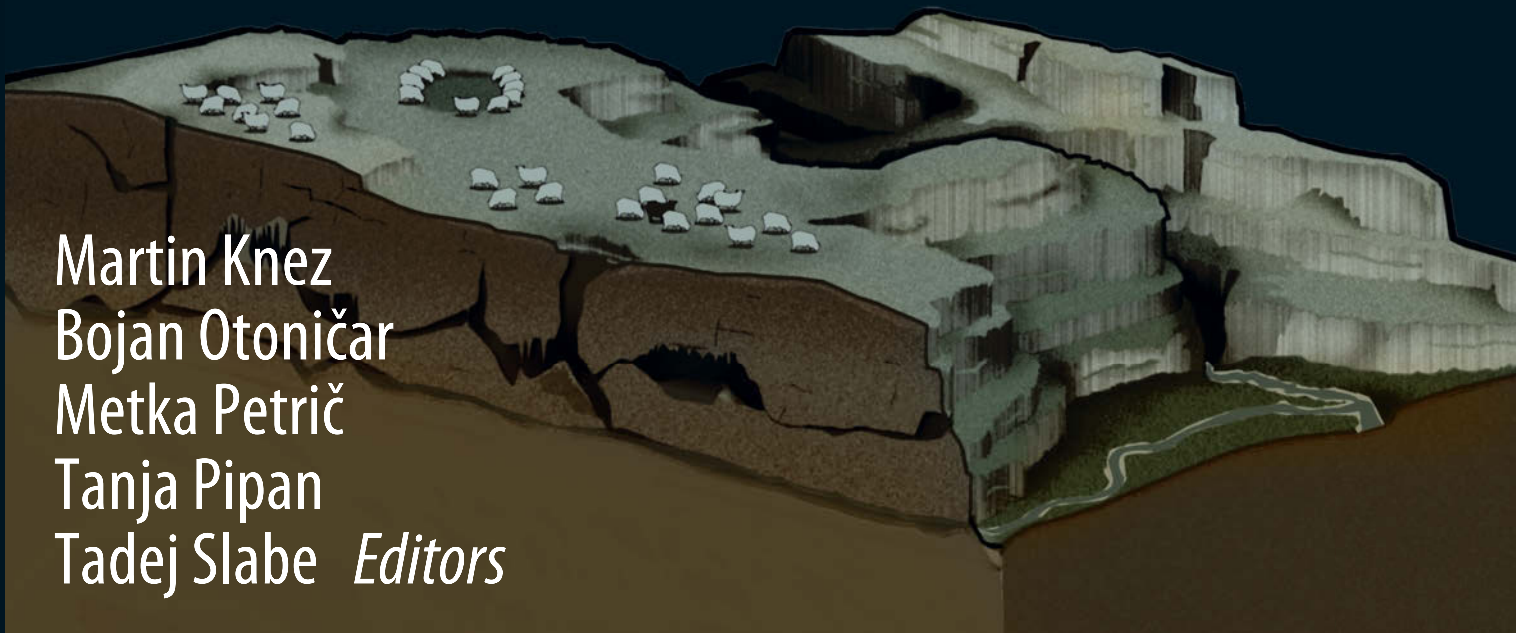
Advances in Karst Science



Martin Knez
Bojan Otoničar
Metka Petrič
Tanja Pipan
Tadej Slabe *Editors*

Karstology in the Classical Karst

Springer

Advances in Karst Science

Series Editor

James LaMoreaux, Tuscaloosa, AL, USA

This book series covers advances in the field of karst from a variety of perspectives to facilitate knowledge and promote interaction thereby building stepping stones in this process. Methodologies, monitoring, data analysis and interpretation are addressed throughout the wide range of climatic, geological and hydrogeological contexts in which karst occurs. Case studies are presented to provide examples of advancement of the science.

Issues to be addressed include water supply, contamination, and land use management. These issues although occurring on a local basis share many of the same features on the global stage. This book series is a critical resource to the scientific community allowing them to compare problems, results, and solutions. The presented information can be utilized by decision makers in making decisions on development in karst regions. Contributions presented may be used in the classroom and to work with stakeholders, scientists, and engineers to determine practical applications of these advances to common problems worldwide.

The series aims at building a varied library of reference works, textbooks, proceedings, and monographs, by describing the current understanding of selected themes. The books in the series are prepared by leading experts actively working in the relevant field. The book series *Advances in Karst Science* includes single and multi-authored books as well as edited volumes. The Series Editor, Dr. James W. LaMoreaux, is currently accepting proposals and a proposal document can be obtained from the Publisher.

More information about this series at http://www.springer.com/series/15147

Martin Knez • Bojan Otoničar • Metka Petrič •
Tanja Pipan • Tadej Slabe
Editors

Karstology in the Classical Karst

With Contributions by

Matej Blatnik, David C. Culver, Franci Gabrovšek, Martin Knez, Blaž Kogovšek, Janja Kogovšek, Hong Liu, Cyril Mayaud, Andrej Mihevc, Janez Mulec, Magdalena Năpăruş-Aljančič, Bojan Otoničar, Metka Petrič, Tanja Pipan, Mitja Prelovšek, Nataša Ravbar, Trevor Shaw, Tadej Slabe, Stanka Šebela, Nadja Zupan Hajna

Springer

Editors
Martin Knez
Research Centre of the Slovenian Academy
of Sciences and Arts, Karst Research Institute
Postojna, Slovenia

UNESCO Chair on Karst Education
Vipava, Slovenia

University of Nova Gorica
Nova Gorica, Slovenia

Metka Petrič
Research Centre of the Slovenian Academy
of Sciences and Arts, Karst Research Institute
Postojna, Slovenia

UNESCO Chair on Karst Education
Vipava, Slovenia

Tadej Slabe
Research Centre of the Slovenian Academy
of Sciences and Arts, Karst Research Institute
Postojna, Slovenia

UNESCO Chair on Karst Education
Vipava, Slovenia

Bojan Otoničar
Research Centre of the Slovenian Academy
of Sciences and Arts, Karst Research Institute
Postojna, Slovenia

UNESCO Chair on Karst Education
Vipava, Slovenia

Tanja Pipan
Research Centre of the Slovenian Academy
of Sciences and Arts, Karst Research Institute
Postojna, Slovenia

UNESCO Chair on Karst Education
Vipava, Slovenia

ISSN 2511-2066 ISSN 2511-2082 (electronic)
Advances in Karst Science
ISBN 978-3-030-26826-8 ISBN 978-3-030-26827-5 (eBook)
https://doi.org/10.1007/978-3-030-26827-5

Technical editing done by Alenka Možina

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

As karstologists in the country of the Classical Karst, we are striving to develop Slovenia's Karst Research Institute as one of the leading international karstology research and education centres. Almost half of Slovenia is karst and more than half of its water supply comes from karst aquifers. We are developing a comprehensive science of karstology incorporating all of its most important fields. With the goal of understanding the three-dimensional karst landscape, we link interdisciplinary research of the karst surface, caves, waters, and ecology, a unique approach that is also our international advantage. We are developing karst geography, geology, geomorphology, speleology, hydrogeology, biology, and microbiology. We connect field studies (including the establishment of monitoring networks and long-term measurements of water, cave climate, etc.) with laboratory investigations and laboratory and computer modelling. Lithological studies of carbonate rock are led by Martin Knez, structural geology by Stanka Šebela, and paleokarst by Bojan Otoničar; Nadja Zupan Hajna and Andrej Mihevc focus on the development of the surface, karst caves (with sediments), and karst as a whole; Tadej Slabe connects studies of cave rock and surface forms; cave and aquifer research employing mathematical modelling is being developed by Franci Gabrovšek, Matej Blatnik, and Cyril Mayaud, and hydrological studies by Metka Petrič, Nataša Ravbar, Blaž Kogovšek, and Janja Kogovšek; Mitja Prelovšek is focusing on geomorphic, hydrochemical, and meteorological aspects of present-day speleogenetic processes; research on subterranean biology section is run by Tanja Pipan and microbiological by Janez Mulec; Magdalena Năpăruş-Aljančič connects the development of our part of European infrastructural network, and Trevor Shaw coordinates study of history of karstology and speleology. David Culver comes from American University in Washington DC and Hong Liu from International Joint Research Centre for Karstology of Yunnan University.

At the international level we are expanding the basic knowledge of karst that serves as a starting point for the rational planning of life in vulnerable regions; participating in numerous directly useful projects involving water supply and conservation, the planning and construction of traffic routes, etc.; and developing and providing courses for university students. We carry out Slovenia's primary Karst Research Program. We lead and participate in numerous domestic and international projects. At the University of Nova Gorica we offer a Doctoral study in karstology that is the only one of its kind in the world and also acts as UNESCO Chair on Karst Education. We work together with karstologists from around the world. We initiated the foundation of the International Karstological Academy and continue to direct its work. We organize the International Karstological School "Classical Karst", the largest international annual conference of karstologists. The Karst Research Institute also hosts the seat of the International Union of Speleology. Together with Yunnan University in Kunming in the province of Yunnan in China we established the International Centre for Karst Research. We publish *Acta carsologica*, one of the world's leading karstological scientific journals, and edit the karstological anthology *Carsologica*. We assist in the development and promotion of karstology in numerous countries around the world.

