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Heterogeneously composed Lozice fossil landslide in Rebrnice area, Vipava Valley

Heterogeni fosilni plaz Lozice na območju Rebrnic v Vipavski dolini

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Ključne besede: fosilni plaz, sedimentni faciesi, 3-D model, lidar, Lozice, Rebrnice

Abstract

The Rebrnice area in the Upper Vipava Valley, SW Slovenia, is covered by Quaternary slope deposits that are very complex in their genesis and composition. Some of the sediments are deposited in the form of heterogeneously composed fossil landslides. One of these landslides in the Rebrnice area is the Lozice fossil landslide located above the village of Lozice. Analysis of this landslide includes geological mapping of the fossil landslide, classification of different sedimentary facies, 3-D modelling of the landslide, and transverse and longitudinal cross-sections. The geological mapping of the fossil landslide is based on field work mapping and analysis of shaded digital terrain models (DTMs) with a resolution of 1 × 1 m obtained by airborne laser scanning. Lithological data from boreholes and excavation trenches have been classified into eight specific sediment facies that had been defined in previous studies. The 3-D model of the landslide was made using the ArcScene application in the program ESRI ArcGIS. For each sediment facies, a surface was made in the form of a Triangulated Irregular Network (TIN), which gave us a wireframe object. TIN nets were merged in Multipatch objects and exported to 3-D Analyst, where a 3-D model was created. In addition, a shaded DTM image was added for a better placement of the 3-D model in space. Previous findings indicate that deposition of fossil landslides in the Rebrnice area was influenced by palaeotopography. Based on borehole data, transverse and longitudinal cross-sections of the fossil landslide were made and indicate concave depressions under the Lozice fossil landslide. Analysis of the Lozice fossil landslide indicates its complex structure of intertwined heterogeneous sedimentary facies.

Izvleček

Območje Rebrnic v Vipavski dolini v jugozahodni Sloveniji prekrivajo kvartarni sedimenti, katerih izvor in sestava sta zelo kompleksna. Nekateri sedimenti so združeni v večkompozitne fosilne plazove, med katerimi je fosilni plaz Lozice, ki se nahaja nad vasjo Lozice v Vipavski dolini. Analiza fosilnega plaz Lozice vključuje geološko karto, klasifikacijo sedimentnih faciesov, izdelavo 3-D modela fosilnega plazu ter vzdolžnega in prečnega profila plazu na podlagi podatkov vrtin. Geološko karto smo izdelali na podlagi terenskega dela ter senčenega digitalnega modela višin, ločljivosti 1 × 1 m, pridobljenega iz lidarskih posnetkov. Litološke opise sedimentov iz vrtin in sondažnih jaškov smo kategorizirali v osem sedimentnih faciesov. 3-D model fosilnega plazu smo izdelali z aplikacijo ArcScene v programskem okolju ESRI ArcGIS Analyst. Za vsak sedimentni facies smo naredili ploskev v obliki nepravilne trikotniške mreže (TIN), s katero smo dobili žičnati model površja. 3-D model smo v prostor umestili tudi z uporabo senčenih digitalnih modelov višin. Dosedanje raziskave kažejo, da so fosilni plazovi na območju Rebrnic vezani na paleotopografsko podlago. Na podlagi podatkov vrtin smo izdelali vzdolžni in prečni profil plazu, ki kažeta na konkavne zajede na območju fosilnega plazu Lozice. Celotna analiza fosilnega plazu Lozice predstavlja kompleksno zgradbo med seboj prepletajočih se sedimentnih faciesov.

Introduction

Due to the geological and morphological characteristics of the landscape, landslides and mass flows are in general very common in Slovenia, causing damage to infrastructure as well as danger to people (Komac, 2009). In the past decades, landslides and mass movements have been very common natural hazards in the Vipava Valley (Kočevar & Ribičič, 2002; Logar et al., 2005; Kočevar, 2011; Petkovšek et al., 2011). In addition to recent mass movements, geomorphological indicators of the extensive fossil landslides can be found (Kočevar, 2011). Studies of fossil landslides help us to understand why the recent landslides occurred. Examples of fossil landslides in Vipava Valley are the Selo landslide, which is also the biggest known landslide in Slovenia (Popit, 2003; Popit & Košir, 2010; Košir et al., 2015) and the Gradiška Gmajna and Podrta gora fossil landslides. All three processes can be attributed to an earthquake-related event that transformed the fractured carbonates into rock avalanches (Verbovšek et al., 2017). Research and analysis of fossil landslides is very important, since they can provide us with a more accurate understanding of why and how recent landslides have occurred and relate them to base rock geology, tectonics, and local/regional climate events in the research area.

In this paper we present sedimentary characteristics of the heterogeneously composed Lozice fossil landslide. The landslide is located above the village of Lozice in the Rebrnice area in the Upper Vipava Valley. Previous research on this area and research done during the construction of the Razdrto–Vipava motorway (Skok, 2001, 2002; Popit & Košir, 2010) showed that half of the Rebrnice area is covered by scree deposits in the morphological shape of a fan (Jež, 2005). These fans were created by sedimentary gravity mass movements (Popit & Košir, 2010). Large quantities of slope deposits are concentrated in the forms of sedimentary bodies, formed as multi-component fossil landslides (Popit & Košir, 2010; Popit et al., 2013; Popit, 2016). On the basis of the lithological, stratigraphic and architectural characteristics of the slope deposit, in total sixteen facies were separated in the broader Rebrnice area, indicating the final articles of diverse sedimentary processes within complex and often interlaced and interdependent transport mechanisms in this area (Popit, 2016). Previous studies (Habič, 1968; Jež, 2005; Popit et al., 2011; Popit et al., 2014; Popit, 2016) also suggest that the deposition of Quaternary slope deposits of fossil landslides is bound by depressions and paleo-ravines in Eocene flysch.

Before and during the construction of the Razdrto–Vipava motorway, a large number of boreholes and excavation trenches were drilled and excavated in the vicinity of the motorway route. During the construction of this motorway, a portion of the Lozice fossil landslide started to creep due to construction (Jež, 2007). To prevent further movement, an intensive geotechnical research was performed. During that time, data were gathered in geotechnical reports (Skok, 2001, 2002), which show that the Lozice fossil landslide is heterogeneously composed of different sediments. In the analysis of the slope deposit of Lozice fossil landslide, these sediments were categorized into eight sedimentary facies (Popit, 2016), which follow in a stratigraphic order.

