Chapter 52

Sedimentary Mélanges and Fossil Mass-Transport Complexes: A Key for Better Understanding Submarine Mass Movements?

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Abstract Mélanges originated from sedimentary processes (sedimentary mélanges) and olistostromes are frequently present in mountain chains worldwide. They are excellent fossil examples of mass-transport complexes (MTC), often cropping out in well-preserved and laterally continuous exposures. In this article we will show the results of the integrated study of fossil MTCs, including sedimentary mélanges/olistostromes, with a focus on the Apennines of Italy. Fossil MTCs, especially the basin-wide ones, are composite and multi-event units involving the entire spectra of mass-transport processes. The down-slope motion of these bodies is enabled by the relative movement of discrete masses, with progressive stratal disruption of rocks/sediment involved and flow transformation. Three kinds of MTC are here

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distinguished, in which the movements are enabled by (1) shear-dominated viscous flows within a muddy matrix, (2) mud-silt-sandy matrix sustained by fluid overpressure, (3) concentrated shear zones/surfaces with advection of grains and fluid (overpressured basal carpets). These MTC types may represent end-members of a continuum of products and correspond to different kinematics of transport and emplacement and to different relationship with the substratum. These observations should result in a better knowledge of mass-transport processes and bodies, in relation with the basin floor geometries.

Keywords Submarine landslides • Mass-transport complexes • Olistostromes • Mélanges

52.1 Introduction

The adjective chaotic has been often used to describe mass transport complexes (MTC, see Weimer and Shipp 2004) occurring on the seafloor and within the sedimentary record of continental margins, or exposed in mountain ranges world-wide. This definition takes into account the disruption and amalgamation of strata observed in the field or the chaotic appearance and the transparency using geophysical methods of investigation.

Chaotic rock units defined to as mélanges in the geologic literature crop out widely in orogenic belts. These units are characterized by block-in-matrix fabric and mixing of rocks with different degree of compaction, age, and provenance. Although an exclusive origin from tangential tectonic processes is commonly aprioristically assumed, mélanges can also originate from en-mass sedimentary processes (sedimentary mélanges) and mud/shale diapirism (Cowan 1985; Festa et al. 2010).

Olistostromes (Flores 1955) are sedimentary bodies showing highly disrupted strata up to block-in-matrix fabric and mixing of rocks of different ages and regional provenance. They fall, therefore, within the general definition of mélanges (Silver and Beutner 1980). Both terms have thus been widely used.

Sedimentary mélanges/olistostromes are MTCs usually showing comparable size with the largest modern, submarine landslides (Camerlenghi and Pini 2009). Surprisingly, they have been poorly studied from a sedimentological point of view. Studies in the literature aimed to distinguish these bodies from other mélanges, or to define more or less cyclic tectonic-stratigraphic events (Scherba 1987; Delteil et al. 2006).

This article illustrates the results of the integrated study of fossil MTCs, including sedimentary mélanges/olistostromes, with a focus on the Apennines of Italy. We will also address the main problems concerning the comparison between fossil (exposed on-land) and modern (in marine geophysical records) MTCs.

52.2 Types of MTC

Fossil MTCs, especially the large-scale and basin-wide ones, are complex units involving the entire spectrum of mass transport processes (Lucente and Pini 2003). Moreover, they often comprise discrete sub-units, defined on the base of composition, provenance, structures, and sense of movement. These sub-units can be either single mass transport events, pulses, or discrete masses moving differentially in the same event. Figures 52.1–52.5 represent the three different structural associations recognized.

Type 1 MTCs refer to mud-rich deposits characterized by the cohesive behavior of a viscous matrix. The distinctive fabric consist of centimeter- to meter-sized lithic blocks (limestones/marls, sandstones/siltstones or ophiolites) randomly dispersed in a matrix (Fig. 52.1a). The matrix is prevailingly of clays/shales and characterized by millimeter to sub-millimeter clasts of various composition, including indurate clays (brecciated or clastic matrix; Swarbick and Naylor 1980; Pini 1999) (Fig. 52.1b, e). This kind of fabric also acts as a binder, surrounding and sustaining bed packages of tens of meters up to kilometers in size (floaters, out-sized blocks)

