MASS TRANSPORT-RELATED STRATAL DISRUPTION AND SEDIMENTARY PRODUCTS

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1. INTRODUCTION

1.1 MTDs and MTCs from an outcrop perspective

The terms Mass Transport Deposit (MTD) and Complex (MTC), which are seismo-stratigraphic definitions originally used for divergent margin settings (Weimer, 1989), have been recently used to identify ancient submarine landslide deposits. These units are commonly developed at the seismic scale, and, although modern marine geology highlighted their general morphology and areal extent, several problems as those regarding processes evolution and mass transport mechanics, are still poorly known. Outcrop-scale analyses carried on ancient MTDs revealed the common occurence of a unsorted and strongly mixed matrix, thought to be produced by high degree of stratal disruption involving un- to poorly-lithified sediments. With MTD here we identify one-event units, while MTC is used to define a close association of MTDs.

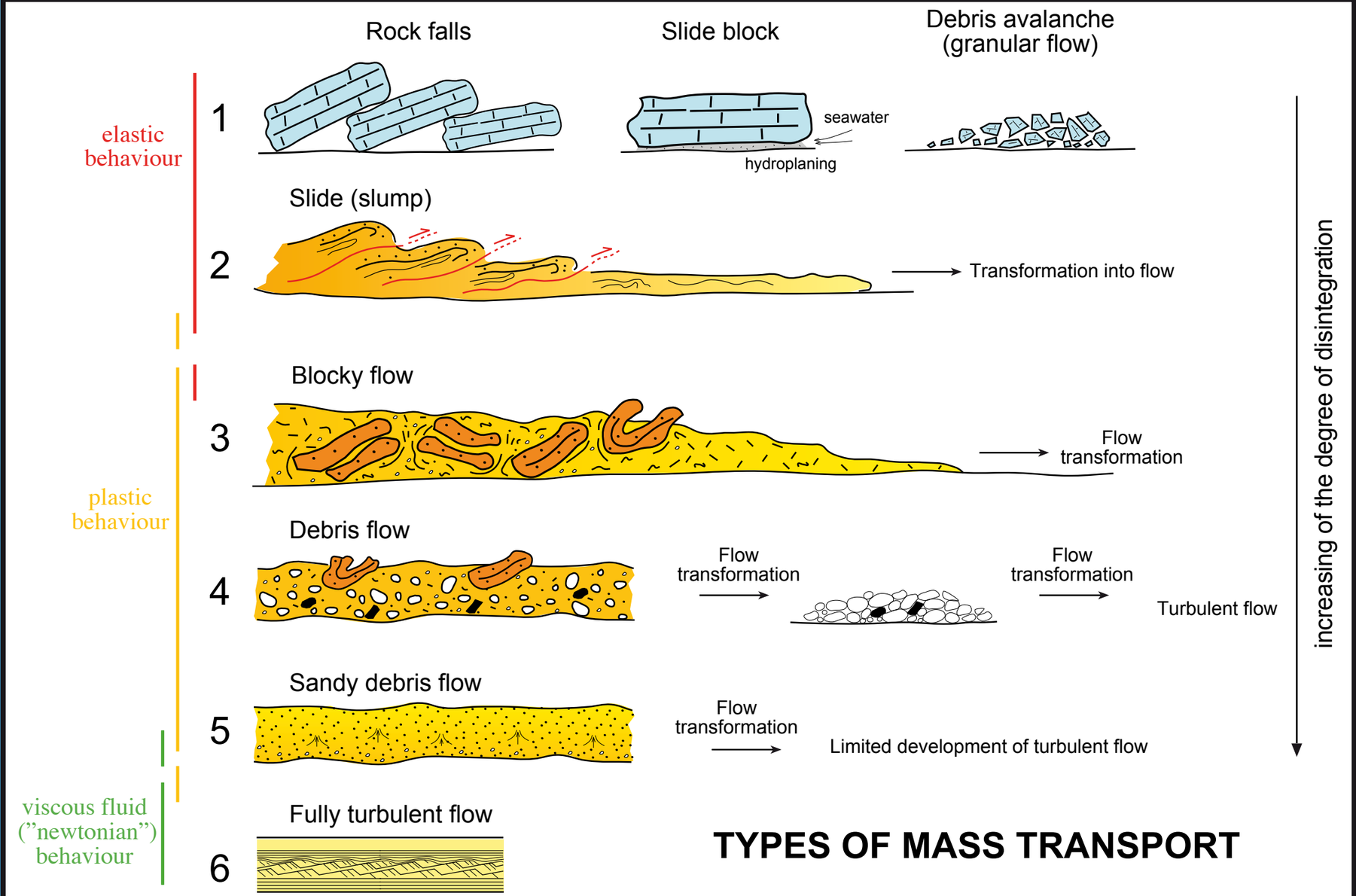


Fig. 1 - Dynamic classification of mass transport deposits which takes into account genetic and evolutionary relationships between generating processes. Block falls and turbidity currents are intended to represent the end-members of such broad spectrum of processes. Particularly, it is here proposed the new category of blocky-flow deposits, which are similar to debris-flow ones except for carrying out over-sized slide blocks, and possibly representing the junction between slumps and debris-flow deposits. From Mutti, Carminatti *et al.*, unpublished data, presented at Houston A.A.P.G. Meeting 2006.

Fig. 2 - Photos showing the matrix appearance from the outcrop- to the microscopic scale (Hammer and one Euro coin for scale). (Specchio Unit, R2/c sub-unit, Mt. Roccone section, Northern Apennines, Italy)

1.2 Matrix definition

The term "matrix" is intended here to define the relatively fine-grained lithology of a mass transport deposit, which envelopes, injects and in most cases, sustains discrete slide elements ranging from km-scale slabs to mm-scale particles. The matrix presents a scale-invariant "block-in-matrix" appearance from the microscopic-scale to the outcrop-scale (fig. 2), and possibly up to the seismic-scale. As general rule, the matrix is always finer than the sustained particle.

2. CASE STUDIES

2.1 Northern Apennines case study

The Specchio Unit is a MTC hosted in the Eocene-Oligocene Ranzano Unit of the Epiligurian succession. The Ranzano Unit is a syn-orogenic coarse-grained turbiditic succession, filling intraslope mini-basins located above the deforming Ligurian oceanic accretionary prism, during its tectonic transport toward and over the Apenninic foreland. The vertical succession of this unit starts with a ten of m-thick discontinuous basal division of deformed intrabasinal sediments, followed by at least 2 stacked large-scale MTD with almost opposite transport directions represented by ten to hundred of m-thick blocky/debris- flow deposits containing dismembered slump folds and out-sized slide blocks (figs. 4 and 5). The largest component MTD shows a conservatively estimated volume of about 150 km³, and can be traced laterally for 60 km in length and 25 km in width (Ogata, 2010).

