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Glaciokarsts

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Márton Veress
SEK, Department of Physical Geography
Eötvös Loránd University
Szombathely, Hungary

Tamás Telbisz
Department of Physical Geography
Eötvös Loránd University
Budapest, Hungary

Gábor Tóth
SEK, Department of Physical Geography
Eötvös Loránd University
Szombathely, Hungary

Dénes Lóczy
Institute of Geography, Department of Physical Geography
University of Pécs
Pécs, Hungary

Dmitry A. Ruban
Southern Federal University
Rostov-on-Don, Russia

Jaroslav M. Gutak
Institute of Mining and Geosystems
Siberian State Industrial University
Novokuznetsk, Kemerovo Oblast
Russia

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Preface

This book describes a specific karst type, the glaciokarst. The cause of the peculiarity of glaciokarst that the karsts belonging to this karst type were and are still affected by diverse effects (karstification, glacial erosion, fluvial erosion, frost weathering, mass movements). In a lot of cases, these effects were repeated and alternated. According to this, these areas have one of the most diverse landscapes regarding karst types and because of this it can be a significant area of researchers' interest.

The need for a better knowledge of glaciokarsts is expected to increase in the present and in the future. On our globe, climate change has an increasing dominance. In order to become familiar with former climate changes, the research of glaciokarstic areas may give data which are less possible to be obtained from other non-karstic areas. Since the features that developed on the karst (and thus, glacial erosional features too) are stabile and can be studied well. Thus, ice cover and climate change of the past 1–2 million years can be studied better on karst than on non-karstic terrains. It makes it possible the better understanding of the climatic events of the near past and present.

The book is divided into nine chapters. Chapter 1 deals with the research history of glaciokarst, Chap. 2 involves the general description of this karst type. Glacial erosion taking place on karst is analysed in Chap. 3, which is special in many aspects since the karst features influenced the type of glaciers and the intensity and way of glacial erosion. Chapters 4 and 5 discuss the features of glaciokarstic areas and their genetics. The karst types of glaciokarst are described in Chap. 6 and the geomorphic evolution of glaciokarstic terrains is presented in Chap. 7. The features and events of some sample sites of glaciokarstic areas are dealt with in Chap. 8. A description of the areas of the glaciokarsts of the Earth can be found in Chap. 9 and thus, it gives an overview on the characteristics of physical geography, on geological data, on the history of glaciation and the features occurring there.

Szombathely, Hungary Márton Veress

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Contents

Contributors

Jaroslav M. Gutak Institute of Mining and Geosystems, Siberian State Industrial University, Novokuznetsk, Kemerovo Oblast, Russia

Dénes Lóczy Institute of Geography, Department of Physical Geography, University of Pécs, Pécs, Hungary

Dmitry A. Ruban Southern Federal University, Rostov-on-Don, Russia

Tamás Telbisz Department of Physical Geography, Eötvös Loránd University, Budapest, Hungary

Gábor Tóth Faculty of Natural Sciences, University of West Hungary, Szombathely, Hungary

Márton Veress SEK, Department of Physical Geography, Eötvös Loránd University, Szombathely, Hungary

Chapter 1
History of Glaciokarst Research

Tamás Telbisz and Gábor Tóth

Abstract In this chapter the research history of glaciokarsts is described from 1880 in the following topics: morphological descriptions (landforms on glaciokarst terrains, cave explorations on glaciokarsts), hydrologic and speleological analysis of subglacial and periglacial karst aquifers, new methodologies in glaciokarst research (dating methods, formal stratigraphy, GIS, computer simulations), age of synthesis, anthropogenic effects and climate change on glaciokarsts.

Keywords Glaciokarst research · Morphological descriptions · Hydrologic and speleological investigations · New methodologies in glaciokarst research Age of synthesis · Anthropogenic effects and climate change on glaciokarsts

1.1 Introduction

The history of glaciokarst research can be approached from two directions, either from the study of glaciations or from the study of karstology. The scientific study of Quaternary glaciations began as early as the 1840s by the pioneering work of Agassiz (1840), and over time, more and more scientists joined this research, and after some decades of work it became evident that continental ice sheets and mountain glaciers covered huge areas during Quaternary glacial periods, among others karst terrains as well. Glaciology became a sound and versatile science, but the presentation of its history is out of the scope of this chapter. As the scientific study of glaciokarsts is rather a branch of karstology, in this short history our subject is approached from the direction of karst research.