With a combination of existing information - lithological data from boreholes, studies regarding detailed sedimentological facies definitons (Popit, 2016) and available shaded digital terrain models (DTMs) obtained by airborne laser scanning, we have integrated this data with several new approaches, never published before. First, mapping of the Lozice fossil landslide was performed to outline the landslide and define its basic engineering-geological properties. From all available data, an informative 3-D model of Lozice fossil landslide has been made, based also on a detailed engineering-geological map of the fossil landslide, produced in ESRI ArcGIS. Such 3-D model, based on detailed facies recognition of the very heterogeneously composed Lozice landslide has not yet been done before for any landslide in the broader region, so we consider this an entirely new approach and result. Lidar airborne laser scanning, performed in the period of 2014–2015 (provided by the Surveying and Mapping Authority of the Republic of Slovenia), was also used to determine the extension of the fossil landslide. Lidar technology has already been successfully used in previous studies (Popit et al., 2011; Popit et al., 2014) to determine geomorphological characteristics on Rebrnice area. In addition, on the basis of borehole data, transverse and longitudinal cross-sections of the Lozice fossil landslide have been made to present the paleo-topography underneath the landslide.

Geological setting

The geological structure of the southwest part of Slovenia is composed of thrusts, nappes, and thrust sheets formed due to thrusting in the early Tertiary and neotectonic faults (Placer, 1981, 2008). The Upper Vipava Valley belongs to three different nappes (from structurally lowest to highest): the Komen, the Snežnik and the Hrušica nappes. The Rebrnice area is defined by a thrust front of Mesozoic carbonates of the Hrušica nappe, which is overthrusted on Tertiary flysch of the Snežnik nappe (Fig. 1). The upper part of the slope of the Vipava Valley is marked by steep carbonate cliffs, while the lower parts of the slope are more gently sloping and are composed of flysch bed rock covered by sedimentary bodies and Quaternary slope deposits (Fig. 1) with very complex genesis and composition (Popit & Košir, 2010; Popit et al., 2014; Popit, 2016). These sedimentary bodies are composed of several beds of mud- and matrix- to clast-supported gravel of carbonate and sandstone clasts and/or blocks (Popit, 2016).

The main objectives of the paper were first the combination of engineering-geological map with already existing data from boreholes and lidar-derived DTM. Engineering-geological mapping was used to determine the extension of the fossil landslide, with field mapping of the facies visible on the surface of the fossil landslide. Second objective was to integrate the data into a 3-D model, based on detailed facies recognition of the fossil landslide. Shaded DTM based on airborne laser scanning with a resolution of 1 × 1 m was very helpful at this stage. It provided the bare earth topography without the vegetation or other artificial constructions (buildings). We analysed information from 42 boreholes and eight excavation shafts made during the construction of Razdrto–Vipava motorway. Boreholes are distributed in a small area alongside and topographically above the motorway. Based on lithological data from boreholes and excavation trenches, sediments were categorized according to the specific sedimentary facies that were defined in previous studies (Popit & Košir,

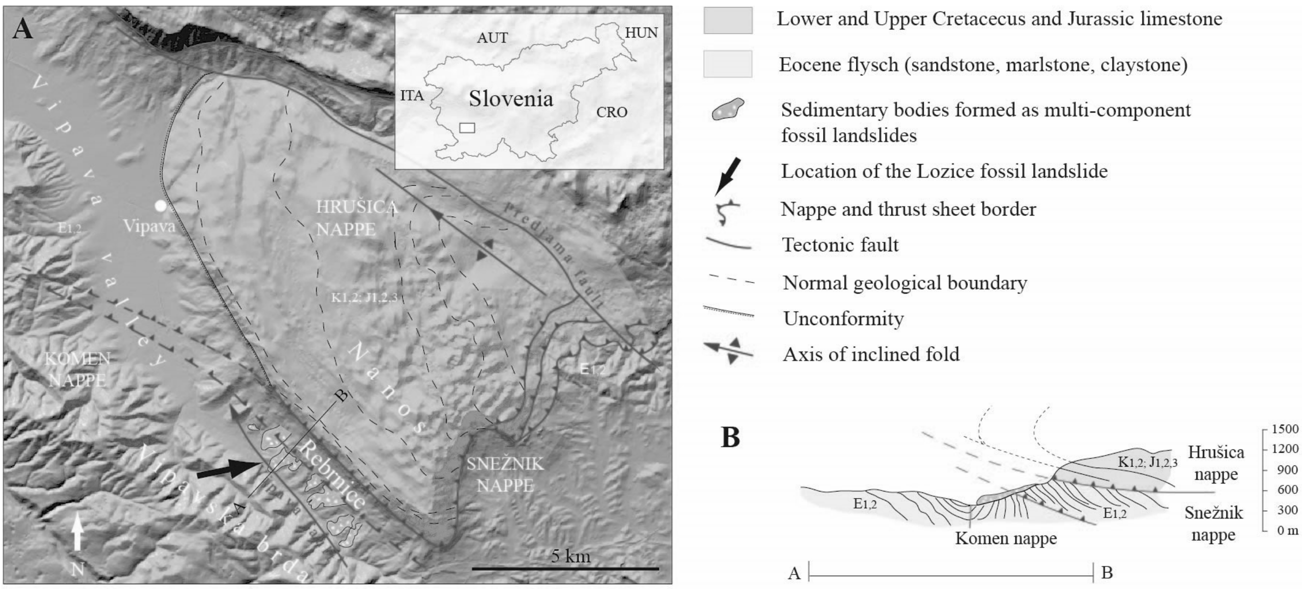

Fig. 1. Location of the studied area with (A) simplified geological map and (B) cross-section of the Vipavska Brda, the Upper Vipava Valley, and the Nanos plateau. Compiled from Placer (1981, 2008) and Popit et al. (2014). The location of the Lozice fossil landslide is marked with a pointer in Fig 1A. *The reader should refer to the online version of the article for the colour figure.*

2010; Popit et al., 2013; Popit, 2016). Sedimentary facies were later organized as GIS information layers, including the borehole name, depth, and geographic coordinates, and categorized facies. For each sedimentary facies logged in the borehole or excavation shaft, the data on its thickness and its upper and lower layers are given in metres above sea level and from the depth of the upper and lower sediment layers from the borehole mouth.