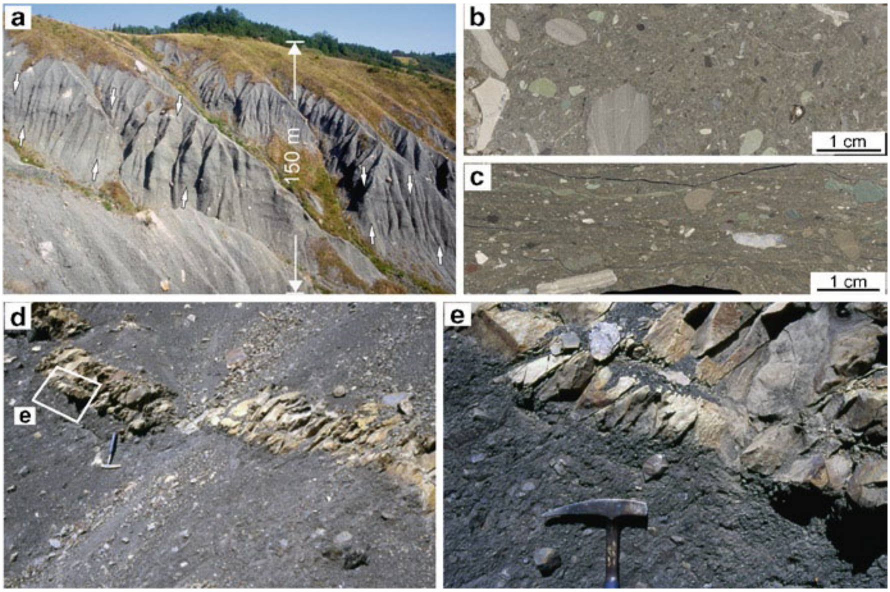

Fig. 52.1 Examples of Type 1 MTCs: (**a**) Olistostrome in the Oligocene-Miocene Epiligurian succession, Bologna area, northern Apennines. *Arrows* point out zones of matrix deformations (*shear zones*) (**b**) Brecciated matrix (**c**) Brecciated matrix deformed in shear zones (**d**) and (**e**) MTC passing upward to deposits by co-genetic turbulent flow. Segavecchia olistostrome, northern Apennines main divide

