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Meso-scale kinematic indicators in exhumed mass transport deposits: definitions and implications

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Abstract

In this study we combine observations and analytical data from large-scale (10 s-100 s of m-thick and 100 m^2-extensive), siliciclastic and carbonate MTD/MTCs belonging to the Oligocene – Miocene foredeep and wedge-top successions of the Northern Apennines and the Paleocene – Eocene Friuli basin of the northwestern Dinarides (Italy and Slovenia), to discuss the deformation processes critical to the emplacement of submarine landslides. We focus on the identification of meso-scale structures, used as diagnostic kinematic indicators of local paleo-transport directions. These structures, represented by linear-planar and complex-shaped elements such as tabular shear zones and detached slump-type folds, are the product of ductile-plastic deformation developed at relatively low-confining pressure that involves water-saturated, un- to poorly-lithified sediments, along with liquefaction/fluidization processes. Their final appearance is thus mainly controlled by the mechanical-rheological behavior of deformed sediments, and eventually by tectonic fabrics inherited from deeper structural levels of deformation. Due to this parallelism these structures have been termed and classified accordingly. They reflect strain partitioning due to differential movements within the slide mass, which is in turn controlled by the overall landslide typology. Due to the parallelism with classified tectonic structures and structural associations, we have thus redefined and classified accordingly meso-scale kinematic indicators in ancient MTD/MTCs.

1. Introduction

Geophysical imaging of modern seafloor surface and subsurface provide the gross morphology, areal extent and overall internal character of single mass transport deposits (MTDs) and composite mass transport complex (MTCs), outlining their importance in practical terms, such as offshore hydrocarbon exploration/production and coastal geohazard assessment/evaluation (see e.g. Kawamura et al., 2012). Conversely outcrop studies on exhumed "fossil" analogues, allow analyses on the internal deformation mechanisms from micro- to map- (i.e. seismic) scale (see e.g. Lucente and Pini, 2003; Alonso et al., 2006; Yamamoto et al., 2009; Ogata et al., 2012). Although scientific drilling provides crucial insights on the anatomy of modern MTD (see e.g. Strasser et al., 2011), the available data are still too punctual, and costly to provide a comprehensive source of information, especially on meso-scale structures, which record the main trace of mass transport-related deformation processes.

We here focus on the meso-scale, syn-sedimentary structures, which spatial-geometric relationships are considered to record the strain direction achieved during and/or immediately after the slide body deposition. Such structures represent important kinematic indicators that can be integrated to unravel the local paleo-transport direction and the internal deformation processes of the slide mass. In this paper we analyze some ancient, seismic-scale MTDs/MTCs analogues, exhumed in the Oligocene – Miocene foredeep and wedge-top sedimentary successions of the Northern Apennines, and the Paleocene – Eocene Friuli basin of the north-western Dinarides (fig. 1A-C; Italy and Slovenia), expanding punctual observations to a broader and more general picture. The systematic occurrence of the described features in basically all the investigated siliciclastic and carbonate examples justifies this effort.

2. Case studies

The Northern Apennines case studies are the Epiligurian Specchio unit (Ogata et al., 2012) and the Marnoso-Arenacea Formation MTDs (Lucente and Pini, 2003; Lucente, 2004). The Epiligurian Specchio unit, Rupelian in age, is a MTC composed of at least two different stacked MTDs (i.e., intra –and extra-basinal lower and upper ones, respectively), deposited in an intra-slope, wedge-top basinal system developed atop the evolving proto-Apenninic orogenic wedge. The Miocene Marnoso-Arenacea Formation MTDs are emplaced at different stratigraphic levels within the migrating Northern Apennines foredeep system. These intra-basinal units are sometimes characterized by the occurrence of extra-basinal lithologies (fig. 1D, E).

The northwestern Dinarides case studies are the Paleocene Friuli Basin MTDs (Ogata et al., 2014), which represent carbonate platform collapses from the basin margins (either from the outer foreland and the inner deformation front) into a narrow foredeep basin plain characterized by mixed siliciclastic-carbonate background sedimentation (fig. 1F, G).

