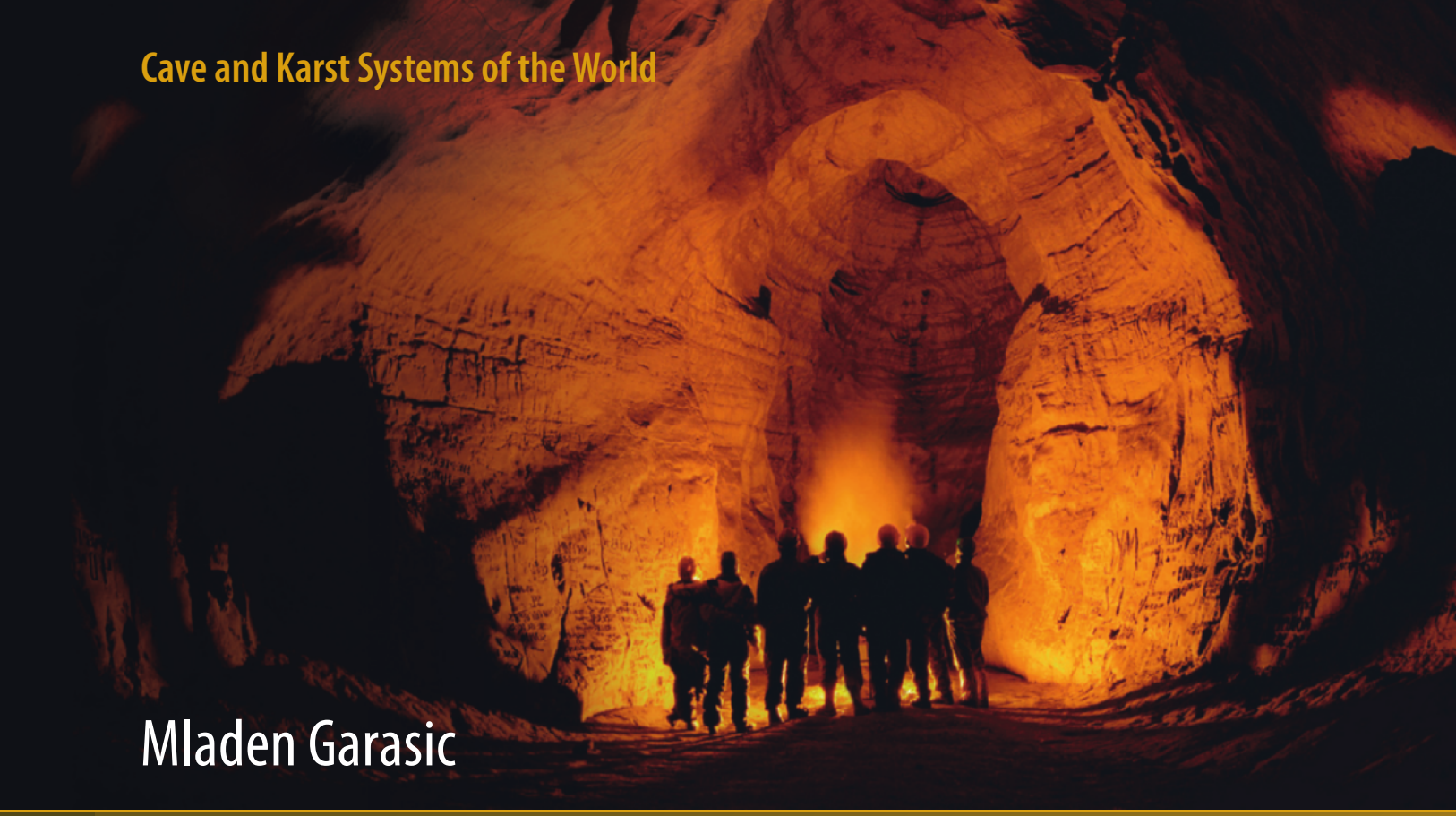
Cave and Karst Systems of the World



Mladen Garasic

The Dinaric Karst System of Croatia

Speleology and Cave Exploration

Springer

Cave and Karst Systems of the World

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Speleology and Cave Exploration

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ISSN 2364-4591 ISSN 2364-4605 (electronic)
Cave and Karst Systems of the World
ISBN 978-3-030-80586-9 ISBN 978-3-030-80587-6 (eBook)
https://doi.org/10.1007/978-3-030-80587-6

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

Preface

One of the most important things I have realized throughout the years of my scientific life was the fact that just because I do not see or know enough about the processes around me it does not mean they do not exist or occur. This is the main driver for developing new ideas and understanding. The underground world of karst is full of mysteries that keep pushing us towards the new discoveries. Exploring the less known or unknown phenomena attracts the scientific interest.

