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Abstract

The studied rock collapse structure is located on the Liburnian coast (Rijeka Bay, channel zone of the NE Adriatic). The relief of the southern part of this coast, with a length of 6.5 km, is a large escarpment with very steep to vertical slopes reaching heights of 100 m above sea level, as a result of tectonic movements along the Kvarner fault zone. These events probably led to a sudden relaxation of the highly fractured rock mass. The progressive expansion occurred at locations where previously favourably oriented faults and fissures had formed a polygonal rock collapse resembling a rock-slide which is the focus of this study. Another aim of this study is to reconstruct and explain the complex morphological evolution of the studied landslide, from the pre-failure deformations, through the failure itself, to post-failure displacements, as well as possible future instabilities. Recent techniques to survey the instability, location and to analyse the evolution of the rupture surface and its dimensions were combined (Unmanned Aerial Vehicle, Side Scan Sonar and Remotely Operated Vehicles). The estimated total volume of displaced rock mass is 950,000 m^3. The lower part of the instability phenomenon was submerged during the Holocene sea level rise. Since then, a large part of the displaced rock mass has been in a stable position, with sporadic rock falls. However, given unfavourable orientation and discontinuity characteristics, as well as unfavourable environmental influences, possible instabilities might also be expected in the future.

1. INTRODUCTION

The Liburnian coast is located on the western coast of Rijeka Bay. It is part of the Kvarner channel zone of the northeastern Adriatic (Figure 1). The relief of the southern part of this coast looks like an escarpment. This escarpment, with a length of 6.5 km, is characterized by very steep to vertical slopes, which reach a height of 100 m above mean sea level. The submarine slopes are also very steep, so that the –50 isobaths run close to the coastline according to the Navionics Chart (Figure 1a).

High seismicity indicates active tectonic activity in recent times in the Kvarner area (MARKUŠIĆ et al., 2019; KORBAR et al., 2020). The northward displacement of the Istrian peninsula has been determined based on GPS measurements (WEBER et al., 2010). An Istrian normal fault or the Kvarner fault zone striking NNE-SSW along the Liburnian coast is very tectonically active (DEL BEN et al., 1991; KORBAR, 2009; PLACER et al., 2010). As a result of tectonic movements, very steep or vertical scarps are formed in the carbonate rocks or at the carbonate - flysch contact according to the authors.

Rock falls and rock slides have been found and described in the Kvarner area in the Rječina river valley along the carbonate – flysch contact (BENAC et al., 2009; BENAC et al., 2011). Several active or dormant landslides of smaller dimensions formed in colluvium deposits on flysch have been found on the Kvarner coasts, and they are a cause of marine erosion (JURAČIĆ et al., 2009; RUŽIĆ et al., 2014). Landslides on the Italian Adriatic coast have a similar cause (IADANZA et al., 2009). However, the correlation between the numerous high escarpments and the possible

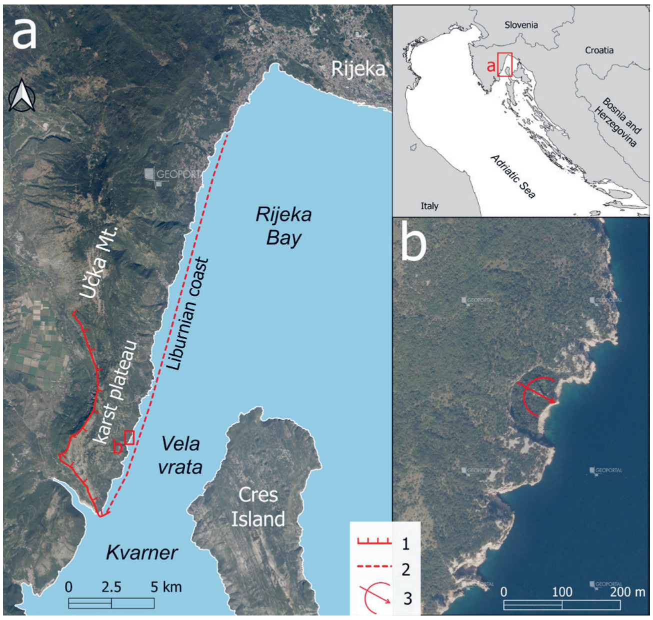

Figure 1. Location maps: a) the Liburnian coast b) study area. Legend: 1. south Učka Mt. reverse faults 2. suposed strike of Kvarner fault zone, 3. studied collapse structure.

instability phenomena along the Kvarner coast has not yet been scientifically explained.

The large gravitational rock collapse on the Liburnian coast studied here (Figure 1b) is located on a terrain with very steep coastal morphology, accessible only from the sea. The vertical scarps bordering the sliding body are up to 100 m high, and the landslide toe is at a depth of about 40 m below mean sea level. Modern techniques offer the possibility to explore the phenomena under these conditions (JAMES & ROBSON, 2012; FONSTAD et al., 2013). Here, the aforementioned scarps were surveyed using an Unmanned Aerial Vehicle (UAV)[1].

