**DOVE & AGAQ meeting, Bovec (Slovenia), 24 march – 29 march 2025**

# QUATERNARY LANDSCAPE DYNAMICS OF THE BOVEC BASIN, SOČA VALLEY AND CLASSICAL KARST REGION (WESTERN SLOVENIA)

**EXCURSION GUIDEBOOK**

**THURSDAY 27 MARCH – SATURDAY 29 MARCH**

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**Ljubljana, 2025**

## EXCURSION ROUTE

On the first day we will focus on mass movements, seismic hazard and glacial sediments in the Bovec Basin and surroundings. The second day will be dedicated to glacial history of the Soča Valley and post-sedimentary deformations. Third day will focus on Classical Karst region including subsurface and exposed karst features (Fig. 1).

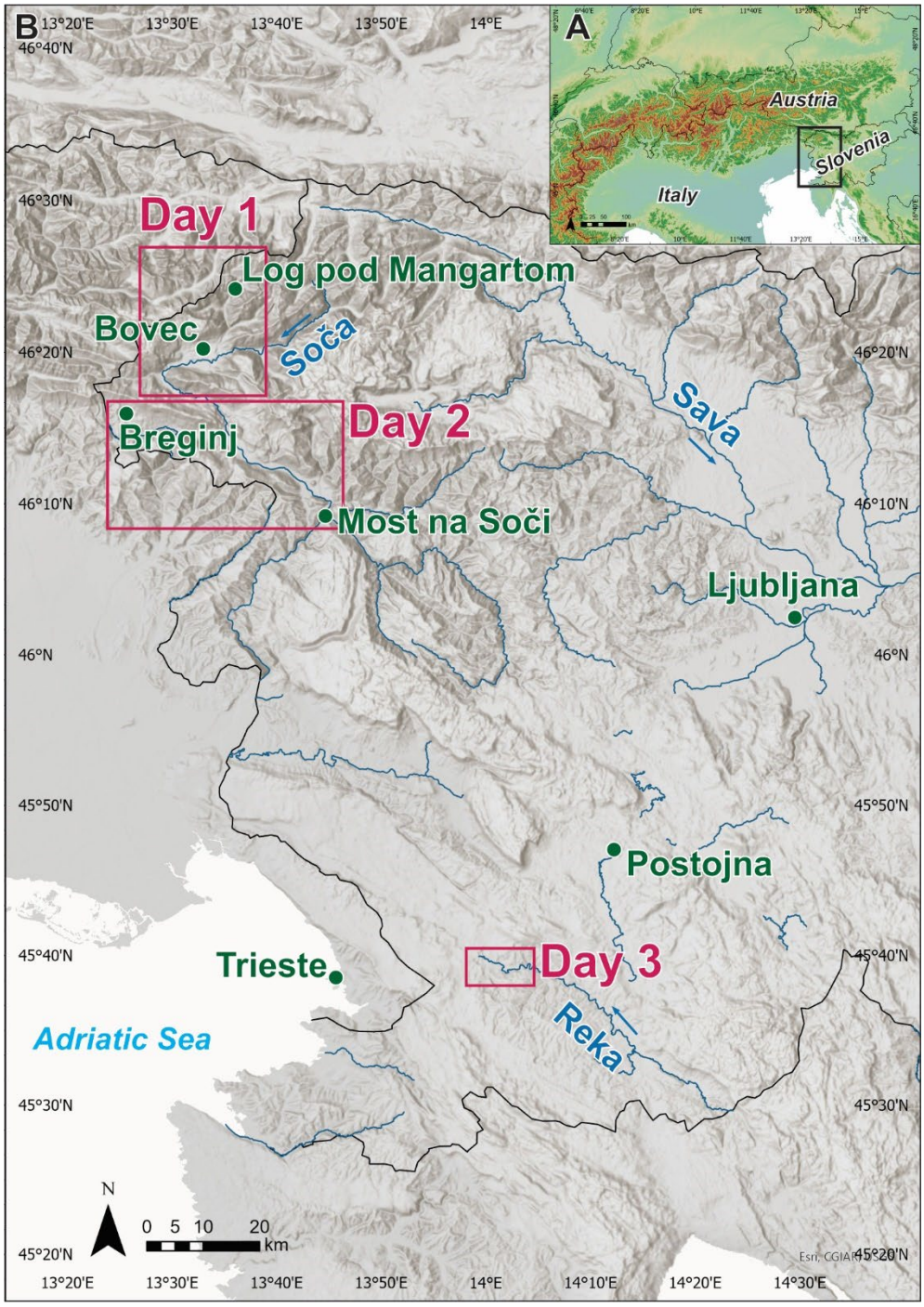


Figure 1: Outline of the excursions.

# QUATERNARY SEDIMENTS OF THE BOVEC BASIN AND GEOLOGICALLY INDUCED HAZARDS; FROM ACTIVE TECTONIC TO MASS MOVEMENTS (THURSDAY 27.03.2025)

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## Outline

- Stop 1: Stože landslide (settlement Log pod Mangartom)
- Stop 2: Stože landslide area
- Stop 3: Rockfall blocked lake or overdeepened valley (Koritnica River)
- Stop 4: Glacial and torrential sediments (settlement Ravni Laz)
- Stop 5: Seismology and earthquake effects (settlement Ravni Laz)
- Stop 6: Idrija Fault (Učja Valley; settlement Žaga)
- Stop 7: Lacustrine sediments (former claypit Srpenica)

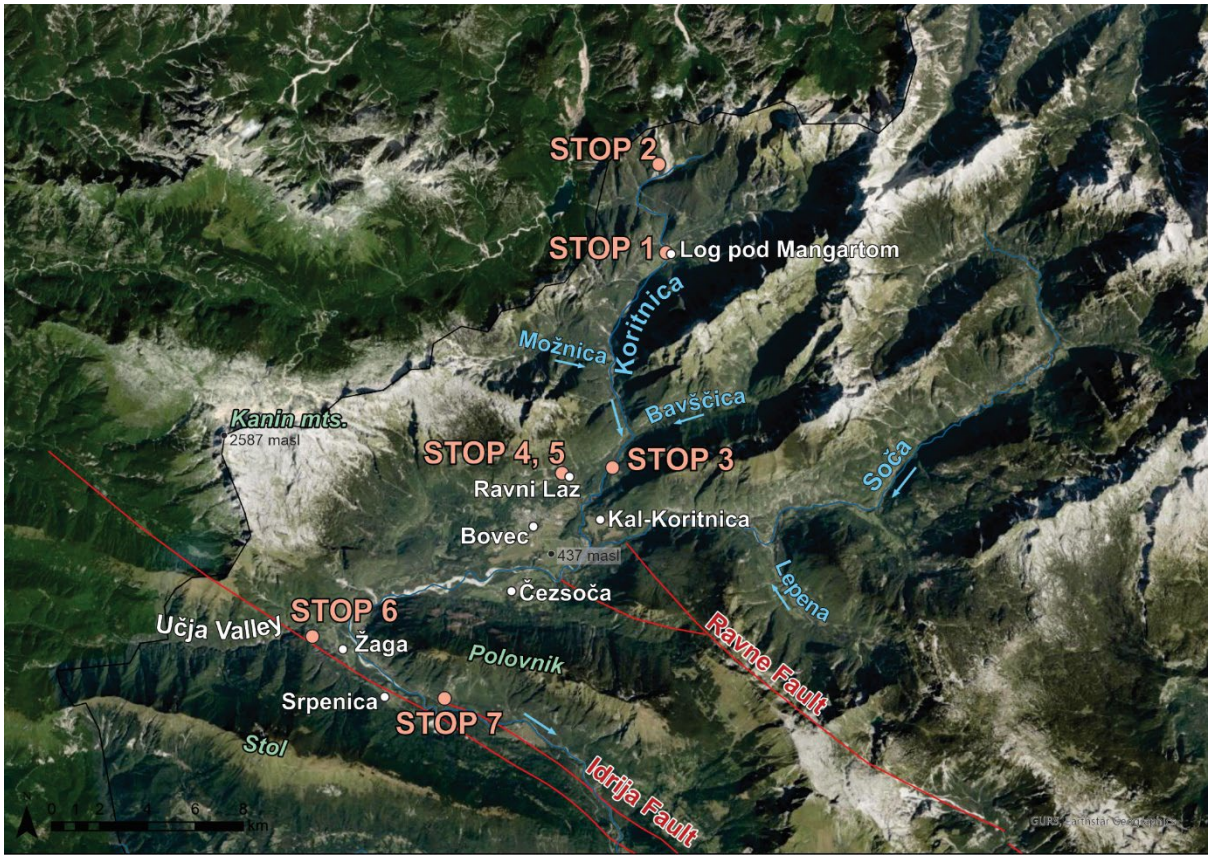


Figure 2: Excursion stops on Day 1 with indicated Ravne and Idrija Fault (from Atanackov et al., 2021).

**GENERAL SETTING OF THE BOVEC BASIN**

The idyllic alpine landscape of the Upper Soča Valley is the product of far-from-idyllic geological events in recent history. The impacts of Quaternary climate changes, both past and present, have been further intensified by the tectonic activity of the broader region. The consequences are well-documented and tangible: earthquakes, landslides, and gravitational slope movements. In this study, we will examine the geological record preserved in sediments and attempt to unravel part of the story behind the formation of the Bovec Basin and its surroundings.

The Bovec Basin is located in the Upper Soča River region in the Southern Julian Alps in northwestern Slovenia (east 13° 32‘ / north 46° 20‘, 350-450 m a.s.l.; Fig. 3A, 3B). It is about 6 km long and 2.5 km wide with its main tributary Soča (Insonzo) River. The basin is located within the extent of the last glaciation in the Soča Valley with the ice was draining from the Julian Alps. The area is characterized by considerable seismic activity, marked by two earthquakes of magnitude 5.6 in 1998 and 5.2 in 2004 (Gosar et al., 2001; Gosar et al., 2007; Gosar, 2008). The Bovec Basin is part of a complex hydrogeological system that combines a regional aquifer of karstified carbonates that forms the steep slopes above the basin and an intergranular aquifer consisting of fluvioglacial sediments filling the basin.

