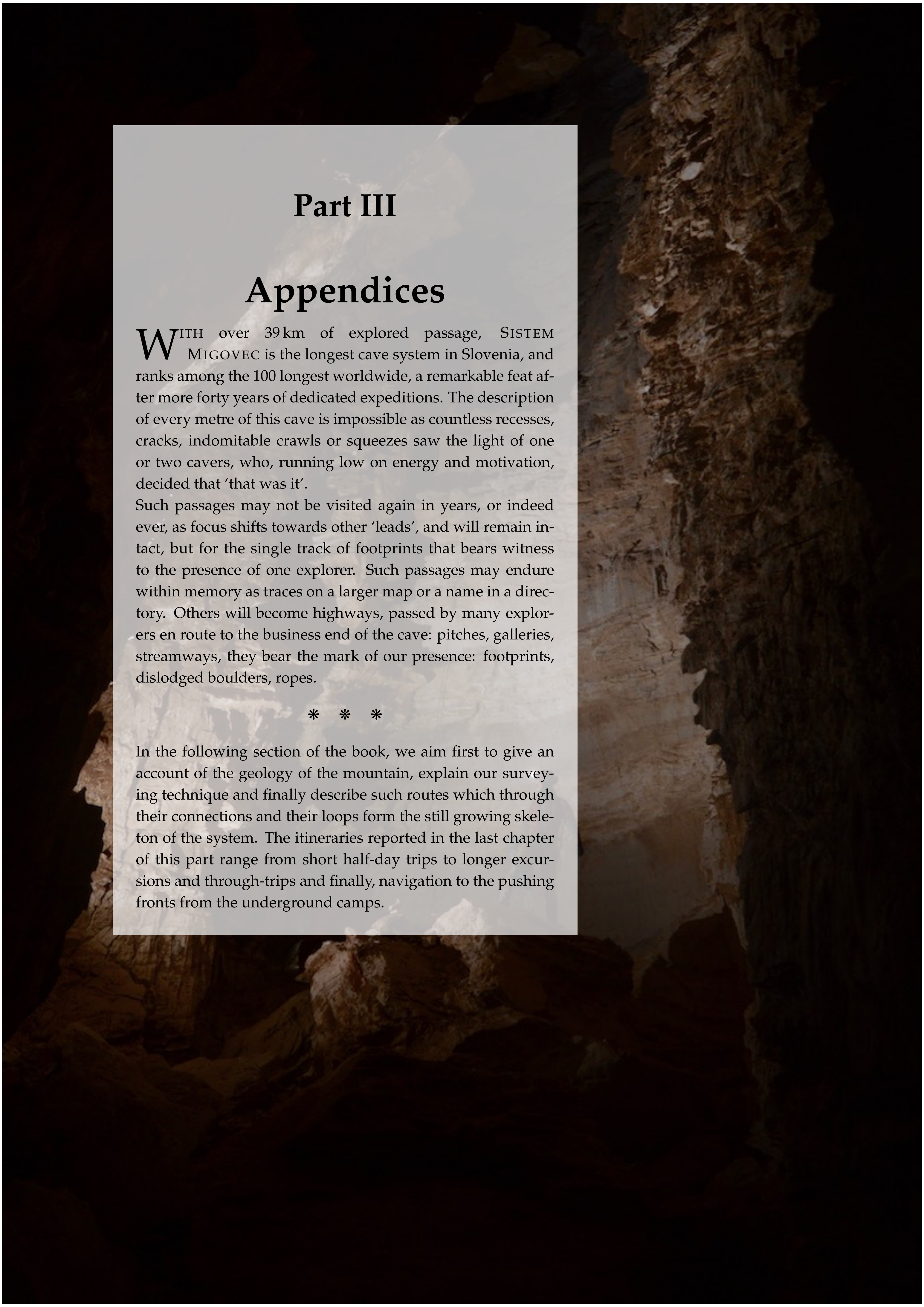


Part III

Appendices

With over 39 km of explored passage, Sistem Migovec is the longest cave system in Slovenia, and ranks among the 100 longest worldwide, a remarkable feat after more forty years of dedicated expeditions. The description of every metre of this cave is impossible as countless recesses, cracks, indomitable crawls or squeezes saw the light of one or two cavers, who, running low on energy and motivation, decided that 'that was it'.

Such passages may not be visited again in years, or indeed ever, as focus shifts towards other 'leads', and will remain intact, but for the single track of footprints that bears witness to the presence of one explorer. Such passages may endure within memory as traces on a larger map or a name in a directory. Others will become highways, passed by many explorers en route to the business end of the cave: pitches, galleries, streamways, they bear the mark of our presence: footprints, dislodged boulders, ropes.

* * *

In the following section of the book, we aim first to give an account of the geology of the mountain, explain our surveying technique and finally describe such routes which through their connections and their loops form the still growing skeleton of the system. The itineraries reported in the last chapter of this part range from short half-day trips to longer excursions and through-trips and finally, navigation to the pushing fronts from the underground camps.

Geology of Migovec

The Julian Alps

Geography

TOLMINSKI MIGOVEC belongs to the JULIAN ALPS, in the easternmost sector of the SOUTHERN ALPS (Bavec et al., 2004). They JULIAN ALPS are bounded by the Pannonian and Fruili-Veneto basins to the east and west respectively, while to the north, they are separated from the EASTERN ALPS by the Periadriatic lineament (see map 7 on the next page). Southward from the South Alpine front, they become the DINARIDES (Placer, 1998; Burrato et al., 2008). This carbonate dominated massif is characterised by high relief with valley floors located 100-400 m asl and peaks in excess of 2000 m asl (Šmuc and Rožič, 2009).

