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Mélanges and chaotic rock units: Implications for exhumed subduction complexes and orogenic belts

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ABSTRACT

Most of mélanges occurring in exhumed subduction complexes and orogenic belts are commonly interpreted as the product of tectonic processes (e.g., underplating and return flow) acting at intermediate to great depths ($T > 250$ °C, depth >10–15 km). Conversely, observations on modern and ancient non- to poorly metamorphosed subduction complexes around the world, clearly show that the largest part (c. 64.7%) of mélanges and chaotic rock units are already formed at shallower structural levels ($T < 250$ °C, depth <10–15 km). They mainly consist of broken formations (>21.5%), sedimentary (c. 20%), polygenetic (>13.7%), and diapiric (c. 6.7%) mélanges. Tectonic mélanges are limited to about 2.7%, suggesting that tectonics is not an efficient mixing process at shallow structural levels. We document that the subduction of structural inheritances (e.g., ocean-continent transition zones, and ocean plate stratigraphy) plays a significant role in forming and differentiate the different types of chaotic units at shallow depths, also controlling the location of the plate interface and the dynamics of the wedge front (i.e., tectonic accretion vs. erosion). However, not all chaotic units that formed at shallow structural levels can be subducted and, as subducted, their fate could be very different if they become part of the plate interface or if they share the fate of the lower plate. Our findings demonstrate that the evidence that the larger part of mélanges and chaotic units form at shallow depths has significant implications for a better understanding of the tectonic evolution of subduction complexes and orogenic belts, ranging from the mode and time of Precambrian Earth evolution and the onset of plate tectonics to the role of mélanges in controlling the seismic behavior.

1. Introduction

Mélanges and, chaotic units are a significant component of most of subduction complexes (i.e., accretionary, and not-accretionary margins) and orogenic belts around the world, regardless of their age (from Precambrian to present day), tectonic evolution, and location (e.g., from the circum-Pacific region to the circum-Mediterranean area, up to the Alpine-Himalayan and Asian orogenic belts and suture zones). Tectonic, sedimentary, diapiric processes and their interaction have been documented to form different types of mélanges and/or chaotic units (i.e., tectonic, sedimentary, diapiric and polygenetic; Raymond, 1984, 2019; Cowan, 1985; Pini, 1999; Bettelli and Vannucchi, 2002; Remitti et al., 2007; Wakabayashi, 201, 2019; Festa et al., 2019 and references therein). Nevertheless, most of the chaotic units preserved in exhumed subduction complexes, particularly metamorphic ones, are commonly interpreted as the product of tectonic processes acting from intermediate (250 °C < T < 400 °C, corresponding to about 10–15 km depth) to great depths ($T > 400$ °C, corresponding to >15 km depth) during convergent stages. The transfer of isolated slices and blocks, detached from the downgoing slab to the upper plate and/or within the plate boundary interface due to tectonic underplating (Dickinson, 1971; Platt et al., 1985; Kimura et al., 1996; Ernst et al., 2009; Meneghini et al., 2009), and the return flow (flow mélanges, *sensu* Cloos, 1982, 1986; Cloos and Shreve, 1988a, 1988b), undoubtedly represents an effective mixing mechanism

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forming mélanges at those depths. However, observations on both modern and ancient subduction complexes clearly show that the different types of mélanges and chaotic units already form at shallow structural levels ($T < 250$ °C, corresponding to <10–15 km depth), indicating that (i) mixing mechanisms are not exclusive of deep processes, (ii) the internal architecture of exhumed subduction complexes may be highly heterogeneous already at shallow structural levels, and (iii) tectonics is not the exclusive process of mélange formation (among many others, Elter and Trevisan, 1973; Aalto, 1981; Raymond, 1984, 2019; Cowan, 1985; Barber and Brown, 1988; Castellarin and Pini, 1989; Bettelli and Panini, 1987; Pini, 1999; Bettelli et al., 1996, 2004; Remitti et al., 2007, 2011; Festa et al., 2010, 2019; Hitz and Wakabayashi, 2012; Vannucchi et al., 2012; Barber, 2013; Moore et al., 2019;Lai et al., 2021).

The above observations suggest that part of mélanges occurring in exhumed metamorphic and polydeformed subduction complexes and orogenic belts not necessary represent the exclusive product of intermediate to deep processes, but they may document the subduction-related tectonic reworking of chaotic rock units formed at shallower structural levels (Raymond, 1984; 2019; Cowan, 1985; Krohe, 2017; Festa et al., 2019; Wakabayashi, 2011, 2019). It is important to stress out that in the geology of mélanges, the structures/fabric inherited from shallow tectonic levels could be an important – although highly underrated so far – factor controlling and conditioning the development of deeper structures. On this issue, misleading interpretations of both the processes and the structural level at which mélanges developed can be also related to the incoherent use of terminology. Not rarely, in fact, the term mélange (i.e., chaotic rock units with "exotic" blocks, Section 2) is incorrectly used to describe broken formations (*sensu* Hsü, 1968), which represent a different type of chaotic rock unit (i.e., without "exotic" blocks), formed by different processes, and characterized by different internal components (Section 2). The consequence of this incorrect and unclear terminology can lead to inaccurate interpretation of the tectonic evolution of the tectonic/geodynamic setting in which chaotic rock units occur.

This paper is aimed to overview the characteristics of mélange and chaotic rock units formed at shallow structural levels ($T < 250$ °C, corresponding to <10–15 km depth), and the implications of the correct distinction and interpretation of their block-in-matrix fabric, after subduction-related reworking, for a better understanding of the evolution of exhumed subduction complexes and orogenic belts, particularly metamorphic and polydeformed ones. After a short overview on the mélanges and chaotic units terminology (Section 2), we review the features, frequency, and size of the different mélanges/chaotic units occurring at shallow structural levels of subduction complexes and orogenic belts (Section 3). In the subsequent Section 4 we investigate the role played by the subduction of structural inheritances (e.g., "Ocean-Continent Transition Zones" – OCTZs, and structural and stratigraphic heterogeneities associated with the "Ocean Plate Stratigraphy" – OPS *sensu* Isozaki et al., 1990) as main preconditioning factors for the formation of chaotic rock units at shallow depth. In Section 5 we examine factors controlling the underthrusting at intermediate to deep depths of mélanges formed at shallow structural levels, and their chance to effectively participate to deeper subduction processes (e.g., underplating). Finally, in Section 6 we discuss the evidence that mélanges and chaotic rock units represent fundamental markers of the tectonic evolution of both accretionary and non-accretionary subduction complexes and orogenic belts, independently of their age (from Precambrian to present days) and location. Our findings document that the understanding of mélanges and chaotic units may have a significant implication for a better understanding of i) the tectonic evolution of exhumed subduction complexes and orogenic belts, ii) the mode and time of early Earth evolution and the onset of plate tectonics, and iii) the role of mélanges and chaotic units in controlling the seismic behavior.

2. Mélange and chaotic units terminology: a short overview

According to the mélange terminology (Silver and Beutner, 1980; Raymond, 1984; Cowan, 1985; Festa et al., 2012), we use the non-genetic term mélange to indicate mappable (at 1:25,000 or smaller scale) chaotic rock units embedding "exotic" blocks within a pervasively deformed matrix (Fig. 1A). The matrix is defined as "deformed" or "fragmented" (Silver and Beutner, 1980; Raymond, 1984), avoiding any specification on its origin (tectonic, sedimentary, or diapiric). The term "exotic" includes all types of blocks that are "foreign" with respect to the matrix of the mélange (Fig. 1A), thus their source is not present in the surrounding lithologic units within a mélange zone, and which are different from any lithology formed in country rocks (Festa et al., 2019 for details). We use the term "native" for "intraformational" blocks, which originated from the disruption of a primary lithostratigraphic unit (Fig. 1A).

Chaotic rock units containing only "native" blocks in a "deformed" or "fragmented" matrix are indicated as broken formations (*sensu* Hsü, 1968; Fig. 1A), another non-genetic term to indicate mappable bodies that in this case correspond to disrupted stratigraphic units (Raymond, 1984; Pini, 1999; Bettelli et al., 2004; Festa et al., 2012), without considering the forming mechanism. In this paper, we use the general and non-genetic terms "chaotic rock unit" (chaotic unit hereafter) to indicate all those units with a block-in-matrix fabric, without distinction between mélanges and broken formations, (Fig. 1A). Chaotic units, mélanges and broken formations may form through different processes (tectonic, sedimentary, and diapiric) or their interaction and superposition. The alternation and/or superposition of different processes (tectonic, sedimentary and/or diapiric) during the multistage evolution of any geodynamic setting, commonly overprints and reworks the primary (original) block-in-matrix fabric of tectonic, sedimentary, and diapiric mélanges/broken formations, forming polygenetic mélanges/broken formations (see Section 3.4 for details) at different scales (Figs. 1A and C; Raymond, 1984; Cowan, 1985; Dilek et al., 2012; Festa et al., 2020c and references therein).

3. Types, size and frequency of chaotic units formed at shallower structural levels

Different types of mélanges and broken formations form at shallow structural levels of subduction complexes, each of which shows diagnostic characteristics and different size and frequency of occurrence (Figs. 1 and 2). Through the review of our published data (Pini, 1999; Camerlenghi and Pini, 2009; Festa et al., 2010, 2012, 2016, 2019; Ogata et al., 2019, 2020), in the following, we overview the most significant characteristics of different types of chaotic units formed at shallow structural levels ($T < 250$ °C) by tectonic, sedimentary, diapiric processes and their interaction and superposition.

3.1. Tectonic mélanges and broken formations

Detailed analyses of the most notable examples of tectonic chaotic units around the world (Festa et al., 2010 and references therein; Fig. 2), clearly document that they mainly consist of broken formations (i.e., without "exotic" blocks) and more rarely of mélanges (i.e., with "exotic" blocks; Brandon, 1989; Cowan, 1974, 1985; Vollmer and Bosworth, 1984; Lash, 1987; Wakabayashi, 1992, 2011; Harris et al., 1998; Pini, 1999; Onishi et al., 2001; Vannucchi and Bettelli, 2002; Bettelli et al., 2004; Festa et al., 2010, 2012), despite the use of the latter term erroneously prevails on

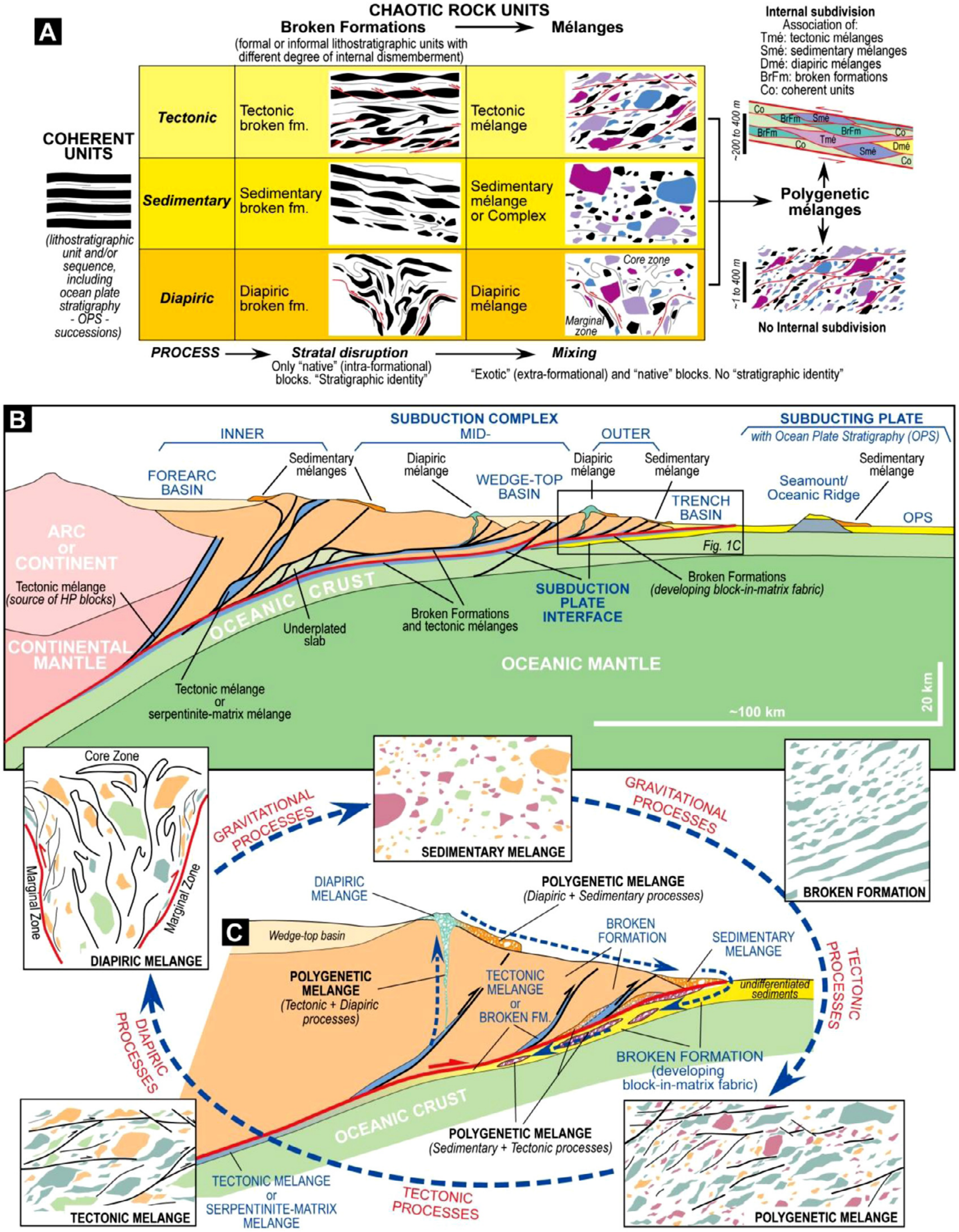


Fig. 1. Deterministic characters of mélanges and broken formations characterizing the transition from a coherent litostratigraphic unit (or sequence) to a polygenetic mélange (**A**, modified from Festa et al., 2019, 2020c) during the tectonic evolution of a subduction complex (**B**, modified from Raymond, 2019). Different mechanisms (stratal disruption vs. mixing) and nature of blocks (native vs. 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 superposition of different processes. On the contrary of mélanges, broken formations preserve their stratigraphic identity, representing formal or informal lithostratigraphic units (see text for discussion). (**C**) Internal fabric of the tectonic, sedimentary, diapiric, and polygenetic mélanges, and broken formations (modified from Festa et al., 2020c).

