

## Article

# The Subterranean Fauna of Križna Jama, Slovenia

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**Abstract:** The karstic cave Križna jama in the South Western part of Slovenia is one of the largest, well known and most beautiful Slovene water caves. The cave consists of more than 8 km of corridors with impressive halls, colossal dripstone formations, a subterranean river and numerous lakes. Considering the subterranean fauna, Križna jama has been identified amongst the richest caves in the world. So far, 60 troglobionts, the obligate subterranean species among them 32 aquatic and 28 terrestrial taxa have been recorded and documented. Križna jama has scientific importance, as well as ten subterranean taxa, which have been described based on specimens from this cave. Despite Križna jama is relatively well-studied, new recent unexpected findings are promising. Thus, further discoveries of specialized subterranean species in the cave are expected.

**Keywords:** caves; Križna jama; biospeleology; subterranean biodiversity; hotspots; troglobiont; checklist



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## 1. Introduction

Križna jama (registered in Slovene Cave Cadaster, Cad. No. 65) is developed under the Križna gora (857 m) hill near the village Lož in the South Western part of Slovenia. It is one of the largest, well known and most beautiful Slovene water caves. Due to its natural beauty, it has been promoted in the Slovene edition of National Geographic magazine [1]. In the first global subterranean biodiversity comparative study [2], Križna jama was listed among the richest caves of the Dinaric range. The cave consists of 8273 m of corridors with impressive halls, colossal dripstone formations, a subterranean river and many lakes (Figure 1). The main passage, called Jezerski or Glavni rov, located approximately in the middle of the cave, at a spot named “Kalvarija”, bifurcates into two separate corridors: Pisani rov and Blatni rov or Blata (Figure 2). Cavers recently discovered some new unknown and still unmeasured passages (Troha A. per. comm.). The cave is mainly horizontal with a difference of only 32 m between the highest and the lowest point of the cave. The lowest drypoint is at the water level of the lakes in Kittl shafts or Kittlova brezna, where the subterranean river sinks into the passage that cannot be accessed.

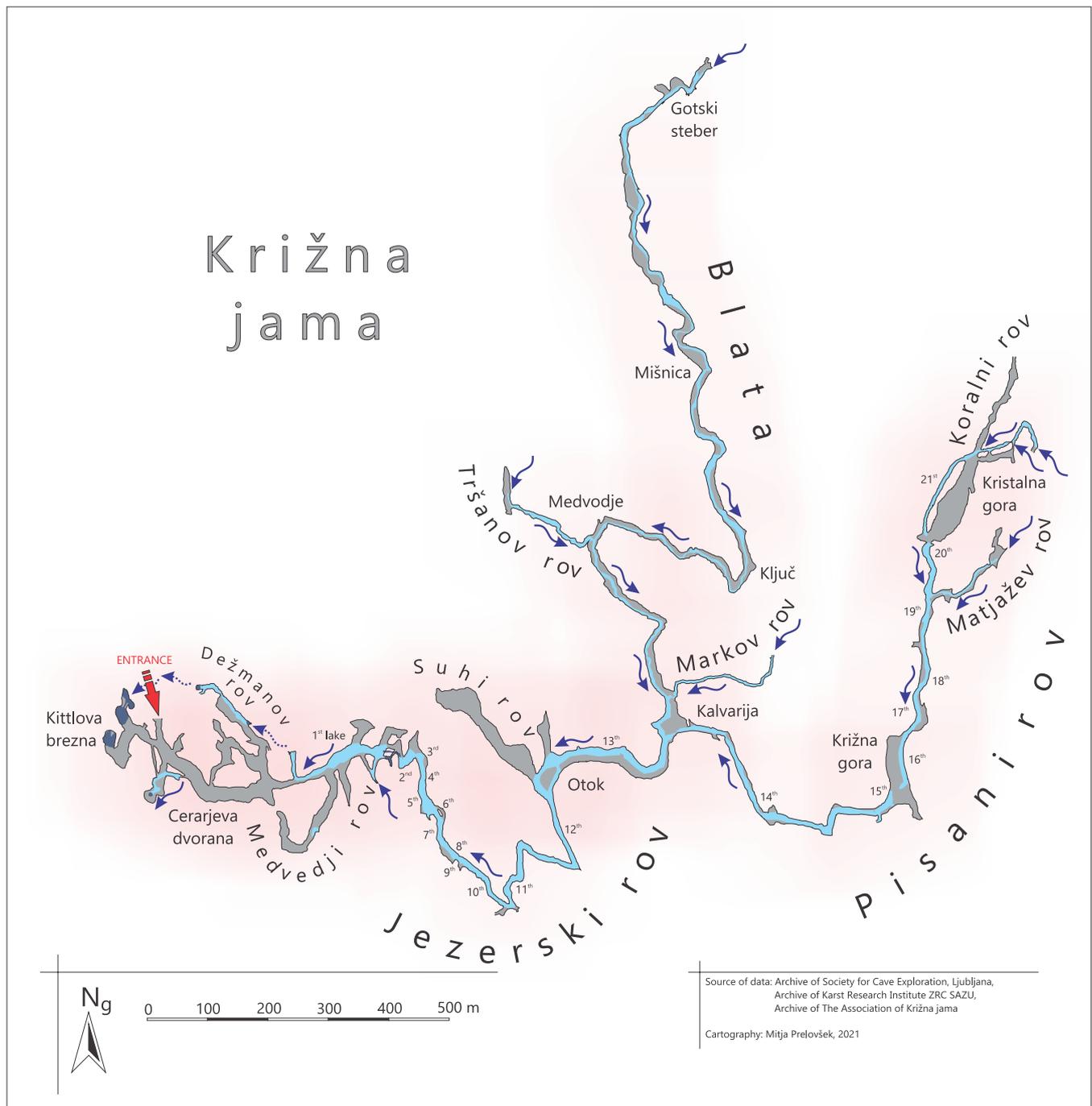
The unique features of Križna jama are its breathtaking clean and emerald green subterranean lakes (Figure 1). In two passages, Jezerski and Pisani rov, there are 22 lakes. Summing these to the lakes in Blatni rov, there are 45 lakes in Križna jama altogether. During the rainy seasons, the running water on its way through the karstic massif dissolves limestones and saturates with calcium carbonate. On its course through the cave, streams deposit carbonates on the riverbeds. Especially on its stream rapids, the permanently deposited sinter creates rimstone barriers that dam and accumulate numerous lakes. An average rate of sinter deposition in Križna jama is estimated to be approx. 0.256 mm per year [3]. From a geological and hydrological point of view, Križna jama is located in a syncline between the Bloke plateau and the Idrija fault zone, where the karstic Ljubljana river flows through a series of karst poljes. It lies within the aquifer of the triangle formed by the Bloke plateau (720 m), the Cerknica polje (550 m) and the Loško polje (575 m).