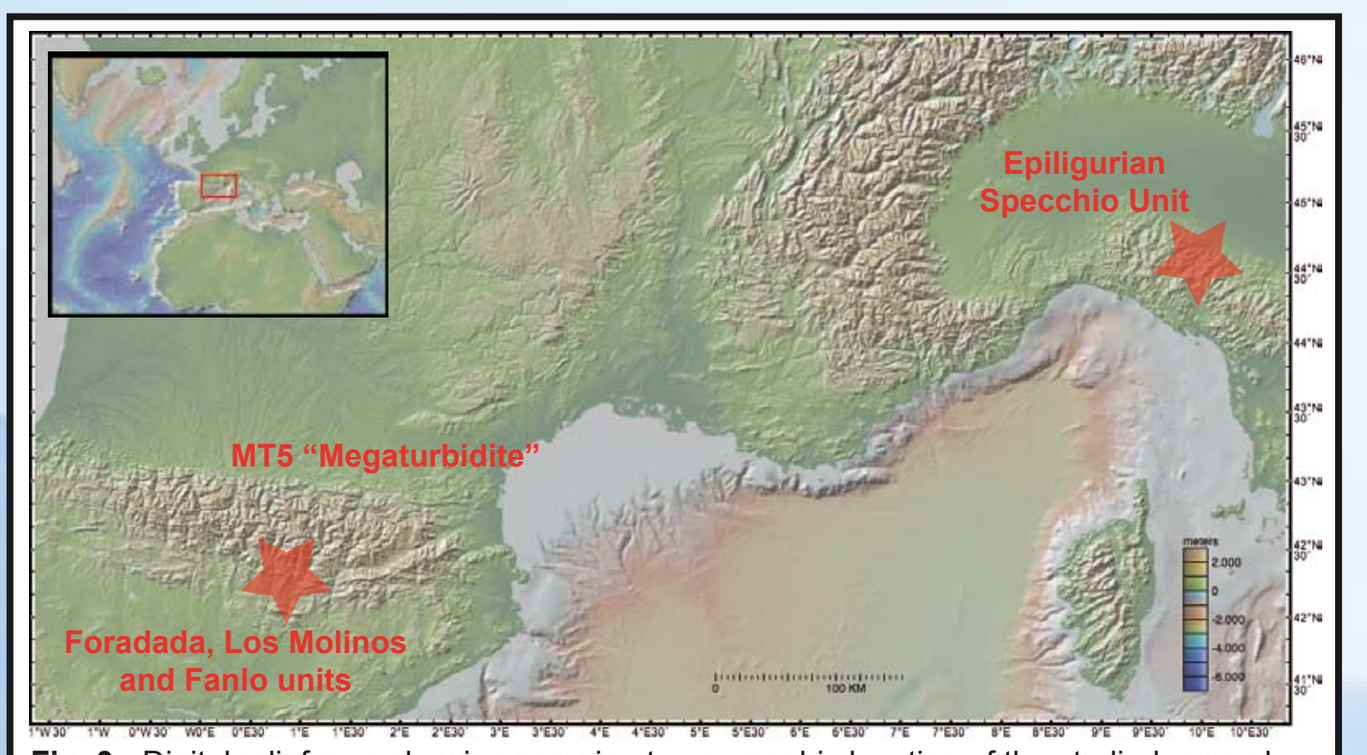


Fig. 3 - Digital relief map showing pproximate geographic location of the studied examples (elaborated with GeoMapApp, 2009).

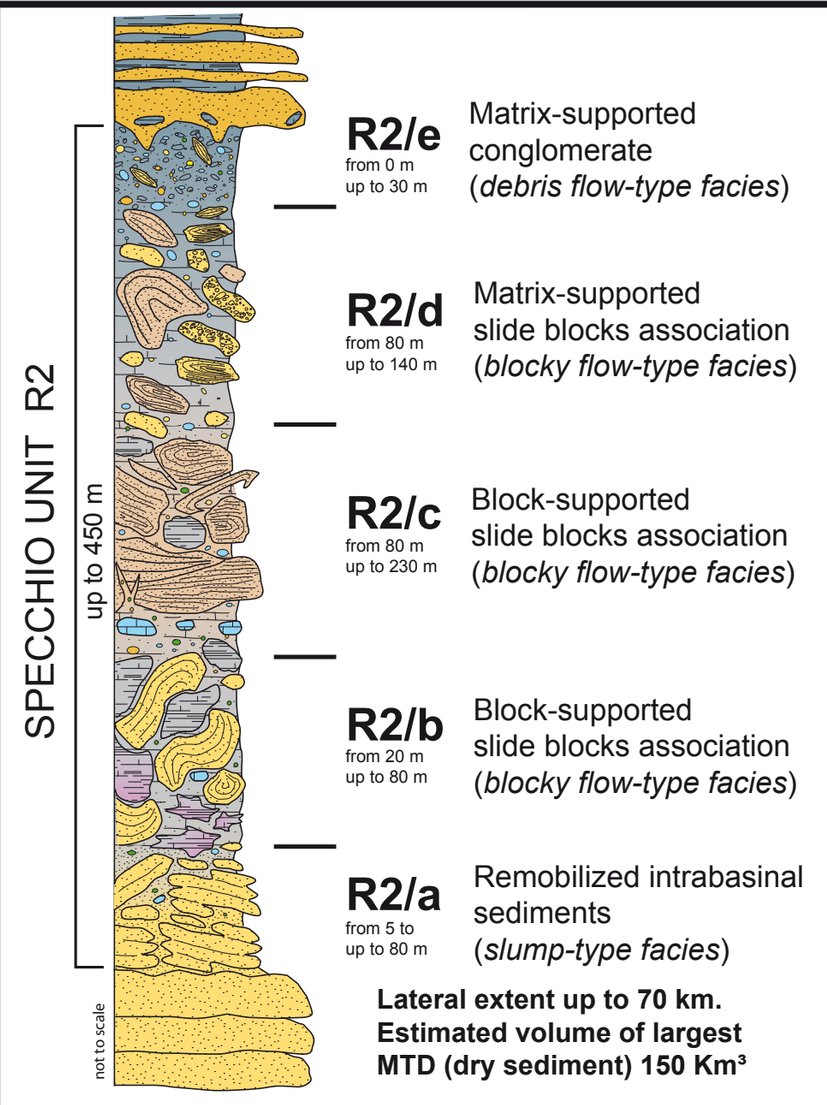
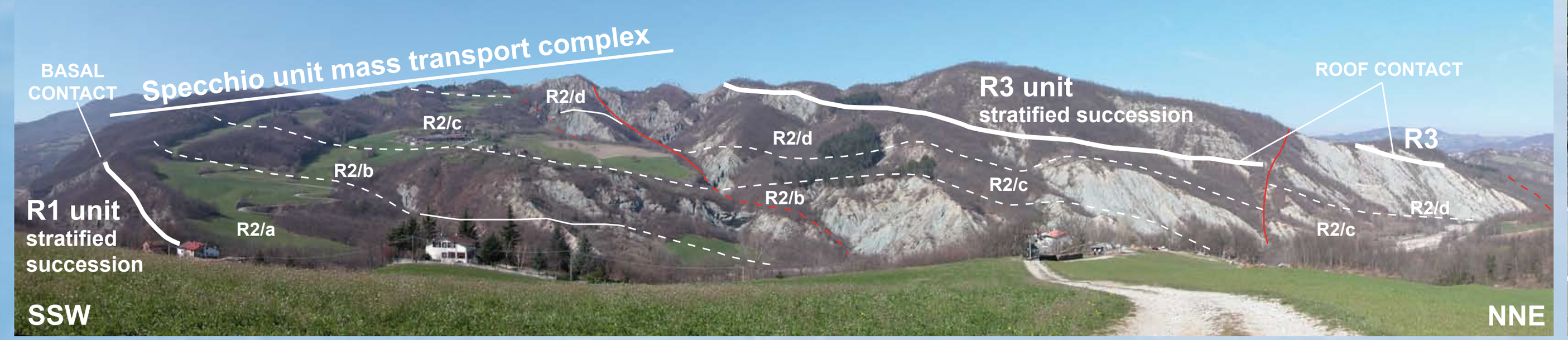


Fig. 5 - Simplified stratigraphic scheme of the Pessola Valley outlier focusing on the internal subdivisions of the Specchio Unit R2. Main features and characteristics, as well as inferred thickness, are described.