the former one in the literature of subduction complexes and orogenic belts. The diagram in Fig. 2C shows, in fact, that broken formations represent about >21.5% of mappable (at 1: 25,000 or smaller scale) tectonic chaotic units formed at shallow structural levels. Broken formations form through the gradual dismemberment (Figs. 3A–C), up to their complete disruption, of previously coherent lithostratigraphic units characterized by internal primary rheological contrasts (e.g., alternating claystone and sandstones trench deposits, Ocean Plate Stratigraphy deposits, etc.). They commonly form inside regional shear zones (i.e., associated with accretionary prisms and/or the plate boundary interface), ranging in thickness from few meters to hundreds of meters (Rowe et al., 2013 and references therein; Wakabayashi, 2021b). They show a gradual decrease of internal disruption toward both the upper and lower margin of the shear zone or in the frontal part of accretionary wedge (Figs. 3A–C), with thickness up to

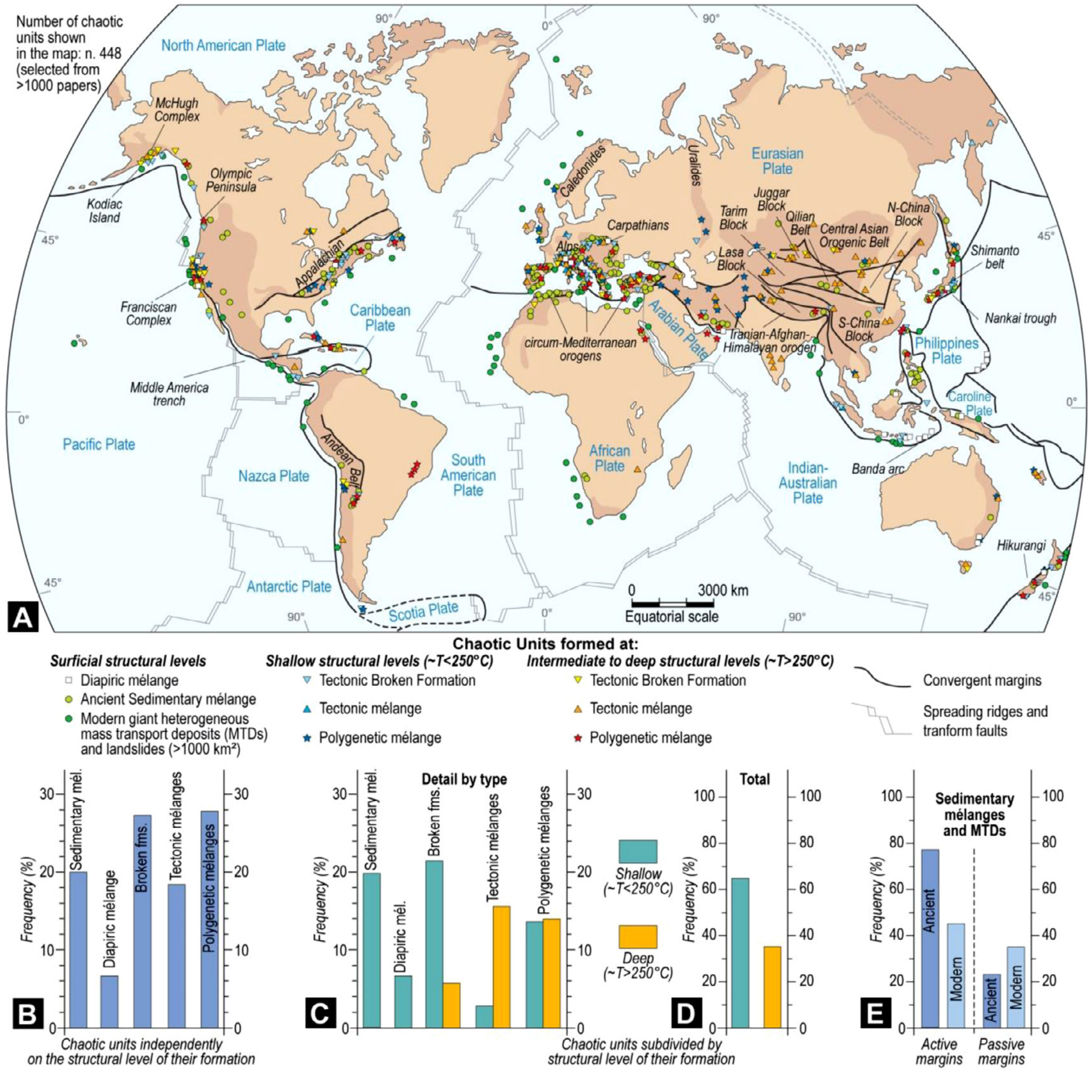


Fig. 2. (**A**) Global distribution of different types of chaotic units (tectonic, sedimentary, diapiric, and polygenetic) formed at shallow ($T < 250$ °C) and intermediate- to deep ($T > 250$ °C) structural levels. Modified and updated after Raymond (1984) and Festa et al. (2010, 2016). Note that the no.448 chaotic units shown in the map have been selected from more than 1000 publications (excluding repetitions of the same chaotic unit) in which the formation processes were clearly indicated by the Authors or easily understandable from data. (**B-D**) Comparative diagrams for the frequency of preservation and occurrence of chaotic units at different structural levels of subduction complexes and orogenic belts around the world. (**E**) Comparative diagram for the frequency of preservation of ancient sedimentary mélanges/mass transport deposits (MTDs) and modern submarine MTDs in passive and active (convergent) margins in the Circum-Mediterranean Region (modified from Festa et al., 2016; data of modern examples from Urgeles and Camerlenghi, 2013).

some kilometers. Notable examples are, among others, the Taconic mélange in the US-Appalachians (Vollmer and Bosworth, 1984; Lash, 1987), the older part of the External Ligurian Units (*Argille varicolori*, Palombini shales, Scabiazza sandstones) of the Northern Apennines in Italy (Bettelli and Panini, 1987; Pini, 1999; Codegone et al., 2012; Festa et al., 2013), part of the Esk Head mélange in the Torlesse Complex (Siberling et al., 1988; Orr et al., 1991; Sunesson, 1993), and the mélange of the Coastal Ridge in New Zealand Pettinga (1982). The degree of internal disruption is controlled by different cooperating mechanisms (e.g., brittle to ductile boudinage, shearing, folding, etc.), depending on the degree of lithification/consolidation, the magnitude of strain at time of deformation, and the structural position of their formation within the subduction complex. On the contrary, tectonic mélanges (with "exotic" blocks; Figs. 3D-F) are rare at shallow structural levels of subduction complexes (about 2.7%; Fig. 2C) and commonly limited to coalescent fault zones, ranging in thickness from few meters to tens of meters (Suppe, 1972; Cowan, 1974; Pettinga, 1982; Moore and Byrne, 1987; Kimura and Mukai, 1991; Doubleday and Trenter, 1992; Kimura et al., 1996; Hashimoto and Kimura, 1999, Codegone et al., 2012; Wakabayashi, 2021a), and plate boundaries (Wakabayashi, 1992; Meneghini et al., 2009; Kimura et al., 2012; Yang et al., 2022) associated with fault thickening processes. Tectonics is, in fact, a poorly efficient mixing mechanism at shallow structural levels (Cowan, 1985; Festa et al., 2012). The ability to embed exotic material (blocks/slices) coming from lithologic units that are not present in the surrounding of the mélange matrix requires very high displacements and/or translation/transposition degrees within a shear zone. Most of the so-called tectonic mélanges with "exotic" blocks, occurring at shallow structural levels of subduction complexes, represent polygenetic mélanges formed by the tectonic reworking of previously formed sedimentary and/or diapiric mélanges as documented in Section 3.4. Some "tectonic mélanges" formed at shallow depth (Tmax $<$ 150 °C), could be more efficiently described as hundreds of meters thick shear zones characterized by multiple faults contemporaneously active, and resulting in a block-on-block (i.e., slices of tens of meters to kilometers in size) internal structures

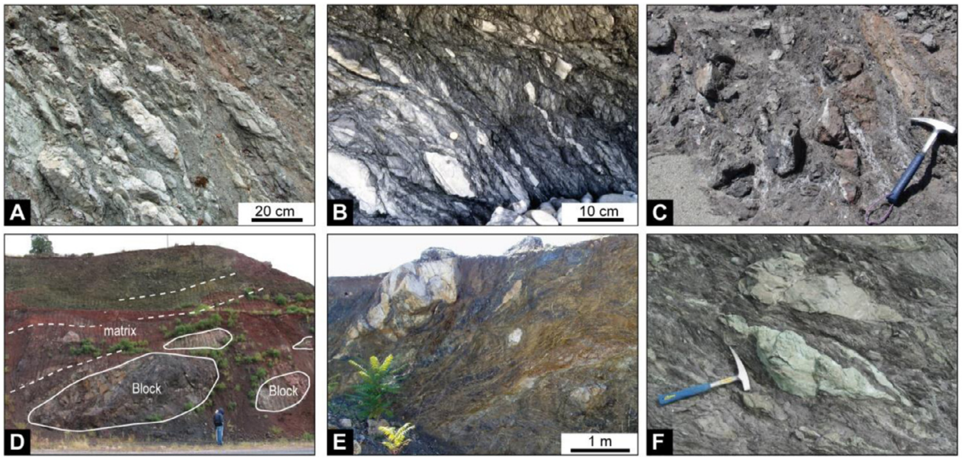


Fig. 3. Different examples of broken formations and tectonic mélanges: (**A**) progressive stratal disruption of a well-bedded unit (Flysch Rosso) forming lozenge-shaped boudins of mudstone in a clayey marl matrix (broken formation) (Aventino valley, Abruzzi region, Central Apennines of Italy); (**B**) lozenge-shaped boudins of sandstone within a mudstone matrix displaying a pervasive scaly fabric (broken formation), due to transposition of upright beds in a fault zone related to an out-of-sequence thrust (Waimarama Beach, South Hawke's Bay, East Coast of North Island, New Zealand); (**C**) disrupted beds to isolated blocks of ocean plate stratigraphy (OPS) embedded in a clayey marl matrix (OPS broken formation) (Paralia Kali Limenes, Southern Crete, Greece). Hammer for scale; (**D**) exotic ultramafic and limestone blocks, lenticular in shape, embedded in a fine-grained green reddish ophiolitic matrix of the Cretaceous Ankara Ophiolitic Mélange (Central Anatolia, Turkey). Geoscientists for scale; (**E**) phacoidal Upper Triassic pelagic limestone blocks in a heterogeneous and variously deformed matrix composed of shale, mudstone, and sandstone in the Jurassic-Cretaceous Avdella mélange (Pindos Mountains, Northern Greece); (**F**) tectonic mélange characterized by phacoidal exotic blocks in a sheared matrix (Franciscan Complex, CA-USA). Hammer for scale.

(Remitti et al., 2007, Remitti et al., 2012; Vannucchi et al., 2008; Mittempergher et al., 2018; Cerchiari et al., 2020). The highly heterogeneous blocks composition is a consequence of the highly heterogeneous source of blocks deriving from the frontal part of a former accretionary prism and its sedimentary cover.

3.2. Sedimentary mélanges and heterogeneous mass transport deposits (MTDs)

Sedimentary mélanges (olistostromes *sensu* Flores, 1955), which represent ancient heterogeneous mass transport deposits (MTDs) and complexes (MTCs; Lucente and Pini, 2003, 2008, Pini et al., 2012, 2020), mainly occur (Figs. 1B-C) in the frontal part of the subduction wedge front and the foredeep (e.g., in present day and fossil exmples, Ranero and von Huene, 2000; Collot et al., 2001; Marroni and Pandolfi, 2001; van Huene et al., 2004; Alonso et al., 2006; Burg et al., 2008; Yamada et al., 2010; Remitti et al., 2011; Yamamoto et al., 2012; Meneghini et al., 2020; Geersen et al., 2020), within wedge-top basins, and in the forearc basin (Ogata et al., 2014b; Barbero et al., 2017, 2020; Festa et al., 2014, 2015b, 2020b; Claussmann et al., 2021). The actual distribution of sedimentary mélanges has been longer underestimated due to a terminological confusion generated using a plethora of different terms. Olistostromes, olitoliths, olistolith swarms or fields, among many others (Camelenghi and Pini, 2009), are sedimentary mélanges, often not interbedded with normal sediments (Abbate et al., 1970; Elter and Trevisan, 1973; Aalto, 1989; Chanier and Ferrière, 1991). Sedimentary mélanges form by mass transport processes, ranging from slumping, sliding, debris flows and blocky flows (Fig. 4; Mutti et al., 2006), showing an internal block-in-matrix fabric that changes in relation to the progressive increase of lithification, the velocity of movement, the rheological contrast between the deformed succession, the geometry and morphology of the depositional setting, and the mode of failure propagation (Ogata et al., 2020 and references therein).

Differently from tectonic processes, gravitational ones are very efficient in incorporating exotic blocks within a poorly lithified matrix during their downslope transport, up to form sedimentary mélanges (allolistostrome *sensu* Elter and Raggi, 1965). The latters represent about 20% of the whole chaotic units formed at shallow structural levels (Fig. 2C). Blocks of different lithologies, age and composition are wrenched from the accretionary or erosive wedge and incorporated within the collapsing poorly lithified sediments (i.e., the future matrix; Ogata et al., 2019 and references therein). Heterogeneous MTDs, consisting of only "native" blocks within a matrix also occur (i.e., endolistostrome *sensu* Elter and Raggi, 1965) in all those cases in which the runout is limited, involving, and disrupting only a single lithostratigraphic unit (Fig. 1A; Naylor, 1981).

