Acta geographica Slovenica, 64-1, 2024, 7–22

# MORPHOGENESIS AND CLASSIFICATION OF CORROSION PLAINS IN SLOVENIA

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The surface of Rajndol Plain is dissected by numerous dolines.

DOI: https://doi.org/10.3986/AGS.11774
UDC: 911.2:551.435.8(497.4)


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# Morphogenesis and classification of corrosion plains in Slovenia

ABSTRACT: A new study of corrosion plains in Slovenia provides a systematic classification based on their geological settings and morphology. They are grouped into four types: karst plains, dry poljes, marginal plains of contact karst, and marginal plains of fluviokarst. Karst plains are the largest, formed through denudation under stable tectonic and hydrogeological conditions. Dry poljes are closed basins composed of bedrock and scattered sediment. Marginal plains of contact karst are formed at the boundary between non-karst and karst environments, while marginal plains of fluviokarst result from multiphase formation of poljes due to tectonic activity. This study enhances understanding of corrosion plains and can assist in their identification and management in karst areas.

KEYWORDS: geomorphology, karst, corrosion plain, Slovenia, Dinaric Karst

# Morfogeneza in klasifikacija korozijskih uravnav v Sloveniji

IZVLEČEK: Raziskava korozijskih uravnav v Sloveniji podaja sistematično klasifikacijo korozijskih uravnav na podlagi njihovih geoloških in morfoloških značilnosti. Klasifikacija jih združuje v štiri kategorije: kraški ravnik, suho kraško polje, robna uravnava kontaktnega krasa in robna uravnava fluviokrasa. Kraški ravniki so največji in nastanejo z denudacijo v stabilnih tektonskih in hidrogeoloških razmerah. Suha kraška polja so zaprte živoskalne kotanje le mestoma prekrite s sedimenti. Robne uravnave kontaktnega krasa so nastale na stiku kraških in nekraških kamnin. Robne uravnave fluviokrasa so nastale z večfaznim razvojem kraških polj zaradi tektonske dejavnosti. Ta raziskava prispeva k boljšemu razumevanju korozijskih uravnav in lahko pomaga pri njihovi identifikaciji in upravljanju v kraških območij.

KLJUČNE BESEDE: geomorfologija, kras, korozijska uravnava, Slovenija, Dinarski kras

The article was submitted for publication on February 25th, 2023.
Uredništvo je prejelo prispevek 25. februarja 2023.

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# 1 Introduction

Karst is a distinct geomorphologic system characterized by the dominance of underground water flows. Chemical denudation, resulting from chemical weathering of bedrock, mainly by congruent dissolution, is the most important process at the surface. The predominance of chemical denudation and the absence of aggradation are evident in the rocky surface and the diversity of landforms (Sweeting 1973; Šušteršič 1986; White 1988; Ford and Williams 2007; Stepišnik 2020; De Waele and Gutiérrez 2022).

Karst areas exhibit a high degree of complexity and variability due to the interplay of both typical karst surface and subsurface processes, as well as diverse sediment transport mechanisms such as fluvial, glacial, and coastal processes. These interactions can lead to a wide array of unique surface and subsurface formations within different karst landscapes. The functioning of these geomorphologic processes is strongly influenced by geologic, hydrologic, and climatic conditions, resulting in significant differences in karst morphology around the world (Jennings 1985; Ford and Williams 2007; De Waele and Gutiérrez 2022).

Early attempts at a typology of karst in Slovenia were based on hydrological and geomorphological characteristics, with Šerko (1947) being the first to establish a classification system. Later typologies of karst areas were subdivided according to a number of geomorphological and hydrological features (Gams 1959; 1972; 1974; 1995; 2004; Habič 1969; 1980; 1982; 1986, Žebre and Stepišnik 2015; Stepišnik 2017; 2020; Stepišnik, Stojilković and Hočevar 2019).

The latest karst typologies in Slovenia (Stepišnik 2020) provide a detailed classification system based on the dominant geomorphologic processes on karst, specifically the morphodynamic characteristics of karst environments. In Slovenia, deep karst and shallow karst are distinguished based on their hydrogeological characteristics (Stepišnik 2017; 2020), while fluviokarst (Roglić 1958; Komac 2004; Stepišnik 2021a; De Waele and Gutiérrez 2022) and glaciokarst (Žebre and Stepišnik 2015; Ferk et al. 2017) are distinct types based on the different surface processes that occur. General classifications of karst landscapes and landforms are also included in almost all landscape typologies of Slovenia (Perko, Ciglič and Hrvatin 2019; 2021).

Deep karst environments are characterized by the pattern of water discharge, with all water flowing underground. Due to this underground flow, there are no surface water streams or stagnant bodies of water present in deep karst areas (Stepišnik 2020). The primary process operating on the surface of deep karst is chemical denudation in a vertical direction, which is not uniform, leading to the development of circular landforms (Šušteršič 1986; 1994; 2000; Stepišnik 2020). These landforms give rise to the conical hills and uvalas that are characteristic of deep karst, forming a distinctive cone karst topography that is often dissected by numerous dolines and collapse dolines. In addition to the cone karst topography, deep karst areas are also characterized by extensive flattened areas known as corrosion plains, which cut horizontaly across geological structures and lithological deformations (Roglić 1957; Gams 2004; Ford and Williams 2007; Bočić, Pahernik and Mihevc 2015; De Waele and Gutiérrez 2022). These bedrock plains extend across all areas of deep karst that are not conical karst, with some corrosion plains measuring tens of kilometres in diameter (Stepišnik 2020). These plains can be impressively planar but are usually intersected by numerous dolines and individual conical hills. Some of the corrosion plains are entrenched by canyons that may or may not be hydrologically active (Roglić 1957; Stepišnik 2020).