The idea about this book was evolving inside me for years. For over fifty years, I have been entering the underground realm of karst. Whether as an amateur, a professional or a scientist, I have visited thousands of caves throughout the world and have written hundreds of scientific articles about them. Therefore, I felt the need to write a book which would succinctly describe the cave phenomena and their research in a Classic Karst environment—The Dinaric Karst. I focused on the Croatian part of Dinaric Karst where I started practising speleology and where I observed some of the phenomena which are rare or still undiscovered in other parts of the world.

Over a thousand caves in the Croatian part of the Dinaric Karst did not have a natural entrance from the surface until recently. They were subsequently discovered during construction works such as tunnelling, building roads, bridges, quarries and hydropower plants. Some of the rare and previously unknown processes that created them were discovered in those caves—caverns. I have visited all continents and got to know the underground world of around eighty countries, thus realizing the Dinaric Karst is special in a lot of ways.

During my stay in New Mexico, Ph.D. Jim Lamoreaux, the editor of the respectable scientific journal *Environmental Earth Science* by Springer, introduced the idea of publishing a series of books about karst and caves of the world. I feel the right moment has come to give the readers a summary about the scientific understanding of a unique part of karst that they will be able to compare to other types of karst in the world. *The Dinaric Karst System in Croatia—Speleology and cave exploring* will be part of the series of books *Cave and karst System in the World* by Springer.

This book is meant for speleologists, geologists, experts in geoscience and students of geoscience as a new source of data and as a useful handbook. I did not want to repeat the information already published in similar books. I simply wanted to point out some things that were not mentioned in the scientific literature before or were not emphasized enough. This is not a book about all the caves in Croatian Karst nor the list of caves in Dinaric Karst. This is a summary of the current speleological understanding about a small, very important and interesting karst area in the world.

I would like to thank all the people that helped me develop my knowledge throughout the years, collecting data and publishing this book. Special thanks goes to Public institution (PI) “Žumberak—Samoborsko gorje Natural Park”, Dugopolje Tourist board, Fužine Tourist board, PI “Učka Natural Park”, PI “Natura Jadera”, PI “Paklenica National Park”, PI “ Mljet National Park”, PI “Priroda Dubrovačko—Nevetvanska” Dubrovnik, PI “Priroda” Rijeka, PI “Priroda” of Šibenik—Knin County, Silvio Legović, Jama Baredine, Institute for Quaternary Paleontology and Geology of Croatian Academy of Sciences and Arts (HAZU), academician Ivan Gušić, Prof. Ph.D. Meho Saša Kovačević, mr.sc. Slobodan Kolbah, Prof. Ph.D. Maša

Surić, Prof. Ph.D. Tomislav Malvić, Prof. Ph.D. Josipa Velić, Ph.D. Kristina Pikelj, Prof. Ph. D. Čedomir Benac, Neven Korač, mag.ing.geol., Ph.D. Boris Vrbanac, Ph.D. Jadranka Mauch Lenardić, Marija Brajković, dipl.ing.geol., Prof. Ph.D. Darko Mayer, Ph.D. Josip Terzić, Ph. D. Petra Konrad Kovač, Ph.D. Natalija Matić, Ph.D. Vesna Štamol, Milica Bjelić, dipl.iur., Croatian Environmental Protection Agency, PI "Sjeverni Velebit National Park", Damir Lacković, dipl.ing.geol., Ph.D. Neven Cukrov, Ph.D. Gordan Lukač, Zlatko Marasović, Ph.D. Dubravka Kljajo, Ivana Maras, Donat Petricioli, Vladislav Brnčić.

Aside from the majority of photographs I have taken personally, some of the best speleophotographers like Boris Krstinić, Dinko Stopić, Alan Kovačević, Tihomir Kovačević, Gordan Polić, Željko Marunčić, etc. allowed me to use some of their photographs in this book.