During the Pleistocene, the Bovec Basin and its surroundings was strongly influenced by glacial activity. The snowline during Pleistocene climate minima dropped to approximately 1400 m above sea level, implying that all areas above this elevation served as accumulation zones for glaciers. Traces of high-altitude ("slope") glaciers are best documented in the Kanin Mountains, while other high-altitude regions have been primarily covered in overview studies (e.g., Kunaver, 1975, 1980, 1982; Melik, 1954a, b).

Slope glaciers and valley tributaries from Koritnica, Možnica, Bavšica, Lepena, and other smaller valleys fed a large valley glacier collectively known as the Soča Glacier. This extensive glacier reached thicknesses of several hundred meters, with some estimates suggesting up to 700 m (Melik, 1954b). Geomorphological interpretations are highly complicated by long lasting (and relatively high rate) tectonic activity thus various interpretations exist regarding its maximum extent.

For the last two Alpine glaciations, some observations suggest that the Soča Glacier reached as far as Bovec or that its tributary branches likely melted before reaching the Bovec Basin (Bavec, 2002; Bavec et al., 2004). Earlier Pleistocene glaciation extents are less well documented but may have extended as far as Tolmin or Most na Soči (Brückner, 1891; Penck & Brückner, 1909; Kuščer et al., 1974; Kunaver, 1975). According to this interpretation, the longest branch of the Soča Glacier extended from Zadnja Trenta to Tolmin, spanning over 60 km.

Recent interpretations (e.g., Jamšek Rupnik et al., 2020; 2022) suggest, however, that the interpretation proposing a (dramatically) smaller glacier extent during the last two glacial periods Bavec, 2002; Bavec et al., 2004) may have been (dramatically) incorrect. Instead, traditional interpretations of glacier extent were likely more accurate in depicting reality. This implies that the Late Pleistocene glacier(s) also extended beyond Tolmin—all the way to Most na Soči.

The bedrock of the Bovec Basin mostly consists of Mesozoic carbonates and Cretaceous flysch overlain by Quaternary sedimentary deposits. The sequence of Quaternary sediments is comprised of older sedimentary assemblage outcropping in the basin and its vicinity and younger sequence buried in the basin. The older assemblage is comprised of fluvial, glacial, and lacustrine sediments. Several ages are available from the outcrops in the basin and its vicinity. The ages range from 130 to 200 ka and correspond to MIS 5-6 (Bavec, 2002). Despite the uncertainties described in regard to the methodological limits, these ages represent a geochronological ground base.

The younger buried deposits of the Bovec Basin also consist of fluvial, glacial, and lacustrine sediments. The thickness of the buried sequence is shallower in the central part of the basin, reaching about 150 m (near the village of Čezsoča), while in the southwestern part of the basin (near the village of Žaga) it becomes significantly deeper, reaching up to 270 m (Kuščer et al., 1974). Most of the buried sequence consists of lacustrine sediments deposited in the Srpenica paleolake (Fig. 3C). The age of the younger sedimentary sequence is only available for the upper 34 m from the Srpenica clay pit and ranges from about 6 – 16 ka b.p., which corresponds to MIS 1-2 (Bavec, 2002; Šercelj, 1970). The age of the deeper part of the sequence is unknown.

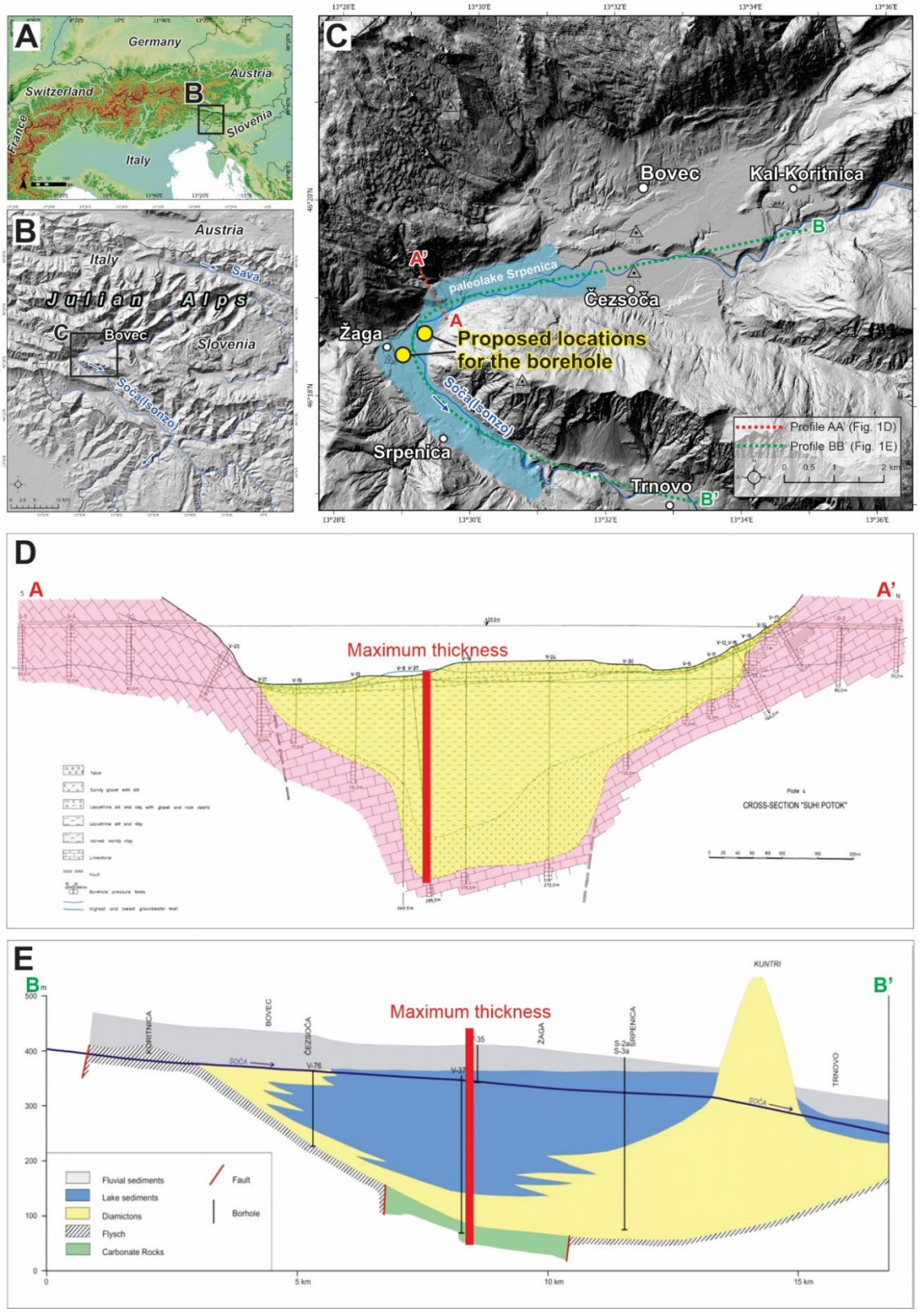


Figure 3: (A) Location of the study area within the Alpine orogen. (B) Overview map of the of the Bovec Basin within the Julian Alps. (C) Bovec Basin with basic geographical features with marked geological section Suhi potok (AA') and longitudinal profile along the Soča River (BB'). Two proposed locations for the DOVE1 borehole and extent of Srpenica paleolake (modified from Bavec, 2002) are indicated. (D) Geological cross-section Suhi potok (Kuščer, 1974) with indicated quaternary sequence with glacial, fluvio-glacial and lake sediments with marked maximum thickness of Quaternary deposits. Boreholes reaching bedrock are marked. (E) Longitudinal profile (BB') along the Soča River with marked maximum thickness of Quaternary deposits near Žaga.

**STOP 1 & 2: STOŽE LANDSLIDE**

The Stože landslide hit the village of Log pod Mangartom on November 17, 2000, killing seven people, destroying 6 houses and 2 bridges, damaging 23 houses and power plants.

In general, permeable carbonate rock sequences, glacial and scree deposits are predominant in this mountainous catchment area, while fine-grained clastic sedimentary rocks with low permeability are present in the base of the landslide. The landslide was triggered by two separate events on November 15 and 17, 2000. On November 15, around 13:00, a large translational landslide occurred on the Stože slope at an altitude between 1340 and 1580 m a.s.l. over an area of more than 20 ha, consisting mainly of glacial carbonate material and colluvium of weathered clastic rocks, with a total volume of more than 1.5 million $m^3$ (Fig. 4). After the accumulation of material in the Mangartski potok valley at an altitude of approx. 1200 m a.s.l., interruption of the river course and continuous heavy rainfall, a devastating debris flow occurred along the Mangartski potok and the Predelica River at around midnight on November 17. The debris flow reached the village of Log pod Mangartom at a distance of 4 km, while the material accumulated further downstream in the Koritnica valley over an area of approximately 14 ha (Fig. 5). The material reached the village in about 5 minutes and moved at an estimated speed of 30 km/h.

Prolonged and intense short-term rainfall was the main trigger. The rain gauge station in the village of Log pod Mangartom recorded 1760 mm of precipitation in October and November (almost ¾ of the average annual precipitation), while 1234 mm of precipitation was measured in November.

After the event, numerous remediation works were carried out. Bridges and supply lines were restored. The Stože slope inclination was partially reduced and natural vegetation was planted, deep drainage work was carried out and torrent channels were realigned. The most important structural measure was the construction of a large, 11 m high reinforced concrete barrier directly above the village of Log pod Mangartom in case debris flows were triggered on the Stože slope in the future.

There are still 1.7 million $m^3$ of unstable masses in the source area of the landslide, which are moving slowly. The monitoring system set up after the event was damaged and is currently not operational. The Ministry of Natural Resources and Spatial Planning is currently preparing a project to re-establish monitoring of landslide movements.

Figure 4: Stože landslide source area (Stop 2).

Figure 5: Aero view of the debris flow deposits in Log pod Mangartom after the devastating debris flow in November 2000 (Stop 1).

**STOP 3: MASS MOVEMENT DEPOSITS, ROCKFALL BLOCKED LAKE OR OVERDEEPENED VALLEY (KORITNICA RIVER)**

The Koritnica Valley has been extensively affected by mass movement processes in the past. At least two generations of large mass movement deposits can be observed in the village of Log pod Mangartom, identifiable through geomorphology and archaeological findings.