The oldest rocks of the syncline are the Upper Triassic dolomites, while the youngest are the Upper Jurassic limestones. Between them, there are a series of limestone strata, with lenses or nests of dolomites. The syncline shows a relatively weak faulting but local faults, together with tectonised bedding planes, can guide the formation of some Križna jama passages [4,5].

During periods of low water levels, Križna jama is mainly characterised by the flow of percolated water from the nearby hilly karst area. When water levels are high, Križna jama drains a small extent of allogenic water from the Bloke plateau, mainly from the Bloščica and the Farovščica streams too [5]. Underground water courses and connections have been elucidated by a series of tracer tests [6,7]. The water flowing through Križna jama sinks near the cave entrance in the deep Kittl shaft or abyss which ends with a syphon and reapers downstream in the Štebrščica spring at the edge of the Cerknica polje [6]. Speleo-divers tried to follow the stream in the Kittl shaft in an attempt to find further subterranean connections. Passing the flooded syphons at the depth of 70 m however, appears to be technically too difficult. Instead, cavers in the attempt to find easier access to the subterranean cave passages, tried to find some hidden entrance on the surface. In a long-term effort after 200 h of digging, in 1991 cavers finally enlarged a small hole (known as Dihalnik v Grdem dolu). Until that time, only the edible dormice (*Glis glis*) have regularly used this small entrance. This new small entrance led to the discovery of additional 1415 m long virgin cave, popularly called “Križna jama 2”. Due to the fragile dripstone formations, this cave is extremely sensitive to visit. After proper investigation and measuring, this cave has been closed and strictly protected, with less than 30 cavers ever visited it. Although it is undoubtedly part of the same cave system, Križna jama 2 (registered in Slovene Cave Cadaster, Cad. No. 6286, as Dihalnik v Grdem dolu) is considered as a separate cave object from Križna jama.



**Figure 1.** The unique features of Križna jama are its breathtaking clean and emerald green subterranean lakes.



**Figure 2.** Plan of Križna jama. Archive of Karst Research Institute ZRC SAZU, cartography Mitja Prelovšek.

Križna jama crystal clean lakes and dripstone formations attracted numerous explorers, cavers and visitors early in the 20th century. Uncontrolled visits in the early time resulted in some damage of dripstone formations and local pollution of the cave. The local cavers soon closed the entrance and within a couple of volunteer actions successfully cleaned up the cave. Križna jama nowadays accepts about 10,000 guided visitors per year, but only a small part of the visitors are lucky enough to enjoy the beautiful lakes in the inner parts of the cave by boat. Due to the fragility of the sinter dripstones and the sensitivity of the cave, the number of guided visits is limited and strictly controlled.

## 2. Materials and Methods

To complete an updated list of troglobiotic fauna in Križna jama, we consulted the available literature. Species recognized as troglaphiles and troglloxenes are discussed in the text but not listed in Table 1. In searching for subterranean fauna reports in dispersed publications within the last, almost 200 years, we encountered difficulties concerning the different names used for Križna jama. In our review we recorded many different names, all referring to Križna jama: Mrzla jama am Fuss des Kreuzgebirges [8], Berühmte Grotte von Podlaz [9], Mrzla Jama [10], Krizna jama, ou Kreuzöhle sur le versant D. du Kreuzberg [11], Mrzla jama, á Blazka Poliza, distr. De Logatesc and Krizna jama/Kreuzhöhle/sur le Kreuzberg, près de Lass [12] and Kreuzberghöhle (1700 m N Laas and N Hang des Kreuzberges) [13]. Križna jama [14] cave should not be mistaken with another cave with a similar name—Mrzla jama pri Ložu (registered in Slovene Cave Cadaster, Cad. No. 79), located 1.7 km heading south. A third “Mrzla jama” cave (1.5 km heading north) is a small cave with a water stream called Mrzla jama pri Bločicah (registered in Slovene Cave Cadaster, Cad. No. 1176). The fauna of all these three caves is however similar or probably equal.

**Table 1.** An updated list of stygobiotic and troglobiotic species encountered in the Križna jama. Tb.—terrestrial (troglobiont), Stb.—aquatic (stygobiont), Stb. pop.—stygobiotic population, Tl.—type locality in Križna jama, new—new, unpublished data.