The history of glaciokarst research can be divided into five periods, nevertheless, these periods have different lengths, and they are partly overlapping (Table 1.1). The first period since the end of the nineteenth century to the 1970s (but occasionally further on) is the time of morphological explorations and descriptions, and processes are interpreted mainly in qualitative terms. In the second period from about 1960 to the end of the 1980s, geochemical and hydrological measurements made glaciokarst studies more quantitative, while periglacial and subglacial environments were more thoroughly explored. The third period is characterized by the

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Table 1.1 Steps of glaciokarst studies

Period	Name	Characteristic approach	Outstanding scientists
1880–1970	Morphological analysis	Study of landforms, typical glaciokarst terrains, qualitative analysis of processes, cave explorations	Corbel, Cvijić, Grund, Horn, Martel
1960–1990	Hydrology and geochemistry of subglacial and periglacial karsts	Analysis of water samples and dissolution processes, speleological exploration of subglacial caves	Atkinson, Dreybrodt, Ek, Ford, Smart
1975 (2000)–	Methodological boom	Speleothem dating by U-series; Cosmogenic dating of superficial and cave sediments; GIS	Atkinson, Ford, Gascoyne, Harmon, Häuselmann, Hughes, Lauritzen, Spötl
2000–	Synthesis	Synthesis of periods and extensions of glaciations; application to glaciokarsts	Audra, Hughes, Maire
2000–	Anthropogenic effects on glaciokarsts	Role of glaciokarst in CO_2 budget; effects of climate change on glaciokarsts; direct anthropogenic effects	Viles, Zeng

application of new methodologies, partly since the end of the 1970s, but the largest boom occurred since the beginning of the 2000s. U-series dating of speleothems was the first among these new methods that really revolutionized views related to the age and development of glaciokarsts. Further improvements are due to cosmogenic nuclide techniques, which are also suitable for dating cave materials, but these methods became available only after the turn of the millennium. Besides cave sediments, cosmogenic nuclide techniques can be used also to infer exposure age of superficial landforms such as moraines or limestone pavements. The integration of spatial data, statistical analysis of morphometrical parameters, recognition of spatial patterns and relationships have become easier due to the widespread distribution of Geographic Information Systems (GIS), which had its impact on glaciokarst studies also since the 2000s. Theoretically, the age of synthesis is presented as a distinct period in this historical overview, however, it basically overlaps the previous period. At the beginning of the twenty-first century, a number of glaciological syntheses have been published. They are based on a wealth of field data and previous research, and they focus the extent and phases of glaciations including both continental ice sheets and mountain glaciers. These syntheses usually serve as inputs or background data to glaciokarst studies, but in many cases, glaciokarst studies themselves contributed to glaciological synthesis with new field data. Finally, studies dealing with anthropogenic effects on glaciokarsts are mentioned, especially those which are related to the present-day global warming. To now, these studies have relatively few importances within the domain of glaciokarst studies, but they mark that climate change, one of the top issues in today's earth sciences, is not negligible from the viewpoint of glaciokarsts, and it is likely that this direction will get more focus in the future.

1.2 Morphological Descriptions

1.2.1 Landforms on Glaciokarst Terrains

For a long time, especially at the beginnings, the exploration and study of glaciokarsts basically went on two parallel paths according to the two main geographic zones in which glaciokarsts are found. Some scientists dealt mainly with *alpine* glaciokarsts, whereas others studied *arctic* glaciokarsts, thus in this short history, we also present these research lines separately at first, but they are tied together afterwards.