The two latest books published in this collection (*The Beka-Ocizla Cave System, Karstological Railway Planning in Slovenia*, 2015, and *Cave Exploration in Slovenia, Discovering Over 350 New Caves During Motorway Construction on Classical Karst*, 2016) were devoted to developmental challenges on karst. This book is a part of the fundamental karst research, which remains the primary mission of the Institute even at its 73rd anniversary. We have selected the most important recent research findings.

In our research, results of which are presented in this book, we cooperated closely with Tatiana Akimova, Asma Al-Farraj, Pavel Bosák, Wolfgang Dreybrodt, Manuel Roberto Gutiérrez Domech, Jože Janež, Naško Janež, Jernej Jež, Igor Kalmykov, Luiz Eduardo Panisset Travassos, Petr Pruner, Josip Rubinić, Rosario Ruggieri, Ela Šegina, Nataša Šimac, Mirka Trajanova, and Kazuko Urushibara-Yoshino.

Postojna, Slovenia The Editors

Acknowledgements

The authors acknowledge the Karst Research Programme (research core funding No. P6–0119), the research projects (J7-7100: Natural resources of karst show caves: a balance among protection, exploitation, and promotion; J6-8266: Environmental effects and karst water sources: impacts, vulnerability and adaptation of land use; L1-7555: Development and application of method for quantity and quality assessment of ground-water resources in karst; L6-9397: Methodology for monitoring the sustainable use of karst show caves with automatic measurements—role model—Postojna cave; L7-8268: Karst research for sustainable use of Škocjan Caves as World heritage) and the Young Researchers Programme financially supported by the Slovenian Research Agency. Additional financing was provided by the Public Service Agency Škocjan Caves Park, the company Postojnska jama d. d., and the public companies Komunala Kočevje and Kovod d.o.o.

Some of the results presented were achieved in the frame of the European projects: EPOS Implementation Phase and EPOS Sustainability Phase (H2020-EU.1.4.1.1. Developing new world-class research infrastructures), RI-SI EPOS and RI-SI-2 LifeWatch (Operational Programme for the Implementation of the EU Cohesion Policy in the period 2014–2020, Development of Research infrastructure for international competition of Slovene Development of Research infrastructure area—RI-SI, European Regional Development Fund, Republic of Slovenia Ministry of Education, Science and Sport), eLTER H2020 (H2020 INFRAIA and H2020 INFRADEV Advance eLTER), eLTER RI (Long-Term Ecosystem, critical zone and socio-ecological systems Research Infrastructure; ESFRI 2018 Roadmap), LifeWatch ERIC (e-Science and Technology European Infrastructure for Biodiversity and Ecosystem Research), GEP and Škocjan–Risnjak (European Regional Development Fund Cross-Border Cooperation Programme Slovenia–Italy and Slovenia–Croatia 2007–2013). Research was included in the framework of the UNESCO IGCP project No. 661 and UNESCO Chair on Karst Education.

The authors acknowledge Leon Drame, Franjo Drole, Grega Juvan, Peter Kozel and Borut Peric for field work assistance, Mateja Zadel and Sara Skok for laboratory support.

We would like to thank reviewers Gregor Kovačič, Barbara Luke, Andreea Oargă-Mulec, Robert Armstrong Osborne, Lejla Pašić, Lukas Plan, Ira D. Sasowsky, Samo Šturm, Cheng Zhang.

Translations and language editing was provided by Amidas d.o.o., Milena Djokić, Vanessa Johnston, Barbara Luke, Robert Armstrong Osborne, Ira D. Sasowsky, Wayne Tuttle. Graphical design was made by Tamara Korošec, and photos review by Igor Lapajne and Marko Zaplatil. Technical editing was done by Alenka Možina.

We are also thankful to colleagues from Yunnan Institute of Geography, Yunnan University. Research of stone forests has been enabled by Stone Forest Research Centre of Stone Forest Scenic Spot Administration, Yunnan, China.

Contents

Contributors

Matej Blatnik Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

David C. Culver American University, Washington, DC, USA

Franci Gabrovšek Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Martin Knez Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Blaž Kogovšek Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Janja Kogovšek Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Hong Liu Yunnan University, Kunming, China

Cyril Mayaud Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Andrej Mihevc Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Janez Mulec Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Magdalena Năpăruş-Aljančič Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Bojan Otoničar Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Metka Petrič Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Tanja Pipan Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Mitja Prelovšek Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Nataša Ravbar Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Trevor Shaw Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Tadej Slabe Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Stanka Šebela Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

Nadja Zupan Hajna Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia

1 Structural–Geological Mapping of Karst Areas

Matej Blatnik, David C. Culver, Franci Gabrovšek, Martin Knez, Blaž Kogovšek, Janja Kogovšek, Hong Liu, Cyril Mayaud, Andrej Mihevc, Janez Mulec, Magdalena Năpăruş-Aljančič, Bojan Otoničar, Metka Petrič, Tanja Pipan, Mitja Prelovšek, Nataša Ravbar, Trevor Shaw, Tadej Slabe, Stanka Šebela, and Nadja Zupan Hajna

For understanding geological structure of karst areas (Palmer 2007), it is inevitably to have detailed geological maps. But karst areas are mostly geologically mapped only as parts of basic geological maps (1:100,000 in Slovenia). If we deal with the example of Slovenia, we need to stress that besides basic geological maps we have tectonic maps and sketches of smaller areas in SW Slovenia, which help to better understand the tectonic and geodynamic situation (Placer 1981, 1982, 1996; Placer et al. 2010; Čar 2018). And we have a geological map of the southern part of the Trieste–Komen Plateau (Cretaceous and Paleogene carbonate rocks) in the scale 1:50,000 (Jurkovšek et al. 1996). But detailed structural–geological maps of karst areas in the sense of Čar and Gospodarič (1984) are still rare. For understanding development of karst features, it is thus significant to make very detail structural–geological maps in scales as 1:5,000, 1:1,000 or even 1:500 of caves and of the karst surface.

After the Second World War, karst areas of Slovenia were primarily studied by stratigraphy. In this sense, Pleničar (1960) described stratigraphic development of the Cretaceous rocks of the Notranjska region and determined that passages of the Postojna Cave are mostly parallel to the beds (Pleničar 1961).

The dependence of the origin and formation of cave passages on the faults and fissures of the Postojna Cave, including the wider area of SW Slovenia, has been researched in particular by Gospodarič (1963, 1964, 1965, 1968, 1969a, b, 1976). He produced detailed maps of the lithostratigraphic units of both the Postojna karst surface and underground as well as maps of the Postojna anticline structure together with the faults and fissures intersecting the anticline.

In the SW Slovenia field mapping of karst surface expanded in 1980s in the scale 1:5,000 (Čar 1982; Čar and Gospodarič 1984). Čar (1982) divided tectonically fractured zones into fissured, broken and crushed zones regarding different intensities of tectonic change of the rock. In fissured zones, the carbonate rocks are least fractured, and stratification is still visible. Broken zone is more fractured zone where rock often occurs as blocks, which may be physically displaced. Crushed zone is most fractured where stratification has been destroyed and rocks are crushed to the degree of tectonic breccia and clay. Fractured zone properties may change from one pattern to another in horizontal and vertical directions (Čar 1986).

By using the method of detailed tectonic–lithological mapping of the surface at a scale of 1:5,000, cave passages of the caves Planinska Jama, Črna Jama and Pivka Jama were connected with the already determined tectonically fractured zones on the surface with some degree of accordance (Čar 1982; Čar and Gospodarič 1984).

In 1990s, the method of detailed structural–geological mapping was transmitted to karst caves, such as Predjama (Šebela and Čar 1991; Šebela 1996) and Postojna Cave (Šebela 1992, 1998) owing to good speleological maps. This was an important progress in understanding the formation of karst caves regarding the structural–geological elements. The mapping was carried out according to Čar's (1982) classification of tectonically fractured zones. For the first time, this method was used experimentally in the cave passages and chambers of Predjama at a scale of 1:1,000. At a vertical distance of about 100 m, some tectonically fractured zones in the cave with outcrops on the surface by means of the longitudinal sections of the cave and those of the surface above were connected (Šebela and Čar 1991).