Fig. 4 - Panoramic photo-mosaic showing the western side of the Pessola Valley outlier, with line drawing of the internal subdivisions from base to top.



2.2 South-central Pyrenees case studies

The Eocene Hecho Group "megaturbidites" are tri-partite large-scale MTDs (figs. 6 and 7). These deposits are the product of a carbonatic platform collapse resedimented in a siliciclastic basin plain succession (Johns *et al.*, 1981; Labaume *et al.*, 1987). The MT5, with an average thickness of about 200 m, is one of the biggest among these deposits, and it can be traced across the basin for distances exceeding 100 km. The other examples: the Foradada, Los Molinos and Fanlo units (fig. 8), come from eastern deltaic-influenced marginal equivalents of the basin plain Hecho Group turbidites and are represented by m- to dam-thick blocky/debris flow deposits with relatively limited lateral extent, mainly due to the lower amount of involved material and to the more complex basinal morphologies with respect to the basin plain ones (Mutti *et al.*, 1988).

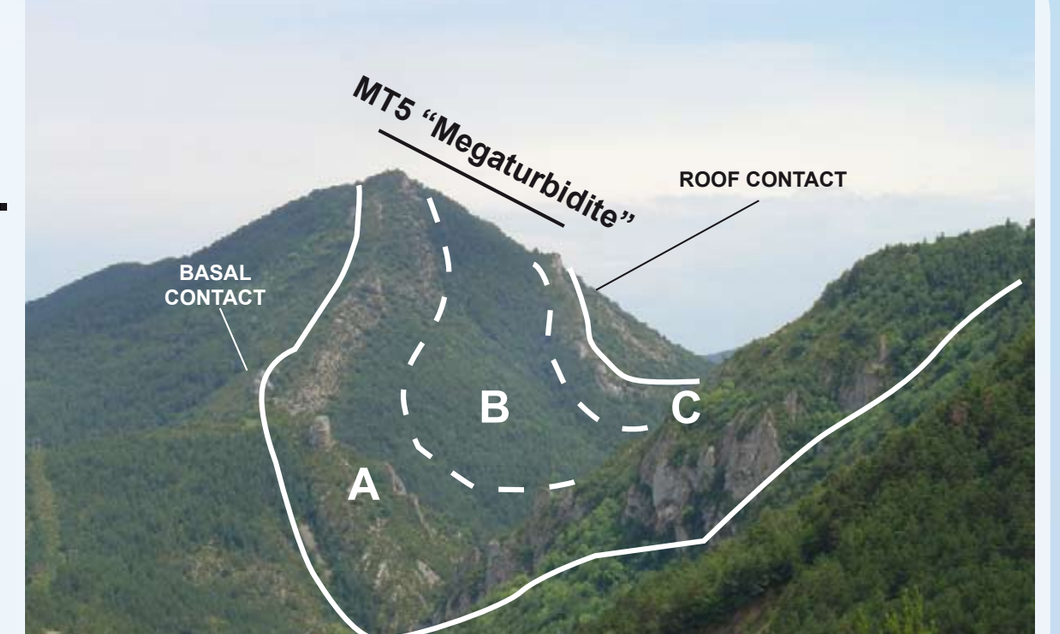


Fig. 6 - Panoramic view of the verticalized MT5 "Megaturbidite", recognizable in the landscape by erosional relief (Ansò Section, South-central Pyrenees, Spain).

Fig. 8 - Outcrop appearance of the Fanlo unit, debris flow-type deposit. Upper and lower contacts are covered (Prof. Mutti for scale). Eocene Hecho Group, Cotefablo-Broto Section (overturned), South-central Pyrenees .

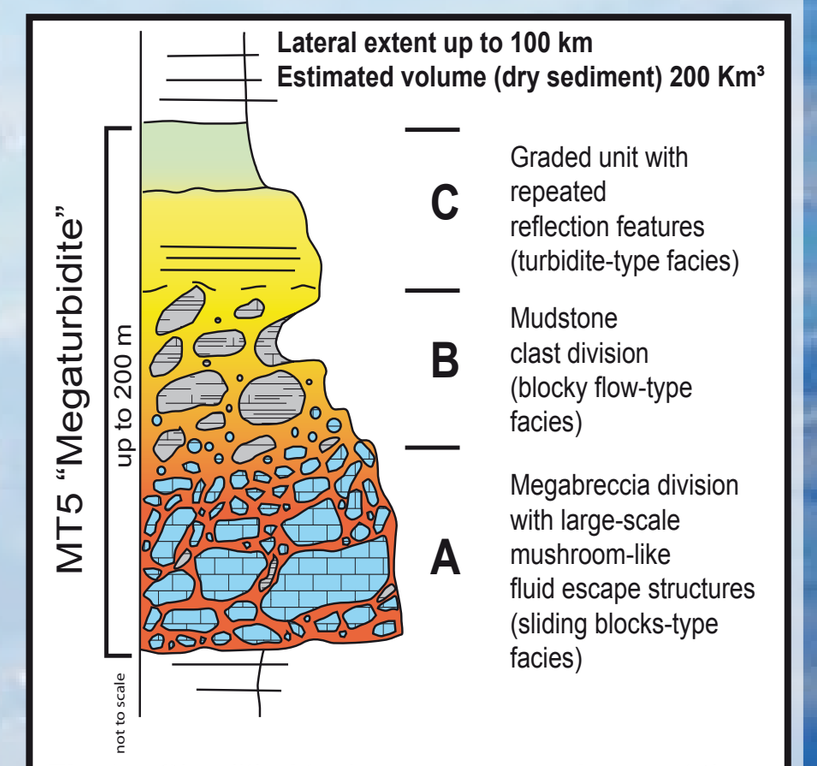


Fig. 7 - Simplified facies sequence scheme of the MT5 "Megaturbidite". Main sedimentary features, as well as inferred thickness, are described. Redrawn from Mutti *et al.* (1999)

3. DATA AND DISCUSSION

3.1 Matrix features (mesoscale)

Careful analysis carried out on the above-mentioned different mass transport deposits allow the interpretation of this kind of matrix as a 4-phase system, in which, each phase is thought to behave in a different rheologic manner: solid, plastic, pseudo-plastic and fluid (Mutti *et al.*, 2009; fig. 9). Proportions of each phase can vary case-by-case, also within the same deposit, along with the relative position within the unit, and thus, depending on the local strain partitioning. Poorly lithified blocks and intraclasts usually show different degrees of soft sediment deformation while liquidization evidences (*sensu* Allen, 1977, 1982) characterize the surrounding finer portions.

