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Rock collapse structure on the Liburnian coast (Rijeka Bay, NE Adriatic)

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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 extension occurred in places where previously favourably oriented paraclases of faults and fissures had formed a very large and complex rock collapse. The width of the displaced mass along the coast is 375 m and the estimated total volume of the displaced rock mass is 2,400,000 m³. The lower part of the instability phenomenon lies 40 m below MSL and it was submerged during the Holocene sea level rise. A large part of the displaced rock mass was in a stable position, with sporadic rock falls. Recent techniques to survey the instability site and to analyse the evolution of the rupture surface and its dimensions above and below the sea level were used and combined (Unmanned Aerial Vehicles, and Remotely Operated Vehicles).

Keywords coastal instability, tectonic movements, rock collapse, marine erosion, SfM-MVS photogrammetry, underwater survey

Introduction

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

The terrain is extremely inaccessible, so that the use of modern research techniques was necessary. The aforementioned scarps were surveyed using an Unmanned Aerial Vehicle (UAV) and the 3D point cloud was generated using the Structure from Motion (SfM) with Multi-View Stereo (MVS) photogrammetry. The submarine zone was surveyed using scuba-diving equipment and Remotely Operated Vehicles (ROVs). Using these methods, successful research was carried out on a large rock slide in the southern part of the aforementioned escarpment (Benac et al., 2023).

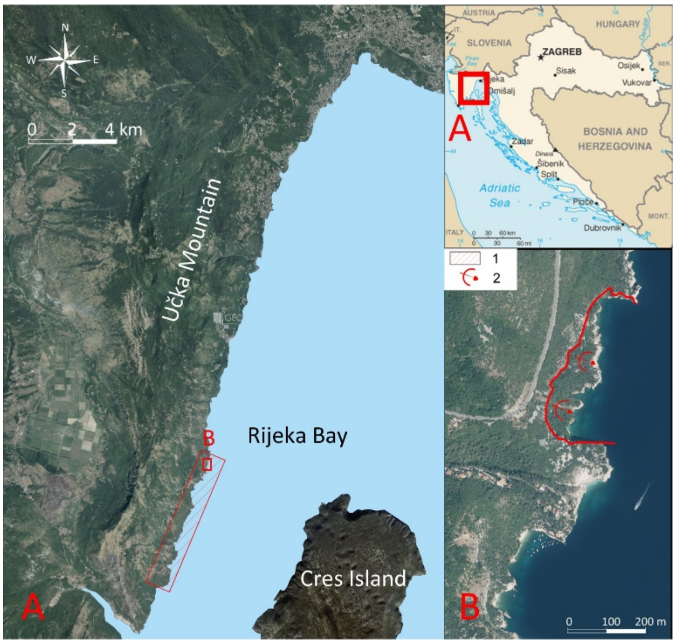

Figure 1 Location and simplified geological maps A) the Liburnian coast: 1- position of escarpment B) study area: 2 - studied collapse structure.

The instability studied in this paper is one of the largest and most interesting instability phenomena on the aforementioned part of the Liburnian coast. Based on the results obtained with the proposed methodology and the analyses presented in this paper, the origin and geomorphologic evolution of the investigated rock collapse are presented and discussed.

Geological setting and geomorphological evolution

The wider study area is part of the lower (southern) overthrust of the ridge of the Učka Mt. Overturned folds and reverse faults of the paraclasis dipping to the northeast, are common within the lower overthrust. Upper Cretaceous rudist limestone predominate in the southern Liburnian coastal zone. The limestone rock mass is tectonically strongly deformed and exhibit distinct bedding. The bedding planes are mostly inclined to the east and southeast. The layers are 10 to 100 cm thick. The flysch rock mass is squeezed between the carbonate rocks and is mostly covered by younger colluvial deposits. Tectonic breccias have been found near reverse faults (HGI, 2009).

During the first phase of the Dinaridic compression, the Istrian peninsula was separated from the strongly deformed Adriatic segment by the Kvarner fault zone and rotated towards the northeast where it is underthrusting 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 and the Učka Mt. ridge acquired its present NNE-SSW (meridional) strike (Marinčić & Matičec, 1991). Transpression and radial extension during the last phase of regional stress caused the 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 a consequence of the Kvarner fault zone. The interruption of the geological structures of the Kvarner islands towards the northwest is visible on geological maps (Korbar, 2009).