M. Blatnik · F. Gabrovšek · M. Knez (✉) · B. Kogovšek · J. Kogovšek · C. Mayaud · A. Mihevc · J. Mulec · M. Năpăruş-Aljančič · B. Otoničar · M. Petrič · T. Pipan · M. Prelovšek · N. Ravbar · T. Shaw · T. Slabe · S. Šebela · N. Zupan Hajna
Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia
e-mail: knez@zrc-sazu.si

D. C. Culver
American University, Washington, DC, USA

H. Liu
Yunnan University, Kunming, China

M. Knez et al. (eds.), *Karstology in the Classical Karst*, Advances in Karst Science,
https://doi.org/10.1007/978-3-030-26827-5_1

After structural–geological mapping of Predjama, Postojna Cave was selected to be mapped in detail. An advantage of the Postojna Cave was its good cartographic base–ground plans, cross sections and longitudinal sections at a scale of 1:500 which were made by Gallino Petrini and Sartori in 1933–34, and supplemented by Hribar and Michler in 1948–60 (Caves Registry). Additional modifications and improvements were made in 1972 and 1983–84 by Kenda, and were supplemented in 1989–98 by Drole (Caves Registry).

Positions of Postojna anticline and interbedded slips due to thrusting and folding deformations were shown as important structural–geological elements that influenced the formation of cave passages. On the basis of the cross sections in the tourist part of Postojna Cave and those of the cave section of the underground Pivka River, it was established that 41.2% of the cross sections have been developed in tectonically fractured zones (Šebela 1998).

The importance of selected bedding planes for the formation of phreatic channels was determined as well by Knez (1996) in the case of Velika Dolina collapse doline in Škocjan Caves.

Surface structural–geological mapping was as well going on, and geological–structural position of vertical karst objects was presented for the area above Pivka and Črna Jama of the Postojna Cave system (Čar and Šebela 1997). Geological maps of the karst springs at the contact between non-carbonate and carbonate rocks in the Vipava Valley were presented by Janež (1997) and Janež and Čar (1997). Different cases of shaping of dolines regarding structural–geological conditions on the karst surface were shown by Čar (2001) and Šebela and Čar (2000). Development of karst at thrust contact limestone–dolomite was presented in 2001 (Čar and Šebela 2001).

Based on detailed structural–geological cave maps, Šušteršič et al. (2001) determined that position of collector channels is dependent on deflector fault, which in Postojna Cave has a Dinaric trend (NW–SE). The collector channel gathers underground streams that should cross the broken zone of the deflector fault (Šušteršič 2006).

Structural–geological map of the Škocjan Caves has been published by Šebela (2009). This was a compilation map of field mapping from the period 1991–2009 where field mapping represented big challenges due to high (up to 120 m) and big cave passages and due to the lack of good visibility.

Connections between underground cave passages, structural geology and hydrology of water channels were shown with structural–geological mapping in the 1:5,000 scale above passages of the cave Kačna Jama near Divača (SW Slovenia) (Žvab Rožič et al. 2015).

Recently, LiDAR tool is enabling important geomorphological upgrade for karst regions (Zlot and Bosse 2014; Mahmud et al. 2016), which helps geological field mapping but cannot completely replace it. By using LiDAR and UAV (unmanned aerial vehicle) in semi-arid Brazil karst fracture system, connection between development of karren features and fracture systems was shown (Silva et al. 2017).

Detailed structural–geological cave and karst surface maps are the base for other karst-related researches as karst hydrology, chemistry of percolated waters in caves, geophysical research in karst (georadar, geoelectricity, seismicity), displacement monitoring of active tectonic structures, hydraulic modelling of karst areas, etc.

1.1 Case Studies

1.1.1 Longitudinal Geological Cross-Section Snežnik Mountain–Planina Cave

In the case when a geological map is needed for understanding oscillations and direction of groundwater flow in the mountainous karst area, basic geological maps can help, especially if no other more precise geological maps are available and if there is not enough time or financial support to perform time-consuming detailed field geological mapping in forested and mountainous area. Here, we present the karst area of Snežnik Massif–Javorniki Mountains (Fig. 1.1) in SW Slovenia (Petrič et al. 2018) between Snežnik Mountain (1796 m a.s.l.) and Malni karst spring at the base of Planina polje (448 m a.s.l.), where carbonate rocks can reach the thickness of up to 3,300 m (Pleničar 1970; Šikić and Pleničar 1975).

In tectonic sense, this area is part of External Dinarides. Thrust fault structure typical for NW part of External Dinarides is conditioned by paleogeographical conditions of the Adriatic–Dinaric carbonate platform (Placer et al. 2010). Thrust deformations started at the end of Cretaceous and especially after deposition of Eocene flysch. In the area of Snežnik Massif–Javorniki Mountains neotectonic structures as Predjama Fault as well as folds as secondary structures of the thrusting are detected. Faults show multi-phase tectonics with reactivations. This area is tectonically active (e.g. an earthquake on the western side of Javorniki Mountains in April 2014 with $M = 4.4$).

The area was studied because of the location of Poček (Fig. 1.2), which is a military training area in Slovenia and completely belongs to karst (Kogovšek et al. 1999). A principal underground water flow from Poček is in the direction towards north to the Malni spring, which is a principal drinking water catchment for Postojna town. At Poček, carbonate rocks are tectonically broken in two principal fault orientations: NW–SE and NE–SW. For the vertical and horizontal water flow, the most favourable are tectonic zones in N–S and NE–SW orientations. Those are open fissures, which developed in relaxation tectonic conditions.

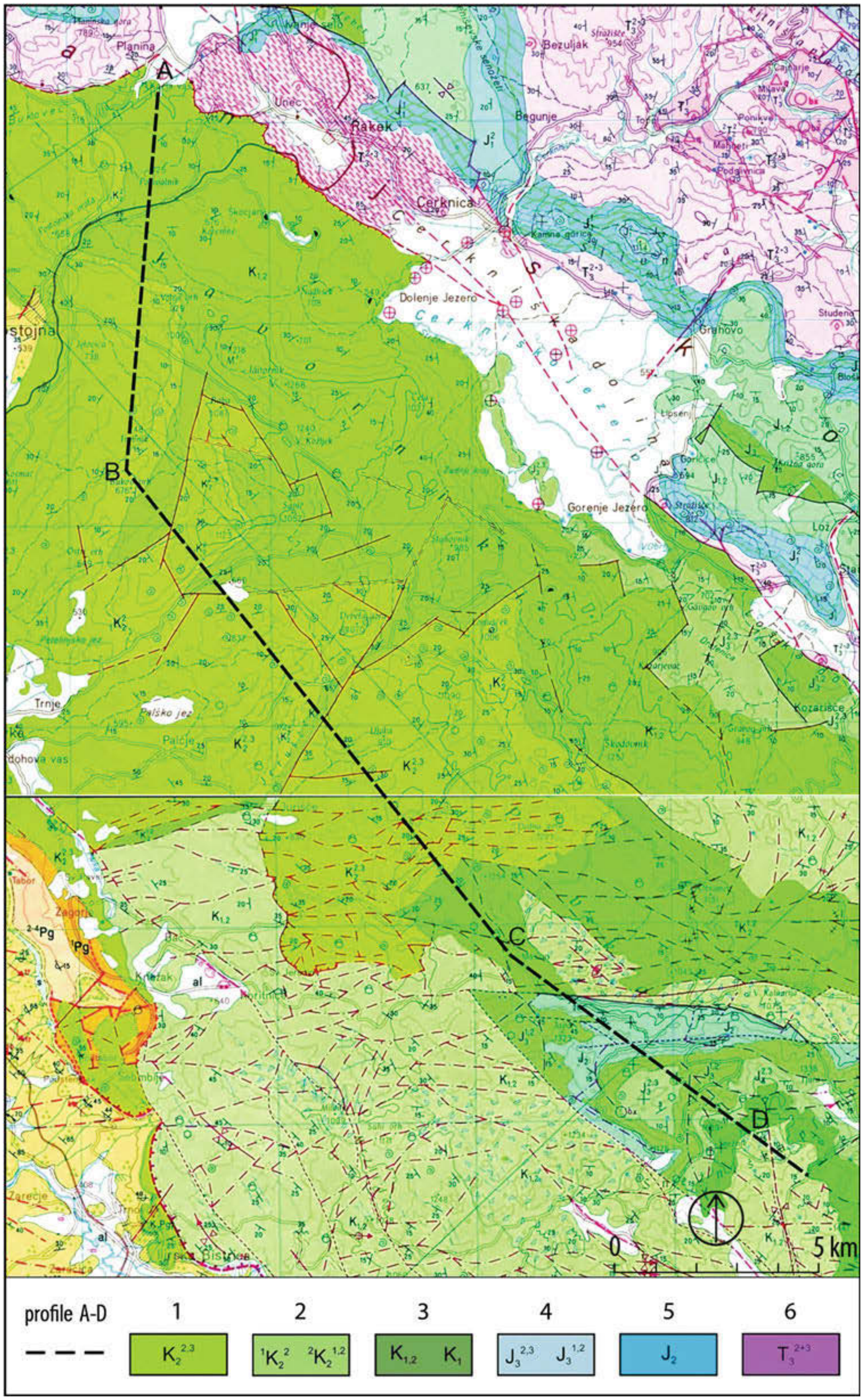


Fig. 1.1 Course of longitudinal geological profile A–D (*A* Malni, *B* Poček, *C* Mašun, *D* Snežnik) on selected sector of basic geological maps 1:100,000 Postojna (Buser et al. 1967) and Ilirska Bistrica (Šikić et al. 1972). *Legend* *1* $K_2^{2,3}$—Cretaceous limestone with rudists and thinner dolomite layers; *2* $_1K_2^2$ and $_2K_2^{1,2}$—Cretaceous limestones with some dolomites; *3* $K_{1,2}$—Cretaceous limestone with layers of bituminous dolomite, limestone and dolomite breccias on Snežnik Mountain, K_1—limestones and partly dolomites; *4* $J_3^{1,2}$ and $J_3^{2,3}$—Jurassic limestone; *5* J_2—Jurassic dark grey dolomite in alteration with grey limestone; *6* T_3^{2+3}—Upper Triassic dolomite