Further downstream, at least one surface level likely corresponds to the event of 1468 a.d., when it was described that *"the whole village of Log was only gravel."* A horseshoe finding corroborates this dating.

Near the confluence of the Koritnica and Možnica rivers, a bedrock barrier is obstructing the Koritnica stream, which is now sharply incised to allow river flow. In the past, this barrier blocked the valley, as evidenced by a sequence of lacustrine sediments upstream. The bedrock barrier was clearly covered by rockfall in the past, raising the question of whether the valley was blocked by tectonic processes, rockfall, over-deepening by a local glacier, or a combination of these processes.

**STOP 4: GLACIAL, MASS MOVEMENT, AND TORRENTIAL DEPOSITS (RAVNI LAZ)**

In the Bovec Basin, diamictite is found extensively in Ravni Laz, Radeljec, Stržišče, above Kal-Koritnica, and near Jablenca. Everywhere, it is deposited directly on the pre-Quaternary bedrock. At Ravni Laz and Stržišče, it is covered by a conglomerate cap (Fig. 3), while at Radeljec, an erosional remnant of lacustrine sediments lies on top of it. In contrast, at Kal-Koritnica and Jablenca, the diamictite remains uncovered.

Dating using IRSL (Infrared Stimulated Luminescence) at Ravni Laz yielded the following age estimates for diamictite: ≈155 ± 23 ka and for the conglomerate: ≈200 ± 43 ka (Bavec, 2002). Additionally, U/Th dating of the cement in the conglomerate provided a preliminary result of ≈153 ka BP. Due to the low content of radioactive isotopes, these dates are relatively uncertain, yet they offer at least a broad chronological framework for paleoenvironmental interpretations.

It is known that this represents the oldest known Quaternary sediment in the Bovec region, a fact recognized even before the first absolute dating results. For instance, Winkler (1926) estimated that the diamictite at Ravni Laz and Stržišče was the oldest, likely a Mindel or Günz moraine of a valley glacier. Meanwhile, the diamictite at Kal-Koritnica and Radeljec was considered pre-Würm, possibly Rissian (Kunaver, 1975). The diamictite here could as well be a debris flow deposit (or deposit of multiple debris flows) that formed during or after the melting of glacial ice (e.g., Bavec, 2002; Bavec et al., 2004).

**STOP 5: SEISMIC INDUCED ROCKFALLS CAUSED BY THE 1998 $M_W$5.6 EARTHQUAKE IN JULIAN ALPS**

The 12 April 1998 Mw5.6 Krn Mountains earthquake with a maximum intensity of VII-VIII on the EMS-98 scale caused extensive environmental effects in the Upper Soča valley and Julian Alps (Vidrih et al., 2001). The application of the EMS-98 intensity scale, based on the effects felt by humans, effects on objects and damage to building,s was limited in the epicentral area, because it is a high mountain area and thus very sparsely populated. On the other hand, the effects on the natural environment were prominent and widespread. These facts and the introduction of a new Environmental Seismic Intensity (ESI 2007) scale (Guerrieri & Vittori, 2007) motivated the research aimed to evaluate the applicability of ESI 2007 to this event (Gosar, 2012a). All environmental effects were described, classified and evaluated by a field survey, analysis of aerial images and analysis of macroseismic questionnaires. These effects include rockfalls, landslides, secondary ground cracks and hydrogeological effects. It was realized that only rockfalls (78 were registered) are widespread enough to be used for intensity assessment, together with the total size of affected area, which is around 180 $km^2$. Rockfalls were classified into five categories according to their volume. The volumes of the two largest rockfalls were quantitatively assessed by comparison of Digital Elevation Models to be $15x10^6$ $m^3$ (V. Lemež Mt.) and $3x10^6$ $m^3$ (Osojnica Mt. on Fig. 6) Distribution of very large, large and medium size rockfalls has clearly defined an elliptical zone (Fig. 7), elongated parallel to the strike of the seismogenic Ravne fault, for which the intensity VII-VIII was assessed. This isoseismal line was compared to the EMS-98 isoseism derived from damage-related macroseismic data (Fig. 7). The VII-VIII EMS-98 isoseism was defined by four points alone due to spares population, but a similar elongated shape was obtained. This isoseism is larger than the corresponding ESI 2007 isoseism, but its size is strongly controlled by a single intensity point lying quite far from others, at the location where local amplification is likely (Gosar, 2012a).

The ESI 2007 scale has proved to be an effective tool for intensity assessment in sparsely populated mountain regions not only for very strong, but for moderate earthquakes as well. This study has also shown that the quantitative definition of the rockfall size and frequency, which is diagnostic for each intensity, is not very precise in ESI 2007, but this is understandable, since the rockfall size is related not only to the level of shaking but also depends highly on the vulnerability of rocky slopes.

Figure 6: Large rockfall on Osojnica Mountain in the Tolminka valley induced by the 1998 earthquake (Foto: A. Gosar).

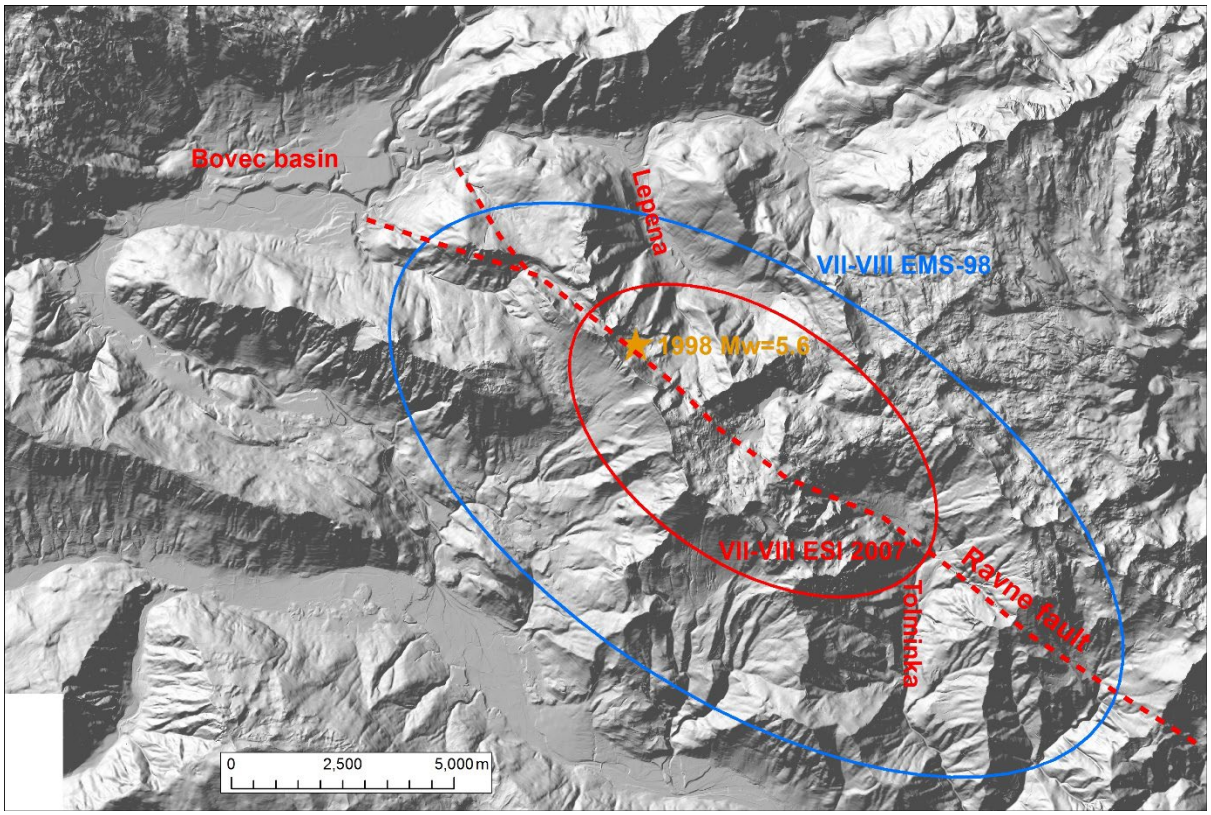


Figure 7: Comparison of two isoseisms for 1998 earthquake: VII-VIII EMS-98 isoseism from the buildings damage macroseismic data and VII-VIII ESI 2007 isoseism from the distribution of rockfalls (Gosar, 2012a).

**STOP 5: MICROTREMOR HVSR STUDY FOR ASSESSING SITE EFFECTS IN THE BOVEC BASIN RELATED TO 1998 $M_W$5.6 AND 2004 $M_W$5.2 EARTHQUAKES**

The Bovec Basin, which is filled with glacial and fluvial sediments, has recently been struck by two strong earthquakes (1998 and 2004) which caused extensive damage (VII–VIII EMS-98). Strong site effects resulted in large variations in damage to buildings in the area, which could not be explained by the surface variations in Quaternary sediments. The microtremor horizontal-to-vertical spectral ratio (HVRS) method was therefore applied to a 200 m dense grid of free-field measurements to assess the fundamental frequency of the sediments (Gosar, 2007). Large variations in the sediment frequency (3–22 Hz) were obtained, with most of the observed values in the range 7–11 Hz (Fig. 8). The observed frequencies cannot be related to the total thickness of Quaternary sediments (mainly sand and gravel), but can be explained by the presence of conglomerate or lithified moraine at shallow depths. The results were compared also with the velocity structure derived from seismic refraction data (Gosar et al., 2001). Microtremor measurements performed in several two and some three- and four-storey houses (masonry with RC floors), which prevail in the Bovec basin, have shown that the main building frequencies in the area are in the range 6–11 Hz. This indicates that damage to houses in both earthquakes in some parts of the basin was enhanced by site amplification and soil-structure resonance. Considerable changes in fundamental frequencies within short distances were established in the town of Bovec. Their values are as high as 22 Hz in the central part of the town, but diminish to 6–11 Hz in the adjacent Brdo and Mala vas districts. This is in agreement with the distribution of damage in both earthquakes, which was considerably higher in Brdo and Mala vas, although the houses in the central part of the town are older (Gosar, 2007).

