The Migovec System, a deep alpine cave system of the Julian Alps, NW Slovenia

ABSTRACT

The 41.8 km long Migovec system is located in the Triglav National Park, Julian Alps (NW Slovenia). The cave system, whose exploration started in 1974, is the longest in Slovenia. There are eight entrances, located between 1715 m and 1861 m a.s.l. 25 years of joint exploration by Imperial College Caving Club (ICCC) and Jamarska Sekcija Planinskega Društva Tolmin (JSPDT) have revealed the presence of at least four main phreatic cave levels, connected by a dozen of separate vadose shaft and canyon series. Vadose invasion cave development reaches a thickness of up to 972 m with seven major siphons located at elevations between 881 and 917 m a.s.l. This article presents an overview of the local geology and derives a tentative speleogenetic history of the cave system based on passage morphologies.

ZUSAMMENFASSUNG

Das Migovec System, ein tiefes alpines Höhlensystem in den Julischen Alpen, NW Slowenien

Das Migovec Höhlensystem befindet sich im Triglav Nationalpark der Julischen Alpen. Mit 41,8 km Ganglänge ist dieses Höhlensystem, dessen Erforschung 1974 begann, das längste Sloweniens. Die acht Eingänge liegen zwischen 1715 m und 1861 m Seehöhe. Die seit 25 Jahren gemeinsam vom Imperial College Caving Club (ICCC, Großbritannien) und Jamarska Sekcija Planinskega Društva Tolmin (JSPDT) durchgeführte Exploration führte zur Entdeckung von mindestens vier phreatischen Haupthöhlenniveaus, die ein Dutzend Schächte und Canyons verbinden. Die vadose Höhlenbildung erstreckt sich über 972 m Höhenmeter und umfasst sieben zwischen 881 m und 917 m Seehöhe liegende große Siphone. Dieser Artikel bietet einen Überblick über die lokale Geologie und leitet die speläogenetische Geschichte dieses Höhlensystems anhand seiner Gangformen ab.

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INTRODUCTION

The distinctive limestone face of Tolminski Migovec (1881 m a.s.l) in the Julian Alps towers over the neighbouring valleys, making it easily visible from Tolmin, the nearby town straddling the rivers Soca and Tolminka (Fig. 1). The rugged landscape of the Julian Alps is dominated by bare grey white peaks bearing strong imprints of karstification, which no doubt played a role in drawing in early explorers to the region (Middleton & Waltham, 1986). Nearby massifs like those of Rombon and Kanin enjoy a deserved reputation for deep alpine caves, e.g. Cehi 2 (depth: –1505 m, length: 5536 m, Registry Number 6200) and Sistem Mala Boka (–1319 m , No. 3200), indicating the strong potential for discoveries in the region.

From 1974 onwards, expeditions by the local caving association Jamarska Sekcjia Planinskega Društva Tolmin (JSPDT) yielded two promising caves on the Migovec Plateau but interest in the club then shifted to the Mala Boka in the early 1980s due to a lack of manpower (Frost & Hooper, 2007).

The local cavers welcomed ICCC in the summer of 1994, when the first of many 6-week expeditions were held on the mountain. A third cave was discovered, and within a couple of years all three entrances were connected to forge the first cave system under Migovec. With discoveries coming thick and fast, the friendship between ICCC and JSPDT only grew stronger, and the summer expeditions continued every year into the

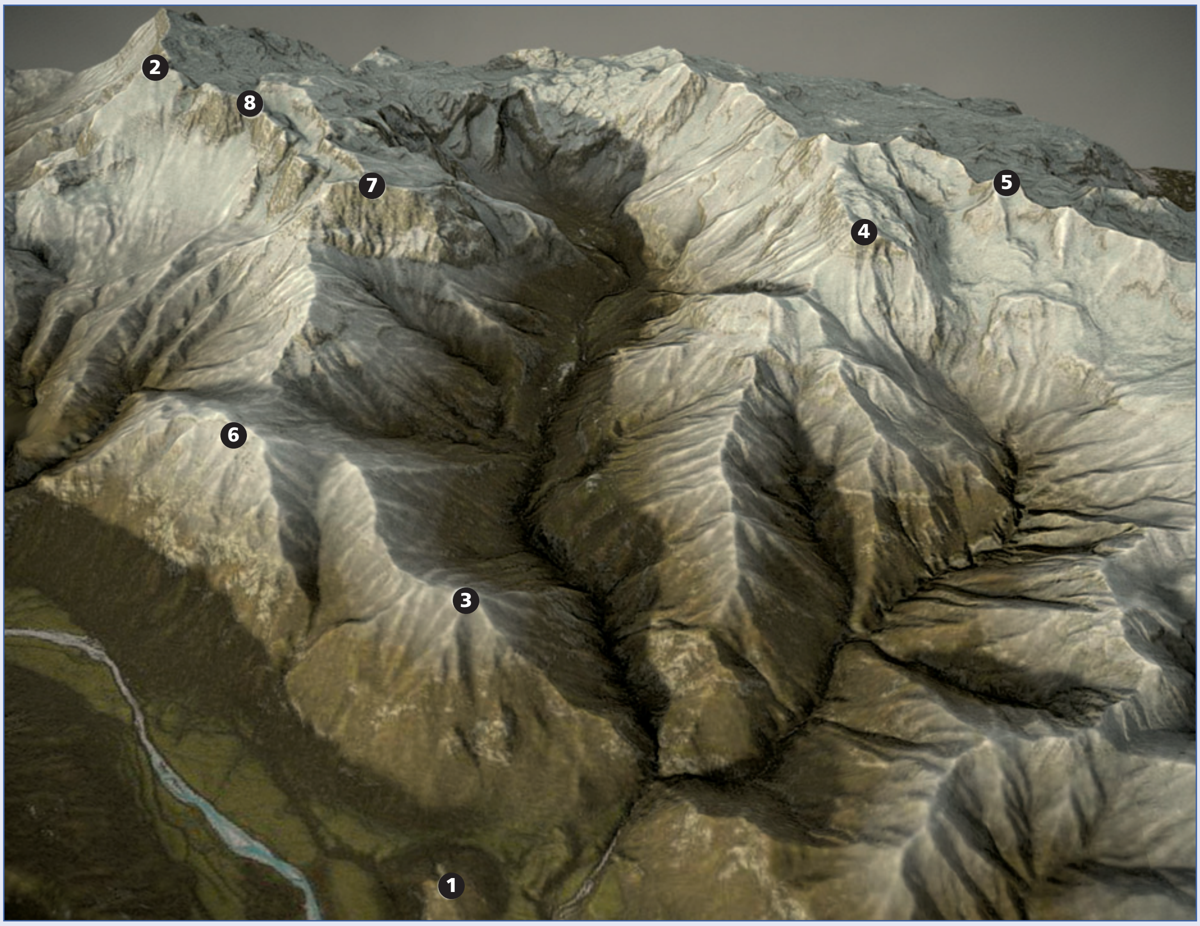

Fig. 1: 3-D surface model of the Tolminski Migovec massif. (1) Koslov Rob, (3) Vodil Vrh, (4) Tolminski Migovec, with in the background a range of NW-SE oriented peaks (Krn (2), Vrh nad Škrbino (5)). (6) Mrzli Vrh, (7) Rdeci Rob, (8) Batognica. Left of Tolminski Migovec is the river Tolminka valley, while to the right is the Zadlaščica. Both rivers join the river Soča at the town of Tolmin. The view is to the north.

Abb. 1: 3D-Darstellung des Tolminski Migovec Massivs. (1) Koslov Rob, (3) Vodil Vrh, (4) Tolminski Migovec. Im Hintergrund sind die Gipfel des Krn (2) und Vhr nad Škrbino (5) zu sehen. (6) Mrzli Vrh, (7) Rdeci Rob, (8) Batognica. Links des Tolminki Migovec liegt das Tolminka-Tal und rechts fließt der Zadlaščica-Fluss. Beide sind Soča-Nebenflüsse und vereinigen sich in der Stadt Tolmin. Blickrichtung Nord. Modell: Peter Leban

new millenium. Other entrances into the mountain were also discovered and explored, to be finally connected to Sistem Migovec in 2012 and 2015. To date, the cave is 41.8 km long and 972 m deep, making it the longest and one of the ten deepest cave systems in Slovenia (Možnic, 2018).