Earlier researchers explained the formation of corrosion planes by fluvial processes (Cvijić 1893; 1901; 1918; Penck 1900; Davis 1901; Grund 1914). Roglić (1957) undertook a systematic study of corrosion plains and divided them into four types based on their geomorphological-hydrological position. He also stated that the formation of corrosion plains is a consequence of suitable climatic conditions (Roglić 1957). Other researchers, who studied karst in different parts of the world (Lehmann 1954; Wissmann 1954), reached similar conclusions. In the literature, corrosion plains are thought to form by dissolutional planation at the base level, followed by lateral extension of periodically flooded plains. Their formation is not dependent on climate, although prolonged and stable periods of base level flattening are favourable (Ford and Williams 2007; Mocochain et al. 2009; De Waele and Gutiérrez 2022).

Although there are numerous interpretations in the literature, the processes involved in the formation of corrosion plains are much more complex than previously thought. Corrosion plains are formed not only by the base level flattening, but also in specific lithologically conditioned environments where sedimentary deposits are superimposed over the karst surface.

Depending on the morphographic and morphogenetic features, different terms for corrosion plains are used in the literature, such as karst plain, corrosion terrace, pediment, plateau, marginal plain, marginal flattening, dry polje, etc. (Roglić 1951; 1957; Gams 1973; 2004; Gams, Kunaver and Radinja 1973; Mihevc 1986; De Waele and Gutiérrez 2022). Also, corrosion plains are not always clearly distinguished from flat areas in aggradational environments (e.g., poljes, accumulation terraces, etc.). The inconsistencies and use of various terms has led to confusion in their classification and understanding. Furthermore, corrosion plains in Slovenia have not been thoroughly studied, and there is a pressing need for a comprehensive study of these features in the region. To address this gap, the authors of this article propose a systematic approach to distinguish the basic types of corrosion plains.

The aim of this research was: (1) to identify and analyse corrosion plains in Slovenia; (2) to evaluate the morphogenesis of these features by assessing their morphographic, morphometric, and morphostructural characteristics using data from the existing literature; (3) to propose a new classification system for corrosion plains based on their geological settings and morphology by interpreting the processes involved in their formation and function.

This classification system has been adapted for karst areas in Slovenia and is transferable to other similar areas in the Dinaric Karst and worldwide where similar karst processes occur or have similar geological and hydrological characteristics. The results of this study will lead to a better understanding of the formation and evolution of karst environments in Slovenia and provide a valuable basis for future research in this field. The proposed classification system will also allow a more accurate and comprehensive analysis of corrosion plains and related processes in karst environments.

# 2 The evolution of the understanding of corrosion plains: a historical overview

In the transition from the 19$^{th}$ to the 20$^{th}$ century research of karst features and processes became increasingly popular with the focus especially on the Dinaric Karst (Cvijić 1893). Among other things, Cvijić (1900) also discussed corrosion plains, the formation of which he interpreted as the final stage of development of corrosion and denudation processes through the understanding of cyclic surface development at the time, when the surface is flattened near the water table level in karst. At that time, the scientific debate on the formation of corrosion plains was influenced by contemporary interpretations of processes in fluvial geomorphology (Penck 1900; 1904; Davis 1901). Influenced by the early interpretations of Cvijić (1900), Grund (1903; 1910; 1914) linked the formation of corrosion plains to hydrographic zones in karst. He explained their formation by the groundwater level in the karst aquifer near the surface, which prevents denudation into the depths. Denudation only affects the shallow zone of the surface above the karst water table and lowers it to this level, creating extensive flat plains. Cvijić (1900) tried to build on his original interpretation that karst flattening occurs near the water table by introducing fluvial processes. He defined corrosion plains as fluviokarst features (Cvijić 1909) that could not be formed by karst processes alone (Cvijić 1918), but rather by a gradual transition from a prekarst phase to a karst phase - a process he defined as *karstification* (Cvijić 1921). Some authors have interpreted specific corrosion plains as marine abrasion terraces (Cvijić 1924, Stefani 1930). An alternative explanation for the origin of the corrosion plains was provided by Terzaghi (1913), who attributed the flattening at the surface to accelerated corrosion due to the effect of biochemical processes in the soil. His ideas were not confirmed and accepted by the wider scientific community until several decades later (Roglić 1951; Birot 1954; Oertli 1954).

After a period of several decades without significant progress in understanding karst processes, Roglić (1951, 1957), who undertook a systematic study of corrosion plains, made an important breakthrough. Roglić (1957) focused on corrosion plains and divided them into four types according to their geomorphological-hydrological position: (1) plains along rivers (e.g., the Severnodalmatinska Zaravan along the rivers Krka, Čikola and Zrmanja), (2) plains open to the sea (e.g., Istria), (3) plains in closed basins (e.g., Popovo Polje, Lika Polje) and (4) plains on the margins of poljes (e.g., Gatačko Polje, Duvanjsko Polje, Livno Polje). He concluded that plains form in the area of contact karst, where water from the non-karst environment brings sediment into the karst, similar to what he observed in the blind valleys of Matarsko Podolje Plain and Istria. Sediment is deposited on the periodically flooded surfaces, keeping moisture close to the surface and allowing the growth of vegetation, which through biochemical processes causes accelerated corrosion of the carbonate bedrock and expansion of the plains through lateral corrosion. Other researchers who have studied corrosion plains have come to the same conclusion: Lehmann (1954) in his studies of karst in Cuba, Wissmann (1954) in his studies of karst in SE Asia. Based on observations from tropical karst, where flattening processes are very active, Roglić (1957) concluded that the plains of the Dinaric Karst are relics from a time when a suitable climate prevailed (he assumed a Pliocene age).