Microtremor investigations have proved an effective tool for assessment of site effects in cases of complex geological structure commonly encountered in young Alpine basins filled with glaciofluvial sediments which are partly cemented. Lithified layers can considerably change the fundamental frequency and, consequently, the site effects. By taking additional measurements in buildings possible soil-structure resonance can be identified (Gosar, 2012b). After the 2004 earthquake, several portable seismological stations were deployed to record aftershocks. Additional spectral ratio methods using ambient noise and earthquake date were applied to better understand prominent site effects caused by heterogeneous sediments in the Bovec basin (Gosar, 2008).

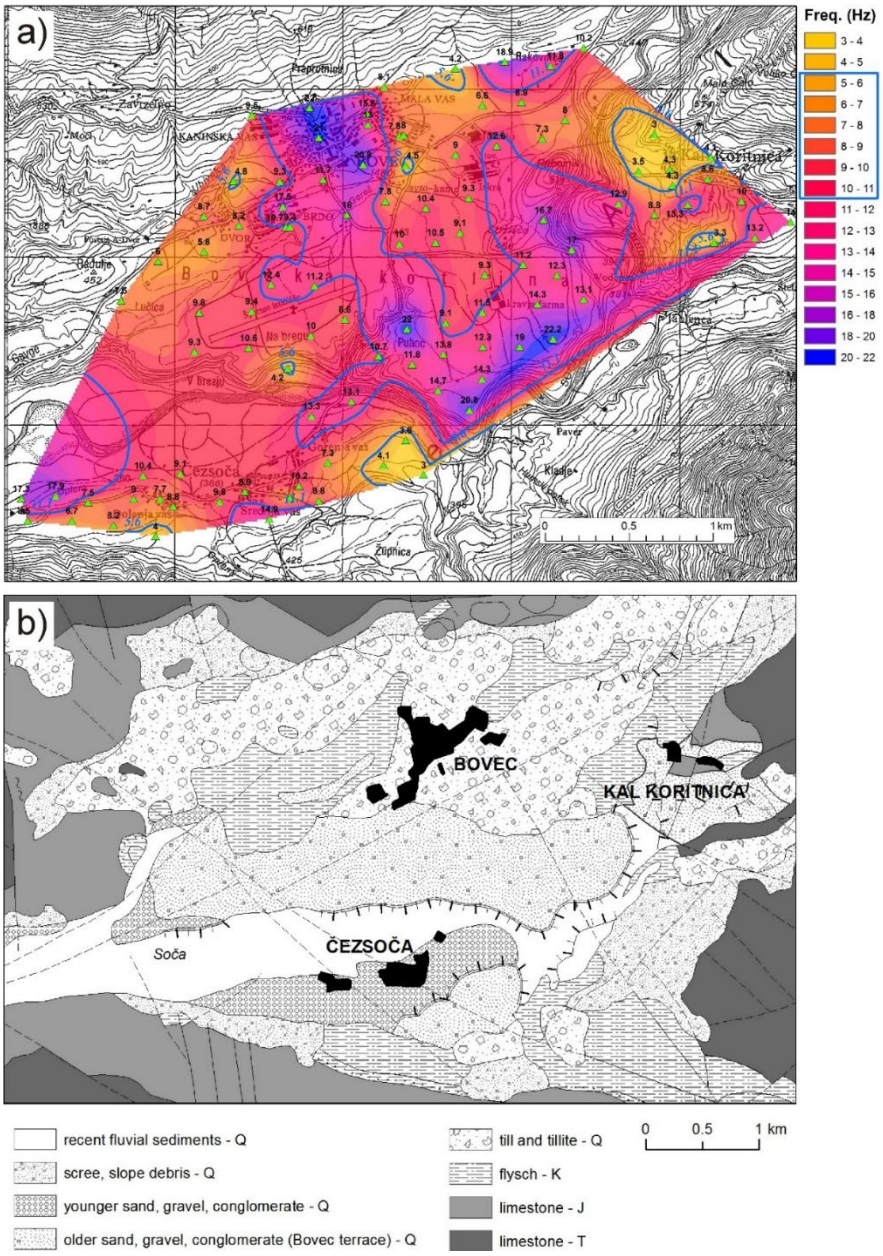


Figure 8: a) Map of the sediments over bedrock main resonance frequency derived from microtremor HVSR measurements in the Bovec basin (Gosar, 2012b). Triangles indicate points of free-field measurements; labels indicate the frequency of the HVSR peaks. 59 % of the surveyed area is characterized by a frequency range (confined by 5.6 and 11.1 Hz blue contour lines) of the possible occurrence of sediments-buildings resonance. b) Simplified geological map.

## STOP 6: MEASUREMENTS OF TECTONIC MICRO-DISPLACEMENTS WITHIN THE IDRIJA FAULT ZONE IN THE ALPS-DINARIDES TRANSITION ZONE (W SLOVENIA) NEAR THE BOVEC BASIN

A recent displacement-rate of an active fault is one of the most important seismotectonic parameters in seismic hazard assessment. However, in slowly deforming regions, it is not easy to determine, and an interdisciplinary approach is needed for a reliable estimate. The 120 km long, NW-SE trending dextral strike-slip Idrija fault, is the most important fault in the Alps-Dinarides transition zone, with large seismogenic potential, still needed to be researched. The largest known historical (a.d.1511) earthquake in Slovenia, with estimated magnitude 6.8, most probably occurred on it. On the other hand, recent seismicity associated to this fault is very low. The research methods applied so far on the Idrija fault to estimate its slip-rate can be grouped into geodetic, tectonic geomorphology, paleoseismology, outcrop dating and seismological methods. Measurements of tectonic micro-displacements using extensometer can provide additional insight into recent activity (Gosar, 2020). Such measurements are possible with crack-gauge instruments, installed on the crack which separates two tectonic blocks. Since the Idrija fault runs mostly along river valleys and karst fields, there are very few outcrops suitable for detailed tectonic analyses. The best exposure of the fault is in the Učja valley at the far NW end of the fault, close to the Bovec basin, because it extends transversely to the fault and forms a small canyon. In the canyon the structures of outer and inner fault zones are very good visible (Fig. 9). The recent deformation is evident from the dissection of Quaternary breccia and dextral offsets of the river. Therefore, it was selected for the installation of TM 71 extensometer, developed at the Institute of Rock Structure and Mechanics of the Czech Academy of Sciences in the frame of the COST 625 project *3D monitoring of active tectonic structures*. It operates on the principle of Moire optical effect (Košťák, 1991), with displacements measured through interference pattern formed by two optical grids engraved in glass plates which undergo a relative shift (Stemberk et al., 2003). Measurements on the crack within the inner fault zone are conducted from the year 2004. In 20 years of observations a systematic horizontal displacement with average rate of 0.21 mm/year and subordinate vertical displacements of 0.06 mm/year were established (Fig. 9), proving the activity of this fault (Gosar, 2020). Recent geodynamics of the region is controlled by CCW rotation of the Adriatic microplate in relation to relatively stable European plate. GNSS measurements in W Slovenia revealed general movements of the territory in the north direction of 2-3 mm/year. Related deformations are distributed over numerous faults of NW-SE direction and some W-E trending thrusts. In a recent study on the present-day kinematic behavior of active faults in the Eastern Alps using extensometers, it was found that annual displacement rates of the monitored faults were mostly about an order of magnitude smaller than the rates of the entire crustal wedges revealed from GNSS. This is consistent with our observations on the Idrija fault. Displacement rates are beside for geodynamic interpretations important for improvement of seismotectonic models for seismic hazard assessment.

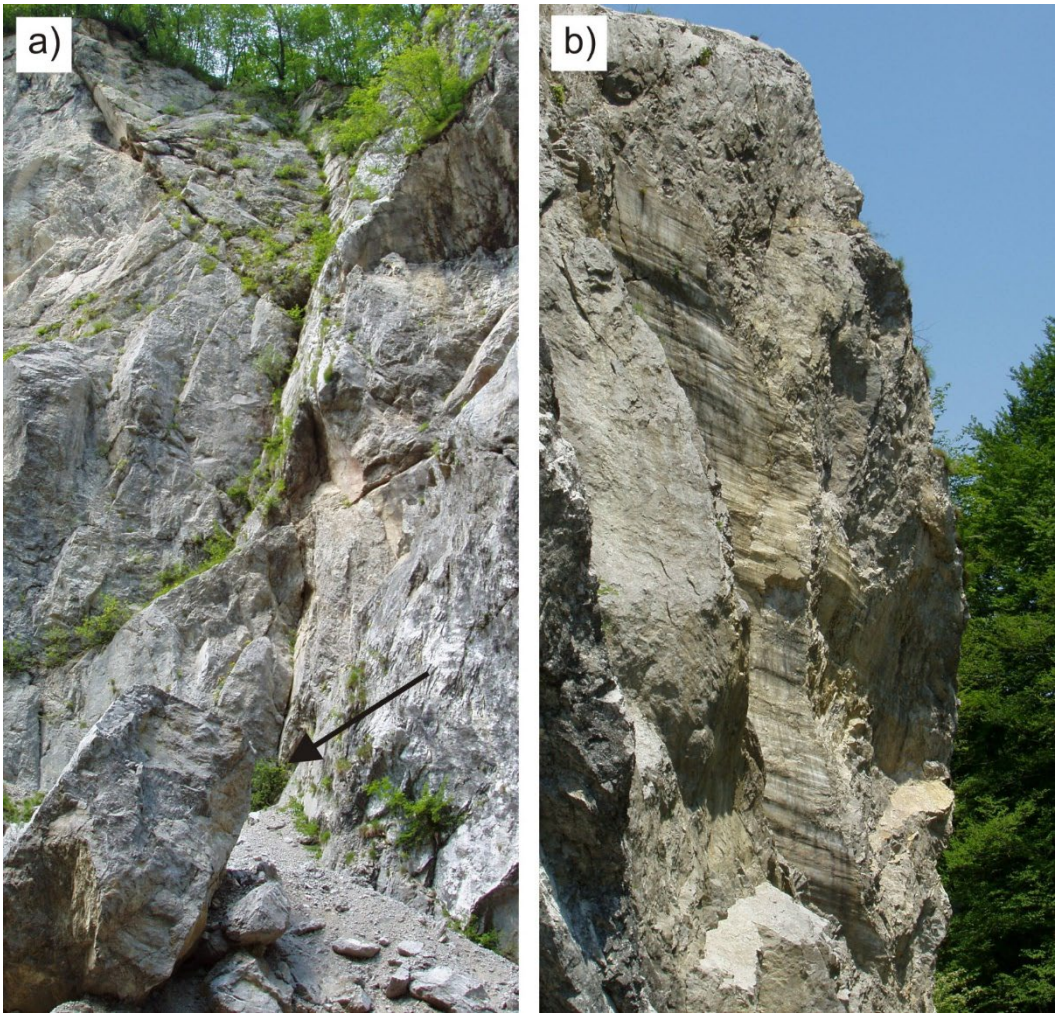


Figure 9: a) A crack in the Idrija fault inner fault zone in the Učja valley. The arrow indicates the location of the TM 71 extensometer. b) Outcrop of another fault plane located 50 m to the east with clear striations indicating subhorizontal movements (Gosar, 2020).

