–Piedmont oceanic basin and the thinned passive margin of Adria. The inherited wedge-shaped architecture of this OCT zone, which gradually closed toward the north between the Sesia Zone (future Australpine domain) and the passive margin of Adria in the present-day Canavese Zone (see Festa et al. 2020), controlled the Late Cretaceous–early Eocene flysch deposition at the trench of the External Ligurian accretionary wedge during the oblique subduction. This strongly conditioned the structural architecture and evolution of the External Ligurian accretionary wedge during the subduction stage. The inherited configuration coupled with the propagation of an oblique subduction, favouring the formation of an accretionary wedge that increases in thickness and elevation from the Western Alps–Apennines junction toward the SE.

The result of this field-based work on chaotic rock units agrees well with numerical models on active accretionary prisms (see Malatesta et al. 2013), suggesting that along an accretionary margin, driven by oblique subduction, the wedge size variations at the trench are controlled by the amount of flysch accumulation, as well as by the lateral migration of sediments incorporated in the accretionary prism. Therefore, the recognition and distinction of different reworked mélanges (i.e. polygenetic mélanges) provide (1) new constraints for the palaeogeographical reconstruction of the northern termination of the Ligurian–Piedmont oceanic basin (Northern Alpine Tethys) in the Western Alps–Apennines junction sector and (2) significant information for a better understanding of the inherited along-strike variations of OCT zones in controlling the location of subduction-zone development, and the subsequent structural–morphological evolution of accretionary wedges.

The reconstruction of the structural–morphological evolution of accretionary wedges is also recorded within polygenetic mélanges described by Meneghini and others (Meneghini et al. 2019), which achieved a complete cycle from downslope gravitational emplacement to subduction and exhumation. The sedimentological and structural features of a sedimentary mélange (the Bocco Shale) allow reconstruction of its complex trajectories along and across the plate interface during the evolution of the Internal Ligurian accretionary complex in the Northern Apennines (Fig. 3). This case study documents that early Paleocene heterogeneous MTDs (i.e. sedimentary mélanges) record a long-lived history of subduction-related recycling, which started with the frontal accretion of fragments of oceanic crust into an accretionary prism. The lower slope of this prism was subsequently involved in tectonic erosion, with consequent instability leading to the generation of mass-transport phenomena and their transfer and accumulation to the lower plate. The MTDs were subsequently underthrust and then again transferred at the base of the accretionary prism by coherent underplating before their exhumation to the surface. This study is therefore important to show how submarine gravitational processes both at the prism front and on the prism slope, possibly induced by alternating accretion and erosion regimes, are efficient mechanisms of lithological mixing and recycling in subduction margins.

The role of the downslope emplacement of medium-sized (10–1000 km^2) to giant-sized (>1000 km^2) heterogeneous, mud-rich MTDs (i.e. sedimentary mélanges) in controlling and modifying the dynamic equilibrium of the outer wedge of subduction complexes is well documented in modern and ancient settings (see, e.g. von Huene et al. 2000; Remitti et al. 2011; Festa et al. 2015, 2018; Artoni et al. 2019; Ogata et al. 2019a, 2020b). Here, different interrelated factors (e.g. tectonics, sea-level changes, global climate changes, dissociation of gas hydrates, etc.) may concur in triggering submarine landsliding. Through the study of mid-Eocene polygenetic mélanges interpreted as sedimentary mélanges reworked by tectonics, Festa and others (Festa et al. 2019a) document the relationships between regional-scale (over an area of thousands of square kilometres) submarine landslides, accretionary tectonics, the dissociation of gas hydrates and changes in the global climate (the Early and Mid-Eocene Climatic Optimum (EECO and MECO) stages) during the evolution of the External Ligurian accretionary wedge in the Northern Apennines (Fig. 3).

The distribution of methane-derived carbonate (septarian) concretions in the core of thrust-related anticlines, systematically located below the base of mid-Eocene sedimentary mélange units over an area of c. 300 km long and tens of kilometres wide suggests that the dissociation of gas hydrates was triggered by accretionary tectonics rather than climate change. Submarine landslides occurred in a deep marine environment, probably at the beginning of a regressive trend, and were not related to EECO and MECO global warming events. By contrast, although residual minor tectonic activity could have been present, a period of large-scale instability occurred during the tectonic quiescence phase, which followed the Ligurian Tectonic Phase. Therefore, the emplacement of cohesive MTDs restored the rugged seafloor topography, dynamically re-equilibrating its slope instability. These results constrain well the role of slope failure in restabilizing the dynamic equilibrium of the outer wedge of the External Ligurian accretionary wedge at the end of the subduction stage (the early–middle Lutetian Ligurian Tectonic Stage).