To make the longitudinal geological profile A–B–C–D, morphology was taken from the 1:50,000 morphological map. Lithological and tectonic data were taken from more sources as the Basic geological map Postojna (Buser et al. 1967) and Ilirska Bistrica (Šikić et al. 1972), from the structural–geological map of Čar and Gospodarič (1984) and from the tectonic map of Poljak (2000). Elevation of cross section of the Rak water channel at Planina Cave was added according to

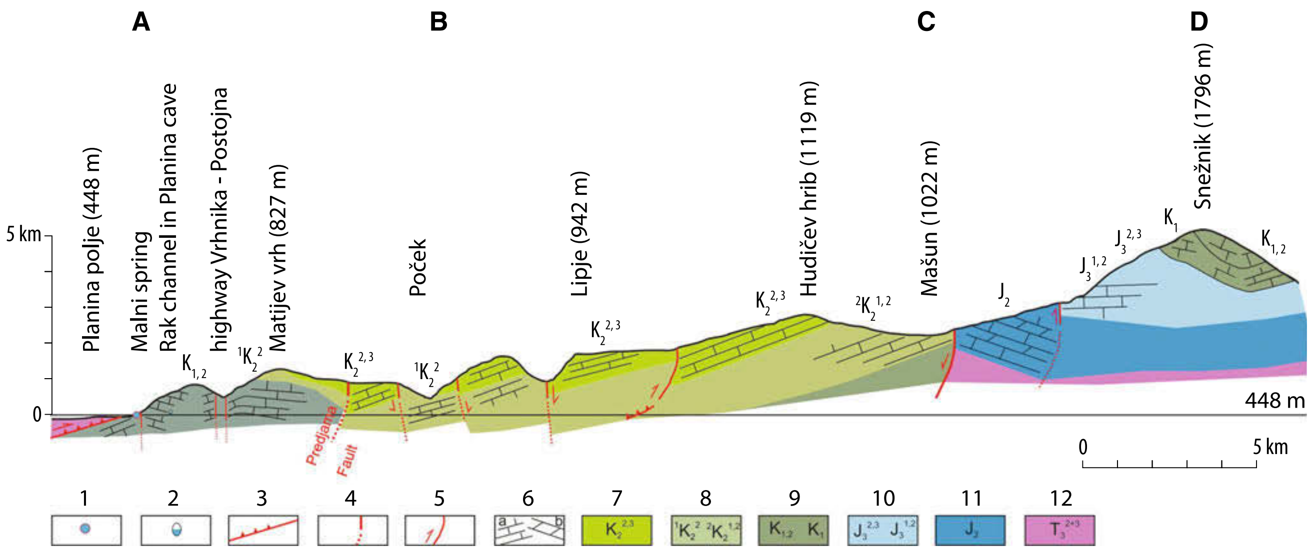


Fig. 1.2 Longitudinal geological profile A–D (*A* Malni, *B* Poček, *C* Mašun, *D* Snežnik). *Legend 1* Malni spring; *2* cross section of the Rak channel in Planina Cave; *3* thrust fault; *4* a fault with possible continuation; *5* vertical movement along a fault; *6a* limestone; *6b* dolomite; *7* $K_2^{2,3}$—Cretaceous limestone with rudists and thinner dolomite layers; *8* $_1K_2^2$ and $_2K_2^{1,2}$—Cretaceous limestones with some dolomites; *9* $K_{1,2}$—Cretaceous limestone with layers of bituminous dolomite, limestone and dolomite breccias on Snežnik; K_1—limestones and partly dolomites; *10* $J_3^{1,2}$ and $J_3^{2,3}$—Jurassic limestone; *11* J_2—Jurassic dark grey dolomite in alteration with grey limestone; *12* T_3^{2+3}—Upper Triassic dolomite. Longitudinal cross section modified by S. Šebela after Buser et al. (1967), Čar and Gospodarič (1984), Poljak (2000), Šikić et al. (1972). Profile heights are not in the same scale as the profile length

speleological data. Direction of fault movements was determined regarding the position of stratigraphic units and the dip angle of bedding.

We see that some extent already existing geological maps with some additional self-made longitudinal sections can help in specific karst-related studies.

1.1.2 Detailed Structural–Geological Mapping of the Postojna Cave Area

The area of Postojna Cave (cave and surface) was first mapped by Gospodarič (1965, 1976). Besides lithology, he studied fault planes and fissures in the cave which were not described as zones. The new tectonic–lithological mapping of Postojna Cave was done in the scale 1:500 (Šebela 1998). For the development of cave passages, importance of interbedded movements (flexural slip) which represent secondary deformations of the Postojna anticline with axis orientation NW–SE was specially stressed (Šebela 1998, 2012).

Duplex in Postojna Cave (Fig. 1.3a) is attributed to the period of overthrusting of the Upper Cretaceous limestones over Eocene flysch rocks. This was the same period that caused the vergence of the Postojna anticline axis towards SW for 7°–14° (Šebela 1998).

A result of detailed structural–lithological mapping of karst caves is a very precise structural–geological map. An example of such map is presented in Fig. 1.4. This is a hand-drawn map from 1994 of the part of Postojna Cave. We can see that there are numerous fissures that are combined to zones. When we put fractured zones on the cave map, we are able to get the image of different directions of the fractured zones and connections between them (in the sense which fractured zone is cut by another zone).

With studies of 93 cross sections in Postojna Cave (Šebela 1998), it was determined that 37.6% of cross sections are shaped according to bedding. It was shown that selected cave passages are formed along bedding planes (Fig. 1.3e), moved bedding planes and connective fissures. The advantage for speleogenesis of some bedding planes and moved bedding planes is represented with their connection into penetrative effective porosity in specific structural block (Čar and Šebela 1998).

In the same period as geological mapping of the cave, structural geological mapping of the surface directly above Postojna Cave was accomplished (Šebela 1998, 2012). Principal fault zones on the surface were connected with fault zones mapped in cave passages. If we add LiDAR map on geology and cave ground plan, we get a clear detailed morphological and structural–geological map of the area above Postojna Cave (Fig. 1.5).

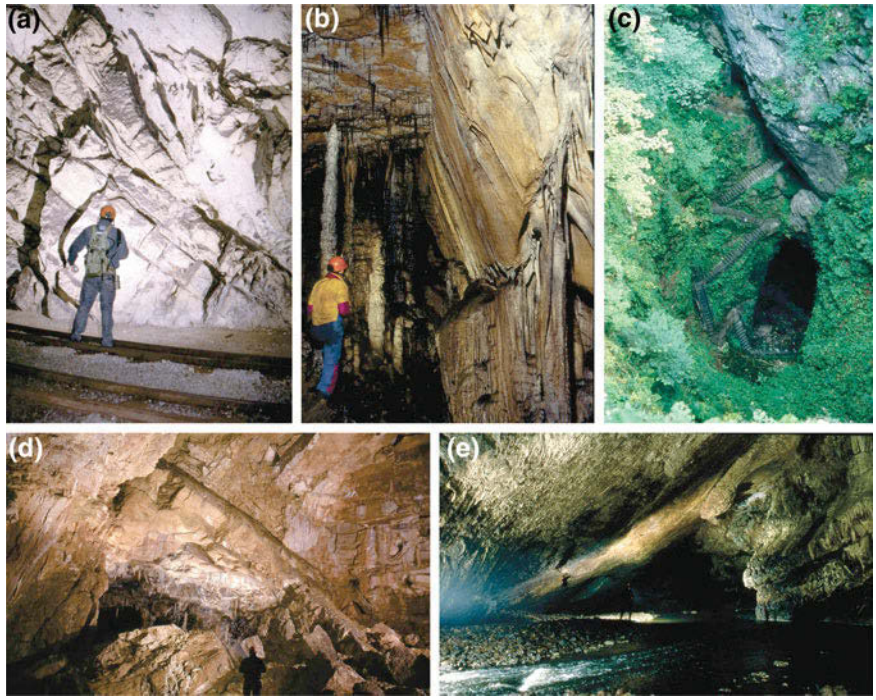


Fig. 1.3 Geological structures in Postojna Cave. *Legend* **a** Duplex due to overthrusting in Stara Jama, **b** fault plane is building a cave wall in the passage Rov brez imena, **c** entrance to Pivka Jama is developed along fault zone, **d** fault plane with low angle dip in Pisani rov collapse room, **e** underground Pivka River channel follows direction of bedding planes visible on the cave ceiling

According to the Basic geological map (Buser et al. 1967), the limestones which make up the Postojna Cave as well as the surface above may be attributed to the Upper Cretaceous, i.e. the Turonian and Senonian $K_2^{2,3}$ and Cenomanian K_2^1 age. *Chondrodonta* lumachelle horizon may be observed in a road cutting between Risovec blind valley and the cave Pivka Jama. The horizon is attributed to the Upper Cenomanian by Rižnar (1997). In Fig. 1.5, we left this horizon inside Turonian $\left(K_2^2\right)$. Čar (2018) divided K_2^3 horizon into K_2^3 and $K_2^{3,4}$. In Fig. 1.5, we did not divide Senonian K_2^3 horizon. Regarding recent field observations, Maastrichtian (the most upper part of the Upper Cretaceous) carbonate rocks are present in the area of Postojna karst (Otoničar, pers. comm. 2019).