During the next decades the theories of corrosion plain formation were increasingly linked to their tectonic predisposition; an extensive literature review on corrosion plain formation is provided by Bočić, Pahernik and Bognar (2010) who studied the formation of the Slunj Plain. Internationally, the formation of corrosion plains was summarised by Ford and Williams (2007) and De Waele and Gutiérrez (2022). According to them corrosion plains form by dissolutional planation at the base level by solutional removal of surface irregularities to the level of the water table, after which the periodically flooded plains expand laterally. Usually the plains form at the output side of karst terrains, however they are also found at the input margins and as corrosion terraces within poljes. The morphogenesis of these landforms is not reliant on specific climatic conditions; however, extended periods of adequate humid environments and tectonic stability are needed for their formation (Ford and Williams 2007; De Waele and Gutiérrez 2022).

# 3 Materials and methods

The analysis was conducted in two stages, utilizing the polygon layers of the extent of karst rocks in Slovenia (Gostinčar and Stepišnik 2023) and lidar data digital elevation model (DEM) obtained from the Slovenian national aerial laser scanning between 2011 and 2015 (the lidar data was provided by the Slovenian Environmental Agency).

In the first stage a polygon of karst areas was created based on the layer of the extent of karst rocks in Slovenia (Gostinčar and Stepišnik 2023). By using ArcGIS Pro 10.8.1 a surface slope map was created for all karst areas and than a smoothed topography to 20-m grid cells was created to eliminate noise in the data. Subsequently, the polygons representing the levelled karst areas with a slope of less than 3° were manually delineated. To identify corrosion plains, we primarily looked for areas without conical hills and uvalas, which are characteristic of cone karst topography. Additionally, we excluded regions containing flattened sections of shallow karst covered by alluvium (i.e., poljes) (Stepišnik 2021b). This approach led to the mapping of corrosion plains in Slovenia.

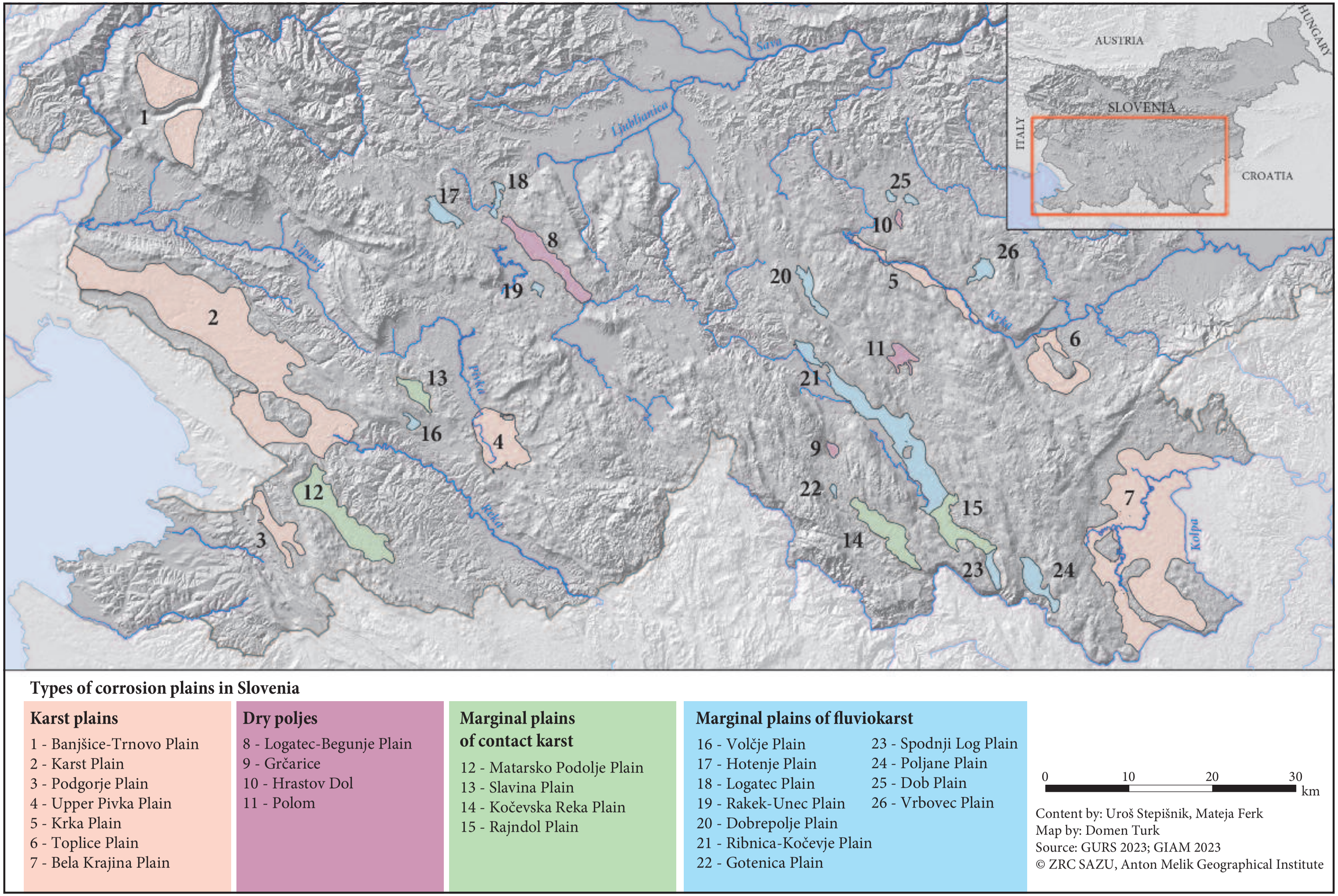
In the second stage, we classified the corrosion plains based on their geological settings and morphology; their morphographic, morphometric, and morphostructural characteristics were examined in detail, which are essential for the morphogenetic interpretation and classification. Morphographic features were visualy interpreted from lidar DEM data (hillshade) and field analyses of individual sites to verify the initial interpretation from the lidar-derived data. The morphometric analysis of each corrosion plain was performed with GIS analyses using ArcGIS Pro, providing the extent of the corrosion plains. The morphostructural analysis relied on the geological map of Slovenia at a scale of 1:100,000 (Buser 2009; Pleničar, Ogorelec and Novak 2009; Hrvatin 2016) in combination with lidar DEM data (hillshade). Based on the lithological characteristics of the tributary parts of marginal plains, we determined the specific type of marginal plain (i.e., contact karst, fluviokarst).

