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FACTORS INFLUENCING THE ROCKWALL RETREAT OF FLYSCH CLIFFS ON THE SLOVENIAN COAST

VPLIVNI DEJAVNIKI UMIKANJA FLIŠNIH KLIFOV NA SLOVENSKI OBALI

Ela Šegina, Blaž Komac, Matija Zorn

BOJAN ERHARTIČ

Bathers are often staying close to the most dangerous sections.
Kopalci se posebej radi zadržujejo pod najbolj nevarnimi odseki flišne obale.

Factors influencing the rockwall retreat of flysch cliffs on the Slovenian coast

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ABSTRACT: This study identifies factors that affect the speed of rockwall retreat of flysch cliffs between Kane Point and Strunjan on the Slovenian coast. Individual factors were combined in a geographical information system with mapped recent erosion features. The results indicate the influence of individual factors on the formation of erosion rills, gullies, surfwave breaks, slumps, and rockfalls; that is, flysch coast retreat processes. Special attention is dedicated to the occurrence of major slope processes, specifically slumps and rockfalls, which are an important contributing factor in cliff retreat. The article also presents the rockfall and slump risk of individual sections of the coast.

KEYWORDS: geography, geomorphology, erosion, rockwall retreat, flysch, coast, cliff, Slovenia

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Contents

1 Introduction

This article presents ten factors that interact in the development of coastal relief along the longest natural stretch of the Slovenian coast between Strunjan and Saint Simon Bay (*Zaliv Sv. Simona*) at Izola. We have determined the contribution of individual factors to the occurrence of slope processes, from the smallest erosion features, such as erosion rills, through gullies and slumps, to major rockfalls. Because major slope processes such as slumps and rockfalls have a significant effect on safety below cliffs, we have examined them in greater detail. Nineteen such processes were found in the study area.

The findings show that slump formation is affected by rock composition and fissuring, intermittent sea contact, and slope inclination. Areas south of Strunjan Point, Holy Cross Bay (*Zaliv svetega Križa*; also known as Moon Bay, *Mesečev zaliv*), and some smaller areas near the point in the bay below Belvedere are most susceptible to slumps.

The presence of sandy carbonate or limestone turbidite (Peckmann 1995) and a predominance of sandstone in flysch are essential for the formation of rockfalls on flysch cliffs.

Rockfalls most often occur in sections with direct contact between the cliff and the sea, which reduces the stability of the cliff at its base. A somewhat lesser effect is created by thin layered sandstone and clastic rock. The places most susceptible to rockfalls are Strunjan Point, the western part of Holy Cross Bay, and the point at the Bele skale beach.

To date, Slovenian geography literature contains only a few general geographical surveys dealing with rockwall retreat of flysch cliffs on the Slovenian coast. Gams (1970/71) and Orožen Adamič (2002) described relief features above and below the water on the Slovenian coast. Žumer (1990) assessed the speed of retreat of cliffs for specific areas based on historical studies, and Šifrer published a study on terraces as a result of changes in sea level during the Holocene (1965). Based on analysis of relief and relief features, Radinja (1973) indirectly drew conclusions about the morphogenetic dynamics of the southern coast of Strunjan Bay. Morphometric analyses based on remote sensing (Kolega 2009; Kolega and Poklar 2012) and works on coastal geomorphology (Bogunović 2002; Mesec 2003; Šegina 2011; 2012) are of a more recent date. The drainage basin of Rokava River has also been studied regarding rockwall retreat of flysch slopes in the coastal hinterland, which makes an interesting comparison with coastal processes on the same geological base and under similar weather conditions (Zorn 2009a; 2009b; Zorn 2012). Quantitative geomorphological studies of the Slovenian coast have been published by researchers from the University of Trieste, specifically with an overview of the morphology of coastal plains along the entire Slovenian coast and geomorphological processes at Fat Point (*Debeli rtič*; Furlani 2003; 2007; Furlani et al. 2011b). Geologists recently developed a risk assessment for swimming areas (Ribičič and Galič 2010).

2 Study area and methods

We studied ten factors that contribute to the intensity of geomorphological processes on flysch cliffs on the Slovenian coast. In order to determine the extent to which the selected factors are connected with the occurrence of slope processes in the coastal zone, we compared their spatial distribution with the incidence of individual morphological features on cliffs.

Specifically, we studied major slope processes on cliffs: five slumps and 14 rockfalls. With regard to the frequency of an individual factor in connection with a selected slope process, a corresponding weighting factor was assigned. By crossing (aggregating) the layers of individual factors with the appertaining factor, we obtained a map that shows the degree of susceptibility to a slump or rockfall being triggered.

The study included a 4.13 km coastal stretch between Kane Point and Strunjan that is almost entirely in its natural state. The width of the study zone encompasses the area between sea level and the edge of the cliffs.

Despite the uniform rock structure of the area, two flysch series must be differentiated in the cliffs; they were deposited in the upper Lutetian stage (Middle Eocene) and are separated by a layer of limestone turbidite.

The first flysch series (Figure 1) is composed of alternating layers of marlstone and sandstone. In between there are also some layers of mudstone and four layers of sandy carbonate turbidite. In comparison with sandstone, turbidite is more resistant to weathering and so it forms shelves on the slopes, and on coastal

Figure 1: Flysch series separated by limestone turbidite.

plains it is preserved as larger or smaller broken-off blocks depending on the thickness of the individual layer, which is between 12 and 18 cm (Peckmann 1995). For the formation of rockfalls, a layer of limestone turbidite 3.58 to 3.75 m thick is important; this appears in the cliff between Holy Cross Bay and Strunjan Point (Pavšič and Peckmann 1996).

In the second flysch series the layers of marlstone are thinner and the ratio between marlstone and sandstone is the most equal – specifically, 1.3 : 1 (Pavšič and Peckmann 1996). The inclination of the layers is between 0° and 65° along the entire coastal cross-section. Greater inclinations (around 30°) appear at the points (Kane, Ronek, Strunjan), and in the bays the average inclination is around 10°. An exception is the area south of Strunjan Point, where the inclination of the rock layers is very great (up to 65°) due to folds.

We also quantified the erosive action of the sea in the study area but because of the absence of suitable measuring equipment it was difficult to assess the erosive effect of the sea, which is clearly an important factor in the morphological development of cliffs. With the help of data on the main direction of waves at the Vida oceanographic buoy (4.2 km northwest of the coastal study area), we were able to assess coastal exposure to the action of the sea with regard to its orientation. Analysis of data on wave height and direction on the buoy shows that the highest and at the same time most frequent waves come from the northeast (60°) and are created by the bora wind (Kavčič and Malačič 2008). This direction is also the most frequent orientation of the coast in the study area, although due to the short length of the fetch zone its effect is very small, which means that the waves created with this wind do not achieve the greatest possible dimensions, speed, and periods that they otherwise could. The greatest length of the fetch zone for the northeast direction is approximately 9 km. Ronek Point and Izola prevent the waves from this direction directly reaching the coast of Holy Cross Bay and Kane Point.

In determining sea erosion, contact of the cliff with the sea is important. In the study area there are some sections with direct contact and some sections where the sea never reaches the base of the cliffs. For the most

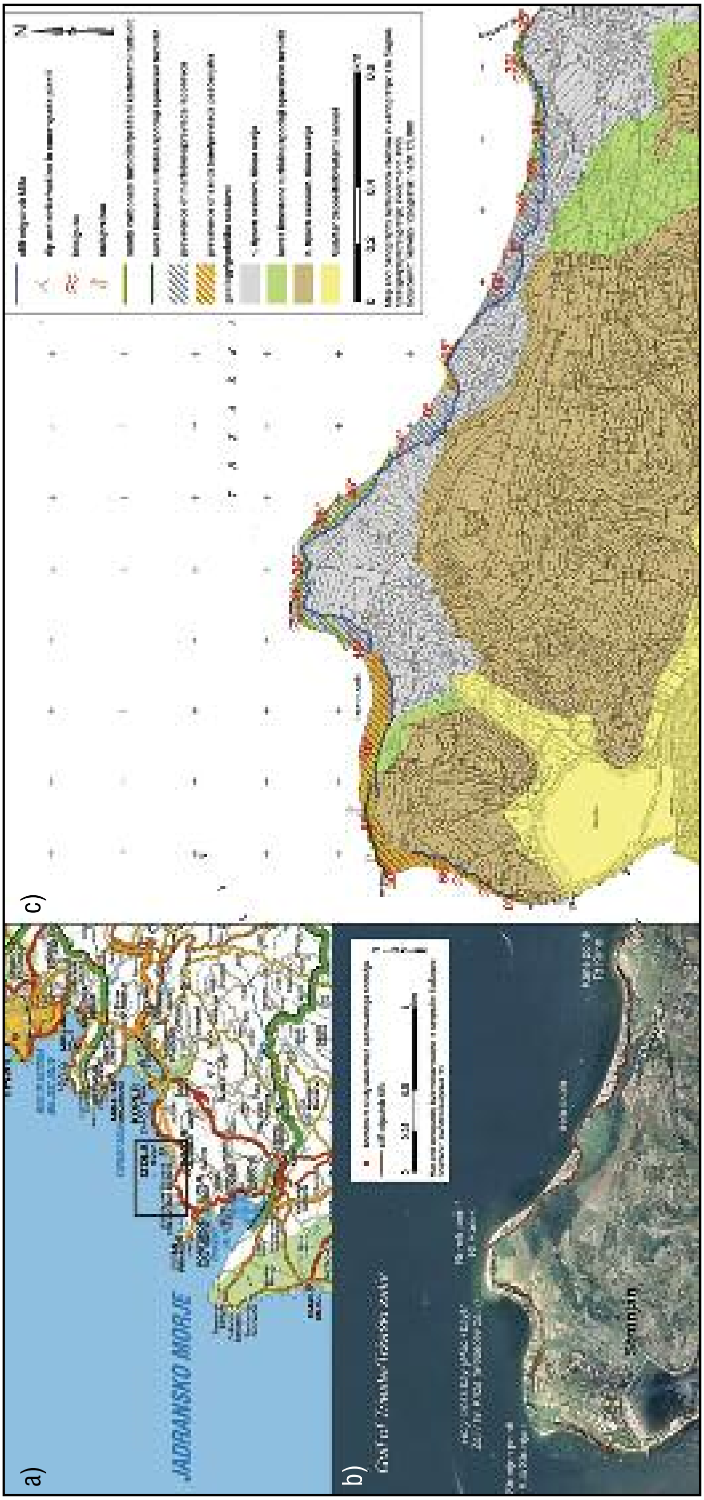


Figure 2: Slovenian Istria with detail (a), the study area (b), and its geological composition (c).

part there is intermittent contact of the surface of the sea with the cliffs during syzygial tide (Geografija 2001) or a tide that is increased due to weather conditions (the sirocco or low barometric presure).