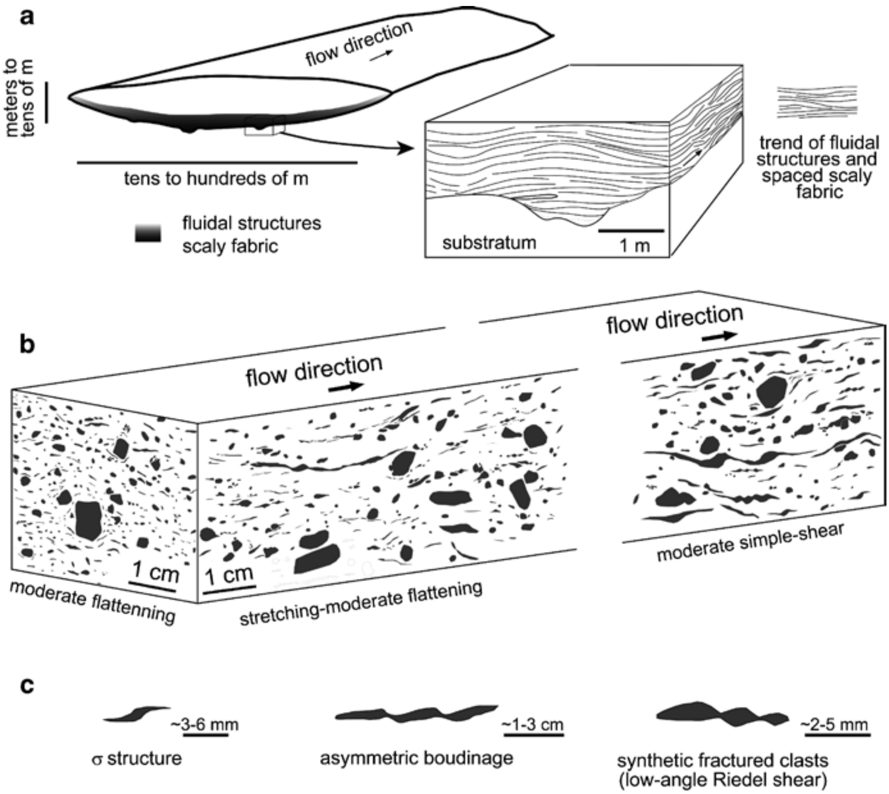

Fig. 52.2 Distribution, general attitude (**a**) and internal structures of the matrix (**b**) into the shear zones in Type 1 MTCs (**c**) deformation of clasts related to simple shear

(Marroni and Pandolfi 2001; Burg et al. 2008). Floaters surrounded by matrix can also predominate (Lucente and Pini 2003).

The block-in-matrix fabric derives from the further disruption and disaggregation of already deformed, mud-dominated, block-in-matrix units (broken formations/mélanges). The matrix derives from remolding of already mixed and deformed (scaly) clays. Floaters are the remnants of the protolith, which maintain the original fabric. Inverse grading of the largest blocks is observable for each individual flow. Meter to tens of meter-scale blocks, prevailingly composed of rocks from the substratum, are also concentrated at the base of MTCs in confined basins (Pini 1999).

The base of the bodies is characterized by spaced scaly fabric and by banding and fluidal structures of the matrix at meter to centimeter-scale at a low angle to the basal contact (Fig. 52.2a). Poorly consolidated clasts display extreme elongation in the direction of flow (Fig. 52.1c) together with a moderate flattening in other directions, and simple shear-related structures (Fig. 52.2b, c). These deformed zones accommodate the flow; simple shear may develop in reason of the increased coupling with the substratum.

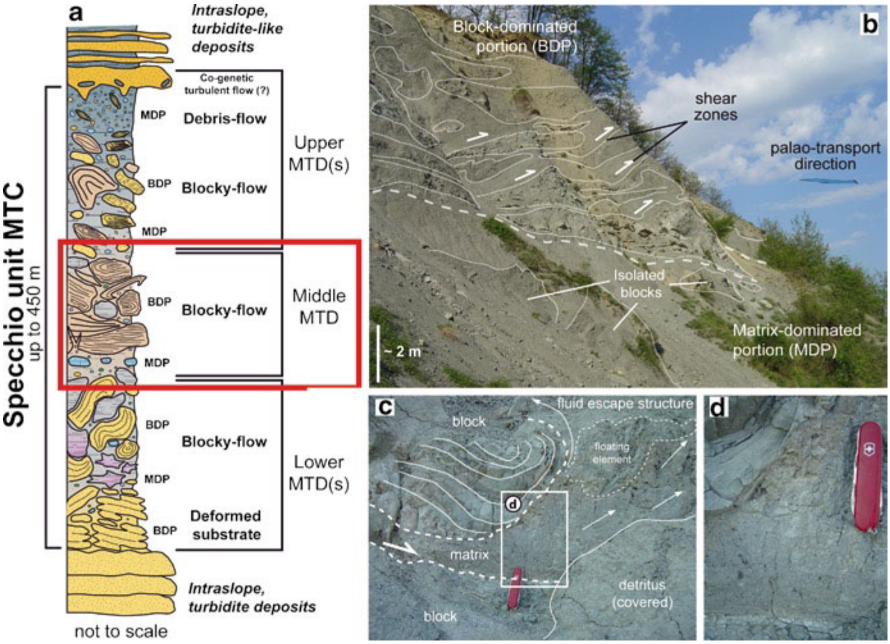

Fig. 52.3 Type 2 MTCs: (**a**) Conceptual stratigraphic log of the Specchio unit composed of at least three individual mass transport deposits (*MTDs*). Early Oligocene Epiligurian succession, northern Apennines. *MDP*=matrix-dominated portions, *BDP*=block-dominated portions (**b**) Outcrop appearance of the middle MTD (*red box* in *a*) (**c**) Picture of a *matrix-underlined* shear zone originating a fluid escape/injection structure. Note the soft sediment folding at the structure margin and the occurrence of hydro-plastically deformed clast floating in the matrix (**d**) Typical outcrop appearance of the liquefied (overpressured) matrix (location in *c*) (From Ogata 2010, adapted)

Such a kind of structure is also evident inside thick olistostromes, corresponding with zones of bock iso-orientation and matrix banding (Pini 1999; Burg et al. 2008) (Fig. 52.1a). These zones may represent the base of individual depositional events (Swarbick and Naylor 1980), or shear zones accommodating internal deformation in a single large-scale event (up to 400 m in thickness).