3. Baseline MTD architecture and facies associations

The investigated units share comparable stratigraphy, with laterally/vertically alternating subdivisions characterized by two main specific facies associations: blocky/debris flow- and slide/slump-type (Pini et al., 2012; Ogata et al., 2012). The first implies a viscous-cohesive flow-like deformation accommodated by the yield strength of an hyper-concentrated, fine-grained matrix, whereas the second testifies a coherent, *en-masse* translation of preserved slide blocks driven by localized shearing and folding. In both cases fluid overpressure plays a crucial role as suggested by the widespread occurrence of fluidization/liquefaction-related structures. The main subdivisions are briefly described in the following, from base to top (see fig. 1B).

The subdivision 0 consists of sediments belonging to the substratum, deformed *in situ* or short-travelled, and thus not formally part of the main, far-travelled slide mass. The characterizing slide/slump-type deformation is likely due to the dynamic/static loading of the overlying slide mass during the syn-depositional and/or early post-depositional phases. Its thickness is highly variable being related to the size, type and down-slope position of the overlying MTD.

The subdivision 1 varies in thickness from few centimeters to tens of meters, characterized by a pervasive highly-sheared, matrix-dominated, blocky/debris flow-type facies association with the dominance of a fluidization/liquefaction-related fabric. This interval, which achieves most of the deformation, represents the "lubricating" layer lowering the basal friction of the major slide mass.

The subdivision 2 is the most represented in terms of vertical and lateral extension and can be further subdivided into a lower sub-unit 2a and an upper sub-unit 2b, sometimes laterally inter-fingering. The subdivision 2a is characterized by block-dominated, slide/slump-type facies associations, represented by meters- to hundreds of meters-sized bedded rafts (i.e. slide blocks), mainly of proximal/marginal origin (i.e. originally located close or within the main evacuation area), in close contact. The subdivision 2b is characterized by matrix-dominated, blocky/debris flow-type facies associations, interpreted as the product of a cohesive-viscous flow enclosing isolated slide block (1-10s meters wide) and comprising mainly distal/basinal origin (i.e. originally located in the transfer zone and incorporated into the slide mass). The relative thickness of both these sub-units generally varies from tens to hundreds of meters.

The subdivision 3 comprises a meter- to tens of meters-thick, grain- to turbulent flow-type facies with evidence of ponding/reflections, representing diluted sediment flow developed atop the moving slide mass. This subdivision is significantly thicker in the carbonate-dominated MTDs.

4. Meso-scale structures and kinematic indicators

Eight types of meso-scale structures (fig. 2A) characterize different parts of the investigated MTDs (fig. 2B), appearing unrelated to syn-kinematic fracturing and mineralization. The absence of metamorphic signature and brittle deformation supports ductile/plastic, soft-sediment deformation mechanisms rather than tectonic processes, as also confirmed by microscopic analyses highlighting independent particulate flow with minor or no grain breakage.

The striking similarities with ductile structures documented in deeper metamorphic rocks allow us to adopt the same descriptive, non-genetic terminology used in structural geology (e.g. Passcher and Throw, 2005). In geometrical terms, these structures can be treated as lines and planes, and their spatial arrangement can be used to infer the local strain, as for the classical plotting and interpretation of structural tectonic data.

Asymmetric boudinage records coupled pure/simple shear-related, layer-parallel extension of poorly-consolidated sandstone-mudstone interbeds with high rheological contrast. Along with a progressive amount of deformation, generally it consists of "pinching-and-swelling" layers to detached and aligned phacoidal/lozenge-shaped elements, whose asymmetry defines the associated stress direction. These structures may also rework sheet-shaped structures such as sedimentary dykes and matrix injectites (see below) if their elongation direction matches with the local shear stress field.