3 Factors in cliff retreat

Based on the literature and fieldwork, we defined the following factors that affect the speed of erosion processes and thus the speed of cliff retreat:

- Thickness of sandstone layers;
- Ratio between marlstone and sandstone in flysch;
- Presence of limestone or sandy carbonate turbidite;
- Layering direction and inclination;
- Structural deformations: folds and faults;
- Geological strength index;
- Slope inclination;
- Groundwater in fissures;
- Vegetation;
- Degree of sea erosion.

3.1 Thickness of sandstone layers

The results of measuring compressive strength with a Schmidt hammer – which is used in geomorphological studies to study the weathering of rock, among other things (Goudie 2006) – showed that the compressive strength of sandstone in thin layers (less than 10 cm thick) is significantly less (< 10 MPa) than the compressive strength of sandstone in thicker layers (up to 58 MPa for layers over 10 cm thick). Considering this, areas in which thin layers of sandstone dominate ought to show greater susceptibility to the occurrence of minor erosion processes. In sections with direct sea exposure, thin layers of sandstone are more susceptible to sea erosion. In contrast, thick layers are potential places for rockfalls when the layer of sandstone is suspended due to the faster weathering of the marlstone below it.

The spatial distribution of the categories in Figure 3 show that thick layers build the exposed Ronek and Kane points, whereas the thinnest layers form the central part of the bay between the two points. (This does not apply to Strunjan Point. Its relief is primarily influenced by a thick layer of limestone turbidite.) We believe that, in addition to other factors, the lesser thickness of the sandstone layer contributes to accelerated retreat of the coastline into the interior of the land.

In sections with thicker layers, erosion rills and slumps form on slopes, whereas in sections with thinner layers rockfalls are more frequent. Thinner layers are more exposed to weathering and are not easily able to retain thick layers of limestone or sandy carbonate turbidite.

3.2 Ratio between sandstone and marlstone

The ratio between the presence of individual flysch rocks affects the speed and manner of rock disintegration. Sandstone generally breaks into polygonal pieces, whereas marlstone breaks into fine irregularly shaped debris even at a slight touch.

Because marlstone weathers more quickly than sandstone, it would be expected that areas in which it predominates are also areas of faster coastal retreat. Such sections are exposed to constant, small slope retreat and to debris scattering along the slopes. Because of the absence of measurements on flysch coast, the speed of this process is unknown. Making use of measurements for flysch breakdown from the coastal hinterland, it can be expected that flysch slope retreat also takes place at a rate of approximately 5 cm per year on the Slovenian coast (Zorn 2009b, 292).

In contrast, the triggering of major slope processes is more influenced by the presence of thick layers of sandstone. These layers are more resistant to weathering, but with the gradual falling away of marlstone they lose their support, break off, and fall to lower positions.

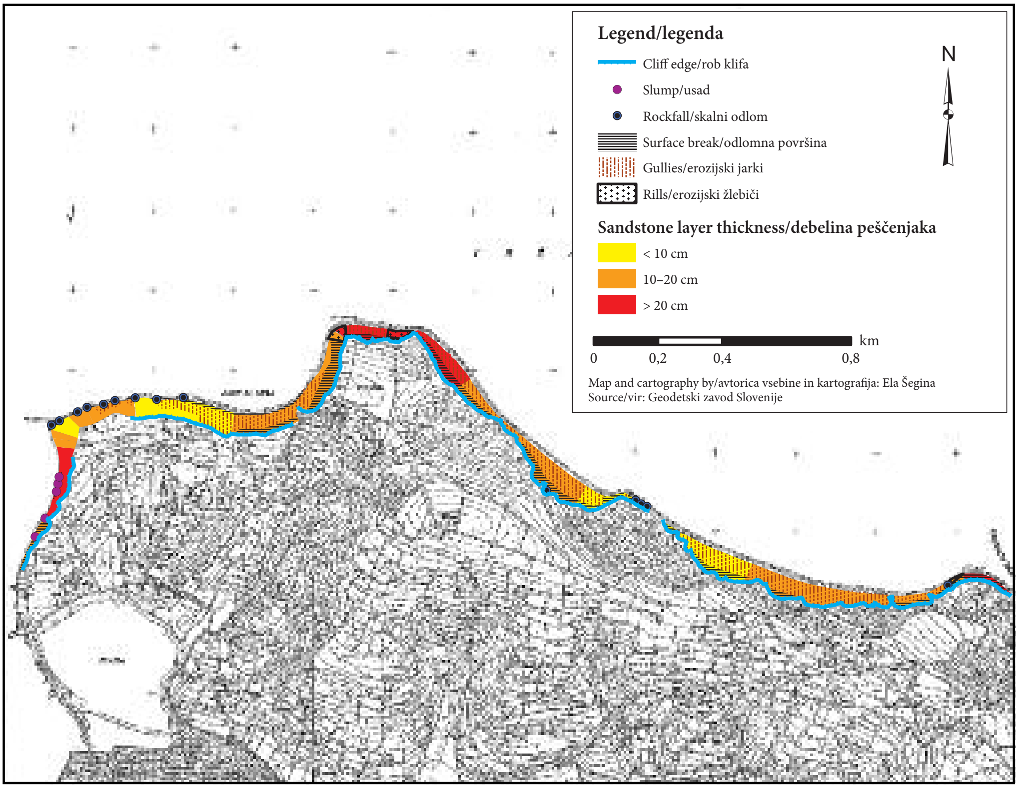


Figure 3: Spatial distribution of flysch by thickness of sandstone layers.

The study area of the coast is dominated by areas with mostly marlstone, which builds both the points and the bays. There are erosion rills and slumps in these sections, but rockfalls mostly occur in areas where sandstone dominates.

3.3 Presence of layers of sandy carbonate or limestone turbidite

Similar is true of the presence of sandy carbonate or liemstone turbidite (Peckmann 1995), which is rather resistant to weathering. At Struinjan Point the great amount of broken rock is unsurprising if one is aware that some of the layers of limestone turbidite are nearly 4 m thick.

Turbidite layers are not present in the entire coastal zone. It is interesting that wherever these layers are present they have formed points. It can be concluded that sections with the presence of these layers are subject to slower cliff retreat even though it is also true that the occurrence of rockfalls is directly dependent on their presence. Based on this, we conclude that, despite the large amount of material that they have moved along the slopes of coastal cliffs, rockfalls do not play a significant role in shaping the coastline because of their infrequency. The presence of layers of sandy carbonate or limestone turbidite is not connected with the occurrence of slumps, gullies, and erosion rills.

3.4 Geological strength index

The geological strength index (GSI) encompasses the characteristics of rock (Marinos and Hoek 2000; Sonmez and Ulusay 1999) that are measurable and affect its hardness. The key parameters are the volu-


KATARINA ŽNIDARŠIČ, ELA ŠEGINA

Figure 4: Marlstone is predominant in most of the study area. The ratio between stones is important due to differing susceptibility to weathering: marlstone breaks into debris (upper right figure), whereas sandstone breaks into polygonal pieces.

ELA ŠEGINA

Figure 5: Blocks of limestone turbidite accumulate at the foot of cliffs (upper figure). One of the layers of sandy carbonate turbidite is sinking under the accumulation of material on a gravelly beach in the bay below Belvedere (lower figure).

Table 1: Some characteristics of flysch on Slovenian coastal cliffs.

Measurement point	No. cracks on axis			Jv[1]	SR[2]	Rr[3]	Rw[4]	Rf[5]	SCR[6]	GSI[7]	GSI class
	y	x	z								
1	16	9	9	34	27	1	6	6	13	43	Mid
2	19	14	14	47	20	1	6	6	13	42	Mid
3	8	14	14	36	22	1	6	6	13	42	Mid
4	18	28	28	74	18	1	6	6	13	41	Mid
5	20	28	28	76	18	1	6	6	13	41	Mid
6	18	7	7	32	25	1	6	6	13	43	Mid
7	8	9	9	26	28	1	6	6	13	44	Mid
8	34	30	30	94	16	1	6	6	13	35	Low
9	11	140	140	291	10	1	6	6	13	38	Low
10	16	18	18	52	20	1	6	6	13	42	Mid
11	10	12	12	34	23	1	6	6	13	43	Mid
12	12	34	34	80	18	1	6	6	13	41	Mid
13	16	18	18	52	20	1	6	6	13	42	Mid
14	8	8	8	24	30	1	6	6	13	44	Mid
15	12	14	14	40	22	1	6	6	13	42	Mid
16	4	4	4	12	48	6	6	6	18	62	Mid
17	6	2	2	10	50	6	6	6	18	63	High
18	4	7	7	18	34	6	6	6	18	56	Mid
19	6	3	3	12	48	0	6	6	12	47	Mid
20	2	7	7	16	40	1	6	6	13	46	Mid
21	6	8	8	22	30	1	6	6	13	44	Mid
22	6	6	6	18	32	1	6	6	13	44	Mid
23	6	6	6	18	32	1	6	6	13	44	Mid
24	10	36	36	82	18	1	6	6	13	41	Mid
25	19	10	10	39	23	1	6	6	13	43	Mid
26	18	6	6	30	25	1	6	6	13	43	Mid
27	20	9	9	38	23	1	6	6	13	43	Mid
28	16	8	8	32	24	1	6	6	13	43	Mid
29	14	12	12	38	23	1	6	6	13	43	Mid
30	4	17	17	38	23	1	6	6	13	43	Mid
31	12	7	7	26	28	1	6	6	13	44	Mid
32	5	4	4	13	48	1	6	6	13	49	Mid
Average	12	17	17	45	27	1	6	6	13	44	Mid

[1] volumetric joint count; [2] structure rating; [3] roughness rating; [4] weathering rating; [5] infilling rating; [6] surface conditions rating; [7] geological strength index.

metric joint count (Jv) and surface conditions rating (SCR). The SCR encompasses three parameters: roughness rating (Rr), weathering rating (Rw), and infilling rating (Rf).