Structural style

Overall, the tectono-stratigraphic setting [37] of the JULIAN ALPS is a result of continued northward motion of about 2 mm.a^{-1} (Burrato et al., 2008) and since the Miocene, counter-clockwise rotation of the Adriatic microplate (Marton et al., 2003). The convergence of the Adria microplate with the Eurasian plate is quantitatively described by GPS velocity fields (Grenerczy et al., 2005). Such convergence has led to the formation of Alpine and Dinaric mountain chains and still generates earthquakes today ($M_w > 5$) in the parts of the shallow crust where shortening is accommodated by brittle deformation.

Slovenia, and in particular the area north east of Tolmin are located in the north-eastern corner of the Adria-Europe collisional belt. This area, at the critical juncture between the Alpine and Dinaric chains overlook a rim of high topography around the relatively rigid, undeformed Adria micro-plate, whose rocks are exposed in the Istrian (West Croatia) peninsula (Šmuc and Rožič, 2009). It is buried under a thick cover of foredeep [38]sediments in the Friuli-Venetian plain.

It is useful to define a hierarchy for the subdivision of tectonic units within the Tolmin area. At first order, the SOUTHERN ALPS lie between by the Periadriatic lineament and South Alpine front (Placer, 1998). Second order units, e.g. the Zlatna, Julian (locally Krn) and Tolmin nappes are slices bounded by south verging thrust faults. This reverse thrusting resulted in an inversion of stratigraphical order, which places massive upper Triassic limestones at the top of the sequence

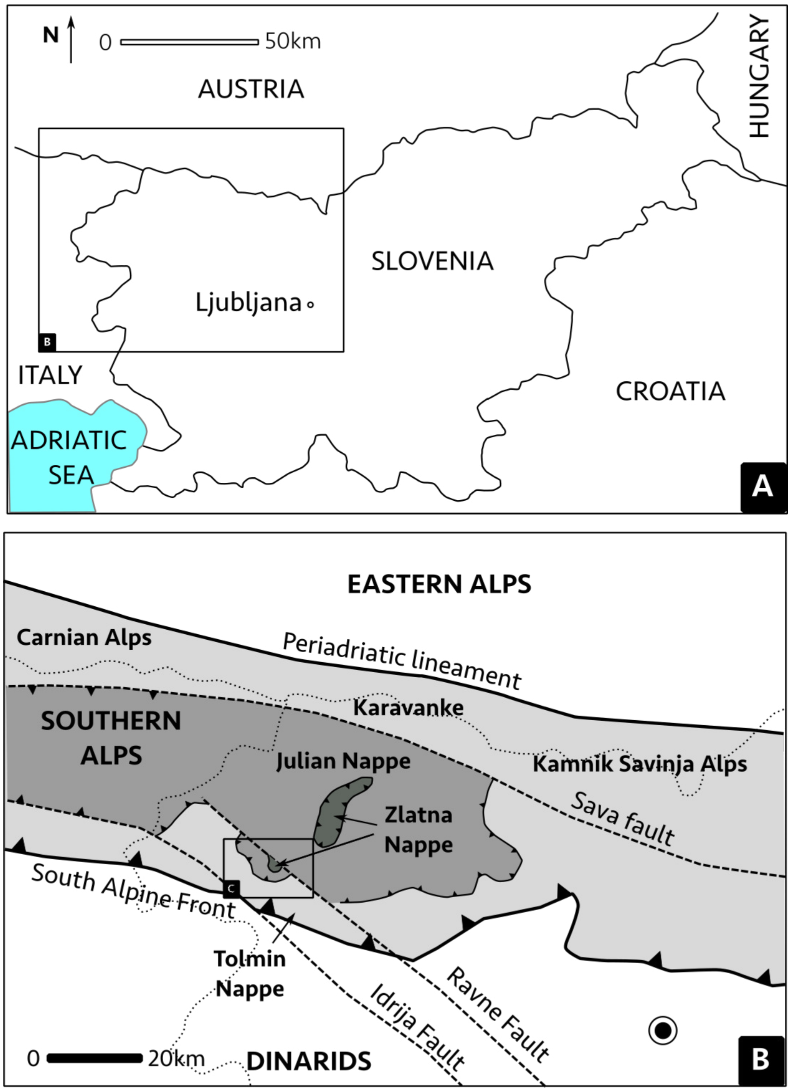
[37] The interplay between relief generation, erosion and sedimentary deposition during *orogenesis* or moutain building events

[38] Foredeep basins form in the immediate vicinity of collisional belt as thickened crust deforms the somewhat elastic plate underneath, creating a trough where the material sourced from the nearby mountains is preferentially deposited

with younger Jurassic/Cretaceous marls and limestones outcropping underneath, at much lower elevation (see map 8 on page 283).

Alpine deformation

That the Julian Nappe, which comprises the cave forming Dachstein Formation of the Krn-Migovec area was transported towards the south during the Alpine orogen is commonplace in the litterature (Doglioni and Bosellini, 1987; Placer, 1998). The weak and easily deformed Carboniferous clastics basement of the Julian Alps provided a detachment horizon along which the nappe was transported from the north southwards. The question of the timing of transport of this nappe is somewhat more difficult. Buser (1986) attributes a Neogene (23 Ma to 3 Ma BP) age to this tectonic structure, while Placer (1998) argues it could be slightly older, starting in mid to Late Oligocene (28 Ma BP).