Recent surveying techniques are also being used in investigating submarine zones (SHANG et al., 2019). In this research, the submarine zone was surveyed using a side-scan echo sounder and diving equipment, and Remotely Operated Vehicles (ROVs). Based on the results obtained from the proposed methodology and analyses presented in the paper, the origin and geomorphological evolution of the investigated rock collapse is presented and discussed.

2. GEOLOGICAL STRUCTURE AND GEOMORPHOLOGICAL EVOLUTION

The wider study area is part of the lower (southern) overthrust of the ridge of the Učka Mt. (Figure 1a). Overturned folds and reverse faults of the paraclasis dipping northeast, are common within the lower overthrust. Upper Cretaceous rudist limestones predominate in the southern Liburnian coastal zone. The limestone rocks exhibit distinct bedding. The bedding planes are mostly inclined to the east and southeast. The flysch rock mass is squeezed between the carbonate rocks and is mostly covered by younger colluvial deposits. Tectonic breccia has been found near reverse faults (ŠIKIĆ et al., 1969; HGI, 2009).

The movement of the Adria plate towards the northeast and north is the main cause of the geodynamic evolution of the Istrian peninsula and the Kvarner area (MARINČIĆ & MATIČEC, 1991). This evolution took place in two phases: the first phase from the Eocene to the Pliocene and the second phase from the Upper Pliocene to the present. During the first phase, the principal regional stress was NE–SW. The structures formed during this phase have a Dinaric strike (NW–SE). It is considered that the main uplift with exhumation in the Kvarner area occurred during the first phase of the Dinaridic compression. The absence of Miocene and Pliocene marine sediments indicates that the eastern slopes of Učka Mt. may have remained emerged since the late Neogene (KORBAR, 2009). This emersion caused the denudation of siliciclastic sediments and the beginning of intense karstification. The Istrian peninsula was separated from the highly deformed Adriatic segment with the Kvarner fault zone and rotated towards the northeast where it is underthrust beneath the External Dinarides (PLACER et al., 2010).

During the second phase of the orogeny, the principal regional stress changed to a N-S direction. This change caused the reactivation of pre-existing structures. During this tectonic phase the Učka Mt. ridge acquired its present-day NNE-SSW (meridional) strike (MARINČIĆ & MATIČEC, 1991). Transpression and radial extension during the last phase of regional stress caused deformation of younger diagonal and transverse dextral strike-slip faults and opposite vertical tectonic movements on the eastern slopes of Učka Mt. The key prerequisite for the appearance of today's very steep southern Liburnian coast is the structural arrangement of the discontinuities in the carbonates along the Kvarner fault zone (MIHLJEVIĆ, 1996). The relatively rectilinear extension of the Liburnian coast is believed to be a consequence of the Kvarner fault zone or the Istrian fault (DEL BEN et al., 1991). The interruption of the geological structures of the Kvarner islands towards the northwest is visible on geological maps (KORBAR, 2009).

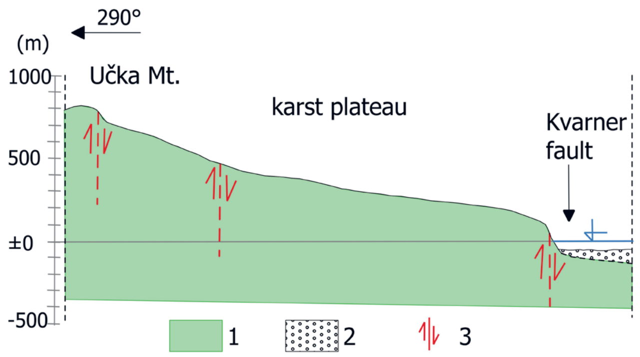

Figure 2. Simplified geological cross-section of the wider area. 1 – carbonate rock mass, 2 – marine sediments, 3 – neotectonic fault

A relatively narrow and elongated karst plateau is located between the ridge of the southern Učka Mt. and Rijeka Bay. This plateau is slightly inclined towards Rijeka Bay and is strongly limited by the aforementioned escarpment along the Liburnian coast. Due to the carbonate rock mass disintegration and erosion, slope deposits have accumulated at the foot of the fault (MIHLJEVIĆ, 1996). This rock mass is karstified to about 70 m below recent sea level. Intense morphogenetic processes caused by neotectonic movements and rapid changes in sea level, as well as climatic changes, have shaped the present form of the Kvarner area, and also the relief of the studied area (BENAC & JURAČIĆ, 1998) (Figure 2).

3. METHODS

A wide coastal area was surveyed using a UAV in October 2021. The survey covered a coastal strip with a length of about 6.5 km and an average width of about 100 m. Based on UAV acquired images, a photorealistic 3D model was created. After a detailed analysis of this photorealistic model, the instability phenomenon and a study zone were selected for a detailed survey.