# 4 Results: corrosion plains in Slovenia

**Corrosion plains (slv. *korozijske uravnave*)** are a unique feature of karst landscapes, characterized by extensive, flat areas made up of a rocky karst surface with patchy sediment coverage (Roglić 1957). They are usually dissected by dolines and other karst formations. Unlike plains in other geomorphologic environments, which are formed primarily by fluvial or coastal aggradation of sediments, corrosion plains are formed in the bedrock (Sweeting 1973; Benito-Calvo and Pérez-González 2007).

In the scientific karst literature (see introduction chapter), different terms are used for corrosion plains; e.g., karst plain, corrosion terrace, pediment, plateau, marginal plain, marginal flattening, dry polje, etc. The use of various terms in the scientific karst literature to describe corrosion plains has led to confusion in their classification and understanding. To address this, the authors of this article propose a systematic

Figure 1: The location and classification of corrosion plains in Slovenia. ➤ p. 12


AUSTRIA
HUNGARY
SLOVENIA
ITALY
CROATIA
Sava
Ljubljanica
Vipava
Pivka
Reka
Krka
Kolpa
Types of corrosion plains in Slovenia
Karst plains
1 - Banjšice-Trnovo Plain
2 - Karst Plain
3 - Podgorje Plain
4 - Upper Pivka Plain
5 - Krka Plain
6 - Toplice Plain
7 - Bela Krajina Plain
Dry poljes
8 - Logatec-Begunje Plain
9 - Grčarice
10 - Hrastov Dol
11 - Polom
Marginal plains of contact karst
12 - Matarsko Podolje Plain
13 - Slavina Plain
14 - Kočevska Reka Plain
15 - Rajndol Plain
Marginal plains of fluviokarst
16 - Volčje Plain
17 - Hotenje Plain
18 - Logatec Plain
19 - Rakek-Unec Plain
20 - Dobrepolje Plain
21 - Ribnica-Kočevje Plain
22 - Gotenica Plain
23 - Spodnji Log Plain
24 - Poljane Plain
25 - Dob Plain
26 - Vrbovec Plain
0 10 20 30 km
Content by: Uroš Stepišnik, Mateja Ferk
Map by: Domen Turk
Source: GURS 2023; GIAM 2023
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approach to distinguish four different types of corrosion plains in Slovenia (Figure 1): (1) **karst plain (slv. *kraški ravnik*)**, (2) **dry polje (slv. *suho kraško polje*)**, (3) **marginal plain of contact karst (slv. *robna uravnava kontaktnega krasa*)**, and (4) **marginal plain of fluviokarst (slv. *robna uravnava fluviokrasa*)**.

**Karst plains** are the largest type of corrosion plains found in karst areas around the world (e.g., the 200,000 km$^2$ large Nullarbor Plain in Australia). These plains are characterized by their vast size, reaching up to tens of kilometres across, and their exceptionally flatt surface cutting horizontaly through the underlaying bedrock. Karst plains, like other corrosion plains, are typically dissected by a large number of karst depressions, such as dolines and collapse dolines, as well as occasional cone-shaped hills. The unique feature of karst plains compared to other corrosion plains are canyons, which dissect their surface. The canyons are hydrologicaly active, if they reach the water table of the regional aquifer (i.e., the process of river entrenchment is still active). Hydrologicaly inactive canyons are in the vadose hydrographic zone and are an indicator of past hydrological processes (Nicod 1997).

Slovenia has a number of extensive karst plains, each with its own unique characteristics. The largest of these is the Karst Plain (slv. *Kraški ravnik*) and covers an area of 217 km$^2$ (Figure 2). The Bela Krajina Plain (slv. *Belokrajnski ravnik*) is the second largest with an area of approximately 187 km$^2$. The Upper Pivka Plain (slv. *Ravnik Zgornje Pivke*), the fragmented Krka Plain (slv. *Krški ravnik*) located upstream between Krka and Dvor, and the Toplice Plain (slv. *Topliški ravnik*) southwest from Novo Mesto, are also considered as karst plains. Despite their different sizes and geological compositions, these karst plains share one common feature: they are intersected by canyons. In the Karst Plain, the Veliki Dol and the Mali Dol are two such canyons, which are hydrologically inactive (dry canyons). Other karst plains have hydrologicaly active canyons: Kolpa, Lahinja, and Krupa rivers in the Bela Krajina Plain, Pivka River in the Upper Pivka Plain, Krka River in the Krka Plain, and Sušica River in the Toplice Plain.