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 escarpment along the Liburnian coast. Intense morphogenetic processes caused by neotectonic movements and sea level oscillations, 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; Juračić et al., 2009). Several large rockslides have been recorded on this coast (Benac et al., 2023).

Results

The studied collapse structure is separated from the edge of the karst plateau by a system of fractures (faults and fissures) that form an irregular elongated outline of the main escarpment. Three normal faults with almost parallel extensions are visible above the main scarp of the landslide (Figure 2).

The collapse structure consists of two lithologic types. Cataclastic breccia is found in the southern part of the studied instability. This rock mass consists of angular fragments originating from limestone. The range of fragments is a few centimeters to blocks with a diameter of one meter. The matrix is calcitic reddish clay (Figure 3). A strongly fractured and karstified limestone rock mass there is in the central and northern parts of the collapse structure (Figure 4).

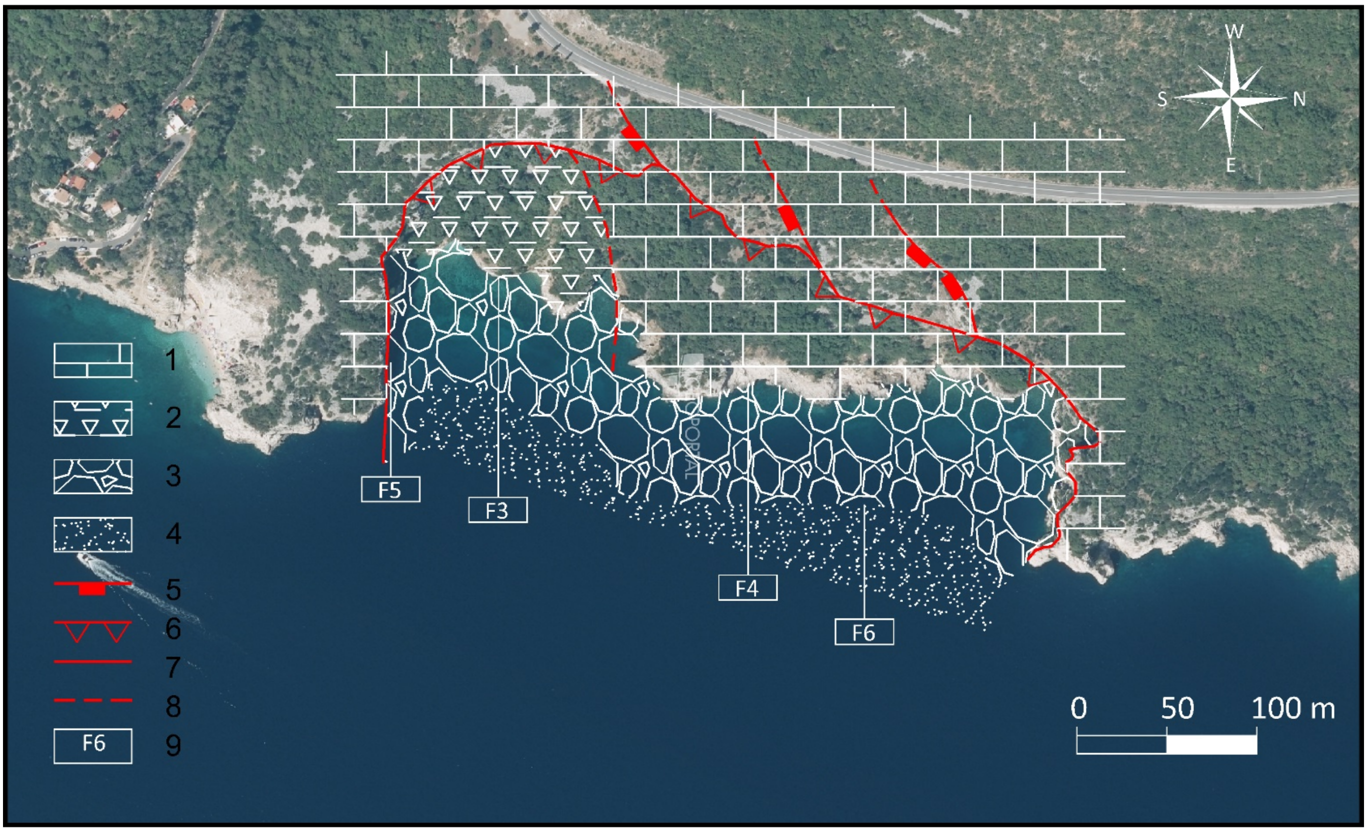

Figure 2 Geological map of collapse structure 1-Upper Cretaceous limestone, 2-cataclastic breccias, 3-colluvial cobles, and boulders, 4 coarse sand and silty sand, 5-normal fault with a position of hanging wall, 6-main scarp, 7-lateral discontinuities, 8-approximate geological boundary, 9-position of photos.