The second UAV survey was conducted in May 2022. The 3D point cloud was generated using the Structure from Motion (SfM) with Multi-View Stereo (MVS) photogrammetry. The image sets were processed using SfM-MVS software Agisoft Metashape Professional, v1.7.1. Images were captured in JPG format using the UAV DJI Phantom 4 Professional, FC6310 camera with 20-megapixel, 100 CMOS sensor, 8.8 mm focal length. Due to its complex morphology, images were taken from different distances from the coastline, and from different camera angles. The overlap between images was constant, with all areas covered by more than 9 overlapping images. A total of 604 images were acquired for the 0.0437 km² of complex coastline. The flight altitude was 26 m, resulting in a ground resolution of 1.05 cm/pixel.

ShapeMetriX UAV is used for metric acquisition of rock and terrain surfaces and noncontact measurement of geological/geotechnical parameters through 3D metric models. Results obtained include comprehensive documentation of the 3D model, geometry of imaged rock faces, measurement of geometric features such as points, distances, areas, spatial orientations, and integrated features for determining space, or hemispherical plots.

Site mapping, i.e., seafloor morphology analysis, which included bathymetry survey, 3D mapping, and seafloor profile scan-

[1] Shape Metrix UAV - 3D imaging for measuring and assessing rock and terrain surfaces - drone imagery. User Manual for Version 4.3. 3GSM GmbH, Graz, 2021. https://3gsm.at/produkte/shape-metrix-uav/

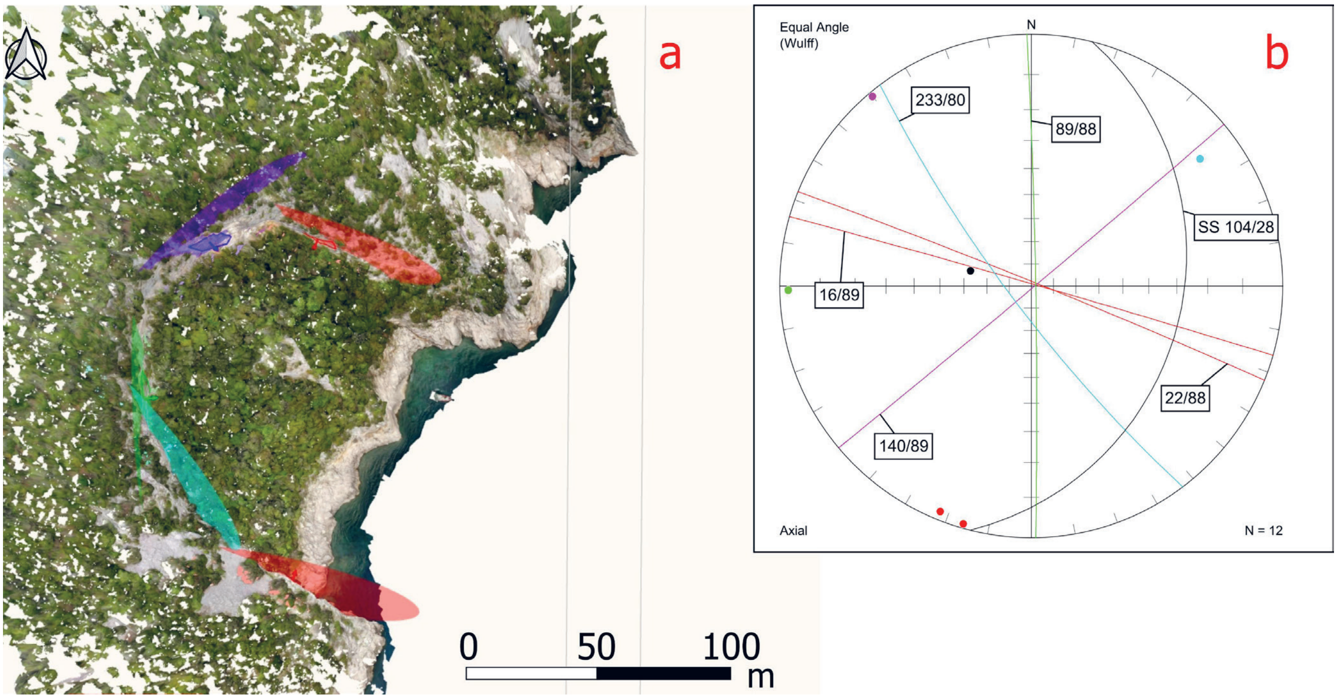

Figure 3. a) Photorealistic 3D model of the study area, acquired by SfM-MVS photogrammetry, b) analysis of the orientation of discontinuity planes (faults and fissures).

ning, was conducted with Humminbird Solix 12 side-scan sonar CHIRP MSI + GPS G2. The measurements were post-processed using Humminbird's Autochart Pro software. This sonar combines tournament-ready MEGA Side Imaging+, MEGA Down Imaging+, and Dual Spectrum CHIRP sonar technologies. This high-resolution 1,100 kHz sonar is suitable for selected sites, i.e., for measurements at relatively shallow depths down to 60 metres. Other operating frequencies of the sonar are 200, 455, and 800 kHz.