In contrast to modern tectonic settings, in which most of heterogeneous MTDs occur in association with the evolution of passive margins (Mienert et al., 2003; Camerlenghi and Pini, 2009), in ancient and exhumed subduction complexes and orogenic belts about 78% of sedimentary mélanges (Fig. 2E) is associated with the evolution of active margins (Festa et al., 2016). Their size mainly ranges from few meters to several hundreds of meters in thickness (rarely few kilometers), and from tens of meters to several thousands of kilometers square. For example, the Miocene Makran olistostrome in Iran (Burg et al., 2008), the sedimentary mélange in the Cretaceous Ayabacas Formation in Southern Peru (Callot et al., 2008), and the Late Carbonifeous Porma mélange in the Northern Spain (Alonso et al., 2015), reach sizes up to 10,000 km^2. These sizes are well comparable with several modern examples of MTDs such as, for example, the Poverty Unit in the Hikurangi margin of New Zealand (Mountjoy and Micallef, 2012; Ogata et al., 2014a), the Giant Chaotic body of Gibraltar (Torelli et al., 1997), and the MTCs from the Southern Magdalena Fan offshore Colombia (Ortiz-Karpof et al., 2018).

3.3. Diapiric mélanges

Diapiric mélanges associated to the evolution of subduction complexes at shallow structural levels, mainly consist of mud/shale and serpentinite matrix, and occur (Figs. 1B-C) in the upper slope of the frontal wedge, and in the forearc basin (Barber et al., 1986; Orange, 1990; Maekawa et al., 1993, Maekawa et al., 2004; Kopf, 2002; Barber, 2013; Festa et al., 2013; Moore et al., 2019). Triggering factors necessary for their formation mainly depend on well determined physical and mechanical conditions such as the presence of fluid overpressure, the rate of consolidation of sed-

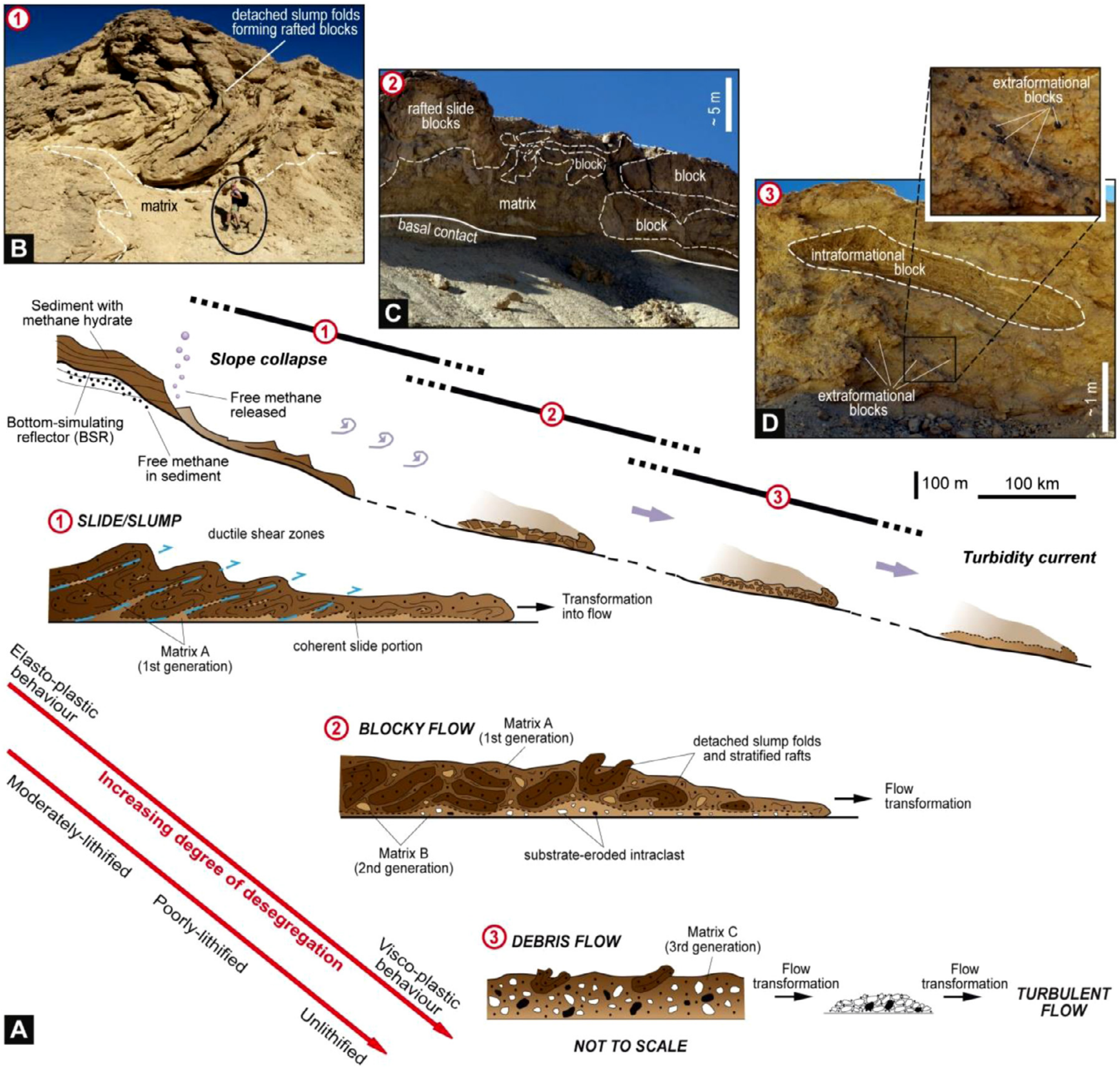


Fig. 4. Dynamic classification (**A**) of mass transport deposits (i.e., sedimentary mélanges) showing genetic and evolutionary relationships among various processes responsible for their formation (modified from Nisbet and Piper, 1998; Ogata et al., 2012b). Slide/slump (**1**) and turbidity currents (**2**) represent the end-members of such broad spectrum of geological processes. Blocky-flow deposits (**3**, Mutti et al., 2006), which are similar to debris-flow deposits, except for carrying over-sized slide blocks, represent a transitional type between slumps and debris-flow deposits. Field examples of a Miocene mass transport deposit (Siani, Egypt), showing the downslope evolution from slump- (**B**) to blocky flow- (**C**), up to debris flow-type facies (**D**) type facies (modified from Ogata et al., 2019).

iments, and the state of inferred stress. Under these conditions, both sudden loading provided, for example, by rapid deposition of MTDs along the wedge slope, and emplacement of tectonic nappes and/or accreted units, could trigger diapiric processes forming mélanges (Orange, 1990; Kopf, 2002; Dela Pierre et al., 2007; Codegone et al., 2012; Barber, 2013; Festa and Codegone, 2013; Festa et al., 2015c; Moore et al., 2019).

Exotic blocks are wrenched from the hosting rocks along the margins of the diapir (Figs. 5A–C), during the upward rise of the unlithified fine-grained matrix (mud, shale, or serpentinite mud). Depending on the source area and the lithological composition of the hosting rocks, the nature of blocks embedded in the matrix may show different degrees of allochthony with respect to the matrix, ranging from tens to hundreds of meters. A notable example is documented by the occurrence of blueschist blocks sourced from the subduction plate interface, which are embedded in a non-metamorphic serpentine mud in diapiric edifices (up to 30 km^2 wide and 2 km high), of the Mariana subduction zone (Maekawa et al., 1993, Maekawa et al., 2004; Fryer et al., 1999; Tamblyn et al., 2019).

Although diapiric mélanges represent minor products both in size and number with respect to sedimentary mélanges and tectonic chaotic units, their frequency in subduction zones is notable (about 6.7% of chaotic units formed at shallow structural levels; Fig. 2C). However, their preservation in ancient subduction complexes and orogenic belts is strongly limited by the reworking of their block-in-matrix fabric acted by the superposition of tectonic and sedimentary processes forming polygenetic mélanges, during accretionary and erosive tectonic processes.

3.4. Polygenetic mélanges

Most of the above-described types of mélanges (tectonic, sedimentary, and diapiric), as well as broken formations, are commonly overprinted (at different structural levels) by tectonic deformation, and/or in several cases also by sedimentary and diapiric processes, during the evolution of the subduction complex and the formation of orogenic belts. These processes and related deformation rework their primary block-in-matrix fabric to form polygenetic mélanges (Fig. 1C; Raymond, 1984, 2019; Cowan, 1985; Balestro et al., 2015;

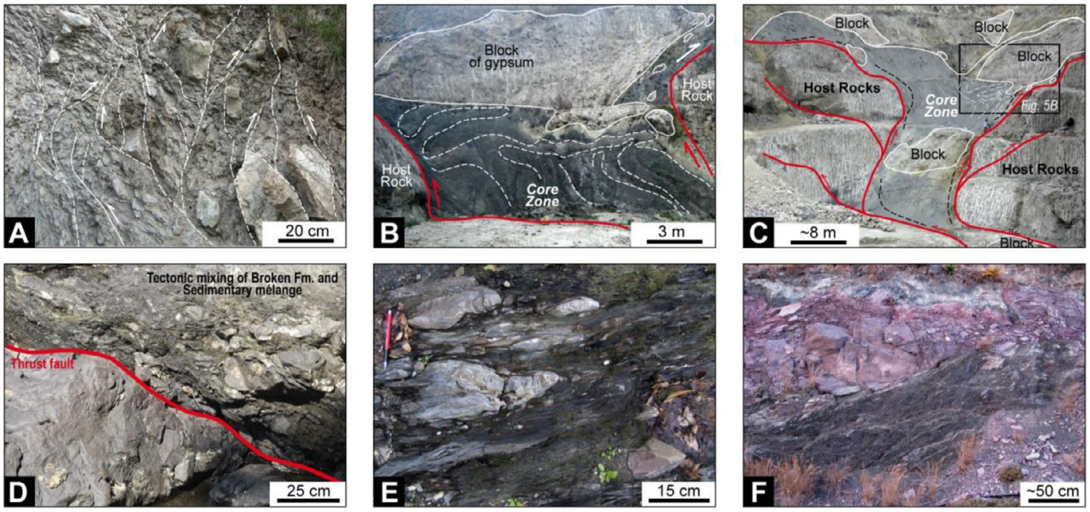


Fig. 5. Different examples of diapiric mélanges (**A-C**) and polygenetic mélanges (**D-E**): (**A**) lenticular to (rarely) tabular limestone and sandstone blocks aligned parallel to the subvertical fluidal fabric (dashed white lines) of the shaly matrix within a diapiric mélange (Northern Apennines, Italy; modified from Festa et al., 2013); (**B**) gypsum block, tens of meters wide, enveloped within a marly matrix at the core zone of a diapiric mélange (Northern Apennines, Italy; modified from Dela Pierre et al., 2007; Festa, 2011). The black marly matrix is deformed by strongly asymmetric folds (white dashed lines). Red lines represent intrusive contacts with the hosting rocks; (**C**) panoramic view of the diapiric mélange of B, showing the block-in-matrix arrangement (Northern Apennines, Italy); (**D** and **E**) close-ups views of polygenetic mélanges formed by tectonic reworking of previously formed sedimentary mélanges at Poetstenkill Gorge and Hoosic River (Northern Appalachians, NY-USA); note that it is hard to distinguish their block-in-matrix fabric with respect to that one of a "true" tectonic mélanges (**F**) (Arvi Unit, South Crete, Greece).

Ernst, 2016; Tartarotti et al., 2017; Festa et al., 2020c). Tectonics is commonly the more pervasive overprinting process, able to modify sedimentary- or diapiric-related block-in-matrix fabrics to a tectonic resemblance (Figs. 5D–E), which results hard to be distinguished from that of "true" tectonic mélanges (Fig. 5F, see also Fig. 3E–F). This is at the base of a long-lasting debate on the nature and processes responsible for formation of subduction-related mélanges, particularly in the Circum-Pacific Region but also in most all orogenic belts and suture zones around the world. The main question is whether the block-in-matrix fabric of mélange occurrences in subduction complexes and orogenic belts represents the product of tectonic processes or that one of tectonic reworking of primary diapiric and sedimentary mélanges. Detailed discussion on this topic can be found in Berkland et al. (1972), Hsu (1974), Raymond (1984), Cowan (1985), Pini (1999), Bettelli et al. (2004), Alonso et al. (2006), Wakabayashi (2015); Krohe (2017), and Festa et al. (2019, 2020c) among others.

Our evaluation of the most notable cases of chaotic units around the world shows that, statistically, polygenetic mélanges represent the largest part of all chaotic units in exhumed subduction complexes (>27.7% in Fig. 2B), particularly on metamorphosed one (Festa et al., 2010). They mainly occur along the main shear zones of subduction complexes such as, for example, at the base of the accretionary wedge and thrust sheets (Fig. 1C) through the reworking of sedimentary mélanges within the shear zone (Pini et al., 2004; Landuzzi, 2005; Festa et al., 2010; González Clavijo et al., 2021; Lai et al., 2021). They also occur within the accretionary complex where out-of-sequence thrusts embed and rework heterogeneous MTDs or diapiric mélanges (Vollmer and Bosworth, 1984; Codegone et al., 2012; Smeraglia et al., 2019; Fig. 1C). Although less frequent, both tectonic and diapiric mélanges occurring at the wedge front of subduction complexes may be reworked by mass transport processes forming an additional type of polygenetic mélange (Fig. 1C; Bettelli and Panini, 1987; Bettelli et al., 2004; Festa et al., 2013; Lai et al., 2021). Detailed analyses and the reevaluation of the wider and most famous mélange belts around the world (i.e., from the Franciscan Complex to the Circum-Mediterranean region, up to the Asian orogenic belts and suture zones), clearly document that they mainly consist of the continuous and multistage reworking and juxtaposition of different mélange types (tectonic, sedimentary, and diapiric) and broken formations (Osozawa et al., 2009; Wakabayashi, 2011; Raymond, 2015, 2019; Festa et al., 2013, 2019; Lai et al., 2021). These polygenetic mélanges cover, in fact, areas of tens to several hundreds of thousands of square kilometers, which are wider than those consisting of tectonic, sedimentary, and diapiric mélanges.