Methods

Analysis of the Lozice fossil landslide included engineering-geological mapping of the landslide, classification of sediments based on data from geotechnical reports (Skok, 2001, 2002), and classification of facies from previous studies (Popit & Košir, 2010; Popit, 2016), resulting in an informative 3-D model of a part of the fossil landslide and cross-sections through the fossil landslide.

The 3-D model of the landslide was made with the ArcScene application in ESRI ArcGIS software. For each facies layer, the upper and lower surfaces were made in the form of Triangulated Irregular Network (TIN) surface, which produced a wireframe object. TINs were made with 3-D Analyst Toolbox and were merged in 3-D Multipatch objects in ArcGIS. These were later exported to 3-D Analyst (Internet 1).

Data from boreholes and excavation shafts were also used to create transverse and longitudinal profiles through the landslide body. In these profiles, each facies is presented in a stratigraphic column with its corresponding thickness. Based on both profiles, a representation of the paleo-topography in the Eocene flysch under the fossil landslide was made, as well as correlations of some facies between the boreholes, in order to gain a better insight in a complex landslide body structure.

Results and discussion

Classification of sedimentary facies and field mapping

Five facies compose the body of the heterogeneously composed fossil landslide, while two form the bedrock underneath the landslide and one represents younger sediments deposited on the surface of the landslide. The facies (Popit & Košir, 2010; Popit et al., 2013; Popit, 2016) (generally ordered by top-most units) are as follows:

- (OGc) Facies of scree deposit of younger limestone gravel sediments, partially covering the surface of the fossil landslide and derives from carbonate cliffs via rock falls and toppling. In the topographically lower parts of its depositional area, the gravel is strongly agglutinated to the carbonate breccia. The facies is not part of the body of the fossil landslide.
- (C(M)Sc) Clast- (conditionally matrix-) supported carbonate gravel with a subordinate amount of carbonate cobbles and big blocks of a few cubic metres. Layers of this facies are from one to a few metres thick with sharp, mainly erosional and normal contacts. The facies is part of the body of the fossil landslide.
- (MCSfc) Matrix- to clast-supported sandstone, marlstone, and mudstone gravel ("flysch" gravel), with subordinate carbonate gravel. Clasts are occasionally normally graded in layers with erosional contacts deposited in the forms of lenses onto older sediments. The facies is part of the body of the fossil landslide.
- (MSf-B) Rare matrix-supported sandstone, marlstone, and mudstone gravel ("flysch" gravel), with clays and silts. Sediment is part of the body of the fossil landslide.
- (MCScf) Matrix to clast-supported carbonate gravel with subordinate sandstone, marlstone, and mudstone gravel ("flysch" gravel) with chaotic textures. The facies is part of the body of the fossil landslide.
- (MScf) Matrix- to clast-supported carbonate gravel, subordinate sandstone, marlstone, and mudstone gravel ("flysch" gravel) with clays and silts. The facies forms layers and lenses a few metres thick with sharp contacts. The facies is part of the body of the fossil landslide.
- (Wf) This facies of weathered Eocene flysch (sandstone, marlstone and mudstone) is part of the bedrock underneath the fossil landslide.
- (f) This facies of Eocene flysch is part of the bedrock underneath the fossil landslide.

Facies OGc, C(M)Sc, MCSfs, and f are visible on the surface and, on the basis of their outcrops, the geological map of the fossil landslide with its boundary was made (Figure 2). On the surface of the fossil landslide, the boundary between facies C(M)Sc and facies OGc is gradual between the heights of 400 and 450 m above sea level. Since the transition from facies C(M)Sc to facies OGc is gradual, the upward extension and the crown of the fossil landslide have been determined mainly by shaded DTMs obtained by airborne laser scanning and also by the last outcrops of the facies C(M)Sc on both flanks of the fossil landslide. With the exception of scree deposits, the surface of the Lozice landslide is covered by facies C(M)Sc and covers an area of 48 ha. It is divided into two fossil landslides, Lozice 1 and Lozice 2 (Fig. 2). Lozice 1 is smaller and covers 6 ha, while the Lozice 2 landslide is bigger and covers an area of 42 ha (Fig. 2). They are divided by a small narrow stream, which cuts and erodes probably all facies down to the bedrock of Eocene flysch (f).

Classification of facies and borehole data of the Lozice fossil landslide

Facies occur at different depths with lateral variableness in all 42 boreholes and eight excavation shafts (Table 1). The most common facies is C(M)Sc, which it is found in 32 boreholes and excavation shafts and overlays all the other facies. This is supported by field work data. Facies Wf is logged in 35 boreholes and excavation shafts and Eocene flysch (f) in 37. Another two