Map 7: *(a)* Overview map of Slovenia *(b)* The structural setting of northwestern Slovenia shows the Tolmin area straddling the active Idrija and Ravne faults. The Migovec System is developed within the Slatna overthrust and the underlying Dachtsein limestone. Inset C is shown in the geological map from Buser (1986). Figure modified from Šmuc and Rožič (2009) and Celarc et al. (2014)

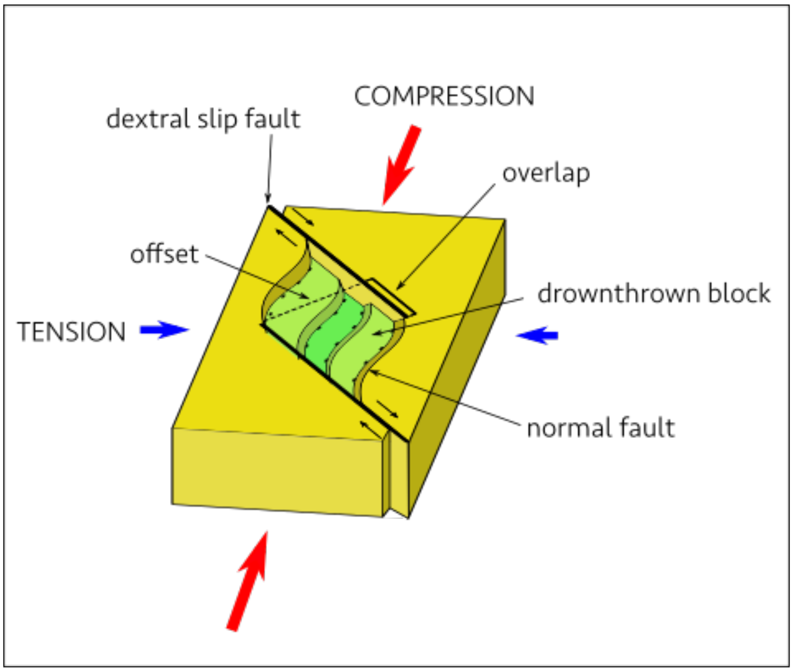


Figure 166: A simplified block diagram showing development of a pull apart basin. Redrawn from Wu et al. (2009)

Present day stress regime

The activity on this heavily faulted boundary between Adria and Eurasia is highlighted by recent destructive earthquakes: M_w=6.4 on the Italian side in 1976 (Pondrelli et al., 2001), and M_w=5.7 and M_w=5.2 on the Slovenian side in 1998 (Bajc et al., 2001) and 2004 (Aoudia et al., 2005) respectively. To highlight the vulnerability of this region, it is also worth keeping in mind that the largest earthquake ever at this junction between the SOUTHERN ALPS and the DINARIDES was the 1511 western Slovenia earthquake (M_w= 6.8). It is believed to have resulted in at least 12,000 deaths (Fitzko et al., 2005). Fault plane solutions for the many M_w=4-6 regional quakes demonstrate that the mode of deformation on the Italian side is chiefly by thrusting (Poli et al., 2002), while deformation is accommodated by dextral slip on the Slovenian side (Poljak et al., 2000). The main strike-slip faults in NW Slovenia i.e. the IDRIJA, RAVNE and SAVA faults from south to north have a spectacular topographic expression.

The RAVNE and IDRIJA faults' expression was mapped by Cunningham et al. (2006) with the aid of LiDAR data. The RAVNE fault is actively growing and supports dextral slip motion through right stepping segments (Kastelic et al., 2008). This results in local transtensional stress regimes which generate steep normal faults which are involved in building the topography between BOVEC, through to RAVNE.

Seismic source modelling suggests a 13 km segment was involved in the 1998 earthquake, therefore it is possible that this fault generated stronger earthquakes in the past; it is thought it was involved in the devastating 1511 earthquake (Fitzko et al., 2005). On the geological map the NW-SE trending fault passes to the NE of Krn, between Grušnica and Tolminski Migovec and heads towards Tolminske Ravne hamlet (see map 8 on the next page).

Crucially, the Ravne fault segments pass through the Tolminka springs basin, and its Quaternary (3 Ma to Present) activity has played a primary role in the building local topography of the Tolminka valley (±1200 m relief), which is described as a small pull-apart basin 2.1 km long and 510 m wide (Cunningham et al., 2006; Kastelic et al., 2008). With respect to figure 166 on the preceding page, the overlap between the two segments of the Ravne fault is 370 m and their offset is 300 m. The total topographic lowering related to fault activity during the last 3 Ma is 1200 m.

In short this basin highlights the interplay between old Alpine structures, recent cross-cutting faults, glacial and hillslope erosional processes and karst development.

Summary of tectonic history

Kastelic et al. (2008) recognise three main phases of tectonic activity with topographic and clear structural expression within the Southern Alps.

- Dinaric reverse thrusting within the Eocene (56 Ma-33 Ma BP). Reverse faults with orientations NW-SE orientations develop (Castellarin and Cantelli, 2000).
- South Alpine thrusting transport of the Mesozoic carbonate platforms which form the Julian Alps as described by Placer (1998) and Buser (1986) from possibly mid-Oligocene to mid-Miocene. The resulting compressional tectonic structures are mostly E-W oriented (Castellarin and Cantelli, 2000).
- Neogene (Pliocene to Recent) dextral-slip faulting cross-cutting the Alpine generated topography, producing youthful landforms such as the Tolminka springs basin, continuing today, highlighted by earthquake activity (Šmuc and Rožič, 2009; Cunningham et al., 2006).