4. Preconditioning factors for the formation of tectonic chaotic units: the role of structural inheritances

The tectonic dismemberment and transfer of slices and blocks, detached from the downgoing slab to the upper plate and/or within the plate boundary interface, is commonly described as the effect of different factors and processes occurring at intermediate to deep depths (depth >10–15 km; Dickinson, 1971; Platt et al., 1985; Hacker et al., 1995; Moore and Vrolijk, 1992; van den Beukel, 1992; Kimura et al., 1996; Okamoto and Maruyama, 1999; Yamasaki and Seno, 2003; Ernst et al., 2009). However, observations on both modern and ancient subduction complexes pointed out that the subduction of structural inheritances represents a primary, even if poorly considered, factor in the formation of tectonic mélanges and broken formations, which already operates at shallow structural levels ($T < 250$ °C). In the following we examine the role played by two types of structural inheritance, which characterize the architecture of the shallower portion of the subducting plate and are represented by the heterogeneity of the Ocean Plate Stratigraphy (OPS) and the architecture of the Ocean-Continent Transitional Zone (OCTZ).

4.1. Role of the ocean plate stratigraphy (OPS) heterogeneity

In the last decades, it has become apparent that the Ocean Plate Stratigraphy (OPS) is highly heterogeneous (Isozaki et al., 1990; Bradley and Kusky, 1992; Wakita and Metcalfe, 2005; Safonova, 2009; Kusky et al., 2013; Safonova and Santosh, 2014; Wakita, 2015; Khukhuudei et al., 2022) in function not only of

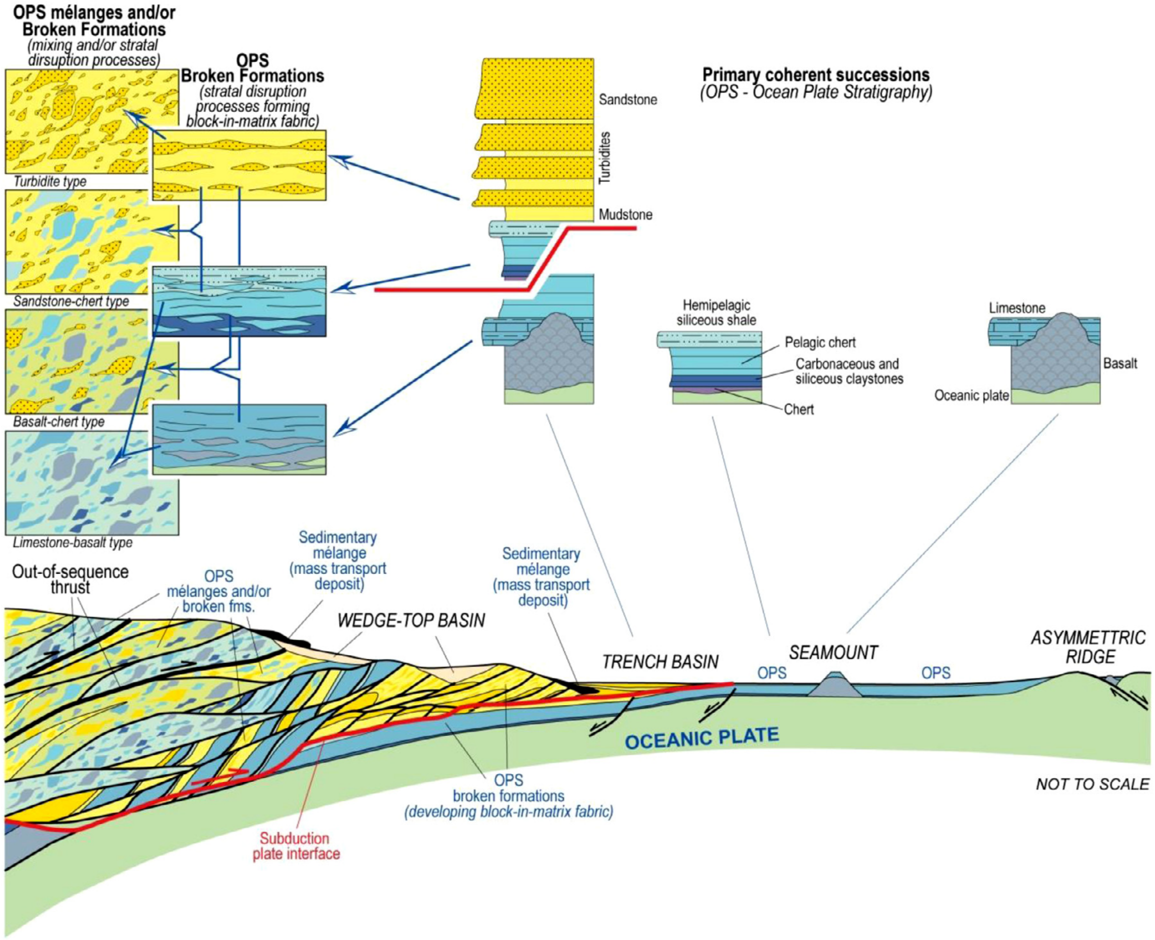


Fig. 6. Conceptual model showing the role of structural inheritances, represented by the heterogeneous ocean plate stratigraphy (OPS), in the formation of OPS mélanges and broken formations through subduction and accretion at convergent margins (modified from Wakita, 2015; Kusky et al., 2013, and Festa et al., 2019). The OPS is progressively disrupted and fragmented to form a broken formation (early stages of deformation) and then broken formations and/or mélanges with the increasing of tectonic deformation, depending on the portion of OPS involved in the deformation and the degree of mixing. Note that mélanges formed only with the contribution of mixing processes.

the tectonic setting (OPS originated in hot spot vs. suprasubduction zone, vs. Mid-Oceanic Ridge – MOR) but also because strongly influenced by the spreading rate (fast vs slow vs ultraslow) and the magmatic activities (robust vs starved segment) of the MOR, and the proximities of transform faults (Dick et al., 2006; Karson et al., 2015). The occurrence of topographic features (e.g., oceanic plateaus, seamounts or oceanic core complexes, and transform faults), and the nature, internal structures (e.g., extensional faults, detachment faults, etc.), thickness and lateral continuity of the oceanic crust further influence the OPS. These factors represent significant heterogeneities in the oceanic lithosphere, which could be enhanced by the deformation and roughness added at the outer rise, and by seafloor hydrothermal and metamorphic processes. As a result, the seafloor could have a variety of basements that could have rugged topographies, determining the characteristics of the depositional basin and, thus, different thickness (from few hundreds of meters to kilometers) of the pelagic and trench sediments (Fig. 6). The variability is both along and normal to the trench, and it is apparent at different scales resulting in different OPS (e.g., serpentinite-basalt-chert, serpentintite clastics or serpentinite-basalt-cherts-clastics, etc.; Kusky et al., 2013; Wakita, 2015 and references therein).

Depending on the stratigraphic and/or structural level sampled by the plate interface (i.e., décollement) or shear/fault zones at shallow structural levels, different portions of the OPS could be stripped off and incorporated within the accretionary prism (Fig. 6). This process is also influenced by the topography of the subducting plate (i.e., seamount and/or asymmetric ridge). The serpentinite, gabbro, basalt, chert will become hard blocks in a softer matrix (Fig. 6). The latter consists of poorly lithified and water rich trench and/or slope sediments, which commonly represent the upper part of the OPS. Incorporation of this heterogeneous material in the accretionary prism and/or along the plate interface could result in a tectonic disruption of the heterogeneous succession, forming chaotic units (Raymond, 1984; 2019; Cowan, 1985; Hajná et al., 2013, 2014, 2019; Kusky et al., 2013; Wakabayashi, 2015, Wakabayashi, 2021a; Wakita, 2015; Ackerman et al., 2019), which consist of OPS combinations (Fig. 6), such as serpentinite-basalt-chert (plus or minus breccias), serpentinite clastics or serpentinite-(mafic plutonics)-basalt-cherts-clastics. In spite of the apparent heterogeneity, these units consist of broken formations (with only "native" blocks) rather than mélanges (with "exotic" blocks) as they represent the dismemberment and juxtaposition of part of the same primary oceanic succession (Wakabayashi, 2015, 2017a, 2017b). Serpentinite and/or basalt and chert clasts, derived from oceanic core complexes, transform faults, and fracture/fault zones at spreading center interactions represent, in fact, "native" and not "exotic" portions of the OPS (Hajná et al., 2013, 2019; Wakita, 2015; Wakabayashi, 2015; Tartarotti et al., 2017; Balestro et al., 2019; Festa et al., 2021). Therefore, large part of OPS chaotic units observed at shallow structural levels of subduction complexes and consisting of ophiolite blocks within a trench- to slope sediments-derived matrix, commonly developed during early stages of deformation through the progressive disruption and dismemberment of the primary heterogeneous OPS.

The rheological and tectono-stratigraphic heterogeneities of the OPS strongly influence the nature and composition of chaotic units developed at shallow structural levels (Wakabayashi, 2015, 2017a; Wakita, 2015; Raymond, 2017; Ackerman et al., 2019; Hajná et al., 2019; Festa et al., 2019, 2020a; Barbero et al., 2021a, 2021b; Pandolfi et al., 2021). The number of combinations of different types of "native" blocks within a matrix, thus increases with the increasing heterogeneity degree of both the primary OPS and the oceanic lithosphere (Fig. 6). Only with the increase of shearing and deformation, components of different broken formations, which eventually formed in different environments and portions (i.e., different distances from the oceanic ridge and/or the passive margin) of the subducting plate, can be mixed along shear zones forming OPS mélanges (Raymond, 2017). However, mixing is generally apparent at the map scale but not effective at the outcrop or hand sample scales, except along faults that are commonly very thin, ranging from decimeters to few tens of meters in thickness (Rowe et al., 2013; Wakabayashi, 2021b).

The distinction between OPS broken formations and OPS mélanges, outlines that the appropriate use of the terminology (i.e., mélange vs broken formation; Section 2 and Fig. 1A) is not a mere terminological debate but has a primary significance in distinguishing very different processes of formation of chaotic units (e.g., mixing vs. stratal disruption). These different processes reflect very different degrees of strain, whose understanding is useful to better constrain the tectonic evolution of the subduction complexes and orogenic belts in which mélanges and broken formations occur. However, caution is necessary in their interpretation in ancient and exhumed orogenic belts as the downdip tectonic reworking and/or metamorphic transformations of both OPS tectonic mélanges and broken formations, strongly complicate the distinction on the nature of blocks ("exotic" or "native"; Raymond, 1984; 2017; Cowan, 1985; Platt, 2015; Ernst, 2016; Wakabayashi, 2017b; Festa et al., 2020c).

4.2. Role of the ocean-continent transition zone (OCTZ)

Independently on the different model and degree of stretching and lithospheric thinning, which drive the decrease in crustal thickness and the strong decoupling between upper crust and continental mantle (Brun and Beslier, 1996; Manatschal et al., 2001; Moulin et al., 2005; Osmundsen and Ebbing, 2008; Ranero and Perez-Gussinyé, 2010; Frasca et al., 2016), the OCTZ architecture represents a significant tectonic and tectono-stratigraphic heterogeneity (Fig. 7A) whose subduction may strongly control the localization and migration in time and space of the subduction plate interface. This can trigger alternating episodes of tectonic accretion (transfer of material from the lower to the upper plate) and erosion (transfer of material from the upper to the lower plate), playing a significant role in controlling the nature and composition of offscraped blocks, and contributing to form tectonic chaotic units with different internal components. For example, during the subduction of extensional allochthons of hyperextended margins, the plate interface is favored to develop at the base of the siliciclastic and poorly lithified post-extensional (i.e., post rifting) succession (Tavani et al., 2021 and references therein) while the below lithified basin to platform carbonate succession is completely subducted (Fig. 7B). Only the topmost portion of the basin to carbonate platform succession, which is lithified and rheological more competent than the above siliciclastic succession, can be stripped off by shearing and incorporated within the plate interface or accreted as tectonic blocks/slices (Figs. 7B-C). These OCTZ-derived blocks can be juxtaposed and eventually mixed with previously accreted OPS-derived broken formations (with ophiolite blocks), forming tectonic mélanges at the map scale (i.e., mixing of "exotic" OCTZ-derived blocks and "native" OPS-derived ones). Notable examples are documented in the Late Cretaceous (sedimentary) mélanges of the External Ligurian Units of the Northern Apennines (Marroni et al., 1998, 2010, 2017; Barbero et al., 2020 and references therein), the Miamu mélange in Crete (Bonneau, 1991), the Dinaric-Hellenic orogenic belt (Bortolotti et al., 2013 and references therein), and several mélange occurrences in the Central Asian Orogenic Belt – CAOB (Yang et al., 2022 and references therein).

