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Karst structures in heterogeneous lithological units as a potential geo-engineering hazard factor for mining and civil infrastructures

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Abstract The planning of civil engineering infrastructures and the exploitation of mineral resources in lithologically and structurally heterogeneous carbonate-dominated rock assemblages should take into account associated complex karst structures as potential geohazards. A recent study on the Paleocene-Eocene sedimentary succession outstandingly exposed in the Anhovo quarry (Outer NW Dinarides, Slovenia) points out the occurrence of paleokarst structures that are the result of localised dissolution processes along phreatic channels. These fluid flow pathways follow the directional anisotropy provided by a complex network of lithological matrix/clasts contacts in a matrix-rich depositional unit of ancient, large-scale submarine landslides (mass transport deposits; MTDs), which is in turn originated by specific sedimentary and post-sedimentary processes. Among primary sedimentary processes, down-slope gravitational transport favoured the lithological disaggregation and mixing of slide blocks and clasts into a marly-silty matrix, which later played an important role in controlling subsequent diagenetic processes on such exhumed MTDs. In this framework, groundwater flow followed different lithological and structural contacts, and block/clast boundaries, allowing the formation of contact karst structures, consequently providing favourable conditions for the formation of geomechanical labile systems in heterogeneous lithological units. The complex "worm-like" network of such phreatic channels, with certain anatomical features defined by the shape and orientation of structures and slide block/clast contacts, represents a zone potentially prone to gravitational collapse. The presented results suggest that the correct interpretation of syn-sedimentary structures, backed up by e.g. georeferencing of the contacts and the orientation of the slide blocks axes, allows us to identify or predict potential geomechanically weak areas of the quarry slopes where landslides could well be activated, and thereby contributes to better, more efficient decision-making on issues related to safe mining and/or civil engineering practices.

Keywords paleo submarine landslides, karst structures, geohazard

Introduction

Mass-transport deposits (MTD) or mass-transport complexes (MTC) are highly heterogeneous bodies/units deriving from *en-mass* subaqueous sedimentary processes, such as rock avalanches, hyperconcentrated flows, slides and slumps, acting in a sedimentary basin and often related to continental margins located at the edges of lithospheric plates and seismic zones (Pini et al. 2012; Festa et al. 2014; Festa et al. 2016).

The understanding of sedimentary and post-sedimentary processes (Ogata et al. 2014; Petkovšek et al. 2011) occurring within these geological bodies exhumed in orogenic belts (Pogačnik et al. 2015) allows for a proper spatial planning strategy (Cano and Tomás 2013) for the construction of infrastructures, as well as for the prevention and remediation of natural disasters.

The investigated MTDs, which occur in W Slovenia, are related to the Mesozoic and Cenozoic sedimentation in the north (Šmuc 2005; Rožič and Šmuc 2011) and central (Ogata et al. 2014) Soča Valley (Fig. 1).

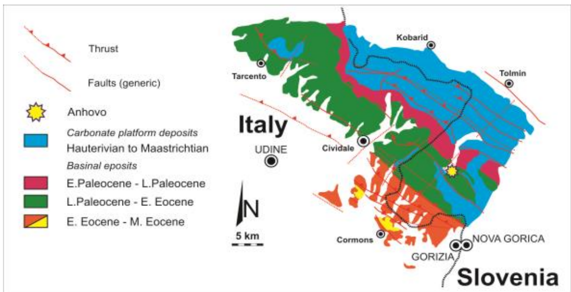

Figure 1 Position of Anhovo MTDs and generalised geological situation (after Ogata et al. 2014).

In the Anhovo region, a sequence of very thick MTD bodies of Middle Paleocene age crops out with an average dipping of 28° towards SW. Each body displays a sequence of lithological intervals corresponding to the internal depositional units (Fig. 2) defined by Tunis and Venturini (1992): calcareous breccia with oversized carbonate olistoliths (U1), calcareous breccia with bedded siliciclastic-carbonate and marly olistoliths (U2), graded calcareous breccia, calcirudite (U3), graded and laminated calcarenite (U4) and massive/laminated marlstone (U5).