Taxonomic Group	Familia	Genus/Species/Subspecies	Status	References
Ciliata	Lagenophryidae	<i>Lagenophrys monolistræ</i> Stammer, 1935	Stb.	[14,15]
Turbellaria	Dendrocoelidae	<i>Dendrocoelum cf. spelaeum</i> (Kenk, 1924)	Stb.	[14]
Turbellaria	Scutariellidae	<i>Stygodyticola hadzii</i> Matjašič, 1958	Stb.	[14,16]
Gastropoda	Hydrobiidae	<i>Belgrandiella superior</i> Kuščer, 1932	Stb.	[14,17,18]
Gastropoda	Hydrobiidae	<i>Belgrandiella crucis</i> (Kuščer, 1928)	Stb., Tl.	[13,14,19]
Gastropoda	Hydrobiidae	<i>Belgrandiella schleschi</i> (Kuščer, 1932)	Stb., Tl.	[13,14,19]
Gastropoda	Hydrobiidae	<i>Hauffenia michleri</i> Kuščer, 1932	Stb.	[13,14,19]
Gastropoda	Moitessieriidae	<i>Phaladilhiopsis</i> sp.	Stb.	[14]
Gastropoda	Ellobiidae	<i>Zospeum exiguum</i> Kuščer, 1932	Stb., Tl.	[14,18–20]
Gastropoda	Ellobiidae	<i>Zospeum kusceri</i> A. J. Wagner, 1912	Tb.	[14,18,20]
Gastropoda	Ellobiidae	<i>Zospeum isselianum</i> Pollonera, 1887	Tb.	[14,18,20]
Oligochaeta	Haplotaxidae	<i>Delaya bureschi</i> (Michaelsen, 1925)	Stb.	[14]
Oligochaeta	Lumbriculidae	<i>Trichodrilus strandi</i> Hrabe, 1936	Stb.	[14]
Oligochaeta	Lumbriculidae	<i>Trichodrilus ptujensis</i> Hrabe, 1963	Stb.	[14]
Oligochaeta	Lumbriculidae	<i>Trichodrillus pragensis</i> Vajdovsky, 1876	Stb.	[14]
Oligochaeta	Naididae	<i>Rhyacodrilus omodeoi</i> Martinez-Ansemil, Sambugar & Giani, 1997	Stb., Tl.	[14]
Oligochaeta	Naididae	<i>Rhyacodrilus sketi</i> Karaman, 1974	Stb.	[14]
Oligochaeta	Naididae	<i>Tubifex pescei</i> (Dumnicka, 1980)	Stb.	[14]
Ostracoda	Entocytheridae	<i>Sphaeromicola</i> sp.	Stb.	[14]
Copepoda	Canthocamptidae	<i>Elaphoidella jeanneli</i> (Chappuis, 1928)	Stb.	[14]
Copepoda	Canthocamptidae	<i>Elaphoidella stammeri</i> Chappuis, 1936	Stb.	[14]
Copepoda	Canthocamptidae	<i>Lessinocamptus</i> n.sp. Stoch unpubl.	Stb., Tl.	[14,21]
Copepoda	Canthocamptidae	<i>Bryocamptus (Rheocamptus) balcanicus</i> s.l. (Kiefer, 1933)	Stb.	[14]
Copepoda	Cyclopidae	<i>Megacyclops viridis</i> s.l. (Jurine, 1820)	Stb.	[14]
Copepoda	Cyclopidae	<i>Acanthocyclops kieferi</i> (Chappuis, 1925)	Stb.	[14]
Copepoda	Cyclopidae	<i>Acanthocyclops troglophilus</i> (Kiefer, 1932)	Stb.	[14]
Copepoda	Cyclopidae	<i>Diacyclops languidoides goticus</i> Kiefer, 1931	Stb.	[14]
Copepoda	Cyclopidae	<i>Diacyclops charon</i> (Kiefer, 1931)	Stb.	[14]
Copepoda	Cyclopidae	<i>Speocyclops infernus</i> (Kiefer, 1930)	Stb.	[14]
Amphipoda	Niphargidae	<i>Niphargus orcinus</i> Joseph, 1869	Stb., Tl.	[13,14,22]
Amphipoda	Niphargidae	<i>Niphargus wolffi</i> Schellenberg, 1933	Stb.	[14]
Amphipoda	Niphargidae	<i>Niphargus stygius</i> (Schiödte, 1847)	Stb.	[14]
Amphipoda	Crangonyctidae	<i>Synurella ambulans</i> (F. Müller, 1846)	Stb. pop.	[14]

Table 1. Cont.