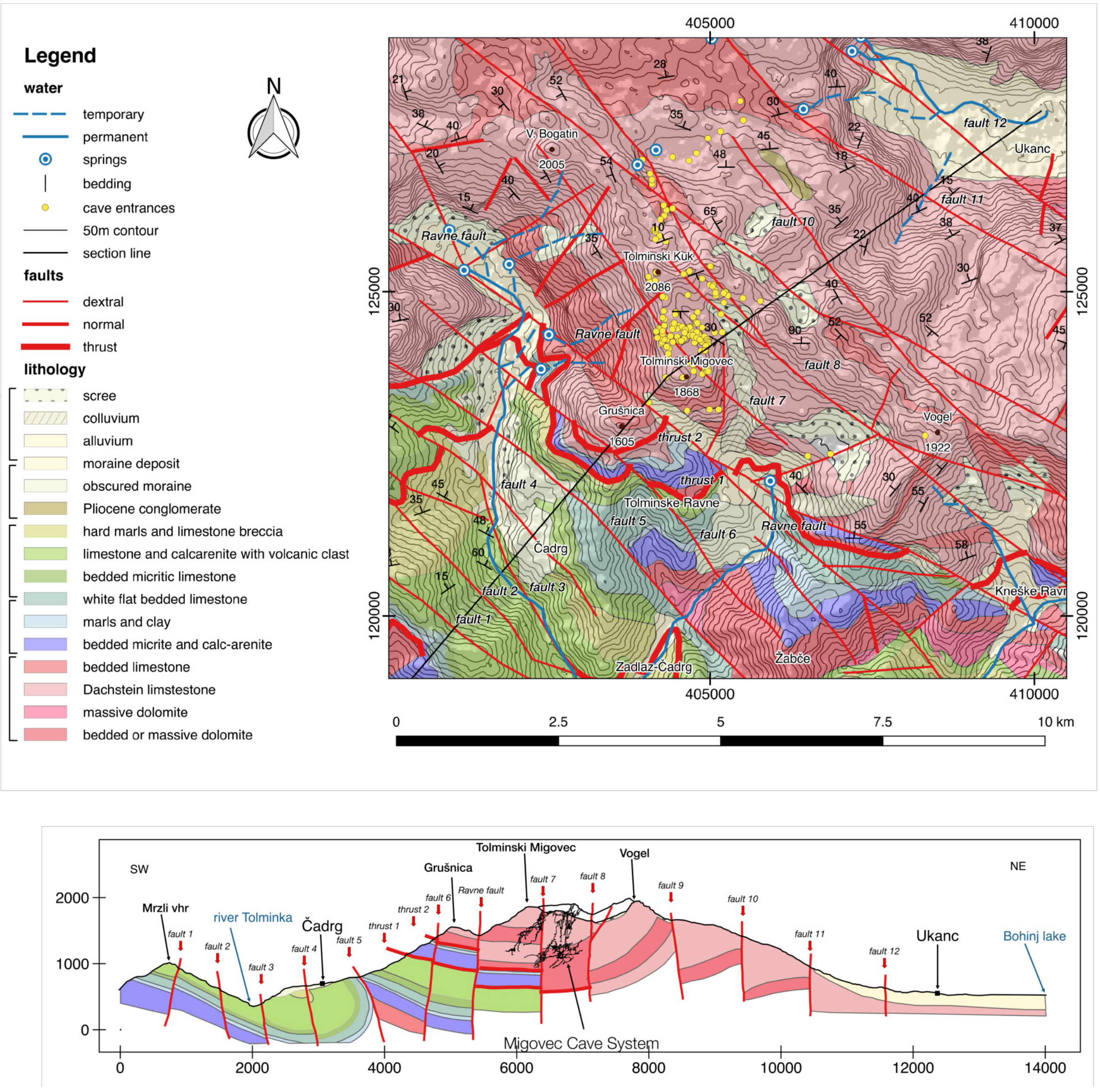
Landscape development and controls

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 and Buser, 1996). The carbonates, which also contain patches of dolomite, form a continuous sequence reaching nearly km thick (Buser, 1986). In cave observations of well exposed canyon and shaft walls suggest that at least part of the sequence is made up of alternating carbonate facies e.g. light grey mudstone, cream to grey horizons of wackestones containing fossil algae, mud clasts and gastropod shells (e.g. in Hall of the Mountain King,figure 111a on page 182). The light grey beds are likely a deeper lagoonal facies, while the cream-coloured beds were deposited closer to the reefs. Light grey horizons are often 1-2 m thick, while the cream-coloured facies are usually made up 0.5 m thick beds.

Although coral reef buildups have been recognised in the surrounding areas (Buser, 1986; Ogorelec and Buser, 1996), none have been reported so far in the Migovec cave system.

The underlying formation of bedded to massive dolostone (the Main Dolomite Formation) is shown to outcrop on the NE side of the Tolminka valley on the geological map of Tolmin (Buser, 1986).



Map 8: Geological map of the Tolmin Area, modified after Buser (1986)

This formation, less karstified than the overlying Dachstein Formation, acts as a local aquiclude, as is shown for the Kanin massif whose geological context is similar (Turk et al., 2015).

Lithology describes the summary of the gross characteristics of a rock

The rock formed during the Upper Triassic Norian to Rhaetian age (228 -101.3 Ma) and now forms the backbone the Southern Calcareous Alps (Bosellini and Rossi, 1974) and crops out all over the Northern Calcareous Alps (Fischer, 1975; Schwarzacher, 2005). It has given rise to spectacular landscapes spread over Southern Europe, from Hungary (Haas, 2004) to Sicily (Catalano et al., 1974). Its ubiquity has wide ranging implications for the palaeogeography of this region in Norian to Rhaetian times.