Type 2 MTCs are characterized by a clastic matrix represented by an unsorted, liquefied mixture of different grain-size populations dispersed within a fine-grained lithology (see Callot et al. 2008; Ogata 2010) (Fig. 52.3), resembling the typical characteristics of an hyper-concentrated suspension (sensu Mutti 1992). These types of MTC generate from a complex flow that is a debris-flow carrying out-size coherent blocks (meters to hundreds of meters across) usually arranged in isolated slump-like folds (blocky-flow deposits, Mutti et al. 2006) (Fig. 52.3b); generally speaking, their internal arrangement resembles a bipartite body, with a block-dominated portion overlying a matrix-dominated one (Ogata 2010) (Fig. 52.3a).

In outcrop, the usual appearance of this matrix is that of sandy/pebbly mudstone/siltstone (Fig. 52.3d) and it can be either diffused within the slide mass and/or concentrated in the basal portion and along the boundaries of discrete internal

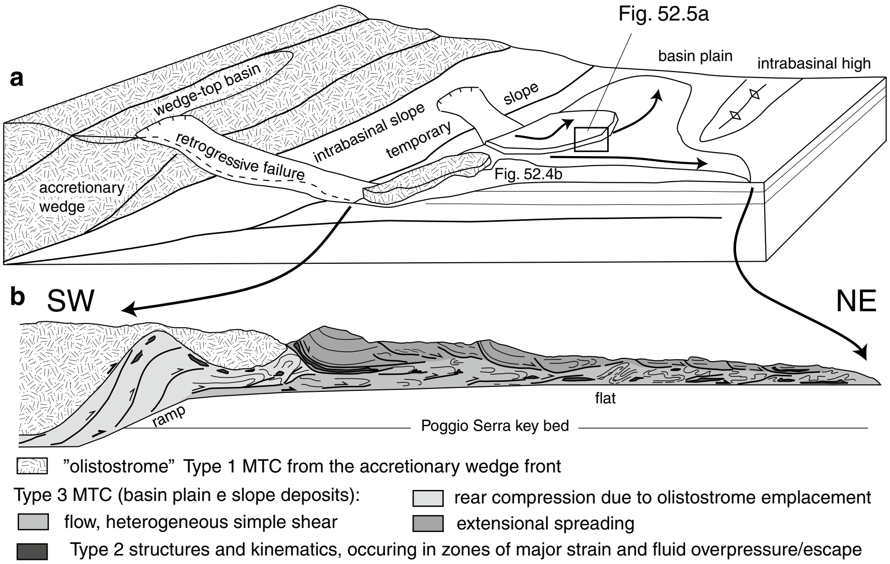

Fig. 52.4 Interpretative paleogeographic block diagram (**a**) and idealized section (**b**) of the Casaglia-Monte della Colonna MTC, Marnoso-arenacea Formation, middle Miocene foredeep of northern Apennines (*b* from Lucente and Pini 2003, modified, reprinted by permission of the American Journal of Science)

components (slide blocks). In particular, this matrix is commonly arranged within heterogeneous shear zones separating slide blocks, and it forms clastic injections (sedimentary dykes), which intrude discrete slide elements (Fig. 52.3c).

The matrix originates from the stratal disruption of poor- to un-lithified sediments, leading to a complete disaggregation and mixing of the involved lithologies, during the down-slope motion of the slide mass. Evidence of liquification (including fluidization, cyclic loading- and shear-related liquefaction; Allen 1982) highlights the occurrence of very rapid deformation acting in undrained conditions. The component sedimentary material primarily derives from the incorporation (erosion) of sediments covering the overridden seafloor and from the partial disaggregation of the blocks carried by the slide. The loose sediments of the uppermost part of the failed sedimentary succession may play a significant role as well.