A simplified GSI estimate is taken from Furlani et al. (2011b), based only on parameters for sandstone. This approach was used because of the comparison with data for Fat Point (Furlani et al. 2011), which lies somewhat further north of our study area along the Italian border. In the future it will be necessary to obtain the actual GSI values for flysch on the Slovenian coast. Marinos and Hoek (2000) suggest that this should take into account the specific percentage values for sandstone and others for siltstone, and the ratio depends on the lithological composition, structure, and assessment of the surface for stratigraphic flysch discontinuities.

The GSI study for Fat Point, which describes not only the lithological properties of flysch, but also its structural properties to some extent, showed that the stability of flysch depends little on the surface conditions rating, whereas the main reason for the crumbling of cliffs is the number of cracks in sandstone (volumetric joint count; Furlani et al. 2011b). In addition to structural deformations, an important factor is lithological heterogeneity, which results in fissuring between layers. In the bay east of Strunjan Point, marlstone fissuring due to weathering greatly decreases at a depth of 12 cm. Zorn (2008, 33) states that for bare flysch cliffs in the coastal hinterland the number of cracks already greatly decreases at 5 to 10 cm below the surface, and that deep fissuring of sandstone is similar to horizontal fissuring. Table 1 shows the degree of fissuring, surface conditions rating, and GSI for sandstone at 32 points between Kane Point and Strunjan.

The study area almost entirely contains mid-range GSI values. Two exceptions are the low GSI value east of Strunjan Point and the high GSI value in the Ronek Point area. The main factor in a low GSI value is thin layering or major fissuring on both of the remaining axes, which is a result of fracturing. The high GSI value at Ronek Point results from an extremely low degree of fissuring (two cracks per meter of layer) and rippling of the cracks, which increases rock strength. The spatial distribution of the GSI shows that this is not a significant factor in shaping the coastline. It is interesting that the occurrence of erosion rills is connected with sections with a medium to high GSI value, which could mean that some other factor, such as thickness of the marlstone layer, is more important for their formation. Gullies appear everywhere except in areas with very low GSI values, where rockfalls predominate. Rockfalls also appear in areas with low to medium GSI values. Slumps are found in areas with a medium GSI value, but the break surfaces are not connected to the GSI level because they occur in all categories. Furlani et al. (2011b) report that the GSI for the Fat Point area is between 15 and 45, which would indicate a lower GSI value in comparison to our study area, but the differences could also be an artifact of the subjectivity of assessments.

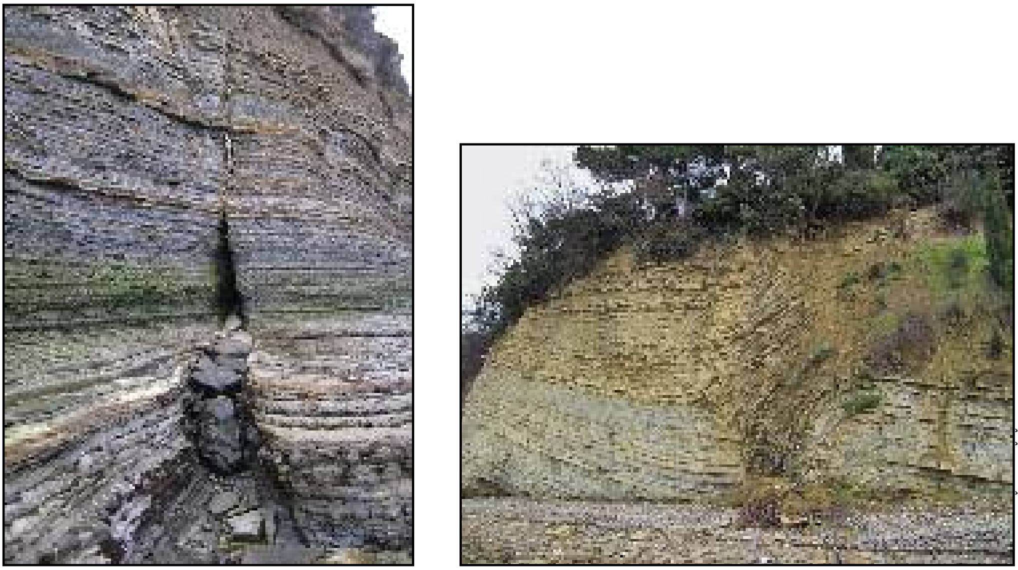
3.5 Dip and strike

The layers in the entire study area do not align with the slope, but are inclined in the direction toward the land, because of which there is slope non-congruence. In the entire area the inclination of the layers most often does not exceed 15°, whereby greater inclinations are the result of a local fold. More distinct inclinations of layers (Kane Point and the point in the bay below Belvedere) are reflected in a concave shape of the coastal profile but do not play a significant role in the speed of erosion processes or cliff retreat. Namely, all categories of layering direction and inclination appear both at points and in bays in the study area; the same is true of erosion features (erosion rills, gullies, slumps, and rockfalls).

3.6 Structural deformations

Because structural deformations represent a greater degree of fissuring, it is expected that these are less stable areas of cliffs that are more subject to the occurrence of slope processes.

Nonetheless, overlapping layers of folds and faults do not show any particular connection with the occurrence of individual erosion features. In sections with structural deformations, erosion rills form more often, and slumps and rockfalls are less frequent. Gullies and rockfall areas do not show a connection with folds and faults. The greatest degree of structural deformation appears south of Strunjan Point. Perhaps the reduced stability of the slopes due to structural deformations is the reason for the intense cliff retreat in the past, due to which cliffs are found in clearly leeward positions. Today this is a cliff section that is not in contact with the sea, as a result of which it is being shaped solely by land factors.



KATARINA ŽNIDARŠIČ

Figure 6: Faults (left) and folds (right) are common in the study area; for example, at Strunjan Point.

3.7 Groundwater in fissures

Flysch rock has poor to medium water permeability (Fabjan 2010, 22). Marlstone is especially nonpermeable, whereas layers of sandstone contain small amounts of interstitial and perched water, which seeps along cracks

KATARINA ŽNIDARŠIČ

Figure 7: Flysch fissure springs. In the winter, water in the slopes of the cliffs occasionally freezes.

and bedding planes (Dular 2000), and so springs are found along individual layers in the coastal area. Flysch fissure springs are not high-volume springs, but water trickles from them the entire year (Dular 2000, 8).

The influence of groundwater in fissures shows no connection with the occurrence of individual erosion features. Fissure springs mainly occur in bays, but their low yield and number is difficult to connect with a clear influence on the speed of cliff retreat.

3.8 Slope inclination

The inclination map was obtained by processing a 12.5 m digital elevation model, and the division of the inclination into categories follows a classification that connects individual inclination categories with predominant geomorphic processes (Demek et al. 1972; Natek 1983).

Coastal cliffs mostly belong to the inclination category of 32° to 54.9°, in which rock particles are in a labile position due to exceeding their natural angle of repose. All of the slope erosion features appear in this inclination category. There are also sporadic inclinations greater than 55°, but not at the upper part of the cliffs, which may be an artifact of the precision of the digital elevation model (Hrvatin and Perko 2005). The greatest continuous surface slope over 55° is in the western part of Ronek Point, where there is an extensive rockfall area. The lower part of the cliffs mostly belongs to the inclination category of 20° to 31.9°. Slumps are characteristic of this inclination category. Slopes less than 11.9° include the coastal plain zone.

3.9 Vegetation

Vegetation appears mainly on areas with less active erosion and areas where erosion material is deposited, whereas the upper parts of cliffs are almost completely bare. There, vegetation does not play a noticeable role in consolidating the slope and preventing major slope processes. However, vegetation holds back minor erosion processes in the lower parts of slopes, where it grows on deposited material. Where the gentler part of cliffs has large numbers of trees, these can hold back considerable material; it is only material with large dimensions ($d > 0.50$ m) that they cannot retain (Ribičič and Galič 2010).

ELA ŠEGINA

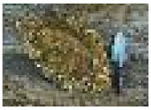
Figure 8: The lower parts of cliffs are covered by grass and trees due to their gentler inclination, whereas the steep rockfall areas in the upper parts are mostly bare.

The ridges of gullies, which remain unaffected by intensive gully erosion, are covered with pioneer vegetation. This is all that remains of the forest that probably grew on the slope in the past. Slumps are mainly triggered on sections without vegetation, whereas rockfall areas have no vegetation due to their great inclination.

3.10 Coastal sea exposure

The degree of sea erosion and coastal transport are directly dependent on wave energy, and this on wave height (Airy 1845; Komar and Inman 1970, cited in Pethick 2001). Here it is essential whether these processes actually reach the foot of the cliff, and so we determined the type of contact between the sea and cliffs.

Table 2: Granulation classes used in the study (photos: Matija Zorn).

Granulation class	1	2	3	4	5
					
Descriptive	Fine debris	Small pebbles	Medium-large pebbles	Large stones	Small boulders
Type of material	Marlstone and sandstone	Sandstone	Sandstone	Sandstone	Sandstone
Average length of three sides of clast (cm)	Longest side <3	1×4×3	3×11×7	30×15×10	30×40×20
Total volume (m^3)	0.03	0.03	0.03	0.01	0.02
Number of clasts	Uncountable	Uncountable	200	3	1
Roundness	Low	Medium (0.44)	Medium (0.49)	Low	Low

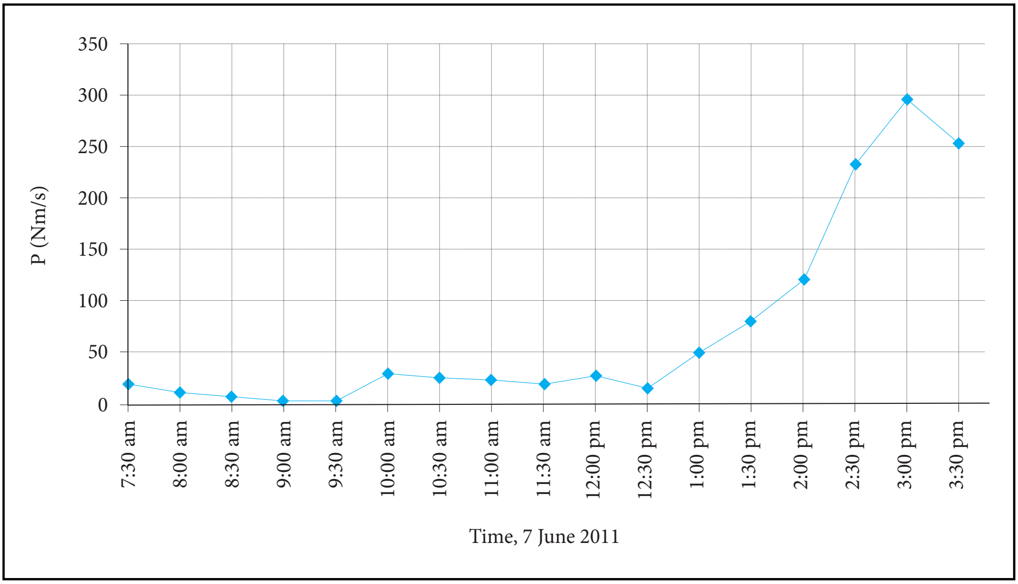


Figure 9: Wave strength on the open sea 4 km from the study area on 7 June 2011. The first granulation category was swept away from the coastal shelf into the bay at Strunjan Point around 12:00 am. The second and third granulation categories were swept away around 1:30 pm and the fourth around 2:00 pm when the tide reached its peak (Agencija … 2011).

