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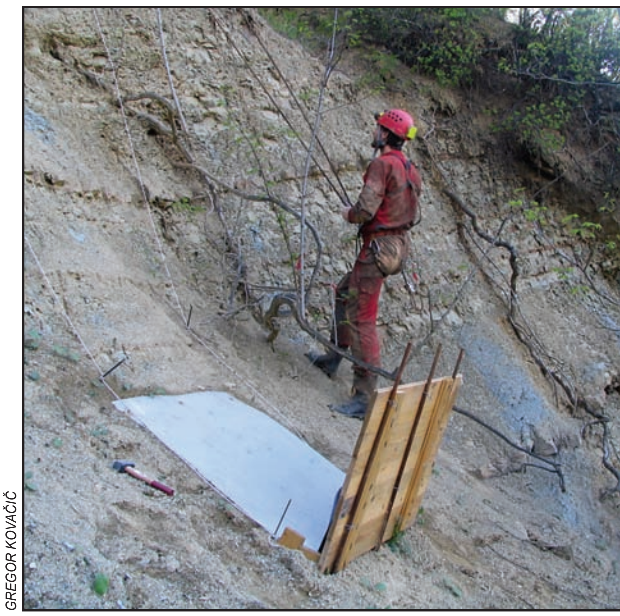
SEDIMENT PRODUCTION IN FLYSCH BADLANDS: A CASE STUDY FROM SLOVENIAN ISTRIA

Gregor Kovačič



Measuring the catchment areas of erosion plots in the Strane Badlands in the Rokava River headwaters, April 28th, 2008.

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Sediment production in flysch badlands: A case study from Slovenian Istria

ABSTRACT: This article deals with the results of seven years of measurements of sediment release from the flysch badlands in the Rokava River headwaters. Measurements of sediment production were carried out in erosion plots, and measurements of cliff (or rockwall) retreat using erosion pins. Selected meteorological time series from the Portorož Airport meteorological station were included in the analysis. The calculation showed that from 2008 to 2015 (149 measurements) sediment production was 36 kg/m² per year and the flysch cliff retreated by 146 mm or 21 mm per year. The amount of sediment produced is moderately positively correlated with the number of days between successive measurements ($r = 0.51$), with a recorded daily transition of air temperature over/below 0 °C ($r = 0.56$) and slightly more weakly correlated with the precipitation amount ($r = 0.45$). On the other hand, the amount of sediment produced has a low negative correlation with average air temperature ($r = -0.29$) and average minimum air temperature ($r = -0.30$). However, no statistically significant correlation was calculated between the amount of sediment produced and average wind speed.

KEY WORDS: geomorphology, geomorphic processes, erosion processes, sediment production, cliff retreat, geography, Slovenian Istria, Slovenia

Sproščanje gradiva na erozijskih žariščih v flišu v slovenski Istri

POVZETEK: Prispevek obravnava sedemletne meritve sproščanja fliša z erozijskega žarišča Strane v povirju Rokave. Meritve sproščanja kamninskega gradiva smo opravljali s pomočjo erozijskih polj, meritve umikanja flišne stene pa tudi s pomočjo erozijskih žebljičev. V analizo smo vključili podatke izbranih meteoroloških časovnih vrst s postaje Portorož – letališče. Izračuni kažejo, da je bila v obdobju 2008–2015 (149 meritev) intenzivnost sproščanja fliša 36 kg/m²/leto, stena pa se je umaknila za 146 mm oziroma 21 mm/leto. Količina sproščenega gradiva je zmerno pozitivno povezana s številom dni med meritvami (r = 0,51) ter številom dni s prehodom temperature zraka preko/pod 0 °C med dvema meritvama (r = 0,56), manj z višino padavin (r = 0,45), medtem ko s povprečno dnevno temperaturo (r = –0,29) in povprečno minimalno temperaturo zraka (r = –0,30) kaže nizko negativno povezanost. S povprečno hitrostjo vetra količina ne kaže statistično značilne povezanosti.