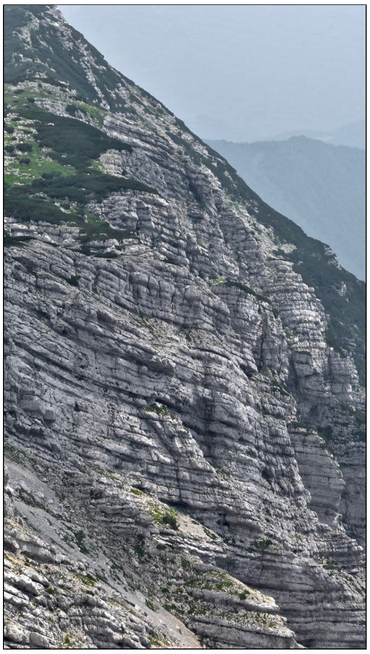


Figure 167: The well bedded Dachstein Formation outcrops on the western cliffs of Tolminski Migovec 📷 *Rhys Tyers*

The deposition of the Dachstein Formation ended at the end of the Triassic (≈ 200 Ma BP) with the dislocation of the carbonate platform. Some regions stayed near the sea level (the so-called 'Julian High') while others were periodically drowned, leading to a loss of carbonate productivity and the deposition of mudstones and shales within the limestone sequence, at Jurassic and Cretaceous (Šmuc and Rožič, 2010) times; they are shown on figure 168 on the facing page.

Debate is ongoing as to the origin of the cyclic pattern of the limestone beds often called *Lofer cyclothems* — so named after the Lofer locality in Austria where they were first described. These cyclothems were identified and interpreted by Fisher (1964) as cyclic sequences tracking deepening upwards depositional environments. The idealised cyclothem model shows three groups A, B, C corresponding to subaerial, tidal and subtidal deposition environments respectively.

This is demonstrated by palaeokarst solution vugs, the presence of argillaceous — here terrestrially derived — and often iron oxide rich residues and evidence of subaerial weathering, even palaeokarst in Group A.

Group B is often characterised by the presence of dessication cracks, partial dolomitisation; it is often laterally discontinuous, with variable thicknesses (5-155 cm).

Group C, often the most abundant, comprises wackestones (limestones rich in carbonate mud) and packstones (dominated by biogenic fragments).

Often, the measured sections differ from the ideal model by the absence of certain members of the sequence. Indeed compared with the Dachstein formation deposited in the Dinaric range, the limestones of the Krn area show more numerous and more pronounced periods of local emersion (Ogorelec and Buser, 1996).

With some authors favouring local tectonic control as a causal mechanism for relative changes in sea level (Goldhammer et al., 1990; Enos and Samankassou, 1998), others (Fisher, 1964; Balog et al., 1997; Haas, 2004; Cozzi et al., 2005), prefer orbitally forced environmental fluctuations such as *Milankovitch cycles* which result from periodic fluctuations in solar insolation linked with the Earth's *precession*, *tilt* and *ellipticity* cycles.

Figure 169: 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. 📷 *Jana Čarga*

Glacial landforms

Bavec et al. (2004) used a combination of geological mapping and dating the identified glacial deposits in order to constrain the extent of late Quaternary glaciation in the upper Soča valley, which is relevant to the Tolmin area.

Most notably, they find no clearly expressed glacial geomorphic features downstream of the town of Bovec; on the contrary, all landforms such as end moraines or glacial cirques are limited to the high reaches on the valleys.

Locally, the bowl shaped hanging valley between the Migovec Plateau and Vrh Nad Škrbino is one example of glacial cirque. Notably, the high resolution mapping of Cunningham et al. (2006) could not find any signes of side or end moraine, nor any other glacially derived deposits within the Tolminka springs basin and interpreted the sheer walls near Polog as segments of the Ravne fault in a pull-apart basin. This is consistent with the view of Šmuc and Rožič (2009) on the relative primacy of tectonics over glacial processes on landscape building in the Triglav area.

A Karstic landscape

Karst terrain arises from the combination of high rock solubility and well developed secondary fracture porosity (Ford and Williams, 2013).

Such terrains exhibit several key features: fluted outcrops, sinks, caves, springs, blind valleys etc... These landforms are generated by the dissolution of rock along natural subterranean pathways provided by geological features (joint, bedding planes, faults). The chemical pathways and rates of fissure enlargement are described in detail in Dreybrodt (1996).

Shakehole dolines and closed depressions of varying size (5-50 m diameter) riddle the Migovec Plateau surface see map 2 on page 25.

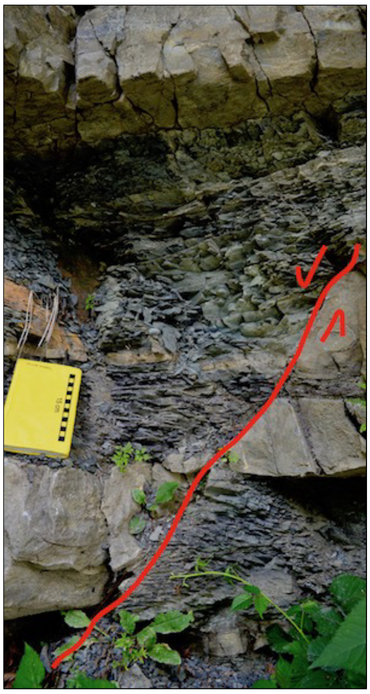


Figure 168: An example of the Jurassic marl and limestone succession, which is heavily faulted 📷 *Tanguy Racine*, on the Slovenska Geološka Pot

The majority are between 10 and 3 m deep and contain snow plugs. Shakeholes are distributed preferentially along lines of fractures and develop at the intersection of those fracture sets see map 8 on page 283. 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 (e.g. figure 42 on page 64).

Bedding control of karst development is seen north of Tolminski Migovec, in an area of well developed *Schichttreppen* [39] 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 (figure 170).