Considering that the scale, style and distribution of the mid-Eocene sedimentary mélanges are directly comparable with those observed in modern subduction complexes (e.g. the Hikurangi margin, the Nankai accretionary wedge, the Middle America Trench and the Peru margin; see, e.g. Festa et al. 2014, 2016; Moscardelli & Wood 2016, and references therein), this field-based study represents an important baseline for a better evaluation of the impact of tectonic and climatic factors and their relationships to the frequency and magnitude of submarine slope failures in modern subduction settings. This example also shows that the exhumation of heterogeneous chaotic material (mélanges and broken forma- tions) and poorly consolidated argillaceous successions, as commonly occur in modern accretionary wedges, represents a significant contributor in providing sufficient material prone to be remobilized downslope, with potential for coastal geohazard (e.g. tsunamis).

Analytical methods

Several meso- to map-scale structural criteria have been proposed and successfully applied in ancient convergent margins to decipher the strong morphological similitude of the block-in-matrix fabric of chaotic rock units formed by different mélange-forming processes, and their interplay and superimposition (polygenetic mélanges; e.g. Raymond 1984, 2019; Cowan 1985; Lash 1987; Bettelli et al. 1989, 2004; Pini 1999; Alonso et al. 2006, 2008; Osozawa et al. 2009; Vannucchi & Bettelli 2010; Wakabayashi 2012, 2019; Festa et al. 2013, 2019c; Balestro et al. 2015; Raymond & Bero 2015; Tartarotti et al. 2017; Ogata et al. 2019a, 2019b; Roda et al. 2019). In contrast, complications occur in modern subduction settings where, commonly, the scale of observation of such diagnostic fabrics is well below the standard seismic resolution, and sediment cores or well logs offer only limited 1D datasets, which are not comparable with field observations. Therefore, the application of analytical methods, as an alternative to or in addition to field-based criteria (see, e.g. Orange 1990; Yamamoto et al. 2012; Robustelli Test et al. 2019), is of primary importance in discriminating the nature of chaotic rock units, at every scale of observation.

Through a high-resolution deep seismic reflection survey in the Pieniny Klippen Belt in Poland (Fig. 3), Marzec and others (Marzec et al. 2019) illustrate how some seismic attributes are effectively usable in the interpretation of mélange occurrences in a complex geological area. Sedimentary mélanges (olistostromes) and isolated olistoliths are characterized by different petrophysical parameters (velocity, density and resistivity) and seismic attributes in comparison with the surrounding flysch units. The selected seismic attributes (low-pass filter, energy, energy gradient, dip-steered median filter, Prewitt filter, Laplacian edge enhancing filter and square root of the energy gradient) emphasize changes of the seismic image inside mélange zones, showing that sedimentary mélanges and olistoliths are tectonically reworked within imbricated thrust structures, thus forming polygenetic mélanges. Olistoliths are here distributed parallel to the flysch layering and thrust. These findings suggest that the Pieniny Klippen Belt consists of several north-vergent thrust sheets containing large, non-reflective Jurassic–Early Cretaceous olistoliths and smaller high-reflective blocks. The results document the occurrence of two olistostromal belts within the Pieniny Klippen Belt structure. Miocene strike-slip processes resulted in deformation of earlier formed distinctive belts but did not completely overprint previously formed mélanges.

Changing scale of observation, Kuranaga and others (Kuranaga et al. 2019) describe in detail the progressive development of microfabrics in heterogeneous MTDs (sedimentary mélanges) from initial deposition to slump or slide deformation in cores recovered during the Integrated Ocean Drilling Program (IODP) Expedition 333 in the Nankai Trough (SW Japan; see Fig. 3). Through the analysis of the AMS and scanning electron and polarized microscope observations, the authors document that during gravitational deformation of hemipelagic sediments, the microfabric changed with increasing burial depth from a ‘cardhouse’ fabric to a ‘bookhouse’ fabric. The ‘cardhouse’ fabric consists of clay flakes with edge-to-edge (E–E) and/or edge-to-face (E–F) contacts, whereas the ‘bookhouse’ fabric consists of clay flakes with E–F and/or face-to-face (F–F) contacts, developed during burial and pure shear deformation. During slumping, the fabric deformed under simple shear, resulting in clay chains with F–F type contacts. The results of this study therefore add microscopic scale support to the evidence that analytical methods, such as the analysis of AMS, may provide useful information on the types of deformation mechanism and process forming the final internal arrangement of mélanges.