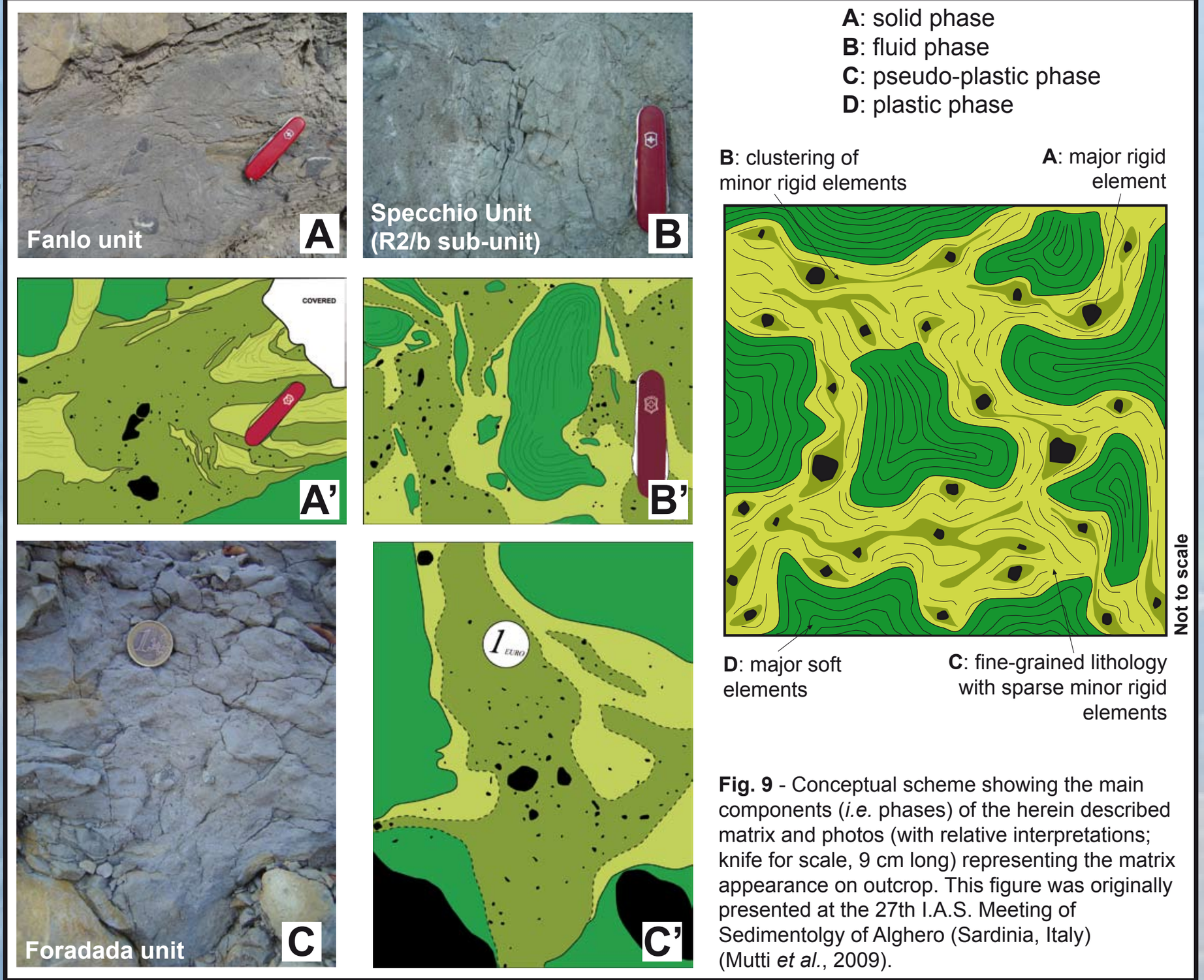


Fig. 9 - Conceptual scheme showing the main components (i.e. phases) of the herein described matrix and photos (with relative interpretations; knife for scale, 9 cm long) representing the matrix appearance on outcrop. This figure was originally presented at the 27th I.A.S. Meeting of Sedimentology of Alghero (Sardinia, Italy) (Mutti *et al.*, 2009).