The size of the surveyed area (at the sea surface) was approximately 190 m × 80 m or 15,200 m^2. The sonar was mounted on a RIB (Rigid Inflatable Boat) below the hull and engine to avoid interference. During the survey, the sea was calm and the cruising speed was 2 knots. To obtain the most accurate data, the area was surveyed in a mesh pattern, i.e., navigating parallel and perpendicular to the shoreline at 10 m intervals. The depths obtained were corrected for tidal height during recording and therefore represent depths based on a hydrographic datum (chart datum).

Interesting parts of the submarine slopes were surveyed using diving equipment and an ROV. Video and photo documentation of the sea bottom relief was obtained using the Blueye Pioneer inspection class ROV manufactured by Blueye Robotics and installed on a boat anchored in the middle of the surveyed area near the coast. The ROV has a built-in FHD camera with a light-sensitive wide-angle lens (1080p / 30 fps) and a powerful 3300-lumen LED, which allows recording at night, at great depths, and/or in poor visibility conditions. Four powerful 350-watt thrusters enabled fast and precise movements in all directions.

The ROV was immersed in the sea and imaging began immediately from the sea surface. This vehicle was operated according to a predetermined movement and recording plan. The plan called for recording two straight transects perpendicular to the shoreline. The first transect ran from the shallowest part of the sea bottom near shore along the entire slope to its end at depth, i.e., to the area where the shallow sea-bottom with fine sediments begins, at approximately -50 m. The second transect was in the opposite direction, from the bottom of the slope to the shallowest area near the shore. Both transects were located in the central part of the study area and were approximately 30 m apart.

It should be emphasised that the ROV used is designed to always be in an upright position, which means that all underwater objects and slopes seen in the photos and videos are as in reality. Based on the video documentation recorded by the ROV, a geological map of the submarine part of the investigated site was created. However, data obtained from SfM-MVS photogrammetry were very useful in interpreting the surface part of the geological map. All modern imaging techniques of both the surface and underwater parts of the study area were used in the detailed interpretation and morphological evolution analysis of the resulting rock mass failure. Using the overall 3D model and known facts from the previous research, the morphological analysis of the wider area was presented. Key points needed to complete the whole theory of the origin of the rock mass failure were analyzed in detail, presented in the results, and later discussed in the morphological evolution of investigated rock slide as well as in the tectonic interpretation of the collapse structure.

4. RESULTS

The extension of the linear coastal escarpment, located at the edge of the karst plateau of the southern Liburnian coast, is interrupted by the semi-circular rock collapse. The studied collapse structure is separated from the edge of the karst plateau by a system of fractures (faults and fissures) which form a polygonal outline of the main escarpment.

The analysis revealed several sub-vertical discontinuities (89/88°; 16/89°; 22/88°; 140/89°; 233/80°) that define the position of the main scarp and lateral fracture. This is visible in a photorealistic model (Figure 3a) and is shown on the diagram in the stereographic projection (Figure 3b). It was also established that the strike direction and dip angle of the bedding plane (104/28°) are the same on both sides of the collapse structure (Figure 3b).

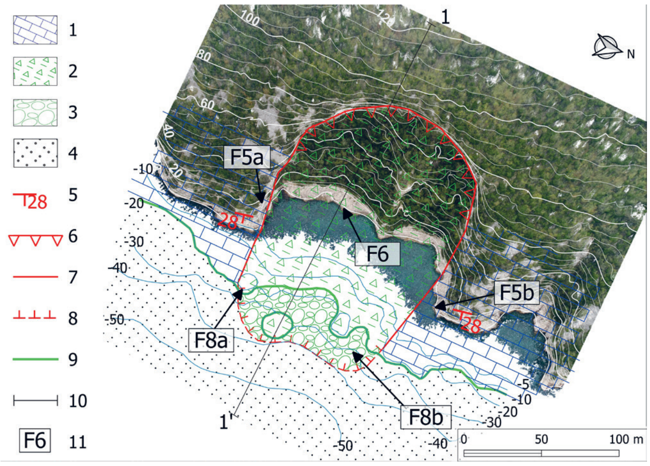

Figure 4. Geological map of rock slide 1-Upper Cretaceous limestones, 2-cataclastic breccias, 3-colluvial boulders and blocks, 4-seabed sand with coarse fragments, 5-strike and inclination of bedding plane, 6-main scarp, 7-lateral discontinuities, 8-landslide toe, 9-geological boundary, 10-cross section (see Figure 7), 11-position of photos.

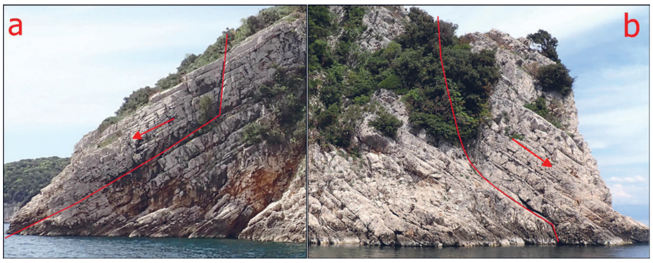

Figure 5. Structural interpretation of a possible slide in layered Upper Cretaceous limestones: a) south side, b) north side. Both red arrows are oriented to the east.