The works of three Croatian experts of speleology and geology Dr. Josip Poljak, academician Dr. Mirko Malez and Dr. Srećko Božičević, who were my predecessors in many researches of Croatian Karst motivated me to continue with their research and to inspire the future generations to do the same.

I would also like to thank the hydrogeologists and geologists who expertized in solving the problems in Croatian Karst and whose works are used in this book: Željko Babić, Željko Blagus, Dinka Borčić, Božidar Biondić, Ranko Biondić, Luka Bojanić, Srećko Božičević, Franjo Fritz, Ivan Gušić, Milan Herak, Mladen Juračić, Vladimir Jurak, Mladen Kuhta, Antun Magdalenić, Mirko Malez, Darko Mayer, Ante Pavičić, Josip Poljak, Andrej Stroj, Josip Terzić, Kosta Urumović, Željko Vulić …

I would like to thank posthumously my friends speleologists who helped me with the research: Tomislav Marinčić, Mladen Šebian, Ljubiša Kalinić, Boris Resimić, and Drago Opašić.

I would like to thank all the members of DISKF, especially Tihomir Kovačević, Tihomir Jukica, Alan Kovačević, Boris Watz, Ivan Krpina, Tomislav Gospodinović, Davor Garašić, Toni Terzić, Krešimir Ajduković, Ivan Drnić, Goran Kresnik, Mislav Krvavica, Nebojša Anić, Tomislav Jech, Hrvoje Jelković, Tomislav Jech, Edo Aganović, Miljenko Garašić, Miroslav Hranjec, Zlatko Piškorić, Nevio Putinja, Eugen Ujčić, Vedran Putinja, Mladen Raškaj, Tibor Perok, Slobodan Meničanin, etc. who helped me with the research of many dangerous caverns and caves.

I am grateful and thankful for the international help from the members of the UIS bureau Ph.D. Fadi Nader, Ph.D. George Veni and academician Ivan Gušić for advises and review of this book.

A special thanks goes to "Jama Baredine" and my friend Silvio Legović that helped me finance the English translation and the proof reading of this book. I would like to thank Davor Garašić and Eleni Ktisti for the English translation, editing and proof reading.

Years of working on this book must have affected my family so I am sincerely grateful for the understanding and support during the time of writing. Without the support of my family, this book would have never been written.

Zagreb, Croatia Mladen Garasic

Acknowledgements

Photographs: The author of all photographs printed in this book is Mladen Garasic except if state otherwise. Other authors are: Srećko Božičević (Fig. 6.7), J. P. Bresser (Fig. 3.35), Mark Burkey (Fig. 4.26), Luigi Casati (Fig. 3.33), Alan Kovačević (Fig. 3.30), Tihomir Kovačević (Figs. 3.16 and 7.12), Boris Krstinić (Figs. 1.1, 1.4, 1.12, 2.14, 3.19, 3.46, 3.50, 4.12 and 9.8), Damjan Krstinić (Fig. 2.9), Željko Marunčić (Figs. 3.9 and 10.35), Gordan Polić (Figs. 3.42, 4.27, 4.44 and 9.13), Tonći Rađa (Fig. 10.32), Krzysztof Starnawski (Fig. 3.37), Dinko Stopić (Figs. 3.5, 3.6, 3.52, 3.53, 4.13, 9.12, 10.31 and 10.41), Goran Šafarek (Fig. 3.29), Boris Vrbek (Fig. 4.6).

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About the Author

Prof. Mladen Garasic, Ph.D. is one of the world's well-known caver and speleologist with more than 56 years of continuous activity in international caving and speleology.

He has Ph.D. in geology, hydrogeology, and geological engineering and ScD. in earth sciences.

Born in Zagreb, Croatia, in 1951, Mladen Garasic graduated in geology and karst hydrogeology in 1977. He earned his master's degree in 1981, and doctorate in geosciences and geological engineering in 1986. He is a scientist and a professor of geology, karst hydrogeology, applied geology, engineering geology and speleology at the University of Zagreb and Technical University of Graz (Austria). He has authored more than 360 scientific and professional papers and about 800 speleological and geological reports. He serves as a Karst committee secretary for the Croatian Academy of Sciences and Arts (HAZU), he is the member of UNESCO World Heritage Team for the Dinaric Karst, International Association of Hydrogeologists, International Association for Engineering Geology and the Environment, etc.