ELA ŠEGINA

Figure 10: The numbers mark granulation categories and the arrows show the direction of transport.

In nearly the entire area observed there is intermittent contact of the foot of cliffs with the surface of the sea, and the presence of blocks of rock depends on the presence of layers of sandy carbonate or limestone turbidite in the cliff. Their presence was not seen to have a demonstrable influence on the degree of sea erosion. There is direct sea contact only at Strunjan Point and east of it, and at the point at the Bele skale beach. The investigation at Strunjan Point showed that coastal transport during a somewhat high tide with ordinary waves was able to move slope material with a maximum side < 11 cm without difficulty and to shift rocks with a maximum side < 30 cm that accumulate at the foot of the cliffs during a possible slope process.

The type of contact was also connected with the formation of erosion features. Erosion rills and gullies do not form on sections with direct contact because these are bare surfaces. Slumps are connected with areas with intermittent contact, where a significant quantity of slope material can accumulate at the foot of slopes so that slumps can occur. Rockfalls occur with all types of contact.

4 Danger to swimmers below cliffs

Because slumps and rockfalls are the most important with regard to danger to swimmers, these are examined in greater detail.

In order to determine sections of the coast more susceptible to these processes, we overlapped the factors that coincide in a particular coastal section. Because the selected factors have an unequal influence on the occurrence of individual slope processes, it was necessary to appropriately weight them with regard to their degree of association with individual erosion features. An individual factor received a weight based on the absolute value of its occurrence in connection with a particular erosion feature. Based on this, maps were made of slump and rockfall susceptibility in the study area (Figures 11 and 12).

In the study area, the occurrence of slumps is most often associated with the factors of lithological composition (sandstone predominates) and fissuring (GSI), type of sea contact (intermittent), and slope inclination (> 20°). Slumps are somewhat less frequent in bare areas with a small layering inclination, in

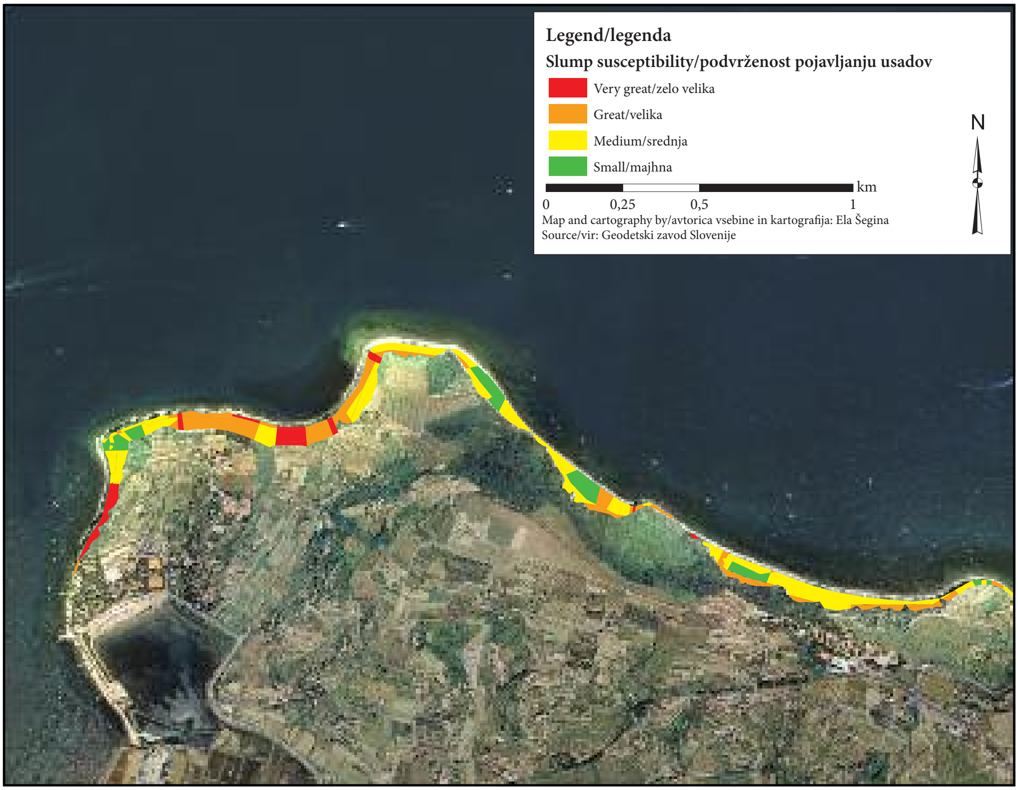


Figure 11: Map of slump susceptibility (Šegina 2012).

areas with thick layers of sandstone, and near major structural deformations. Interstitial water and layers of limestone or sandy carbonate turbidite do not affect the occurrence of slumps. However, the most important factor is certainly intermittent sea contact because this makes it possible for sufficient material to be deposited below the cliff so that a landslide can occur. Judging from Figure 10, the sections south of Strunjan Point and Holy Cross Bay are most susceptible to slumps.

Table 3: Presence of individual factors in slump occurrence.

		Slump 1	Slump 2	Slump 3	Slump 4	Slump 5	Σ
GSI	40–43	×	×	×	×	×	5
Sandstone predominates		×	×	×	×	×	5
Intermittent sea contact		×	×	×	×	×	5
Slope inclination	20°–31.9°	×	×	×	×	×	5
Layer inclination	5–15°		×	×	×	×	4
	Horizontal	×					1
Vegetation	None	×		×	×	×	4
	Forest		×				1
Sandstone thickness	>20 cm			×	×	×	3
	10–20 cm	×	×				2
Structural deformations		×	×				2

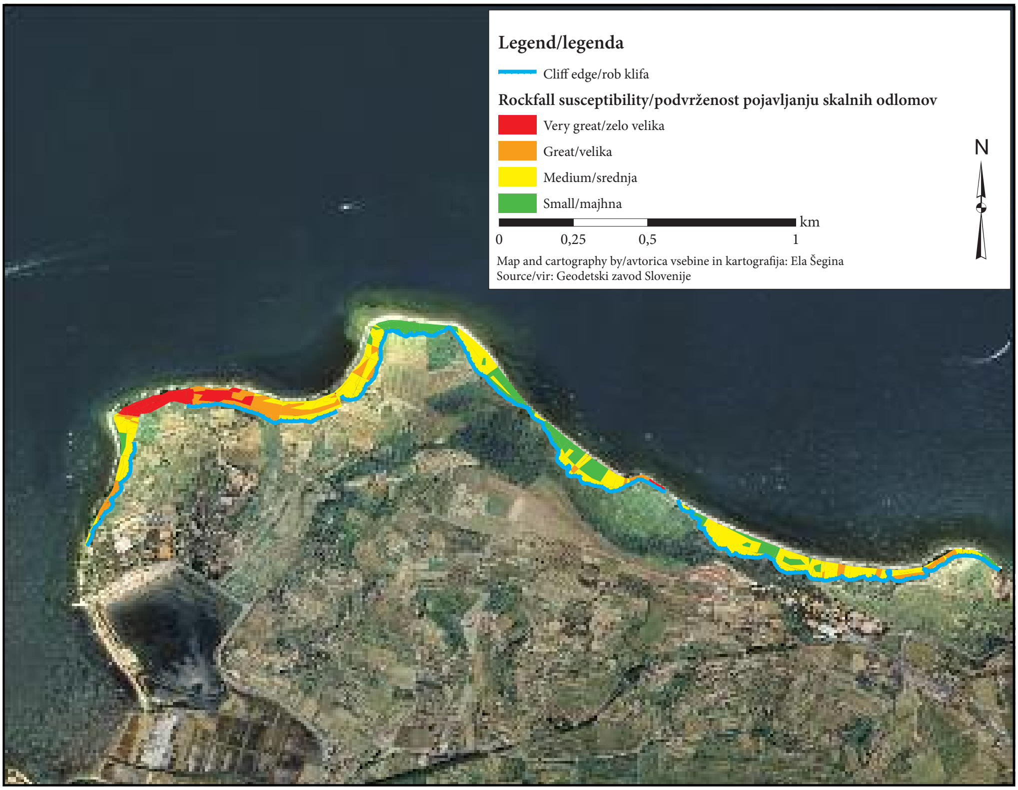


Figure 12: Map of rockfall susceptibility (Šegina 2012).

Table 4: Presence of individual factors in rockfalls.

ROCKFALL:		1	2	3	4	5	6	7	8	9	10	11	12	13	14	Σ
Limestone or sandy carbonate turbidite		×	×	×	×	×	×	×	×	×	×	×	×	×	×	14
Lithology: predominantly	Sandstone	×	×	×	×	×	×	×	×	×		×	×	×		12
	Marlstone										×				×	2
Sea contact	Direct	×	×	×	×	×	×	×	×	×		×	×	×		12
	Intermittent										×				×	2
Layer inclination	5°–15°					×	×	×	×	×		×	×	×	×	9
	Horizontal	×	×	×	×						×					5
Vegetation	Forest	×	×	×	×	×	×	×	×	×						9
	None										×	×	×	×	×	5
GSI	40–43	×	×					×	×	×	×	×	×	×	×	9
	35–39			×	×	×	×									4
Layer thickness	<10 cm	×	×					×	×	×		×	×	×		8
	10–20 cm			×	×	×	×				×				×	6
Slope inclination	32°–54.9°	×	×			×	×			×	×				×	7
	>55°			×	×			×	×							4
	20°–31.9°											×	×	×		3
Structural deformations		×	×	×	×	×	×								×	7
Interstitial water											×		×	×		3

On flysch cliffs in the study area, the presence of layers of sandy carbonate or limestone turbidite and a predominance of sandstone are essential for the occurrence of rockfalls because turbidite and sandstone are the source of the broken-off material. Rockfalls are also influenced by direct sea contact, which reduces the stability of the base of the cliffs. Somewhat less influence is exerted by thin layering of sandstone and a greater GSI, whereas vegetation apparently does not retain rockfalls because there are more rockfalls in sections with trees than in those where there is no vegetation. Structural deformations and slope inclination have less of an effect on the occurrence of rockfalls, whereby rockfalls predominate in the inclination category of 32° to 54.9°, and interstitial water has a negligible influence. Based on Figure 12, areas most susceptible to rockfalls are in Holy Cross Bay, especially the western part of the bay, the point in the bay below Belvedere, and to a somewhat lesser extent the area just before Strunjan and the eastern part of Kane Point.