Taxonomic Group	Familia	Genus/Species/Subspecies	Status	References
Isopoda	Trichoniscidae	<i>Titanethes albus</i> (C. Koch, 1841)	Tb.	[14]
Isopoda	Trichoniscidae	<i>Androniscus stygius tschameri</i> Strouhal, 1935	Tb.	[14,23]
Isopoda	Sphaeromatidae	<i>Monolistra racovitzai</i> Strouhal, 1928	Stb., Tl.	[13,14,24]
Araneae	Dysderidae	<i>Stalita taenaria</i> Schiödte, 1847	Tb.	[10,13,14,25–28]
Araneae	Dysderidae	<i>Parastalita stygia</i> (Joseph, 1882)	Tb.	[10,13,14,26,28]
Araneae	Dysderidae	<i>Mesostalita nocturna</i> (Roewer, 1931)	Tb.	new
Araneae	Linyphiidae	<i>Troglohyphantes excavatus</i> Fage, 1919	Tb.	[10,13,14,29,30]
Pseudoscorpiones	Neobissidae	<i>Neobisium spelaeum</i> (Schiödte, 1847)	Tb.	[14,31]
Pseudoscorpiones	Chthoniidae	<i>Chthonius (Globochthonius) speleophylus</i> Hadži, 1930	Tb.	[14,32]
Opiliones	Nemastomatidae	<i>Hadzinia ferrani</i> Novak & Kozel, 2014	Tb.	[33]
Diplopoda	Attemsidae	<i>Attemsia falcifera</i> Verhoeff, 1899	Tb.	[13,14,34]
Diplopoda	Anthogonidae	<i>Haasia largescutata paligera</i> (Strasser, 1940)	Tb.	[35]
Diplopoda	Polydemidae	<i>Brachydesmus inferus concauus</i> Attems, 1898	Tb.	[35,36]
Diplura	Campodeidae	<i>Plusiocampa (Stygiocampa) nivea</i> (Joseph, 1882)	Tb.	[13,14,25]
Collembola	Arrhopalitidae	<i>Arrhopalites/Pygmarrhopalites</i> sp.	Tb.	[10]
Collembola	Paronellidae	<i>Troglopedetes pallidus</i> Absolon, 1907	Tb.	new
Collembola	Oncopoduridae	<i>Oncopodura cavernarum</i> Stach 1934	Tb.	new
Collembola	Onychiuridae	<i>Absolonia gigantea</i> (Absolon, 1901)	Tb.	new
Collembola	Onychiuridae	<i>Onychiurus/Onychiurides</i> sp.	Tb.	new
Collembola	Tomoceridae	<i>Tritomurus scutellatus</i> Frauenfeld, 1854	Tb.	[10,13,14]
Coleoptera	Carabidae	<i>Typhlotrechus bilimekii fragens</i> Jeannel 1928	Tb., Tl.	[13,14,37,38]
Coleoptera	Carabidae	<i>Anopthalmus heteromorphus</i> (G. Müller 1923)	Tb., Tl.	[13,14,37–40]
Coleoptera	Staphylinidae	<i>Machaerites ravasinii</i> G. Müller, 1922	Tb.	[14,41–44]
Coleoptera	Leiodidae	<i>Bathyscimorphus (Drovenikia) trifurcatus</i> Jeannel, 1924	Tb., Tl.	[12–14,45,46]
Coleoptera	Leiodidae	<i>Bathysciotes khevenhuelleri</i> (Miller, 1852)	Tb.	[12–14]
Coleoptera	Leiodidae	<i>Aphaobius milleri</i> (Schmidt, 1855)	Tb.	[12–14,47]
Coleoptera	Leiodidae	<i>Leptodirus hochenwartii</i> Schmidt, 1832	Tb.	[8,11–14]

In the stygobiotic and troglobiotic faunal checklist (Table 1), we report only valid names of taxa. Those were checked using online world taxa databases as WoRMS for aquatic taxa and MilliBase, Pseudoscorpions of the World, MolluscaBase, etc. For some taxa, we updated recently synonymized names. Species listed in the former checklist that are not accepted as valid taxa were excluded from the list. In the older literature, some dubious records are persistently appearing. For the precautionary reason, we excluded such taxa from the list if the specimens were not collected or reported recently. In some cases, taxonomic experts explicitly stated that specimens found in Križna jama belong to a new, yet undescribed species.

As the last published checklist of Križna jama troglobionts [14] was mostly focused on aquatic fauna and there was a lack of terrestrial fauna studies, in the autumn of 2020 and early spring of 2021, we sampled the terrestrial fauna. In a few excursions, we investigated the cave up to the point called Križna gora (Figure 2). We searched for fauna mostly by eye on speleothems, cave walls, among rocks and especially near the bat guano deposits. The use of rubber boats, provided by the managers of Križna jama, was essential to investigate deeper parts of the cave. To collect additional terrestrial fauna we deployed a smaller number of plastic pit-fall traps along the transect in the surveyed cave corridor. The traps were baited with cheese and rotten meat. As the traps were without a fixative, we examined them after five days. We took macrophotographs of most of the captured animal species “in situ” in the cave. Specimens needed for future research were stored in alcohol and are deposited in the Zoological Collection of the Notranjska Museum Postojna. Collembolan fauna was preliminarily determined by Marko Lukić (Zagreb) but a detailed study of the collected specimens is still pending. Especially at the cave entrance, we sifted the soil and gravel with entomological sieves but using this method we did not find any significant troglobiotic fauna. During our recent field trips, we also sampled aquatic fauna. Larger crustaceans were sampled with aquatic nets in the water of the cave river, pools and lakes.

Some of the sampled aquatic fauna was later photographed in the laboratory. A large sample of gravel and silt was collected from the bottom of the lakes, sieved and examined in the laboratory to study smaller invertebrate species, especially molluscs and annelids. Microscopic slides with informative details of the species were made for the identification of some invertebrate species. In some cases, taxa are identified to genus level since no detailed and final study on the collected specimens is made.