Mélanges and seismicity

In recent years, interest in the role played by mélange zones and their particular block-in-matrix fabric in controlling the seismic behaviour at convergent margins has been gradually increasing (e.g. Meneghini et al. 2009; Fagereng & Sibson 2010; Fagereng 2011; Bürgmann 2018; Festa et al. 2018; Beall et al. 2019). Mélanges made up of the mixing of competent blocks with incompetent fluid-saturated trench-fill sediments, and marked differences in the proportion between competent blocks and weak matrix material, create a high competence gradient. This mixture exhibits both discrete and distributed deformation with minimum interaction between adjacent blocks, creating unstable sliding material enclosed by frictionally stable sliding of conditionally stable matrix (Fagereng & Sibson 2010; Fagereng 2011). Therefore, large ruptures may not nucleate but the development of several micro-slip surfaces can trigger repetitive slip with micro-displacements, favouring the slow end-member of the spectrum of slip behaviour (e.g. tsunami earthquakes, slow slip events, very low frequency earthquakes, non-volcanic tremors, aseismic creep). These types of seismic behaviour are also expected consequently to the subduction of heterogeneous MTDs (sedimentary mélanges). Their chaotic internal fabric has been interpreted to be responsible for modifications in the structure and physical state of a plate boundary (see Festa et al. 2018). The scattered distribution of several MTDs may also favour the development of anastomosing fault networks within the subduction plate boundary. Their heterogeneous (commonly less permeable) internal composition and block-in-matrix fabric are expected to influence the redistribution of overpressured fluids, shear strain, and therefore the seismic behaviour (Festa et al. 2018; see also Geersen et al. 2013).

The relationships between structurally controlled fluid pathways and tectonic loading during the seismic cycle within a mélange zone are described by Cerchiari and others (Cerchiari et al. 2020), who combine petro-structural and geochemical analyses in tectonic veins sampled along an exhumed thrust fault. This fault zone bounds the base of the Sestola Vidiciatico Tectonic Unit in the Northern Apennines (Fig. 3), a megathrust zone mélange, which represents a field analogue for the shallow portion (T_{max} around 100–150°C) of the subduction megathrust. In the shear veins a positive Eu anomaly suggests an exotic fluid source, probably hotter than the fault environment. Small-scale extensional veins derived instead from a local fluid in equilibrium with the fault zone rocks. Mutually crosscutting relations between two sets of extensional veins, parallel and perpendicular to the megathrust, suggest a repeated shifting of the σ_1 and σ_3 stresses during the seismic cycle. This is consistent with the following phases: (1) a seismic phase, with brittle failure along the thrust, crystallization of shear veins from an exotic fluid, stress drop and stress rotation; (2) a post-seismic phase, with fault- normal compaction and formation of fault-normal extensional veins fed by local fluids; (3) a reloading phase, where shear stress and pore pressure are gradually restored and fault-parallel extensional veins form, until the thrust fails again.

The results indicate that the combination of geochemical and structural analyses in veins from megathrust field analogues represents a promising tool for a deeper understanding of the interaction between stress state and fluids in mélange-bearing subduction zones. In particular, the oxidation–reduction behaviour of Eu is crucial to identify the redox ambient conditions and to trace possible inputs of external fluids. This case study supports the interpretation that the seismic cycle is closely dependent on both the reaccumulation of fluid overpressure along the plate interface and the increase of shear and strain along the megathrust, as proposed by Sibson (2013) for the 2011 M_S 9.0 Tohoku–Oki megathrust rupture.