KLJUČNE BESEDE: geomorfologija, geomorfni procesi, erozijski procesi, sproščanje gradiva, umikanje pobočij, geografija, slovenska Istra, Slovenija

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1 Introduction

Studying erosion in its broadest sense – that is, all exogenous processes of rock and eluvium removal and transportation (Kladnik et al. 2005) – is difficult because these processes are usually slow and most landforms take a long time to develop (Howard and Kerby 1983). Direct observation and measurement or erosion prediction models (erosion models; Stroosnijder 2005, cf. Zorn 2008b) can be used at different time and spatial scales (Turowski and Cook 2017). However, the production and calibration of erosion models, which allow faster acquisition and interpretation of erosion data for larger areas, also require data obtained through direct measurement in the natural environment or laboratories (Stroosnijder 2005). Direct measurement methods are technically complex and time consuming, and the results obtained are difficult to extrapolate to longer time periods and larger spatial units (Zorn 2008b). Due to their complexity, measurements are usually possible only in erosion plots of various sizes, and the results are difficult to extrapolate to larger areas (for more, see Zorn 2008b). Due to greater storage capacity, the amount of sediment produced usually decreases with increasing size of the study area (Nadal-Romero et al. 2011). Erosion process measurements are rare in Slovenia (Zorn 2015). Measurements in flysch badlands were performed by Zorn (2008a; 2009) and in dolomite badlands by Komac (2003) and Švigelj (2015). There have been a few studies examining the intensity of soil erosion on various types of farmland; the findings are published in Komac and Zorn (2005; 2007), Zorn and Komac (2005), and Zorn (2008a).

Extremely well suited for studying geomorphic systems at small spatial and time scales (Wainwright and Brazier 2011) are badlands, where geomorphic processes are intense and landform changes are rapid, allowing effective use of direct observation and measurement methods (Campbell 1997; Gulam et al. 2014). General overviews of badlands and badland-forming processes have been provided by various authors (e.g., Scheidegger et al. 1968; Bryan and Yair 1982; Howard 1994; 1997; 2009; Campbell 1997; Saunders and Young 1983; Torri et al. 2000; Gallart et al. 2002; Harvey 2004).

Badlands can be defined as landforms with or without sparse vegetation, with steep slopes, a dense network of erosion rills and gullies, and few or no eluvial deposits produced in loose or poorly consolidated, impermeable, or poorly permeable rocks, usually with a significant share of clay (Gulam et al. 2014). In badlands, rocks are directly exposed to weathering processes, the effects of raindrops, runoff, and wind erosion (Zorn 2008a; 2009; 2012). This results in the formation of taluses under steep rockfaces (Jurak and Fabić 2000; Zorn 2009; 2012). Badland formation is influenced by various factors, with geological and climate factors being the predominant ones (Bryan and Yair 1982; Gulam et al. 2014). An important factor for their preservation is the absence of vegetation or sparse vegetation cover, which is also disappearing in some places due to human impact (Harvey 2004; Nadal-Romero and Regüés 2010; Gulam et al. 2014). In some areas, the abandonment of farming on steep slopes and afforestation have resulted in a significant (i.e., 70–85%) decrease in the area of badlands (Ciccacci et al. 2008; Staut and Mikoš 2008).

Badlands are being studied across the globe (e.g., Schumm 1956; 1962; Liu et al. 1985; Feoli et al. 2002; Boardman et al. 2003; Eriksson et al. 2003; Curry and Morris 2004; Poesen et al. 2006; Achten et al. 2008; Maerker et al. 2008; Joshi et al. 2009), including the Mediterranean (e.g., De Ploey 1974; Yair et al. 1980; Alexander 1982; Imeson et al. 1982; Rendell 1982; Wise et al. 1982; Clotet et al. 1988; Benito et al. 1992; 1993; Torri et al. 1994; Wainwright 1994; Poesen and Hooke 1997; Sirvent et al. 1997; Clarke and Rendell 2000; 2006; Nogueras et al. 2000; Cantón et al. 2001; Gallart et al. 2002; Wainwright and Thornes 2003; Regüés and Gallart 2004; Díaz-Hernández and Juliá 2006; Piccaretta et al. 2006; Nadal-Romero et al. 2007; 2008; 2011; Ciccacci et al. 2008; Miščević et al. 2009; Nadal-Romero and Regüés 2010; Martínez-Murillo et al. 2013). They are also typical of the flysch areas in Istria (southwest Slovenia and northwest Croatia), which have been studied by various researchers (e.g., Jurak and Fabić 2000; Jurak et al. 2002; 2003; Petkovšek 2002; Petkovšek and Mikoš 2003; Staut and Mikoš 2008; Zorn 2007; 2008a; 2008c; 2009; 2010; 2012; Zorn and Mikoš 2008; Zorn and Komac 2011; Gulam et al. 2014; 2018). They usually cover up to ten hectares and are small compared to others elsewhere around the globe, which can cover up to several dozen square kilometers (Bryan et al. 1987; Howard 1994). However, in Istria they are very common. Gulam, Pollak, and Podolszki (2014) inventoried 5,568 badlands with a total area of 10.7 km^2 in the flysch areas of Croatian Istria. In Istria, sediment release in badlands can be up to eight hundred times greater than in areas covered with vegetation (Jurak and Fabić 2000). The percentage of badlands in individual Istrian watersheds can reach up to 12% (Gulam et al. 2014). A simplified model of the formation and development of a badland on flysch rocks is presented in Gulam (2012) and Gulam, Pollak and Podolszki (2014).