Geographic setting

Tolminski Migovec is located on the western border of the Triglav National Park, in the northwest corner of Slovenia (Fig. 2). To the south west of the massif runs the river Soča, featuring in Ernest Hemingway's ”Farewell to Arms“, a large blue green river taking its source further north in the Trenta valley. The mountain belongs to a broad chain of peaks – Krn (2244 m), Tolminski Kuk (2086 m), Vogel (1922 m) – running from Kobarid to the NW and decreasing in elevation, towards Podbrdo. Northward of this chain lies the high-altitude plateau of Komna (1800-2000 m) and the waterfall resurgence of the Savica river, which forms the main affluent of Lake Bohinj and belongs to the Danube watershed. South- and westward of the chain lie lower hills and eventually the bay of the Adriatic.

The water from precipitation on the Julian Alps is thus shared predominantly by the Soča and Sava river basins. Because of its high relief, the area from Tolmin up to Kanin receives high annual precipitation (2500 to 3000 mm/yr), with a large proportion of it solid (Kunaver, 1982).

The area of exploration is more precisely located between the peaks of Tolminski Migovec and Tolminski Kuk, defining a broadly rectangular

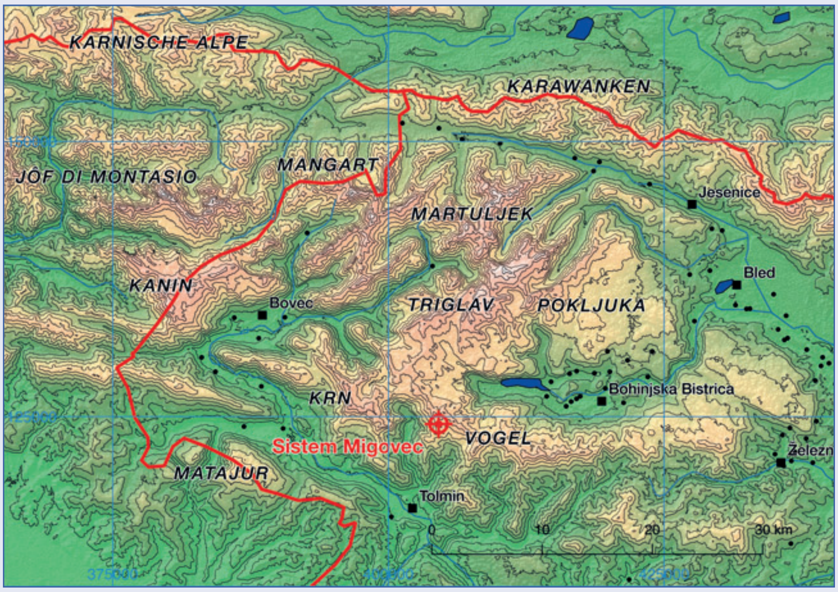

Fig. 2: Topographic map of the western Julian Alps showing neighbouring karst areas of Krn and Triglav. Slovene National Grid (EPSG: 3794).
Abb. 2: Topografische Karte der westlichen Julischen Alpen, worin die benachbarten Krn- und Triglav-Karstgebiete eingezeichnet wurden.

karstified plateau of 1 x 2 km at a mean elevation of 1850 m. The traditional western border of the exploration area is a N-S-line of cliffs dropping from the plateau altitude to a path ca. 300 m below (Fig. 3).
Further down, a second series of approx. 200 m cliffs reaches the floor of the valley of the Tolminka (Fig. 1). The source of the river is a resurgence through boulders on the NW corner of the valley which does not account for the full discharge of the stream. It is therefore hypothesised that further hidden resurgences are located at the base of the cliffs.
Immediately south of the Tolminski Migovec peak lies a series of alps (Planina Kal) with renovated sheperds' huts. One of them is co-owned by the JSPDT, providing easy access to the mountain via the signposted hiking trails. Vegetation on the plateau itself is dominated by dwarf pine and grasses (between 1550 m to 1900 m). Below, a deciduous forest of beech trees dominates the landscape, while above only grasses are found.
To reach the mountain by car, it is possible to drive on the tarmac road to the hamlet of Tolminske Ravne (924 m). From there a forest trail leads up to Planina Kal, the alpine meadow just south of Tolminski Migovec. The final ascent is a trail which snakes its way up the western slope of the mountain and upon reaching the plateau level, splits between a branch leading to Tolminski Kuk, and the other switching south to the summit of Tolminski Migovec.
The Migovec Plateau is far from flat, with many dolines, open shafts and sections of limestone pavement readily visible. Several grassy areas in the centre of the plateau provide adequate camping ground and one of the dolines serves as a base of operations with e.g. a kitchen, equipment store and water collection tarpaulins.

Climate

Long precipitation records from 1960 to 1990 indicate that the average annual precipitation in Tolmin (208 m a.s.l.), is 3412 mm/yr and the average annual evaporation is 538 mm/yr. The mean annual air temperature recorded in Krn (878 m a.s.l.) over that period was 7.9 °C. With a local lapse rate of –0.55 °C/100 m the MAAT at the elevation of Tolminski Migovec (1880 m) is 2.4 °C (ARSO, 2019).
Overall, the climate is temperate Mediterranean with mountainous influence. Water is sourced from the Adriatic Sea, and transported by dominant south-westerly winds. The orographic precipitation makes this one of the wettest regions in Slovenia, together with the Dinarides near the Croatian border. As a result, snow depths in excess of 7 m are locally recorded in the high-altitude plateaus of the region (Kunaver, 1982). Thus, the expected recharge of the karst aquifer should reach an annual maximum in mid to late spring, when the snow smelt coincides with a local precipitation maximum.

Geology

Tectonic setting

The Julian Alps belong to the easternmost sector of the Southern Alps (Bavec et al., 2004), which are bounded by the Friuli-Veneto basin to the west and the Pannonian basin to the east. South from the South Alpine