**STOP 7: LACUSTRINE SEDIMENTS (SRPENICA)**

The Kuntri Hill (530 m a.s.l.), also known as Hrib pri Srpenici, has been interpreted in numerous ways—as a moraine, a rockfall deposit, or a combination of both. It appears to have formed through a combination of rockfalls from Polovnik (from the South) and the southern slopes of Stol (from the North), with the majority of the material originating from Polovnik. This is supported by the distinct concave depression on the slopes of Polovnik and the lithological composition of the debris.

It is unlikely that the rockfall was solely responsible for damming of the rather extensive lake. Lacustrine sedimentation followed synsedimentary subsidence of the accumulation basin, as evidenced by systematic increases in laminae inclination in some boreholes (Bavec, 2002). Glacial overdeepening has not yet been considered the primary agent in deepening the basin floor, though future data may change this.

The timing of lake formation and the onset of sedimentation remain undetermined. However, given that the full thickness of lake sediments exceeds 200 m (Kuščer et al., 1974), and considering that the uppermost 34 m accumulated over approximately 8,000 years (Bavec, 2002), one may speculate that the lake formed at least between 50 and 100 ka ago. The lake extended as far as Čezsoča, and sedimentation continued deep into the Holocene (until 6590–6910 calibrated years BP).

The sediment is layered and, in places, finely laminated, consisting almost entirely of allochthonous material, predominantly carbonate detritus (Dolenec et al., 1984). In the central part of the basin, the lamination is distinctly horizontal, characterized by contrasting color and grain size variations. The chemical differences between light and dark laminae indicate that the lamination is not seasonally controlled and thus does not represent varves. Instead, it reflects the influence of different sediment source areas: higher flysch content results in darker laminae while higher carbonate content results in lighter laminae (Gosar et al., 2008).

At a depth of approximately 34 m, two layers containing seismites were identified (Fig. 10). These provide evidence of an earthquake that occurred approximately 15 ka ago (Marjanac et al., 2001).

Figure 10: The upper part of the “Srpenica lake” sedimentary sequence and the seismites dating at approximately 15 ka b.p.

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## RECONSTRUCTION OF THE SOČA GLACIER IN THE LGM AND POST-SEDIMENTARY DEFORMATIONS OF GLACIAL SEDIMENTS (FRIDAY, 28.03.2025)

**Guided by: Dr. Manja Žebre[1], Dr. Petra Jamšek Rupnik[1], Dr. Eva Mencin Gale[1]**

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### Outline

- Stop 1: Soča glacier in the Breginj area – overview of the past and recent studies
- Stop 2: Most na Nadiži outcrop – LGM deposits
- Stop 3: Selo outcrop – Lateglacial deposits
- Stop 4: Legrada outcrop – LGM glacial lacustrine deposits
- Stop 5: Modrejce succession


Figure 11: Excursion stops on Day 2 with indicated Ravne and Idrija Fault (from Atanackov et al., 2021).

**STOP 1-4: GEOMORPHOLOGICAL, SEDIMENTOLOGICAL AND CHRONOLOGICAL EVIDENCE FOR THE SOČA GLACIER IN BREGINJ DURING THE LGM**

The Slovenian Alps were glaciated during the Last Glacial Maximum (LGM) and formed the south-eastern part of the Alpine ice sheet (Seguinot et al., 2018). The Soča glacier was one of the largest valley glaciers in Slovenia. Although the glacigenic deposits along the Soča catchment have been studied since the second half of the 19th century (e.g. Hauer, 1857; Stur, 1858; Tarramelli, 1870; Brückner, 1891; Tellini, 1898), it is still unclear where exactly the terminus of the Soča glacier was during the LGM. The reconstructions of the Soča glacier made by various authors differ considerably. Some researchers concluded that one terminus of the glacier should have reached the town of Most na Soči (Kunaver, 1975; Kuščer et al., 1974; Penck and Brückner, 1909; Šifrer, 1965) and the other the settlement of Breginj (Tellini, 1898), while others assumed that the Soča glacier never extended beyond the Bovec Basin (located more than 30 km upstream of Most na Soči) during the LGM (Bavec et al., 2004). These ambiguous conclusions result from the almost complete lack of absolute age data and undetailed geological and geomorphological maps. During the 4-year project (2020-2024) entitled Past climate change and glaciation at the Alps-Dinarides junction, funded by the Slovenian Research and Innovation Agency, we addressed this challenge by collecting new detailed data on the Soča glacier. We collected all published data on the Soča glaciation in a Database of glacial landforms of the Alps-Dinarides junction, which is freely accessible on the eGeologija web portal. On this basis, we started working in the field, checking the already known locations of glacigenic deposits and also looking for completely new evidence of glaciation. Our study area was roughly between Breginj and Most na Soči. Here we carried out geomorphological mapping, logged 39 profiles and dated 49 samples using bulk 14C radiocarbon method. This study is still ongoing. During this fieldtrip, we will make 4 stops in the Breginj area, where we will present preliminary results on the timing and extent of the Soča glacier.

## STOP 5: LATE QUATERNARY SEDIMENTARY SUCCESSION AND ITS DEFORMATION IN MODREJCE, MOST NA SOČI (SOČA VALLEY): IMPLICATIONS FOR GLACIAL AND TECTONIC PROCESSES

Late Quaternary sedimentary succession in Modrejce near Most na Soči (Julian Alps, Western Slovenia) lies in an ice-marginal area during the Last Glacial Maximum and within the deformation zone of the Idrija Fault (Fig. 12). Idrija Fault is an important regional dextral strike-slip fault, which has been active with a slip rate of 1.15 ± 0.15 mm/year (Moulin *et al.*, 2014, 2016) and has a significant seismogenic potential (Atanackov *et al.*, 2021) as demonstrated by historical and paleoseismic history (Grützner *et al.*, 2021). The sedimentary succession in Modrejce holds evidence of paleoenvironmental changes and deformations, studied using geomorphological and structural geological mapping, sedimentary facies analysis, and optically stimulated luminescence dating to understand the landforms and sediments. Findings show that the succession includes glaciofluvial, glaciolacustrine, glacial, and slope deposits from two glacial advances of the Soča Glacier (Jamšek Rupnik *et al.*, 2020). The glacier reached the Most na Soči area during the Penultimate Glaciation and the Last Glacial Maximum. Staircase-shaped slope formed during and after the Last Glacial Maximum, when glacial and post-glacial processes carved into older deposits (Fig. 13). Slope deposition was established during the Holocene.

The older glaciofluvial succession, which is tilted and cut by a series of faults and joints, and includes glaciolacustrine layers exhibiting soft-sediment deformations, was studied through photogrammetric and levelling surveys, paleoseismological techniques, and ground penetrating radar surveys (Fig. 14) (Jamšek Rupnik *et al.*, 2022). The analysis revealed at least five deformation events that occurred during the deposition of the studied succession of the Penultimate Glaciation. An anticline with an N-S to NE-SW oriented axis, dissected with NE-SW striking faults that are approximately perpendicular to the primary Idrija Fault, was identified from ground penetrating radar profiles and outcrop observations. Considering the local geologic setting there are three possible mechanisms that could have caused these deformations: glaciotectonics, gravitational faulting due to ice-decay or slope instability, and tectonic faulting. Following a detailed structural analysis, the observed deformations were interpreted as secondary structures resulting from paleoseismic activity of the Idrija Fault and as structures resulting from glaciotectonics and gravitational faulting. The transtensional nature of the deformations at the studied site indicates a local character of the Idrija Fault, which can be explained by a local releasing bend in Modrejce Valley.

The study of succession in Modrejce reveals the late Quaternary glacial history of the Most na Soči area and seismic activity of the Idrija Fault and suggests a highly dynamic environment resulting from climatic changes and tectonic activity. It also provides valuable new data for understanding the seismic hazard of this important fault, including the first paleoseismic evidence from the Penultimate Glaciation.