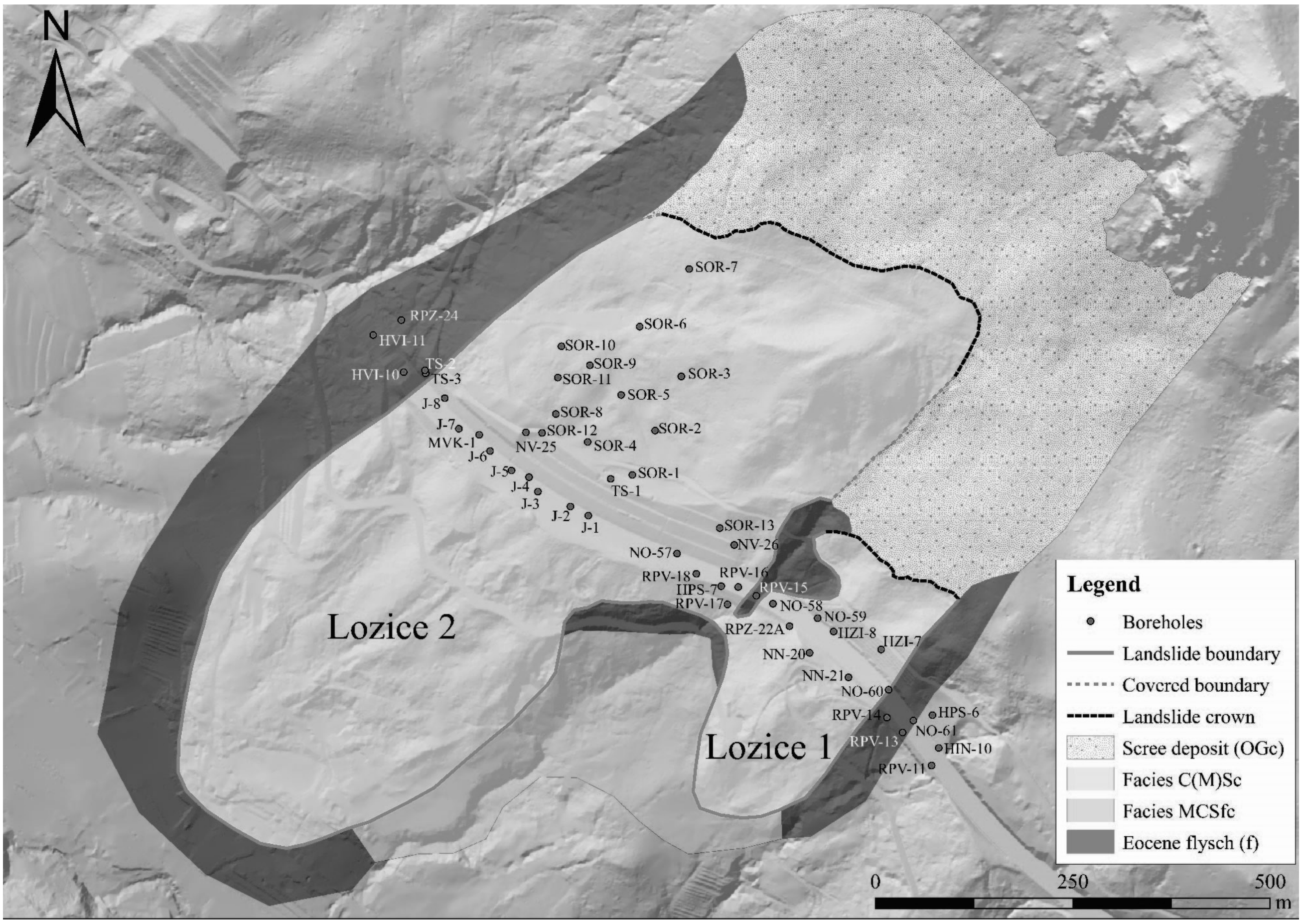

Fig. 2. Engineering-geological map of the heterogeneously composed Lozice fossil landslide, divided into two fossil landslides (after Novak, 2013; Popit, 2016). Boreholes and excavation shafts used as the data source in this research are located alongside the motorway. *The reader should refer to the online version of the article for the colour figure.*

common facies are MCSfc and MSf-B. Facies MCSfc is logged in 23 boreholes and excavation shafts and facies MSf-B in 17 boreholes and excavation shafts. Another two facies, MCScf and MScf, are logged in only a few boreholes or excavation shafts and are scattered all over the body of the Lozice fossil landslide. Later on, in the 3-D model, we represented only the five most common facies [C(M)Sc, MCSfc, MSf-B, Wf, and f] that are found in the body of Lozice fossil landslide. Since the other two types of facies, MCScf and MScf, are less common, we assume that they form lenses in the body of the landslide. Some facies are logged twice in two boreholes (SOR-10 and HZI-7). We assume that the reason for this is the intercalated lenses inside the body of the Lozice fossil landslide. The thickness of the Lozice fossil landslide varies and was estimated from borehole data at their locations. The deepest locations of bedrock based on the depth of facies Wf and f are at 37.7 in borehole SOR-12, 34.9 m in SOR-11, and 34.0 m in SOR-10. Other greater depths are at 21.5 m in SOR-9, 19.9 m in TS-1, 19.3 in SOR-13, 16.8 m in SOR-5, and 16.1 in SOR-4. These boreholes are located in the central and thickest part of the Lozice 2 fossil landslide. In other areas, the landslide is much shallower: it does not exceed 15 m in thickness and has an average thickness of 10.7 m; however the thickness of Lozice 2 fossil landslide is much greater than that of Lozice 1 fossil landslide. Based on borehole data, the average thickness of the Lozice 1 fossil landslide is 6.2 m, while the average thickness of the Lozice 2 fossil landslide is 13.3 m.

The water table was measured in boreholes SOR-1, 2, 3, 4, 6, 7, 8, 9, 10, and 13 between April and May 2002 (except for SOR-13, which was measured in July 2002). Depths to the water table varied a lot in this period, ranging between 8.9 and 20.2 m. There was no spatial correlation among the boreholes. As there was no continuous monitoring of the water tables, we cannot comment on the influence of ground water on the landslide movements. However, the calculated height of the water column above the well bottoms ranged from 1.4 to 30 m (12 m on aver-

Table 1. Distribution of facies in boreholes and excavation shafts of the Lozice fossil landslide. Data for total borehole or excavation shaft depth and facies thickness are given in metres.