5 Conclusion

In studying coastal cliffs, the greatest challenge is to estimate the speed of their retreat. Because of the lack of long-term erosion measurements on flysch cliffs on the Slovenian coast, at present the speed of erosion processes can only be estimated as a few centimeters per year.

This article has presented the influence of certain natural factors on the occurrence of individual erosion processes and relief features on coastal cliffs and the spatial distribution of major slope processes (slumps and rockfalls). Based on the findings, we hypothesize that slumps are important »accelerators« of erosion on slopes and rockfalls on capes.

Comparisons between individual factors and the shape of today's coastline indicate that the coastline is mostly dependent on the thickness of sandstone layers and the presence of sandy carbonate or limestone turbidite. From this it can be concluded that the moderate cliff retreat in bays, where these layers do not exist, affects the shaping of the coastline relatively quickly and with greater impact than instantaneous erosion or slope processes. Slope processes are closely connected with the presence of thicker turbidite layers or thicker layers of sandstone, and they are more frequent on more exposed points. Major rockfalls, which move a large amount of material in a short time, are too rare in the study area to have exerted a significant effect on shaping the coast.

What future change is anticipated for cliffs in the study area? The answer to this question is closely linked to predicted changes in the relative height of sea level, which governs the degree of sea erosion and coastal transport.

Lambeck et al. (2004) believe that from the end of the last ice age (approximately 12,000 years ago) to today the most important factor in the relative variation of sea level in the Mediterranean area has been tectonics. Specifically, because of the absence of alluvium from the last interglacial period at Trieste, based on the known eustatic and glacio-hydro-isostatic level they conclude that the surface has been subsiding at a rate of –0.15 mm/year (Lambeck et al. 2004). The levels of geomorphological and archeological finds between Saint Bartholomew Bay (*Zaliv Sv. Jernej*) and Saint Simon Bay (*Zaliv Sv. Simona*), calculated based on various eustatic and glacio-hydro-isostatic models, indicate a subsidence rate between –0.44 and –1.53 mm/year ± 0.72 mm in the past 2,000 years (Antonioli et al. 2009). Based on rock shelters in the calcareous coastal area between Miramare and Duino (north of our study area, Italy), today found at various depths below sea level, they conclude that there has been subsidence of the sedimentation basin in the last 10,000 years towards the northwest due to faster subsidence of the northern part of the Bay of Trieste (at a rate of more than –1.99 mm/year) in comparison to the southern part (approximately –0.6 mm/year; Furlani et al. 2010). The uneven subsidence is a result of various movements of tectonic blocks separated by faults perpendicular to the Dinaric direction (Furlani et al. 2011a) or the result of eustatic and glacio-hydro-isostasy (Lambeck et al. 2004). The degree of eustatism is believed to have had a different significance for fluctuations in sea level in the Mediterranean Sea, and glacio-hydro-isostasy is believed to have contributed only 10 to 15% to total sea level, whereby alpine glaciation has only a negligible impact (Lambeck et al. 2004). Uplifting of the surface due to isostasy after the last ice age is thus believed to have amounted to only +0.1 to 0.2 mm/year in the northern Mediterranean (Peltier 2001, cited in García 2007).

Sea level at the Koper tide-gauge station has been rising by approximately 1 mm/year, which is in line with the trend of a rising sea level in the Mediterranean Sea (Ličer et al. 2010) and is also connected with steric effects due to change in volume of seawater accompanying temperature and salinity variations, and due to change in water balance (Creado-Aldeanueva 2008). This trend and simultaneous subsidence, eustatism, and glacio-hydro-isostasy prevent the fossilization of coastal features. Due to the relative rise in sea level, in the future one can also expect that the current coastal relief features and operative processes will be preserved.

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Vplivni dejavniki umikanja flišnih klifov na slovenski obali

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IZVLEČEK: V raziskavi smo identificirali dejavnike, ki vplivajo na hitrost umikanja flišnih klifov med rtičem Kane in Strunjanom na slovenski obali. Posamezne dejavnike smo v geografskem informacijskem sistemu združili s kartiranimi recentnimi erozijskimi oblikami. Ocenili smo vpliv posameznih dejavnikov na nastanek erozijskih žlebičev, jarkov, odlomnih površin, usadov in skalnih odlomov oziroma na procese umikanja flišne obale. Posebno pozornost smo posvetili pojavljanju večjih pobočnih procesov, in sicer usadov in skalnih odlomov, ki so pomemben pospeševalni dejavnik umikanja obalnih sten. V članku je predstavljena tudi ogroženost posameznih odsekov obale zaradi pojavljanja skalnih odlomov in usadov.

KLJUČNE BESEDE: geografija, geomorfologija, erozija, umikanje pobočij, fliš, obala, klif, Slovenija

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Vsebina

1 Uvod

V članku je predstavljenih deset dejavnikov, ki součinkujejo pri razvoju obalnega reliefa na najdaljšem naravnem odseku slovenske obale med Strunjanom in Simonovim zalivom pri Izoli. Ugotovili smo prispevek posameznih dejavnikov k pojavljanju manjših erozijskih oblik, kot so erozijski žlebiči, prek erozijskih jarkov do usadov in skalnih odlomov. Ker slednji pomembno prispevajo k nevarnosti kopalcev pod klifi, smo jih natančneje obdelali in na opazovanem območju našteli 19 tovrstnih pojavov.

Na nastanek usadov vplivajo kamninska sestava in razpokanost, občasen stik z morjem in naklon pobočja. Usadom so najbolj podvrženi odseki južno od rtiča Strunjan, zaliv Sv. Križa ter nekaj manjših območij pri rtiču pri Belih skalah.

Na nastanek skalnih odlomov na flišnih klifih najbolj vplivajo plasti peščenega karbonatnega ali apnenčevega turbidita (Peckmann 1995) in prevlada peščenjaka v flišu.

Skalni odlomi se največkrat pojavljajo na odsekih z neposrednim stikom obalne stene in morja, kar zmanjšuje stabilnost obalne stene pri njenem vznožju. Nekoliko manjši vpliv imata plastovitost peščenjaka in razpokanost kamnin. Odlomom so najbolj podvrženi rtič Strunjan, zahodni del zaliva Sv. Križa in rtič pri Belih skalah.

V slovenski geografski literaturi je bilo do sedaj objavljenih nekaj geografskih del o flišnih klifih na slovenski obali. Gams (1970/71) in Orožen Adamič (2002) sta opisala podvodne in površinske reliefne oblike na slovenski obali. Žumer (1990) je ocenil hitrost umikanja obalnih sten na podlagi zgodovinskih preučevanj, Šifrer (1965) pa je prispeval študijo o terasah kot posledici spreminjanja morske gladine v holocenu. Radinja (1973) je na podlagi analize reliefa sklepal na morfogenetsko dinamiko južne obale Strunjanskega zaliva. Novejše so morfometrične analize na podlagi daljinskega zaznavanja (Kolega 2009; Kolega in Poklar 2012) in dela o obalni geomorfologiji (Bogunović 2002; Mesec 2003; Šegina 2011; 2012). Z umikanjem skalnih flišnih pobočij v zaledju obale, ki so zanimiva primerjava z obalnimi procesi na isti geološki podlagi in ob podobnih podnebnih razmerah, so se pred kratkim ukvarjali v porečju Rokave (Zorn 2009a; 2009b; 2012). Kvantitativne geomorfološke študije slovenske obale so prispevali kolegi s tržaške univerze, in sicer gre za pregled morfologije obalnih ravnic vzdolž celotne slovenske obale in geomorfnih procesov na Debelem rtiču (Furlani 2003; 2007; Furlani in ostali 2011). Geologi so pred kratkim izdelali oceno ogroženosti kopalnih območij (Ribičič in Galič 2010).

2 Opazovano območje in metode

Preučili smo deset dejavnikov, ki prispevajo k intenzivnosti geomorfnih procesov na flišnih klifih slovenske obale. Da bi ugotovili, v kolikšni meri so izbrani dejavniki povezani z nastankom pobočnih procesov v obalnem pasu, smo primerjali njihovo prostorsko razširjenost s pojavnostjo posameznih morfoloških oblik na klifih.

Natančneje smo na klifih preučili večje pobočne procese: pet usadov in 14 skalnih odlomov. Glede na to, kako pogosto se posamezni dejavnik pojavlja v povezavi z izbranim pobočnim procesom, mu je pripadel sorazmeren faktor obtežitve. S prekrivanjem (seštevanjem) slojev posameznih dejavnikov s pripadajočim faktorjem smo dobili zemljevid, ki kaže stopnjo podvrženosti proženju usadov oziroma skalnih odlomov.

V raziskavo je bil vključen 4,13 km dolg obalni odsek med rtičem Kane in Strunjanom, ki je z antropogenega vidika skoraj nedotaknjen. Širina opazovanega pasu zajema pas med morsko gladino in robom obalnih sten.

Kljub enotni kamninski sestavi območja, moremo na klifih razlikovati dve flišni seriji, ki sta se usedali v srednjem eocenu, in sta ločeni s plastjo apnenčevega turbidita.

Slika 1: Flišni seriji loči apnenčev turbidit.
Glej angleški del prispevka.

Prvo flišno serijo sestavljajo izmenjujoče se plasti laporovca in peščenjaka (slika 1). Vmes so plasti laporovca ter štiri plasti peščenega karbonatnega turbidita. Turbidit, ki je v primerjavi s peščenjakom odpornejši na preperevanje, je na pobočjih ustvaril police, na obalnih ravnicah pa se ohranjajo večji ali manjši odlomljeni bloki, odvisno od debeline posamezne plasti, ki je med 12 cm in 81 cm (Peckmann 1995). Za nastanek skalnih odlomov je pomembna 3,58–3,75 m debela plast apnenčevega turbidita, ki se v obalnem prerezu pojavlja med zalivom Sv. Križa in rtičem Strunjan (Pavšič in Peckmann 1996).