The study of *alpine glaciokarsts* is essentially as old as karstology itself. Karst research began in the Classical Karst of Slovenia and Italy at the end of the nineteenth century. The continuation of the Classical Karst, the Alps to the north and the Dinaric Alps to the south (Fig. 1.1) contain a lot of formerly glaciated high karst mountains easily accessible for the early researchers. Recognizing the signs of glaciations, even Jovan Cvijić, the "father of karstology" published several works about glaciokarst terrains in the Balkan Peninsula (Cvijić 1899, 1900, 1903, 1913, 1917, 1920). In his publications, he thoroughly discussed the relationship of karst processes and glaciations, and presented how depressions are jointly formed by these effects. In his work of 1917, he even used a special term, "karstic glaciers". He recognized that in some mountains of the Balkan, notably in the Orjen and Lovćen mountains (in Montenegro), Pleistocene glaciers stretched down to surprisingly low elevations, even below 1000 m asl. Although some of his observations had to be corrected later (see Milivojević et al. 2008), but his principal theses have remained valid till now. Parallel with Cvijić, or following him, other scientists also began to study glaciokarst morphology mainly in the Balkan. Albrecht Penck, who was the doctoral supervisor of Cvijić, analysed the glacial morphology of Balkan Peninsula (Penck 1900), similarly to Grund (1902, 1910) and Sawicki (1911) . In addition, Penck studied the glaciations of the Pyrenees (Penck 1885) and of the Alps (Penck and Brückner 1901) as well, but in those works, glaciokarsts are not emphasized at all.

Publications focussing especially on glaciokarsts of the Alps have been published only later, first about French territories. Allix (1930), for example compared the landforms of the French Préalpes to the Dinaric sample areas, using Cvijić's conceptions, and discussing the preglacial or postglacial formation of cirques. After the forced break of the Second World War, glaciokarst studies became more widespread in space and in thematics. The pivotal works of Bögli about karren morphology were published in the 1960s (Bögli 1960, 1964). He studied the genesis and characteristics of small-scale dissolutional forms, which are partly of glaciokarstic origin. His field work was mostly based on sample areas within the Alps. The first thorough publications about the glaciokarst morphology of the Pyrenees (Miotke 1968; Bertrand and Bertrand 1971; Smart 1986) and of the Rocky Mountains (Ford 1971b) were published some years later. Meanwhile, in the context of the Dinaric Alps, and the glaciation of the Mediterranean region, it was already the time of the first morphological syntheses (Roglić 1961; Messerli 1967).

Fig. 1.1 Typical glaciokarst scenery in the Dinaric Alps, Prokletije Mountains (photo by Telbisz)

The term *arctic glaciokarst* refers to karst terrains, which were affected by the continental ice sheet during the Pleistocene glaciations. Nonetheless, these terrains are not necessarily "sensu stricto" arctic, i.e. their latitudes are in some cases much lower than the Arctic Circle. The classical scene of arctic glaciokarst studies is the British Isles, as it was nearly completely covered by the Pleistocene ice sheet, further on, karst terrains are also numerous here, though not dominant. Moreover, these landscapes were naturally "given" for British earth scientists and karst researchers. The scientific study of British glaciokarsts started roughly at the same time as the description of Dinaric glaciokarsts. Davis already published a paper about the Norber erratics in 1880. Norber is found in Yorkshire, which is one of the best known British glaciokarsts. Hughes (1901) presented a detailed study about Ingleborough, which is also located in Yorkshire. Thus, Yorkshire became a locus classicus of glaciokarst, and it was also the subject of a large number of further studies, namely about the morphology and genesis of limestone pavements, the role of glaciations, and the corrosional erosion rates calculated from the parameters of erratic blocks (Sweeting 1966; Goldie 1973; Vincent 1995). Another extended and thoroughly studied glaciokarst of the British Isles is the Burren (Fig. 1.2), which is situated in western Ireland. It is also famous about the limestone pavements (Williams 1966), but other landforms, such as caves and dry valleys also occur either in Burren, or in Yorkshire. One of the oldest publications (Reid 1887) is related to the development of dry valleys, which are characteristic landforms in some of the British karst terrains, and they are typically formed on Cretaceous chalk limestones in periglacial climate.