Hydrogeology

The following discussion is largely drawn from in-cave observations and work carried out by ICCC and JSPDT between 1996 and 2001, which had a clear focus on the then known M2/M16/M18 cave system. It has been updated to include observations carried out in Vrtnarija from the period 2012-2015, during which two additional

Figure 170: A view of the Tolminski Migovec plateau, towards the south, as seen from the summit of Tolminski Kuk. The Dachstein Formation is well karstified, with prominent dolines and snow pits. To the left is the Vrtnarija valley, and to the right, the valley of the Tolminka river. 📷 *Tanguy Racine*

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[39] Staircase limestone pavement

deep siphons were discovered, as well as more recent exploration in PRIMADONA (2016-2018).

It is hypothesised that either a lithological boundary e.g. local dolomite patch or the contact with the underlying Main Dolomite Formation (Ogorelec and Buser, 1996), or structural discontinuity e.g. the sole thrust of the KRN nappe, whichever is shallower, controls the geometry of the water table. The position of such dolomitic basement is likely complicated by the series of dip-slip faults which segmented the massif in a broad NW-SE direction during the Miocene.

North of the RAVNE fault, the Triassic carbonates are downthrown by as much as 300 m relative to the Jurassic and Cretaceous sequence (Figure 3), and the sole of the thrust is obscured by Quaternary deposits (Buser, 1986; JSPDT, 2007). This argues evidence for significant normal movement along the tectonic structures of dinaric affinity. Normal displacements of 1-10 m scale are also consistent with the in-cave observations and argue for a topographically complex water table surface at depth, similar to that of Kanin (Kunaver, 1983; Audra, 2000).

The dip of the Dachstein Formation and plunge of the syncline towards the WSW are consistent with in-cave observations of underground drainage organisation in a broad W direction Five of the seven of the seven deep siphons are fed by stream passages heading towards the valley of the TOLMINKA, and all five also lie near or at the level of the ZADLAŠČICA river resurgence (880 m asl). Although five attempts (1996-2001 by ICCC and JSPDT, 2007) have so far failed to conclusively determine the resurgence of the MIGOVEC system, it is more 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 $\approx$9 km^2 catchment area of TOLMINSKI MIGOVEC contributes mostly to the TOLMINKA river, with a calculated average contribution of 0.8 m^3.s.$^{-1}$, which amounts to $\approx$10% of the river's annual discharge.

No major underground 'collector' has yet been found under TOLMINSKI MIGOVEC, instead a series of separate stream passages, with discharges rarely exceeding 0.002 m.s^{-1} in normal summer conditions. Explorations have so far have revealed $\approx$20 active and independent stream passages draining the carbonate massif in a broad western direction, towards the TOLMINKA valley.

All together, these observed underground streams contribute a very rough total of 0.04 m.s^{-1} during periods where it is safe to explore the cave (by necessity, periods of dry settled weather), a discharge which amounts to 5% of average discharge. Bearing in mind the large uncertainty, this is consistent with highly variable discharges karst aquifers, which are characterised by high hydraulic conductivity. Water depth monitoring in selected streams during the spring and autumn discharge maxima is required to refine our understanding of the MIGOVEC karst aquifer.

Figure 171: The above photograph demonstrates the various stages of cave development: the ellipical ceiling of the passage near DÉJÀ VU junction is phreatic in origin. The sinuous rift below, as well as the mud and gravel deposits are vadose in origin 📷 *Jarvist Frost*

The karst aquifer of Migovec

The karst aquifer is divided into two main zones. The *phreatic* zone is situated below the water table and consists of a network of water-filled conduits and planes of fracture.

The *vadose* zone is situated above the water table and consists of dry abandoned passages and/or deeply incised stream canyons or waterfall shaft series (active part of the cave). These passages are accessible to non-diver speleologists and often contain sediment banks or *speleothems*. All are modified by the mechanical breakdown of the cave roofs, which can generate large underground chambers or caverns or block the continuation at *boulder chokes*.

The thickness of the vadose zone on MIGOVEC, that is the elevation difference between the high entrances on the PLATEAU and the sump levels, reaches a thickness of 972 m a.s.l. The recharge of the MIGOVEC aquifers occurs through precipitation directed on the karstic catchment, thus it is autogenic and diffuse (Ford and Williams, 2013). Rainwater collects within the innumerable fissures on the surface into small underground streams. These have formed a dozen of mapped shaft and canyon series (but there are probably more), which often end at impassable fissures or a sump.

Over the course of 40 years of exploration, we have not found a master streamway, that is to say, a collector underground stream ending in a sump, whose resurgence is known (JSPDT, 2007). Rather, we have followed the disparate streams to at five different sumps located each within 30 m of 890 m asl. Other shallower siphons within the System are called ’perched’ as they are presumably the sign of a local aquiclude (water table) (e.g. RED COW: 1046 m, TRUE ADVENTURES: 975 m, or even TERMINUS: 1465 m).

Speleogenesis

The cave system under TOLMINSKI MIGOVEC forms a complex 3D network of connected passages . 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 972 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 (GALAKTIKA CHAMBER.

Horizontal cave levels

Several horizontal levels were recognised early in the exploration of the cave, with two high altitude levels in the ‘old’ system (M2-M16-M18) and two deeper levels in VRTNARIJA. These levels were pre-