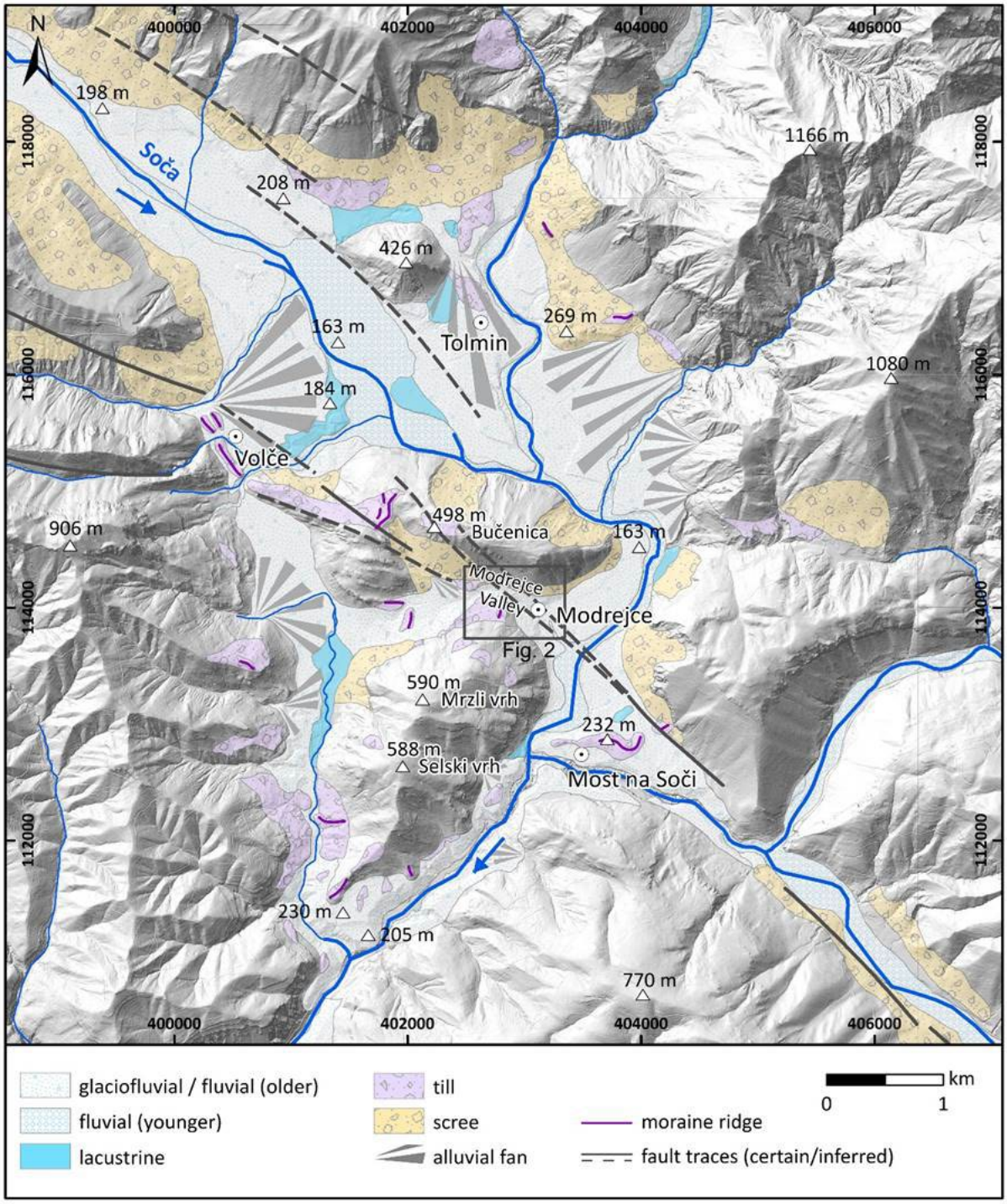


Figure 12: Quaternary deposits and Idrija Fault traces in Tolmin and Most na Soči areas (modified after Jamšek Rupnik et al., 2022). D48 coordinate system.

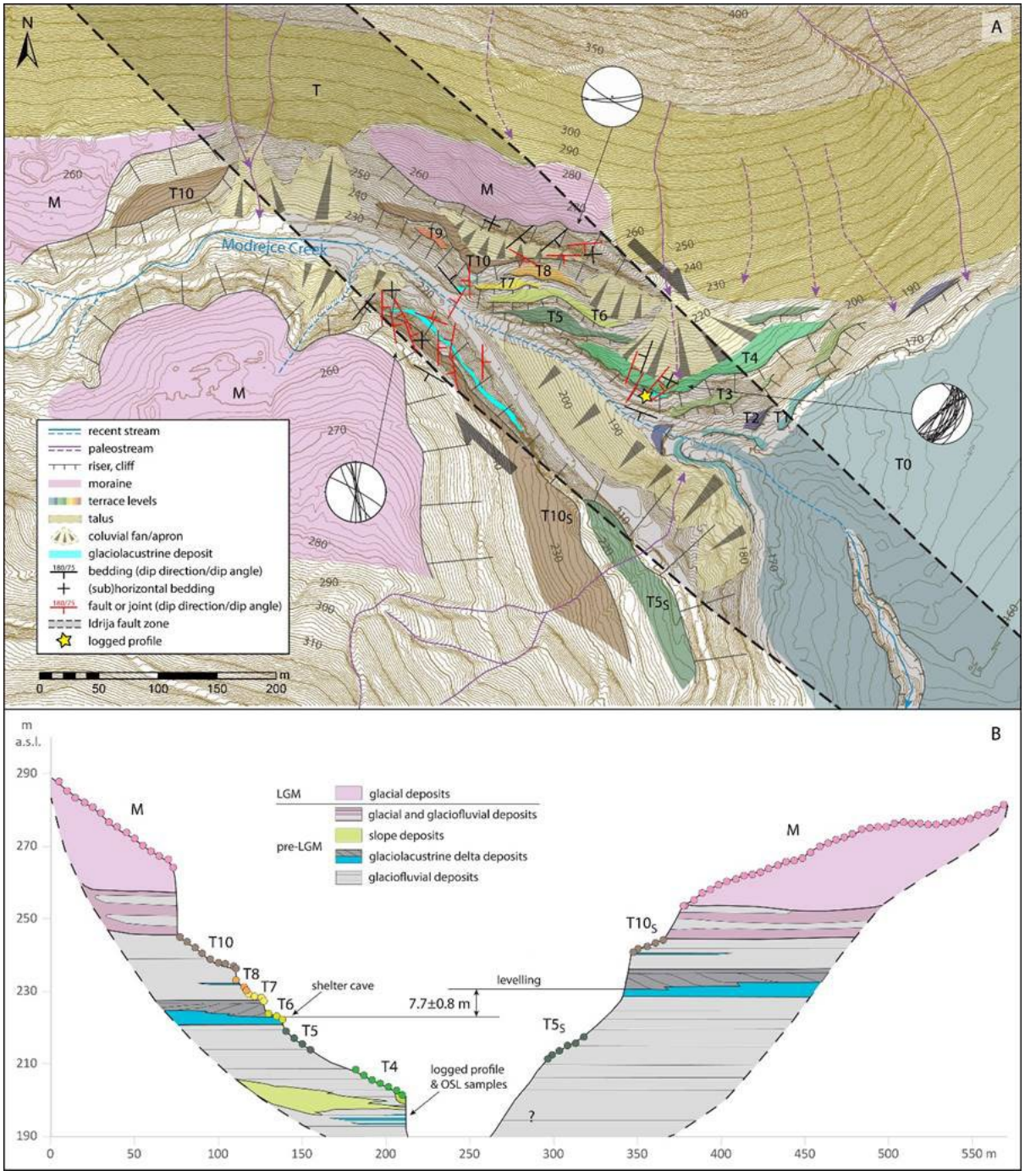


Figure 13: Landforms, deposits and structural features of Modrejce Valley (modified after Jamšek Rupnik et al., 2022). A - Geomorphic and structural map including lower hemisphere stereographic projections of the fault and joint planes. B - A stacked cross-section of landforms and deposits.

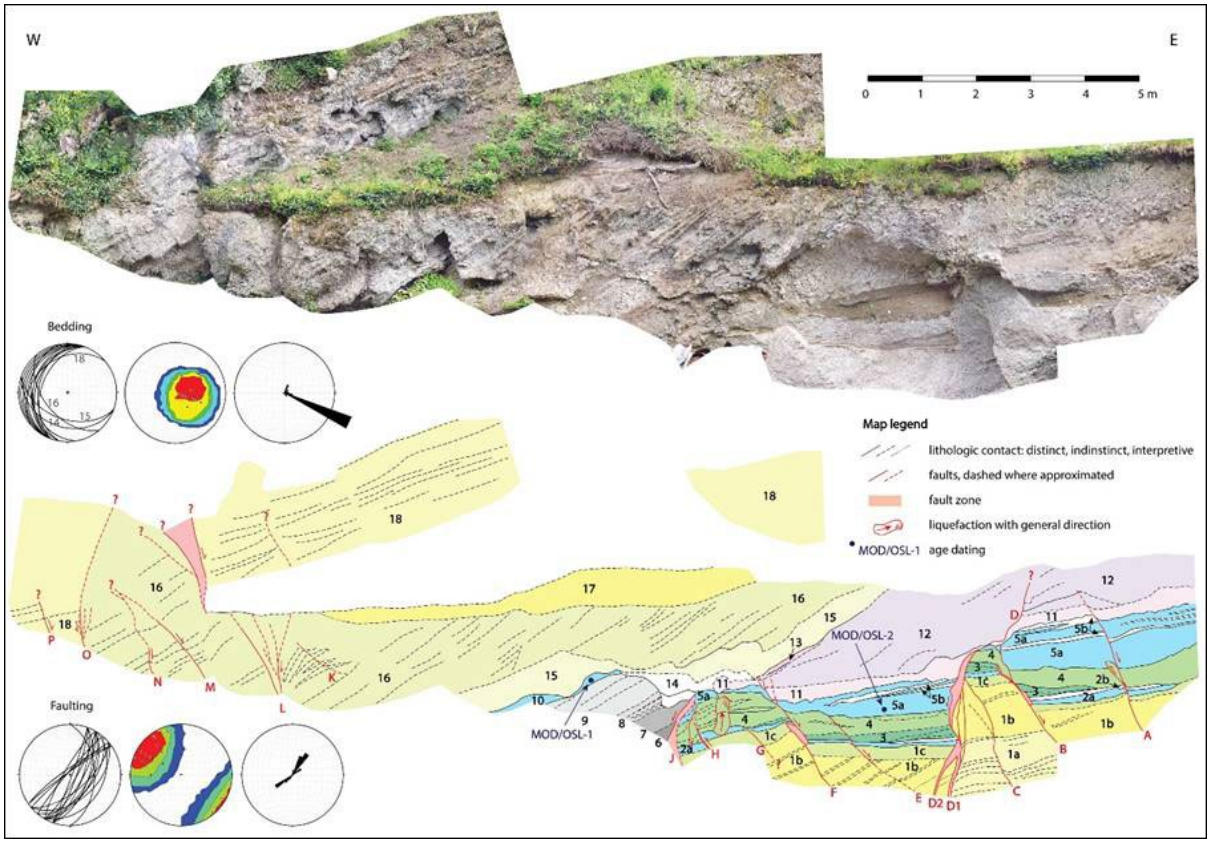


Figure 14: Digital orthophoto and profile log of deformed Quaternary deposits in Modrejce with lower hemisphere stereographic projections of the bedding and faulting measurements (modified after Jamšek Rupnik et al., 2022). Bedding/fault planes (left projections), bedding/fault plane poles with contours showing the distribution of the poles (middle projections) and rose diagram of bedding plane poles or fault planes (right projections).