### 3. Results

#### 3.1. A Historical Overview

Local people have been visiting Križna jama for millennia. Evidence of that are fragments of pottery dating from the Bronze Age found within the cave. The oldest signature found on a cave wall is dated back to 1557. The first explorations of the cave are documented by the evidence that Jožef (Josip) Cerar (in German Johann Zörrer) visited Križna jama in November 1824 and in July 1825 with a group of local people from Lož and Cerknica. His report, the cave description and its first map, unfortunately, did not appear until 1838 [48]. He was the first to report that some cave passages contain cave bear (*Ursus speleus*) bones. In his report, he used the German name of the cave “Heiligen-kreutz”, despite the locals knew the cave as “Mrzla jama” (cold cave). The first known printed account of this cave comes from an Englishman John James Tobin diary who accompanied Sir Humphry Davy during his cave visit, in 1832. At that time, only the first 500 m or so of the cave were accessible and known. Tobin’s report of proteus (*Proteus anguinus*) seen in the cave is very interesting [49]. Soon after that, Aleksander Škofic in 1847 and Adolf Schmidl in 1854 wrote detailed descriptions of the cave. Their reports about plenty of cave bear bones and teeth made Križna cave famous. These reports encouraged the Austrian geologist Ferdinand von Hochstetter to start digging bones in Križna jama in 1878 and 1879. Hochstetter and his workers collected out an impressive number of 4600 cave bear bones from more than 100 individuals [50]. Two complete cave bear skeleton reconstructions, displayed in the Museum of Natural History in Vienna, originated from this time [51]. The first to report about the presence of the cave slender-neck beetle *Leptodirus hochenwartii* in Križna jama was Heinrich Müller in 1857 [8]. The German naturalist Gustav Joseph visited several Slovenian caves in the period from 1853 to 1881. Despite the fact that his collection is not preserved, he published basic data about the Križna jama fauna in one of his publications [10]. Additional faunal reports from Križna jama can be found in Hamann’s catalogue [25]. In the 19th century, mostly cave beetle collectors visited Križna jama. There were Eduard Knirsch, Joseph Müller, Anton Haucke, Josip Sever, Alfonz Gspan, Ivan Dolar and Egon Pretner. Roman Kenk and Albin Seliškar visited Križna jama in 1928 and first collected aquatic fauna as well. Ljudevit Kuščer studied and published descriptions of some Križna jama new subterranean snails [17,19]. The first list of Križna jama fauna reported and described taxa by various European leading taxa specialists [12,24,52] was published in Wolf’s catalogue [13]. After World War II, Egon Pretner made many visits to Križna jama, mostly leading foreign and other Slovene biologists who sampled the fauna. Jože Bole investigated the gastropods of Križna jama and its surrounding springs [18,53]. From the 70’s onwards, Boris Sket and his colleagues visited Križna jama on several excursions and gathered samples, mainly focusing on aquatic fauna [14]. Nevertheless, no detailed ecological investigations have been done in the cave. Based on collected samples, significant progress has been made about the presence of some less investigated animal groups, such as Oligochaeta [54,55]. Sket published a second paper in Slovene about the Križna jama fauna in 1986 [56], and a scientific overview with Fabio Stoch in 2014 [14]. Recently, the authors carried out an additional survey, mainly focused on terrestrial fauna. In this paper, new and so far unpublished data on the presence of some terrestrial troglobiotic fauna is given.

### 3.2. The Subterranean fauna of Križna Jama

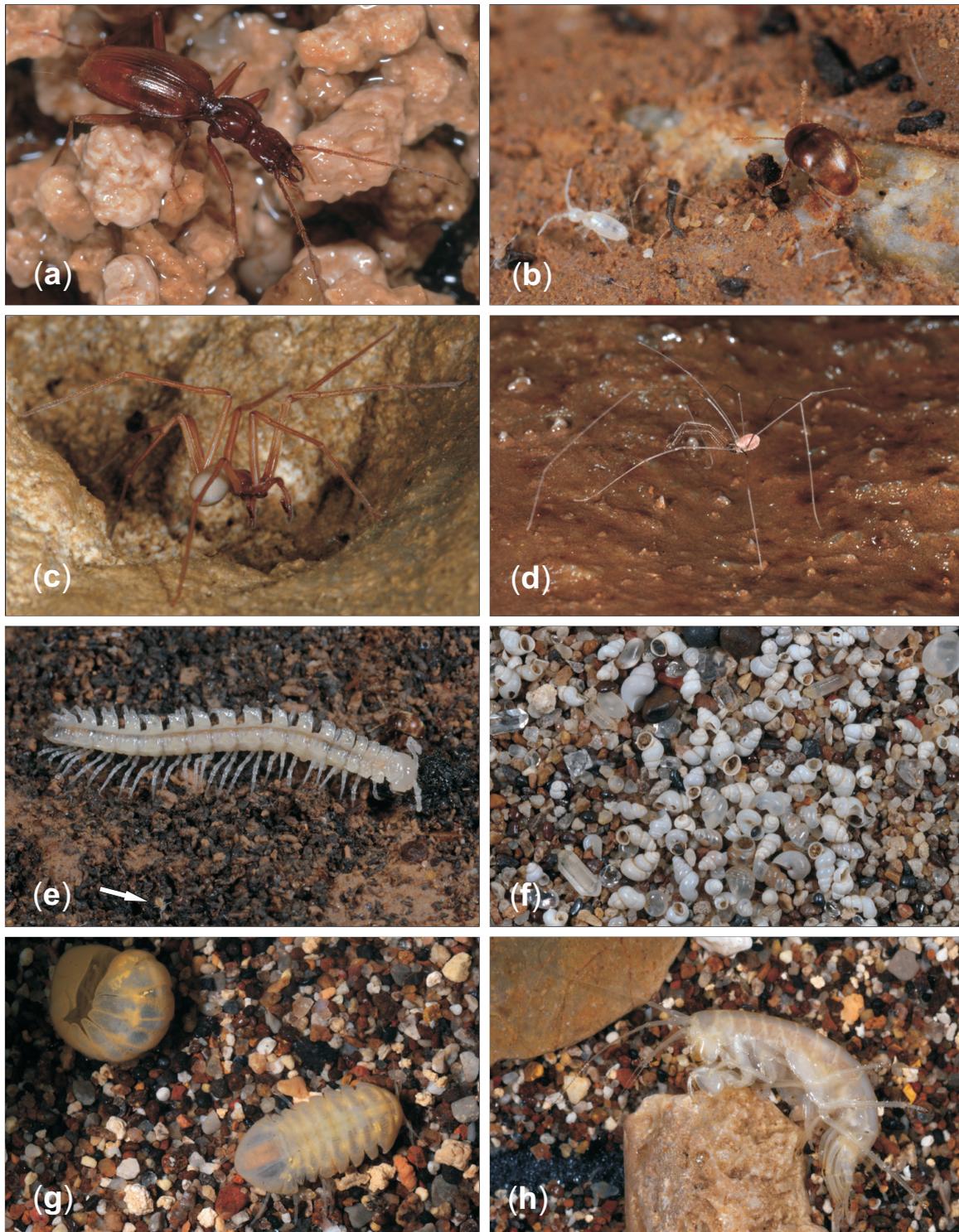
The entrance hall of Križna jama is voluminous and due to the artificially enlarged entrance, daylight penetrates deep inside the cave. Within the first part of the cave next to the entrance, numerous trogliphilic and troglaxene animals can be regularly seen. Especially in winter geometrid moths *Triphosa dubitata* and noctuids *Scoliopteryx libatryx*, as well as cave crickets (*Troglophilus* spp.), are common as parietal fauna on the walls. Different species of harvestmen (Opiliones), spiders (Araneae), caddisflies (Trichoptera) and various flies and mosquito (Diptera) considered as trogliphiles and troglaxenes are common here. In the bottom of the entrance hall rich with humus, some other soil fauna, not considered as trogliphilic, is present. Stone martens (*Martes foina*) and edible dormice (*Glis glis*) regularly penetrate deeper into the cave corridors. On the contrary, the tawny owl (*Stryx aluco*) is usually found dormant only at the cave entrance.