SOR-1	**SOR-2**	**SOR-3**	**SOR-4**	**SOR-5**
C(M)Sc (10.3 m)	C(M)Sc (3.8 m)	C(M)Sc (0.8 m)	C(M)Sc (10.2 m)	C(M)Sc (5.6 m)
MScf (0.8 m)	MCSfc (7.7 m)	MCSfc (9.9 m)	MCScf (3.4 m)	MSf-B (11.0 m)
MCSfc (2.0 m)	Wf (0.4 m)	MSf-B (2.6 m)	MCSfc (2,3 m)	Wf (1.0 m)
Wf (5.0 m)	f (9.9 m)	Wf (2.0 m)	Wf (2.7 m)	f (4.2 m)
f (3.2m)	Total depth: 21.8 m	f (8.5 m)	f (5.2 m)	Total depth: 21.8 m
Total depth: 21.3 m		Total depth: 23.8 m	Total depth: 23.8 m	
SOR-6	**SOR-7**	**SOR-8**	**SOR-9**	**SOR-10**
C(M)Sc (5.5 m)	C(M)Sc (1.2 m)	C(M)Sc (11.7 m)	C(M)Sc (10.4 m)	C(M)Sc (9.8 m)
MCSfc (3.3 m)	MCSfc (8.2 m)	MScf (1.2 m)	MSf-B (6.2 m)	MCScf (6.4 m)
Wf (1.8 m)	f (11.4 m)	MCSfc (8.2 m)	MCSfc (4.7 m)	MCSfc (0.8 m)
f (10.9 m)	Total depth: 20.8 m	MSf-B (18,9 m)	Wf (2.8 m)	MSf-B (5.9 m)
Total depth: 21.5 m		Wf (1.0 m)	Total depth: 24.1 m	MCSfc (3.3 m)
		f (3.0 m)		MSf-B (6.1 m)
		Total depth: 44.0 m		MCSfc (1.5 m)
				Wf, (6.0 m)
				Total depth: 39.8 m
SOR-11	**SOR-12**	**SOR-13**	**TS-1**	**TS-2**
C(M)Sc (11.8 m)	C(M)Sc (11.1 m)	C(M)Sc (1.6 m)	C(M)Sc (13.8 m)	f (12 m)
MSf-B (19.1 m)	MSf-B (4.9 m)	MCSfc (16.4 m)	MCScf (0.4 m)	Total depth: (12.0 m)
MCSfc (3.8 m)	MCSfc (21.7 m)	Wf (2.7 m)	MCSfc (5.7 m)	
f (0.2 m)	f (1.3 m)	Total depth: 20.7 m	Wf, (1.1 m)	
Total depth: 34.9 m	Total depth: 39.0 m		Total depth: 21.0	
TS-3	HPS-6	HPS-7	HIN-10	HVI-11
f (12 m)	MCSfc (7.7 m)	C(M)Sc (2.5 m)	MCSfc (10.2 m)	MCSfc (0.9 m)
Total depth: (12.0 m)	f (9.0 m)	MCSfc (2.3 m)	Wf (1.5 m)	Wf (3.5 m)
	Total depth: 16.7 m	Wf (2.0 m)	f (7.0 m)	f (10.4 m)
		f (14,0 m)	Total depth: 18.7 m	Total depth: 14.8 m
		Total depth: 20.8 m		
RPV-11	**RPV-13**	**RPV-14**	**RPV-15**	**RPV-16**
f (16.8 m)	MCSfc (6.4 m)	f (9.8 m)	MCScf (1.4 m)	MCSfc (6.6 m)
Total depth: 16.8 m	Wf (0.5 m)	Total depth: 9.8 m	MCSfc (4.6 m)	f (8.2 m)
	f (6.8 m)		f (5.8 m)	Total depth: 14.8 m
	Total depth: 13.7 m		Total depth: 11.8	
RPV-17	**RPV-18**	**NO-57**	**NO-58**	**NO-59**
MCScf (4.7 m)	C(M)Sc (1.5 m)	C(M)Sc (0.7 m)	MSf-B (0.8 m)	MCScf (1.2 m)
Wf (2.0 m)	MSf-B (2.2 m)	Wf (3.2 m)	Wf (5.0 m)	Wf (2.1 m)
f (6.0 m)	Wf (3.2 m)	f (15.9 m)	f (6.0 m)	f (4.5 m)
Total depth: 12.7 m	f (4.8 m)	Total depth: 19.8 m	Total depth: 11.8 m	Total depth: 7.8 m
	Total depth: 11.7 m			
NO-60	**NO-61**	**HZI-7**	**HZI-8**	**MVK-1**
C(M)Sc (0.6 m)	MSf-B (1.1 m)	C(M)Sc (3.3 m)	C(M)Sc (10.0 m)	C(M)Sc (11.2 m)
Wf (5.2 m)	MCSfc (2.2 m)	MCScf (3.0 m)	MSf-B (0.8 m)	MSf-B (0.7 m)
f (6.9 m)	Wf (0.5 m)	MCSfc (2.8 m)	Wf (6.0 m)	Wf (1,2 m)
Total depth: 12.7 m	f (3.0 m)	MCScf (1.0 m)	f (9.0 m)	f (10.3 m)
	Total depth: 6.8 m	Wf (2.5 m)	Total depth: 25.8 m	Total depth: 23.4 m
		f (8.5 m)		
		Total depth: 21.1 m		
HVI-10	**NN-20**	**NN-21**	**RPZ-22A**	**RPZ-24**
MCSfc (0.6 m)	C(M)Sc (6.0 m)	C(M)Sc (3.6 m)	MScf (3.7 m)	f (5.3 m)
Wf (4.1 m)	Wf (7.6 m)	MScf (1.8 m)	Wf (2.7 m)	Total depth: 5.3 m
f (10.1 m)	f (1.0 m)	Wf (4.7 m)	f (5.3 m)	
Total depth: 14.8 m	Total depth: 14.6 m	f (0.4 m)	Total depth: 11.7 m	
		Total depth: 10.5 m		
NV-25	**NV-26**	**J-1**	**J-2**	**J-3**
C(M)Sc (10.0 m)	C(M)Sc (8.1 m)	C(M)Sc (1.7 m)	C(M)Sc (1.6 m)	C(M)Sc (0.6 m)
Total depth: 10.0 m	Wf (1.9 m)	MSf-B (1.0 m)	MSf-B (1.6 m)	MSf-B (0.8 m)
	f (1.7 m)	Wf (0.4 m)	f (0.2 m)	MCScf (3.0 m)
	Total depth: 11.7 m	Total depth: 3.1 m	Total depth: 3.4 m	Total depth: 4.4 m
J-4	**J-5**	**J-6**	**J-7**	**J-8**
MCScf (1.7 m)	C(M)Sc (0.2 m)	C(M)Sc (3.0 m)	C(M)Sc (1.8 m)	C(M)Sc (4.2 m)
Wf (0.7 m)	MSf-B (1.4 m)	Total depth: 3.0 m	MSf-B (1.0 m)	Total depth: 4.2 m
Total depth: 2.4 m	Wf (0.4 m)		Wf (0.2 m)	
	Total depth: 2.0 m		Total depth: 3.0 m	