Fig. 1.2 Typical glaciokarst scenery in Burren (photo by Mari)

The French Jean Corbel was a broad-minded karstologist, who carried out research in varied karst environments, notably in tropical, alpine (Corbel 1956 1957a) and arctic (Corbel 1952b, c) areas alike. Thus, he had the knowledge and the experience to connect the study of alpine and arctic glaciokarsts (Corbel 1952a, 1957b, 1959). However, in spite of his huge synthesizing work, he is known about a remarkable error in the history of karstology. According to him, karstification is weak below glaciers, but karst corrosion is the most intensive in areas where snow is abundant, since CO_2 is relatively better dissolved in cold than in warm waters. However, several of his statements were later refuted (e.g. by Smith and Atkinson 1976), because the partial pressure of CO_2 is a much more important factor in the karstic dissolution than the temperature, and in turn, CO_2 content is usually several magnitudes higher in tropical soils, thus karstification is the most intensive in warm and wet climates (Jakucs 1977).

The variegated relationship of glaciation and karstification has been synthesized by Ford (1983a) using Canada as an example. This country gives a highly favourable opportunity for synthesis, because there are both alpine and arctic glaciokarsts in Canada. Ford summarized the impact of glaciers on karst terrains and demonstrated examples for destructive, deranging, inhibitive, preservative and stimulative effects.

Naturally, the morphological approach has not been terminated in the 1980s, it is still present, but usually it is completed with several new methods, thus glaciokarst studies became more complex in general since that time.

Somewhat surprisingly, certain glaciokarst terrains were discovered quite recently, that brought even new landform types to light. Of the unknown or recently discovered glaciokarsts, the most famous are the two islands of Diego de Almagro and Madre de Dios in Patagonia (Chile). The islands between 50°S and 52°S latitudes were first explored by a French expedition in 1995. The first trip was followed by nine further expeditions until 2017, with an increasing Chilean participation. The results of the ten expeditions demonstrate that probably most active glaciokarst on Earth is found at the coast of Chile, from both glacial and karstic aspects. Based on the measurements of Maire et al. (1999), the solution rate is 3.5–4 times higher than the highest data measured in the Alps (60 mm/ka). The morphology perfectly records the alternating geomorphological heritage. Intensive glacial effects formed the islands during glacials, and an extremely high dissolution rate was the rule during interglacials. Hydroeolic karren features, unique in the world have been described by the French expeditions and a Hungarian research team (Veress et al. 2006). Due to tectonic movements and glaciokarstification, huge cave systems also evolved, but they have been partly ruined as a result of intense erosion. Since the last deglaciation, 10–12 m of glacio-isostatic uplift have been measured by French researchers.

1.2.2 Cave Explorations on Glaciokarsts

Obviously, cave explorations played a crucial role in the discovery of glaciokarsts. At the beginning (and still now) caving was motivated by nature loving, alpinism, paleontology, sport, etc., however, scientific interest was also an issue almost since the beginnings, that gave birth to speleology. In general, the exploration and investigation of glaciokarst caves is a difficult challenge because of several reasons. First, shafts are common features in alpine caves, and moving in them requires advanced technical skills. Second, in many cases, even the access to glaciokarst caves is difficult, especially in case of arctic caves, which are often situated in remote, rarely populated lands. In case of long and hard caves, it is often necessary to spend several days continuously within the cave. Moreover, glaciokarst caves may be dangerous due to abrupt floods, especially during summer, therefore visiting them is possible only in winter, that, in turn, causes difficulties related to cold temperature, and finally, in case of alpine caves, avalanches may threaten cavers approaching the cave.

The exploration of alpine caves began in the second half of the nineteenth century, in Switzerland, Austria and Italy in the framework of the starting alpinism. It was also the time, when the first caving clubs were founded (Shaw 2004). One of the best known ice caves, the Eisriesenwelt in Austria (Fig. 1.3) was explored in 1879 by a naturalist, Anton Posselt from Salzburg. The Mamut Cave and the Ice Cave of Dachstein Mountains (also in Austria) were discovered some decades later, at the beginning of the twentieth century, with Friedrich Simony playing a key role in the explorations (Pavuza and Stummer 1999).