So far, seven species of bats have been recorded in Križna jama [57,58]. The most common is the lesser horseshoe bat (*Rhinolophus hipposideros*). It overwinters in both Križna jama and in Križna jama 2 in significant numbers. Regularly about 900 individuals overwinter here and this represents the second-highest concentration of bats compared to other Slovene caves [58]. Other species like the great mouse-eared bat (*Myotis myotis*), Daubenton's bat (*Myotis daubentonii*), the serotine (*Eptesicus serotinus*) and the barbastelle bats (*Barbastella barbastellus*) are occasionally found in smaller numbers. Schreibers' bat (*Miniopterus schreibersii*) have so far been spotted in Križna jama only once [58]. There are no bat breeding colonies in Križna jama. Bat parasites such as the bat tick (*Ixodes vespertilionis*) can be regularly found on walls next to the hibernating bats. Numerous trogliphilic and trogliphilic collembolans, mites, diplopods and beetles are attracted by owl pellets and bat guano as well as by marten scats and dormice droppings all over the cave.

Among the trogliphilic cave beetles are relatively numerous. The most famous of all, the slenderneck beetle *Leptodirus hochenwartii*, is rare and mostly found in the deeper cave spaces far from the entrance. In the entrance hall, as well as all along the immense cave tunnels of Križna jama, the small bathyscioid leptodirine beetle *Bathyscimorphus trifurcatus* (Figure 3b) is the commonest trogliphilic beetle [11,45,46]. The leptodirine beetle *Bathysciotes khevenhuelleri* is regularly trapped in pitfall traps in the entrance hall between the stones and the soil in the habitat that resembles the MSS, while the leptodirine *Aphaobius milleri* have been collected only sporadically [47]. *Bathysciotes khevenhuelleri* is relatively common in Snežnik-Javorniki wider area in mesovoid shallow substratum (or "Milieu souterrain superficiel"—MSS) [59], while *Aphaobius milleri* prefers to some extent colder cave microclimates in the area which can be found right after the Križna jama entrance. Two species of trogliphilic ground beetles are known from Križna jama and for both taxa Križna jama is their type locality. The subspecies of the trechine *Typhlotrechus bilimeki fragens* (Figure 3a) is relatively common [37,38] in many places, while the endemic *Anophthalmus heteromorphus* is extremely rare and thus much sought by collectors [38–40]. The trogliphilic pselaphine beetle *Machaerites ravsinii* is occasionally found among the rocks in the entrance hall of Križna jama [41–44]. Some other subterranean beetle species occasionally reported for Križna jama are doubtful and need further recent confirmation.

The Collembolan fauna of Križna jama has not been studied in details until recently. Joseph [10] described two species of *Sminthurus* from Križna jama, but they are not considered valid in later works. In Wolf's catalogue [13] there are records of five species of collembolans, which were questioned as doubtful in the last Križna jama list of trogliphilic [14]. In recent samplings, the collembolan species *Troglopedetes pallidus* (Figure 3b), *Oncopodura cavernarum*, *Absolonia gigantea* and some undefined species of Onychiuridae and Arrhopalidae are documented. Small, eyeless and strongly trogliphilic collembolan specimens of taxonomically not yet determined species of the complex *Arrhopalites/Pygmarrhopalites* (Figure 3e) can be found on bat guano regularly. Trogliphilic collembolans are all common on the bat guano and similar organic debris, especially stone marten scats in deeper parts of the cave. *Tritomurus scutellatus* is common only near the entrance, but still within the cave's

dark zone. The dipluran species *Plusiocampa (Stygiocampa) nivea* is rare but widespread in Križna jama.



**Figure 3.** Troglobiotic and stygobiotic fauna from Križna jama: (a) Ground beetle (*Typhlotrechus bilimekii frigens*). (b) Leptodirine beetle (*Bathyscimorphus (Drovenikia) trifurcatus*), on the right and Collembolan (*Troglopedetes pallidus*), on the left. (c) Cave spider (*Parastalita stygia*). (d) Cave Harvestman (*Hadzinia ferrani*). (e) Cave Millipede (*Brachydesmus inferus concavus*) and Collembolan (*Pygmarrhopalites* sp.), indicated with white arrow. (f) Various species of aquatic snails from family Hydrobiidae and quartz crystals. (g) Sphaeromatid isopod (*Monolistra racovitzai*). (h) Cave amphipod (*Niphargus orcinus*).