Pseudo-Sigma structures resemble the typical Sigma structures of the ductile tectonic deformation, consisting of millimeters- to meters-sized, asymmetric, sigma-shaped plastic objects deformed by shearing-related viscous flow, and thus recording directional informations. Such elements comprise cohesive lithologies, usually different from the surrounding matrix (e.g. mudstones), coming from the disaggregation of the transported and eroded bedded sediments.

As for the preceding ones, **pseudo-SC structures**, show strong morphological correspondence with the typical tectonic counterparts, comprising discrete zones (mm-to cm-thick shear bands) of high shear strain (i.e. C-surfaces) that bound systematic, pervasive, sigmoidal foliation planes (i.e. S-surfaces). These surfaces are represented by disaggregation-, deformation- and compaction-bands.

Intrafolial folds, centimeters- to meters-sized, are observed to internally deform the layered intervals (i.e. laminae, beds), with the main reference surfaces being traceable laterally into unfolded parts. Typical soft sediment deformation-related thickening of hinge zones is usual observed, showing a sheath-type geometry in three-dimensions. Since these overturned folds commonly form to adsorb the slip related to the upward propagation of a blind and flat-ramp shear fault, an overall fault-propagation fold mechanism is inferred.

Ductile shear zones, low-angled, ranging in thickness from millimeters to meters, with lengths from centimeters to tens of meters are observed throughout the entire slide body. Due to the general absence of geometric references, displacements are usually difficult to resolve, although they seem to increase according to their size. As for the classic tectonic fault architecture, damage zones roughly symmetrical to a core zone accommodating the largest displacement characterize these structures, recording the transition from relatively undeformed to completely disrupted sediments (i.e. matrix) is achieved. The rate and amount of accommodated deformation appear to be proportional to the relative matrix abundance, which reflects the degree of mechanically-induced lithological mixing. No clear slip surfaces are observed in the core zones, and deformation seems distributed through its entire thickness, with the local development of disaggregation-deformation-compaction bands, sometimes arranged in swarms. On the other hand, damage zones show plastically deformed lithologies where the original sedimentary features (e.g. layering) are still partly recognizable. The relative movement is due to the evolutionary phase, type of mass transport process, and lateral/vertical position within the slide mass, with generalized normal faulting in the earlier evolutionary phases and in the upper/up-slope parts, and thrusting in the later phases and the lower/down-slope parts. Mutual reworking and deformation (e.g re-folding, bending) of these shear zones are commonly observed and interpreted as related to syn- and post-emplacement phases.

Pipe- (i.e. linear) and sheet-, and wedge-shaped (i.e. planar) **cuspidate injections** of matrix are observed in different positions within the slide mass, ranging in thickness from millimeters to meters, and in length from centimeters to tens of meters. They are diagnostic of an original over-pressurized, liquefied/fluidized state of the sedimentary matrix, and thus able to actively penetrate slide blocks via hydrofracturing-type processes and/or passively flow into the low-pressure zone created by their progressive deformation. Such cuspidate injections are developed in randomly-distributed, pervasive, web-like systems or systematically arranged along the bounding surfaces between matrix-rich and coherent lithologies (e.g. blocks' margins, basal contact). In this latter case they provide directional information on the shear sense and the relative movements of the overpressured matrix flow.

Duplex-type structures, centimeter to tens of meters-sized, are made up by the localized imbrication of isolated blocks along flat-ramp to sigmoidal shear surfaces which all tie together, and are bounded above and below by major shear surfaces merging laterally to a single one. Isolated blocks constituting the duplex-type structure belongs from a multilayer, progressively stacked and imbricated to accommodate the shortening of the hangingwall, causing consequent formation of roughly symmetrical folds.