This article presents the analysis results of measurements of sediment release from the cliff in the flysch in the Strane Badlands in the Rokava headwaters in Slovenian Istria, conducted between 2008 and 2015. Some results for the period from 2008 to 2012 have already been published in Zorn et al. (2017). The analysis included selected meteorological variables, and their correlation with or impact on sediment production was established using data retrieved from the Portorož Airport meteorological station.

2 Geographical location of the test site, methods, and materials

The Strane Badlands are located on the left, shady side of the Rokava Valley, above one of the left meanders of the Rokava (or Pinjevec) River, 1.5 km south of Marezige and 300 m west of Rokavci (Figure 1). Like the entire Dragonja Basin, which the Rokava River is part of, the badlands extend in an east–west direction. The area is made of Eocene flysch, with alternating layers of siliciclastic sediment and carbonate-siliciclastic turbidites of sandstone and marl (Placer et al. 2004). The flysch areas in Istria are also characterized by calciturbidites 1.5 meters or more thick (megalayers), but there are none in these badlands. The barren flysch marlstone is highly non-resistant to exogenous processes (Vivoda Prodan and Arbanas 2016; Vivoda Prodan et al. 2017), which is also the case in the badlands studied, where the marlstone is fractured to a depth of 5 to 10 cm (Zorn 2008a).