The troglobiotic arachnid fauna of Križna jama is rich as well. So far, only one of the lyniphiid *Troglohyphantes* species is reported from Križna jama [10,14,27,29,30]. The troglobiotic dysderid spider species *Stalita taenaria* and *Parastalita stygia* (Figure 3c) live in Križna jama sympatrically [26–28]. The coexistence of these two related species in the same cave is rare [60]. Surprisingly enough, a third distinctly smaller dysderid species *Mesostalita nocturna* was found deep inside Križna jama during one of the last excursions (Delić T. per. comm.). In one of the recent ecological studies [60], it was demonstrated that the shift in the trophic niche amongst related species minimizes the interspecific competition and enables related dysderid spider species coexistence. The fact that the Križna jama is a tourist cave and is regularly visited, the recent discovery of fully troglomorphic harvestmen was an unexpected surprise. A detailed study of the only known single male and female specimens showed that they belong to a recently described species *Hadzinia ferrani* (Figure 3d) from the cave Ferranova buža, situated 40 km northwest from Križna jama [33,61]. Amongst the pseudoscorpions in Križna jama two troglobiotic species are known [31,32]. The relatively giant *Neobysium speleum* is rarely encountered on wet walls and stalactites of the deeper parts of the cave. The second smaller species *Chthonius (Globochthonius) spelaophilus* is reported recently from the cave too [32].

Among the Myriapod, a only troglobiotic millipedes have been recorded in Križna jama so far, although the cave centipede *Lithobius stygius* is expected to be found also as it was recently confirmed in nearby Mrzla jama pri Ložu [62]. The most abundant among the millipedes are the polydesmid *Brachydesmus inferus concavus* (Figure 3e) [35,36,63], which was reported as *B. subterraneus* or *B. sp.* in former works [13,14]. On any organic material, even in the deeper parts of the cave, all development stages (larvae and mating adults) of this millipede are commonly seen. Two other millipede species, *Attemsia falcifera* [13,14,34], reported as *A. pretneri* in older works and *Hassia largescutata paligera*, reported as *Acherosoma cornuatum paligerum*, endemic species of the region, are living in Križna jama too [35,63–65].

Two species of terrestrial isopod crustaceans are regularly found in Križna jama. The giant cave woodlouse *Titanethes albus* lives on wet spots in deeper parts of the cave, while the smaller species *Androniscus stygius tschammeri* [23] is usually found on rotting wood or organic debris near the entrance of the cave. Visitors to Križna jama can regularly encounter the aquatic sphaeromatid isopod *Monolistra racovitzae* (Figure 3g) [13,14,24]. In some permanent cave lakes, these crustaceans slowly crawl on rocks and flooded rimstones. In the same cave lakes, the monolistrians are regularly accompanied by the relatively rarer predatory amphipod crustacean *Niphargus orcinus* (Figure 3h) [14,22]. This *Niphargus* species can reach up to 3 cm in length and it is a relatively giant invertebrate. Studying crustaceans specimens of the genus *Monolistra* and *Niphargus* under the microscope, the presence of ostracodan *Sphaeromicola stammeri* and turbellarian *Stygodyticola hadzii* as epizoans or exterior parasites have been found [14,16]. Two smaller amphipod species *Niphargus wolffi* and *Niphargus stygius* live in Križna jama too. While the former is usually found in loam and rimestone pools fed by percolated water dripping from the cave ceilings, *N. stygius* is found in cave lakes too [14]. In such pools, significant fauna of copepod crustaceans like *Elaphoidella* spp., *Speocyclops infernus* and *Acanthocyclops kieferi* have been sampled [14,21,66,67]. These pools can be occasionally flooded by the subterranean river during the floods. Larger waters, the lakes and mainstream rivers in both corridors of the Blata and Pisani rov, are oligotrophic and the fauna here is relatively scarce. Besides *Monolistra* and *Niphargus*, smaller copepod fauna such as *Acanthocyclops troglophilus* and *Diacyclops charon* have been recorded [14]. Despite most of the river corridor bottoms being covered in sinter deposits in some places, especially in the corridor Blata, the river bottom consists of very loose silt and loam mixed with sand. Here the large and colourful troglobiotic oligochaete *Delaya bureschi* is common. Six other troglobiotic oligochaetes have been recorded for Križna jama so far [14,55]. In the subterranean waters of Križna jama two species of troglobiotic turbellarians are reported as well.

In the lakes, river and streams of Križna jama, six aquatic, including four hydrobiid, snail species are found [17–19,53,68]. Based on specimens from Križna jama, two species

*Belgrandiella crucis* and *B. schleschi*, were described. *Belgrandiella superior* and *Hauffenia michleri*, have been described from cave waters from a surrounding Ljubljana river catchment area. Specimens of the aquatic snail from the genus *Paladilhilopsis* are still to be determined [14]. Aquatic snails live all along permanent water streams, where specimens can be found mainly on the bottom among the rocks, gravel and silt. In the lakes, where small amounts of organic debris drop from the surface (such as particles of fallen leaves), the populations of snails are more abundant. Besides hydrobiid snails, three species of primarily terrestrial troglobiotic snails live in Križna jama. The species *Zospeum kusceri* and *Z. isselianum* can be usually found on wet walls and stalactites. A third species *Zospeum exiguum*, described from Križna jama, is considered as at least a partly aquatic. Living specimens of *Z. exiguum* were collected mainly on the submerged rocks in lakes and streams so far [19,20]. However, the easiest way to collect empty snail shells is to collect sand on certain spots on the lake edges, where empty shells are deposited in significant numbers as a tanatocenoses (Figure 3f).