Rootless folds, in contrast to intrafolial ones described above, appear as completely detached, isolated slump-type fold hinges dispersed within a fine-grained matrix. The three-dimensional shape of these structures usually resemble strongly asymmetric sheath folds, typically isoclinal, with marked thickening of the hinge zone, and characterized by sedimentary matrix injections along the outer-arc zones, limbs and into the cores. Axial planes, usually low-angled with dominant up-slope dips, become locally steeper toward the inferred margins of the slide mass, reflecting structural confinement effects. These structures, along with the intrafolial counterparts, are important kinematic indicators for the interpretation of paleo-transport directions and several methods have been proposed in the inherent literature to analyze the related structural data (e.g. Lucente and Pini, 2003; Ogata et al., 2014).

5. Discussion and conclusions

Mixed pure- and simple-shear deformation mechanisms due to the coupled, cyclic action of the dynamic/static loading and the differential movements of the slide mass and its internal components produce a variety of asymmetrical structures ranging from the hand specimen- to the outcrop-scale (fig. 2A). Due to their shape, spatial arrangement and geometric relationships such structures can be used as standalone kinematic indicators to record the local differential movements between the internal slide parts, or in combination for a robust interpretation of the general paleo-transport directions (fig. 2B). These structures, specifically distributed within the slide body, are interpreted as products of high-rated strain, soft sediment deformation developed at low confining pressure (i.e. superficial conditions) involving undrained, water-saturated, poorly- to un-consolidated sediment, both failed and eroded from the overridden seafloor. These factors, combined with the high strain partitioning, favor localized fluid over-pressure conditions, with consequent fluidization/liquefaction phenomena. The identification of these structures, and integrated outcrop analogue studies in general, allow the correct interpretation of the general and local slide kinematics, bridging the gap between the small-scale, punctual datasets provided drill cores/borehole logging and large-scale, 2D/3D geophysical imaging.