On the contrary, during the subduction of the proximal and stretched portion of the passive margin, the location of the plate interface is favored by the tectonic inversion of pre-existing (i.e., rifting-related) extensional faults with deep-ward migration of the plate interface in the middle crust (Figs. 7C-D; Tavani et al., 2021). In this case, the location of the plate interface may also reactivate inherited (i.e., rifting-related) low-angle extensional detachment faults that controlled the stretching of the continental crust. Consequently, the down-deep migration of the subduction plate interface allows to incorporate huge portions, up to several kilometers thick, or blocks of the passive margin succession and related basement rocks into the accretionary wedge (Figs. 7C-D). They may show a different nature, composition, and age (i.e., from basin-platform sediments to volcanic and metamorphic crystalline rocks) with respect to those scraped off during the subduction of extensional allochthons. The tectonic juxtaposition with previously accreted OPS broken formations at different stages and depth of subduction, may form tectonic mélanges with mixed continental and oceanic blocks. Notable examples occur in the Western Alps (e.g., the *"Faisceau de Cogne"* in the Urtier Valley of Ellero and Loprieno, 2018 and Tartarotti et al., 2021, the Banchetta-Rognosa Tectonic Unit of Corno et al., 2021; the Susa Shear Zone of Ghignone et al., 2020, and the Valmala Shear Zone of Balestro et al., 2019, Groppo et al., 2019) where huge continental-derived slices and disrupted successions, tens of meters to kilometers in size, are juxtaposed and mixed with ophiolite components, potentially representing the product of mixing of OCTZ and ophiolitic units occurred, at least in part, at shallow structural levels (i.e., before the P-T metamorphic peak).

The incorporation within the accretionary wedge of huge sectors of passive margin may also have a two-fold role, favoring: (i) the gravitational instability of the wedge front, and thus triggering mass transport processes and sedimentary mélanges (with "exotic" blocks) emplacement into the trench (Fig. 7B-D), and (ii) the change of subduction rate, favoring the switch from tectonic accretion to erosion and the upward migration of the plate interface (Fig. 7D). We have shown in Section 3 that heterogeneous MTDs (sedimentary mélanges) represent a significant component of subduction complexes and orogenic belts, and can emplace over wide areas, ranging from hundreds of square meters to thousands of square kilometers. Depending on the runout distance and the dynamics of the frontal wedge (accretionary vs non-accretionary) they may be subducted or not as we document in the following section (Section 5). This switch from tectonic accretion to erosion may also represent an additional factor able to wrench new tectonic slices from a different stratigraphic and structural position (i.e., top of the passive margin succession), mixing them with those incorporated within the detachment fault shear zone.

5. Subduction of "shallow" chaotic units: how much of the internal structure of metamorphic chaotic units is inherited from shallow structural levels?

At least part of chaotic units occurring in exhumed (metamorphic) subduction complexes and orogenic belts could have inherited their internal structure and/or internal mixing (up to the hand

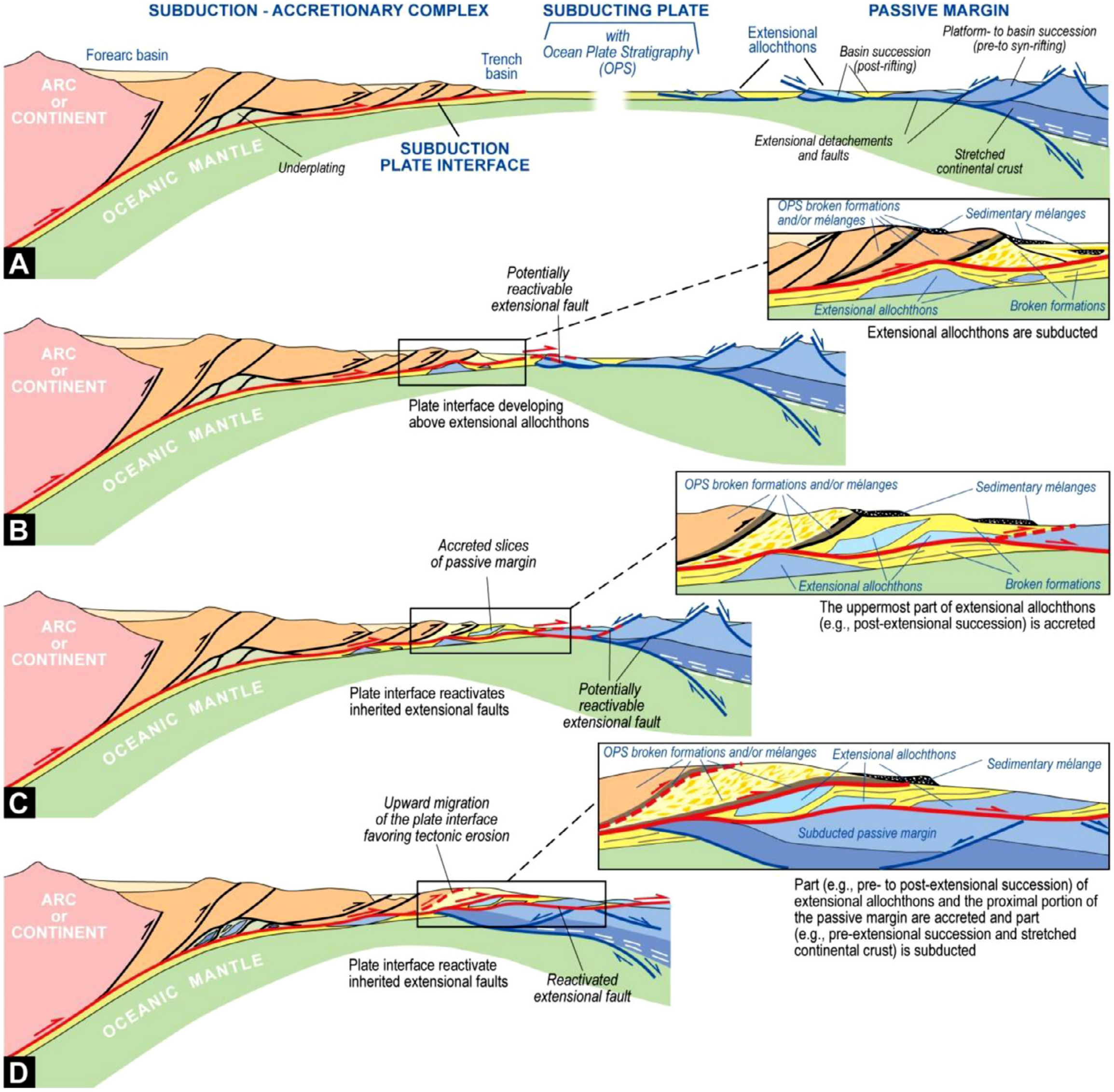


Fig. 7. Conceptual model (**A-D**) showing the role of subduction of structural inheritances, which are represented by the heterogeneous architecture of the ocean-continent transition zone (OCTZ), in controlling the localization of the plate interface (modified from Tavani et al., 2021). Depending on the architecture of the OCTZ (i.e., the subducting plate), the plate interface develops and/or locate in different positions: (**B**) subduction of extensional allochthons favors the localization of the plate interface at the base of the siliciclastic and poorly lithified (post-rifting) succession, allowing the below lithified sediments of the extensional allochthon to be subducted; (**C-D**) subduction of the proximal and stretched portions of the passive margin favors the tectonic inversion of inherited (syn-rifting) extensional features with deep-ward migration of the plate interface in the middle crust (or along pre-existing extensional faults) and the accretion of huge portions of the passive margin succession. Passive margin blocks (i.e., from basement to sedimentary cover) may be mixed with previously accreted OPS broken formation/mélanges after accretion. The subduction of the passive margin may also trigger a kinematic impasse to the offshore migration of the plate interface, favoring (**D**) its upward migration and the onset of a tectonic erosion stage.

sample scale) from those formed at shallow structural levels. However, not all chaotic units formed at shallow structural levels can be subducted and, as subducted, their fate could be very different becoming part of the plate boundary interface or shear zone or sharing the fate of the lower plate. Their chance mainly depends on where the plate interface develops with respect to their structural position (Fig. 8A). In the following we analyze two different cases in which the chaotic units formed at shallow structural levels are located (i) in actively accretionary margins, or (ii) on non-accretionary (erosive) margins, respectively.

5.1. Subduction of chaotic units in actively accretionary margins

Where an accretionary prism is actively growing with consequent transfer of lower plate material to the upper plate (and therefore the progressive downward migration of the plate boundary interface), the chance to subduct shallow chaotic units formed inside (e.g., broken formations) or atop (e.g., sedimentary mélanges/mass transport deposits – MTDs) of the accretionary prism is very low. Normally, accretionary margins are characterized by slow convergent rates (<7.6 cm/yr) and/or trench sediments thickness >1 km (Clift and Vannucchi, 2004), and the plate interface commonly develops at the base or within the trench sediments, implying that chaotic units have been accreted (Figs. 8B-C). This is the case, for example, of most of Cretaceous chaotic units in the External and Internal Ligurian Units in Northern Apennines (Bettelli et al., 1989; Pini, 1999; Meneghini et al., 2009, 2020; Marroni et al., 2010; Barbero et al., 2020), the Frentani Mélange in Southern Apennines (Vezzani et al., 2010), the Lichi mélange in Taiwan (Lai et al., 2021 and references therein), the McHugh mélange in Alaska (e.g., Fisher and Byrne, 1987), and part of the Franciscan Complex at Mt. Diablo (Wakabayashi, 2021a).

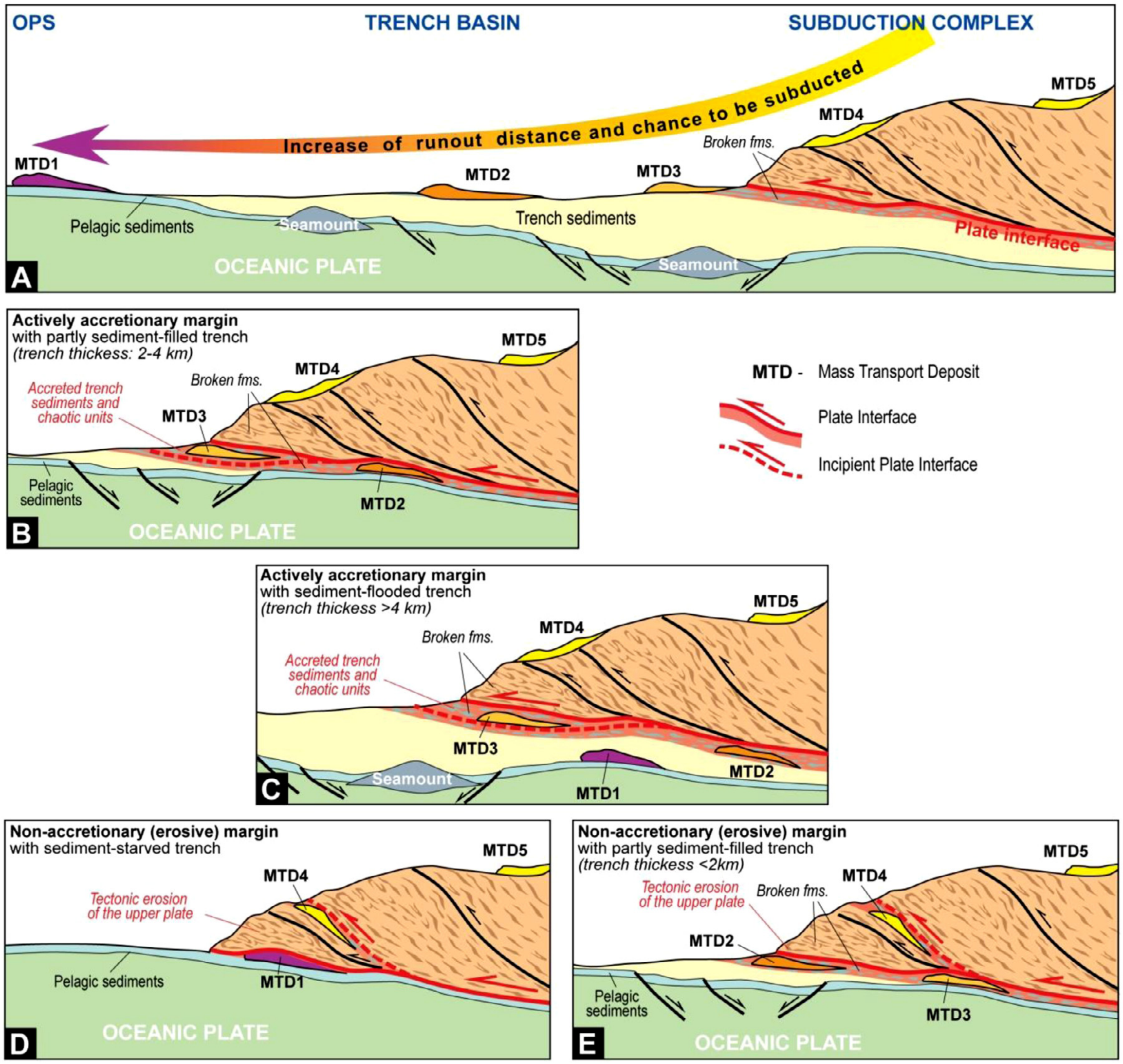


Fig. 8. Conceptual model of the structural control on the subduction of mass transport deposits (MTDs) and broken formations in convergent margins (modified from Geersen et al., 2020). (**A**) Depending on the runout distance, MTDs sourced from the subduction complex or generated offshore show different chances to be subducted: in both actively tectonic margins with partially sediment-filled trench (**B**; 2 km < trench thickness < 4 km), in actively tectonic margins with sediment-flooded trench (**C**; trench thickness >4 km), and non-accretionary (erosive) margins with sediment starved trench (**D**), MTDs emplaced close or above the oceanic basement (see MTD1) have the highest changes to be subducted; (**C**) in actively tectonic margins with sediment-flooded trench (trench thickness >4 km), MTDs with short runout (see MTD2 and 3) can only be subducted if the thickness of subducting sediments is higher than that one of sediments under the MTD, otherwise it will be added to the subduction complex (see MTD2 in C); in non-accretionary (erosive) margins with both sediment-starved trench (**D**) and partly sediment-filled trench (**E**, trench thickness <2 km), the MTDs, emplaced on the upper plate slope, as well accreted broken formations, have the highest potential to be subducted when the plate boundary migrate upward in the upper plate (see MTD4) and interfere with the subduction plate interface.