He started with caving in 1963 and was one of the founder and president of several caving clubs in Croatia. He served as the first president of the Croatian Speleological Federation from 1990 to 2010 (elected five times on general Assemblies of CSF).

Since 1993 to 2018, he has served as Croatia's delegate to the International Union of Speleology—UIS (24 years) and to the European Speleological Federation—FSE beginning in 2009 (8 years).

Prof. Garasic has conducted research in, and explored and visited more than 5150 caves in 80 countries on all continents. He has led many speleological expeditions in the longest and deepest caves in Croatia, Europe and the world. He also studied about 1050 caves without natural entrances, discovered by tunnels and quarries, and evaluated their hydrogeology and engineering geology.

He was the youngest member ever in Croatia who passed exam for cavers in caving organizations. He is cave diver and cave rescuer. He was founder of Zagreb Speleological School in 1971, school that has one of the longest tradition and every years teach 20–30 new cavers. He was editor and one of the authors of the first Manual for cavers on Croatian language (1976). Cave photographer (he has taken more than 300,000 photos from the caves) and bibliophile of speleological literature (collected more than 30,000 speleo editions).

He was one of rare Croatian scientists who wrote and passed doctorate (1986) on speleology field. He is member of many organizing and scientific international, regional and national committees on congresses and conferences (speleology, karstology, geology, hydrogeology, geotechnics, etc...). He and his team projected and constructed the longest bridge in the world (58 m long) ever made in big cave chamber in the highway's tunnel (2006–2008).

He was invited speaker for more than twenty times the entire world and attended 12 International Congresses of Speleology. He was the first and the only member of NSS from Croatia (Yugoslavia) tens of years which he began in 1977. He is member of Geological Society of America for years too.

He is experienced instructor in caving, made several exploring and teaching expeditions (Africa, Asia, Middle East, South America, Caribes...) and got some awards for these jobs. He is editor and coordinator of UIS Caver's International Dictionary written on 29 languages (!), speleological Bulletin Spelaeologia Croatica (1990–2007), cave diver, cave rescuer (1971–1979).

Croatia is small country with well-known karst, with four caves deeper than 1000 m (the deepest is Lukina jama -1432 m), and the longest inside vertical cave channel in the world (-518 m), and the second entering vertical (-553 m) cave channel in the world, deep karst river spring (Una river dive to -248 m), etc. All these are in world well-known Dinaric Karst, with several UNESCO World heritage localities (Plitvice Lakes, Dubrovnik, Split, Trogir, Zadar, etc.). The first speleological organization in Croatia was founded on 20th of February 1892—the fourth in the world.

Mladen Garasic is Adjunct Secretary of International Speleological Union (UIS) for periods 2013–2017 and 2017–2021, and Vice President of European Speleological Federation (FSE) for period 2015–2019.

For his professional and scientific speleological works, he has been proclamated as honorary member of several speleological federations and associations in Croatia and the World.

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Introduction to Karst and Geology of Croatia

1

Abstract

The Dinaric Karst of Croatia was formed in a tectonically active area, where several geotectonic plates of variable size are in direct contact. The African tectonic plate, with its smaller Adriatic plate, extends northwards towards the Alps. The Adriatic plate subducts under the Dinaric plate, which is the base part of the Dinaric Mountains. Therefore, this is a seismically palaeo and neotectonically active area with many earthquakes. Since these area is composed mainly of soluble carbonate rocks (mostly Mesozoic and Cenozoic ages) that are up to 8 km thick in this area, with favourable hydrogeological conditions, the karstification processes are very prominent. A brief overview of the geology of Croatia also indicates the complexity of hydrogeological processes in this area.

Dinaric Karst is the area where the first scientific exploration and research on the surface and underground began. In this area, the first theories about the movement of the groundwater in karst were born. Therefore, it is not surprising that one part of the Dinaric Karst is called Classic Karst. Dinaric Karst is the birthplace of speleology and cave explorations as well as the modern hydrogeology of the karst (Ford and Williams 2007; White 1988).

It is important to mention that the word karst originated from the area of Dinaric Karst. This area was the birthplace of some other internationally accepted terms such as polje, ponor, dolina, etc., which describe certain karst phenomena and relief.