Druga flišna serija v celoti sestavlja obalne stene južno od skrajne točke rtiča Strunjan. V primerjavi s prvo flišno serijo so plasti laporovca tanjše, razmerje med laporovcem in peščenjakom pa je skoraj izenačeno, in sicer 1,3 : 1 (Pavšič in Peckmann 1996). Vpad plasti je vzdolž celotnega obalnega prereza med 0° in 65°. Večji vpadi (okoli 30°) se pojavljajo na rtih (Kane, Ronek, Strunjan), v zalivih pa so povprečni vpadi plasti okrog 10°. Izjema je odsek južno od rtiča Strunjan, kjer je vpad kamninskih plasti zaradi gub ponekod zelo velik (do 65°).

Slika 2: Slovenska Istra s preučevanim izsekom (a), preučeni odsek (b) in njegova geološka sestava (c).
Glej angleški del prispevka.

Na opazovanem območju smo kvantificirali tudi erozijsko delovanje morja, a je bilo zaradi odsotnosti merilnih naprav težko natančneje oceniti erozijsko delovanje morja, ki je nedvomno pomemben dejavnik morfološkega razvoja klifov. S pomočjo podatkov o glavni smeri valovanja na oceanografski boji Vida (4,2 km severozahodno od preučevanega dela obale) smo lahko ocenili izpostavljenost obale delovanju morja glede na njeno usmerjenost. Analiza podatkov o višini in smeri valovanja na boji kaže, da najvišji in obenem najpogostejši valovi prihajajo od severovzhoda (60°), povzroča pa jih burja (Kavčič in Malačič 2008). V to smer je tudi sicer usmerjena obala na opazovanem območju. Zaradi kratkega privetrišča je učinkovitost burje zelo majhna, kar pomeni da valovi ne dosežejo višine, hitrosti in periode, ki bi jih sicer lahko. Največja dolžina privetrišča iz severovzhoda je okoli 9 km. Rtiča Ronek in Izola preprečujeta valovom iz te smeri, da bi neposredno dosegli obalo zaliva Sv. Križa in rtiča Kane.

Za erozijo morja je pomemben stik klifa z morjem. Na preučevanem odseku je nekaj območij z neposrednim stikom in nekaj odsekov, kjer morje nikoli ne doseže podnožij obalnih sten. Povečini smo priča občasnemu stiku morske gladine s klifi ob najvišjem plimovanju ali plimovanju, ki je povišano zaradi juga ali nizkega zračnega tlaka.

3 Dejavniki za umikanje obalnih sten

Na podlagi literature in terenskega dela smo opredelili sledeče dejavnike, ki vplivajo na hitrost erozijskih procesov in s tem na hitrost umikanja obalnih sten:
- debelina plasti peščenjaka,
- razmerje med laporovcem in peščenjakom v flišu,
- prisotnost apnenčevega ali peščenega karbonatnega turbidita,
- smer in naklon vpad plasti,
- strukturne deformacije: gube in prelomi,
- geološki trdnostni indeks,
- naklon pobočja,
- prisotnost talne vode v razpokah,
- rastje in
- stopnja erozije morja.

3.1 Debelina plasti peščenjaka

Tlačno trdnost kamnine smo merili s Schmidtovim kladivom, ki se v geomorfoloških raziskavah med drugim uporablja za preučevanje preperelosti kamnine (Goudie 2006). Tlačna trdnost peščenjaka v tanjših plasteh debeline manj kot 10 cm je občutno manjša (< 10 MPa) od tlačne trdnosti peščenjaka v debelejših plasteh (do 58 MPa). Glede na to bi morala območja, kjer prevladujejo tanjše plasti peščenjaka, izkazovati večjo podvrženost pojavljanju erozijskih procesov. Na odsekih, neposredno izpostavljenih morju, so tanke plasti peščenjaka bolj podvržene eroziji morja, debele plasti pa so potencialna mesta za skalne odlome.

Slika 3 kaže, da debele plasti peščenjaka gradijo izpostavljena rtiča Ronek in Kane, medtem ko najtanjše plasti gradijo osrednji del zaliva med obema rtoma. To sicer ne velja za rtič Strunjan, saj njegov relief v prvi vrsti oblikuje debela plast apnenčevega turbidita. Ocenjujemo, da manjša debelina plasti peščenjaka poleg drugih dejavnikov vpliva na pospešeno umikanje obalne črte v notranjost kopnega.

Slika 3: Debelina plasti peščenjaka.
Glej angleški del prispevka.

3.2 Razmerje med peščenjakom in laporovcem

Razmerje med posameznimi flišnimi kamninami v flišu vpliva na hitrost in način preperevanja kamnine. Peščenjak se praviloma lomi na poligonalno oblikovane bloke, laporovec pa se drobi v droben grušč nepravilnih oblik.

Ker laporovec hitreje prepereva kot peščenjak, bi pričakovali, da so območja, kjer prevladuje, obenem tudi območja hitrejšega umikanja obale. Takšni odseki so izpostavljeni stalnemu, a manjšemu umikanju pobočij ter usipanju grušča po pobočjih. Zaradi odsotnosti meritev na flišni obali hitrost procesa ni znana. Za primerjavo: meritve sproščanja fliša v zaledju slovenske Istre kažejo, da poteka umikanje flišnih klifov s hitrostjo približno 5 cm/leto (Zorn 2009b, 292).

Na nastanek večjih pobočnih procesov vplivajo debele plasti peščenjaka, ki so odpornejše na preperevanje, vendar izgubljajo oporo zaradi manjše odpornosti laporovca, se lomijo in padajo v nižje lege.

Na opazovanem odseku obale prevladujejo območja s prevlado laporovca, ki pa gradijo tako rte kot zalive. Na teh odsekih nastajajo erozijski žlebiči in usadi, odlomi pa se večinoma pojavljajo na območjih, kjer prevladuje peščenjak.

Slika 4: Na večjem delu preučevanega območja prevladuje laporovec. Razmerje med kamninama je pomembno zaradi različne podvrženosti preperevanju: laporovec se drobi v grušč (zgoraj desno), peščenjak pa se lomi na poligonalno oblikovane kose.
Glej angleški del prispevka.

3.3 Plasti peščenega karbonatnega ali apnenčevega turbidita

Peščeni karbonatni ali apnenčevi turbidit (Peckmann 1995) je precej odporen na preperevanje.

Turbiditne plasti niso prisotne na celotnem obalnem odseku, vendar so se povsod, kjer plasti so, izoblikovali rti. Sklepamo lahko, da se na takšnih odsekih klif umika počasneje. Zaradi redkosti takšnih pojavov sklepamo, da skalni odlomi kljub obilici gradiva, ki ga premaknejo po pobočjih klifov zaradi časovne redkosti pojavljanja niso najbolj pomembni za oblikovanje obale. Plasti peščenega karbonatnega ali apnenčevega turbidita ne vplivajo na nastanek usadov, erozijskih jarkov in žlebičev, so pa na rtiču Strunjan pogosti skalni odlomi. Nekatere plasti apnenčevega turbidita so debele skoraj 4 m!

ž

Slika 5: Skalni bloki apnenčevega turbidita se kopičijo na podnožju obalnih sten (zgornja slika). Ena izmed plasti peščenega karbonatnega turbidita tone pod akumulirano gradivo na prodnati plaži v zalivu pod Belvederjem (spodnja slika).
Glej angleški del prispevka.

3.4 Indeks trdnosti kamnin

Indeks trdnosti kamnin (tudi: geološki trdnostni indeks, ang. *geological strenght index*) zajema tiste značilnosti kamnine, ki so merljive in vplivajo na njeno trdnost (Marinos in Hoek 2000; Sonmez in Ulusay 1999). Ključna parametra sta število razpok/m^3 in stanje razpok, ki obsega tri parametre: hrapavost razpok, preperelost razpok in odprtost razpok ter vrsta polnila v njih.

Po Furlaniju in ostalih (2011b) je privzeto poenostavljeno ocenjevanje indeksa trdnosti kamnin, ki temelji zgolj na parametrih za peščenjak. Takšen pristop je bil uporabljen zaradi primerjave s podatki za Debeli rtič (Furlani in ostali 2011b), ki leži nekoliko severneje od našega območja preučevanja ob italijanski meji. V prihodnje bo treba pridobiti dejanske vrednosti indeksa trdnosti kamnin za fliš na slovenski obali. Marinos in Hoek (2000) predlagata, da se pri tem upoštevajo določene odstotne vrednosti za peščenjak in druge za laporovec, razmerje pa je odvisno od litološke sestave, strukture in ocene stanja površine stratigrafskih diskontinuitet fliša.

Preglednica 1: Nekatere značilnosti flišnega peščenjaka na klifih na opazovanem območju.

merilne točke	število razpok na osi			število razpok/ m^3	stopnja razpokanosti	hrapavost razpok	preperelost razpok	polnilo in odprtost razpok	stanje razpok	geološki trdnostni indeks	razred indeksa trdnosti kamnin
	y	x	z								
1	16	9	9	34	27	1	6	6	13	43	srednji
2	19	14	14	47	20	1	6	6	13	42	srednji
3	8	14	14	36	22	1	6	6	13	42	srednji
4	18	28	28	74	18	1	6	6	13	41	srednji
5	20	28	28	76	18	1	6	6	13	41	srednji
6	18	7	7	32	25	1	6	6	13	43	srednj
7	8	9	9	26	28	1	6	6	13	44	srednji
8	34	30	30	94	16	1	6	6	13	35	**nizek**
9	11	140	140	291	10	1	6	6	13	38	**nizek**
10	16	18	18	52	20	1	6	6	13	42	srednji
11	10	12	12	34	23	1	6	6	13	43	srednji
12	12	34	34	80	18	1	6	6	13	41	srednji
13	16	18	18	52	20	1	6	6	13	42	srednji
14	8	8	8	24	30	1	6	6	13	44	srednji
15	12	14	14	40	22	1	6	6	13	42	srednji
16	4	4	4	12	48	6	6	6	18	62	srednji
17	6	2	2	10	50	6	6	6	18	63	**visok**
18	4	7	7	18	34	6	6	6	18	56	srednji
19	6	3	3	12	48	0	6	6	12	47	srednji
20	2	7	7	16	40	1	6	6	13	46	srednji
21	6	8	8	22	30	1	6	6	13	44	srednji
22	6	6	6	18	32	1	6	6	13	44	srednji
23	6	6	6	18	32	1	6	6	13	44	srednji
24	10	36	36	82	18	1	6	6	13	41	srednji
25	19	10	10	39	23	1	6	6	13	43	srednji
26	18	6	6	30	25	1	6	6	13	43	srednji
27	20	9	9	38	23	1	6	6	13	43	srednji
28	16	8	8	32	24	1	6	6	13	43	srednji
29	14	12	12	38	23	1	6	6	13	43	srednji
30	4	17	17	38	23	1	6	6	13	43	srednji
31	12	7	7	26	28	1	6	6	13	44	srednji
32	5	4	4	13	48	1	6	6	13	49	srednji
povprečje	12	17	17	45	27	1	6	6	13	44	srednji