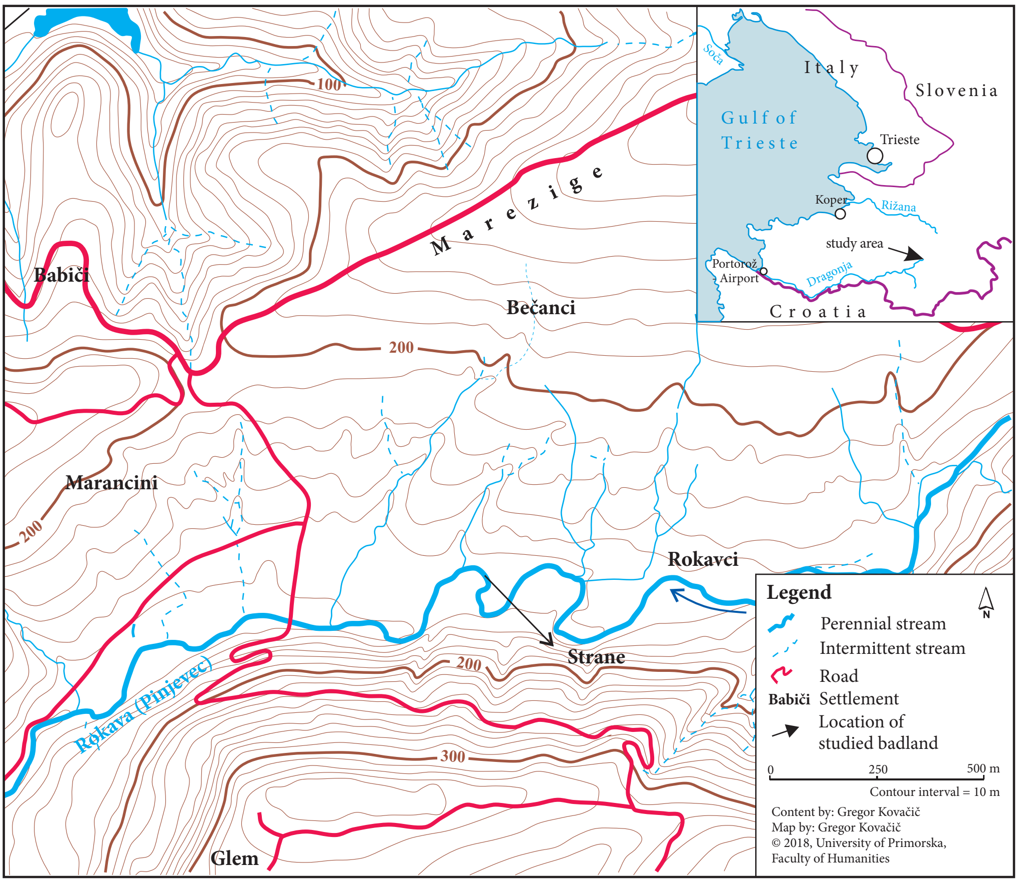

Figure 1: Location of the Strane Badlands in the Rokava headwaters.

Over the past twenty years, the Dragonja Basin has frequently been the subject of studies examining geomorphic processes, especially using various erosion models, whereas direct measurements of geomorphic processes have been less common (Globevnik et al. 1998; Globevnik 2001; Petkovšek 2002; Petkovšek and Mikoš 2003; 2004; Staut 2004; Keesstra 2006; 2007; Keesstra et al. 2005; 2009; Staut and Mikoš 2008; Zorn 2008a; 2009; 2012).

The study area has a transitional climate between the coastal and mainland temperate Mediterranean climates, with annual precipitation between 1,100 and 1,200 mm (Ogrin and Plut 2009). The total area of the central part of the badlands composed of a flysch cliff and a largely overgrown talus beneath it covers approximately 0.8 hectares, and the wider area of more intense erosion and denudation processes covers approximately 1.8 hectares. The highest part of the cliff edge is at an elevation of approximately 203 to 210 m, and the Rokava riverbed is at an elevation of 150 m. The badlands lie above the outer edge of the meander and are thickly overgrown, which is why the Rokava River washes away material from its lower parts only when precipitation is very intense (Zorn 2008a), keeping the badlands active. The contact between the running water and the talus is key to preserving the badlands (Gulam et al. 2014).

On March 19th, 2008, four semi-open erosion plots for measuring the amount of sediment released from the flysch cliff were set up at approximately the same micro-locations as used by Zorn, who performed the measurements from 2005 to 2006. The plots lay at an elevation of 198 to 203 m and were delimited on the upper side by the edge of the badlands and were open on the sides. They had a northeast orientation. The erosion plot barriers were made of wood and plastic (Figure 2) and were placed approximately 2.0 to 2.5 m from the wall. The plastic edges of individual erosion plots, which were placed on the slope to prevent the material produced from mixing with the older material on the talus, were set approximately 0.5 m from the wall. To prevent material from slipping past the barriers, wooden slats were placed on the sides of the plots. The catchment areas of individual erosion plots that followed one another in a north–south

Figure 2: Location of erosion plots in the Strane Badlands (March 19th, 2008).

direction measured 9.63 m² for the first plot, 8.38 m² for the second, 4.13 m² for the third, and 2.61 m² for the fourth, or a total of 24.74 m² altogether, which was twice as much as with Zorn's measurements (2008a; 2009). The inclinations of the plot barriers ranged from 32° to 55°, which is more than the natural angle of repose of loose material, and the inclination of the erosion plots ranged between 80° and 90°. The slope above the edge of the cliff is less steep and it is overgrown with mixed forest consisting of Austrian pine and downy oak.