"Dinaric Karst" was named after the Dinara Mountain which is the highest mountain in Croatia (Fig. 1.1). Dinara Mountain spreads from north-west to south-east which suggests the significant era of karst genesis in this part of Europe (Fig. 1.2). The largest area of Dinaric Karst is located in Croatia, but there are areas of it in Italy, Slovenia, Bosnia and Herzegovina, Montenegro, Serbia and Albania. Almost all of the Dinaric Karst area under the Adriatic Sea is located in Croatia.

Unlike the term "Dinaric Karst", the terms "Dinarides" or "Dinaric Alps" represent the area consisting both of karst and non-karst.

1.1 Karst Reliefs

Josip Roglić a world-known Croatian geographer, geomorphologist, the second president of Croatian Speleological Society (later Federation), defines karst as a set of phenomena related to flow of water and forms of relief in carbonate rocks. In one of his subsequent works, Roglić (1974) states: "Karst is a specific form of relief and circulation of water on soluble rocks (limestones), but karst also appears in saddle (gypsum) terrains. Water drainage and the creation of karstic relief are mutually causal and functionally linked and need to be observed together."

Milan Herak wrote in the well-known university textbook *Petrography and Geology (1966)*: "For karst it is characteristic that underground water communication is stronger than on the surface (Bögli 1980; Bakalowicz 2005) and is related to hollows of different dimensions which gradually expand due to the solubility (corrosion) of limestone and dolomite." Karst areas in Croatia are very widespread and the karst morphological and hydrological particularities are mostly well developed. Their historical significance is also great because the foundations of the karstic doctrine are set up precisely in these terrains. In the classification of karstic fields, Herak and Stringfield (1972) uses a tectogenetic approach and on the basis of specific morphological and hydrogeological features. He distinguishes between two types of karst. "Epirogenetic" (deep) karst with tabular and bored basin and "orogenetic" (accumulated) karst with oblique, bored, dissected basin.

Hydrologist Bonacci (1987) in the book *Karst Hydrology* states: "Karst represents an area composed of a special surface and underground relief and a surface-underground hydrographic network resulting from the circulation of water

M. Garasic, *The Dinaric Karst System of Croatia*, Cave and Karst Systems of the World,
https://doi.org/10.1007/978-3-030-80587-6_1

Fig. 1.1 Dinara Mountain is the highest mountain in Croatia

Fig. 1.2 Dry riverbed of the karst river and Dinara Mountain

and its aggressive chemical and physical action on fractures, fissures and cavities in layers of soluble rocks such as limestone, chalk, dolomite, gypsum and salt. Karst inherent soluble rocks are located on or near the ground surface. The karstification process is the result of the physical and chemical action of water dissolving and transferring dissolved solids from the rock mass."

Srećko Božičević in his work *Fenomen krša* (1992), writes: "From the geological point of view, karst is a characteristic form of relief on the limestone-dolomite substrate, predominantly on the rocky carbonate surface, formed by the long run of precipitation and flowing water. The karst as a morphologically-hydrogeological peculiarity of the relief is characteristic or specific to a series of irregular spiked or toothed peaks on a rough stone surface where we do not regularly find surface water flows."

Garašić (1986, 1991), in several papers, points out the essential conditions for forming the karst: "water-soluble rocks, intensive tectonic activity (cracking breakdown) and hydrogeological conditions (a significant amount of water acting on the primary rocks)". The karst is a specific form of relief that develops on soluble rocks (limestone, dolomite, salt, gypsum). We primarily associate it with limestone and dolomite (carbonates, $CaCO_3$ i $MgCO_3$) because of their extreme susceptibility to chemical (corrosion) and mechanical wear (erosion, abrasion) and high dispersal. The karst is characterized by specific hydrological and hydrogeological relations. These relationships are defined by absence of surface water (Fig. 1.3). Namely, surface water flows are rare and largely allogeneic, with the expressed abundance of water in the underground (Fig. 1.4). In the karst, underground runoff is always higher than surface runoff, and there are significant differences between the topographic (surface) and hydrogeological (underground) boundaries between the basins. The fractural porosity is characteristic of karst, while the phreatic water does not exist in the classical sense. It is located in several levels, depending on capillary elevation, hydrogeological dynamics of groundwater, rocks water flow, flow rate (slope, quantity, etc.). It is a fractural secondary porosity, as opposed to the primary or intrinsic porosity that occurs in cluster sediments (pebbles, sands, etc.).