Type 3 are slump/slide-like MTCs developed in sandy sediments (foredeep turbidites), in which the transport and emplacement is allowed by differential movement of individual bed-packages of different dimensions (Figs. 52.4b, 52.5a). The relative movement occurs along shear zones, represented by millimeters-thick surfaces characterized by "films" of silt and centimeters- to tens of centimeters-thick deformational bands in sandstones (Fig. 52.5c, d), associated to transport and rotation of clasts (occurring both independently and with grain breakage) and fluid elutriation (Dykstra 2005). Relatively wide (some m-thick) zones characterized by isoclinal folding, boudinage, liquification of sandy sediments and disaggregation of pelitic beds, develop less frequently (Lucente and Pini 2003), corresponding to localized Type 2 structures and behavior. The bed packages are characterized by folds, boudinage, extensional and contractional duplexes, and mesoscale thrusts.

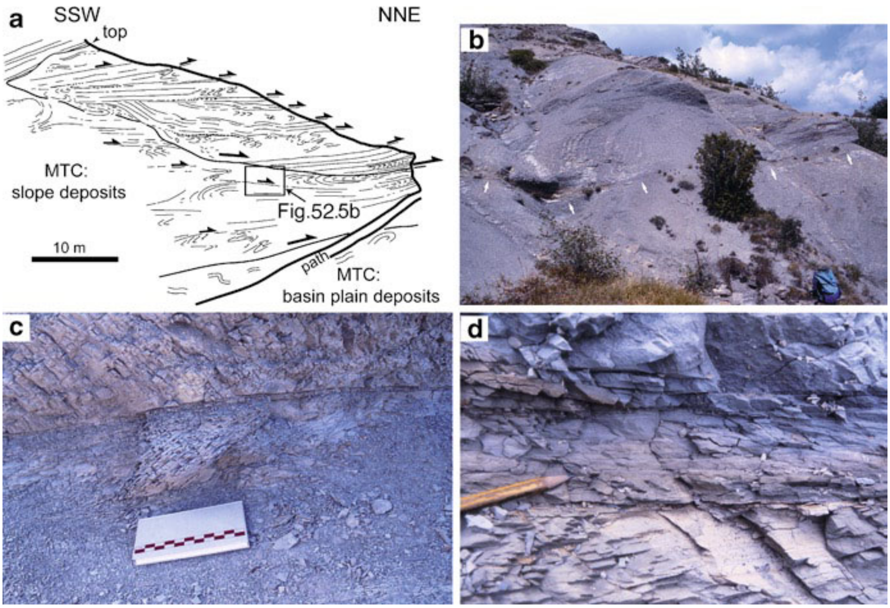

Fig. 52.5 Casaglia-Monte della Colonna Type 3 MTC (**a**) Sketch of the Campanara outcrop showing the main internal subdivisions (bed packages) and their reconstructed, relative movements. Location of the outcrop is in Fig. 52.4a (From Lucente and Pini 2003, modified, reprinted by permission of the American Journal of Science) (**b**), (**c**) and (**d**) Outcrop appearance of a belt of shear surfaces (highlighted by *white arrows* in *c*) at the base of a bed package

A decrease in dimensions of bed packages and an increase of stratal disruption is observable down-flow. The larger bed packages at the slide top imply a high competence to the flow, and/or to their preservation related to lower conditions of strain, giving rise to a hummocky upper surface (Trincardi and Normark 1989).

52.2.1 Mechanisms of Failure, Transport-Emplacement and Coupling with the Substratum

Basin-wide MTCs in the northern Apennines are commonly composed of an intrabasinal component, giving Type 2 or 3 sub-units, and an extrabasinal, "exotic" component resulting in Type 1 sub-units. The assemblage of Type 1 and 3 occurs in deep marine settings, in the foredeep (Lucente and Pini 2003), and is related to the retrogressive failure of the basin plain, the basin margin (slope), and the front of the accretionary wedge (Fig. 52.4a). Type 1 and 3 MTCs are associated with composite bodies originating in shallow marine to coastal setting in wedge-top basins (Ogata 2010; Ogata et al. 2012), where MTCs originated by retrogressive sliding of the basin margins. The "exotic" components with Type 1 behavior were supplied by intrabasinal highs confining the "mini-basins". Retrogressive sliding, cutting back the basin margins, is therefore a recurrent character of the studied MTCs.