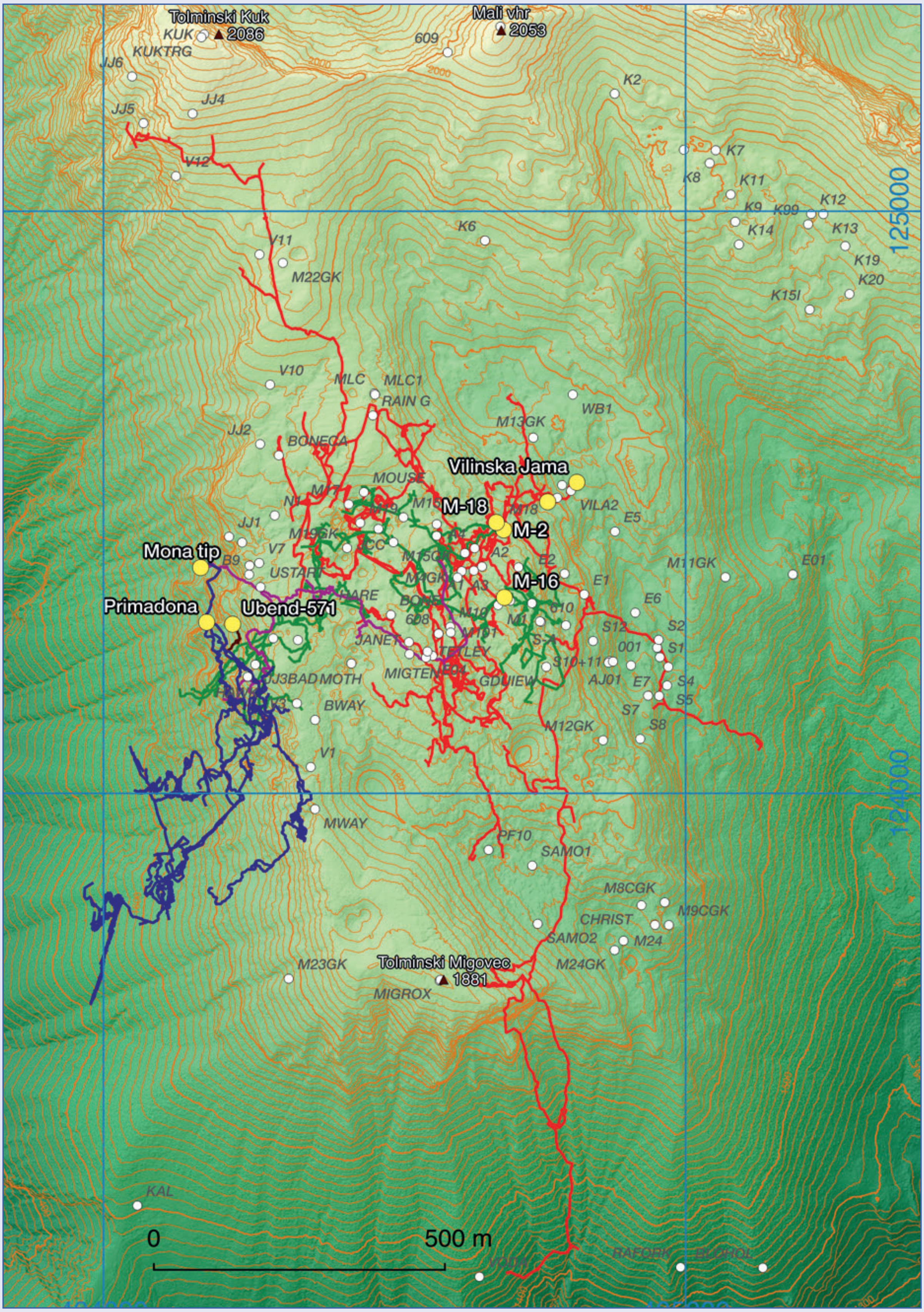

Fig. 3: Outline of Sistem Migovec over topographic map, Slovene National Grid (EPSG:3794).
Abb. 3: Grundriss des Migovec Höhlensystems. Kartengrundlage: Slowenisches Landesnetz (EPSG:3794).

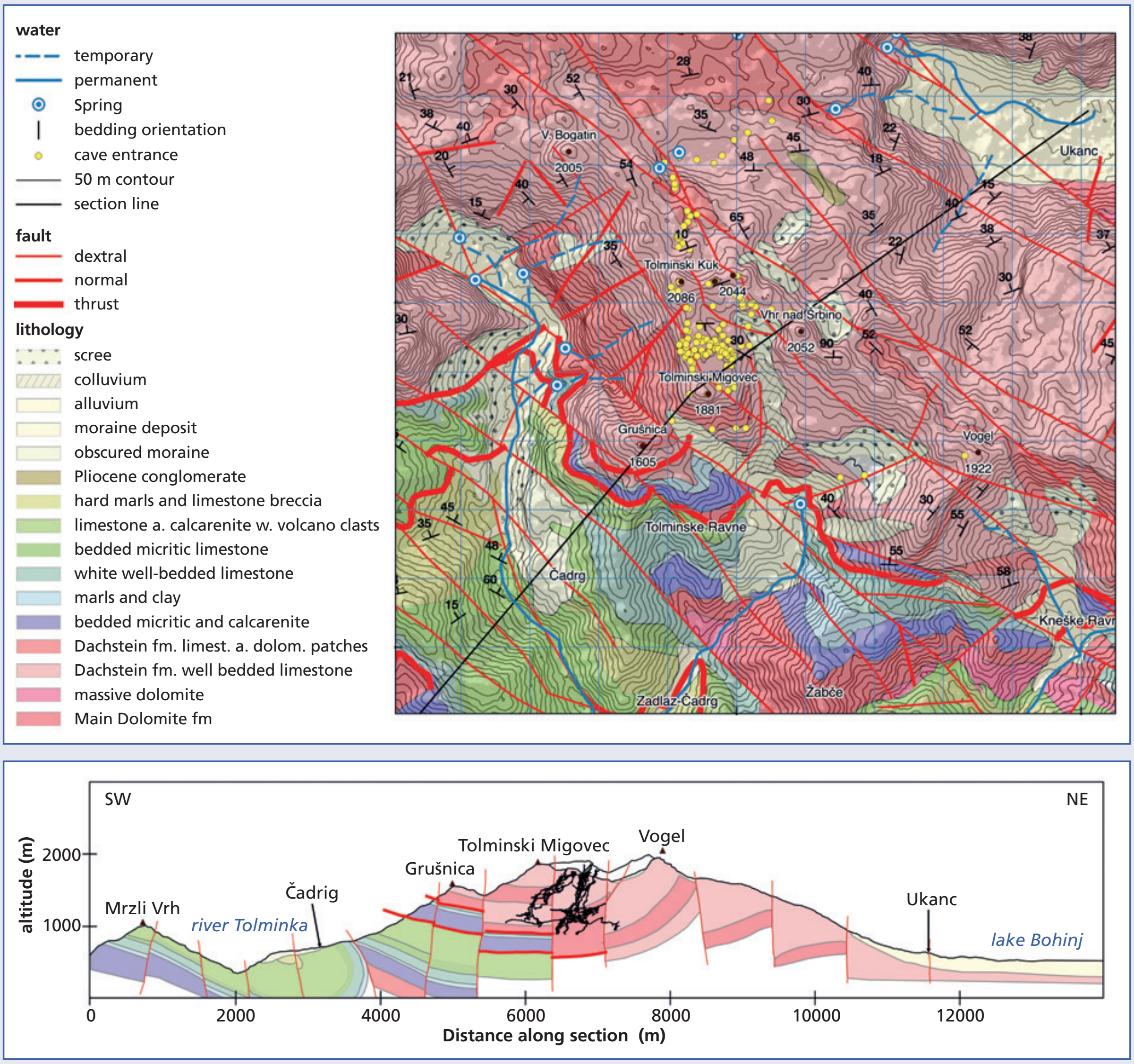

Fig. 4: Geological map and simplified section of the Migovec area, based on the geological map by Buser (1986). Slovene National Grid (EPSG: 3794).

Abb. 4: Geologische Karte und Schnitt des Migovec Gebiets, basierend auf der geologischen Karte von Buser (1986). Grundlage: Slowenisches Landesnetz (EPSG: 3794).

front lie the Dinarides. The impressive carbonate massif of the Julian Alps is characterised by high relief with valley floors located in 100–400 m and peaks in excess of 2000 m (Šmuc and Roži, 2009).

The structural deformation style of the region is a result of convergence of the Adria microplate indentor and the Eurasian plate at a rate of 2 mm/yr (Vrabec and Fodor, 2006; Burrato et al., 2008), which has led to the Alpine and Dinaric orogenesis. The structural geology of the area is governed first by thrust nappes (locally the Zlatna and Krn nappes), which brought Upper Triassic carbonate units over younger Jurassic and Cretaceous marls and limestone sequences. These high carbonate peaks form the backbone of the NW-SE oriented ridge to which Tolminski Migovec belongs (Fig. 4). Later strike-slip activity of Dinaric activity led to the development of long NW-SE active dextral faults (Grenerczy et al., 2005). The local area of Tolmin is shown to straddle such active faults as the Idrija and Ravne faults (Kastelic et al., 2008).

Lithology

The Migovec cave system is formed principally in well stratified and heavily faulted Dachstein Formation. These highly permeable and well karstified limestones were deposited on the Julian carbonate platform (Ogorelec & Buser, 1996). The underlying formation of bedded to massive Main Dolomite Formation out-

*Table 1: Terminal siphons of Sistem Migovec. Survex data from ICCC. *M-2 cave entrance.*
Tabelle 1: Endsiphone des Migovec Höhlensystems. Survex Daten: ICCC *Eingang der M-2 Höhle.

Cave region	Name	Elevation (m)	Depth below entrance (m)*	Date explored
M-16	Pencil sump	886	965	1998
	Good not Grand	895	956	1997
	Water Hope	884	967	1997
	Earthquake Way	917	934	1998
Vrtnarija	Watership Down	879	972	2012
	Aja?!	884	967	2014
	Lethe	988	863	2013

crops on the NE side of the Tolminka valley on the geological map of Tolmin (Buser,1986). This formation, less karstified than the overlying Dachstein Formation, acts as a local aquiclude (Audra, 2000; Turk et al., 2015). Overall, the underground drainage is to the west, in the direction of the Tolminka Valley. Though some dye tracer tests with fluorescine were carried out from 1997 to 2001, no conclusive link was drawn to either the river Tolminka to the west, Zadlaščica to the SE or Savica to the NE. Although the surface of the water table is likely complex as a result of the intersection of faulted blocks and local dolomite patches (Kunaver, 1982), it is likely that the flow is directed down-dip towards the Tolminka valley, 200 m below and 1 km away, rather than updip to the Zadlaščica resurgence, twice the distance away, with little hydraulic gradient. Therefore, we propose here that the roughly 9 km^2 catchment area of Tolminski Migovec contributes mostly to the Tolminka river (Fig. 5), with a calculated average contribution of 0.8 m^3/s, which amounts to ~10 % of the river's annual discharge. Some contribution to the Zadlaščica river to the south-west, and to the Bohinj Lake to the north cannot be excluded, however.