The vertical scarps adjacent to the rock collapse are several tens of metres high. Based on this survey and analysis, it was concluded that the polygonal shape of the sliding surface is predisposed by the location of the favourably oriented faults and fissures.

Rock mass surrounding the rock collapse consists of the Upper Cretaceous rudist limestones. The limestones show a distinct layering, with bedding planes uniformly inclined to the southeast with a dip angle of 28°. The layers are 10 to 100 cm thick. In addition to bedding planes, vertical or oblique fissures are also visible. This kind of structural fabric can favour the collapse of both sides of the described collapse structure (Figures 5a and 5b).

The rock mass in the collapse structure consists of cataclastic breccias. The size of the angular fragments ranges from a few centimetres to blocks over one metre in diameter. The matrix consists of calcitic reddish clay (Figure 6).

The landslide toe is located at a depth of about 40 m below mean sea level. The total volume of the displaced rock mass was estimated from the 3D model as about 950,000 m^3. Based on the underwater survey, the roughness of the submarine relief is expressed, and the slope has a very uneven inclination (Figure 4). The bare rocky part is visible at a depth between 15 and 20 m (Figures 4, 7 and 8a).

Boulders with a diameter of up to one metre reach a depth of 40 m (Figures 4 and 8b). The deeper part of the bottom is slightly inclined and covered with sandy sediments.

Figure 6. Cataclastic breccia in collapse structure (Photo: Č. Benac).

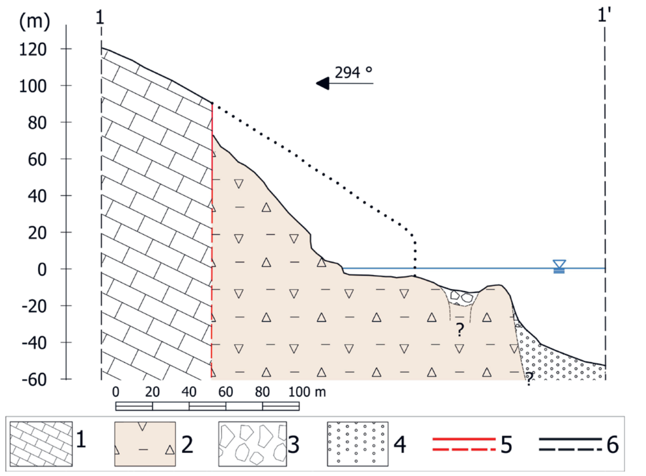

Figure 7. Geological cross-section (see Figure 4): 1-Upper Cretaceous limestones, 2-cataclastic breccia, 3-boulders and fragments, 4-seabed sand with coarse fragments, 5-boundary of collapse structure (established or assumed), 6-geological boundary (established or assumed).

The total height (from the crown to the landslide toe) is 130 m. The geometry of the studied instability was described according to the nomenclature for landslides proposed by WP/WLI (IAEG, 1990) (Figures 4 and 7):

– the total length: L = 210 m;
– the length of the displaced mass: L_d = 200 m;
– the width of the displaced mass: W_d = 135 m;
– the width of the fracture surface: W_r = 135 m.

The investigated collapse structure cannot be strictly classified into one type of landslide. In the initial phase of development, it was a rock collapse, because sliding of a rock mass occurred on a rupture surface consisting of several planes. Rock collapse occurred on an irregular rupture surface consisting of a number of randomly oriented joints, separated by segments of intact rock. In the second phase, lasting until the present day, rock falls are still occurring, according to the Varnes classification (HUNGR et al., 2013).