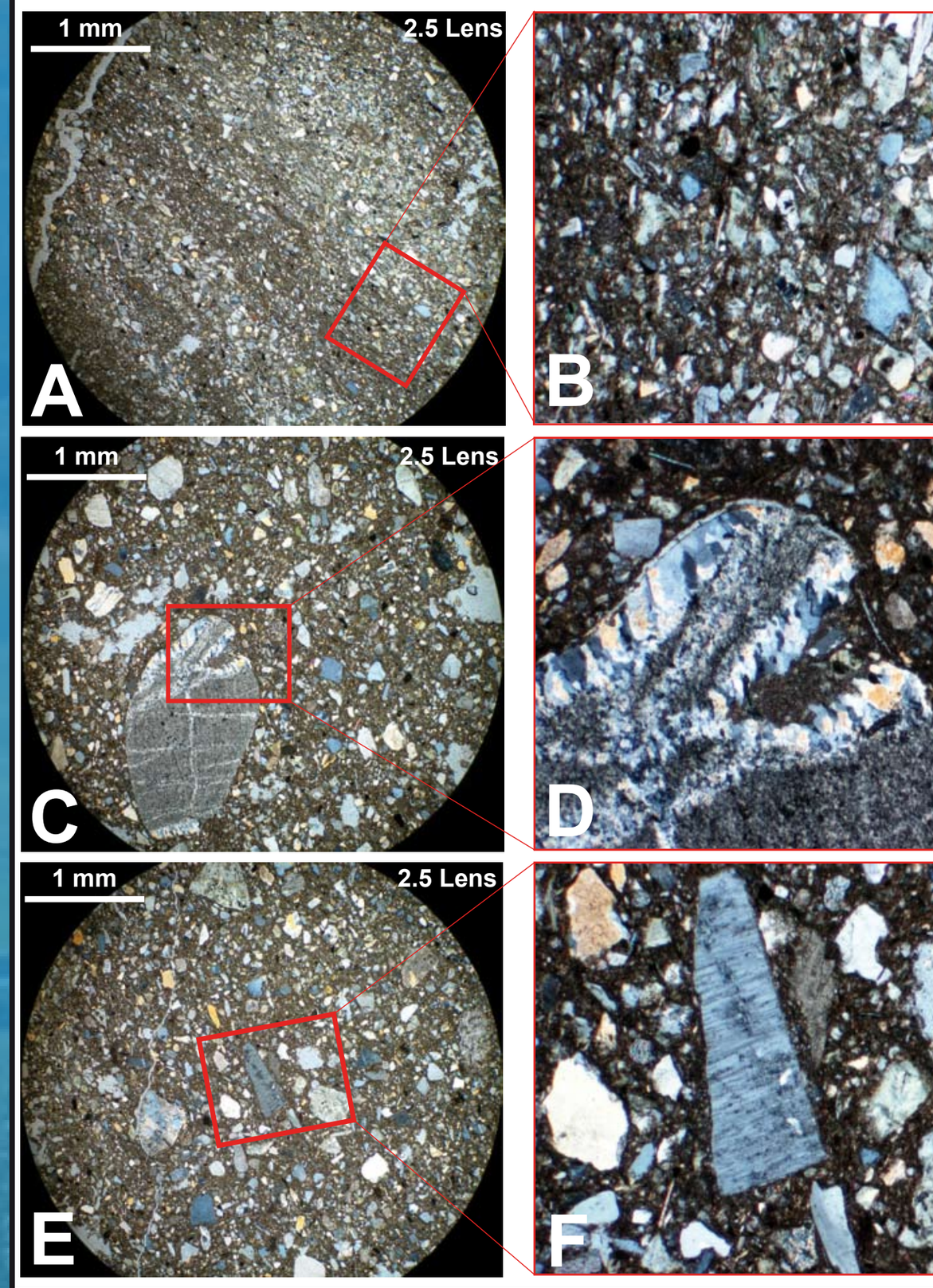


Fig. 10 - **A**: Microscopic overview of a banded fine-grained portion, with the fine-grained material arranged in "ribbon"-like patches and deformation-like bands. Lineations are also highlighted by the preferential alignment of particles, along their long axis. **B**: Close-up of A, showing the boundary between two relatively fine- and coarse-grained elongated clusters. A faintly recognizable transitional interval seems to separate finer material from coarser particle cluster. The overall appearance of the contact is quite gradational (merging and interconnection of finer enveloping material), nonetheless a distinct separation plane between coarser and finer particles seems to exist. These lineations are interpreted plastic deformation bands, in which the overall movement is achieved by an independent particulate flow (no evidences of grain breakage). **C**: Overall view of the sustained "block-in-matrix"-like appearance characterizing the coarse-grained portion of the matrix. The well-rounded, mm-sized, lithic pebble (metamorphic?) observable in the lower-left side of the photo is internally characterized by at least two systems of preexisting mineralized (quartz?) veins; note the intrusion of the finer material into the voids left by these mineralized veins (upper and lower margins). Particles dispersed within the finer material seem to envelope the major elements. Note also the faintly recognizable shear-like band passing tangentially to the upper-right margin of largest pebble, and trending obliquely the photo, from the upper-left side to the lower-right side. **D**: Close-up of C, showing in detail the primary mineralized vein and the injected fine-grained material. This evidence supports the fluid-like state of the matrix and the overpressured conditions. Note the thin calcite veneer developed along the upper margin of the pebble, and the fluidal-like appearance of the surrounding matrix, simulating pebble boundaries. **E**: Another general view of the coarse-grained portion of the matrix, showing a more iso-oriented arrangement of particles. Note how the finer material envelopes major grains. **F**: Close-up of E, showing an angular fragment of a fibrous mineral (quartz vein fragment?).

3.2 Matrix features (microscale)

Optical analyses carried on thin sections allow the recognition of some common features shared by this kind of matrix (fig.10): **1**) fine-grained intrusions actively injecting granule boundaries and filling pre-existing voids, **2**) microscopic deformation-like bands, highlighted by elongated clusters of particles and preferred iso-orientations of particle long axis, **3**) enveloping relationships of surrounding fine-grained lithologies around particle boundaries (testifying grain rotation), **4**) overall matrix-sustained texture with clast-sustained clusters. These evidences suggest a deformation mechanism involving an independent particulate flow without friction-related grain breakage.

3.3 Syn-sedimentary shear zones

The matrix is commonly localized along internal ductile shear zones, which commonly separates discrete and relatively coherent portions of a MTD (figs. 11 and 12), as well as along the main basal surface. These shear zones may affect the entire deposit and are commonly rooted in the basal shear zone, and/or be confined within unconsolidated blocks and discrete, relatively less deformed portions of the slide body. Evidence of isolated patches of different matrix textures into another, suggests incomplete mixing of different matrix generations (fig. 13).

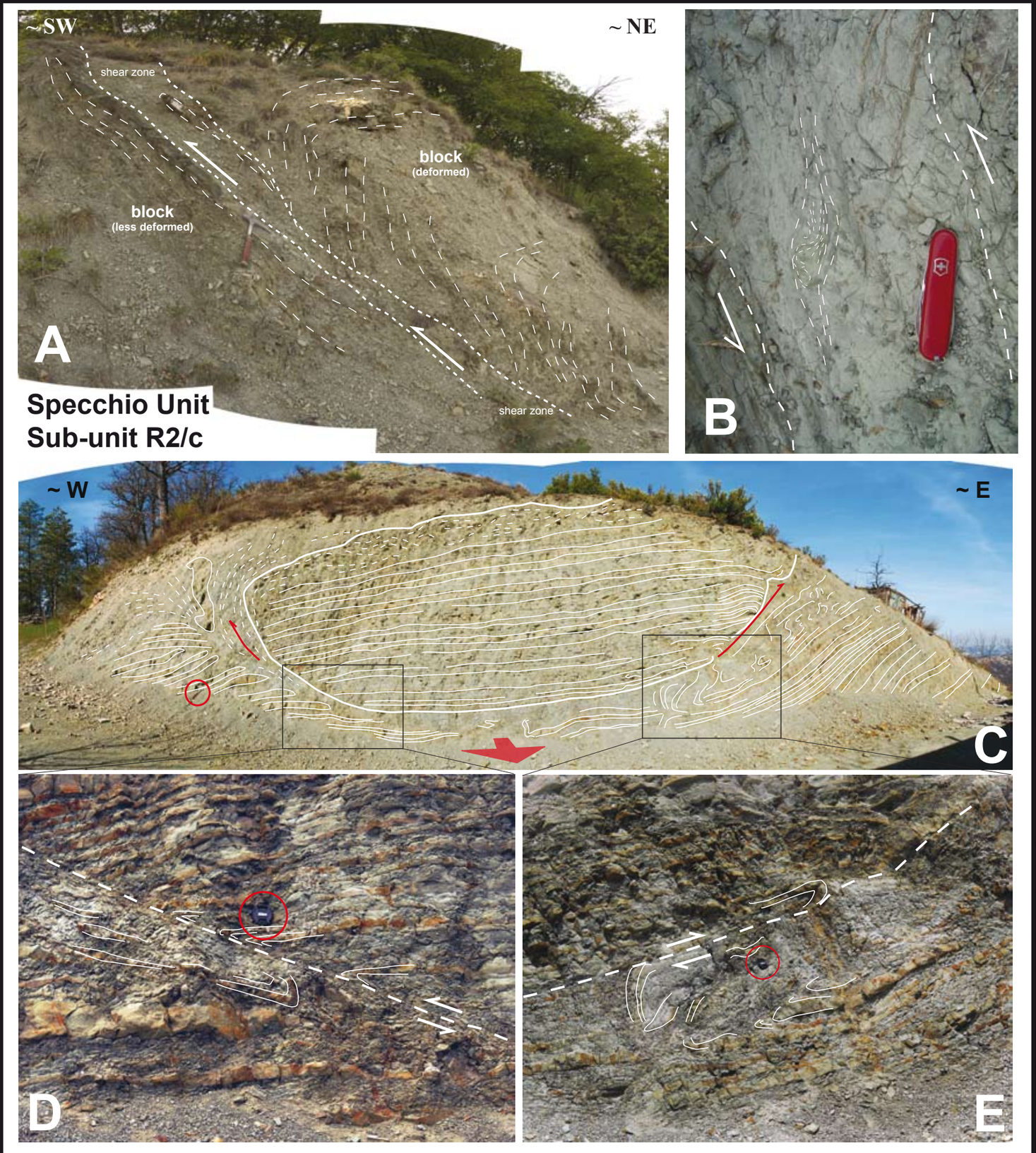


Fig. 11 - **A**: Photo-mosaic and line drawing representing a shear zone underlined by a matrix horizon, which separates two block portions (intra-block thrust). This structural association represents the longitudinal cut with respect to the main transport direction. Hammer for scale. **B**: Detail of an intra-block shear zone. Note the matrix development and the occurrence of sigmoidal-like structures, useful as kinematic indicators. Knife for scale, 9 cm long. **C**: Photo-mosaic and line drawing showing a block overriding another through an intra-block shear zone. The cut is roughly perpendicular to the main inferred transport direction (labeled with the transparent red arrow). Close-ups D and E show in detail the same shear surface characterized by two apparent opposite shear senses. This structural association represents the transversal side of the block diagram shown in A. Hammer and Camera lens cap (circled) for scale, 7 cm in diameter.