Fig. 5: The Tolminka river, with Tolminski Kuk in the background. The view is to the north.
Abb. 5: Der Tolminka Fluß, mit Tolminski Kuk im Hintergrund.
Foto: Tanguy Racine

Geomorphology

The Migovec Plateau is an undulating surface with an overall slope to the east. It is bounded to the west by an undulating line of cliffs. The degree of karstification across the plateau is unequal. Rockfall and scree production are locally dominant landscape modifiers. The prospection area covers a broad northern half of the plateau where the signs of limestone dissolution are clearly imprinted on the landscape (Fig. 6).

Shakehole dolines and closed depressions of varying size (5–50 m diameter) riddle the plateau surface. The majority are between 10 and 30 m deep and contain snow plugs. Shakeholes are distributed preferentially along lines of fractures and develop at the intersection of those fracture sets. The large closed depressions are theatre-shaped, with clear bedding control on the development of scree and cliff. This results in a pattern of depressions with 5–20 m rock cliffs to the south, and scree slopes to the north.

Bedding control of karst development is seen north of Tolminski Migovec, in an area of well developed Schichttreppen karst. Locally the bare limestone beds outcrop as a succession of inclined surfaces, where fractures were enlarged by bedrock dissolution to form deep, snow-filled fissures. The east slope of the Tolminski Migovec plateau is developed in a staircase pattern, with bedding surfaces sloping to the southwest and joints or vertical fractures surfaces sloping to the northeast.

Fig. 6: A closed depression on the Migovec Plateau, where the bedding dip and fold patterns controls the geometry of the snow pit. The differential erosion of the limestone strata leads thinly bedded, more heavily fractured horizons to provide a disproportionate amount of frost-shattered debris to the scree cone.
Abb. 6: Eine Schachtdoline auf dem Migovec-Plateau, deren Geometrie vom Schichteinfallen und dem Faltenmuster kontrolliert wird. Die unterschiedliche Erosion der Kalkschichten führt dazu, dass dünne Lagen überproportional zur Produktion von Frostschutt beitragen.
Foto: Jana Čarga

HISTORY OF EXPLORATION

Early exploration

Exploration on Migovec started in 1974, with small expeditions during weekends where members of the JSPDT would camp on top of the plateau and explore the various and ubiquitous vertical pits that riddle the surface of the mountain (Rejec, 2011). A total of 17 caves, numbered M-1 to M-17 were thus discovered and surveyed with an old army compass and home-made clinometer. Of special note is M-2 cave, also known as Kavka Jama, explored to a depth of –350 m as a series of deep vadose shafts, and where an underground camp was set up to allow exploration of the deeper passages. A succession of constrictions at the bottom of the cave were enlarged artificially but the next section proved to be too tight to follow. Interest shifted to M-16 cave, which, with a vertical development of –547 m, was deeper than M-2. M-16 ended in the impressive Galaktika chamber, the largest so far discovered in the system, with a floor area of ca. 5000 m² and an average height of 90 m. Another cave of interest, surveyed and registered on the Slovene Registry in 1983 is M-17 (Frigidare), a 98 m deep cave formed of several shafts open to the surface converging in one large ice rink chamber at ca. –50 m below the surface. The cave therefore hosts the largest known underground ice accumulation in the massif. Finally, it is during this early period that the JSPDT started to camp on top of the Migovec-plateau for as much as one week at a time, especially during the autumns of 1976 and 1977.

1994–2000, exploration of M-2, M-16 and M-18

In 1994, the brothers Jim and Mark Evans from Imperial College Caving Club visited for the first time the area around Migovec, with the help of local JSPDT cavers Andrej Fratnik, Simon Gaberšček and Dejan Ristič, who showed them the location of the known big caves of the plateau, at the time M-2 and M-16. During that summer the first of many expeditions took place on Migovec, with a team of eight cavers staying for a full six weeks on the mountain. Disappointingly, this first year of expedition did not yield impressive new entrances: lots of surface shafts were relocated and subsequently resurveyed.
The most notable discovery of 1994 was M-18, the cave of the *Torn T-shirt* (JSPDT, 2007). What started as just another entrance located less than 10 m away from M-2 ended after reaching 78 m depth in a narrow rift passage where the way on was far from obvious. Coming back in 1995, the attention of the Imperial College cavers was initially directed at other leads: small caves were fully explored on the fringes of the

plateau before a serious return to M-18 was planned. This time, the rift continued, followed by a succession of tight vertical drops that had to be hammered smooth to avoid the critical oversuit damage imparted by the tight, immature cave.

The big breakthrough occurred when instead of dropping yet another shaft, the exploring team swung over the pitch into a black void: the start of a breezy horizontal passage whose floor was covered with a thin black deposit, later called *NCB* (National Coal Board) passage. This passage continued for several hundred metres, leading to many different pitch series. With this new exciting finding, a first shallow underground camp was organised in the horizontal passage, which is located some 150 m below the surface.

The next year therefore led to continued attention on M-18. One particularly deep pitch proved to be the connection with M-2, the old cave. Another passage led to a second horizontal level at depth 250 m. The large tunnel (*Level 2)* also had many shafts waiting to be descended, but it was the traversing along the horizontal passage which enabled the connection with M-16 cave, and a much easier way into the deep parts of Sistem Migovec. Over the winter 1997, the Slovene cavers explored a pitch series to a depth of nearly 700 m, finding another likely spot for the underground camp (*Hotel Tolminka*). With the system showing no sign of reaching its end, expeditions became thus a regular staple of ICCC summers, cementing its members together. In the summer of that year, the deepest point so far was reached, at –967 m (Table 1), where the steeply inclined passage carried a stream to a sump. Shortly thereafter, two further sumps were discovered, lying at very similar depths.

Although these deep passages were very wet and a long way from even the new underground camp, this type of exploration continued for a couple of years, but the magic '1 km' mark was never broken. In the meantime, the high level leads of the system were systematically pushed: pitch series going to –500 m or beyond followed one after another, adding yet more length to the cave and providing true opportunities of exploration for the younger, more novice members of the club.

2000–2009, the three systems of Migovec

Surface exploration picked up in the 2000's, rewarded initially by the tremendous find of Vrtnarija (English: Gardeners' World cave). The entrance to this cave had already been noted during the early explorations, but a combination of better leads elsewhere and the necessity to dig out rocks for further progress meant it was not until 2000 that a first breakthrough was made possible. Small pitch followed small pitch until the explorers broke into much larger cave: a large 20 m diameter shaft named *Pico (P59)*, where a not-insignificant stream appeared. At the bottom, the draughty passage led on to a series of other large drops: *Tesselator* (P45), *Space Odyssey* (P30, P20), *Concorde* (P66), *Alchemy* (P32). These are clean washed vadose shafts with nearly circular cross-sections. Their floors were extremely smooth grey ledges which looked like concrete to the first explorers. In the year of its discovery, *Vrtnarija* had clocked up a depth of 343 m, and the way on was wide open: a 40 m undescended shaft.

From winter 2000 onwards, the JSPDT started exploring a new cave on the other side of the mountain. This cave was located mid-way through the cliff and only reached by climbing a steep slope, or abseiling from the top of the plateau. Here also, the discoveries went quickly although the cave was of a more horizontal nature, a way to –350 m was also found, with wide-open continuation. The following years JSPDT increased the depth of Primadona and stopped at –597 m, where the way on was extremely wet, and a long way from the surface. No camp had been set up in Primadona, and exploration shifted elsewhere in the system until 14 years later.

Back in Vrtnarija, the year 2001 brought a significant breakthrough. After many pushing trips, small pits followed one another to a final 50 m shaft, at the bottom of which, a large horizontal level was finally reached, whose depth was at –550 m. *Friendship Gallery* led for more than 400 m to the start of another large pitch; it was draughty, muddy and dry, and provided the ideal place for a new campsite. Over the years 2003 and 2004, underground camps were set up first in *Friendship Gallery*, then 100 m deeper to aid with the exploration of the rapidly expanding network of horizontal galleries found at this particular level. One branch led nearly 1km north into hitherto unexplored blank mountain, right underneath Tolminski Kuk, with the exploration stopping at *Colarado* sump, a perched siphon located at a depth of –794 m below the entrance of Vrtnarija.