Concluding remarks and future prospects

The case studies presented in this thematic collection highlight the importance of the correct recognition and understanding of polygenetic mélanges, which probably represent the most common type of chaotic rock units in exhumed convergent margins. However, the complex internal architecture of polygenetic mélanges can be easily confused with that of tectonic mélanges, contributing to mask a significant part of the local tectonostrati- graphic evolution of a convergent margin. The systematic implementation of field-based stratigraphic and structural criteria, and geological detailed mapping (Barbero et al. 2019; Marzec et al. 2019; Meneghini et al. 2019; Siemińska et al. 2019), as well as of multidisciplinary analytical approaches (Kuranaga et al. 2019; Marzec et al. 2019; Cerchiari et al. 2020), demonstrates that the different processes that contributed to the formation of a polygenetic mélange can be recognized. Such distinction outlines the

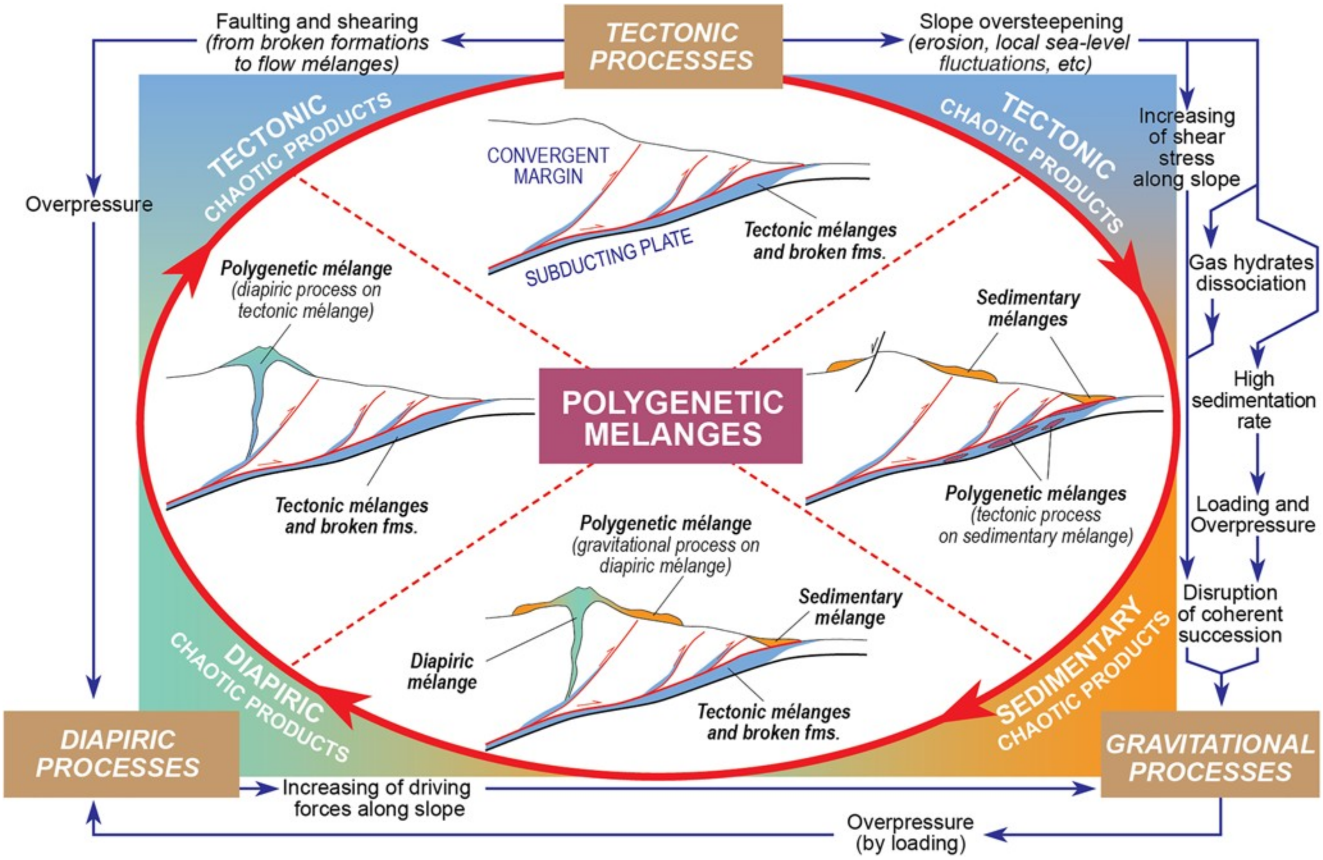

Fig. 4. Diagram showing the interlinks between tectonic, gravitational and diapiric processes in the formation of polygenetic mélanges. The blue arrows show that tectonic processes play a major role as triggering mechanisms in the formation of sedimentary and diapiric mélanges, but also that diapiric and sedimentary processes may have a mutual triggering. The red arrows show the superimposition of the different processes in forming different types of polygenetic mélanges associated with the different structural position within a convergent margins.