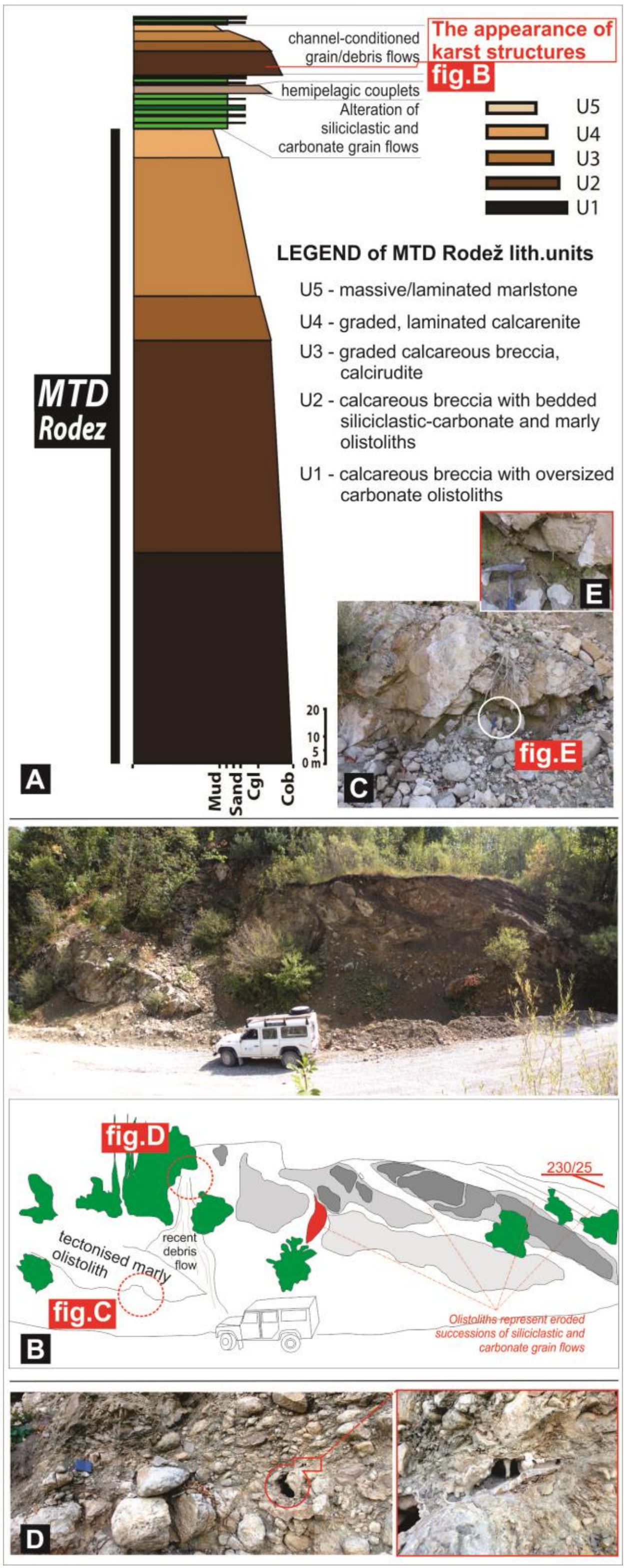

Figure 2 (A) Schematic lithostratigraphic succession of MTD Rodež with appearance of karst structure; (B) Field outcrop view of unit U2 with structurally deformed marly olistolith as conduits for groundwater percolation, different structurally damaged pebble-boulder and pebble conglomerate (dark grey), olistoliths with muddy sand matrix (light grey), and plastic deformed eroded successions of siliciclastic and carbonate grain flows; (C and E) NE-oriented tectonic deformation and travertine stalactite (location in B); (D) Typically oriented pebbles and boulders with their mutual contact and evidence of karst structures.

Due to the specific internal organisation of individual units such as the orientation of clast long axes (Enos 1977; Major 1998), their mutual contacts and the permeability of contact surfaces, these rocks represent a potentially significant geohazard to be considered in the design and proper use of mining space. Internal organisation depends on rheological and palaeotopographic factors (occurring during sedimentation) and early (as compaction structures) and late diagenetic activation of labile zones.

The overall impact of meteoric water (Pánek et al. 2011) and groundwater in structural and lithological heterogeneous rocks like those of the MTDs creates specific structures such as karst contact caves (Mocchiutti 2001; Zupan 2004; Mocchiutti and Maddalena 2005; Knez et al. 2005; Kenz and Slabe 2009, 2016; Pánek et al. 2011) of various shapes (Margielewski and Urban 2005; Pánek et al. 2011; Urban and Margielewski. 2013; Lenart et al. 2014; Lenart 2015) and sizes (Margielewski and Urban 2005).