The 2005 expedition focussed on a shallower side branch starting from the middle of *Pico* pitch, which provided the opportunity of new exploration for less experienced members of the expedition. The *Captain Kangaroo* branch turned out to be tight and difficult to push, but progress was made nonetheless in subsequent years. The fact that one part of the cave seemed to come close to a pitch in M-2, the old cave motivated many trips, as well as the expenditure of a large quantity ofequipment and manpower in order to forge a connection between Vrtnarija and the M2-M16-M18 system.

Table 2: Lengths and depths of different systems in Tolminski Migovec area at the end of Sledi Vetra 2012 expedition. Source: ICCC und JSPDT (2012).
Tabelle 2: Gesamtlänge der verschiedenen Höhlensysteme des Tolminski Migovecs am Ende der Sledi Vetra 2012-Expedition.

Cave system	Entrance	Depth (m)	Length (km)
sistem Migovec	M-2 kavkna jama M-16 M-18 jama strgane srajce	970	11,864
sistem Vrtnarija	Vrtnarija Vilinska jama	898	13,692
sistem Primadona	Primadona Mona tip U-bend 571	645	3,637

Over the years 2008 and 2009, much effort went into finding the connection, as the nearest passages were shown to be within about 30 m. As this branch was particularly tight and difficult, a shallow camp was set up in 2009 to enable cavers to spend more time working away at the connection. The side branch of *Captain Kangaroo* however led deeper in the mountain, and finally away from M-2. Eventually, after a very impressive 80 m pitch, the explorers entered a small meander and spotted a rusted spit. Upon entering the survey data in the mountain top computer, they discovered that they had found another way to a small meander located underneath *Friendship Gallery*. Thus, the exploration of this side branch came to a close, and plans were laid out once again for the exploration of Vrtnarija from the deep camp.
Going back a few years, from 2007 there was also interest in the potential new entrances both to the east and to the west of the Plateau. To the east, one entrance named Vilinska Jama was pushed for 100 m before being connected back to Vrtnarija at a high level. To the west and not 100 m north of the large entrance to Primadona, another likely hole was explored, which became known as Monatip. The cave began as a rather horizontal crawling passage, soon breaking into a series of small up and down climbs which led to a sizeable chamber with several ways on. The early explorers went down, following a narrow meander for a series of small drops. Initially, there was a lot of excitement for this cave, as it spear headed east into the mountain, in the direction of and at the same altitude as the existing horizontal levels of Sistem Migovec. Unfortunately, soon the canyon veered back to the south and then to the southwest, before connecting into Primadona cave at a relatively high level. Another cave called U-bend-571 also was connected to Primadona through the expansion of a very nasty squeeze, which only the slimest member of the team was able to pass before finding the original Primadona ropes on the other side. At this time, there were therefore three main systems under Tolminski Migovec: sistem Migovec in the centre, Vrtnarija to the east and Primadona-Mona tip to the west.

2010–2015, deep camping in Vrtnarija and pushing in Mona tip

A group of ICCC and JSPDT cavers with renewed interest for deep exploration rebuilt the camp in *Friendship Gallery* and started exploring another continuation of the gallery, quickly finding a parallel shaft and many new leads. One of them was led to the *Royal Albert Hall*, and many 100 m of horizontal, abandoned galleries of phreatic origin. This part of the cave was found to host panels covered in crystals of calcite and gypsum (Čarga, 2011). Exploration at this cave level eventually led to a connection with deep passages of Sistem Migovec in the summer of 2012, making the system just under 25 km long at the time (Table 2). For the first time, Sistem Migovec was the longest cave in Slovenia.
The depth of the cave was also increased to –972 m below the highest entrance (M-2) with the discovery of two deep siphons in Vrtnarija. *Watership Down* is a 5 m diameter sump pool, undived to this day, located at an altitude of 879 m a.s.l.
The cave was also significantly extended to the south, with the exploration of *Atlantis*, the only passage discovered so far where a dozen of 10–40 cm stalagmites, stalactites and helictites are found in the cave. Further south, the abandoned phreatic level extends nearly 1 km in the direction of Planina Kal, at an average altitude of 1100 m and comes within 250 m of the surface (Racine, 2019).
During this time, aid climbing in Mona tip cave led to the discovery of an abandoned horizontal level at 1730 m, which headed in the direction of Sistem Migovec, specifically for the horizontal levels discovered in 1995 and 1996, which had proved key to the

early connections. Perseverance over 2009-2015 eventually led to a key breakthrough and connection with *NCB* passage in October 2015, connecting the last of the three big systems under Migovec and raising the length of cave to over 35 km (Ristič & Fratnik, 2015).

2016–2018, a return to Primadona

Recent work on Migovec has focussed primarily on Primadona with the specific aim of resurveying and reevaluating the leads left from the 2000-2002 expeditions. In 2016, exploration was directed at a side branch which led to a series of 40-50 m shafts and culminated with the discovery of *Upside Down* chamber, the second biggest chamber in the system, and the connection of a horizontal passage (*What a Coincidence!*) with the old deep route. 2017 saw renewed interest in this old deep route, and many passages were found on another side branch which ended with an impassable breakdown area, with a strong draught disappearing between car-sized boulders. The unlikely discovery of yet another side branch (*Fenestrator*) opened up possibilities of exploration between Primadona and the rest of the system, in an area of blank mountain (Racine, 2017; ICCC & JSPDT, 2019).

A new underground camp was set up during the summer of 2018 to aid with exploration of the deep old route, which had been previously abandoned due to the amount of water and distance to the surface. This led to the discovery of another branch, a series of very small pits connected by a tight meander, which broke out into a 75 m tall rift named *Klic Globin*, the "Call of the Deep". The linear fault guided rift extends for 250 m to the SSW and remains an open lead, which carries a significant stream (Racine, 2018). Aside from this rift, a muddy abandoned phreatic passage, also decorated with panels of calcite wall crystals was discovered. This led for about 200 m to a parallel rift and shaft series, which it itself was pushed to a depth of -630 m below the entrance of Primadona making it the deepest part of this cave area. During the 2018 Klic Globin expedition, the cave system grew over 40 km long (Možnic, 2018).

SPELEOGENESIS

The cave system under Tolminski Migovec forms a complex 3D network of connected passages (Fig. 7). During its exploration it has been divided in a number of zones, which are believed to reflect different styles of genesis. Broadly, two main styles of passages have been explored: horizontal and sub-horizontal passages, which often exhibit signs of phreatic origin and vertical to steeply inclined pitches, extending for the greater part of 970 m vertical development of the cave. All passages show some degree of subsequent breakdown modifications, which generates more or less impressive rooms and chambers, the biggest of which is up to 90 m tall and 100 m long.

Horizontal cave levels

Several horizontal levels were recognised early in the exploration of the cave with two high altitude levels in the 'old' system (M-2/M-16/M-18) and two deeper levels in Vrtnarija (Fig. 8). Recent exploration in the Primadona section of the system has added complexity to this simple categorisation. Short sections (< 100 m) of horizontal passage of clear phreatic origin have been explored across an altitudinal range (between 1200 and 1600 m). By contrast, the other systems (Vrtnarija, M-16), conspicuously lack any sort of horizontal development at these altitudes. As a testament to their importance in the focus of exploration, the greater part of connections between separate shaft systems have occurred along one of these major and minor horizontal levels.

Level 1 – 1710–1730 m

Passages formed in phreatic conditions, which exhibit a typically elliptical cross-section are readily seen in Sistem Migovec. First to be discovered is *NCB* passage, whose morphology is unmistakably of phreatic origin (Fig. 9), with subsequent breakdown modification. The passage of the highest level is between 2 to 5 m high and between 5-8 m wide. The north branch of this passage, first discovered in 1995 from M-18, trends sub-horizontally at SE for distance of over 400 m. After a 90° turn down-dip to SW, the passage trend turns again along the strike of the beds, to the NW, with subhorizontal parts broken into different segments at varying elevations, eventually ending at the Mona tip entrance, on the side of the plateau. These elevation jumps and drops are likely due to the position of "cave forming" horizons shifted by fault block movement. The relative chronology of fault movement and passage formation is obscured at the critical junctions, due to later vadose pitch invasion.