importance of the study of this type of mélange as an important tool for better interpreting the evolution of convergent margin settings. As sedimentary and diapiric chaotic products record episodes of geologically instantaneous stratal disruption and mixing, and tectonic ones record different stages of a continuum of deformation, polygenetic mélanges preserve the full record of the multistage evolution of convergent margins, providing clues on the interplay and superimposition of different deformational mechanisms and processes (Fig. 4; see Festa et al. 2012). They may preserve traces of previously formed chaotic products and inherited features, which are commonly subsequently reworked, for example, with different deformational styles, according to progressive variations in the consolidation degrees, metamorphic recrystallization and metasomatic processes, strain rate, stress direction, and alternating coaxial and non-coaxial strain paths. Therefore, polygenetic mélanges potentially record significant information on the temporal and spatial relationships between the different factors (physical conditions, mechanisms and processes) that acted during the evolution of a convergent margin at different scales. In particular, none of the geological processes forming chaotic rock units operate in isolation (Fig. 4), and the formation of such units records the balance between external factors (physical and mechanical conditions) and a focused deformation (e.g. Byrne 1994; Camerlenghi & Pini 2009; Festa et al. 2012).

The case studies presented in this thematic collection document that wide sectors of chaotic rock units, previously interpreted as mainly formed by tectonic processes, consist instead of reworked sedimentary and diapiric mélanges, outlining that the associated processes play a more important role in the evolution of convergent margins than previously defined. This role is commonly underestimated, as well as the size, distribution and recurrence interval of sedimentary and diapiric products. Sedimentary mélanges preserved in exhumed convergent margins show substantial similarities in size, distribution, recurrence interval and runout distance to modern submarine slide deposits (e.g. Camerlenghi & Pini 2009; Ogata et al. 2014, 2020a; Festa et al. 2016), ranging from tens to several thousand square kilometres in dimensions (see, e.g. Woodcock 1979; Bettelli et al. 1989; Macdonald et al. 1993; Pini 1999; Callot et al. 2008; Lucente & Pini 2008; Remitti et al. 2011; Ogata et al. 2014, 2019a, 2020b; Alonso et al. 2015; Festa et al. 2015, 2016). Similarly, mud and serpentinite diapiric mélanges are documented to reach several kilometres in diameter in both ancient (e.g. Barber 2013, and references therein) and modern (Maekawa et al. 1993; Fryer et al. 1999; Tamblyn et al. 2019) convergent margins.

The recognition within polygenetic mélanges of the proofs of previously formed sedimentary mélanges, which represent fundamental markers for tectonic events (see Festa et al. 2016), is not only useful to better constrain the tectonic evolution of the area, but it also allows us to improve our knowledge on the relationships between the evolution of modern convergent margins and natural hazards, and related societal implications (Fig. 5). The study of ancient convergent margins may provide new insight to better understand how the different mélange-forming processes cyclically interact to maintain the dynamic equilibrium of the wedge in modern settings (Fig. 4). Therefore, such studies indirectly allow us to improve our understanding of the causative links between tectonics and submarine slope failure events potentially triggering tsunami waves (Festa et al. 2019a, in this thematic collection). In addition, recognizing the traces of sedimentary mélanges within