In this tectonic setting (i.e., accretionary margin) there is a chance to subduct a previously formed chaotic unit just for MTDs emplaced above or close to the oceanic basement or inherited from OPS (compare Fig. 8A and Figs. 8B-C). The latter ones represent the product of gravitational processes (i.e., MTDs – mass transport deposits) associated with structural highs (oceanic ridges and seamounts, transform and fracture zones, etc.) and/or occurred during rifting processes. These different types of chaotic units have high chance to be subducted due to their position directly above (i.e., in little-sedimented trench with sediment thickness <2 km; Fig. 8B) or close to the top of the oceanic basement (see MTD1 in Figs. 8A and 8C). However, they less likely will interact with the plate boundary shear zone (for a detailed discussion see Gerseen et al., 2020). Another option regards those MTDs deposited on trench sediments (see MTD2 and MTD3 in Figs. 8A-C), but their chance to be subducted is inversely proportional to the increasing thickness of trench sediments and the decreasing of the runout distance (Geersen et al., 2020).

In the case of a moderate (sediments thickness 2–4 km; Fig. 8B) to heavily sedimented trench (sediments thickness >4 km; Fig. 8C) and short runout, MTDs can only be subducted if the thickness of subducting sediments is higher than that one of sediments under the MTDs (see MTD2 in Figs. 8A and 8C; Geersen et al., 2020 for details). This is the case, for example, of the Reloca Slide off Central Chile (24 km^3 and 18 km of maximum runout distance; Völker et al., 2009, 2013) and the 44-North Slide offshore Oregon (100 km^2 and 20–25 km of maximum runout distance; Tominaga et al., 2018, Lenz et al., 2019). Conversely, MTDs with long runout distance (see MTD1 in Figs. 8A and 8C) may be emplaced on top of the pelagic (or OPS) section or seaward of the point where trench sediments onlap the pelagic sediments on the outer trench slope, progressively increasing their depth within the trench stratigraphy during their travel toward the subduction zone and, thus, the chance to be subducted (Geersen et al., 2020). The North Giant Slope Failure (500 m thick and possibly about 55 km runout distance) offshore of central Chile, and the Ruatoria Debris Avalanche at the Hikurangi margin offshore New Zealand (about up to 2000 m thick; Collot et al., 2001; Barnes et al., 2018), represent two of the most notable examples of long runout MTDs emplaced seaward of the point where trench sediments onlap on pelagic sediments of the outer trench slope (Geersen et al., 2020). This potential for MTDs to be subducted thus increases with the increasing of their runout distance (Fig. 8A). In this case, it is high also the probably of these MTDs to interact with the plate boundary interface.

5.2. Subduction of chaotic units in non-accretionary (i.e., erosive) margins

Growing evidence suggests that cycles of growth of accretionary prisms followed by tectonic and/or sedimentary dismantling of the same prism (tectonic erosion *sensu lato*) with underthrusting of previously accreted material are common (Vannucchi et al., 2008 for the tectonic erosion and underthrusting of the frontal part of the wedge; Marroni and Pandolfi, 2001; Ogata et al., 2012a; Malavieille et al., 2016; Marroni et al., 2017; Meneghini et al., 2020 for the sedimentary dismantling by submarine collapses of the frontal part of the wedge). For example, the Nankai Trough documents short periods of about 10 m.y. of tectonic erosion, and the Japan trench active margin is commonly categorized as erosive margins even if the frontal part of the wedge is made by former Jurassic and Cretaceous accretionary prism (Regalla et al., 2017). In this condition, there is high change for previously accreted chaotic units (mélanges and broken formations), as well as sedimentary and diapiric mélanges emplaced at the front, atop or intruded within the prism, to be subducted (see MTD4 in Figs. 8D-E) and thus overprinted and reworked by deeper processes and metamorphic recrystallization. Processes of transfer of chaotic units from the upper to the lower plate could be both sedimentary (i.e., gravitational; Figs. 8A), and therein associated to the formation of sedimentary mélanges and related to mixing (Geersen et al., 2020 and references therein), or tectonic (Figs. 8D and 8E), related to the upward migration of the plate boundary interface (Vannucchi et al., 2008).

Tectonic erosion, which mainly characterizes margins with thin trench sediments (<1 km in thickness) and convergent rates exceeding about 6 cm/yr (Clift and Vannucchi, 2004), favors the subduction and, in some cases, the juxtaposition and/or mixing of previously accreted OPS chaotic units, MTDs, and trench sediments with slices or blocks of crystalline crust tectonically removed from the overriding plate (Fig. 8D; Miller, 1970; Murauchi, 1971; Sholl et al., 1977). Therefore, alternating periods of tectonic accretion and erosion, and the migration in time and space of the plate interface, may strongly contribute to form different types of chaotic units and/or control their possibility to be preserved at shallow structural levels or to be subducted. In the latter case, their diagnostic internal block-in-matrix arrangement, which documents the primary process of formation, can be preserved, or strongly reworked, depending on the subduction history and the location of shear deformation.

In the case of little-sedimented trenches (sediments thickness < 2 km) and where the plate boundary develops within the upper plate or at its base (non-accretionary margins), MTDs has the highest potential to be subducted (MTD4 in Fig. 8E). Notable examples are represented by the subduction of MTDs (20–23 km^3 with 400 m thickness, Hühenberhch et al., 2005) associated to the Jaco and Parita scars (von Huene et al., 2000; Hardens et al., 2011; Geersen et al., 2011, 2020). When incorporated within the plate interface, the diagnostic arrangement of the primary block-in-matrix fabric of sedimentary mélanges (i.e., the random distribution of block in a brecciated matrix) is gradually reworked up to closely resemble a “structural ordered” block-in-matrix fabric of tectonic mélanges at $T > 150$ °C (>5 km of vertical burial; Festa et al., 2018 for details). Therefore, after subduction, the primary block-in-matrix fabric of sedimentary mélanges can be preserved only if it escapes from shear deformation.

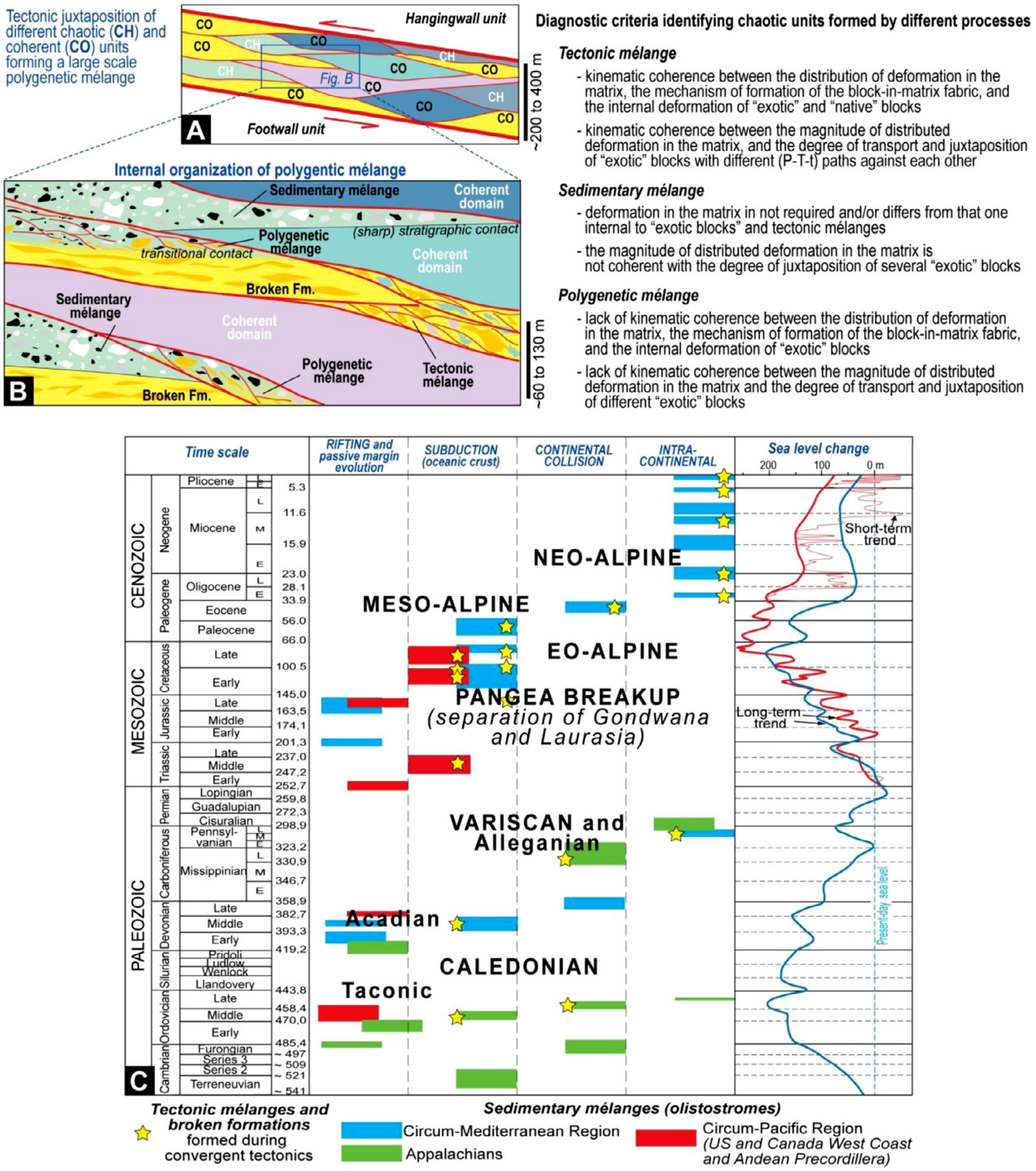
6. Discussion: mélanges and their implications in the evolution of subduction complexes and orogenic belts

Our systematic examination of several examples of mélanges and chaotic units, document that although many of those preserved in metamorphic and polydeformed subduction complexes and orogenic belts are commonly interpreted as the exclusive product of deep tectonic processes (e.g., underplating, return flow, etc.), a significant part of them (i.e., about 64.7% in Fig. 2D) already formed at shallow structural levels ($T < 250$ °C, corresponding to $<$10–15 km of vertical burial) through different processes (tectonic, sedimentary, diapiric and polygenetic). During subduction, the primary and diagnostic block-in-matrix fabric of those chaotic units could be tectonically reworked, especially when deformed along the plate boundary interface, and/or overprinted by metamorphic recrystallization, forming polygenetic mélanges (Figs. 1C, 5D-F) whose internal fabric closely resembles that one of tectonic mélanges formed by underplating and return flow processes at intermediate to deep depths (Raymond, 1984, 2019; Cowan, 1985; Krohe, 2017; Wakabayashi, 2019; Festa et al., 2020c; Fig. 1). This resemblance of different block-in-matrix fabrics strongly complicates the interpretation of both the primary process/es and the structural level of formation of chaotic units, having strong implications on a correct reconstruction of the temporal and spatial tectonic evolution of the subduction complex or orogenic belt in which they occur. This is particularly true for those recording a complete orogenic cycle (i.e., from rifting to subduction, collision, and exhumation) with polyphasic deformation and metamorphism recrystallization.

In the following we discuss three different but complementary aspects that represent, among several others, excellent examples of implications that a correct understanding of chaotic units may have for a better comprehension of subduction complexes and orogenic belts, independently on their age (from Precambrian to present days) and location. These are (i) the significance of mélanges and broken formations as markers of tectonic events, (ii) their potential contribution in understanding early Earth processes and the onset of plate tectonics, and (iii) their influence in controlling the seismic behavior of the shallow-level subduction plate interface.

6.1. Mélanges and broken formations as markers of the tectonic evolution of exhumed subduction complexes and orogenic belts

The close association between different types of chaotic units and different processes of formation (tectonic, sedimentary, diapiric, and polygenetic), which operate and alternate during the evolution of subduction complexes and orogenic belts, clearly document that chaotic units represent fundamental markers of tectonic events (Festa et al., 2010; 2019 and references therein). However, the correct temporal and spatial definition of these events is closely constrained by the correct interpretation of the primary process/es and the structural level of formation of chaotic units, as well as the history of their eventual tectonic reworking. Two aspects of chaotic units, which are discussed in the following, are essential to be taken into consideration on this issue: (i) the recognition of the primary characteristics of the chaotic unit,



Diagnostic criteria identifying chaotic units formed by different processes

Tectonic mélange

- kinematic coherence between the distribution of deformation in the matrix, the mechanism of formation of the block-in-matrix fabric, and the internal deformation of "exotic" and "native" blocks
- kinematic coherence between the magnitude of distributed deformation in the matrix, and the degree of transport and juxtaposition of "exotic" blocks with different (P-T-t) paths against each other

Sedimentary mélange

- deformation in the matrix in not required and/or differs from that one internal to "exotic blocks" and tectonic mélanges
- the magnitude of distributed deformation in the matrix is not coherent with the degree of juxtaposition of several "exotic" blocks

Polygenetic mélange

- lack of kinematic coherence between the distribution of deformation in the matrix, the mechanism of formation of the block-in-matrix fabric, and the internal deformation of "exotic" blocks
- lack of kinematic coherence between the magnitude of distributed deformation in the matrix and the degree of transport and juxtaposition of different "exotic" blocks

Fig. 9. Conceptual model showing the potential arrangement and juxtaposition of different tectonic units forming a large-scale polygenetic mélange (**A**-**B**), and synthesis of the characteristics of primary formed tectonic, sedimentary, and diapiric mélanges (modified from Festa et al., 2019). (**A**) Polygenetic mélanges associated with shear/fault zones commonly result in the mixing and/or juxtaposition of larger coherent domains (i.e., non-chaotic rock units or layered primary successions), smaller reworked mélanges of different origin (sedimentary, diapiric and/or tectonic), and broken formations, forming in an "apparent" tectonic mélange organization. (**B**) Depending on the degree of deformation and mixing, and the repartition of deformation, poorly- to un-deformed domains of primary sedimentary, diapiric and/or tectonic mélanges may be preserved at different scales. (**C**) Correlation between main events of chaotic units formation (tectonic and sedimentary mélanges and/or broken formation), tectonic settings, orogenic stages and sea-level changes in the Circum-Mediterranean Region, Appalachians and the American portion of the Circum-Pacific Region (modified from Festa et al., 2016). Sea-level changes from Haq et al. (1987) for the Cenozoic, and Haq and Schutter (2008) and Snedden and Liu (2010) for the Paleozoic and the Precambrian.

and its process of formation after the subduction-related reworking (Section 6.1.1), and (ii) the constraints provided by the composition and nature of their block-in-matrix arrangement (Section 6.1.2).