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Figure Captions

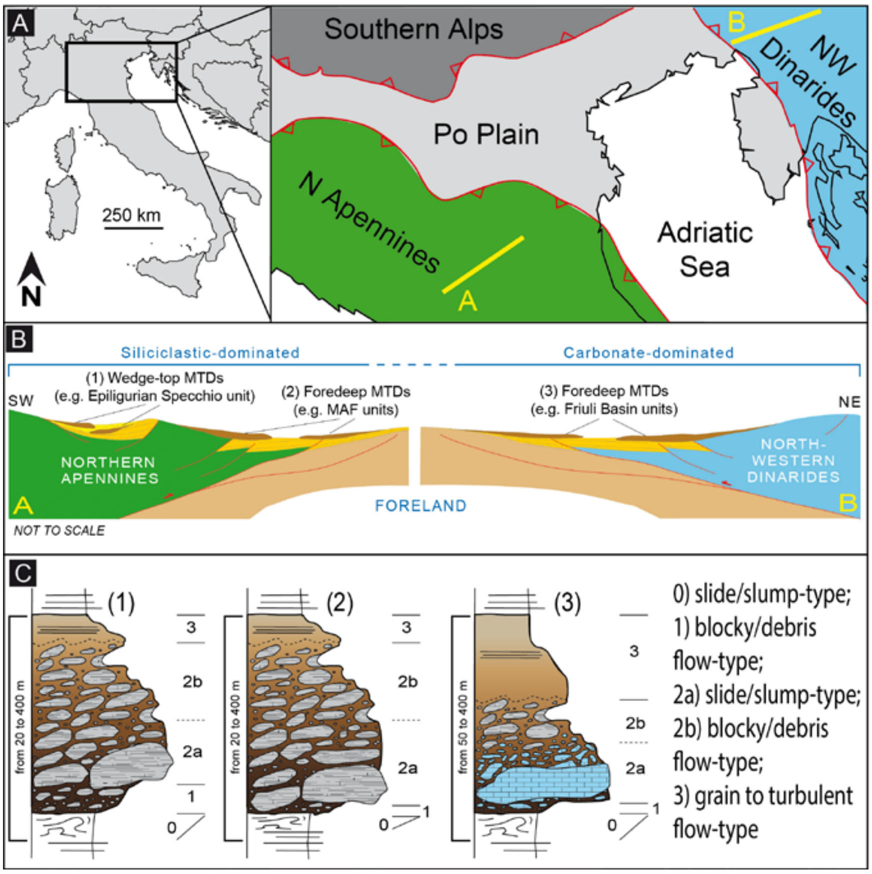

Figure 1. A. Simplified map showing the location of schematic cross sections presented in C, reconstructed for the Northern Apennines and northwestern Dinarides orogenic systems. B. Conceptual stratigraphic logs (not to scale) summarizing the internal subdivisions and characterizing facies associations of the investigated MTDs (see text for discussion). C. Schematic cross sections representing the inferred general physiographic setting of the investigated MTDs during the Cenozoic.

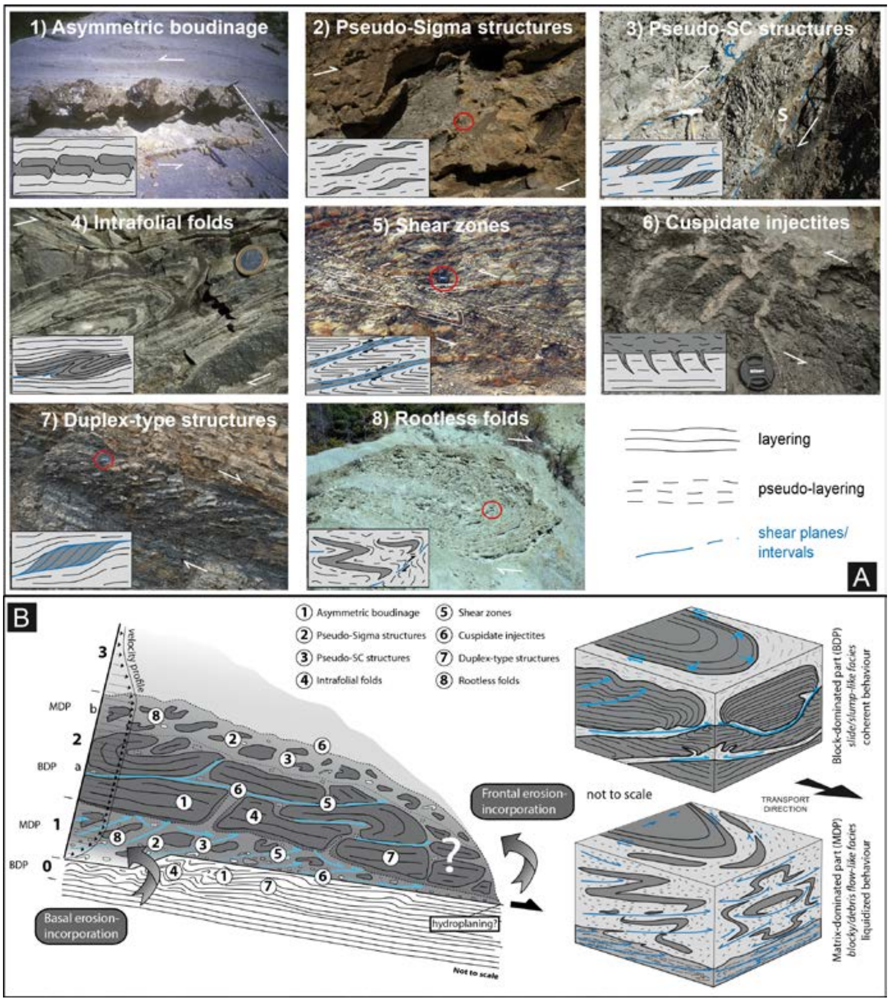

Figure 2. A. Summary of the structures discussed in this work. For a detailed description see Section 4 (modified from Ogata et al., 2014). B. Conceptual representation of an evolving slide body with identification and labelling of the main internal subdivisions, facies associations and mesoscale structures, and their typical distribution in relation to the main transport direction. Inferred processes are also highlighted (after Ogata et al., 2012; 2014).