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## UNROOFED CAVES: LINKING SURFACE AND DYNAMIC KARST PROCESSES (SATURDAY, 29.03. 2025)

**Guided by: Dr. Nadja Zupan Hajna[4]**

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### Outline

- Stop 1: Reka River and its ponor(s)
- Stop 2: Vremska dolina blind valley, contact (allogenic) karst
- Stop 3: Škocjanske jame (Škocjan caves)
- Stop 4: Unroofed cave Lipove doline

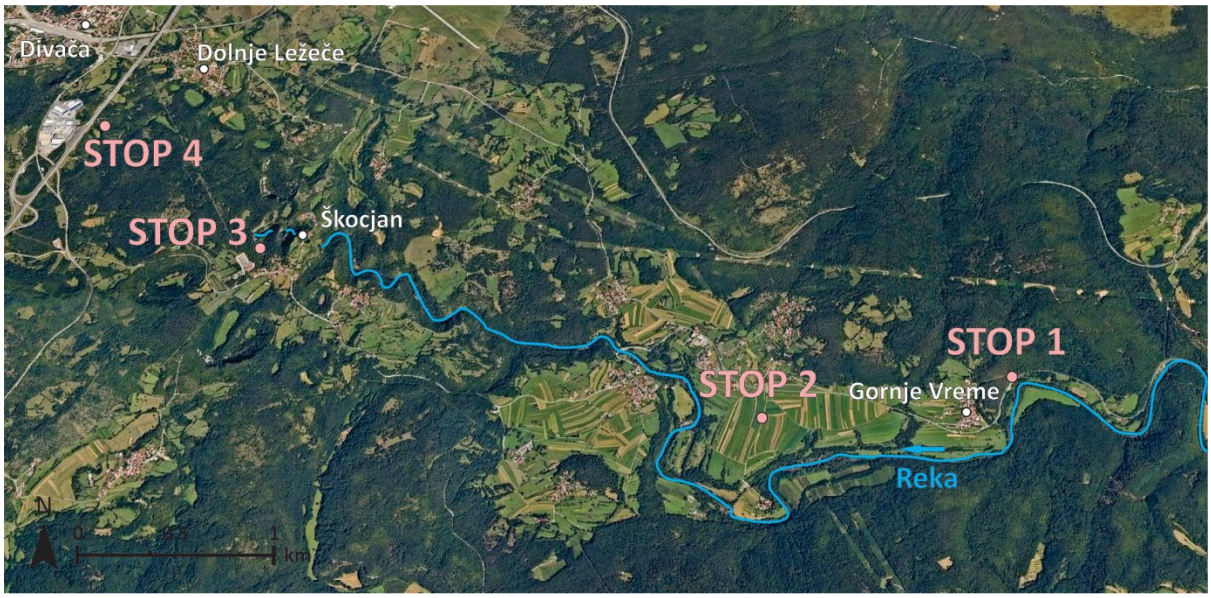


Figure 15: Excursion stops on Day 3.

**INTRODUCTION**

Dating karst processes is inherently challenging due to the scarcity of surface sediments, particularly in the Classical Karst region of southwestern Slovenia. However, cave sediments, found either in the subsurface of karst landscapes or in exposed, unroofed (denuded) caves, often serve as primary sources of information for studying past environments and processes such as climatic changes and tectonic activities (*e.g.* Zupan Hajna *et al.* 2020, 2021, 2024, 2025). These sediments are essential for reconstructing the geological history and environmental changes in karst systems.

Cave sediments are broadly categorized into two main types based on their origin: allogenic and autogenic (*e.g.* Ford & Williams 2007). Allogenic sediments are transported into caves from external sources, such as rivers and streams, and consist of materials like quartz sand, gravel, clay, and other detrital particles (*e.g.* Sasowsky 2007; White 2007; Farrant & Smart 2011). These deposits typically accumulate during flood events or sustained water flow. In contrast, autogenic sediments form in caves, primarily through the precipitation of minerals from cave water (*e.g.* calcite speleothems). Speleothems, for example, record chemical processes occurring in the cave environment and provide valuable paleoclimate data (*e.g.* White 2007).

In sedimentary sections in caves, alternating layers of flood sediments and speleothems (*e.g.* flowstone) are often observed. The speleothem layers can be used to date calcite precipitation and associated flood events. Moreover, stable isotope compositions provide insights into climatic variability during calcite formation (*e.g.* Zupan Hajna *et al.* 2021). Thus, cave sediments not only reflect internal environmental changes in the cave (*e.g.* Sierpień *et al.* 2021; Pawlak *et al.* 2024) but also represent distinct speleogenetic phases across successive hydrological karst zones (*e.g.* Ford & Williams, 2007; Farrant & Smart 2011; Zupan Hajna *et al.* 2024) during the evolution of the karst system.

As a result of variable recharge and complex aquifer geometry, karst systems are characterized by large vertical oscillations of the water table, which can range from several tens to over a hundred meters. The temporarily variable flood zone, also called the epiphreatic zone, lies between the permanently flooded phreatic zone and the air-filled vadose zone and is of utmost hydrological and speleological importance. Floods in the epiphreatic zone often transport and deposit significant amounts of sediment into the karst system, contributing to its sedimentary record and evolution.

The Škocjanske Jame cave system provides an exceptional example of karst evolution over time through its sedimentary records. Its well-preserved geological and hydrological features, combined with multi-proxy sedimentary records, offer an overview of speleogenesis, karst system evolution, and interactions between tectonics, climate, and hydrology. Despite extensive research on the speleogenesis of Škocjanske Jame (*e.g.* Habič *et al.* 1989; Mihevc 2001; Gabrovšek *et al.* 2014; Zupan Hajna *et al.* 2024), significant gaps in knowledge remain, particularly regarding the timing of speleogenetic processes and the factors influencing passage formation and the overall evolution of the cave system.

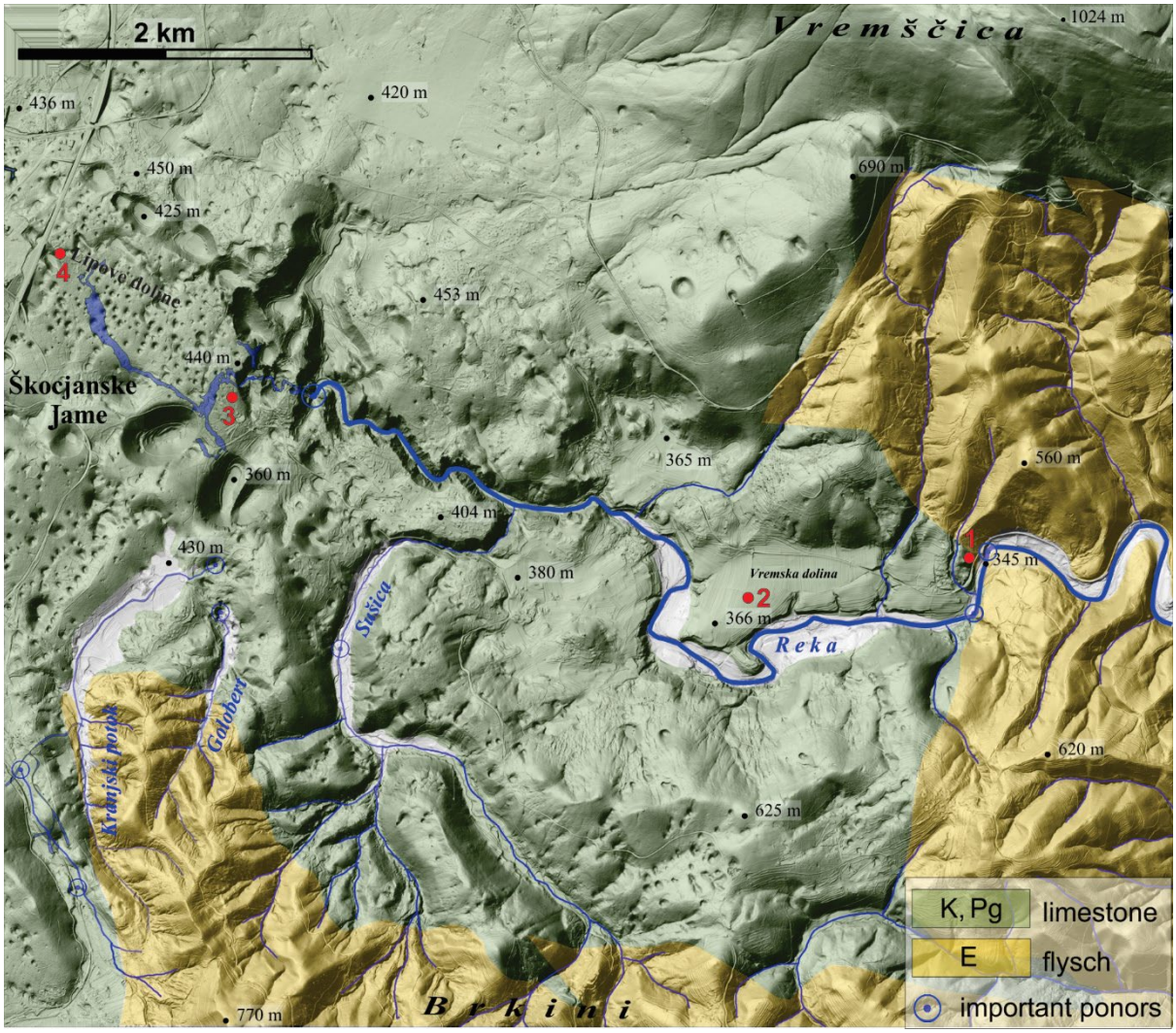


Figure 15: A hillshade DEM illustrating the lithology and surface morphology at the contact between impermeable Eocene flysch rocks (E) and Cretaceous-Paleocene limestones (K, Pg), with a sinking river, a blind valley, collapse dolines, solution dolines, and map of Škocjanske Jame and location of Unroofed cave Lipove doline (after Zupan Hajna et al. 2024). Source of Lidar data: Geodetski oddelek ARSO. Excursion Stops on Day 3 in red: 1– Reka River and its Ponor(s); 2– Vremska Dolina, Contact (Allogenic) Karst; 3– Škocjanske Jame; and 4– Unroofed Cave Lipove Doline.