6.1.1. Recognizing "shallow"-derived chaotic units and process of formation after subduction-related reworking

Our overview of different types of chaotic units clearly shows that most of those formed directly by tectonic processes consist of broken formations (Fig. 2B). Independently on the structural level of development, they show two diagnostic characteristics that allow to not confuse them with mélanges after subduction-related reworking of their block-in-matrix fabric (Fig. 9). Their block-in-matrix fabric shows, in fact, a kinematic coherence between both (i) the magnitude of the distributed deformation in the matrix and the degree of tectonic dismemberment and/or juxtaposition of "native" blocks, and (ii) the distribution of deformation in the matrix and the tectonic mechanism of their block-in-matrix fabric (i.e., the "deformation criterion" of Festa et al., 2019; Fig. 9). This is the case of broken formations formed, for example, by the dismembered of OPS and/or OCTZ units at shallow levels of an accretionary complex and/or at the plate interface. Although the internal degree of dismemberment commonly increases with the increasing of shear deformation with depth and it is overprinted by a prograde metamorphic P-T path, broken formations preserve both the two above characteristics and their primary "stratigraphic" organization (i.e., the primary lithological and chronological identity). This is well-documented by the fact that exhumed HP-metamorphic broken formations may commonly preserve remnants of pre-orogenic (intra-oceanic) structures and coherent portions of stratigraphic successions, even if partially disrupted and overprinted by subduction-related deformational processes (Tartarotti et al., 2019, 2021; Balestro et al., 2014, Balestro et al., 2018, 2019; Agard, 2021; Festa et al., 2015a, 2021 and references therein).

The mixing of single "exotic" blocks/slices, which are scraped off from different OPS and/or OCTZ portions and embedded in a common matrix to form a mélange, rarely occurs at shallow structural levels, except for very narrow and not mappable (i.e., decimeters thick) shear/fault zones bounding different broken formation units (Section 3.1). Tectonics, in fact, is not an efficient process of mixing at shallow structural levels as opposite to gravitational and diapiric processes (Fig. 2C). On the contrary, mappable mélanges (i.e., hundreds of meters or more in thickness) with exotic blocks, which are interpreted to be formed directly and exclusively by tectonic processes, mainly developed at deeper structural levels (Fig. 2C) when specific mechanical conditions and mechanisms occur within subduction channels (i.e., return flow, Cloos, 1982).

During subduction and then exhumation processes, broken formations can be underplated and juxtaposed to other chaotic units (including reworked sedimentary and diapiric mélanges), which were subducted at different depths and, thus, characterized by different P-T-t paths. This contributes to form a particular type of large-scale heterogeneous shear zone, ranging in thickness from hundreds of meters to kilometers (Behr and Bürgmann, 2021; Oncken et al., 2021; Wakabayashi, 2021b; Yang et al., 2022), which is commonly overprinted during exhumation by a common retrograde metamorphic P-T path (Roda et al., 2020; Corno et al., 2021), complicating the recognition of the primary origin and nature of each juxtaposed unit. Although commonly described as tectonic mélange in most of metamorphic orogenic belts, this type of shear zone represents a polygenetic mélange (Figs. 9A-B) because of the mixing of units with different P-T-t paths and/or different nature and origin (Festa et al., 2020c). Several notable examples of these polygenetic mélanges are documented around the world from Western Alps and circum-Mediterranean orogenic belts (Guillot et al., 2009; Balestro et al., 2019; Di Rosa et al., 2019; Ghignone et al., 2020; Roda et al., 2020; Corno et al., 2021; De Broucker et al., 2021) to the US-Western Cordillera (Tewksbury-Christle et al., 2021) up to the Asian orogenic belts (Kusky et al., 2020).

On the contrary of tectonic processes, gravitational and diapiric ones are very efficient in mixing "native" and "exotic" blocks, forming mélanges (sedimentary and diapiric) already at shallow structural levels of subduction complexes and orogenic belts (Fig. 2C). Although during subduction their block-in-matrix fabric is commonly reworked by tectonics (and metamorphism) forming polygenetic mélanges, two important and complementary observations (Fig. 9) allow to distinguish both the remnants of their primary diagnostic fabric and the processes of their formation and, therefore, the structural level at which they formed. Reworked sedimentary mélanges and the central part (i.e., the core zone) of diapiric mélanges are characterized (Fig. 9), in fact, by the lack of (i) kinematic coherence between the distribution of deformation in the matrix, the mechanism of formation of the block-in-matrix fabric, and the internal deformation of "exotic" blocks, and of (ii) kinematic coherence between the magnitude of distributed deformation in the matrix and the degree of transport and juxtaposition of different "exotic" blocks (Festa et al., 2019 for details). "Exotic" blocks consisting of metamorphic rocks, may commonly record different P-T-t metamorphic paths (Krohe, 2017 and Festa et al., 2019 for details).

Recognizing sedimentary mélanges (olistostromes) after their subduction-related block-in-matrix tectonic reworking is a challenge with significant implications. The recurrence time of gravitational bodies emplacement appears, in fact, to be directly related to the frequency of tectonic stages, and their control on depositional cycles. They also commonly show a strong correspondence with transgressive-regressive sedimentary cycles and with both the local and eustatic sea level variations (Fig. 9C), being the different mass transport processes diagnostic of specific system tracts, such as falling stage and transgressive ones (Vail and Mitchum, 1980; Haq et al., 1987; Sherba, 1989; Haq and Shuffer, 2008; Snedden and Liu, 2010). Therefore, sedimentary mélanges can be interpreted as fundamental markers of tectonic and climatic events (Fig. 9C), and the recurrence time for their emplacement, which ranges from thousands to millions of years (Sherba, 1989; Graziano, 2001; Delteil et al., 2006; Camerlenghi and Pini, 2009; Urgeles and Camerlenghi, 2013; Festa et al., 2016; 2019; Ogata et al., 2020), may provide excellent constraints for the frequency of tectonic events during the evolution subduction complexes and orogenic belts, and the related changes of the dynamic equilibrium of the frontal wedge (Festa et al., 2016). These changes may also provide significant constraints on the space and time migration of the plate interface and its re-localization, and thus on the alternating of tectonic accretion and erosion stages (Remitti et al., 2011). The latter are, in turn, recorded by tectonic chaotic units with different internal composition as discussed in the following section.

6.1.2. Constraints from the composition and nature of chaotic units

It is well-documented that the composition and nature of blocks and the matrix show a specific genetic relationship with the primary tectonic/geodynamic setting of mélanges formation (Festa et al., 2010). Components and their nature should, in fact, be compatible with the tectonic environment of the mélange formation and occurrence (i.e., the "tectonic environment criterion" of Festa et al., 2019). These aspects are, therefore, very useful to overcame complications in distinguishing the processes of formation of chaotic units after tectonic reworking and metamorphism, and to better understand the evolution of subduction complexes and orogenic belts. For example, in Section 4 we have documented that the nature and composition of both blocks and the matrix sourced from the dismemberment of the OPS are quite different from those sourced from the OCTZ. The former consists of the combination of oceanic mantle rocks and related volcanic rocks and sedimentary cover, differing from the latter because of the lack of blocks and portions of the passive margin succession and related crystalline basement. Among several Authors (MacPherson et al., 1990; Wakabayashi, 2015), Raymond and Bero (2015) provided an excellent and detailed example that distinguished gravitational processes from tectonic one in the formation of part of mélanges with exotic blocks in the Franciscan Complex because of the occurrence of a sandstone matrix, rather than a slate one, in which huge olistoliths (blocks) of specific turbiditic facies and grain-flow deposits are embedded. Huge blocks and the matrix are, in fact, stratigraphically and sedimentologically well consistent with parts of the lower slope - base of slope sedimentary succession and not with a tectonic product formed by tectonic sharing along the plate interface. We remand to Festa et al. (2010, 2016) for a detailed description of several other examples on the genetic relationships between mélange components and the primary tectonic/geodynamic setting of their formation, which allowed to distinguish different types of mélanges, with different and diagnostic block-in-matrix fabric, associated with the evolution of passive margins, strike-slip tectonics and transform margins, convergent margins and ocean crust subduction, obduction, collision and intracontinental settings.

The definition of the above discussed genetic relationships also allows to better constrain the dynamics of the frontal wedge, distinguishing, for example, periods of gravitational instability induced by tectonics, from those of tectonic quiescence and/or, reconstructing the structural and stratigraphic position of the plate interface, its re-localization in space and time and, therefore, alternating periods of tectonic accretion and erosion. As presented in Section 4.2., for example, the different nature and lithology of components (i.e., blocks and the matrix) characterizing the final mélange or broken formation product, represent significant constraints on the position and re-localization of the plate interface during subduction of an OCTZ. This is also documented by the occurrence of different combination of OPS fragments such as, for example, in the mélanges of the Bangong-Nujiang Suture in Tibet (Zeng et al., 2021), in the Shimanto and Mino belts in Japan Wakita (2015), the Franciscan Complex and the Kodiak Islands (Wakabayashi, 2012; Kusky et al., 2013). The age of mélange formation also provides important constraints to the temporal and spatial evolution of subduction complexes and orogenic belts as demonstrated, for example, by Yang et al. (2022) in the CAOB. The occurrence of different types of ophiolitic mélanges showing a rejuvenation trend from north to south allowed, in fact, to document the southward migration of the subduction-initiation in the CAOB from 1.02 Ma to Early Cambrian (Yang et al., 2022 and references therein).

To summarize, the different types of chaotic units and their internal characteristics represent significant markers of tectonic events (Fig. 9C). Hence, their correct interpretation may have significant implications for a better understanding of the tectonic evolution of subduction complexes and orogenic belts, independently on their age (from Precambrian to present days) and location.

6.2. Understanding processes of early Earth evolution and the onset of plate tectonics

Considering that mélanges represent a significant component of subduction complexes and orogenic belts, their occurrence in the Precambrian orogenic belts may provide significant constraints for a better understanding of the processes of early Earth evolution. The occurrence of mélanges may contribute, in fact, to the long-lasting debate on when plate tectonics began to operate on Earth at global scale and its difference with Phanerozoic plate tectonics (Stern, 2005, 2020; Cawood et al., 2018; Holder et al., 2019; Palin et al., 2020; Stern, 2020; Windley et al., 2021; Furnes and Dilek, 2022 for a detailed discussion). Modern episodes of plate tectonics have been attributed to Neoproterozoic Stern (2018), according to the paucity of accretionary prisms in the rock record before 0.9 Ga (Hamilton, 1998). However, several tectonic mélanges, which represent the product of active plate tectonics, have been documented in Archean terranes (Fig. 10) and interpreted as the product of accretionary prism deformation (Komiya et al., 1999; Kitajima et al., 2001; Peng et al., 2020). Notable examples occur in the Shreiber-Hemlo greenstone belt (2.75–2.70 Ga) in the Superior Province of Canada (Polat and Kerrich, 1999; Yang et al., 2019), and the Meso- to Neoarchean deformed sedimentary-volcanic sequence, including the Abitibi greenstone belt in Quebec (Mueller et al., 1996), and the Tokwe terrane in Zimbawe (Kusky, 1998). These occurrences fit well with interpretation that plate tectonics (Fig. 10) is widely considered to have started during Neoarchean (∼2.8–2.5 Ga) or Paleoproterozoic (2.5–2.3 Ga) on Earth (Cawood et al., 2006, 2018; Sizova et al., 2010; van Hunen and Moyen, 2012; Brown et al., 2020; Kusky et al., 2020). However, Eoarchean (∼3.8 Ga; Shervais, 2006; Furnes et al., 2007, 2009; de Wit et al., 2018; Furnes and Dilek, 2022) and Hadean (Harrison, 2009; Turner et al., 2014) ages have been argued for plate tectonics, although the style may have been different Foley (2018).

In this scenario, considering that the block-in-matrix fabric of mélanges shows a close relationship with the geodynamic setting of their formation and occurrence (Festa et al., 2010; 2019), their internal features (i.e., nature, composition, age, metamorphic degree of blocks and the matrix) may provide significant information on the characteristics of plate tectonics on early Earth. For example, through the comparison between Mesozoic (i.e., the McHugh mélange in Alaska), Paleozoic (i.e., the Proto-Tethyan Laohushan mélange of the Qilian Orogenic Belt), and the Neoarchean mélange that marks the suture between the Eastern Block and Central Orogenic Belt of the North China Craton, Kusky et al. (2020) document that structures, rock types, subduction zone geothermal gradients, and the history of the forearc mélanges of the Central Orogenic Belt are remarkably similar, except for the absence of blueschists and biogenic cherts. This allowed to interpret that convergent margin processes have remained similar for the past 2.5 Ga, and that plate tectonics was existent on Earth at least by the end of the Archean Eon (Kusky et al., 2020).