In the badlands studied, the sediment release from the flysch cliff was measured by weighing the sediment accumulated behind the erosion plot barriers (Figure 3). A digital hanging scale (with a precision of 10 g) was used to measure both the total mass of the sediment and the masses of three different grain sizes of sediments (up to 13, 13 to 25, and over 25 mm; Figure 4). This article presents the results for the total mass of sediment produced in individual erosion plots. The analysis took account of the total mass of dry material. The ratio between the wet and dry material was defined in the laboratory; with the same volume of material, the mass of wet material is 7% greater. In parallel, direct cliff retreat was measured using erosion pins placed in the cliff's marlstone and sandstone (the measurements are conducted every six months, Figure 5). When a pin falls from the cliff, it has to be replaced. Occasionally the pins in the lower part of the cliff or the upper part of the talus are covered by debris. During the measurements, the measurement plots were damaged several times, which to some extent affected the results.

The rate of cliff retreat and the amount of sediment produced per area were calculated using the data on the size of the catchment areas in the rockfaces above the erosion plots and the flysch mass (1,712.04 kg/m³) that Zorn (2008a) had used in his calculations.

This article presents the results of 149 measurements conducted at various intervals between March 19th, 2008 and February 17th, 2015 (a total of 2,527 days). The measurement data were correlated with the data of selected meteorological variables measured and processed at the Portorož Airport meteorological station just over 14 km west of the badlands studied at an approximately 180 m lower elevation (Table 2, Figure 1). Data on the mass of the sediment accumulated in the erosion plots between two successive measurements were correlated with data on the average air temperature, average minimum air temperature,

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Figure 3: Material accumulated behind the barrier of an erosion plot (June 6th, 2012).


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Figure 4: Weighing the accumulated sediment with a hanging scale, October 23rd, 2017.


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Figure 5: Erosion pins for direct measurements of flysch cliff retreat, April 28th, 2008.

average wind speed, total precipitation and average daily precipitation, and the total and average number of days with a recorded transition of air temperature over/below 0 °C calculated for the periods between the two successive measurements. The information on changes in temperature is important for studying the effect of frost weathering on the production of flysch sediment during the cold half of the year. This effect on the amount of the sediment produced in badlands has been demonstrated by various authors (Zorn 2008a; 2012; Regüés et al. 1995; 2000). The direction and strength of correlation between various pairs of variables were analyzed using the Pearson correlation coefficient ($p < 0.05$).

From October 20th, 2010 to November 13th, 2012 (742 days), air temperature was measured at one-hour intervals above the badland talus (facing east) and on the slope above the edge of the badlands (facing north). A regression analysis between the average and minimum daily air temperatures measured at the Portorož Airport station and the data obtained in this study showed exceptionally high correlation ($r^2 = 0.98–0.99$). Regression functions were used to calculate the average and minimum daily air temperatures in the badlands, which were included in the aforementioned analysis of correlation between the mass of sediment produced and the values of meteorological variables.

3 Results and discussion

3.1 Weather conditions: comparison with long-term average values

The typical air temperatures in the badlands were as follows: the average air temperature was 12.88 °C, the absolute minimum air temperature was −9.5 °C (February 14th, 2012), and the absolute maximum air temperature was 38.3 °C (July 2nd, 2012). Over the seven-year period of measurements, there were 335 days with a recorded transition of air temperature over/below 0 °C, which is 36% more than what was measured at the Portorož Airport station. These changes in temperature are only typical of the cold half of the year (from October to March). The average number of days with a recorded transition of air temperature over/below 0 °C per day for 149 observation periods was 0.11 and in the cold half of the year it was 0.36. During the measurement period, the annual precipitation at the Portorož Airport station was 1,027 mm, which is 6% more than between 1981 and 2010 (Agencija … 2017). Due to higher annual precipitation in Istria's interior, another 100 to 200 mm can be added to the total annual precipitation in the measurement area. Compared to the period from 1981 to 2010, the following months were wetter in the period studied: July (59% more precipitation), February (41% more), and November and May (both with 15% more precipitation). The average August precipitation amounted to only 66% of the long-term average, and the average precipitation in October only 74%. Average daily precipitation was 2.7 mm. The average annual and daily precipitation are not direct indicators of the erosive force of precipitation (which was not measured), but in general erosivity is greater during the wet part of the year (Petkovšek 2002; Zorn 2008a). Precipitation intensity affects the rate of transfer of the already weathered material down the slope. In turn, the wetness or saturation of the rock affects mechanical weathering by wetting and drying, which is typical of fine-grained sedimentary rock, including flysch marl. The average wind speed during the period studied was 2% higher than from 1981 to 2010. The windier months included February, March, December, and October, with 12%, 7%, 5%, and 4% higher average wind speeds, respectively. The greatest downward deviations were recorded in April (6%) and July (2%). Through wetting and drying, wind is an important factor in flysch weathering, and it also triggers the release of weathered material down the slope.