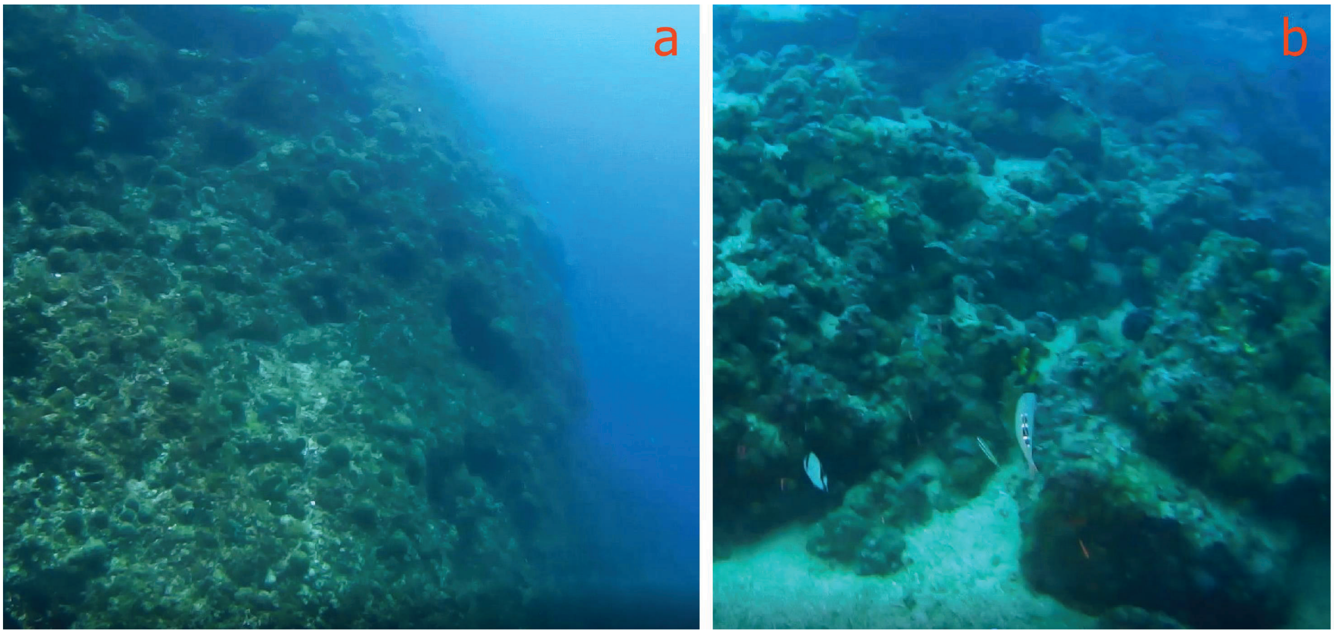

Figure 8. a) Very steep rocky bottom of the submerged part of the rock collapse at a depth of 15 m b) boulders at the landslide toe at a depth of 34 m (Photo: L. Maglić).

5. DISCUSSION

The activity of the fault in the Neogene caused vertical tectonic movements, and at the same time, the ridge of the southern Učka was uplifted (MARINČIĆ & MATIČEC, 1991). During the last phase of the tectonic evolution of the Istrian peninsula and the Kvarner area, tectonic movements along the Kvarner fault zone might have been active (KORBAR, 2009; PLACER et al., 2010). These events could have the main impact on the formation of an escarpment in the southern part of the Liburnian coast. Recent tectonic activity in the wider area (MARKUŠIĆ et al., 2019) probably triggered collapse events and caused the displacement of a large block of cataclastic breccia (Figures 1a and 2). Global positioning system (GPS) and the inferred northward and north-eastward movement of the Istrian peninsula confirms this hypothesis (WEBER et al., 2010). The present form of the described collapse structure has the shape of a rock slump, however, as described earlier, it can be classified as a rock collapse with characteristics of a compound rock slide (HUNGR et al., 2013.). Morphological evolution of the instability probably took place in four phases (Figure 9).

Due to the subsidence of the present seabed, the formation of initial scarps occurred in Phase A. This event led to a relaxation of the rock mass. Progressive extension occurred at the locations of previously formed and favourably oriented paraclases of faults and fissures. In Phase B, detachment of a block of the cataclastic breccia from the main slope and the beginning of a rock collapse or compound rock slide occurred. Phase C led to the disintegration of the frontal part of the sliding body of the detaching large rocky blocks and the onset of periodic rock fall. Sea flooding of the lower part of the displaced material occurred in Phase D, allowing the influence of sea erosion, partial rock fall and debris fall, and sedimentation of fine-grained sediments.

An important question is when the described rock collapse might have occurred. It certainly occurred before the Late Pleistocene and Holocene sea level rise. Clear evidence of this is provided by well-developed tidal notches, which are located on the coast within and around the displaced rock mass. Tidal notches are widespread along the carbonate coasts in the Rijeka Bay and on the Liburnian coast (BENAC et al., 2004). The measurement shows that the roofs of the tidal notches (elevation point E*) are

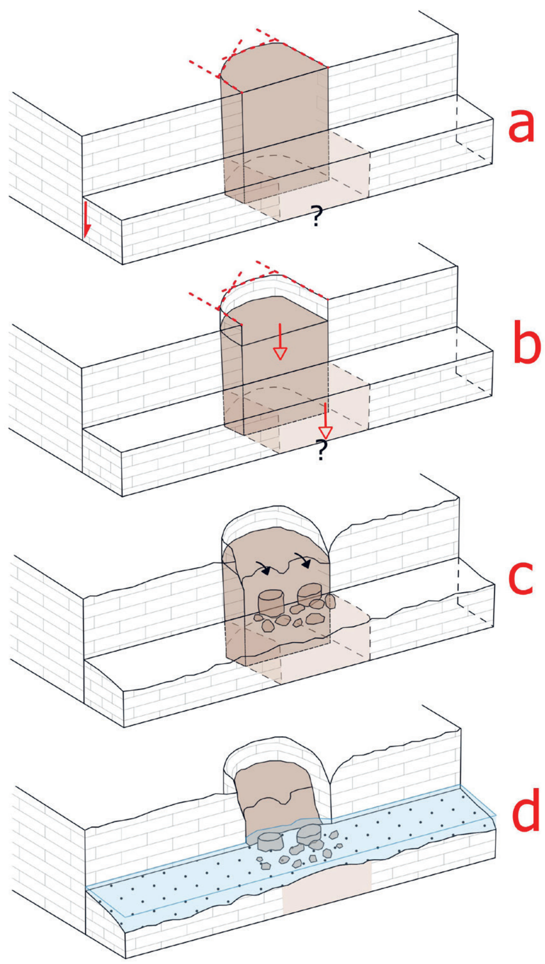

Figure 9. Morphological evolution of the studied instability phenomenon.