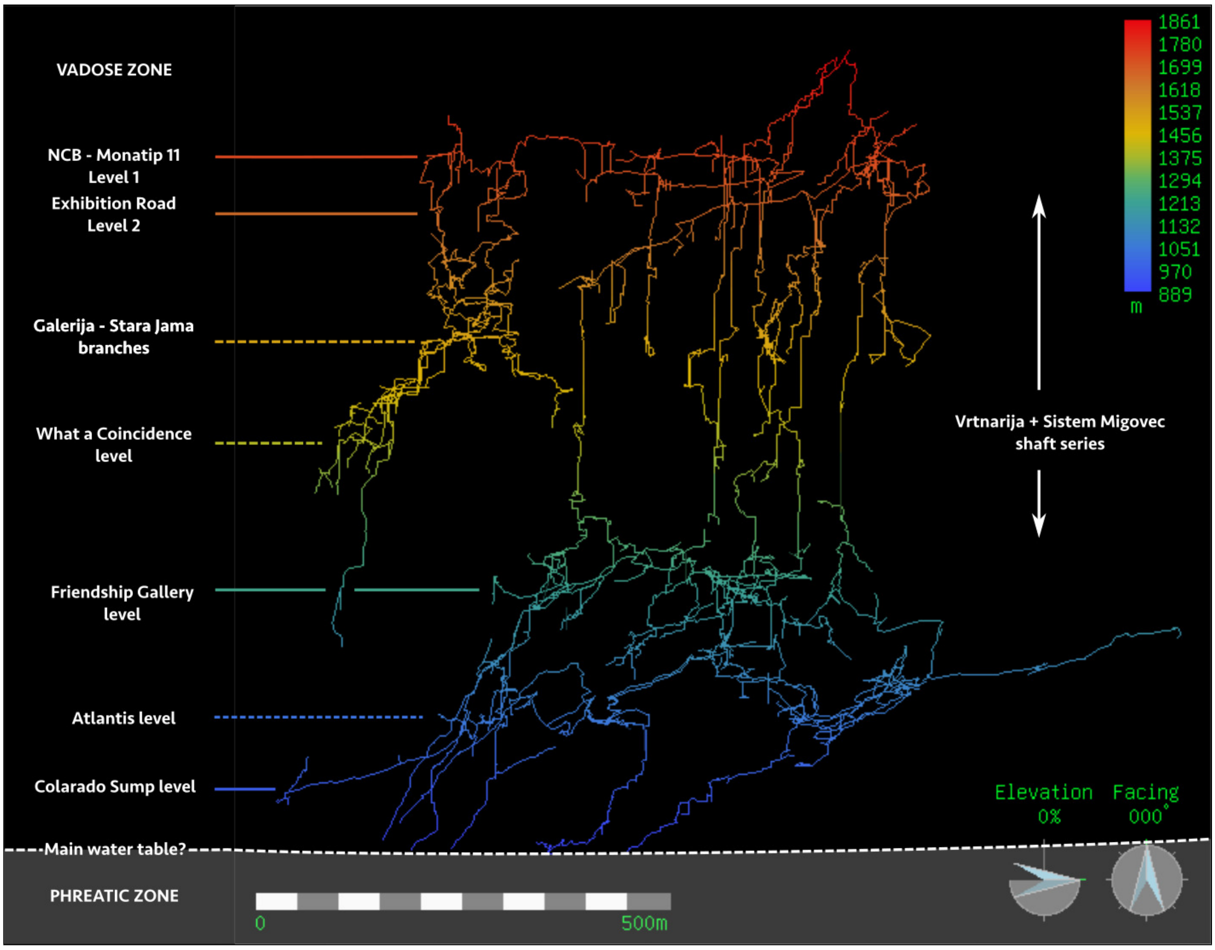

Figure 172: E-W projection of SISTEM MIGOVEC (2017) produced on *Aven* software. Solid lines denote laterally continuous (>500m) horizontal passages of phreatic origin. Steepled lines denote more local horizontal passages of phreatic origin

sumably tied to the elevation of palaeo-TOLMINKA or ZADLAŠČICA rivers. 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 m and 1600 m). By contrast, the other systems (VRTNARIJA, M16), 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, with subsequent breakdown modification. 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 M18, trends sub-horizontally at 145° for distance of over 400 m. After a 90° turn down-dip to 233° the passage trend to the NW-SE resumes, with sub-horizontal parts broken into different segments at varying elevations, eventually ending at the MONATIP 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.

Level 2 — 1560-1720 m LEVEL 2 provides the connection from M18-M2 to M16 and is the cave level 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, parallel to NCB, 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 asl, 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, 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 (figure 173 on the next page). 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 sub-horizontally, connecting the deep shaft series of VRTNARIJA and M16. On the majority of passages, a metre thickness 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 spectroscopy revealed the presence of dominant gypsum and nearly pure hydromagnesite powder. The level is likely controlled by a lithological contact between two strata with different bulk solubility. This is supported by the general lozenge shape of passages with a pronounced upward dissolution pattern.

Level 4 — 950-1120 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. The former was first believed in 2004 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 Formation. 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 has pronounced topographic expression, a surface canyon, is parallel to the deep VRTNARIJA level. It is along that fault that COINCIDENCE CAVE was discovered in 2015.

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 can be observed (figure 62 on page 91).

Figure 173: ZIMMER (P50) in VRTNARIJA is a vadose invasion shaft cutting the previous cave passage (FRIENDSHIP GALLERY), a cave level of phreatic origin whose development was controlled by the intersection between tectonic planes of fault and sedimentary bedding 📷 *Jarvist Frost*

Levels in Primadona Locally, a high density of near horizontal passages of with preserved phreatic morphologies can be found in the Primadona system, located 300 m to the west of the main system. No counterpart to these minor cave levels have yet been identified in the rest of the system at a similar altitude, so they are treated separately here.

At 1510 m elevation, a network of branching sub-horizontal passages between 1-4 m wide with a typical keyhole cross-section which indicates a phreatic origin and later vadose entrenchment is observed. A stream is still present at the base of the passage, but often, the vadose trench is very immature and too narrow to be entered. Abandoned phreatic bypass tubes, lacking vadose entrenchment are also observed. In most places, a thick sedimentary cover is observed, which contains alternating layers of coarse sandy to pebble grade lenses within a finer silty loam matrix (such as in passages near Smer0). Such sedimentary sequences can reach thicknesses of several metres, as seen in small pits incised subsquently to the infilling of the passage (e.g. Galerija.