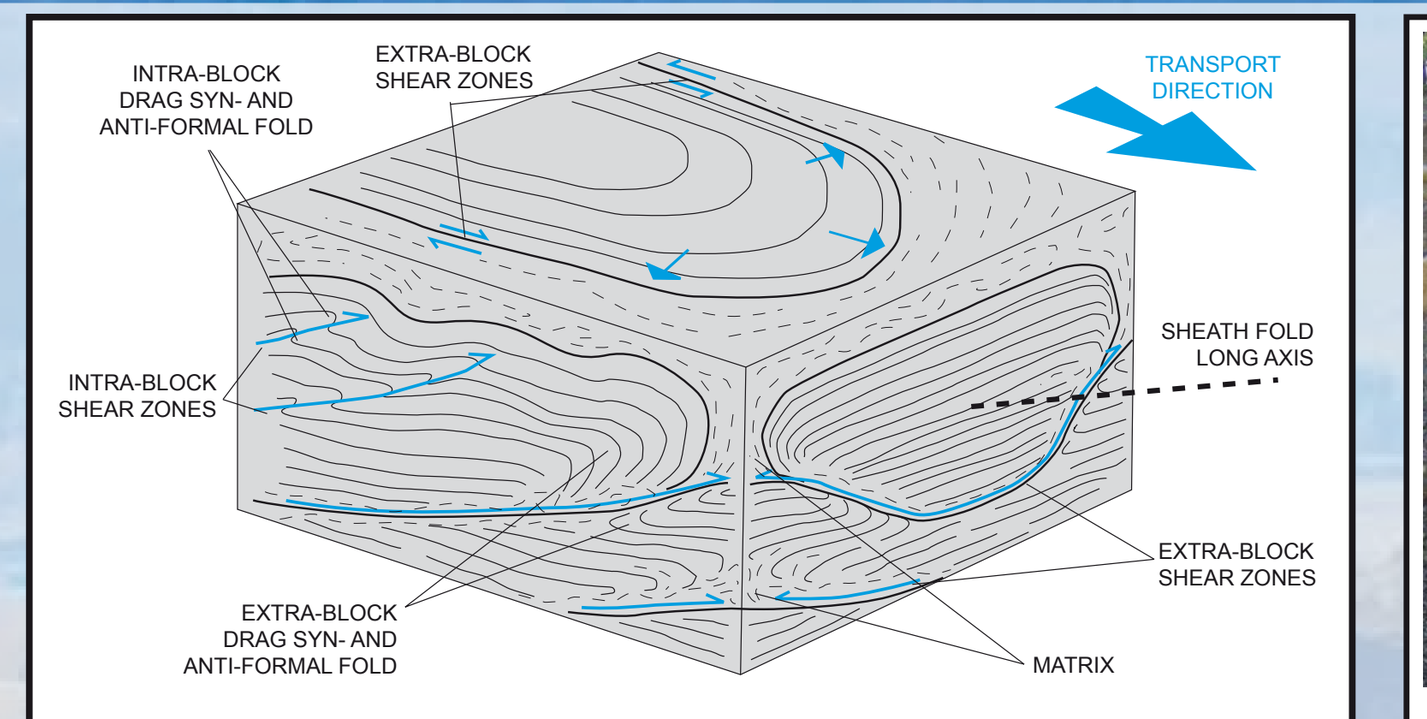


Fig. 12 - Conceptual block diagram showing structural associations (inspired from Bradley and Hanson, 1998), which characterize block-dominated portions (slump-like facies). Representative features and relative structural data useful for kinematic analysis are drawn.

3.4 Fluid-escape structures

These structures are the most prominent evidence of generation and maintenance of excess pore pressure within the matrix during mass translation and deposition (fig. 14). These "mushroom-like" structures, commonly rooted in matrix-dominated portions of the slide body (*e.g.* basal shear surface) are likely to develop during the last evolutionary stages of the mass transport event and/or immediately after the emplacement. The matrix is "squeezed" upwards and laterally along weak zones and discontinuities affecting slide blocks and coherent portions of the slide body, possibly also reaching the surface and developing sedimentary extrusions (*e.g.* mud volcanoes) as observed in other modern and ancient MTD examples. Its movement-related drag force contribute in fold generation.

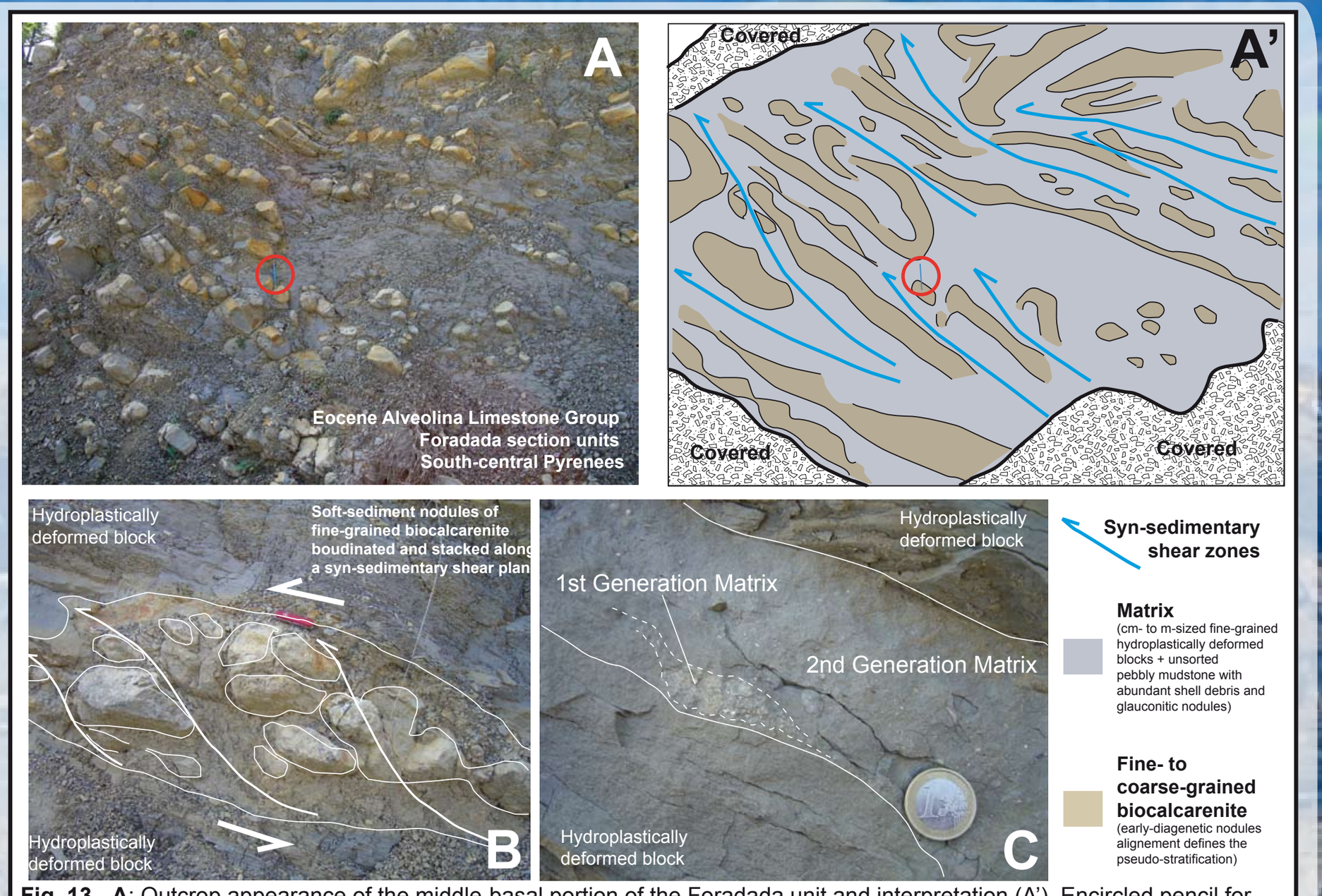


Fig. 13 - **A**: Outcrop appearance of the middle-basal portion of the Foradada unit and interpretation (A'). Encircled pencil for scale. **B**: Detail of a syn- sedimentary shear zone showing a duplex-like stack of discrete bed fagments (boudins?), separating two hydroplastically deformed blocks through sheared contacts (gradual transition from the matrix). **C**: Detail of a syn-sedimentary shear zone highlighting the occurrence of patches of matrix with different texture and composition within a matrix-rich interval. This evidence suggests the possible development of different matrix generations within the same deposit. One Euro coin for scale.