Geochemical evidence that oceanic crust formation through seafloor spreading have already occurred in Paleoarchean to Eoarchean time (Furnes and Dilek, 2022), as well as the discussion on the Archean tectonics and ophiolite types in general (Dilek and Polat, 2008; Dilek and Furnes, 2011, 2014), could be further supported and investigated by looking for the occurrence of chaotic units, which show a different block-in-matrix fabric and composition with respect to those observed in Neoarchean to Phanerozoic convergent settings. It is important to outline, in fact, that the block-in-matrix fabric of chaotic units do not record only subduction-accretionary and convergent processes but all active processes, which operated in different geodynamic settings that formed and developed during the Earth evolution (e.g., passive and active margins settings, seafloor spreading, strike-slip and transform settings, etc., Festa et al., 2010), independently on the age and location. Discovering and redefining different types of mélanges, chaotic units, and particularly polygenetic mélanges, may provide, for example, significant constraints to better understand different stages of Early Earth evolution through the recognition and definition of the record, nature, and evolution of different types of micro-plates (see Li et al., 2018 for details on microplate tectonics) that are now embedded in patches in the interior of "large plates" and orogens. As micro-plates (or micro-blocks) are sometimes the precursors of large plates (Li et al., 2018), their potential association with mélanges and chaotic units may thus record the traces of complete cycles of plate tectonic evolution, ranging from about 200 Myr of a Wilson cycle to more than 700 Myr of a supercontinent cycle.

Discovering Archean mélanges and understanding the nature and composition of their internal fabric, processes, and mechanisms of formation (tectonic, sedimentary or diapiric), in comparison with "modern" ones, may have significant implications for a better understanding of the time and mode of initiation of the plate tectonics regime with respect to episodes of a single-lid tectonics. This may also have significant implications for better understanding the evolution of rocky planets in our solar system (Stern, 2020; Palin et al., 2020 and references therein).

6.3. Influence of mélanges in controlling the seismic behavior of the shallow-level modern subduction plate interface

During last decades an increasing number of studies outline the role of mélanges in controlling the seismic behavior of plate interfaces ($T < 400$ °C) at the down-dip of the seismogenic zone in subduction complexes. The heterogenous block-in-matrix fabric and compositions of mélanges has been suggested as one of the fac-

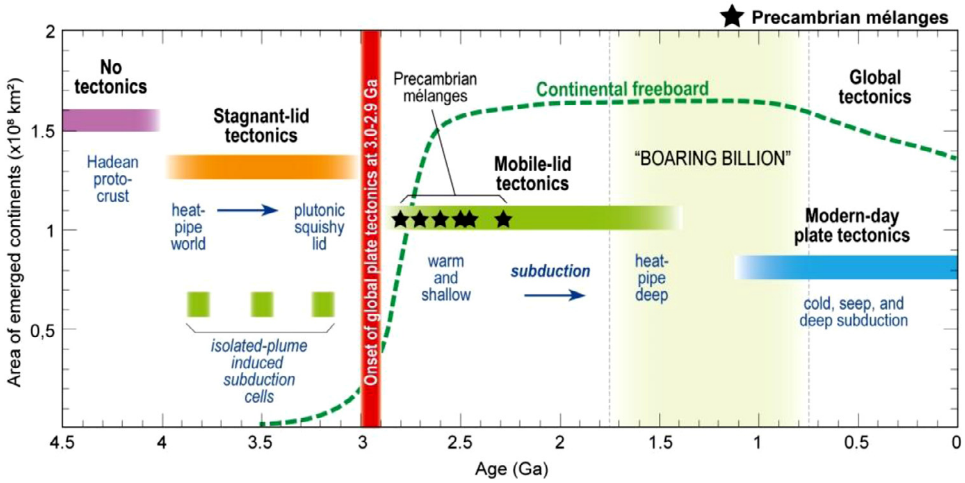


Fig. 10. Diagram showing the first occurrence of mélanges (black stars) in the global geodynamics, and their relationship with the onset of global plate tectonics (modified from Palin et al., 2020). See text for details on Precambrian mélanges.

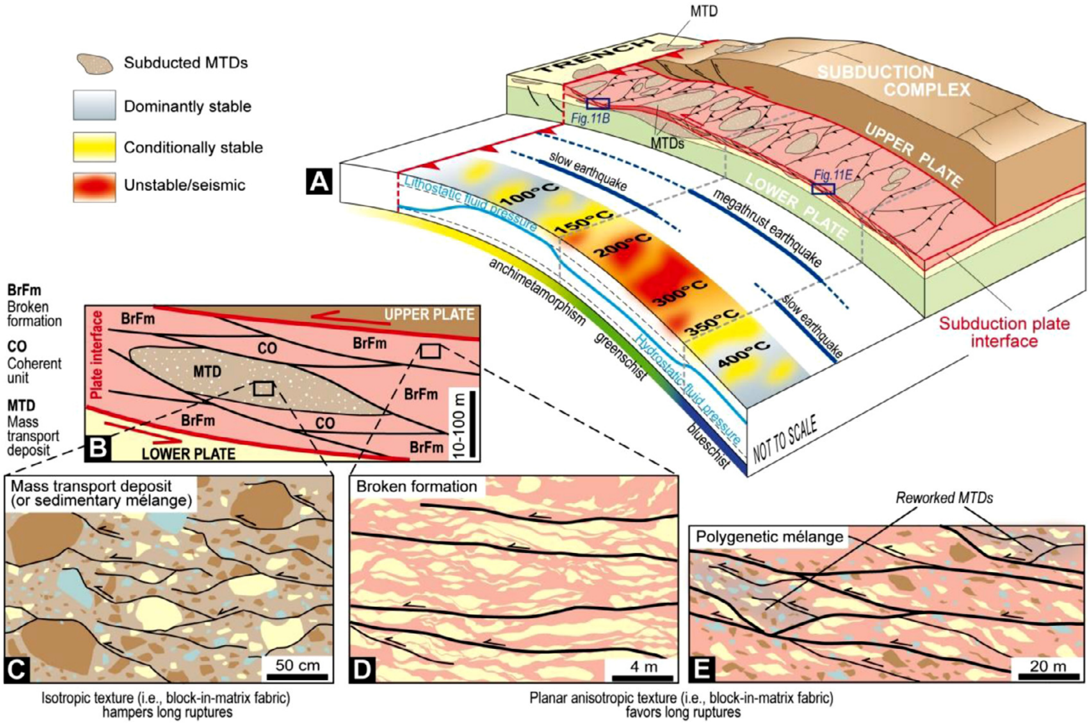


Fig. 11. (**A**) Schematic view of a subduction plate interface showing probable relationships between the distribution of subducted chaotic units (broken formation, mass transport deposits-MTDs, and polygenetic mélanges) and seismic behavior (modified from Festa et al., 2018). Distribution of seismic behavior and of the fluid pressure curve modified from Obara and Kato (2016) and Saffer and Tobin (2011), Fagereng et al. (2018), Oncken et al. (2021), respectively. (**B**-**E**) Conceptual model showing the internal organization of the subduction plate interface at (**B**) shallow (c. T 60–70 °C, corresponding to about 2–3 km depth) and (**E**) intermediate (c. T 250 °C, corresponding to about 10–15 km depth) structural levels. At shallow structural levels (**B**), the primary degree of anisotropy of the block-in-matrix texture of the different types of units (broken formations, and mass transport deposits) is preserved, strongly controlling the length of seismic rupture, which is expected longer within the planar anisotropic texture of broken formations (**D**) with respect to the case of the isotropic texture of mass transport deposits (**C**). At intermediate depths (**E**), tectonic processes form a polygenetic mélange with planar anisotropic (block-in-matrix) texture (i.e., the tectonic reworking and mixing of the primary fabric of mass transport deposits, broken formations, and coherent units), favoring propagation of long ruptures. Note that part of brittle to ductile rupture (and/or boudinage), which is recorded in the broken formations, already occurs at very shallow structural levels (compare **D** and **E**).

tors that diminish the effectiveness of seismic rupture, favoring the occurrence of slow earthquakes, compared to regular earthquakes (Fagereng and Sibson, 2010; Fagereng et al., 2018; Hayman and Lavier, 2014; Bürgmann, 2018; Ujiie et al., 2018; Kotowski and Behr, 2019; Phillips et al., 2020; Behr and Bürgmann, 2021). As the accelerated creep associated to slow earthquakes potentially can initiate or trigger some huge earthquakes (Mw ≥ 8,5) within the same seismogenic zone (Kato et al., 2012; Meng et al., 2015; Obara and Kato, 2016), they obviously deserve significant attentions for the understanding of earthquakes in active subduction zones. Understanding the origin of mélanges is commonly out of the aim of those case studies that focus on the rheological implication of the occurrence of a block- in-matrix fabric, as the nature (i.e., exotic or native) of blocks is considered not-relevant (note that in those studies the term mélange is used in a broad sense including both broken formation and/or mélanges). On this issue, our observations clearly show that:

(1) The different textural characteristics of different mélanges/broken formations could have an impact on the rheology of the whole system (Fig. 11). Different types of inherited heterogeneous material (e.g., OPS- and OCTZ-derived broken formations, sedimentary and diapiric mélanges, etc.) with different states of consolidation, are expected to deform differently in relation to their composition, rheological and mechanical contrasts between blocks and the matrix and fluid content, shifting the transition from macroscopically ductile to brittle deformation (Maltman, 1994; Ogawa, 2019). For example, seismic ruptures within a broken formation with a block-in-matrix fabric defining a planar anisotropy (Fig. 11D), is expected to propagate more easily with respect to through a heterogeneous mass transport deposit (i.e., sedimentary mélange or olistostrome), which is internally characterized by an isotropic texture (Fig. 11C). The latter, however, may gradually change to a planar anisotropy with the increasing of shear deformation with depth (i.e., polygenetic mélange, Fig. 11E), up to shows a degree of anisotropy well comparable with that one of tectonic broken formations. This change is documented to occur at about T>150° (> 5 km of vertical burial) for heterogeneous mass transport deposits subducted within the shear zone of the plate interface (Festa et al., 2018).

(2) it became relevant to investigate if the block-in-matrix arrangement is inherited from shallow process or is actively forming at the downdip limit of the seismogenic zone as, for instance, it implies different inferences on the competence contrast between the matrix and the blocks. For example, if a significant part of brittle to ductile ruptures and/or the boudinage, which are recorded by the block-in-matrix arrangement, already occur at very shallow structural levels, downdip the competence contrast could be reduced or even inverted, influencing the rupture.

The occurrence of different types of chaotic units may thus potentially explain the different types of slow earthquakes (Fig. 11A) detected geophysically at the subduction plate interface (i.e., within 2–4 km of the seafloor; Wallace et al., 2016, 2019; Araki et al., 2017; Barnes et al., 2020). Therefore, evidence that a large part of chaotic units forms at shallow structural levels because of subduction of heterogeneities, such as in the case of subduction of OPS- and OCTZ- related structural inheritances and heterogeneous mass transport deposits, must be accurately investigated taking into considerations constraints provided in this paper. The latter ones are fundamental to better understand the role of mélanges and chaotic units in controlling the seismic behavior, with potential significant societal impacts.

7. Concluding remarks

Our overview and synthesis of many examples of chaotic units that we studied during the last tens of years in convergent margins around the world, pointed out that (i) mixing mechanisms and processes forming mélanges are not exclusive of intermediate to deep depths (T > 250 °C, corresponding to depth >10–15 km), and (ii) the internal architecture of exhumed subduction complexes may be highly heterogeneous already at shallow structural levels (T < 250 °C, corresponding to depth <10–15 km). The larger part of chaotic units (c. 64.7%) already forms at shallow structural levels (Fig. 2D) while “intermediate to deep” mélanges represent, in most of the cases, the tectonic reworking (i.e., polygenetic mélanges) of the block-in-matrix fabric of those different types of chaotic units (i.e., >21.5% of broken formations, c. 20% of sedimentary mélanges, >6.7% of diapiric mélanges, and c. 2.7% of tectonic mélanges) formed at shallower depths. Polygenetic mélanges represent, in fact, the most common (c. 28%) type of mélange observed in exhumed subduction complexes and metamorphic orogenic belts (Fig. 2B).

Considering that different types of chaotic units represent significant markers of active tectonic events and climate changes (Fig. 9C), and the recurrence time for their formation/emplacement may provide excellent constraints for the frequency of those events during the evolution of convergent margins (Festa et al., 2016), the distinction of the processes of chaotic unit formation (tectonic, sedimentary, diapiric or their superposition) and the structural level of their occurrence is thus essential for a better understanding of the tectonic evolution of subduction complexes and metamorphic orogenic belts, independently of their age (from Precambrian to present days) and location. Among several possible examples, our overview documented that the comparison between the nature, composition, and the block-in-matrix arrangement of Precambrian and Phanerozoic chaotic units may provide significant implications for a better understanding of the time and mode of initiation of the plate and/or micro-plate (Li et al., 2018) tectonics regime with respect to episodes of a single-lid tectonics. This also potentially allows to better understand the evolution of rocky planets in our Solar system. Confusing broken formations and mélanges, which differ from each other by the internal block-in-matrix fabric and composition of blocks (i.e., “native” vs. “exotic”), means also to misread chaotic units with different internal arrangement, rheology, degree of anisotropy, and thus with different mechanical behaviors. This is expected to have significant implications on a better understanding of the seismic behavior of subduction complexes as the occurrence of different types of chaotic units may contribute to the diverse seismic behavior (Fig. 11A) detected geophysically at the subduction plate interface (Wallace et al., 2016, 2019; Araki et al., 2017; Barnes et al., 2020). On this issue, the evidence that a large part of chaotic units forms at shallow structural levels must be accurately investigated, representing an excellent opportunity to better understand the role of mélanges and chaotic units in controlling the seismic behavior also at shallow depth, with potential significant societal impacts.

In conclusion, although several papers on mélange topics have been published during the last 100 years, modern and detailed observations on chaotic units (mélanges and broken formations) are fundamental in the challenge to understanding the tectonic evolution of subduction complexes and orogenic belts, and related implications. On this issue, a correct use of mélange terminology is not a mere terminological debate but has a primary significance in distinguishing very different chaotic products, with different rheological and mechanical properties, and formed by different processes, whose distinction may provide very useful and significant constraints for the improving of our knowledge on the tectonic evolution of subduction complexes and orogenic belts.

Author contributions

All authors contributed to conceptualization and design of the study and writing text and preparing Figures. Andrea Festa coordinated the final editing and submission of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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