**STOP 1: REKA RIVER AND ITS PONOR(S)**

At the southeastern edge of the Kras Plateau (SW Slovenia), an area of Eocene flysch exhibits well-developed surface drainage and fluvial morphology (Fig. 16). The Reka River is the primary watercourse in this valley, with most of the flysch area belonging to the Brkini Hills. Before reaching Škocjan, the river flows approximately 50 km through a valley formed in low-permeability Eocene flysch. The Reka catchment area covers more than 365 km², with about 60% of surface runoff occurring on flysch (Peric & Hribar 2010).

Between 1992 and 2021, the lowest recorded discharge of the Reka at the Cerkvenikov mlin hydrological station was 0.25 m³/s, while the mean discharge was 7.89 m³/s (ARSO 2023). During high-water periods, the discharge can exceed 300 m³/s. Due to the impermeable nature of the

flysch, the river's discharge gradually increases downstream until it reaches Gornje Vreme, where the Cerkvenikov Mlin gauging station is located.

Upon reaching the limestone bedrock, the Reka begins to lose water into ponors immediately downstream of the lithological contact. During very low water levels, the river may completely disappear at this point. However, under normal conditions, it continues flowing for another 7 km through a limestone valley before sinking into the Škocjan Caves. From there, groundwater flows toward the springs between Nabrežina/Aurisina and Timava/Timavo in the Gulf of Trieste. Ultimately, all surface waters from the flysch region infiltrate the karst system.

The Reka River is the main allogenic input into the Kras Plateau karst system, with a long-term (1952–2013) average discharge of approximately 8 $m^3/s$. Between 2005 and 2013, the ratio between the highest and lowest flow rates was 1:1700, with a maximum recorded discharge of 305 $m^3/s$ and a minimum of 0.18 $m^3/s$. The river's first ponors are located at the flysch-limestone transition. When discharge exceeds 1 $m^3/s$, the river continues flowing for 7 km before sinking into the Škocjan Caves. However, even when the Reka completely sinks at its main ponor, some water (several L/s) continues to flow in the cave. The fluctuation of groundwater levels in the epiphreatic zone of the karst system is influenced by various factors, such as precipitation (climate), gradient, and secondary porosity. During floods, the highest groundwater levels are not uniform, even within a limited area. The largest groundwater fluctuation, up to 125 m, they measured in the Kačna Jama (Pivetta *et al.* 2021).

**STOP 2: VREMSKA DOLINA BLIND VALLEY, CONTACT (ALLOGENIC) KARST**

Vremska Dolina is a large blind valley formed by the Reka River, measuring approximately 3 km in length and 1.5 km in width. Blind valleys develop when allogenic rivers flow into karst terrain and sink, making them a characteristic feature of contact (allogenic) karst. The high water volume, sediment transport, and variable flow regime of allogenic rivers play a crucial role in shaping the karst landscape. However, the morphology of a blind valley, particularly the width of its floor, is primarily controlled by the karst drainage system and the height of the water table. The evolution of this valley has been influenced by fluctuations in the karst water level, the development of subterranean conduits (*e.g.* Škocjanske Jame), and regional tectonic uplift (Placer *et al.* 2010).

The Reka flows through Vremska Dolina at an elevation between 345 m and 335 m. Above the riverbed, two higher rock terraces are preserved at approximately 360 m and 380 m, covered with thick soils that developed on fluvial sediments containing numerous chert pebbles transported from the flysch. In all studied sediments of the Reka and its tributary Sušica, quartz dominates, accompanied by clay minerals (illite/muscovite group), plagioclase, and chlorite (Zupan Hajna *et al.* 2017). At the northwestern edge of the blind valley, the Reka enters a narrow canyon, which continues toward the Škocjanske Jame, where the river sinks at an elevation of 317 m.

**STOP 3: ŠKOCJANSKE JAME (ŠKOCJAN CAVES)**

The currently active section of Škocjanske Jame is shaped by the sinking Reka. Located in the Divača Karst in southwestern Slovenia, this globally significant cave system has been a key site for scientific

research and conservation. Since 1986, it has held UNESCO World Heritage status due to its extraordinary underground canyon, one of the largest in the world. The caves played a crucial role in 19th-century research on karst phenomena, influencing the development of karst terminology, speleology, and karstology. While initial paths in the cave were built in 1823, major explorations and visitor pathways only began in 1884, led by speleologists from the DÖAV (Littoral Section of the Austrian Alpine Club) in Trst/Trieste. Recognizing its ecological importance, Škocjanske Jame were also designated a UNESCO Ramsar wetland in 1999 and became part of the UNESCO MAB Karst Biosphere Reserve in 2004.

The cave passages have developed within a 300 m-thick sequence of Cretaceous and Paleocene limestones (Šebela 2009). The underground Reka River, flowing through Šumeča Jama and Hankejev Kanal, predominantly follows a 130 m-thick section of the Lipica Formation ($K_2$ 4-5), guided by the bedding-plane dip. Bedding planes affected by interbedding slips (Knez 1996; Mihevc 2001; Šebela 2009) served as inception horizons, facilitating the initial development of cave passages.

Structurally, the cave system lies within the Trieste–Komen Plateau, on the southwestern wing of a regional anticlinal fold (Gospodarič 1965; Jurkovšek 2013). The region exhibits a Dinaric NW–SE strike orientation, with strata dipping southwest. Faults parallel to this strike (NW–SE) dominate, while cross-cutting faults (NE–SW) further influence cave morphology. The area is part of the Adria Microplate, which was overthrust by the External Dinaric thrust belt at the end of the Eocene (Celarc *et al.* 2012). During the Miocene, the Adria Microplate underwent segmentation and counterclockwise rotation, with underthrusting beneath the Dinarides. This tectonic evolution, along with the degradation of the Adriatic–Dinaric carbonate platform and flysch deposition during the Eocene, contributed to the current geological setting (Celarc *et al.* 2012). The most significant regional faults affecting the cave system include the NW–SE-oriented Raša and Divača faults.

The cave's development is primarily controlled by the contact between permeable Cretaceous and Paleocene carbonate rocks and impermeable Eocene flysch. The Reka sinks into the cave at an elevation of 314 m, flowing approximately 35 km underground before re-emerging at the Timavo springs north of Trieste. This extensive subsurface flow has shaped a network of underground passages, collapse chambers, and dolines across multiple inclined levels.

The Škocjanske Jame system consists of nearly 6 km of passages, with dimensions averaging 30 m × 40 m and a maximum height of 145 m in the underground canyon, where the Reka flows. The total cave volume from the ponor in Velika Dolina to Martelova Dvorana (Martel's Chamber) is 6.13 million m³. Martelova Dvorana alone has a calculated volume of 2.55 million m³, with a maximum length of 314 m, width of 143 m, and height of 158 m. As of 2019, this chamber ranked 11th among the world's largest cave chambers and 2nd in Europe after Salle de la Verna (3.6 million m³). However, Martelova Dvorana remains the largest known river passage in Europe. Some of the largest chambers in the system collapsed, forming dolines such as Velika and Mala Dolina.

The Reka and its tributaries act as typical allogenic sinking streams, transporting and depositing sediments throughout the cave system (*e.g.* Gospodarič 1984). Various types of clastic sediments are present along the riverbed from the ponor to the siphon, with flysch sandstone pebbles dominating upstream and limestone pebbles prevailing at the siphon (Kranjc 1989). Flood clays and silts mainly consist of quartz, plagioclase, and clay minerals (Zupan Hajna 1995). Periodic flooding events, influenced by extreme weather conditions or seasonal variations, contribute to sediment deposition, while prolonged dry periods facilitate speleothem growth.

**STOP 4: UNROOFED CAVE LIPOVE DOLINE**

Unroofed caves and their sediments are well preserved on the surface above Škocjanske Jame (*e.g.* Mihevc 2001). Their allogenic sediments, such as gravel, sand, silt, and clay, originate from the Eocene flysch, while limestone gravel and rubble result from the erosion of cave walls. All unroofed caves in this area are situated approximately 200 meters above the present-day passages of Škocjanske Jame and Kačna Jama, representing an earlier stage in the evolution of the underground Reka drainage system. Paleomagnetic studies of sediments from various caves, including Divaška Jama, Trhlovca, the Divača Profile, and Risnik Unroofed Cave, suggest that these alluvial deposits are up to 5 million years old (e.g. Bosák *et al.* 1998; Zupan Hajna *et al.* 2008, 2010, 2020). The mineral composition of these clastic fills, derived mainly from weathered Eocene flysch rocks, remains consistent, indicating a common source, likely a predecessor of the Reka.

The largest known unroofed cave, stretching 1.8 km, is found in Lipove Doline above Škocjanske Jame. The present underground riverbed in Škocjanske Jame lies 230 m below these unroofed caves. Quartz sand was once extracted from its western part, revealing flowstone formations and a large stalagmite. Surface mapping indicates that the unroofed cave is part of a 1,800 m-long series of dolines and elongated depressions, located at approximately 450 m a.s.l., while the Reka currently flows underground at 214 m a.s.l.. The unroofed cave is about 5–10 m below the surrounding surface, while the depression is 20–30 m wide, containing siliciclastic fluvial deposits, sandy clays, and massive flowstone. In terms of dimensions, the unroofed cave in Lipove Doline is comparable to Škocjanske Jame, with passages likely exceeding 20 m in width in some areas. The presence of massive stalagmites and flowstone suggests that the ceiling was still thick during active flowstone deposition. It is estimated that approximately 45,000 m³ of allogenic cave sediments remain preserved in this unroofed cave (Mihevc 2001).

In the continuation of the Lipove doline unroofed cave, the Risnik unroofed cave provides critical insights into the early development of the Škocjanske Jame system (Zupan Hajna *et al.* 2024). There, the initially deposited fine-grained sediments in phreatic conditions (about 5 Ma ago) were later influenced by base-level changes and uplift, transitioning the system into epiphreatic and vadose environments. The sinking river last flowed through what is now an unroofed cave approximately 2.6 million years ago, depositing fluvial sediments (gravel). This indicates that the collapse dolines and canyons of Škocjanske Jame, including its active water passage, are younger.
The chemical denudation, gradually exposed the fluvial sediments, highlighting the dynamic processes that shaped this karst landscape. The denudation process not only exposed these sediments but also contributed to the formation of surface karst features, such as dolines containing fluvial deposits, including intersection dolines (*in sense* of Sauro 2003). These geomorphological features, all younger than 2.6 million years, illustrate the complex interplay between subsurface processes and surface evolution in the ongoing development of the karst system.

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