As far as the transport-emplacement of the bodies is concerned, the three types should correspond to different velocities of movement, while the nature of the components (i.e. age, composition and lithification degree) should be related to the stratigraphic level of the rupture surface (i.e. shallow or deep seated, sedimentological/tectonic characters of the basin and margins).

Type 1 should represent slow moving bodies, being related to "viscous" shear zones in a clay-dominated matrix. With this kind of mechanics, thick olistostrome-like MTCs could not widely expand into the basins and should be proximal deposits, close to the failure areas. The elevated thickness of this kind of MTC may, however, represent the stack of more subsequent events, and, therefore, overcome these kinematic limits. When preserved, deposits from co-genetic turbulent flows evidence the stacking of single mass-transport events (Pini et al. 2004) (Fig. 52.1d, e).

These bodies can run relatively fast and for longer distances if sustained by a basal "carpet" comprising an overpressured mixture of water and loose sediment (hydroplaning, Mohrig et al. 1998). The shear zones at the base, and inside the bodies, can represent, in this case, zones of concentrated fluid overpressure. While related fluid-escape and injection-related structures commonly occur in Type 2 MTCs, no convincing evidence of such features have been observed so far, nor have dedicated studies been systematically carried on Type 1 MTCs.

Several lines of evidence from the Type 2 MTCs testify the high mobility of the matrix, suggesting fluid overpressure conditions as the main driving process. Such features imply a high velocity of the generating event (catastrophic).

In the Type 3 MTCs overall motion is partitioned in more masses, resulting in complex movement with simple shear at the base and extensional-spreading at the top (Lucente and Pini 2003) (Fig. 52.4a). This should imply a relative lower transport/emplacement velocity with respect to Type 2 MTCs.

The substratum seems to be extensively involved: rip-up clasts are evident in small Type 1 MTCs and the large blocks at the base of the largest bodies (Pini 1999) could be, at least in part, related to erosion of the substratum. The inclusion of substratum material (both coherent or completely loose) is typical of the Type 2 bodies, which are characterized by the major transport velocity. The bulk of coupling with the substratum (erosion in sedimentologic sense) should be related to the late evolutionary stages, when the slide mass momentum is, at least in part, transferred to the overridden seafloor (e.g., deceleration and freezing, changes in the slope gradients, impacting onto intrabasinal highs).

52.3 Conclusion

Through detailed field work, we approached sedimentary mélanges and olistostromes from both sedimentological and structural points of view, restoring the "dignity" of MTCs. The three types of bodies defined here show different mechanics of emplacement and transport, which can correspond to different velocity and mobility. The type is predetermined by MTC composition, which is in turn influenced by: (1) the geometry and depositional style of pre-slide, basin margins and (2) the way the failures propagate (Fig. 52.4a). The final geometry of the MTCs and their internal features are also determined by the morphology of the depositional basin (Lucente and Pini 2003; Ogata 2010). Direct transition from a type to another is observable in some cases (Fig. 52.4b). In this framework, the three types may represent different stages of slide development, therefore defining end-members of a spectrum of processes.

Are these observations worthy for the understanding of modern MTCs and the definition and mitigation of the related hazards? The size paradox introduced by Woodcock (1979), pointing out that fossil MTCs were not comparable in size with modern ones, has been recovered through the recognition that huge chaotic units may be MTCs. From the increasing number of papers dedicated to the fossil MTCs, a substantial convergence is emerging among distribution, size and recurrence in time of modern and ancient MTCs in diverse geodynamic environments, progressively filling possible gaps (Camerlenghi and Pini 2009; Camerlenghi et al. 2010). Direct comparisons are tentatively possible when MTCs of comparable size are present in similar tectonic and sedimentological settings, such as the cases of Oligocene wedge-top basins of the northern Apennines (Ogata 2010; Ogata et al. 2012) and the Kumano basin in the Nankai forearc (Strasser et al. 2011).

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