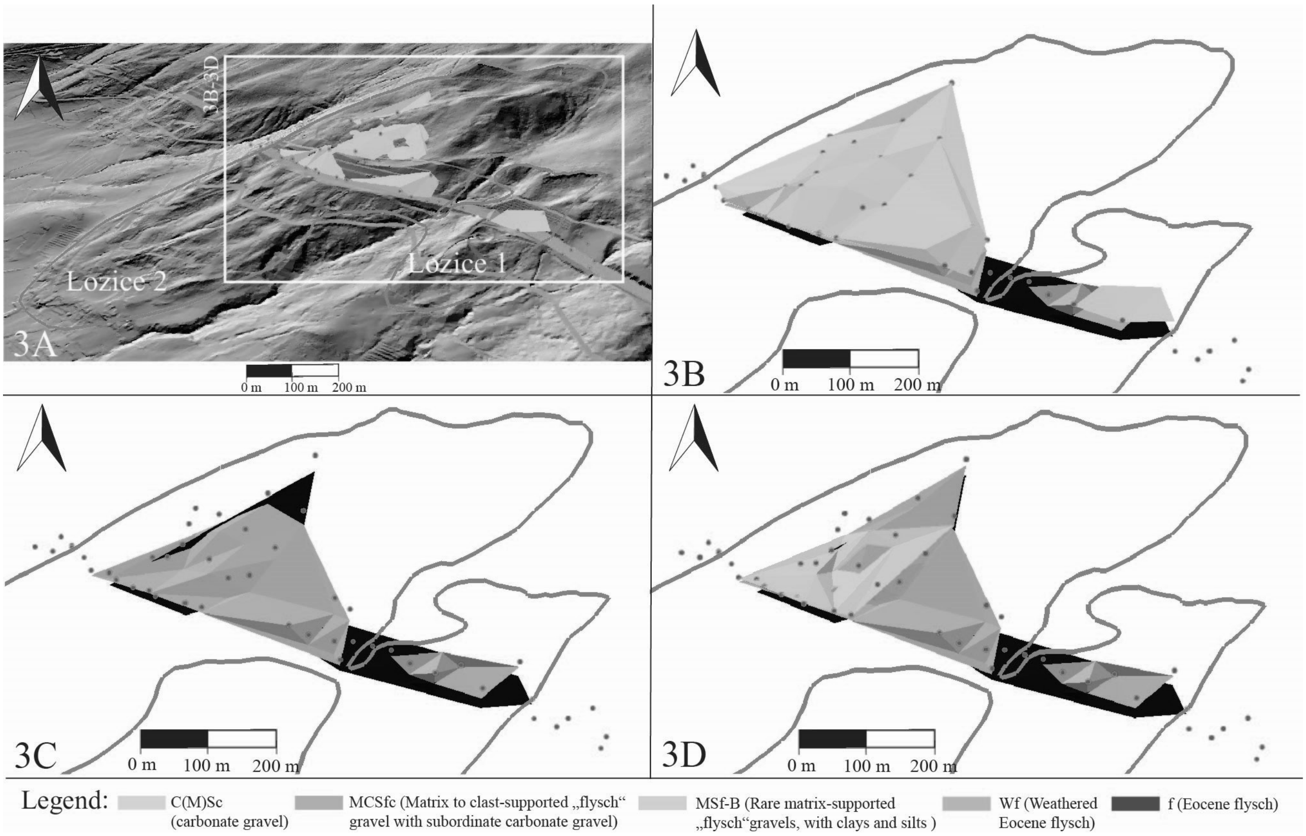

Fig. 3. 3-D model of the Lozice fossil landslide. Fig. 3A shows the fossil landslide on shaded digital terrain models (DTMs) with a resolution of 1 × 1 m obtained by airborne laser scanning with boreholes and facies C(M)Sc, which is visible on the surface of the landslide. Figs. 3B to 3D show the enlarged area of the fossil landslide where the 3-D model is located. Facies C(M)Sc (Fig. 3B, yellow) overlies all the other facies. In Fig. 3C, the Eocene flysch (dark brown) is covered by weathered flysch (light brown) and both facies represent bedrock. Facies MCSfc (violet) and facies MSf-B (light blue) in Fig. 3D lie above bedrock and are intertwined with each other. *The reader should refer to the online version of the article for the colour figure.*

age) in the relatively normal water table season. The height of water above the upper flysch surface was 0.4 to 6 m in the boreholes SOR-1, 2, 3, 4 and 6, 20.8 m in SOR-8, and 2.3 m below the upper flysch surface in SOR-7. Boreholes SOR-9, 10, and 13 did not encounter the flysch facies. Based on these data, we consider the presence of the water to be quite important, as more than 10 m, on average, of saturated sediments and flysch above the borehole bottom and a few metres of saturated deposits above the less permeable flysch contributes to weathering of these sediments and consequently lower their geomechanical properties. Further monitoring of water levels should be performed to investigate the yearly water table fluctuations.

The Razdrto–Vipava motorway is also being built across Lozice fossil landslide. Clast- (conditionally matrix-) supported carbonate gravel deposit of facies C(M)Sc is deposited on facies MSf-B and flysch rocks. The sediment of facies C(M)Sc is unstable and is gradually sliding downslope because of slope inclination, underground water, and clayey zones of MSf-B facies. The recent movements of reactivated parts of the Lozice fossil landslide were measured by means of inclinometer wells and by data from some recent movement in the Rebrnice area. Sliding has already caused regional road deformations, cracks on some new motorway sections, and damage to objects in the village of Lozice. The movements in the geomechanical-inclinometer wells measure between a few millimetres and a maximum of 15 mm monthly. A scarp up to 3 m wide formed high up on the slope. The landslide was stopped by the anchor pile wall (Jež, 2007).

Three-dimensional model of Lozice fossil landslide

Although the map in Figure 2 shows mostly one prevailing facies, the structure of the landslide is much more complex, as inferred from the boreholes. Therefore, a simple 3-D model (Fig. 3) represents the position of the most common facies in the space inside the body of Lozice fossil landslide. Boreholes are not distributed evenly over the surface of the fossil landslide but are