Sifting gravel and sand samples from the mainstream pools, in search of snails, recently revealed unexpected cave sedimentary deposits. In previous Križna jama fluvial sediment studies [69,70] allochthonous oolitic bauxite ooids and quartz pebbles amongst the autochthonous fragments of broken sinter were noted. Searching for snails, we found tiny quartz crystals of a special biterminated shape as well (Figure 3f). Most of the quartz crystals in Križna jama are notably eroded, but some brilliant specimens can be found as well. Such biterminated quartz crystals, popularly called “cerknica diamonds”, are unique and in the region known from the narrow strip of land characteristic by porous sucrose dolomites on the Slivnica Mountain on the eastern side of Cerknica [71]. Accompanied by bauxite ooids, these fluvial sediments clearly show their origin and a fluvial transport from Slivnica—Bloke plateau and demonstrate the river catchment area of at least part of Križna jama running waters. Identification of water catchment area that drains into the Križna jama water system is essential for understanding zoogeographical reasons for species composition as well as for nature conservation reasons. For some rare events of periodic water pollution in the Križna jama, the source stream Farovščica in the Bloke plateau has already been identified, using water tracing methods [6].

The largest aquatic cave animal in Križna jama is to be the cave salamander or proteus (*Proteus anguinus*). Its presence in Križna jama was reported by Tobin in 1832 [49] later by Joseph to [10] and cited by Wolf [13]. Since then, no one has ever seen or mentioned proteus in Križna jama. Sket [72] declared this report as a “most probably erroneous” and therefore proteus has been later omitted from the fauna list of Križna jama. Proteus has a wide holo-dinaric distribution and it is present along all the Ljubljana river drainage area. The closest confirmed localities of proteus are some wells in Loško polje, only a few kilometres away from Križna jama. Its absence in this cave is for this reason of great scientific interest. Similarly to the absence of proteus, the cave shrimp *Troglocaris* has never been reported in the Križna jama, not even in the wider Lož area [73]. The reason for this deficiency might be the same as for the absence of any Thiaridae, Neritidae and Unionidae Mollusca in the neighbouring Cerknica lake [14,18,53,68].

#### 4. Discussion

In one of the first reports on the Križna jama subterranean biodiversity [2] there are listed 45 troglobionts and stygobionts from Križna jama, among them 29 aquatic and 16 terrestrial species what listed this cave on the list of the world’s richest caves [2,74]. In a more recent and updated list [14], the total number of troglobionts and stygobionts reached 50. Among those, 32 species are aquatic and 18 species as terrestrial. In this paper, the number of stygobionts remains the same but we omitted some doubtful taxa reported in older works and added significant new terrestrial troglobiotic taxa that were documented recently. Therefore, we present a list of 60 troglobiotic species, among them 32 aquatic and 28 terrestrial (Table 1). No new taxa have been recently described on basis of the specimens from Križna jama and thus the number of taxa with the type locality in this

cave remains 10 species and subspecies. The fauna of Križna jama is similar to the fauna of other biodiverse caves in the Notranjska region like the Postojna-Planina cave system. In the Križna jama, there are some additional faunistic elements among the terrestrial fauna, which are related to the Dolenjska karst and are not present in Notranjska karst caves. The spider *Parstalita stygia* and millipede *Brachydesmus inferus* are such examples. Aquatic fauna is the most characteristic of the Ljubljanica river drainage system [68]. Geographically located in the temperate climatic zone and in the Dinaric mountain range, which is well known for its rich subterranean biodiversity the high number of troglobionts is not surprising. However, most hot spots of high subterranean biodiversity tend to have high primary productivity or rich organic input from the surface [2]. Contrary to some caves as the Postojna-Planina cave system, Logarček and some other caves situated in the region popularly called Notranjska triangle and well known as a prominent subterranean fauna hotspot [68], Križna jama is to be classified as oligotrophic.

There is no sinking river from the surface passing through the cave that brings significant organic material as for example Pivka River in the Postojna–Planina cave system. Waters in Križna jama are thus clean and of good quality. This is probably the main reason why there are so few non-troglobiotic elements in Križna jama waters. Fauna in Križna jama is due to lack of food, not abundant, but it is well diversified. The only exception could be attributed to Tršanov rov or the so-called Stransko jezero, where occasionally we can find a small amount of organic debris coming from the surface. The aquatic fauna is the richest there. In this part, small stonefly larvae enter the cave and are a presumably welcome food source for cave animals such as *Niphargus orcinus*.

The entrance to the Križna jama is situated on the foothill of Križna gora Mountain. The cave is horizontal and extends directly into the mountain. The thickness of the limestone ceiling rapidly increases and measures 50, 100 and 150 m above the first lake close to the entrance, in the middle of the cave and in the deepest part of the cave, respectively. This immense, to some extent cracked and partly saturated habitat called epikarst, is from a biological point of view mostly unexplored and undersampled [75–77]. Epikarst tends to be a hotspot within a hotspot because the heterogeneous nature of epikarst allows for high species richness. Both the aquatic and terrestrial fauna of epikarst tends to be abundant, with epikarst copepods being the most diverse and best-studied group in some other biodiverse caves [76,77]. To further improve the knowledge of the faunal composition of Križna jama, sampling of the epikarst water seems to be the most promising, both direct sampling of dripping water as well as a detailed sampling of pools and lakes filled with percolating water. The thickness of rock deposits above the cave prevents penetration of organic particles and also incidental soil fauna elements. So food sources scarcity was noted throughout the inner parts of Križna jama too. These are the reasons that in Križna jama the terrestrial troglobiotic fauna is not abundant in numbers but it consists of numerous troglobiotic taxa without the presence of not-troglobiotic representatives. The cave is relatively well studied, however the recent finding of some, even big-sized arachnid species, so far overlooked is promising. Thus, further discoveries of specialized subterranean species in the cave are expected.

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