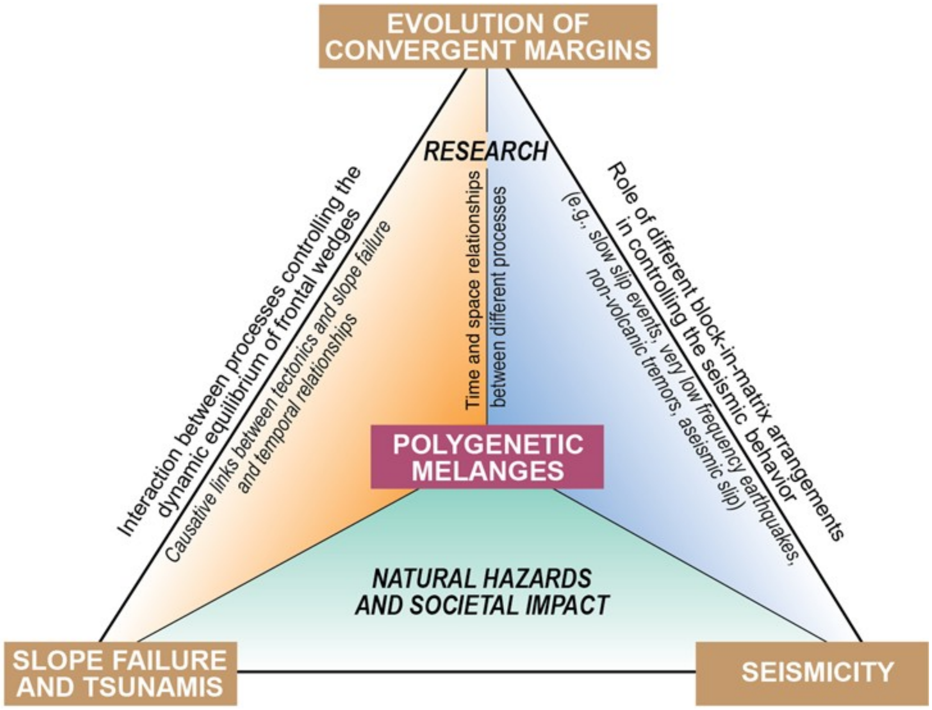

Fig. 5. Triangle diagram highlighting the possible outcomes of studies on polygenetic mélanges. Such results may provide useful information for a better understanding of both academic research problems (e.g. the evolution of convergent margins) and practical implications in terms of natural hazards and related societal impact (e.g. tsunami formation and subduction-related earthquakes).

polygenetic ones represents an important baseline task to quantify, for example, the impact on frequency and magnitude of submarine failure in modern convergent margins characterized by comparable structural–stratigraphic settings. This is also important in considering that, as for tectonic mélanges (see, e.g. Fagereng & Sibson 2010; Fagereng 2011), the subduction of huge heterogeneous MTDs (sedimentary mélanges) may strongly modify the physical and mechanical characteristics of the subduction plate boundary, playing a significant role in controlling the seismic behaviour (e.g. Geersen et al. 2013; Festa et al. 2018). In the literature of this type of studies, however, the use of the term mélange is in several cases misleading. Confusing mélanges with broken formations, which differ from each other by the internal block-in-matrix arrangement and composition (e.g. the occurrence of ‘exotic’ v. ‘native’ blocks), means to misread chaotic rock units with different internal arrangement, rheology, degree of heterogeneity and mechanisms of formation (i.e. stratal disruption v. mixing), and thus with different mechanical behaviours. A correct and updated use of the mélange terminology as summarized in this thematic collection (Fig. 2; for a complete review see also Festa et al. 2019c) is necessary and does not represent a mere academic exercise.

In conclusion, the case studies presented in this thematic collection show that the application of both classical field-based stratigraphic and structural criteria and analytical ones, such as geophysical and micro-scale observations, allows us to recognize and distinguish polygenetic mélanges from other mélange types. This aspect is highly significant in interpreting mélanges in exhumed convergent margins where, in addition to multistage tectonic deformation, metamorphic recrystallization may further complicate the recognition of the mélange-forming processes and their mutual interlinks. It seems a paradox that in most orogenic metamorphic belts, such as the Western Alps and/or the Precambrian and Phanerozoic belts, mélanges are commonly interpreted as only the product of tectonic deformation, mainly occurring at deep structural levels, with just few exceptions (e.g. Osozawa et al. 2009; Hajná et al. 2013, 2019; Balestro et al. 2015, 2018; Tartarotti et al. 2017; Katopody & Oldow 2019). In contrast, most non-metamorphic convergent margins, such as those discussed in this thematic collection, clearly show that the complex internal architecture of polygenetic mélanges is due to the interplay and superimposition of different interrelated processes working at shallow structural levels (Fig. 4). These processes lead to different types of chaotic rock unit (tectonic, sedimentary and diapiric), whose combination leads in turn to the formation of polygenetic mélanges. This ‘chaotic’ structural inheritance must be taken into consideration when interpreting the complex architecture and evolution of metamorphic orogenic belts characterized by mélange occurrences. Therefore, the case studies in this thematic collection document well how the understanding of polygenetic mélanges may provide crucial insights for a detailed interpretation of both modern and ancient convergent margins around the world, particularly in metamorphic belts and Precambrian to Phanerozoic orogens, where this mélange type as well as sedimentary and diapiric ones are still currently poorly described.

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