3.2 Sediment production

Over the course of seven years, just over 5,733 kg of sediment was weighed in the four erosion plots, of which 66.7% had a grain size up to 13 mm, 24% had a grain size between 13 and 25 mm, and 9.2% had a grain size larger than 25 mm (Table 1). Flysch mostly weathers into smaller-grained material, which is a result of the fine-grained composition of sandstone and marl. Occasionally larger pieces of sandstone with a typical oblique rectangular prism shape accumulated in the erosion plots. The largest share of the finest-grained material was recorded in Plot 4 (74%) and the smallest share was recorded in Plot 3 (60%), which can be explained by the different flysch composition in the catchment areas, where there were no thick sandstone layers above Plot 4. In contrast, the largest share of the coarsest-grained material was weighed in Plot 3 (11%) and the smallest in Plot 4 (9%).

The largest share in the total mass of the sediment in the badlands came from Plot 1 (2,072 kg or 36%) and the smallest from Plot 4 (824 kg or 14%; Table 1). Sediment production ranged from 213 kg/m² (Plot 2) to 316 (Plot 4) kg/m², with an average of 250 kg/m². Over the seven years, the annual average sediment production was 36 kg/m²/year (ranging from 31 to 46 kg/m²/year). Over the course of two years, Zorn (2008a, 2009, 2010, 2012) calculated sediment production twice as high, ranging from 58 to 122 kg/m²/year for an individual erosion plot (an average of 80 kg/m²/year). This difference may reflect different weather conditions between the two periods observed and/or a different frequency of field measurements, which were performed weekly from 2005 to 2006 and every two to seventy-four days (or on average every seventeen

Table 1: Selected indicators of values measured and calculated in the Strane Badlands in the Rokava headwaters between March 19th, 2008 and February 17th, 2015.

Indicator	Plot 1	Plot 2	Plot 3	Plot 4	Total (Σ sum, x̄ mean)
Catchment area (m²)	9.63	8.38	4.13	2.61	Σ = 24.75
Accumulated sediment mass (kg)	2,072.71	1,781.62	1,054.50	824.33	Σ = 5,733.16
Accumulated sediment mass (%)	36.15	31.08	18.39	14.38	Σ = 100
Calculated flysch cliff retreat, period (mm)	125.67	124.24	149.18	184.80	x̄ = 145.88
Calculated flysch cliff retreat, annual (mm)	18.16	17.95	21.56	26.71	x̄ = 21.30
Sediment production (kg/m²)	215.14	212.70	255.41	316.39	x̄ = 249.91
Sediment production (kg/year)	299.52	257.46	152.38	119.12	x̄ = 207.12
Sediment production (kg/m²/year)	31.09	30.74	36.91	45.72	x̄ = 36.11
Sediment production (t/ha)	2,151.4	2,127	2,554.1	3,164	x̄ = 2,499
Sediment %, grain size < 13 mm	69.11	64.04	60.35	74.25	x̄ = 66.71
Sediment %, grain size 13–25 mm	21.64	27.27	28.38	17.90	x̄ = 24.05
Sediment %, grain size > 25 mm	9.26	8.69	11.27	7.85	x̄ = 9.24

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Figure 6: Damage to a barrier of erosion Plot 2 caused by sandstone breaking off, October 12th, 2017.

days) from 2008 to 2015. Hence, it is possible that the measurements performed after longer breaks do not cover all the material produced because it may have managed to slip past the barriers due to the erosion plots being overfilled. The same applies to measurements performed after the erosion plots had been damaged (Figure 6). Sediment production is inversely proportional to the size of the erosion plots' catchment areas (Table 1), which may again be the result of sediment slipping past the barriers in erosion Plots 1 and 2. The annual amount of sediment accumulated in erosion plots ranged from 119 (Plot 4) to 300 kg/year (Plot 1), with an average of 207 kg/year.