The U2 unit represents a heterogeneous assemblage from a structural, textural and compositional point of view, with a specific internal organisation that requires a complex approach in order to study the individual and interrelated causal effects that originate peculiar types of speleothem. This paper addresses the factors influencing the formation of karst structures, which are responsible for a triple porosity aquifer (conduits, fractures and matrix) (White 1999) and the potential impact of such structures on the geohazard.

Materials and methods

At the stage of sedimentation, unit U2 can be described as a mixture of solid heterogeneous materials and fluids with different mechanical properties in which a great number of momentum-transfer mechanisms operate, from bulk transitional to grain vibrational kinetic energy and fluid pressure energy (Iverson 1997). In the outcrop, where the karst structures (detail on Fig. 2D) have been detected, a detailed structural, stratigraphic and compositional study has been done, with special attention paid to the type of contact between clasts of different facies and the type of matrix (sandy-muddy), in order to establish a meaningful interpretation of the speleothem occurrence.

Results

Rudist limestone breccia (Fig. 3B), with pronounced karstic structural planes, eroded clasts of sandy matrix, which include angular marly clasts (Fig. 3A), and fine-grained sandstones (Fig. 3D) predominantly display an angular shape, as opposed to resedimented radiolitic breccias, where a rounded shape prevails. Defining the contact geometries among pebbles and boulders (Fig. 3E), a tangential (point) contact (point 1 and 3 on Fig. 3E) appears in its greatest extent, probably related to the

primary depositional processes. It is followed in importance by long axes contacts (point 2 and 4 on Fig. 3E), with the latter probably originating in post-depositional burial and compaction of the U2 unit. A concavo-convex contact between ductile eroded hemipelagic couplets (yellow dashed line-point 5 on Fig. 3E) and/or harder limestone clasts can be found around larger pebbles.
In the empty space between clasts (Fig. 4A, 4B and 4C), the observed speleothems indicate a continuous connection (Fig. 4B, point 2 and 3) of the karst cave system (Fig. 4C; red dashed line). The flame-shaped sandy matrix injections (Fig. 4D, yellow dotted line) between angular pebbles indicate a lithological contact between olistoliths with different muddy-sandy and muddy matrices in unit U2. The traces (Fig. 4E; arrows) of multistage, phreatic channel development are evident on the now exposed walls (Fig. 4E; dashed line) of a phreatic channel (Fig. 4D) opened in a boulder of Rudist limestone breccias.