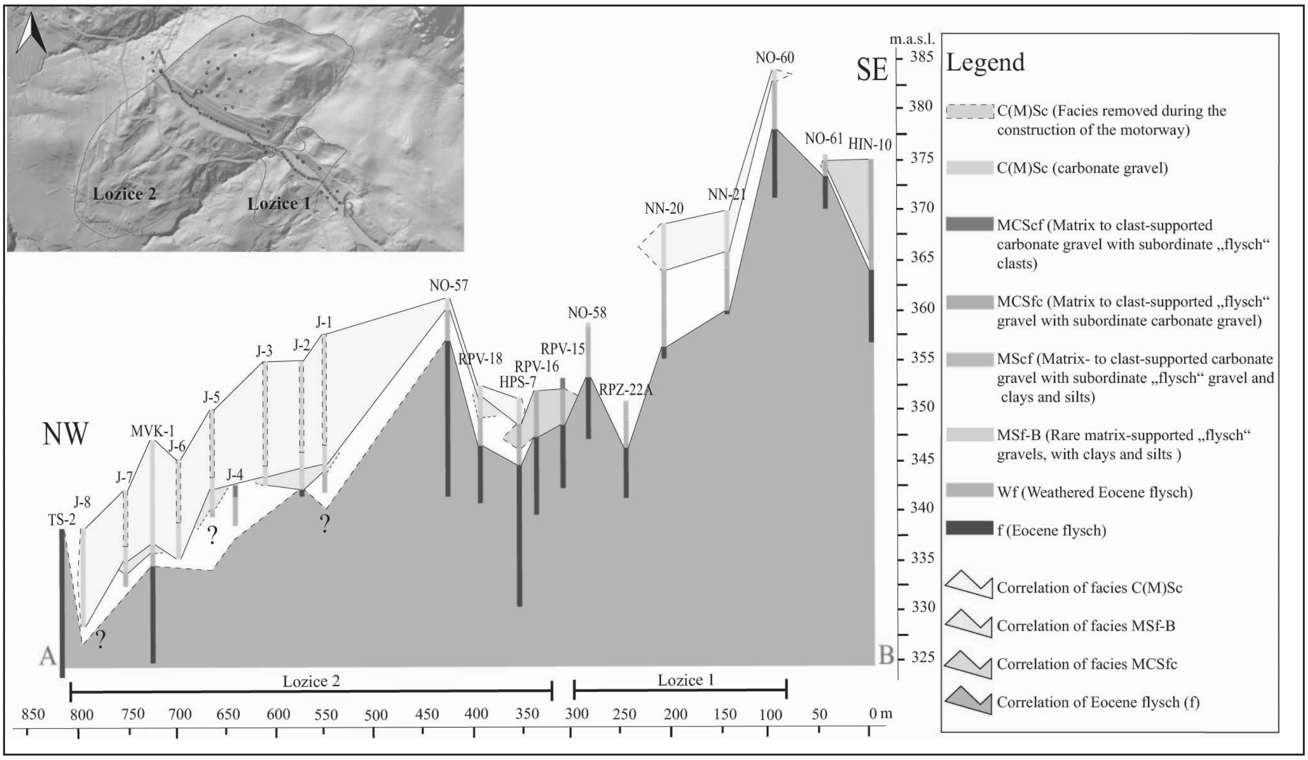

Fig. 4. Transverse cross-section through the Lozice fossil landslide with logged facies and correlations with facies C(M)Sc, MSf-B, MCSfc, and Eocene flysch. *The reader should refer to the online version of the article for the colour figure.*

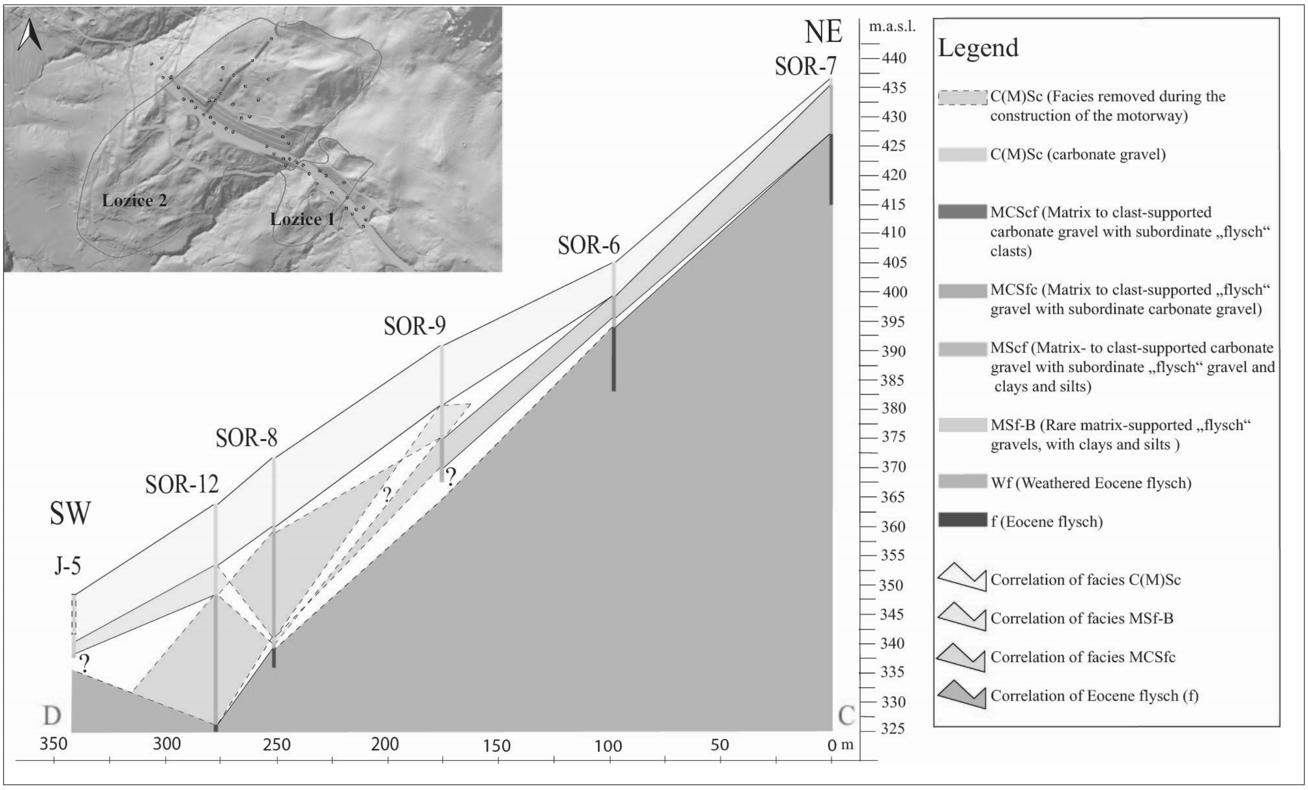

Fig. 5. Longitudinal cross-section through the Lozice 2 fossil landslide with logged facies and correlations with facies C(M)Sc, MSf-B, MCSfc, and Eocene flysch. *The reader should refer to the online version of the article for the colour figure.*

concentrated in a small area alongside and topographically above the motorway. This area covers only 8 ha, which is about one-fifth of the landslide area. That is why the 3-D model, presented in this paper, has an informative nature but still offers a more detailed insight into a smaller part of the landslide. Obviously the facies are distributed vertically in a stratigraphic order. Facies C(M)Sc is stratigraphically the highest and overlays all other facies (Fig. 3A and 3B). It also extends over the complete surface of the landslide, which has also been proven by field mapping. The bedrock is represented by Eocene flysch (f) and weathered Eocene flysch (Wf) facies (Fig. 3C). Flysch (f) and weathered flysch (Wf) facies are overlaid by the MCSfc and MSf-B facies (Fig. 3D) in the Lozice 2 fossil landslide. Facies C(M)Sc, MCSfc, and MSf-B represent the body of the fossil landslide that has been deposited over the flysch facies (f) and weathered flysch (Wf). The facies of MCSfc and MSf-B are clearly intercalated (Fig. 3D), while the facies C(M)Sc overlies all other facies (Fig. 3B). Unfortunately, the data of the Lozice 1 fossil landslide were insufficient to create a 3-D representation of any facies layers other than the bedrock (facies f and Wf) and overlying facies C(M)Sc.