Data on slope retreat across the globe were collected by Young (1969, 1974), Saunders and Young (1983), and Young and Saunders (1986), who report a predominant retreat of up to 1 mm/year. Poesen and Hooke (1997) report significantly higher values for the Mediterranean, ranging from 0.05 to 30 mm/year, and more recent research even reports retreats of up to 65 mm/year (Gulam et al. 2018) and surface lowering of up to 75 mm/year (Ciccacci et al. 2008). It makes sense to compare the results of this study with the results obtained in flysch badlands because the rate of cliff retreat depends strongly on the lithological characteristics of badlands (Bryan and Yair 1982; Gulam et al. 2014). The flysch cliff in the badlands studied retreated 18 to 27 mm/year or 21 mm/year on average. This is half as much as Zorn calculated for individual erosion plots (2008a, 2009, 2010, 2012) – that is, 35–50 mm. Gulam et al. (2018) calculated an annual flysch cliff retreat of 27–33 mm using profilometers and a retreat of up to 65 mm/year using photogrammetry. Jurak et al. (2003) used the same method to calculate a retreat of 21 mm/year, Ogrin (1992) determined a retreat of 20 mm/year using dendrochronology, and Petkovšek (2002) and Petkovšek and Mikoš (2003) reported a retreat of 40 to 50 mm/year. Erosion pins were used to measure a cliff retreat of 19.4 to 41.6 mm/year or 31 mm/year on average. Marl retreats 3 mm/year faster than sandstone. The retreat measured using the erosion pins was larger than the calculated retreats. The differences arise from the measurement method, but partly they can also be explained by material slipping past the erosion plot barriers. The different rates of flysch cliff retreats in the badlands in Istria (Petkovšek 2002; Jurak et al. 2003; Zorn 2008a, 2009, 2010, 2012; Gulam et al. 2018) and a comparison with the results of this study show that sediment production strongly depends not only on lithological characteristics, but also on terrain and climate characteristics.

3.3 Correlation between sediment production and meteorological variables

The sediment masses measured in the erosion plots show high significant positive correlations with meteorological variables (0.70–0.83). In addition, they show moderate significant correlations with the number of days between measurements ($r = 0.43–0.70$), which indicates that sediment production on the cliff is not the same throughout the year. The seasonal aspect of erosion processes and the predominant effect of frost weathering during the cold half of the year and rain erosion during the warm half of the year were reported by Regüés et al. (1995; 2000), Regüés and Gallart (2004), Nadal-Romero and Regüés (2010), and Zorn (2008; 2012). The Pearson correlation coefficient between the total amount of sediment measured in all four plots and the duration of the intervals between measurements was 0.51. The strongest correlation with this indicator was established for Plot 4 (Table 2).

The average air temperature at the measurement site shows a low negative correlation with the amount of sediment produced ($r = –0.29$), and approximately the same values were established for the correlation between the amount of sediment produced and the average minimum air temperature at individual plots ($r = –0.12$ to $–0.40$), which is comparable to Zorn's (2008a; 2012) findings ($r = –0.31$). The fact that frost weathering is an important process affecting flysch release in badlands is proven by the moderate positive significant correlation of the amount of sediment produced with the number of days with a recorded transition of air temperature below/over 0 °C ($r = 0.59$) and the average number of days with a recorded transition of air temperature below/over 0 °C ($r = 0.54$, Table 2). The same was established by Zorn (2008a; 2012), who established a weak significant positive correlation between the number of days with temperatures below freezing and the amount of sediment produced ($r = 0.25$). The measurements for this study were performed on the shady slope, for which Nadal-Romero et al. (2007) determined that alternation between freezing and thawing is a key factor in weathering and sediment production.

The total precipitation between measurements shows low to moderate significant positive correlations with the sediment mass measured in the erosion plots ($r = 0.35–0.67$). Again, the strongest correlation with this indicator was established for Plot 4; the correlation with the total mass of the sediment accumulated was 0.45, which is completely comparable with the 0.43 reported by Zorn (2008a, 2012). Zorn established insignificant positive correlations between the total mass of sediment produced and precipitation indicators (r = 0.21–0.26) and a weak positive correlation with the precipitation erosion indicator (r = 0.35). The results of this study show no statistically significant correlation between the mass of the sediment accumulated in the erosion plots and the average daily precipitation (r = 0.04–0.16). Based on an extensive database on erosion plots in the Mediterranean, Nadal-Romero et al. (2011) report no clear correlations between the amount of sediment produced and temperatures or precipitation, whereas the results of this and Zorn's studies (2008a, 2008b, 2012) show the opposite.