There are two karst plains that offer a distinct set of geological and geomorphological features. The Podgorje Plain (slv. *Podgorski ravnik*) is a more complex karst plain, characterized by its alternating layers of limestone and flysch. It is partially dissected by the Grižnik Canyon, which merges into the Glinščica Canyon across the border in Italy. The canyon was formed through antecedent incision but was eventually stopped due to the bifurcation of water into the karst, resulting in a ponor-type of contact karst (Gams 2004). The Banjšice-Trnovo Plain (slv. *Banjško-trnovski ravnik*) is also a unique karst plain. The former

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Figure 2: The largest karst plain in Slovenia is the Karst Plain.

uniform karst plain is divided in two by the dry canyon Čepovanski Dol. The plain is extensively karstified and has a more dissected surface with karst features compared to other karst plains in Slovenia. This and its high topographic position compared to its surrounding indicate its older age. The Trnovo nappe was formed from Eocene to Miocene (Pleničar, Ogorelec and Novak 2009; Placer, Mihevc and Rižnar 2021), and the subsequent formation of fault zones in the Neogene (Placer and Čar 1975) most probably already caused the hydrological changes that in the end led to the abandonment of the Čepovanski Dol.

Corrosion plains that are located in closed depressions but are not hydrologically active, i.e., not shallow karst or fluviokarst, are defined as **dry poljes**. The flat floors of these dry poljes are rocky, which are only covered by sediment patches. The floor of these poljes is dissected by a high density of dolines, collapse dolines, and small cone-shaped hills (i.e., former hums).

The largest dry polje in Slovenia is the Logatec-Begunje Plain (slv. *Logaško-begunjski ravnik*), covering an area of 22 km$^2$. This plain is situated between Logatec and Begunje pri Cerknici and is characterized by a rocky surface that is only partially covered by sediment. According to the morphodynamic classification of poljes (Stepišnik 2021), the Logatec-Begunje Plain was once an inflow type of polje, as indicated by the sediment on the plain and the former flow of the Cerkniščica River in the area (Šušteršič and Šušteršič 2003). Another example of a dry polje that once functioned as an inflow type of polje is the Hrastov Dol (slv. *Hrastov dol*) in the northern part of the Suha Krajina (Figure 3). This plain has a flat floor dissected by dolines and covered by patches of sediment, its northern slope, which once fed sediment into the polje floor, is now dissected by dry erosion gullies.

Two dry poljes in Slovenia are former overflow poljes, as classified by morphodynamic classification (Stepišnik 2021). One is located in the western part of the Suha Krajina near the settlement Polom, covering an area of approximately 6 km$^2$. Its floor is characterized by a flattened surface, dotted with numerous dolines, and irregularly covered with sediment patches. In some areas, the remnants of a former watercourse are visible, which had its source in two locations in the western part of the polje and drained into a sinking area in the southeastern part. The second dry overflow polje is situated between Ribniška Velika


Figure 3: The sediment-covered part of the floor of the dry polje Hrastov Dol in Suha Krajina is already dissected by suffosion dolines.

Gora and Stojna mountains, near the settlement Grčarice. Its floor is dissected with dolines and features a distinctive pocket valley in the southern part, which once functioned as a karst spring.

The marginal plains are a unique type of corrosion plains that form at the former aggradation areas of contact karst and fluviokarst. These areas were created when fluvial sediments covered the margins of adjacent karst areas. Later, the areas became hydrologically inactive and the sediments were denuded, exposing the flat underlying bedrock (Gams 1973; Stepišnik 2021b).

In Slovenia, the **marginal plains of contact karst** are found at the geological contact between Eocene flysch, Carboniferous and Permian clastic rocks and karstified carbonate rocks. The water from fluvial environments deposited sediments in the form of alluvial fans (Stepišnik et al. 2007a; 2007b; Stepišnik 2009) or flattened alluvial plains over the karst, and once sediment delivery ceased, the subsequent denudation of the sediments caused the previously flat areas to be superimposed on the bedrock, resulting in the formation of the marginal plains of contact karst (Stepišnik 2021b).

Marginal plains of contact karst are the Matarsko Podolje Plain (slv. *Ravnik Matarskega podolja*) and Slavina Plain (slv. *Slavinski ravnik*), where water from Eocene flysch prolongued on the karst surface and deposited sediments (Figure 4). In case of the Kočevska Reka Plain (slv. *Kočevskoreški ravnik*) and the Rajndol Plain (slv. *Rajndolski ravnik*) sediments were sourced from non-carbonate clastic sedimentary rocks of Carboniferous and Permian age. At the lithological contact, blind valleys have formed in the former tributary areas where water still flows underground. In Matarsko Podolje Plain and Slavina Plain, relict alluvial fans are also preserved in the tributary areas, resulting in a slightly sloping surface. The Kočevska Reka Plain and Rajndol Plain are relatively flat up to the lithological contact.

**The marginal plains of fluviokarst** form in areas where sediment from fluviokarst areas (De Waele and Gutiérrez 2022) have accumulated and flattened the surface. These sediment deposits create larger plains, classified as inflow poljes, according to the morphodynamic classification (Stepišnik 2021b). As sediment influx decreases, the distal margin of the poljes move towards the tributary, leading to the eventual hydrologic inactivity of distal parts of the poljes (i.e., formation of relict parts of poljes). The transition between active and relict parts can be gradual or sudden, with active parts shifting to higher, relict

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Figure 4: The Slavina Plain is a marginal plain of contact karst formed at the lithological contact between Eocene flysch and Cretaceous limestone.