Figure 3 Tectonic breccia on the southern edge of collapse structure (Photo: D. Kalajžić).

Figure 4 Strongly fractured and karstified limestone rock on the northern side of the collapse structure (Photo: D. Kalajžić).

The shallow part of the bottom near the coastline has a gentle slope inclination. Marine erosion is more pronounced on the coast, which consists of cataclastic breccias. A narrow marine terrace and a pocket beach have formed there (Figure 3). Tidal notches are formed due to the bioerosion of limestone rocks, predominating on the central-northern part of studied collapse structure. (Figure 4). Based on the underwater survey insight, the bare rock mass is visible on the lateral side of the investigated instability (Figure 5). Boulders with a diameter of up to 50 cm are located at a depth of 40 m (Figures 2 and 6). The deeper part of the bottom is slightly inclined and covered with sandy sediments. The landslide toe is located at a depth of about 40 m below mean sea level. The total volume of the displaced rock mass as about 2,400,000 m^3.

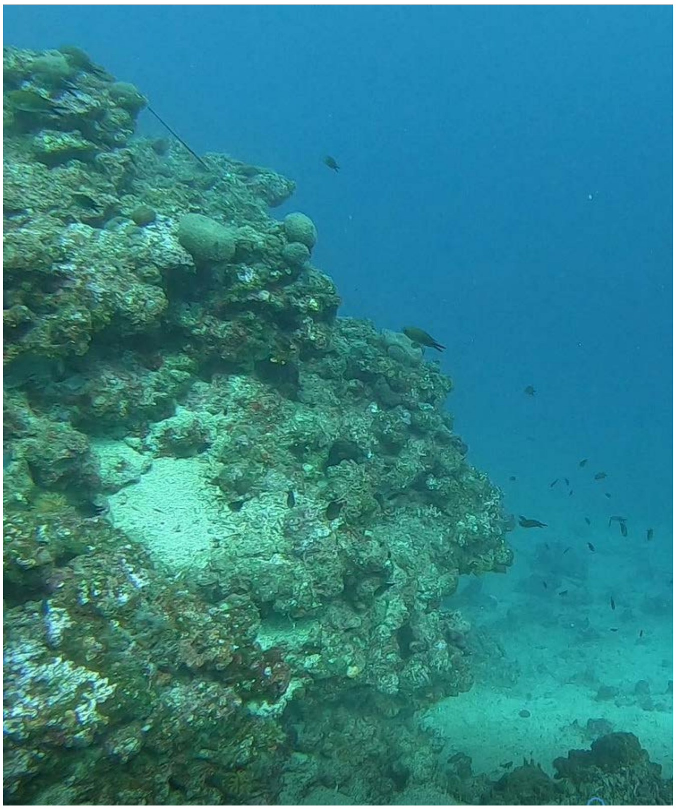

Figure 5 Rock mass on the southern edge of collapse structure (Photo: L. Maglić).