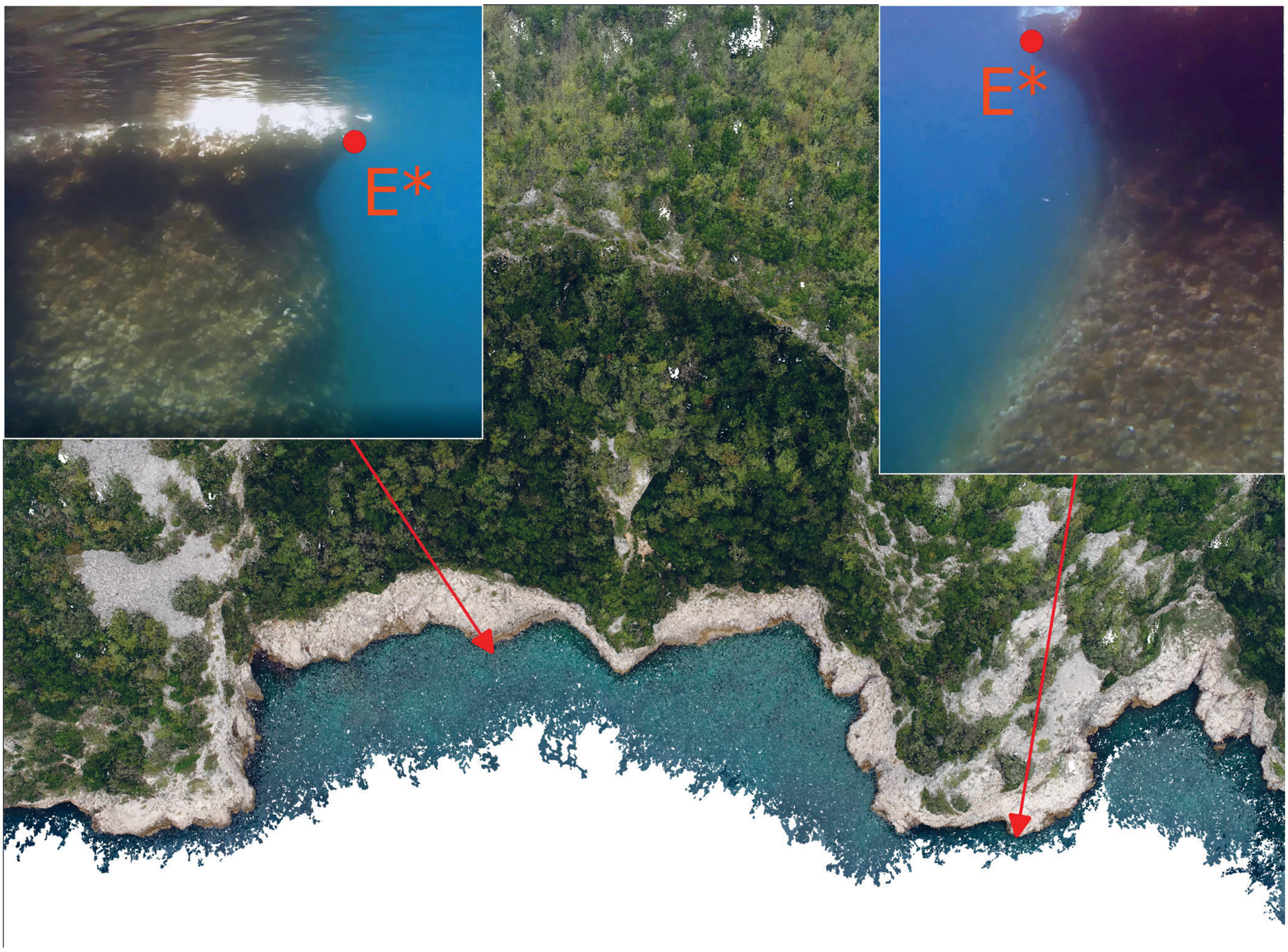

Figure 10. Tidal notches: E* elevation point.

located at a depth of 56 ± 2 cm (collapse structure) and 57 ± 2 cm (northern part of the coast) (Figure 10). Similar depths of elevation points have been found elsewhere on the Liburnian coast (BENAC et al., 2004). Therefore, it can be assumed that the upper part of the sliding body was in a relatively stable position before the Late Pleistocene-Holocene sea level rise.