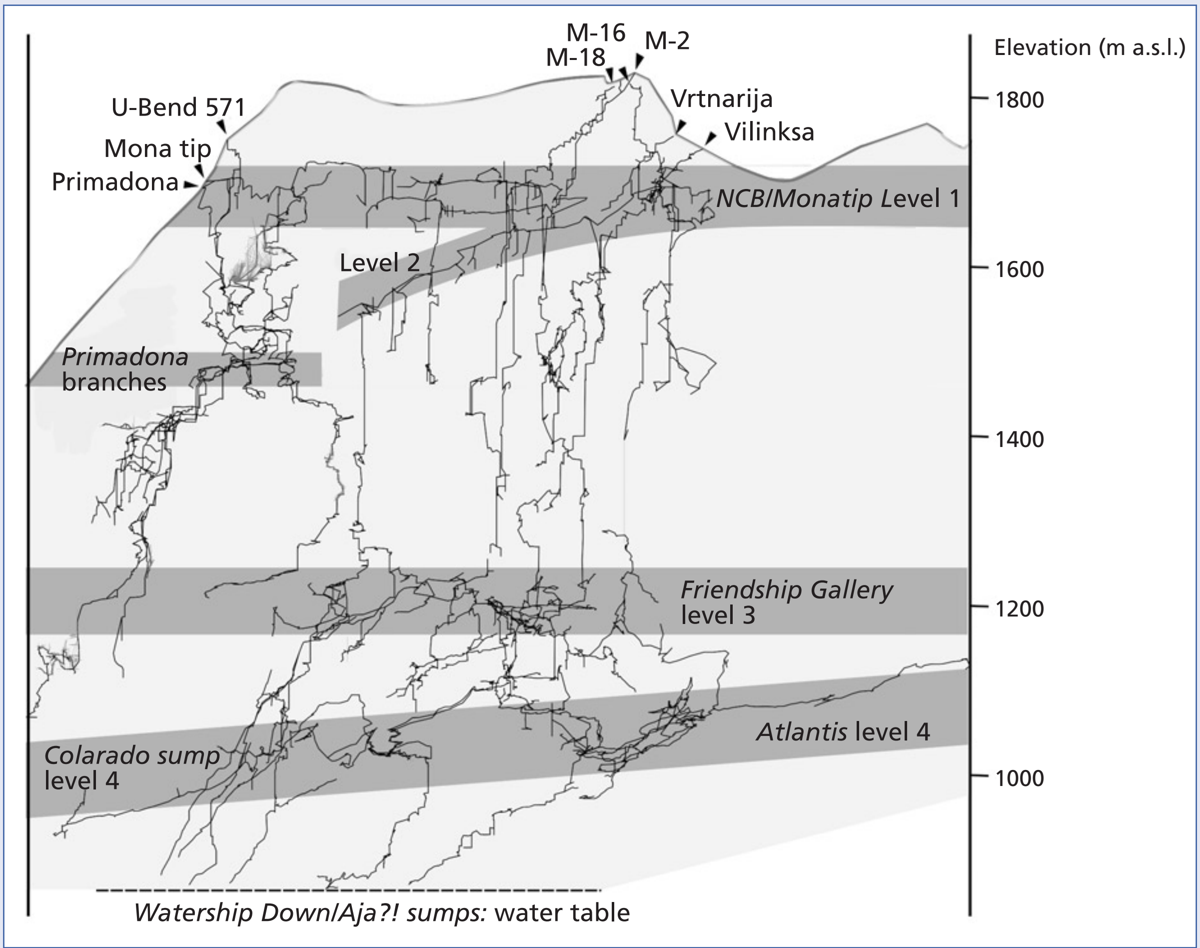

Fig. 7: E-W projection of System Migovec showing the different horizontal cave levels and different shaft and canyon series over a depth of 972 m. Survex data from ICCC.
Abb. 7: E-W Aufriss des Migovec Höhlensystems mit den verschiedenen horizontalen Höhlenniveaus und Schacht- bzw. Canyon-Serien mit einer Tiefenerstreckung von 972 m.

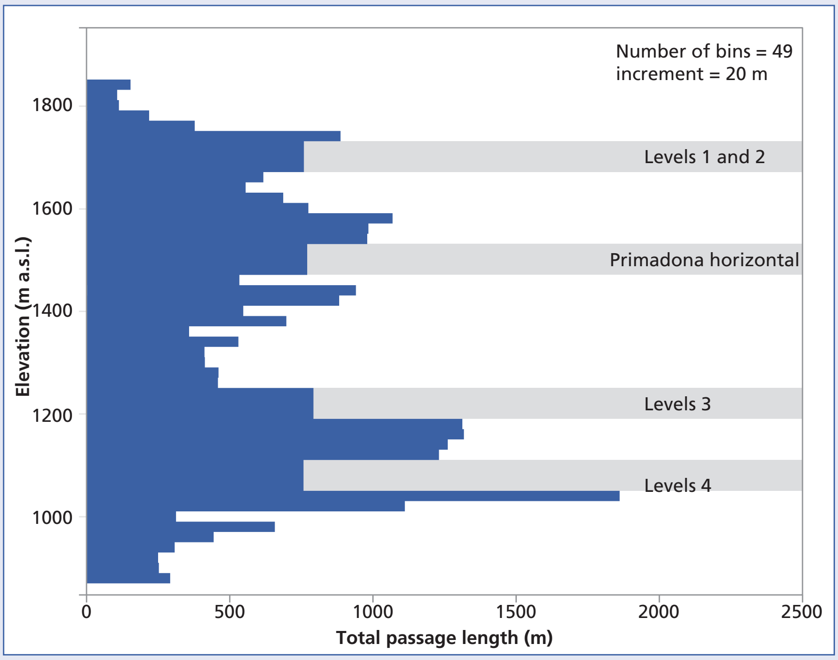

Fig. 8: Total length of all cave passage plotted against elevation. Bin size is 20 m. Survex data: ICCC & JSPDT (2019).
Abb. 8: Gesamtlänge der Höhlengänge in Abhängigkeit von der Seehöhe. Intervallgröße ist 20 m.

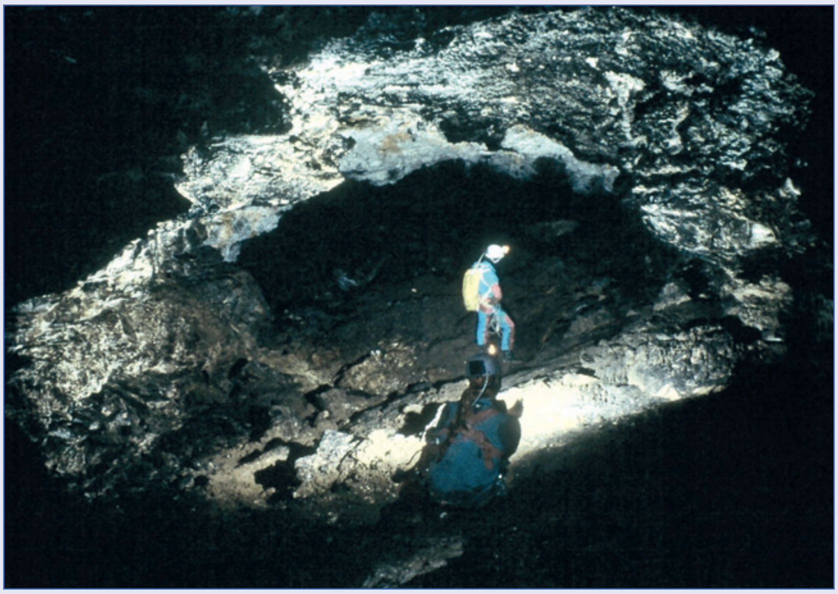

Fig. 9: NCB passage is the highest horizontal level (Level 1), with an average elevation of 1720 m.
Abb. 9: Der NCB-Gang ist das mit 1720 m Seehöhe höchste Höhlenniveau (Ebene 1).
Foto: JSPDT Archiv

Level 2 – 1700–1710 m

Level 2 provides the connection from M-18/M-2 to M-16 and is the cave passage with the largest dimensions to date. It is up to 15 m wide in places, with the ceiling usually 5 m above the boulder floor, but reaching heights of 30 m in the western end of *Exhibition Road*. The passage follows the strike of the bedding, being parallel to *Level 1*, but at greater depth. It is an inclined passage, with its lower end starting at 1560 m elevation, and its upper end *Hotline* at 1720 m, which is similar to *NCB*. This section of passage is very draughty and observations of condensation on the walls and in the air are frequent. Like *NCB*, the hypothesised phreatic origin of this level is obscured by widespread breakdown, and along its length, the passage is intercepted by a dozen of vadose shafts, some blind, others leading to -500 m in separate shaft series.