To understand dependance between formation of karst surface and underground features on structural–geological features, generations and type of regional tectonic activity must be included. Within the area between Postojna, Planina and Cerknica, Čar and Gospodarič (1984) determined generations of fault zones and the structural geometry of the Snežnik thrust sheet between the Idrija and Predjama faults. They established four generations of deformations from the Neogene and supposedly the Quaternary. The tectonic conditions of the treated terrain are divided into

- older movements,
- thrust structures and folds, and
- fault deformations.

At the end of the Eocene or in the Oligocene, the Alpine–Dinaric region was subjected to intense overthrusting. The beds were first folded and subsequently were broken. During the Miocene and Pliocene, the overthrusting was accompanied by folding (Placer 1982).

The faults of the first generation trending NE–SW were active in all the tectonic movements, probably even up to the Holocene. The influence is thought to be present also in collapse dolines around Vodni dol and in those around the blind valley Risovec, as well as in the orientation of the water channels in Črna Jama and Pivka Jama caves. In all these cases, we deal with active water channels which are perpendicular to the folded beds (Čar and Gospodarič 1984).

The Predjama Fault (Fig. 1.5) is steep NW–SE trending fault which is one of the most significant regional faults and runs along the NE part of the Pivka basin, passes Postojna and proceeds to the SE (Placer 1981).

Wider Predjama Fault zone passes Postojna Cave where tectonic micro-displacements are continuously measured since 2004 by TM 71 extensometers (Šebela et al. 2010). In the period 2004–2018, we detected 0.07 mm of dextral horizontal and vertical movement (in the sense of normal fault) along Dinaric oriented (NW–SE) fault zone in Velika Gora collapse chamber. This shows that some tectonic zones in Postojna Cave belonging to wider Predjama Fault zone (Fig. 1.5) are still tectonically active (Šebela 2008; Sasowsky et al. 2003).

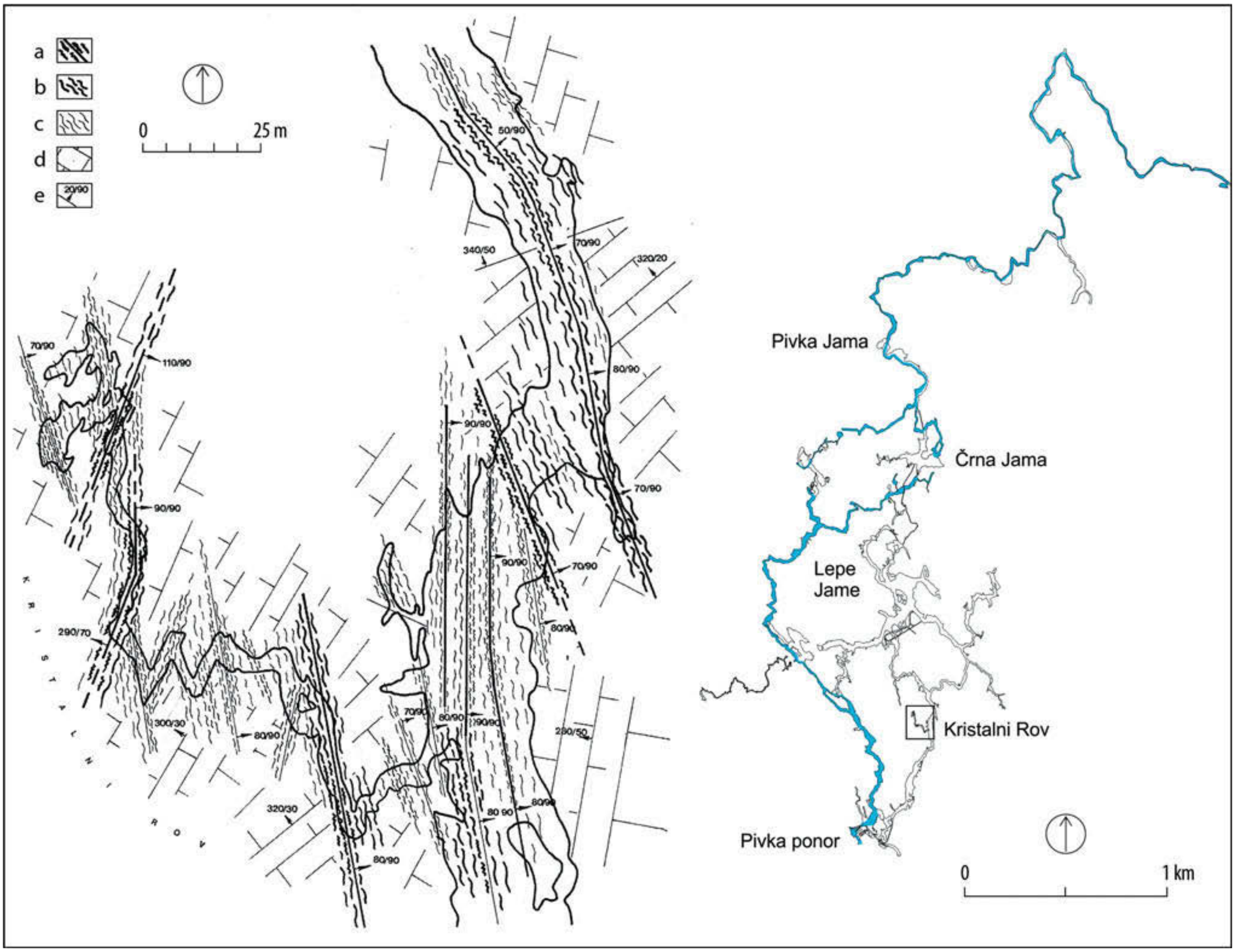


Fig. 1.4 Detailed structural–geological map of Kristalni Rov in Postojna Cave. *Legend a* crushed zone, *b* broken zone, *c* fissured zone, *d* Upper Cretaceous limestone, *e* dip direction and dip angle of bedding planes. Geology mapped and drawn by Šebela in 1994

1.1.3 Folding Deformations and Caves

It is obvious that many cave passages formed accordingly to regional structural geology. Detailed tectonic–lithological mapping in the scale 1:1,000 of the three big cave systems in SW Slovenia (Postojna Cave system, Predjama Cave and Škocjan Caves) showed connections between bedding planes and development of cave passages. Cave passages of the Postojna Cave are developed on both flanks of the Postojna anticline. Syncline axis is expressed north from Škocjan Caves passages, while in the area of Škocjan Caves we can only see dipping of the syncline axis as gentle folds. Relation between eastern passage of Predjama and Stara Jama caves shows the position of anticline axis (Fig. 1.6).

Formation of the Postojna anticline is post- or co-thrusting period of the Upper Cretaceous limestones over Eocene flysch. The same is probably the case in Predjama Cave. Additionally, in Predjama's western passage there is a thrust fault where Upper Triassic dolomite is thrusted over Upper Cretaceous limestones. Predjama's anticline deformation can be related to this even older deformations as well. In the Cave Stara Jama interbedded slips due to folding deformations are well visible and responsible deformation for passage development. Postojna anticline axis is Dinaric oriented (NW–SE), while anticline axis in Predjama is for 55° declined towards north (Fig. 1.6) regarding Postojna anticline.

Syncline axis in the area of Škocjan Caves has cross-Dinaric orientation (NE–SW) and can be related to near-faulting deformations (Divača Fault running in the vicinity), because contact between Eocene flysch and Upper Cretaceous and Paleocene limestone is further away as in Postojna and Predjama Caves.