In the northern Adriatic, near the eustatic peak of Holocene sea level rise, a period of equilibrium between regional tectonic subsidence and hydro-isostatic uplift was postulated. These two opposing processes probably caused relative sea level to remain stable for several thousand years (PIRAZZOLI, 2005; BENJAMIN et al., 2017). However, to explain the elongated shape of the notches in the Kvarner area, their excellent preservation (especially the notch roofs), and their present location, it has already been proposed that there was a long period of rather slow relative sea level rise before rapid tectonic (coseismic) subsidence (BENAC et al., 2004). This relative sea level standstill or very slow rise allowed the development of intertidal notches in relative resistant carbonate rocks. At the same time, the development of cliffs and narrow, pocket beaches on less resistant, highly fractured rocks can be observed (BENAC & JURAČIĆ, 1998; JURAČIĆ et al., 2009).

Wave heights in the channel part of the northern Adriatic are lower than in the western open zone, which is due to the relatively short wind fetch. The strongest northeast wind (bura or bora in Italian), does not produce the highest waves due to the short wind fetch. Alternatively, the stormy southeast wind (jugo or scirocco in Italian) with a speed of 20 m/s can generate the highest waves (over 6 m) on the western open coast of the islands of Cres and Lošinj. The Rijeka Bay and the Vela Vrata Strait are relatively closed channel parts with limited fetch areas and a tidal range between 30 and 35 cm (PENZAR et al., 2001). The studied coastal area is exposed to wind-driven waves from the south, southeast, north and northeast directions, and the waves are lower than in the open Adriatic. As a result of bioerosion, tidal notches are well developed in cataclastic breccias, as well as in the surrounding limestone (Figure 10). This means that the rock mass is sufficiently resistant, so the impact of the waves and mechanical erosion is minimal.

Since the beginning of instrumental measurements, sea level rise in the northern Adriatic has been recorded in the range of 2.0 ± 0.9 – 3.4 ± 1.1 mm/year (TSIMPLIS et al., 2012; SURIĆ et al., 2014). According to new analyses, the predicted sea level rise by the end of the 21st century could be 62 ± 14 cm (ORLIĆ & PASARIĆ, 2013). New climate models predict extreme wave storms (BONALDO et al., 2017) and increased marine erosion (GALLINA et al., 2019).

If we consider the possible future instabilities on this location, with regard to the unfavourable orientation and discontinuity features, but also the described external influences on the rock mass, we should consider possible instabilities of bedding planes on both sides of the studied rock collapse, as the next phase in the morphological evolution. The bedding plane position is 104/28° (Figure 5). Because of their unfavourable orientation in relation to the coastline and their reduced physical-mechanical properties due to marine erosion, sea level rise, strong winds, and wind-driven waves, discontinuities likely serve as initial patterns for the development of instability. Discontinuities that are diagonal to bedding planes, and discontinuity planes with dip vectors that form an oblique dihedral angle with the bedding planes dip vector, both contribute significantly to the development of instability. The aforementioned discontinuities are more persistent than others and run transverse to the bedding plane (Figure 5).

6. CONCLUSION

Along the southern part of the Liburnian coast, there is a 6.5 km long escarpment of carbonate rocks with very steep or vertical slopes more than 100 m high. The submarine slopes are also very steep so the isobath of -50 runs close to the coast. This steep slope was formed during the transpressive deformation along the Kvarner fault zone. Several large rock slides were recorded along this coast. The instability studied is a large gravitational collapse structure or rock collapse. This is one of the most interesting phenomena on this part of the coast.

The earthquakes recorded in the wider Kvarner area probably led to a sudden release of the highly fractured rock mass bounded by the large discontinuities and to the formation of initial scarps. The progressive expansion occurred at the locations of previously formed and favourably oriented paraclases of faults and fissures. Subsequently, the detachment of a block of cataclastic breccia from the main slope and the beginning of a collapse structure or a rock slump occurred. The disintegration of the front part of the rock slump body and the periodic rockfalls continue to the present day. The lower part of the landslide was submerged during the Holocene sea level rise. Since then, a large part of the displaced rock mass has been in a stable position, resulting in a similar height to the reference points of the tidal notches on and around the landslide body.

Due to climate change and sea level rise, higher wave action is expected in the future at the study site. This may lead to accelerated erosion of cataclastic breccias and displacement of blocks located along bedding planes and fracture systems, as well as instabilities of bedding planes on both sides of the studied rock collapse.

The Kvarner area is a relatively well-explored and described area compared to other parts of the Croatian coast. Nevertheless, there is still not enough meaningful evidence to document its geomorphological evolution in detail, especially concerning the age of the tidal notches. In addition, possible tectonic movements and sea level fluctuations in recent times need to be investigated. Therefore, the results of a new investigation, deeply rooted in time and space, would be an important step towards a better understanding of the geomorphological evolution of the studied collapse structures and similar structures on escarpments around the Kvarner area. This could significantly change the current reconstruction not only of relief evolution in the Kvarner area, but also in other parts of the Adriatic channel zone.

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