Preučevanje indeksa trdnosti kamnin na Debelem rtiču, ki opisuje tako kamninske kot deloma strukturne lastnosti fliša, je pokazalo, da je stabilnost fliša malo odvisna od stanja razpok, medtem ko je poglavitni vzrok za krušenje obalnih sten število razpok v peščenjaku (Furlani in ostali 2011b). Pomemben dejavnik je poleg strukturnih deformacij kamninska heterogenost, katere posledica je plastovitost fliša. V zalivu vzhodno od rtiča Strunjan se razpokanost laporovca zaradi preperevanja močno zmanjša na globini 12 cm. Zorn (2008, 33) za gole flišne stene v zaledju obale navaja, da se število razpok močno zmanjša že 5–10 cm pod površjem, globinska razpokanost peščenjaka pa je podobna vodoravni razpokanosti. Preglednica 1 prikazuje stopnjo razpokanosti, stanje razpok in indeks trdnosti peščenjaka na 32 točkah med rtičem Kane in Strunjanom.

Opazovano območje spada skoraj v celoti v razred srednjih vrednosti indeksa trdnosti kamnin. Izjemi sta nizka trdnost vzhodno od rtiča Strunjan ter visoka trdnost na območju rtiča Ronek. Poglavitna dejavnika nizke trdnosti sta tanka plastovitost in velika razpokanost, ki je posledica pretrtosti kamnine. Visok indeks trdnosti kamnin na rtiču Ronek je posledica izredno nizke stopnje pretrtosti in valovitosti razpok, kar povečuje trdnost kamnine. Prostorska razporeditev indeksa trdnosti kamnin kaže, da ta ni bistven dejavnik oblikovanja poteka obale. Zanimivo je, da je pojav erozijskih žlebičev vezan na odseke s srednjo do visoko vrednostjo indeksa trdnosti kamnin, kar lahko pomeni, da je za njihov nastanek pomembnejši nek drugi dejavnik, na primer debelina plasti laporovca. Erozijski jarki se pojavljajo povsod, razen na odsekih z zelo nizko vrednostjo indeksa trdnosti kamnin, kjer prevladujejo odlomi. Slednji se pojavljajo tudi na odsekih z nizko do srednjo vrednostjo indeksa trdnosti kamnin. Usadi so pogostejši na odsekih s srednjim indeksom trdnosti kamnin, vendar odlomne površine niso vezane na stopnjo indeksa trdnosti kamnin, saj se pojavljajo v vseh razredih. Furlani in ostali (2011b) za območje Debelega rtiča pišejo, da je indeks trdnosti kamnin med 15 in 45, kar je nižje kot na našem odseku.

3.5 Smer in naklon vpada plasti

Plasti na celotnem opazovanem območju so nagnjene v smeri proti kopnemu, zaradi česar pobočja niso skladna. Na celotnem območju naklon plasti največkrat ne presega 15°, pri čemer so večji nakloni posledica lokalnega gubanja. Večji naklon vpada plasti (rtič Kane in rtič pri Belih skalah) se odraža v konkavni obliki obalnega prereza, nima pa pomembne vloge pri hitrosti erozijskih procesov oziroma umikanju obalnih sten. Vsi razredi smeri in naklona vpadanja plasti se namreč pojavljajo tako na rtih, kot v zalivih opazovanega območja; podobno velja za erozijske oblike (erozijski žlebiči, jarki, usadi in sklani odlomi).

3.6 Strukturne deformacije

Prekrivanje slojev gub in prelomov ne kaže posebne povezanosti z erozijskimi oblikami. Na odsekih s strukturnimi deformacijami najpogosteje nastajajo erozijski žlebiči, redki so usadi in odlomi. Erozijski jarki in odlomne površine ne kažejo povezanosti z gubami in prelomi. Največja stopnja strukturne deformiranosti je južno od rtiča Strunjan. Morda je prav zmanjšana stabilnost pobočij zaradi strukturnih deformacij razlog za intenzivno umikanje klifov v preteklosti, zaradi česar so se znašle v izrazito zavetrni legi. Danes ta odsek ni v stiku z morjem, zaradi česar pri njihovem preoblikovanju sodelujejo pretežno kopenski dejavniki.

Slika 6: Razpoke (levo) in gube (desno) so pogoste na opazovanem območju, na primer na rtiču Strunjan.
Glej angleški del prispevka.

3.7 Talna voda v razpokah

Flišne kamnine so za vodo slabo do srednje prepustne kamnine (Fabjan 2010, 22). Posebej vododržen je laporovec, medtem ko se v plasteh peščenjaka skladiščijo manjše količine razpoklinske in ujete vode, ki se pretaka po razpokah in lezikah (Dular 2000), zato si izviri na obalnem odseku sledijo vzdolž posamezne plasti. Razpoklinski flišni izviri niso izdatni, vendar se iz njih cedi voda skozi celo leto (Dular 2000, 8).

Vpliv talne vode v razpokah ne kaže povezav s pojavljanjem posameznih erozijskih oblik. Izviri razpoklinske vode se pojavljajo predvsem v zalivih, vendar je njihovo majhno izdatnost in številčnost težko povezati z izrazitejšim vplivom na hitrost umikanja obalnih sten.

Slika 7: Razpoklinski flišni izviri. Pozimi voda na pobočjih obalnih sten občasno zmrzuje.
Glej angleški del prispevka.

3.8 Naklon pobočja

Zemljevid naklonov je bil pridobljen s pomočjo obdelave digitalnega modela višin 12,5 m, delitev naklona na razrede pa upošteva klasifikacijo, ki povezuje posamezni naklonski razred s prevladujočimi geomorfnimi procesi (Demek in ostali 1972; Natek 1983)

Na klifih prevladuje naklonski razred 32°–54,9°, pri katerem so delci kamnine v labilnem položaju zaradi preseganja posipnega kota. V tem naklonskem razredu se pojavljajo erozijske oblike. Sporadično se pojavljajo tudi nakloni večji od 55°, vendar le na spodnjih delih klifov, kar je tudi posledica nenatančnosti digitalnega modela višin (Hrvatin in Perko 2005). Največja sklenjena površina naklona nad 55° je na zahodnem delu rtiča Ronek, kjer je obsežna odlomna površina. Spodnji deli klifov večinoma spadajo v naklonski razred 20°–31,9°. Za ta naklonski razred je značilno plazenje (usadi). Nakloni, manjši od 11,9° vključujejo pas obalnih ravnic.

3.9 Rastje

Poraščena so predvsem erozijsko manj aktivna območja in območja odlaganja erodiranega gradiva, medtem ko so zgornji deli klifov skoraj neporaščeni. Tam rastje nima opazne vloge pri utrjevanju pobočja in preprečevanju pobočnih procesov. Rastje zadržuje manjše erozijske procese v spodnjih delih pobočij, kjer porašča odloženo gradivo. Kjer položnejši del klifov obrašča drevje, lahko ta zadrži precej gradiva, le gradiva večjih dimenzij ne more zadržati (Ribičič in Galič 2010).

Območja ob erozijskih jarkih, na katerih prevladuje površinsko spiranje, porašča pionirsko rastje. Usadi se sproščajo na večinoma neporaščenih odsekih, odlomne površine pa so neporaščene zaradi velikega naklona.

Slika 8: Spodnji deli klifov so zaradi manjšega naklona poraščeni s travnim in grmovnim rastjem, strme odlomne površine v zgornjem delu pa so povečini gole.
Glej angleški del prispevka.

3.10 Izpostavljenost obale morju

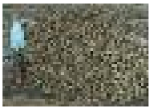
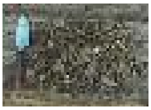
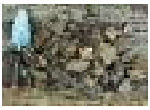
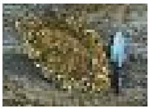
Stopnji erozije morja in priobalnega transporta sta neposredno odvisni od energije valovanja, ta pa od višine valovanja (Airy 1845; Komar in Inman 1970, po Pethick 2001). Pri tem je bistveno, da ti procesi podnožje klife sploh dosežejo, zato smo ugotavljali vrsto stika med morjem in klifi.

Na skoraj celotnem preučevanem območju gre za občasen stik vznožja obalnih sten z morsko gladino, prisotnost sklanih blokov pa je odvisna od prisotnosti plasti peščenega karbonatnega ali apnenčevega turbidita v obalni steni. Ne kaže, da bi njihova prisotnost izraziteje vplivala na stopnjo erozije morja. Neposreden stik z morjem je le na rtiču Strunjan in vzhodno od njega ter na rtiču pri Belih skalah. Poizkus pri rtiču Strunjan je pokazal, da obalni transport ob že nekoliko bolj izrazitem plimovanju z običajnim valovanjem brez težav premešča pobočno gradivo z najdaljšo stranico do 11 cm in prestavlja skale z najdaljšo stranico do 30 cm, ki se ob morebitnem pobočnem procesu kopičijo pri podnožju obalnih sten.

Slika 9: Moč valovanja na odprtem morju 4 km od preučevanega območja 6. 7. 2011. Prvi granulacijski razred je z obalne police v zalivu pri rtiču Strunjan odneslo ob 12:00, drugi in tretji ob 13:30 in četrti ob 14:00, ko je plimovanje doseglo višek (Agencija … 2011).
Glej angleški del prispevka.

Slika 10: S številkami so označeni granulacijski razredi, puščice prikazujejo smer transporta.
Glej angleški del prispevka.

Preglednica 2: Granulacijski razredi, uporabljeni v poizkusu (fotografije Matija Zorn).