Level 3 – 1220–1240 m

This level is specific to Vrtnarija, and exemplified by *Friendship Gallery* (Fig. 7), which is up to 5 m wide and 5 m tall, with an elliptical cross-section of clear phreatic origin. Vadose entrenchment is localised to only a few sections of the passage, e.g. the connection with *Captain Kangaroo* branch at a junction roughly in the middle of the passage. Contrary to the levels described above, silty-loam deposits are abundant in this passage, reaching a local thickness of up to 1 m. At the locality of *Zimmer* pitch, the relative chronology is clear. *Friendship Gallery* formed as a phreatic gallery, later infilled with silty loam, presumably of glacial origin. As the water-table dropped, this passage entered the vadose region, which led to entrenchment along the inclined bend before a final episode of vadose shaft downcutting, which intercepted and cut in half *Friendship Gallery*.

Level 3 extends roughly at an elevation of 1220 m subhorizontally, connecting the deep shaft series of Vrtnarija and M-16. On the majority of passages, a metre thick or more of grey to brown silty loam sediment is present on the floor, while the upper halves are well-decorated in patches. X-Ray fluorescence spectroscropy revealed the presence of dominant gypsum and nearly pure hydromagnesite powder (Čarga, personal communication). In places, the passage morphology exhibits a more pronounced upward dissolution, which can be explained by differences in bulk solubility differences between two strata, and the paragenetic (anti-gravitative) dissolution due to sediments covering the floor of the passages. In the Primadona region, recent exploration (2018) has revealed the presence of passages with very similar morphologies at an altitude of 1160 m.

Level 4 – 1030–1120 m

Level 4 is the deepest abandoned phreatic level, the most extensive with regards to metres of passage. It extends between the pool of *Colarado Sump* and the apex of *Smash* passage and contains the decorated Atlantis passage (Fig. 10). The former was in 2004 believed to be a perched siphon, but revealed to be a 14 m long pool with about 40 cm airspace in 2015. The morphology of the passage forms typical phreatic loops, with an elevation range of 70-80 m, which follows the bedding plane of the Dachstein limestone.

Fig. 10: Atlantis passage, located at -757 m depth in Vrtnarija exhibits the typical elliptical shape of an abandoned phreatic passage. The upper right corner exhibits paragenetic morphologies, which are indicative of a near total sediment infill, presumably of glacial origin. The grey silty loam deposited in the passage was then flushed out. The stalagmites are between 5 and 40 cm tall, and some are clearly embedded in the sediment, perhaps arguing that they were deposited before the last glacial period. Stalactites are short and covered with helictites.
Abb. 10: Der Atlantis Gang auf -757 m weist ein typisches elliptisches Querprofil eines ehemaligen phreatischen Ganges auf, in dem nachträglich grauer, siltiger Lehm, der vermutlich glazialer Entstehung ist, abgelagert wurde. Die Stalagmiten erreichen eine Höhe von 5 bis 40 cm, und manche sind im Sediment eingelagert, was darauf hinweisen könnte, dass deren Wachstum vor der letzten Eiszeit stattfand. Die Stalaktiten sind kurz und mit Excentriques geschmückt. Foto: Jana Čarga

In cave observations reveal that the phreatic loops development is largely constrained by a bedding plane orientations.
The abandoned phreatic loops located in the south exhibit amplitudes of 30-40 m between high and low points. The orientation of the southern extensions is consistent with the intersection of the bedding plane and the local dominant faulting trend. One such fault with pronounced topographic expression, a surface canyon, is parallel to the deep Vrtnarija level (Fig. 3). Along that fault was Coincidence Cave discovered in 2015. Recent digging has revealed a strongly draughting cave 60 m deep (with exploration ongoing), heading north towards the main system. If Coincidence Cave is connected to Sistem Migovec, it will become the lowest entrance so far (altitude: 1341 m).

In the southern extensions, and particularly one passage formed along a large former phreatic ramp known as *Helm's Deep* chamber, a laminated sequence of silty loam is observed today with a thickness in excess of 10 m.

Passages of phreatic origin in Primadona

Locally, a high density of near horizontal passages of with preserved phreatic morphologies can be found in the Primadona system, which is located 300 m to the west of the main system. No counterpart to these very minor cave levels have yet been identified in the rest of the system at a similar altitude, so they are treated separately here. The very deepest passages found in 2018 however (e.g. *Moonraker*, Fig. 11a) are at the same altitude as Level 3 (e.g. *Friendship Gallery*, Fig. 11b).

Fig. 11a: Sediment infill on the bottom half of a palaeo-phreatic tube, in Moonraker, Primadona.
Abb. 11a: Sedimentfüllung in der unteren Hälfte einer paläophreatischen Röhre (Moonraker Gang, Primadona).
Foto: Tanguy Racine

Fig. 11b: Zimmer (P50) in Vrtnarija is a vadose invasion shaft cutting the previous cave passage (Friendship Gallery), a cave level of phreatic origin.
Abb. 11b: Das Zimmer in der Vrtnarija Höhle ist ein 50 m tiefer vadoser Schacht, der einen paläophreatischen Gang (Friendship Gallery) anschneidet. Foto: Jarvist Frost

Fig. 11c: Jack of Hearts siphon, a short section of completely flooded passage. The water is thought to reappear as an inlet of Hallelujah streamway, 50 m south.
Abb. 11c: Der Jack of Hearts Siphon. Es wird vermutet, dass das Wasser 50 m weiter südlich als Teil des Hallelujah streamway wieder austritt. Foto: Jarvist Frost

Fig. 11d: Section of passage between two vertical pits in the Ajdovščina region. The passage profile is characterised by an elliptical roof of phreatic origin, and floor trench with coarse sand to pebble deposits denoting vadose invasion.
Abb. 11d: Teil des Ganges zwischen zwei Schächten des Ajdovščina Bereichs. Der Querschnitt weist eine elliptische Form auf, die einen phreatischen Ursprung anzeigt. Durch das spätere vadose Einschneiden eines Gerinnes wurde grobkörniger Sand und Kies abgelagert. Foto: Jarvist Frost

Fig. 12: Pico pitch, with its 60 m height an impressive shaft located at depth -150 m below the entrance of Vrtnarija, the first of a series of pitches of similar size, which lead almost directly to the Friendship Gallery horizontal level.
Abb. 12: Der Pico-Schacht ist mit 60 m Tiefe ein beeindruckender Teil des Vrtnarija Eingangteiles, der erste einer Folge von Schächten ähnlicher Dimension, die fast direkt zum horizontalen Niveau der Friendship Gallery führen. Foto: Jarvist Frost

At an altitude of 1510–1520 m, a network of branching sub-horizontal passages forms the three main branches of Primadona, namely *Stara Jama* (the "old" cave explored in 2000), *Povezava* ("connection" branch) and *Galerija*. These are intensely interconnected and a half-ellipse remnant is often visible in the roof of the cave passage. In places a >2 m thick sedimentary cover of fine conglomerates and coarse sandy lenses in a clay matrix are visible.

At the altitude of 1430–1470 m, a remarkable knickpoint is observed in the three deep branches of Primadona; both active stream meanders of *Jacks of Hearts* (Fig. 11c) and inactive passages *Plumbers' Paradise*, *Karstaway* and *Déjà Vu* (Fig. 11d) conserve phreatic morphologies in the ceilings, and the underlying vadose streams have a marked shallow gradient. Locally, some small 1 m diameter abandoned phreatic tubes with little or no vadose incision are preserved (*Alabaster*, *Dysentry*). Usually, the tube development along a perpendicular set of fractures is easily recognisable.

Vadose overprint

Vertical shafts

Most vertical shafts in Sistem Migovec follow subvertical faults. The vast majority exhibit vadose morphologies e.g. water-film corrosion scallops in

Fig. 13: Helm's Deep Chamber in Vrtnarija cave contains thick and partly layered deposits of fine-grained sediments.
Abb. 13: Die Helm's Deep Chamber in der Vrtnarija Höhle weist mächtige und teilweise geschichtete Feinsedimente auf.
Foto: Rhys Tyers

vertical of overhanging sections of wall. In almost all cases, the guiding sub-vertical fracture is readily observable underground and the long axis of the shaft cross-section is oriented along such a plane (Fig. 12). Where active, the amount of water encountered in the shafts varies from a film on the walls to small drips, to small waterfalls (very occasionally with summer discharges > 0.02 m^3/s). Abandoned phreatic shafts could be observed in the very southern extensions of Sistem Migovec. One particular shaft (*Final draft*) is oriented on a fault plane dipping at 60° to the west and measures about 5 m diameter for a total height of 30 m.