At 1430-1470 m asl, passages which are both of phreatic origin, as well as relatively low gradient sections of some meanders of vadose origin are seen. In the Hallelujah branch, a 100 m of branching passages of elliptical cross-section was named Plumbers' Paradise due to the nature of sediment infill (a brown loam). Further along the passage, signs of vadose entrenchment are unmistakeable: deep pools and one of the largest active streams under Migove, but the roof retains a hemispheric profile.

Small phreatic bypass tubes such as the top section of Alabaster are also common. Further to the west, the entire horizontal section of Karstaway also retains the classic keyhole shape, with large scallops (10-20 cm) preserved in the ceiling.

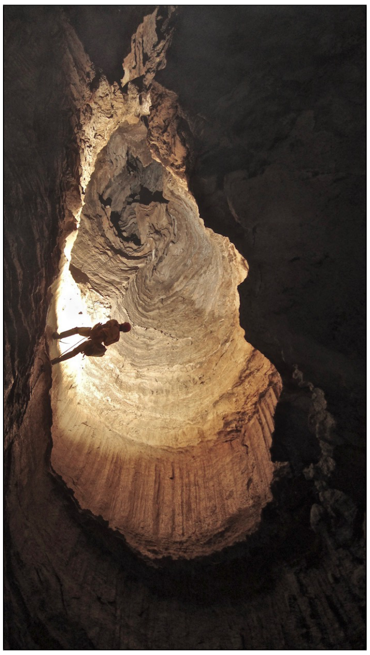

Figure 174: Fistful of Tolars (P40) A typical fluted, circular pitch in the Vrtnarija entrance series which shows corrosion by waterfall spray and canyon incision at the topmost section 📷 *Jarvist Frost*

Vertical development

Pitch series development Most vertical shafts in Sistem Migovec follow sub-vertical fractures or faults. They exhibit vadose morphologies e.g. water-film corrosion scallops in 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. Where active, the amount of water encountered in the shafts varies from a film on the walls to small drips, to a small waterfalls (very occasionally with summer discharges >0.02 m.s^{-1}). Walls flutes and rills, with amplitudes between 1-10 cm and lengths reaching 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 asl, 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 0.002 m.s^{-1}. 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 M16 and Vrtnarija passages, streams ending at sump pools are often preceded by a 60° descent along a tectonic fracture. These passages unusually contain enough water that their exploration can only be safely conducted during the winter dry season. One noteworthy streamway is located at altitude 1210 m in Vrtnarija, i.e. roughly the same altitude as the Level 3. For a distance of nearly 300 m, a stream with discharge $\approx$1 L.s^{-1} flows northwards in a passage with characteristic keyhole cross-section. Banks of small calcite and haematite pebbles in a clay-grade matrix lie on the ledges of large bends. This sub-horizontal stream passage was presumably developed a vadose entrenchment of the higher-level abandoned phreatic tube. The stream continues uninterupted down a series of small pitches before resuming with a sub-horizontal gradient at altitude 1130 m, which marks the beginning of Level 4. The relatively shallow gradient ($\approx$0.02 m.m^{-1}) sections of this large stream (by Migovec standards) are likely due to lithological control, as the local bedding is nearly horizontal, while the pitches in between represent knickpoints in the underground stream profile. 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 altitude 1460 m. The water from these separate minor streams is presumed to be collected into the Hallelujah streamway (combining to provide a discharge of $\approx$1 L.s^{-1}).

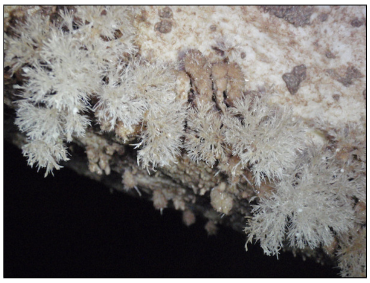

Figure 175: Aragonite needles from the horizontal palaeophreatic level of Palace of King Minos 📷 *Iztok Možir*

Cave sediments and minerals

The distribution of sedimentary sequences and speleothems is unequal. Brown loam appears to be restricted to all but the deepest horizontal segments in Levels 3 and 4. The proximity of large terminal sumps seems to dictate the deposition of laminated silts. Speleothems are patchy in distribution. Stalagmites are restricted to one 20 m section of Atlantis, and the fact that they are covered by sediment of likely glacial origin suggests they were deposited before the last glacial period. U-Th dating could be performed on these to ascertain their true age. The most common speleothems, which are restricted to the deep levels are aggregates of hydromagnesite, gypsum flowers and aragonite needles. Ice is present as snow/firn accumulations in the deep shakehole entrances of M2 and Primadona, as well as many other surface potholes. Notably, the largest ice body found so far under the mountain is located in M17.

Summary

The cave system under Tolminski Migovec is a complex 3D network of passages, where four cave forming 'levels' were identified. The outlook for exploration is still extremely good, due to the number of surface entrances which have been spotted both to the south of the Bivi, and in Area N. While it is likely that the water table was reached at the deep Vrtnarija sumps, the possibility of finding a thicker sequence of Dachstein Formation to the north of Kuk, and therefore a potentially deeper cave system cannot be excluded. Continued work at Coincidence Cave is very encouraging, and with a connection to Vrtnarija secured, access to the lower levels of the system is all but guaranteed to yield more kilometres of cave. There is still much to unlock about the speleogenesis of Tolminski Migovec, especially with regards to the westward bound Primadona, and the eventual fate of the waters there.

Figure 176: A view of the Tolminski Migovec massif, as seen from Kolovrat hill. The >2000 m asl limestone peaks of the Julian Alps ranges are in the background. 📷 *Tanguy Racine*