International Glossary of Hydrology (1992) states that the karst areas are covered with limestones and dolomites characterized by special topography generated by the underground solution as well as the sinking of surface water.

Fig. 1.3 Absence of surface water (Bijela voda)

1.2 Geology of Croatia in General

Croatia geographically belongs to the Mediterranean countries of Europe. From a geological point of view, a part of Croatia (along the Adriatic Sea) is under the influence of geological changes caused by the shifting of the African Geotectonic Plate, and the second, inner part is under the influence of Eurasian Geotectonic Plates (Figs. 1.5 and 1.6). Recently, the assumption about the geosyncline development of the Adriatic plate has been rejected, but the thickness of the carbonate complex is estimated to be about 7–10 km (Herak 1987; Vlahović et al. 2002; Velić et al. 2003).

The structure and composition of the relief of Croatia are determined by its long geological history. From the earliest Precambrian to Cenozoic (i.e. Holocene) era, the relief of Croatia was influenced by the endogenous forces and exogenous processes in the triangle area of Asia–Europe–Africa. All three basic groups of rocks are represented in the relief of Croatia; sedimentary rocks (95% of the relief of

Fig. 1.4 Water from the riverbed infiltrates the underground

Croatia), metamorphic rocks (2–4% of the relief of Croatia) and igneous rocks (1% of the relief of Croatia). Sedimentary rocks are mostly clastic (sandstones, conglomerates, marl, breccias) and organogenetic rocks (limestones and dolomites). Metamorphic rocks are mostly marble, schist, gneiss, while igneous rocks are mostly andesite and granite. The oldest rocks ones are found in the cores of mountains Papuk, Psunj and Moslavačka gora. From the Mesozoic era, the carbonate rocks (dolomites and limestones) prevail in the karst, mostly in Banovina, Kordun, Gorski Kotar, Velebit, Lika and Dalmatia. The youngest rocks belong to the Cenozoic era (clastic sediments) (Mihevc and Zupan 1996). They can be found in the area of Pannonian and Peripannonian basin (Fig. 1.7).

1.2.1 Tectonics and Seismic Activity of Croatia

In Croatia, earthquakes occur in areas of contact between the smaller tectonic units. The cause of the earthquakes in the coastal part of Croatia is the subduction of the Adriatic platform under the Dinarides. Subduction is the result of the movement of the African tectonic plate towards the Euro-Asian tectonic plate (Fig. 1.8).

In the north-western continental part of Croatia, the causes of earthquakes are the compression processes that occur due to the movements of the Dinarides and the Alps. In the area of the Central Slavonian Mountains, the earthquakes are caused by the different movements of certain mountain masses. The margins of this area are predominantly active. The Republic of Croatia is located in the seismically active area. This is particularly true for the coastal area, especially for southern Dalmatia and the north-western part of Croatia. In the coastal area, from north-west to south-east, the earthquake zone extends from the border with Slovenia to the area south of Senj. Seismic activity is less present in the area between Velebit and Bukovica. Further to the south-east the area of strong seismic activity continues all the way to the south of Dubrovnik with a few breaks between Šibenik and Split.

In the Adriatic Sea, the seismic activity of the central and southern parts is stronger. The most prominent activity can be traced south of the island of Lastovo. In the western part of continental Croatia, a zone extending from the border with Slovenia to the west of Karlovac is also prominent. The zone then continues through Žumberak and Medvednica Mountains to Kalnik and the western part of Bilogora. This zone joins the active Zagreb area belt which extends all the