In all three caves, some passages are characteristically formed along interbedded slips which developed due to folding. Bedding planes, especially those deformed by

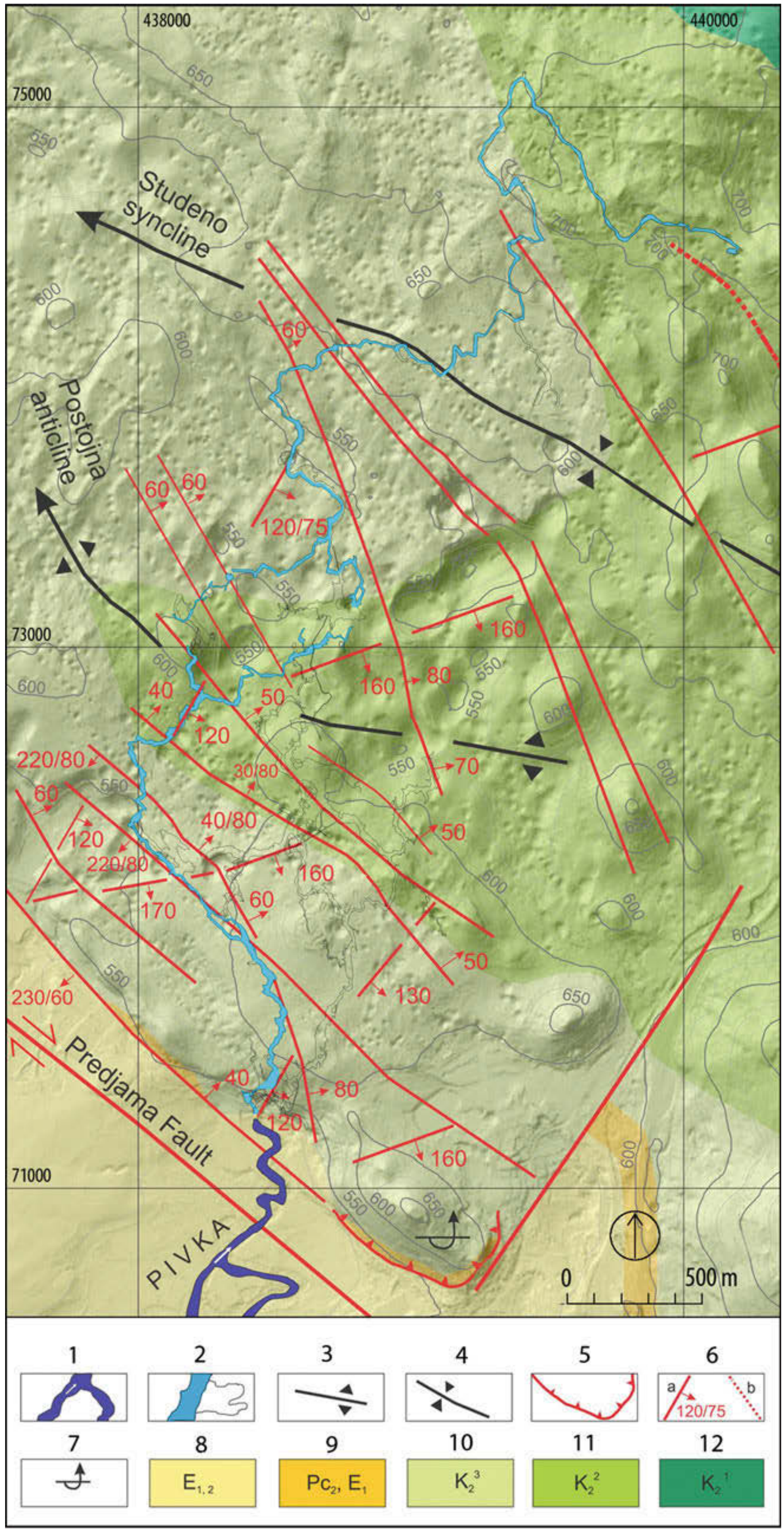


Fig. 1.5 Geological map of the area above Postojna Cave. *Legend 1* surface Pivka River, *2* underground Pivka River, *3* anticline, *4* syncline, *5* thrust fault, *6a* fault dip direction and dip angle, *6b* supposed fault dip direction and dip angle, *7* overturned beds, *8* Eocene flysch rocks, *9* limestone breccia and conglomerate (Pc_2, E_1), *10* Upper Cretaceous limestone–Senonian (K_2^3) after division by Čar (2018), *11* Upper Cretaceous limestone–Turonian (K_2^2), *12* upper Cretaceous limestone–Cenomanian (K_2^1)

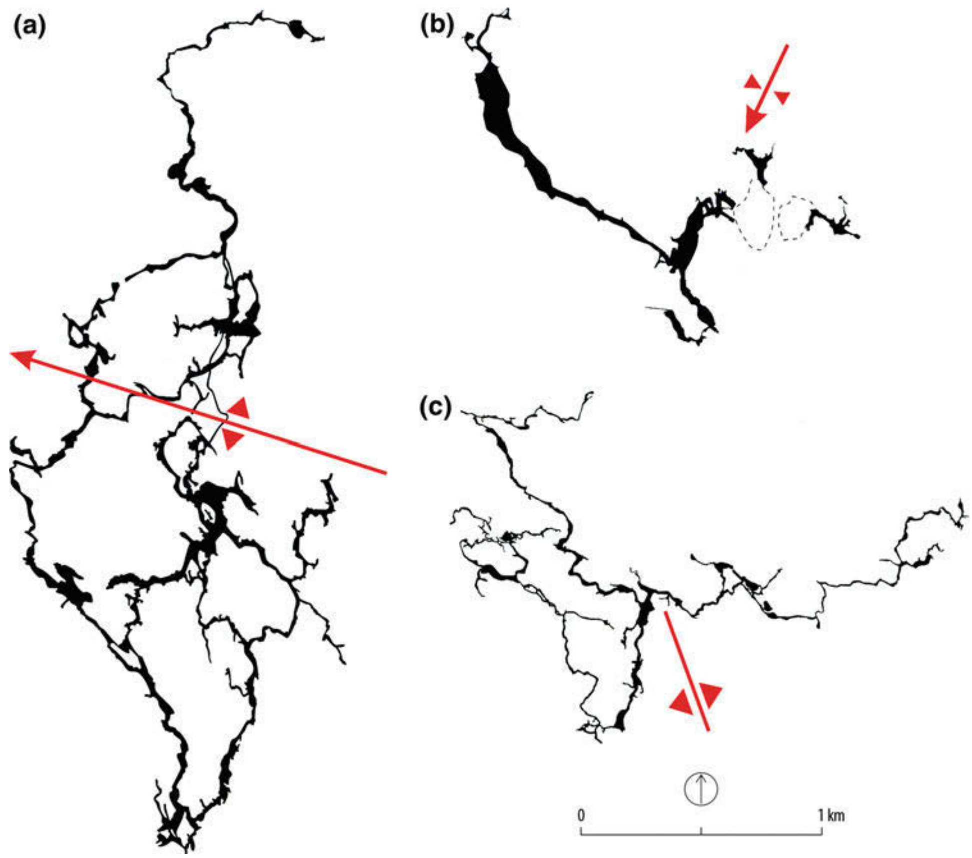


Fig. 1.6 Ground plans of **a** Postojna cave, **b** Škocjan caves and **c** Predjama cave with anticline (**a** and **c**) and syncline (**b**) axis

interbedded slips, are one of the most important structural elements inside or along which cave passages developed. Cave passages of studied caves are formed on both flanks of folds. Anticlines resulted due to compression in folding tectonic events and are primarily not related to younger faulting.

1.2 Conclusion

Fundamental knowledge about the karst forms cannot be separated from an understanding of the geological structure. Karst areas can be regarded as a dynamic, spatial, geological–hydrological and speleological-succession systems, which are under the constant influence of ongoing tectonic movements (Čar 2018).

Detailed field geological mapping of karst in Slovenia in the last 40 years showed strong connection between geological structure and formation of karst surface and underground features. Cave passages are developed according to geological structural elements such as joints, faults, folds, bedding planes and interbedded slips. In studied caves (Postojna Cave, Predjama and Škocjan Caves), tectonised bedding planes play an important role for cave passages formation. Principal regional folds are Dinaric oriented (NW–SE) in Postojna and Predjama Caves. Due to folding interbedded slips or flexural slips developed what represented the weaknesses in carbonate massif used by waters to form underground paths–karst caves. Bedding planes especially those deformed by interbedded slips are one of the most important structural elements inside or along which cave passages developed. Cave passages of Postojna Cave and Predjama are formed on both flanks of anticlines.

Surface tectonic and karst features are well seen on LiDAR maps, but only this information cannot replace field hard-rock geological mapping. Development of digital tools (as photogrammetry) in karst geology is very applicable (Triantafyllou et al. 2019), but detailed field structural–geological mapping cannot be completely exchanged with some kind of automatic method yet. Basic knowledge of karst geology is still waiting for us in the field.