Zorn (2008a; 2012) calculated a low significant positive correlation (r = 0.34) between the average wind speed at the Koper meteorological station and the mass of sediment produced, and a moderate significant positive correlation with maximum gusts (r = 0.42). The results of this study do not show a statistically significant correlation between the average wind speed at the Portorož Airport meteorological station and the mass of the sediment accumulated (r = 0.06–0.14). The Pearson correlation coefficient between the total amount of sediment in all four plots and the average wind speed is 0.11 (Table 2).

In thist study, the amount of sediment produced shows a moderate positive correlation with the number of days between two consecutive measurements with a recorded transition of air temperature over/below 0 °C (r = 0.59) and a weaker correlation with the precipitation (r = 0.45). In addition, it shows a low negative correlation with the average daily temperature (r = –0.29) and the average minimum air temperature (r = –0.30). The findings of the study show the important impact of frost weathering on flysch sediment production. A correlation between the mass of sediment produced and the average wind speed was not confirmed.

Table 2: Pearson correlation coefficients between the mass of sediment accumulated in the erosion plots and selected meteorological variables (n = 149 measurements; statistical significance is tested for $p < 0.05$; *statistically insignificant).

Meteorological variable	Plot 1	Plot 2	Plot 3	Plot 4	Total
Strane: average air temperature	–0.24	–0.39	–0.23	–0.12*	–0.29
Strane: average minimum air temperature	–0.25	–0.40	–0.23	–0.12*	–0.30
Strane: days with air temp. transition over/below 0 °C	0.56	0.60	0.53	0.41	0.59
Strane: avg. days with air temp. transition over/below 0 °C	0.51	0.60	0.41	0.36	0.54
Portorož Airport: average wind speed	0.10*	0.14*	0.06*	0.09*	0.11*
Portorož Airport: precipitation	0.39	0.35	0.43	0.67	0.45
Portorož Airport: average daily precipitation	0.13*	0.04*	0.14*	0.16*	0.11*
Days between measurements	0.45	0.43	0.47	0.70	0.51

4 Conclusion

The results of the seven-year measurements of weathered flysch sediment released from the rockface in the Strane Badlands of the Rokava headwaters in Slovenian Istria showed that on average 36 kg of sediment per m² is produced a year, which is comparable with the results obtained in other Istrian badlands (e.g., Jurak and Fabić 2000; Jurak et al. 2002; Petkovšek 2002; Jurak et al. 2003; Petkovšek and Mikoš 2003; Staut and Mikoš 2008; Zorn 2007; 2008a; 2008b; 2008c; 2009; 2012; Zorn and Mikoš 2008; Zorn and Komac 2011; Gulam et al. 2014, 2018). The cliff retreats at a rate of 21 mm per year.

In the future, research measuring flysch sediment production should be expanded with continuous measurements of selected meteorological parameters at this site, which would allow easier study of the impact of individual climate elements on sediment production during the year and more reliable conclusions about their impact on the rate of erosion-denudation processes. It would make sense to supplement direct measurements with other methods, such as terrestrial photogrammetry. In measuring the direct retreat of the cliff, the pins could be replaced by more accurate profilometers, such as reported by Gulam et al. (2018). Attention should also be directed to dissolved weathering products and fine-grained suspended particles that disappear with water through the weathered material and do not accumulate behind the erosion plot barriers.

Studying geomorphological processes in badlands is important for gaining basic insights into the development of terrain. Because erosion-denudation processes take place relatively quickly in flysch badlands, they can also serve as a good case study for exploring changes in the intensity of geomorphological processes during this period of increasingly evident planetary climate and environmental change, in view of which the importance of studying them is bound to increase. The findings of this study have undoubtedly shown that slope processes in badlands are very effective in shaping flysch slopes.

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