Granulacijski razred	1	2	3	4	5
					
opisno	droben grušč	majhni prodniki	srednje veliki prodniki	večji kamni	manjša skala
vrsta gradiva	laporovec in peščenjak	peščenjak	peščenjak	peščenjak	peščenjak
povprečna dolžina treh stranic klastov (cm)	najdaljša stranica < 3	1 × 4 × 3	3 × 11 × 7	30 × 15 × 10	30 × 40 × 20
skupna količina (m^3)	0,03	0,03	0,03	0,01	0,02
število klastov	neprešteto	neprešteto	200	3	1
zaobljenost	nizka	srednja (0,44)	srednja (0,49)	nizka	nizka

Z vrsto stika je povezan tudi nastanek erozijskih oblik. Erozijski žlebiči in jarki ne nastajajo na odsekih z neposrednim stikom, saj so tam gole površine. Usadi so vezani na območja z občasnim stikom, kjer se ob vznožjih pobočij lahko odloži zadostna količina pobočnega gradiva, da lahko nastajajo usadi. Odlomi se pojavljajo na vseh tipih stika.

4 Ogroženost kopalcev pod klifi

Ker so z vidika ogroženosti kopalcev najbolj pomembni usadi in skalni odlomi, so ti v nadaljevanju natančneje preučeni. Da bi ugotovili kateri deli obale so podvrženi tem procesom, smo kartografsko prekrili dejavnike, ki sovpadajo na določenem obalnem odseku. Ker izbrani dejavniki neenako vplivajo na proženje posameznega pobočnega procesa, jih je bilo treba primerno obtežiti glede na njihovo stopnjo povezanosti s posamezno erozijsko obliko. Faktor obtežitve je posamezen dejavnik pridobil na podlagi absolutne vrednosti pojavljanja v povezavi z določeno erozijsko obliko. Na podlagi tega sta bila izdelana zemljevida podvrženosti pojavljanju usadov in skalnih odlomov na opazovanem območju (sliki 11 in 12).

Preglednica 3: Prisotnost posameznih dejavnikov pri pojavljanju usadov.

		usad 1	usad 2	usad 3	usad 4	usad 5	Σ
indeks trdnosti kamnin	40–43	×	×	×	×	×	5
prevladuje peščenjak		×	×	×	×	×	5
občasen stik z morjem		×	×	×	×	×	5
naklon pobočja	20°–31,9°	×	×	×	×	×	5
vpad plasti	5°–15°		×	×	×	×	4
	vodoravno	×					1
rastje	neporaščeno	×		×	×	×	4
	gozd		×				1
debelina peščenjaka	> 20 cm			×	×	×	3
	10–20 cm	×	×				2
strukturne deformacije		×	×				2

Na opazovanem območju so pri pojavljanju usadov največkrat prisotni dejavniki kamninske zgradbe (prevlada peščenjaka) in razpokanosti (indeks trdnosti kamnin), vrsta stika z morjem (občasen) in naklon pobočja (večji od 20°). Nekoliko redkejši so usadi na neporaščenih območjih z majhnim naklonom plasti, na območjih z debelimi plastmi peščenjaka in ob večjih strukturnih deformacijah. Razpoklinska voda

Preglednica 4: Prisotnost posameznih dejavnikov pri pojavljanju skalnih odlomov.

ODLOM:		1	2	3	4	5	6	7	8	9	10	11	12	13	14	Σ
apnenčev ali peščeni karbonatni turbidit		×	×	×	×	×	×	×	×	×	×	×	×	×	×	14
litologija: prevladuje	peščenjak	×	×	×	×	×	×	×	×	×		×	×	×		12
	laporovec										×				×	2
stik z morjem	neposreden	×	×	×	×	×	×	×	×	×		×	×	×		12
	občasen										×				×	2
vpad plasti	5°–15°					×	×	×	×	×		×	×	×	×	9
	vodoravne	×	×	×	×						×					5
rastje	gozd	×	×	×	×	×	×	×	×	×						9
	neporaščeno										×	×	×	×	×	5
indeks trdnosti kamnin	40–43	×	×					×	×	×	×	×	×	×	×	9
	35–39			×	×	×	×									4
debelina plasti	<10 cm	×	×					×	×	×		×	×	×		8
	10–20 cm			×	×	×	×				×				×	6
naklon pobočja	32°–54,9°	×	×			×	×			×	×				×	7
	>55°			×	×			×	×							4
	20°–31,9°											×	×	×		3
strukturne deformacije		×	×	×	×	×	×								×	7
razpoklinska voda											×		×	×		3

in plasti peščenega karbonatnega ali apnenčevega turbidita ne vplivajo na pojavljanje usadov. Najpomembnejši dejavnik pa je gotovo občasen stik z morjem, saj omogoča, da se pod klifom vendarle odloži vsaj nekaj gradiva, ki je potem podvrženo pobočnim procesom. Sodeč po sliki 11 so usadom najbolj podvrženi odseki južno od rtiča Strunjan in zaliv Sv. Križa.

Slika 11: Zemljevid podvrženosti pojavljanju usadov (Šegina 2012).
Glej angleški del prispevka.

Na flišnih klifih na preučevanem območju je za pojavljanje skalnih odlomov bistvena prisotnost plasti peščenega karbonatnega ali apnenčevega turbidita in prevlada peščenjaka, saj sta turbidit in peščenjak izvor odlomnega gradiva. Na skalne odlome vpliva tudi neposreden stik z morjem, ki zmanjšuje stabilnost obalne stene pri njenem vznožju. Nekoliko manjši vpliv imata tanka plastovitost peščenjaka in večja razpokanost kamnine (indeks trdnosti kamnin), medtem ko rastje očitno ne zadržuje skalnih odlomov, saj je več odlomov na z drevjem poraščenih odsekih, kot na neporaščenih. Manjši vpliv na pojavljanje skalnih odlomov imajo strukturne deformacije in naklon pobočja, pri čemer skalni odlomi prevladujejo v naklonskem razredu 32–54,9°, zanemarljiv vpliv pa ima voda v razpokah. Odlomom so glede na sliko 12 najbolj podvrženi odseki v zalivu Sv. Križa, predvsem zahodni del zaliva, rtič pri Belih skalah ter nekoliko manj odsek tik pred Strunjanom in vzhodni del rtiča Kane.

Slika 12: Zemljevid podvrženosti pojavljanju skalnih odlomov (Šegina 2012).
Glej angleški del prispevka.

5 Sklep

Pri preučevanju klifov je največji izziv ocenjevanje hitrosti njihovega umikanja. Zaradi odsotnosti daljših meritev erozije na flišnih klifih ob slovenski obali lahko hitrost erozijskih procesov zaenkrat le ocenjujemo na nekaj centimetrov letno.

V članku je predstavljen vpliv nekaterih naravnih dejavnikov na pojavljanje posameznih erozijskih procesov in reliefnih oblik na klifih ter prostorska razprostranjenost usadov in skalnih odlomov. Glede na rezultate postavljamo hipotezo, da so v zalivih pomembni »pospeševalci« erozije na pobočjih usadi, na rtih pa skalni odlomi.

Primerjave med posameznimi dejavniki in obliko današnje obalne črte kažejo, da je slednja v največji meri odvisna od debeline plasti peščenjaka in prisotnosti plasti peščenega karbonatnega ali apnenčevega turbidita. Iz tega sklepamo, da je sicer počasno umikanje klifov v zalivih, kjer teh plasti ni, razmeroma hitro in zato bolj vpliva na potek obale, kakor hipni erozijski ali pobočni procesi. Slednji so tesno povezani s prisotnostjo debelejših turbiditnih plasti ali debelejših plasti peščenjaka in so pogostejši na izpostavljenih rtih. Večji skalni odlomi, ki sicer premaknejo obilo gradiva v kratkem času, so na opazovanem območju preveč redki, da bi se njihov prispevek k preoblikovanju obale pomembneje odražal.

In kakšno je predvideno prihodnje spreminjanje obalnih klifov na opazovanem območju?

Odgovor na to vprašanje je tesno povezan z napovedanim spreminjanjem višine morske gladine, ki uravnava stopnjo erozije morja in obalnega transporta.

Lambeck in ostali (2004) za območje Sredozemskega morja ocenjujejo, da je od konca zadnjega poledenitvenega viška (pred okoli 12.000 leti) do danes najpomembnejši dejavnik nihanja morske gladine tektonika. Zaradi odsotnosti nanosov iz zadnjega medledenega obdobja pri Trstu glede na znane evstatske in glacio-hidroizostatske stopnje sklepajo, da se površje greza s stopnjo –0,15 mm/leto (Lambeck in ostali 2004). Višine geomorfoloških in arheoloških najdb med zalivom Sv. Jerneja in zalivom Sv. Simona, preračunane po različnih evstatsko-glacio-hidrostatskih modelih, nakazujejo na hitrost grezanja med –0,44 mm na leto in –1,53 ± 0,72 mm na leto v zadnjih 2000 letih (Antonioli in ostali 2009). Na podlagi spodmolov na območju apnenčaste obale med Miramarom in Devinom (severozahodno od Trsta), ki so danes pod morsko gladino, sklepajo o grezanju sedimentacijskega bazena v zadnjih 10.000 letih proti severozahodu. Severni del Tržaškega zaliva se pogreza hitreje (več kot –1,99 mm/leto), kot južni del (okoli –0,6 mm/leto) (Furlani in ostali 2011c). Neenakomerno grezanje je posledica različnega gibanja tektonskih blokov, ločenih s prelomi, pravokotnimi na dinarsko smer (Furlani in ostali 2011c). Stopnja evstatizma naj bi imela drugoten pomen na nihanje morske gladine v Sredozemskem morju, glacio-hidroizostazija pa naj bi prispevala le 10–15 % k skupni višini gladine morja, pri čemer ima alpska poledenitev le zanemarljiv vpliv (Lambeck in ostali 2004). Dviganje površja zaradi izostazije po zadnjem ledenem obdobju naj bi tako v severnem Sredozemlju znašalo le +0,1 do 0,2 mm letno (Peltier 2001, po García 2007).

Gladina morja na mareografski postaji Koper se zvišuje za približno 1 mm/leto, kar je v skladu s trendom naraščanja gladine Sredozemskega morja (Ličer in ostali 2010) in je povezano tudi s steričnim učinkom zaradi spreminjanja prostornine morske vode ob nihanju temperature in slanosti ter zaradi spreminjanja vodne bilance (Creado-Aldeanueva 2008). Ta trend in pa istočasno grezanje, evstatizem in glacio-hidroizostazija preprečujejo fosiliziranje obalnih oblik. Zaradi dviganja morske gladine lahko tako v prihodnje pričakujemo ohranjanje trenutno prisotnih obalnih reliefnih oblik in delujočih procesov.

6 Literatura

Glej angleški del prispevka.