References

Buser S, Grad K, Pleničar M (1967) Basic geological map of SFRJ, sheet Postojna 1:100000. Zvezni geološki zavod, Beograd
Čar J (1982) Geologic setting of the Planina Polje ponor area. Acta Carsolog 10:75–105
Čar J (1986) Geological bases of karst surface formation. Acta Carsolog 24–25:31–38

Čar J (2001) Structural bases for shaping of dolines. Acta Carsolog 30 (2):239–256
Čar J (2018) Geostructural mapping of karstified limestones. Geologija 61(2):133–162
Čar J, Gospodarič R (1984) About geology of Karst among Postojna, Planina and Cerknica. Acta Carsolog 12:91–106
Čar J, Šebela S (1997) Structural position of vertical karst objects on Postojnska Gmajna. Acta Carsolog 26(2):295–314
Čar J, Šebela S (1998) Bedding planes, moved bedding planes, connective fissures and horizontal cave passages (examples from Postojnska jama cave). Acta Carsolog 27(2):75–95
Čar J, Šebela S (2001) Karst characteristics of thrust contact limestone-dolomite near Predjama. Acta Carsolog 30(2):141–156
Gospodarič R (1963) Exploring the Postojna cave—the gay coloured tunell. Naše jame 4:9–16
Gospodarič R (1964) Traces of the tectonic movements in the glacial period in the Postojna cave. Naše jame 5:5–11
Gospodarič R (1965) Geology of the area between Postojna, Planina and Cerknica. Postojna, unpublished report, p 40 (in Slovene)
Gospodarič R (1968) Les stalactites et stalagmites renversées dans la Grotte de Postojna. Naše jame 9:15–31
Gospodarič R (1969a) Les processus spéléologiques du pleistocene supérieur dans la Grotte de Postojna. Naše jame 10:37–46
Gospodarič R (1969b) Probleme der Bruchtektonik der NW Dinariden. Geol Rundschau 59(1):308–322
Gospodarič R (1976) Razvoj jam med Pivško kotlino in Planinskim poljem v kvartarju (summary The quaternary caves development between the Pivka basin and Polje of Planina). Acta Carsolog 7:8–135
Janež J (1997) Hydrogeology. Karst hydrogeological investigations in south-western Slovenia, 7th SWT. Acta Carsolog 26(1):73–86
Janež J, Čar J (1997) Geologic conditions and some hydrogeologic characteristics of the Vipava springs. Karst Hydrogeological investigations in south-western Slovenia, 7th SWT. Acta Carsolog 26(1):86–91
Jurkovšek B, Toman M, Ogorelec B, Šribar L, Drobne K, Poljak M (1996) Formacijska geološka karta 1:50.000 južnega dela Tržaško-Komenske planote (Geological map of the southern part of the Trieste—Komen plateau 1:50,000). Cretaceous and Palaeogene carbonate rocks. Inštitut za geologijo, geotehniko in geofiziko, Ljubljana, p 143
Knez M (1996) Vpliv lezik na razvoj kraških jam. Primer Velike doline, Škocjanske jame (summary The bedding-plane impact on development of karst caves. An example of Velika dolina, Škocjanske jame caves). Zbirka ZRC 14, Ljubljana, p 186
Kogovšek J, Knez M, Mihevc A, Petrič M, Slabe T, Šebela S (1999) Military training area in Kras (Slovenia). Environ Geol 38(1):69–76
Mahmud K, Mariethoz G, Baker A, Treble PC, Markowska M, McGuire E (2016) Estimation of deep infiltration in unsaturated limestone environments using cave lidar and drip count data. Hydrol Earth Syst Sci 20:359–373
Palmer AN (2007) Cave geology. Cave Books, Dayton, Ohio, p 454
Petrič M, Kogovšek J, Ravbar N (2018) Effects of the vadose zone on groundwater flow and solute transport characteristics in mountainous karst aquifers—the case of the Javorniki-Snežnik massif (SW Slovenia). Acta Carsolog 47(1):35–51
Placer L (1981) Geološka zgradba jugozahodne Slovenije = Geologic structure of southwestern Slovenia. Geologija 24(1):27–60
Placer L (1982) Structural history of the Idrija mercury deposit. Geologija 25(1):7–94
Placer L (1996) On the structure of Sovič above Postojna. Geologija 37–38(1994–1995):551–560
Placer L, Vrabec M, Celarc B (2010) The bases for understanding of the NW Dinarides and Istria Peninsula tectonics. Geologija 53 (1):55–86
Pleničar M (1960) The stratigraphic development of cretaceous beds in Southern Primorska (Slovene Littoral) and Notranjska (Inner Carniola). Geologija 6:22–145
Pleničar M (1961) Beitrag zur Geologie des Höhlensystems von Postojna. Naše jame 1–2(1960):54–58
Pleničar M (1970) Basic geological map of SFRJ 1:100,000. Geology of the Postojna Sheet. Zvezni geološki zavod, Beograd, p 62
Poljak M (2000) Strukturno-tektonska karta Slovenije 1:250,000. Mladinska knjiga tiskarna d.d, Ljubljana
Rižnar I (1997) Geologija okolice Postojne. Magistrsko delo, Univerza v Ljubljani, Naravoslovnotehniška fakulteta, Oddelek za geologijo, Ljubljana, p 78
Sasowsky ID, Šebela S, Harbert W (2003) Current tectonism and aquifer evolution >100,000 years recorded in cave sediments, Dinaric karst, Slovenia. Environ Geol 44(8):8–13
Silva OL, Bezerra FHR, Maia RP, Cazarin CL (2017) Karst landforms revealed at various scales using LiDAR and UAV in semi-arid Brazil: consideration on karstification processes and methodological constraints. Geomorphology 295:611–630
Šebela S (1992) Geological characteristics of Pisani rov in Postojna cave. Acta Carsolog 21:97–116
Šebela S (1996) The influence of tectonic zones on cross section formations in the Predjama cave, Slovenia. Kras i speleologia 8:72–77
Šebela S (1998) Tectonic structure of Postojnska jama cave system. ZRC Publishing 18, Ljubljana, p 112
Šebela S (2008) Broken speleothems as indicators of tectonic movements. Acta Carsolog 37(1):51–62
Šebela S (2009) Structural geology of the Škocjan Caves (Slovenia). Acta Carsolog 38(2–3):165–177
Šebela S (2012) Postojna-Planina cave system, Slovenia. In: White WB, Culver DC (eds) Encyclopedia of caves, 2nd edn. Academic Press, Amsterdam, pp 618–624
Šebela S, Čar J (1991) Geological setting of collapse chambers in Vzhodni rov in Predjama cave. Acta Carsolog 20:205–222
Šebela S, Čar J (2000) Velika Jeršanova doline—a former collapse doline. Acta Carsolog 29(2):201–212
Šebela S, Vaupotič J, Košt'ák B, Stemberk J (2010) Direct measurement of present-day tectonic movement and associated radon flux in Postojna cave, Slovenia. J Caves Karst Stud 72(1):21–34
Šikić D, Pleničar M (1975) Tumač za list Ilirska Bistrica, Osnovna geološka karta 1:100000. Savezni geološki zavod, Beograd, p 50
Šikić D, Pleničar M, Šparica M (1972) Osnovna geološka karta SFRJ, list Ilirska Bistrica 1:100000. Savezni geološki zavod, Beograd
Šušteršič F (2006) Relationships between deflector faults, collapse dolines and collector channel formation: some examples from Slovenia. Int J Speleol 35:1–12
Šušteršič F, Čar J, Šebela S (2001) Collector channels and deflector faults. Naše jame 43:8–22
Triantafyllou A, Watlet A, Le Mouélic S, Camelbeeck T, Civet F, Kaufmann O, Quinif Y, Vandycke S (2019) 3-D digital outcrop model for analysis of brittle deformation and lithological mapping (Lorette cave, Belgium). J Struct Geol 120:55–66
Zlot R, Bosse M (2014) Three-dimensional mobile mapping of caves. J Cave Karst Stud 76:191–206
Žvab Rožič P, Čar J, Rožič B (2015) Geological structure of the Divača area and its influence on the speleogenesis and hydrology of Kačna Jama. Acta Carsolog 44(2):153–168

2 Late Cretaceous and Paleogene Paleokarsts of the Northern Sector of the Adriatic Carbonate Platform

Matej Blatnik, David C. Culver, Franci Gabrovšek, Martin Knez, Blaž Kogovšek, Janja Kogovšek, Hong Liu, Cyril Mayaud, Andrej Mihevc, Janez Mulec, Magdalena Năpăruş-Aljančič, Bojan Otoničar, Metka Petrič, Tanja Pipan, Mitja Prelovšek, Nataša Ravbar, Trevor Shaw, Tadej Slabe, Stanka Šebela, and Nadja Zupan Hajna

In Western Slovenia, a paleokarstic surface with clayey bauxite deposits separates late? Cenomanian to late Turonian strata from middle/late Coniacian palustrine?, peritidal and shallow-marine carbonate deposits along the external-most preserved parts of the Adriatic Carbonate Platform (AdCP). In southwestern Slovenia and Istria (SW Slovenia and NW Croatia), an even more pronounced paleokarstic surface characterised by bauxite deposits separates the Valanginian/Hauterivian to Campanian shallow-marine carbonates of the inner parts of the AdCP from the late Campanian?/Maastrichtian to Eocene palustrine, peritidal and shallow-marine carbonates of the synorogenic carbonate platform.