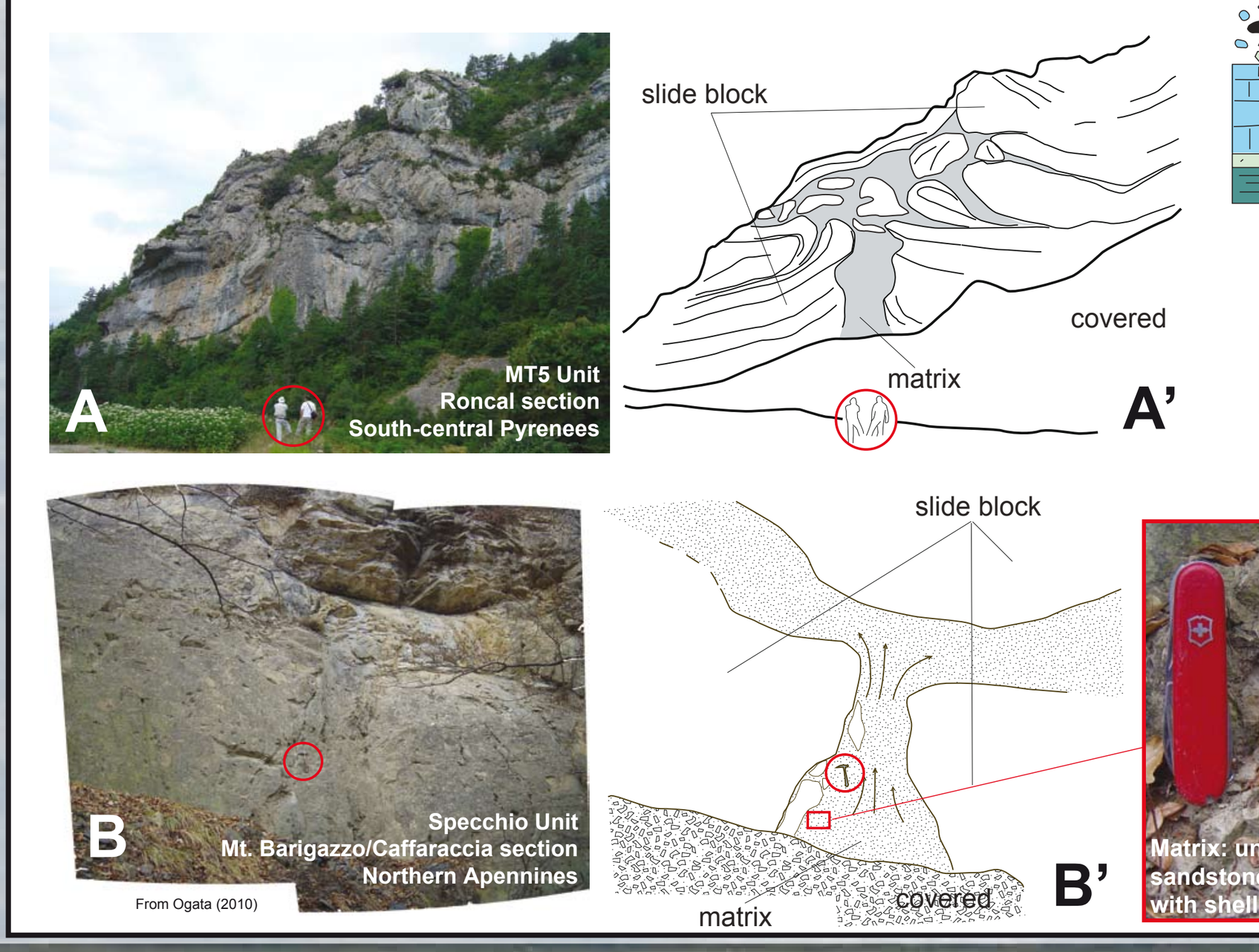


Fig. 14 - **A**: Photo-mosaic and interpretation (A') of a large-scale, fluid escape-related "mushroom"-like structure,observed in the MT5 "megaturbidite". As shown in the related interpretative cartoons (right side), this structure roots in the basal shear surface where the bulk of the matrix occur. Encircled persons for scale. **B**: Photo-mosaic and interpretation (B') of a meso-scale injection-like structure observed within the upper part of the R2/d sub-unit. These kinds of structures dissect the block integrity; probably joining different matrix-rich shear zones through vertical and oblique pathways. The infilling matrix intrudes along weak zones (*e.g.* stratification surfaces), as observable along the margins (secondary lateral injections). Note also the occurrence of sandstone intra-clasts within the infilling matrix, ripped up from structure margins. Encircled hammer for scale. In the close-up (right side) it is shown in detail the intruding matrix appearance. Knife for scale.

4. RESULTS AND CONCLUSIONS

The herein described matrix is thought to develop mainly through heterogenous undrained shearing and loading-unloading cycles, involving layered sequences of un- to poorly-lithified material coming from the eroded substrate and, subordinately, from the partial disintegration of the slide body internal components, thus representing an extreme degree of soft sediment deformation (fig. 15). Progressive shearing, dilation and contraction cycles cause repeated undrained rearrangement of grains, with sudden the rising up of transient excess pore pressure and consequent liquefaction.