Figure 5: The Ribnica-Kočevje Plain is the largest marginal plain of fluviokarst in Slovenia and is the remnant of a former inflow type of polje, once the largest polje in Slovenia.

parts with a slight slope. The relict parts of the poljes become flat rocky plains with patches of sediment cover, and are characterized by a high density of dolines. Although this flattening is often attributed to tectonic activity (Gams, Kunaver and Radinja 1973; Gams 1974), it is actually due to a reduction in the supply of fluvial clastic sediments to the polje floors (Stepišnik 2021a; 2021b).

The marginal plains of fluviokarst in the Slovenian karst are formed at the distal part of inflow poljes in the form of bedrock terraces, intersected by a high density of dolines: Hotenje Plain (slv. *Hotenjski ravnik*), Logatec Plain (slv. *Logaški ravnik*), Rakek-Unec Plain (slv. *Rakovško-unški ravnik*), Vrbovec Plain (slv. *Vrbovški ravnik*) and Dobrepolje Plain (slv. *Dobrepoljski ravnik*). The largest marginal plain of fluviokarst in Slovenia, the Ribnica-Kočevje Plain (slv. *Ribniško-kočevski ravnik*), is located on the eastern edge of the Ribnica and Kočevje poljes, with a total area of 52 $km^2$ (Figure 5). In the past, besides the Bistrica River, which has its catchment in a fluviokarst area, the Tržiščica River also flowed in from the north, from the area of Permian clastic sedimentary rocks. There are quartz pebbles in the plain, which come from the catchment area of the Tržiščica River. The size of this plain is most likely related to the combined inflow from two different catchments. Based on the combined sediment supply, this marginal plain can be defined as a combination of marginal plains of the contact karst and marginal plains of fluviokarst. A riverbed of the Zadnja Rinža River also extends over the plain, which flows from Ribnica Polje to Kočevje Polje only during floods. The spatial dispersion of this floodplain suggests that it once formed a single polje, the largest in Slovenia.

Some marginal plains of fluviokarst in Slovenia are unique in their development as they are not located on the margins of poljes. Instead, they have formed below the fluviokarst slopes from where sediment was once supplied, covering the lower parts of the karst terrain. The interruption of sediment supply led to the denudation of flattened sediment and superimposition into the rocky karst surface, resulting in the formation of these plains. The Poljane Plain (slv. *Poljanski ravnik*) received sediment inflows from the north, where an occasional stream still springs today, while the Spodnji Log Plain (slv. *Spodnjeloški ravnik*) received sediment from the east slope, now marked by a series of inactive gullies.

# 5 Discussion

Corrosion plains are extensive bedrock planation surfaces cutting through various rocks and structures and occur in different climatic settings (Roglić 1957; Ford and Williams 2007; Bočić, Pahernik and Bognar 2010; De Waele and Gutiérrez 2022). Although, they are usually impressively flat, the surface can be dissected by numerous dolines and individual conical hills. Generally, the formation of corrosion plains is attributed to dissolutional planation during prolonged and stable periods of base level flattening, followed by lateral extension of periodically flooded plains (Ford and Williams 2007; De Waele and Gutiérrez 2022). However, corrosion plains form also in specific lithologically conditioned environments where sedimentary deposits are superimposed over the karst surface; e.g., contact karst, fluviokarst. The bedrock dissolution under dump and $CO_2$-rich soils can be particularly intense, causing rapid dissolution and planation of the bedrock at the water-rock boundary (Cui et al. 2002).

The determination of the time frame of corrosion plain formation is particularly challenging. The amount of preserved sediment cover could potentially be an indicator of the relative age when comparing corrosion plains (Bočić, Pahernik and Mihevc 2015). However, the initial amount of sediment differs, as does the geochemical and granulometric composition. The repeated climatic and environmental changes in the Quaternary (Augustin et al. 2004; Lisiecki and Raymo 2007; Šibrava 2010), causing sea-level fluctuations and significant changes in hydrological conditions (Šibrava 1986; Bintanja, van de Wal and Oerlemans 2005; Dumas, Guérémy and Raffy 2005; Zupan Hajna et al. 2008; Edwards 2016; Ferk 2016; Ferk et al. 2019), could have led to certain areas becoming hydrologically inactive (i.e., dry poljes, marginal plains of contact karst and fluviokarst). However, for the formation of larger karst plains it could be assumed, more stable pre-Quaternary environmental conditions would be more favourable, like it was demonstrated in the case of the formation of the Slunj Plain (Bočić, Pahernik and Bognar 2010). Furthermore, in the karst landscapes, corrosion plains are affected only by dissolutional denudation, which evenly lowers the surface (Ford and Williams 2007; De Waele and Gutiérrez 2022). At the same time, there are no geomorphological processes that would break up the surface irregularly in the lateral direction as e.g., fluvial erosion. Due to the principal of »karst imunity« (Mocochain et al. 2009), the corrosion plains can be preserved for considerably long periods of time (Webb and James 2006; Benito-Calvo and Pérez-González 2007; Mocochain et al. 2009; Audra et al. 2012; Burnett et al. 2020). Nevertheless, generalisations are inadequate, and individual corrosion plains have to be independently morphochronologicaly studied to elaborate their age and period of their formation.