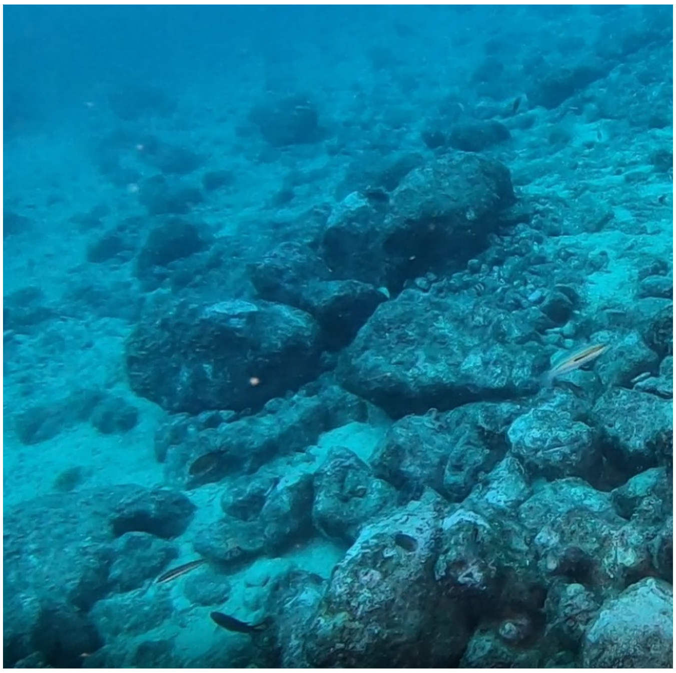

Figure 6 Boulders on the foot of sliding body 40 m deep (Photo: L. Maglić).

The total height (from the crown to the landslide toe) is up to 140 m. The geometry of the studied instability was described according to the nomenclature for landslides proposed by WP/WLI (IAEG, 1990):

- the length of the displaced mass: L_d = 130 m;
- the width of the displaced mass: W_d = 375 m;

The investigated collapse structure cannot be strictly classified into one type of landslide (Hungr et al., 2014). 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 many randomly oriented joints, separated by segments of intact rock. In the second phase, lasting until the present day, rock falls are still occur.

Discussion and conclusion

Several large instabilities have been recorded on the escarpment along the southern part of the Liburnian coast. The rock collapse studied in this article, together with the instability analysed by Benac et al., 2023, is one of the most interesting phenomena on this part of the coast

During the last phase of the tectonic evolution of the Istrian peninsula and the Kvarner area, tectonic movements along the Kvarner fault zone may have been active. The mentioned instabilities were formed during the transpressive deformation along the Kvarner fault zone (Korbar, 2009; Placer et al., 2010). Recent tectonic activity in the wider area (Markušić et al., 2019) probably triggered collapse events and caused the displacement of large blocks of cataclastic breccias and limestone (Figure 2). 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., 2014).

The morphological evolution of the instability probably took place in several phases. Due to the subsidence of the seabed in the present Rijeka Bay, the formation of initial scarps occurred in the first phase. This event led to a relaxation of the rock mass. The progressive extension took place at the site of the previously formed and favourably oriented paraclases of faults and fissures. In the second phase, the detachment of blocks of the cataclastic breccia and limestone from the main slope and the beginning of a rock collapse or compound rock slide occurred. The disintegration of the front part of the sliding body of the detaching large rocky blocks and the onset of periodic rock falls occurred in the third phase. Sea flooding of the lower part of the displaced material occurred in the last phase, allowing the influence of marine erosion, partial rock fall and debris fall, and the sedimentation of fine-grained sediments.

Intertidal notches are visible in relatively resistant limestone rocks mass (Figures 2 and 4). The measurements in other locations show that the elevation points are located at similar depths of elevation points that 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 (Benac et al., 2023). The measurement of elevation points of the tidal notches at the location analysed in this paper could provide interesting data on the recent stability of the collapsed structure.

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 (Surić et al., 2014; Tsimplis et al., 2012). New climate models predict extreme wave storms (Bonaldo et al., 2017) and increased marine erosion in the Adriatic Sea (Gallina et al., 2019). Because of this, wave attacks could be stronger and higher in the future on this studied coast. Marine erosion could be especially expressed in These lees-resistant cataclastic breccias (Figures 2 and 3). It can be a triggering effect for increasing landslide hazard increase.

It will be necessary to carry out detailed research in the future using modern techniques. In this way, they will be able to perform a structural analysis of the rock mass, as well as locate the exact position of the toe of the sliding body. The results of a new investigation, , would therefore 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 coastal evolution in the Kvarner area but also in other parts of the Adriatic channel zone.

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