Transverse and longitudinal cross-sections over the Lozice fossil landslide

A transverse cross-section (Fig. 4) based on borehole data shows a complex composition of the fossil landslide. In the area of the fossil landslide Lozice 1, facies C(M)Sc is laying above the facies Wf and f with a few lenses of facies MCSfc and MScf. In the area of Lozice 2, facies C(M)Sc is present on top of all the boreholes. Its thickness varies from 1 m (boreholes RPV-18 and NO-57) up to 10 m (boreholes MVK-1 and J8). In the excavation trenches (from J-1 to J-8) we have estimated the thickness of facies C(M)Sc based on elevation in the topographic map. A portion of facies C(M)Sc was dug and removed during construction of the motorway, but in most of the excavation trenches, it was still present. The thickness of the facies in the cross-section was extended up to the topographic elevation before the construction of the motorway. Other facies are not present in all of the boreholes. Facies MSf-B is most common, with a maximum thickness of 2.5 m, while facies MCScf is present only in the form of thin lenses (not more than 1 m thick). Facies C(M)Sc is not present in boreholes between fossil landslides Lozice 1 and Lozice 2 due to stream erosion. Facies Wf and f lie under the fossil landslide. They are present in almost all boreholes, but only in half of the excavation trenches. At those locations, the depth of the fossil landslide is unknown. Since the cross-section is based on the location of boreholes, it is not perpendicular to the fossil landslide. A perpendicular cross-section would give us a better cross-section of paleo-topography. The paleo-topography is indicated in the Wf and f facies in the transverse cross-section. Concave depressions are best seen in the case of the Lozice 2 fossil landslide, which confirms the findings of previous studies by Habič (1968), Jež (2005), Popit et al. (2011), Popit et al. (2014) and Popit (2016) that the deposition of fossil landslides in the Rebrnice area was bounded by depressions and paleo-ravines in the Eocene flysch bedrock.

A longitudinal cross-section was made for the Lozice 2 fossil landslide and it passes through five boreholes and one excavation trench (Fig. 5). Facies C(M)Sc is again situated on top, and underneath it are other sediments. The thickness of facies C(M)Sc is over 10 m. In the profile, the overlapping and underlapping of facies MCSfc and facies MSf-B are again visible, as in the 3-D model.

Conclusion

In the paper we have integrated previously available data from boreholes (basic lithological descriptions), sedimentological facies definitions and shaded lidar-derived DTM, with new approaches, never published before: mapping of the landslide, resulting in a detailed map, and more importantly, integration of all data in a 3-D model of the landslide. Such a model, based on facies description of the heterogeneously composed Lozice landslide has not yet been done before. Although the model could not be done for the complete area of the landslide due to presence of boreholes only along the narrow band of the highway, our results show that it can be useful in 3-D visualization and further possible volume quantification of very detailed sedimentological descriptions. Such approach also enables to focus on the individual sedimentological unit, often irregularly-shaped and difficult to visualize in 3-D cross-sections. In the future, the model could be improved by drilling additional boreholes in the complete area of the landslide, and most importantly, in such a case it would be possible to calculate the volumes of each sedimentary facies. Field mapping does not reveal what is below the surface, and separate facies cannot be distinguished on such precise level with ground penetrating radar profiling (or other geophysical research). The only possible method of obtaining the data is therefore by drilling several more boreholes and/or excavation trenches. With both of these, lenses and intertwined facies are clearly distinguished.

A detailed engineering-geological map supported with hillshaded DTM shows, that the Lozice fossil landslide covers an area of 48 ha. It can be broadly divided into the smaller eastern fossil landslide (Lozice 1, 6 ha) and the larger western fossil landslide (Lozice 2, 42 ha), separated by a small stream that has already eroded most of the sediments that belong to the body of the fossil landslide. Both parts are composed of several different facies, making them highly heterogeneous. Based on borehole data we determined, in detail, eight different sedimentary facies, which clearly indicate multiple interlaced and interdependent depositional events and various gravity mass-movement processes ranging from slides to flows. The bedrock is composed of facies of Eocene flysch (f) and weathered Eocene flysch (Wf), which form the base on which the landslide sediments are deposited. The base is clearly visible in cross-sections as paleo-topography, thus confirming previous research findings that the fossil landslides in Rebrnice are deposited and bounded by paleo-topography. Among other facies, the three most common, deposited in stratigraphic order, are facies MCSfc, MSf-B, and C(M)Sc. Facies MCSfc is composed of matrix- to clast-supported sandstone, marlstone, and mudstone gravel with subordinate carbonate gravel. Facies MSf-B is formed of rare matrix-supported sandstone, marlstone, and mudstone gravel with clays and silts, while facies C(M)Sc is composed of clast- (conditionally matrix-) supported carbonate gravel with a subordinate amount of carbonate cobbles and of few cubic metres big blocks. Facies C(M)Sc covers the surface of the fossil landslide, while facies MCSfc and facies MSf-B lie below facies C(M)Sc and occasionally intercalate with each other. Facies MCScf and MScf are less common and we assume that they form lenses in the body of the fossil landslide. Similar lenses were also recognized in other fossil landslides in the Rebrnice area (Popit & Košir, 2010; Popit et al, 2013). Sediments of Lozice fossil landslide are now partially covered (especially in the upper part of the landslide) by the youngest scree deposit (OGc). Due to its highly heterogeneous composition, the genesis and movement of the landslide in the geological past is very complex. It's complex structure, presence of the water table, clayey zones and recent reactivated part of the fossil landslide suggest that future movement is possible.

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