Corrosion plains are not particularly well studied karst features. Usually they are categorised based on their geomorphological-hydrological position (Roglić 1957; Gams 2004; Ford and Williams 2007; De Waele and Gutiérrez 2022), not clearly separating hydrologically active aggradational environments (e.g., poljes) from bedrock planation surfaces (i.e., corrosion plains). The inconsistencies and use of various terms has led to confusion in their classification and understanding. In this study, corrosion plains in Slovenia were identified and analysed based on their morphographic, morphometric, and morphostructural characteristics and a new systematic classification of corrosion plains based on their geological settings and morphology is proposed. Corrosion plains in Slovenia were classified into four basic types (Figure 6): karst plain, dry polje, marginal plain of contact karst, and marginal plain of fluviokarst. The proposed classification focuses on the karst environments in which the corrosion plains were formed through which it provides a robust basis for future studies of the formation and evolution of corrosion plains in Slovenia and in other karst areas.

**Karst plains** are a type of corrosion plains defined by Roglić (1957) as plains along rivers, and by more recent literature (Ford and Williams 2007; De Waele and Gutiérrez 2022) defined as corrosion plains at the base level. These are the largest corrosion plains on a global scale and also in the area of Slovenia.

The exact origin of karst plains remains a topic of debate among researchers. In early literature, the formation of karst plains was linked to the influence of rivers and fluvial or lacustrine sediments in shallow karst areas, which Roglić (1957) referred to as planation of contact karst. The process of sedimentation and subsequent denudation resulted in the superimposition of the flattened areas onto the bedrock, giving rise to karst plains (Roglić 1957). From a climatic geomorphology perspective, Roglić (1957) related the flattening processes to warmer climatic conditions that existed in the Dinaric Karst region during the Pliocene.

More recent literature, however, views the formation of karst plains as a result of base-level levelling (Gams 2004; Ford and Williams 2007; Stepišnik 2017; 2021a; De Waele and Gutiérrez 2022). The stable base level allows for chemical denudation to occur up to that level, with the process halting below it, resulting in extensive rock levelling. This process requires stable tectonic and hydrogeological conditions to persist for a long period of time, allowing the surface to flatten (Gams 2004). Although the specific environmental conditions that enabled these conditions remain unclear, karst plains are widely recognized as a common and defining characteristic of karst landscapes.

The presence of canyons is a distinctive feature of karst plains. The canyons are antecedent valleys created through incision during tectonic uplift or lowering of the erosional base (Summerfield 1996; Nicod 1997). The presence of meandering patterns in the canyons suggests that rivers once flowed in low-gradient floodplains prior to canyon formation (Huggett 2007). The existence of floodplains in karst areas is a characteristic of epiphreatic karst zone, indicating that their formation was closely linked to the proximity of the base level. This is in line with previous interpretations of karst plain formation being regulated by base-level denudation (De Waele and Gutiérrez 2022). In all the karst plains in Slovenia, we confirmed that they were formed through denudation at the base level, followed by tectonic uplift that led to the formation of canyons. In some cases, canyons have become hydrologically inactive as water drains underground.

**Dry poljes** are a type of corrosional plains, which was referred to as »plains in closed basins« by Roglić (1957). Some previous authors have also included hydrologically active poljes and karst basins in their classifications of corrosion plains (Roglić 1957; 1964), which is not entirely accurate, as these are aggradational sedimentary plains and not bedrock plains (Stepišnik 2020). In fact, the flat floors of dry poljes are mostly composed of exposed bedrock with only scattered patches of sediment. Some poljes become dry due to stream piracy or changes in the hydrogeologic conditions within the karst aquifer. The interruption of water inflow from the fluviokarst is a common cause of the absence of surface water in inflow poljes, similarly to the marginal plains of the fluviokarst (Stepišnik 2021a). In these poljes, inactive erosion gullies or dry valleys are preserved on the sides of the tributaries, which once supplied sediment. In addition to former inflow poljes, there are also former overflow poljes in Slovenia (Stepišnik 2021b). These are closed basins with flat bottoms and undisturbed slopes in the surrounding area. All dry poljes have a high density of dolines. In those parts of polje floors that are still covered by patches of sediment, suffosion dolines are formed. However, in some cases dry river beds are still visible that indicate past surface water flow.

**Marginal plains of contact karst** were considered by (Roglić 1964) to be a special type of corrosion plains, where water from the non-karst environment transports sediment into the karst. These plains are also referred to as input-marginal corrosion plains in more recent literature (De Waele and Gutiérrez 2022). In Slovenia, such plains are positioned at the boundary between Eocene flysch and Carboniferous and Permian clastic rocks with karstified carbonate rocks. The surfaces of these plains are densely dissected by dolines and collapse dolines, which are typically formed in the hinterland of submerging streams. At the lithological contact, blind valleys have formed in the former tributary areas, and today the water drains underground.

These plains were formed through the process of denudation, which involved the superimposition of the flattened sedimentary surfaces with the underlying bedrock. In the area of the blind valleys, relict alluvial fans are preserved in the tributary areas and form a gently sloping surface that is in contact with Eocene-age flysch rocks (Stepišnik et al. 2007a; 2007b; Stepišnik 2009). On the other hand, the marginal plains of contact karst, which are in contact with Carboniferous and Permian clastic rocks, are relatively flat near the lithologic contact and lack alluvial fans (Stefanovski, Grk and Hočevar 2021). The reasons for the different shapes of the marginal plains of contact karst in relation to different lithology in the tributary areas, however, remain unclear.

Our interpretation of the formation of the marginal plains of contact karst is supported by a recent example in the northwestern part of Matarsko Podolje Plain near the settlement of Rodik. In this area, watercourses flow from the Eocene flysch toward the karst, transporting significant amounts of sediment. Here, an alluvial fan has formed on top of the karst, which transitions into a flattened alluvial plain at its lower part. Intermittent watercourses flow over the sediment-covered carbonate bedrock, draining into the karst at its edges. This process of formation of such plains is ongoing and can be observed in real-time (Stepišnik et al. 2007a; 2007b).