Walls flutes and rills, with amplitudes between 1–10 cm and lengths reach upwards of 5 m. Due to the well-bedded nature of the rock, they are usually confined to the 2–3 m thick grey limestone horizons, ending sharply at overhanging ledges.

The bottom of the shafts deeper than 10 m is usually obscured by a layer of breakdown, with angular blocks reaching sizes upwards of 10 m in length in the larger pits. A notable exception is the Vrtnarija shaft series between 1400 and 1560 m, where clean, flat ledges with small pools of water are observed.

Meanders and streamways

Passages with perennial streams are few in Sistem Migovec. Those which have been discovered usually contain streams with normal summer discharge rarely exceeding 2 L/s. Usually, it is not possible to follow those streams for a great distance as they are broken up by vadose pitches, or because the enterable passable is found high-up in the now-abandoned dry passages above.

In the deepest M-16 and Vrtnarija passages, streams ending at sump pools are often preceded by a 60° descent along a tectonic fracture. These passages usually contain enough water so that their exploration can only be safely conducted during the winter dry season.

One noteworthy streamway is located at an altitude of 1210 m in *Vrtnarija*, i.e. roughly the same altitude as the Level 3. For a distance of nearly 300 m (*Push Your Luck, Cuckoo's nest*, gradient: 13 %), a stream with a rough discharge of 1 L/s flows northwards in a passage with characteristic keyhole cross-section. Banks of small calcite and haematite pebbles in a clay-grade matrix lie on the ledges of large bends. This sub-horizontal stream passage (between 1210 and 1170 m a.s.l.) was presumably developed a vadose entrenchment of the higher-level abandoned phreatic tube. The stream continues uninterupted down a series of small pitches (*Hydrophobia*, from 1170 to 1145 m asl.) before a 170 m long shallow gradient section between 1145 and 1130 m (*Gravity, Highway 32*, gradient: 8 %), which marks the beginning of Level 4. These rare sub-horizontal sections of this large stream (by Migovec standards) are likely due to lithological control, as the local bedding is nearly horizontal.

Local dolomitic aquicludes are also important in controlling the hydrology of the Primadona sector of the cave. In the region of *Galerija*, four separate sumps are found within a radius of 50 m, at an altitude of 1460 m. The water from these separate minor streams is presumed to be collected into the *Hallelujah* streamway.

Fig. 14: The Déjà Vu passage in Primadona cave contains remnants of a poorly sorted conglomerate dominated by limestone pebbles.
Abb. 14: Der Déjà Vu Gang in der Primadonahöhle führt Reste eines schlecht sortierten Konglomerats, dominiert von Klasten aus hellem Kalkstein. Foto: Jarvist Frost

Clastic sediments

Sediments under Tolminski Migovec are commonplace in the horizontal sections of cave. In steep gradient meanders, or shaft series they tend to be washed out by flood waters or obscured by breakdown. The largest and most consistent accumulations of brown-red silty loam are found in the Levels 3 and 4, where a thickness of up to two metres is reached. Layering is not always obvious, except where a natural cross-section has been carved into the sedimentary succession (e.g. *Helms' Deep* chamber, Fig. 13).

Conglomerate lenses and very coarse sands are found chiefly in the upper levels of Primadona, and occur either as passage filling successions many metres thick (e.g. *Galerija*), or as consolidated ledges on the sides of a vadose meander (e.g. *Dystentry, Déjà Vu*, Fig. 14). Other pebble accumulations are found at the bottom of palaeo-phreatic loops in Vrtnarija (e.g. *Potato, Lazarus* passages); a medium pebble grade is reached. These conglomerates are derived locally from the Dachstein carbonate sequence. Other clasts include subrounded quartz grains and rounded black lithics (<2 vol.%, diameter: 2 to 10 mm). Bean ore (diameter: up to 2 mm) is a very minor component of the sediment here, but it is locally present in protected alcoves of vadose passages. The conglomerate and the walls are covered by a mottled pattern of brown clay piles. Sands and silt banks are globally associated with the nearby presence of sumps and are presumably deposited during the final stages of a flood pulse. They are useful trackers of the height of the epiphreatic zone. Locally this upper flood line tracks a water level rise on the order of tens of metres (e.g. at *Watership Down*, the sump found at the deepest point of the system). Haematite and bean ore are not uncommonly associated with conglomeratic lenses, in places such as M2 (*Fratnik's Treasure Trove*, depth 127 m), Vrtnarija (*Push your Luck* depth 510 m) and Primadona (*Povezava* branch, depth 330 m). The grains are usually no more than 5 mm in diameter.

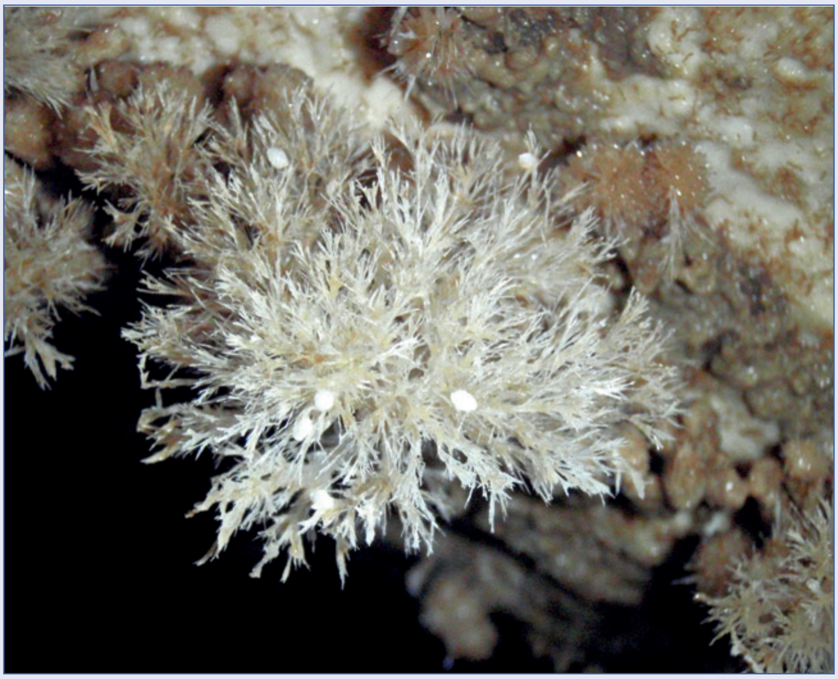

Fig. 15: Aragonite needles from Palace of King Minos (Level 3).
Abb. 15: Aragonitnadeln im Gang Palace of King Minos (3. Ebene).
Foto: Iztok Možir

Speleothems

Sistem Migovec is poor in speleothems. A section of the *Atlantis* passage hosts the only dozen of noteworthy stalagmites (Fig. 9). Stalactites are likewise mostly absent, excepting *Atlantis* and a couple of other places in either levels 3 or 4. Some pre-date the deposition of loam. Calcite popcorn is the most notable and consistent decoration, but it is also globally restricted to the deep levels of Vrtnarija and Primadona.

Gypsum is found in patches, often associated with aragonite needles (Fig. 15). X-ray diffraction analysis reavealed that hydromagnesite aggregates are relatively common on cave walls and floors, together with calcite popcorn. Such aggregates are found in Vrtnarija and Primadona.

OUTLOOK

Recent explorations have focussed on extending the depth of Primadona. This is likely to continue in the future thanks to the promising leads left in this area. As there are still >200 m to go before reaching the local watertable, we will aim to follow the newly found streams (e.g. *The Aqueduct*) and find the terminal siphons there. The karstic area to the north of Tolminski Kuk remains underexplored. One small cave (N9) is still ongoing, and there are numerous blowing holes in winter, which have not all be explored. If the >40 km of cave in 1 km^3 of Migovec are anything to go by, the potential for other deep alpine systems north of Kuk is enormous.

Research projects are ongoing to determine the age of the ice accumulations in M-17 cave and monitor the air temperatures/humidity variations in the well ventilated Level 2 passages. Finally the summer 2019 will see a new dye tracing project at the sump of *True Adventures*, the northernmost passage of Sistem Migovec.

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