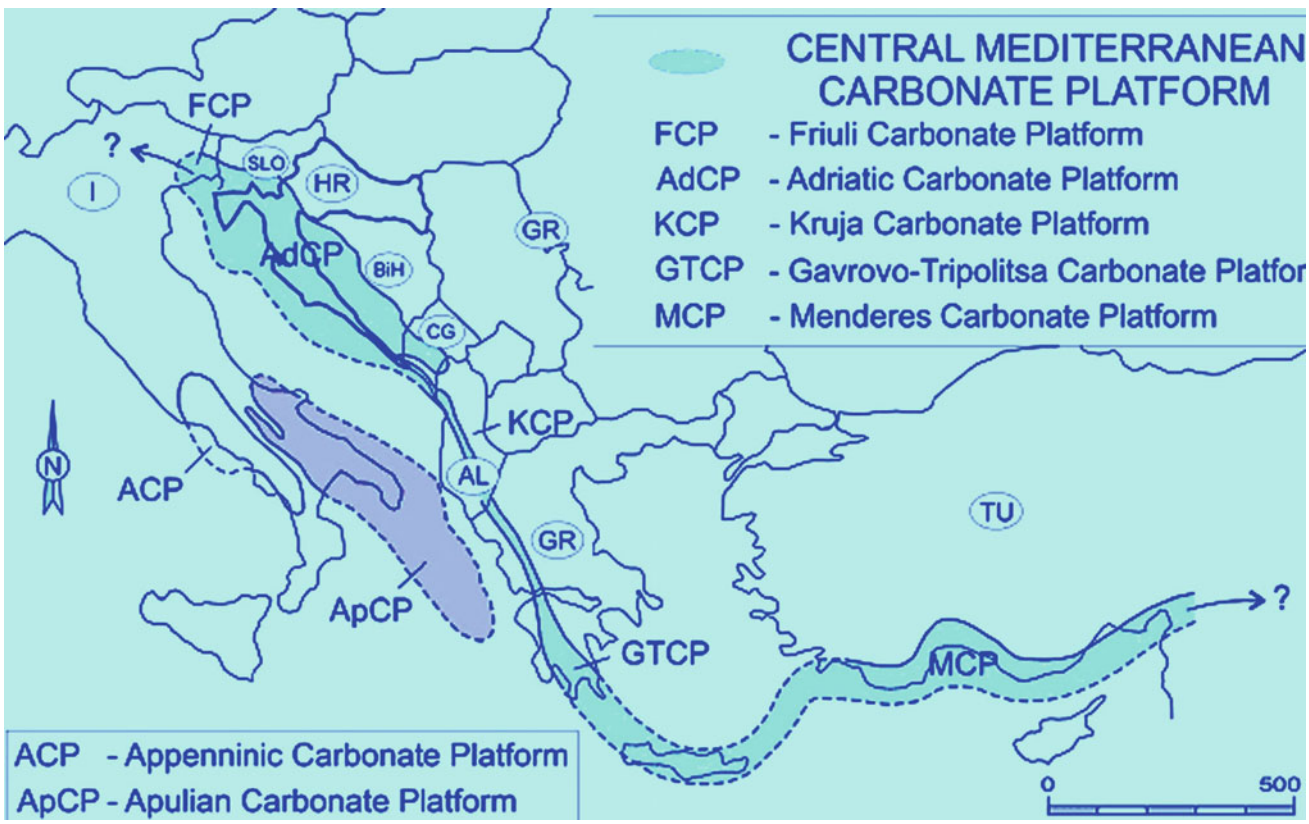

Fig. 1.5 Central Mediterranean carbonate platform

Fig. 1.6 Dinaric carbonate platform

way to Pokuplje. The central and eastern part of northern Croatia is characterized by considerably less seismic activity compared to other parts of the country. There are several more prominently active areas connected with the central Slavonian Mountains of Psunj, Papuk and Dilj-gora.

1.2.2 Hydrogeology of Croatia

There are two hydrogeologically separate units in Croatia. The northern, middle and eastern parts of Croatia belong to the so-called lowland alluvial hydrogeological complex, while the western and southern parts of Croatia belong to the so-called mountain or karst hydrogeological complex. Quantities, movements and chemical composition of groundwater are very different in the lowland and karst regions. In the lowland area (excluding the so-called island mountains in the Pannonian Plain—Medvednica, Ivančica, Papuk, Psunj, etc.), the rocks have a primary porosity and the groundwater flow is laminar. In the karstic regions of Croatia, the rocks have secondary and/or dissolving porosity, and the movement of groundwater is predominantly turbulent (Fig. 1.9).

According to Bionić and Biondić (2014), the karst area of Dinarides is a specific feature of Croatian hydrogeology which, thanks to well-known researchers from Croatia and the wider region, has given numerous Croatian names to the world terminology of karst phenomena such as *ponor, dolina* or *krško polje*.

The terminology derives from continuous extensive research of karst fields of the Dinarides since the middle of