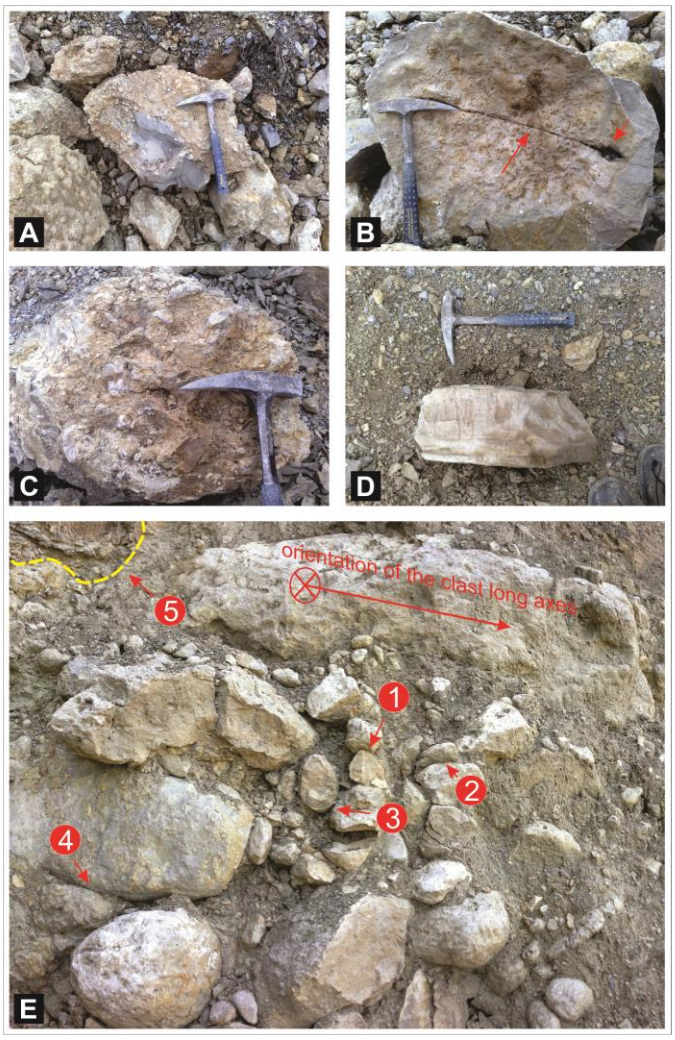

Figure 3 Lithological and geometric diversity (A-D) of clasts, some of them with pronounced karstic structures (red arrows, B); (E) Different types of contacts: tangential-point contact (1 and 3), long axes contact (2 and 4) and concavo-convex contact (5).

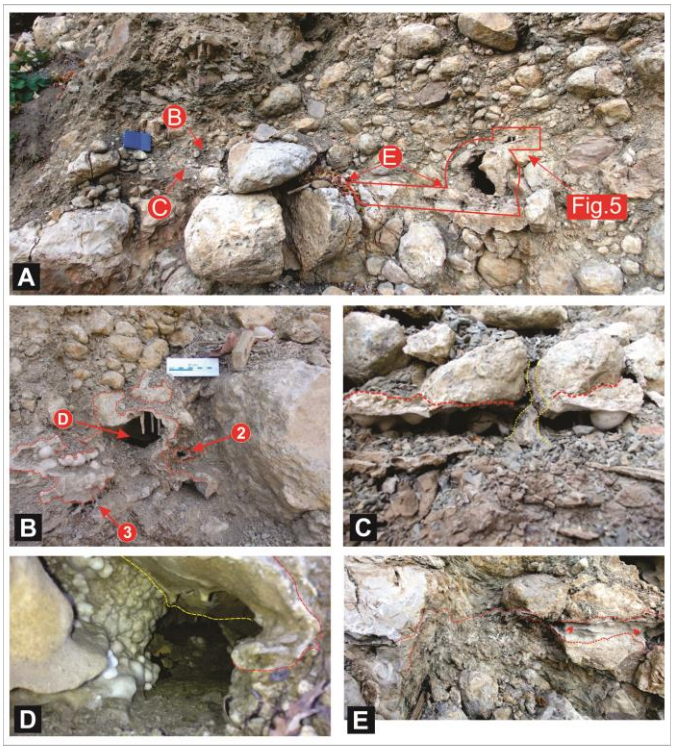

Figure 4 (A) An outcrop with speleothems; (B) Close-up view of worm-shaped cave; (C) Crystallisation of calcite on the concave/half-moon shaped channel ceiling; (D) Crystallisation of calcite on the walls forms a bubbly surface and broken stalactites on the channel ceiling; (E) broken boulder reveals the worm-connected system (broken red line).

Discussion and Conclusions

The crystallisation processes developed in the pore spaces of unit U2 indicate active late diagenetic activity, which can be assigned to either small-scale accommodation processes as a consequence of matrix weathering or the sudden movement of rock masses triggered by a subaerial landslide (Dugonjič Jovančević and Arbanas 2012; Berisavljević et al. 2015; Berti et al. 2017) or other events (Cano and Tomás 2013).

Hypothetically, the U2 unit can be conceived as a "blend" of different matrices (each with its own rheological properties) surrounding clasts that are of uneven shape and size (Fig. 5A) and are oriented in the same direction as the axes of the sedimentary mass transport. To illustrate the fluid transmissivity factors impacting the speleogenesis in unit U2, we have used a combined approach of clasts rotating around their own axes (as a consequence of a directional simple shear during post-depositional tectonics/slide events) and percolation (opening/closing of channels due to rotation of clasts, creating new contacts by extruding the homogeneous matrix).