Because of the asynchronous character of the stratigraphic gaps and their apparent temporal and partially also spatial continuity, Korbar (pers. comm.) proposed that both paleokarsts may have formed during one and the same paleokarstic period as a result of the same geotectonic event. It was further proposed that during the Late Cretaceous these two areas were separated by a deeper marine interplatform basin (i.e. the NE Adriatic trough as a northern continuation of the Budva Basin) (Korbar 2009) which split the northern sector of the Adriatic-Dinaridic carbonate platform (*s. lato*) into the Adriatic and Dinaridic carbonate platforms (*s. stricto*) (Korbar 2009) and also interrupted the uniformity of the paleokarst.

This work aims to show that during the Late Cretaceous two spatially and temporally separated paleokarstic periods occurred in the northern sector of the AdCP which were not in a direct causal relationship. Moreover, we will also show that in the area where both paleokarsts pinched out (i.e. wider Postojna region) or were not developed, no evidence for a deep-marine interplatfrom basin occurs.

Since carbonate platforms are predominantly very shallow-marine depositional systems, not only large, but also a considerably small, relative sea-level falls can expose them to terrestrial conditions and hence karstification. The nature of subaerial exposures with the general geological and depositional evolution of the investigated and adjacent areas, as well as events at plate boundaries and the eustatic sea-level changes, hide the causes for the occurrence of a particular paleokarst. In this chapter, we will follow the classification of Osborne (2000) which defines paleokarst as karst developed largely or entirely during past karst periods, i.e. long-lasting times of continental weathering and groundwater circulation, which was terminated by an ensuing marine transgression over the karstic surface (Bosák et al. 1989). This classification is also in accordance with the general definition of the karst (see Klimchouk and Ford 2000), from which follows that a karst (hydrological) system passes into a paleokarst when its mass transport function has been lost. Thus, from a hydrogeological point of view, a karst aquifer becomes paleokarst when it stops transporting aggressive water and becomes isolated from an active karst system. In this respect a paleokarst does not imply any particular type of a karst but rather refers to a condition, namely a karst as a system that has become fossilized.

Carbonate platforms are depositional systems where most of the world's carbonate sediments/rocks have been deposited. Similarly, as the plate tectonics determines the development of depositional carbonate successions (see Bosellini 1989), bauxite (see D'Argenio and Mindszenty 1995) and karst occurrences among others also depend on the geodynamic evolution and distance of an area from lithospheric plate boundaries. Thus, carbonate platforms may experience

M. Blatnik · F. Gabrovšek · M. Knez (✉) · B. Kogovšek · J. Kogovšek · C. Mayaud · A. Mihevc · J. Mulec · M. Năpăruş-Aljančič · B. Otoničar · M. Petrič · T. Pipan · M. Prelovšek · N. Ravbar · T. Shaw · T. Slabe · S. Šebela · N. Zupan Hajna
Research Centre of the Slovenian Academy of Sciences and Arts, Karst Research Institute, Postojna, Slovenia
e-mail: knez@zrc-sazu.si

D. C. Culver
American University, Washington, DC, USA

H. Liu
Yunnan University, Kunming, China

M. Knez et al. (eds.), *Karstology in the Classical Karst*, Advances in Karst Science,
https://doi.org/10.1007/978-3-030-26827-5_2

an entire geodynamic spectrum of the Wilson cycle during their lifetimes. Each stage of the Wilson cycle yields its own tectonic characteristics that influence not only the depositional history of a certain carbonate platform but also its diagenetic history, constructive and destructive. Carbonate platforms in terms of active sediment systems cease to grow as active sediment systems when they become exposed to conditions where significant production of carbonates is prevented. Such conditions are achieved, among others, if a carbonate platform is exposed to a land, and a relative sea-level fall may be the result of eustatic or/and tectonic processes. So, the platform may be subjected to aggressive waters that cause dissolution or karstification of different extent and duration. At the end, the carbonate platform may literally die away, frequently from the uplift or drowning of substantial parts of the platform due to orogenic processes. Thus, the development of a particular type of karstification is to a great extent a function of the position of the carbonate platform relative to its geotectonic position.

2.1 Geological Setting

During the Mesozoic carbonate platforms that thrived in the area of today's Slovenia were located in dynamic geotectonic realms, greatly influenced by events at the lithospheric plate boundaries in the area close to the various ocean bays of the western Tethys. The passive continental margins of the adjacent continental plates and microplates were prone to extensive colonization by carbonate platforms, which were only occasionally interrupted by the sedimentation of terrigenous clastics. Tectonically-influenced deviations from the expected arrangement of depositional sequences at passive continental margins are often associated with geotectonic events at more or less distant active lithospheric plate boundaries, particularly during their rearrangement. During the Mesozoic, carbonate platforms located in the area of today's Slovenia witnessed to all phases of the geodynamic spectrum of the Wilson cycle.

To a great extent the geological characteristics of Slovenia result from its geotectonic position between the African and Eurasian plates and the intermediate Adriatic-Apulian microplate (AAMP) (*sensu* Stampfli et al. 1998). Currently, three major geotectonic units meet here—the Alps, the Dinarides and the Pannonian basin, which with their specific geological evolution also resulting in somehow different character and abundance of carbonate rocks and related karst.

In Slovenia, a majority of karst terrains are located in the Dinarides and Southern Calcareous Alps in the western half of Slovenia (Fig. 2.1). In the Dinarides, carbonate rocks occupy mainly western and southwestern part of Slovenia or a fold-and-thrust belt of the External Dinarides, while in the Southern Calcareous Alps form a major part of the Julian Alps, Kamnik-Savinja Alps and Karavanke Mountains or its S- to SE-verging fold-and-thrust belt (Fig. 2.1). Mountainous karstic regions of the Dinarides and Southern Calcareous Alps and their foothills are separated from the Central Alps (i.e. the Eastern Alps) by the pronounced Periadriatic fault (Fig. 2.1), while towards the west and east they sink below the Tertiary and Quaternary deposits of the Po and Pannonian Basins and the Adriatic Sea.

Recently, in a geotectonic sense, the area of the western half of Slovenia belongs to the Dinaric-Hellenic plate, while autochthonous Istria (in terms of Placer 1998) belongs to the Adria or the Adriatic-Apulian microplate (AAMP), respectively. For most of the Mesozoic Period the region between Eurasia and Gondwana, or the western part of the 'Great Tethys Bay' of Pangea, was occupied by a more or less uniform AAMP, the size and shape of which have been changing accordingly to the main geotectonic events throughout the geologic history. In the northeastern part of the AAMP, a more or less uniform and isolated Adriatic Carbonate Platform (AdCP) (see below), surrounded by deep-marine interplatform and oceanic basins, was formed after Middle Triassic and Triassic/Jurassic extensional tectonic phases.

According to the tectonic regionalization of Placer (1998), the study area in western Slovenia consists of the External Dinarides and the Dinaric Foreland (Fig. 2.1). A nappe structure in the northwestern part of the External Dinarides contains five successively lower and younger thrust units. From northeast to southwest these follow the Trnovo Nappe, Hrušica Nappe, Snežnik Thrust Sheet, Komen Thrust Sheet and Kras Thrust Edge (Placer 1981, 1998, 2004) (Fig. 2.1).

The External Dinarides and the Dinaric foreland correspond to the northwestern part of the Cretaceous Adriatic Carbonate Platform and the Upper Cretaceous-Eocene synorogenic carbonate platform which occupied the northeastern part of the AAMP. In the Cretaceous, the area of the present-day Southern Alps was a part of the deeper marine realm which comprised the Slovenian Basin (Cousin 1981; Buser 1989) and the area of former Julian Carbonate Platform (Cousin 1981; Buser 1989) (see above).

The geologic and paleogeographic situation started to change dramatically in the Late Cretaceous (see below). Due to a general compressional tectonic regime or to tectonic activities at plate boundaries, a few regional paleokarstic periods interrupted a shallow-marine carbonate deposition on the otherwise passive margin of AdCP from the Middle Jurassic until the Late Cretaceous. In the External Dinarides, the Mesozoic shallow-marine deposits of the AdCP are overlain by the Maastrichtian to Eocene shallow to gradually deeper marine limestone of the synorogenic carbonate platform and prograding hemipelagic marls and deep-water clastics (flysch). At the periphery of the foreland basin, carbonate successions of the AdCP are separated from the