The fourth type of corrosion plains is commonly found in fluviokarst environments (Stepišnik 2020), where sediment is transported into karst basins and forms inflow poljes. As sediment input decreases, the distal parts of the poljes become inactive, leading to faster denudation of sediments than aggradation. This type of plains has been referred to in the literature as plains on the edges of poljes (Roglić 1957) or as corrosion terraces within poljes (Ford and Williams 2007; De Waele and Gutiérrez 2022). In our study, we refer to them as **marginal plains of the fluviokarst** because this term explains the morphodynamic environment in which such plains occur. The morphogenesis of these marginal plains was described by Gams (1973) as being a result of the multiphase formation of poljes due to tectonic activity. A small topographic displacement is often formed between the active and relict parts of the poljes, which separates the two parts. The reason for this elevation anomaly is not well understood and requires further study in the future.

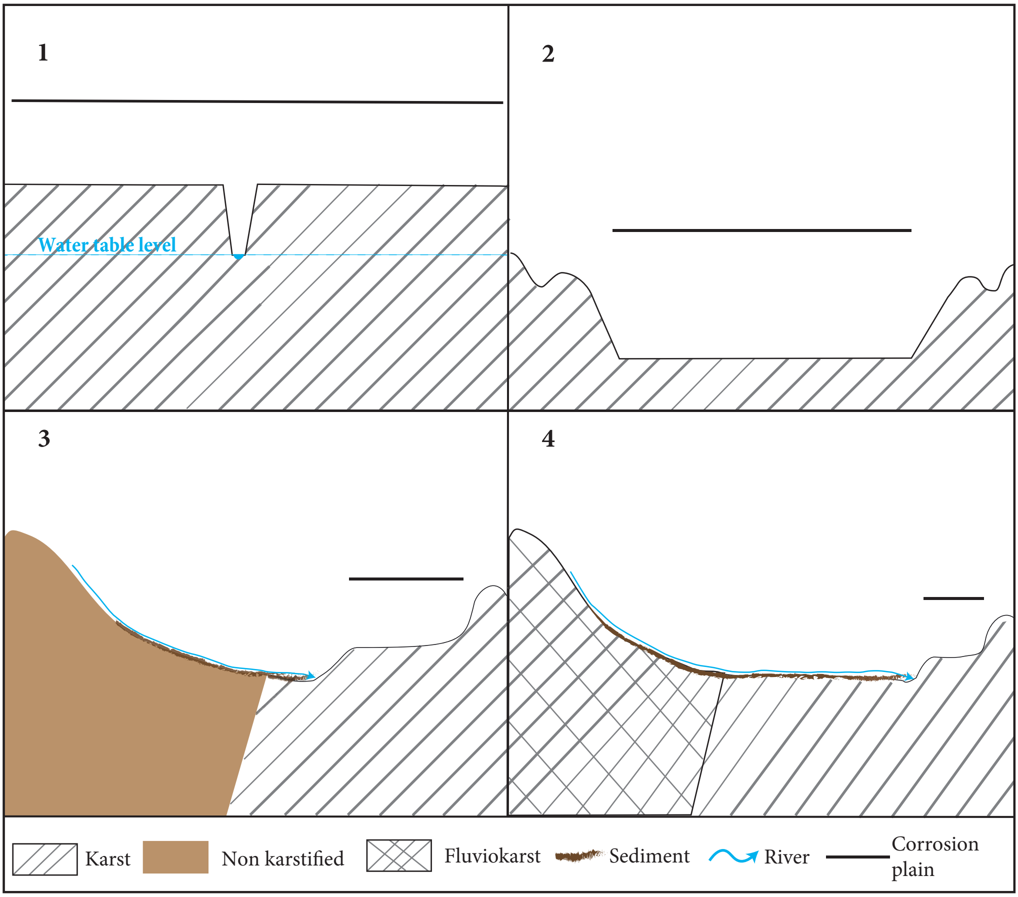


Figure 6: Classification of corrosion plains in Slovenia based on their geological settings and morphology: (1) karst plain, (2) dry polje, (3) marginal plain of contact karst, (4) marginal plain of fluviokarst.

# 6 Conclusion

We classified corrosion plains in Slovenia into four types based on their geological settings and morphology: karst plains, dry poljes, marginal plains of contact karst and marginal plains of fluviokarst.

Karst plains, the largest corrosion plains, are defined by their location along canyons and their extensive bedrock levelling resulting from base-level denudation. The presence of canyons is a distinctive feature of karst plains, indicating the proximity of the base level during their formation.

Dry poljes are found in closed basins and are composed mostly of exposed bedrock with scattered patches of sediment. These poljes become dry due to stream piracy or changes in the hydrogeologic conditions within the karst aquifer.

Marginal plains of contact karst are found at the boundary between non-karst and karst rocks. The formation of these plains is attributed to the process of denudation, which involved the superimposition of the flattened sedimentary surfaces with the underlying bedrock.

Marginal plains of fluviokarst are found in fluviokarst environments where sediment was transported into karst basins and formed inflow poljes. These plains result from the flattening of the sediments being superimposed on the bedrock, with a small topographic displacement often formed between the active and relict parts of the poljes.

The classification of corrosion plains is useful in understanding the morphology and evolution of karst landscapes, and can aid in the identification of similar landscapes in other regions.

ACKNOWLEDGEMENT: The research was financially supported by the Slovenian Research and Innovation Agency (P6-0101, P6-0229).

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