In unit U2, there are cracks and interconnected cracks (Fig. 4B to 4D), which allow the flow of saturated waters with carbonate ions and the consequent formation of speleothems in micro-environments in interparticles and larger channel porosity. If a lithological horizon such

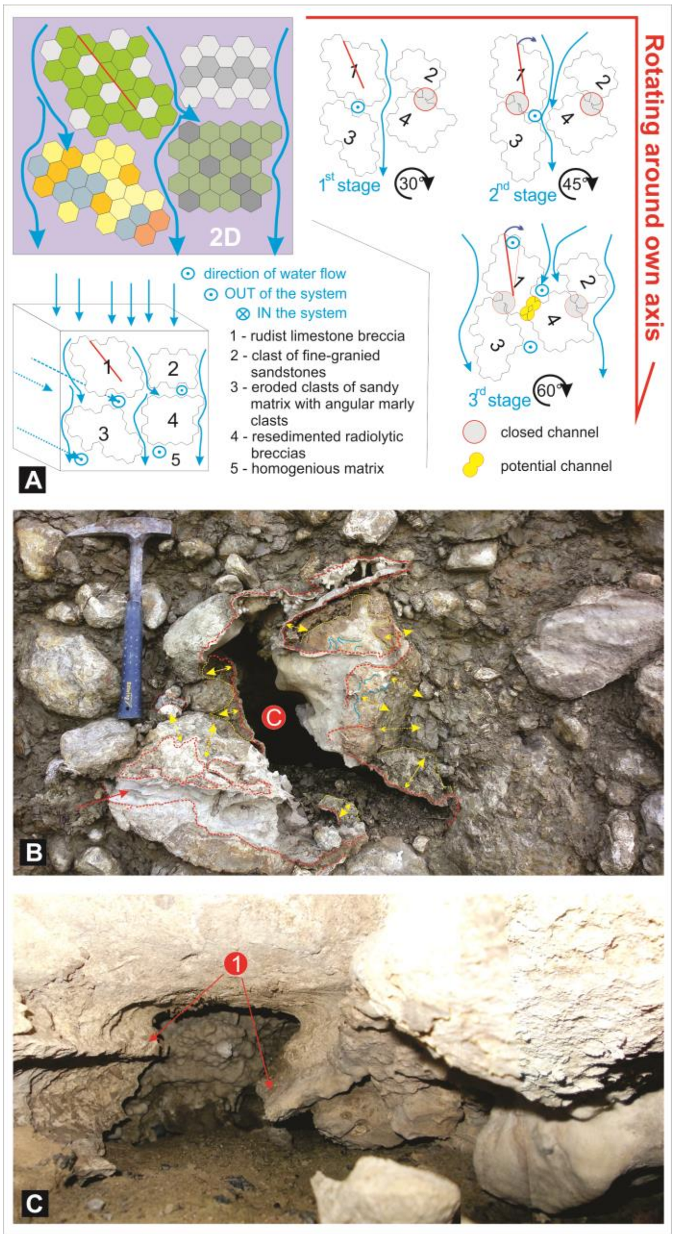

Figure 5 (A) Rotation of clasts around their own axes in a homogeneous muddy-sand matrix and the formation of percolation bulkheads as a consequence of new grain contact types and squeezing of the surrounding matrix; (B) Type of vuggy channel porosity (red dotted line) and diagenetic transformed matrix (yellow dotted line) with orientation of the contact of the speleothem (double yellow arrow). The blue line on the rudist limestone breccia indicates traces of the previous karst system, which was destroyed during diagenesis. The red arrow shows the fasetes, which indicate the process of the corrosion of the rock as the result of the water vortex flow on the rock and the erosion gut, in turn the result of the spilling of low water flow; (C) Part of the keyhole cave system, a result of downcutting from an initial phreatic tube. The width of the system varies depending on the solubility of the wall rock (red arrows as point 1).

as unit U2 is overloaded with a simple shear force (as late diagenetic processes), the clasts and surroundings matrix repack in order to establish a new balance andform a new channel – vuggy porosity (Fig. 5B), where water can form new speleothems. Ductile matrix deformation develops as a result of the new balanced state (Fig. 5B dotted red line) and is characterised by radical degradation of porosity (detail C on Fig. 5B) due to compaction and compaction-related processes (yellow dotted line on Fig. 4C). This can cause additional pore clogs to form a percolation barrier. At that moment in the MTD, a hydrostatic pressure zone may develop, forming new latent mesogenic and/or talogenic landslide structures that destroy the worm-shaped karst caves connected through the channel (Fig. 5C) and/or giant vuggy porosity of unit U2 and trigger a new potential rupture surface on the slope. In order to check this proposed explanation, a geochemical analysis of the speleothems "chemostratigraphy" must be performed (from the matrix to the inside of the structure), to determine whether the various channels and stalactites can be stratigraphically bundled. Positive results would open a new chapter on the geomechanical interpretation of the heterogenous units that form large MTDs and the appropriate interpretation of the geohazards connected with them.

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