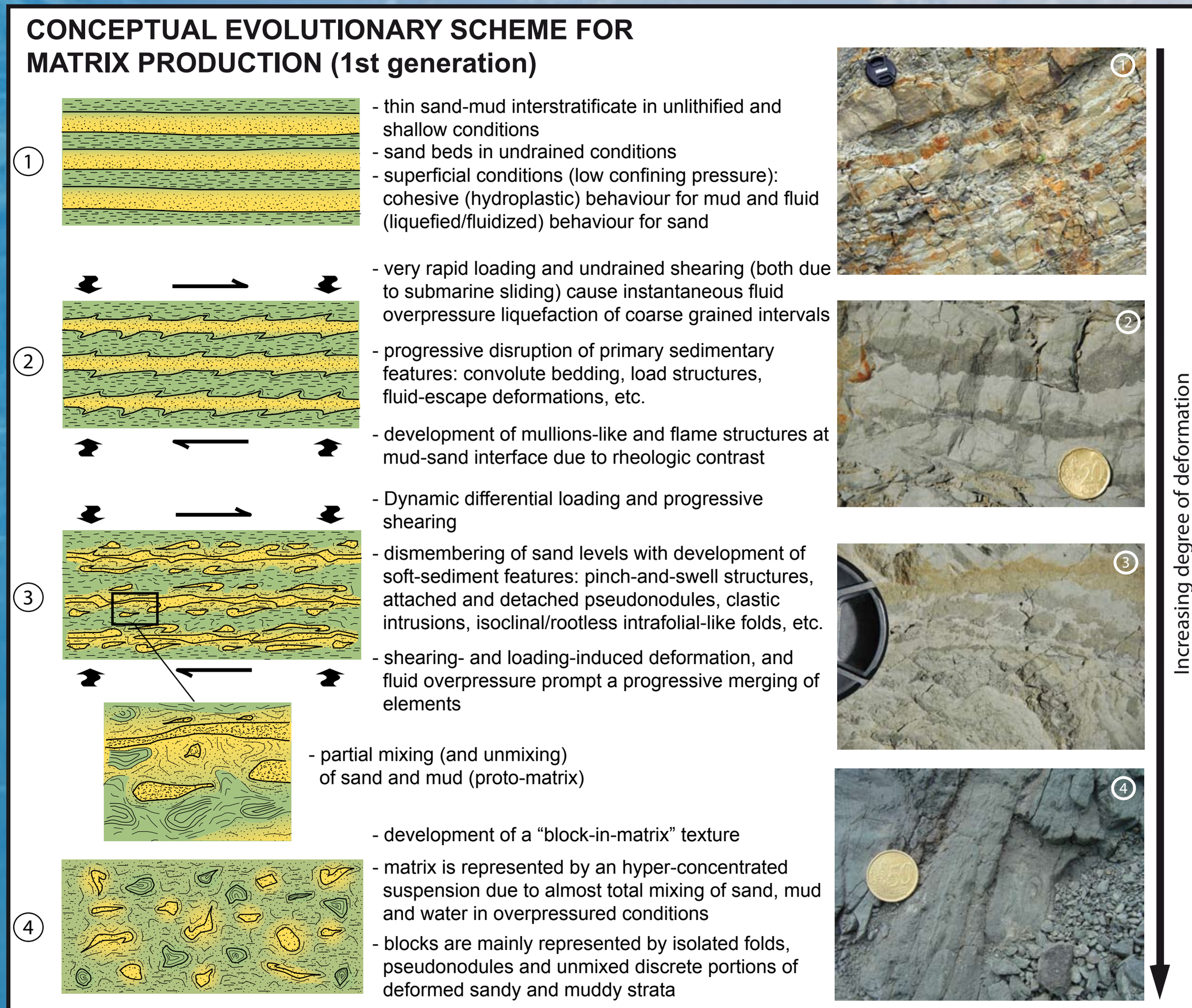


Fig. 15 - Conceptual cartoon representing an attempt to define evolutionary stages of matrix development through progressive stratal disruption of a thin-layered sequence. This kind of matrix can be identified as proto-matrix, due to its "intrabasinal" character. Photos are taken form the Specchio Unit (R2/c sub-unit) in the Pessola Valley outlier.

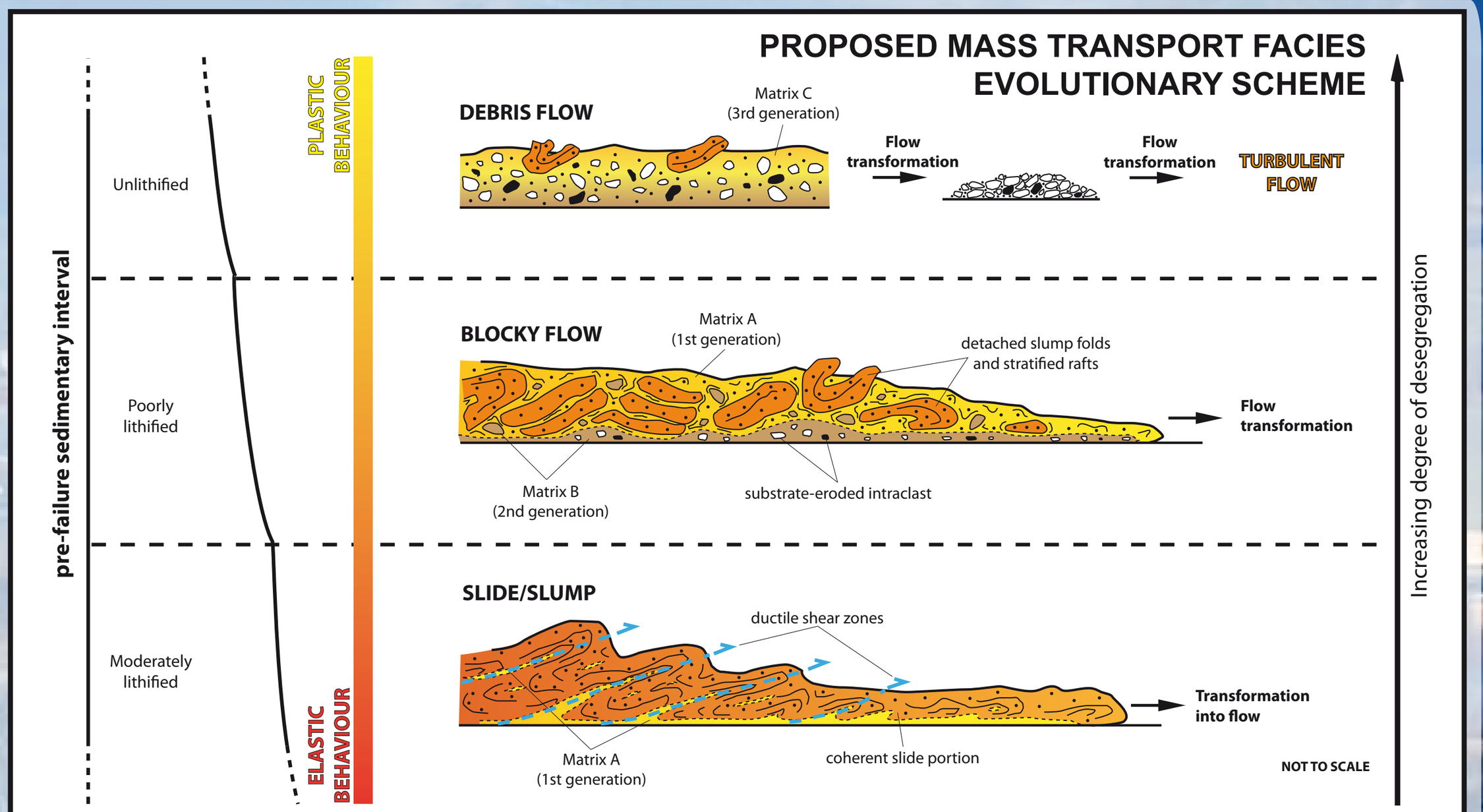


Fig. 16 - Conceptual evolutionary scheme showing the possible relationships between slump, blocky flow and debris flow deposits (modified from Mutti *et al.*, 2006). In this scheme focuses on the structures, rheologic behaviour and disruption degree. In the left side it is tentatively represented the possible linkage between the deposits and the lithification degree of the original (pre-failure) statigraphic succession.

This matrix is thought to work as an overpressured lubricating *medium* accommodating friction forces, sustaining slide components, favoring internal differential movements and enhancing the whole slide mobility. The occurrence of a matrix with the above-mentioned features is supposed to be a necessary condition for a sliding mass to flow, and thus, a diagnostic indicator of a fast moving process (*i.e.* catastrophic). The recognition and characterization of this kind of matrix allow some important consideration regarding:
- mass transport triggering, translation and emplacement processes;
- discrimination of sedimentary products from those originated from shallow crustal level tectonics.

Moreover the matrix abundance is thought to represent mass transport events characterized by a flow-like behavior, and quantifying its relative amount is proposed here as a useful tool in discriminating those intermediate mass transport facies tracts possibly recording evolution from coherent (slide/slump) to cohesive (debris-flows) mass transport events.

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