Fig. 1.3 The Eisriesenwelt Ice Cave in Austria (photo by Egri)

Nevertheless, the most outstanding, pioneering personality of the heroic age of cave explorations was the French Édouard-Alfred Martel, originally an advocate. He participated in many cave explorations, in the French Massif Central at first, then in the French Alps, later in Austria, in the Pyrenees, in the Balkan, and in the United States as well. In many cases, he was the first discoverer of the cave (Audra 2004a, b; Halliday 2004). Beside alpine caves, he could visit arctic glaciokarsts as well, notably in the United Kingdom and in Ireland. He was the first person to descend into the 110 m deep shaft of Gaping Gill, a famous cave in Yorkshire (Judson 2004). He was particularly active not only in explorations, but in scientific descriptions, popularization and in the organization of the speleological public life. It is manifested by the fact that in 1895, he created the French Société de Spéléologie, which was a particularly popular society, which had several foreign members as well (Shaw 2004). In North America, the exploration of glaciokarst caves was somewhat delayed, the first explored alpine cave was the Arctomys Cave in the Rocky Mountains in 1911, and since then, it is the deepest known cave in North America (Halliday 2004).

For a long time, the scientific study of caves generally did not focus on glacial effects, instead, other geologic, hydrographic and hydrologic factors were examined. However, in case of Norwegian glaciokarsts, which are mostly limited in their areal extent, but which were particularly strongly affected by Pleistocene glaciations, the question about the relationship of speleogenesis and glaciations was almost immediately raised. The first review about Norwegian karsts was published by Oxaal (1914), and he already noted the typical situation of caves hanging in high positions at valley sides. Oxaal supposed that cave passages developed during deglaciations, and he emphasized the role of meltwaters in speleogenesis. Horn (1935, 1937, 1947) raised the possibility of *subglacial speleogenesis*, i.e. the formation of cave passages below glacier ice. He also introduced the term *stripe-karst*, which denotes a peculiarity of Norwegian karsts, namely that karsts are usually restricted to relatively narrow marble layers, which are typical in the heavily folded Scandinavian Mountains. These narrow marble bands are commonly bordered by non-karstic metamorphic rocks at both sides. The question, whether the age of Norwegian caves is preglacial, interglacial or postglacial has been the subject of several later studies as well (Lauritzen 1981, 1986). It could be answered only by the new dating methods at the next step of research history.

In parallel with cave explorations, scientific knowledge was increased and different theories about speleogenesis were elaborated. The remarkable differences in the shape, and consequently in the evolution of phreatic and vadose passages were first described during the exploration of Dent de Crolles cave system in 1944. At that time, it was the deepest (−658 m) known cave on Earth (Chevalier 1944a, b).

At the end of the 1960s, Derek Ford led several scientific expeditions into the Castleguard Cave found in the Canadian Rocky Mountains (Ford 1971a, 1983c). This cave is still the longest cave in Canada, and it is especially important, because the passages stretch just below a large present glacier. These expeditions significantly improved our understanding of glaciokarst processes (see mainly in Chap. 5).

Another well documented and glaciokarst focusing expedition was the 1970 British Karst Research Expedition (Waltham 1971). Its aim was to get acquainted with the karstic areas of the High Himalayas so far unknown. At that time, no proper geological map was available, and even the extent of karstifiable rocks was unknown. The main purpose of the research was to explore new cave systems in the region of Annapurna and Kashmir. During the trip, they explored several caves approaching them through sinkholes.

Another significant event was the expedition of French cavers into Greenland in 1983, during which the northernmost glaciokarst of the world was discovered (Loubiere 1987). The cave system, which lies at 80°N latitude in the northeast corner of Greenland, 1100 km from the North Pole, is very difficult to access. The cave is developed in Cambro-Silurian limestones. It was formed in climatic conditions, which are nowhere found in Greenland at present. Based on concretions found in the cave, it was demonstrated that around the Pliocene-Pleistocene boundary, climatic conditions were similar than in the forests of the French Prealps today. Thus, intense karstification was possible at such a latitude during this period.

Since the turn of the millennium, the explorations and scientific studies related to glaciokarst caves have been further increased and deepened, partly due to modern exploration and research techniques, partly due to the growing number of the speleological society, and several new results and theories have been elaborated.

1.3 Hydrologic and Speleological Analysis of Subglacial and Periglacial Karst Aquifers

After the exploration of the surface and subsurface morphology of previously glaciated karst terrains, it was a logical step to go closer to the presently glacier-covered karsts. One of the most important questions was, whether ongoing karst development exists below ice, and if so, how effective it is.

As for permafrost terrains, the general view was that permanently frozen conditions exclude the possibility of karst processes (Brook and Ford 1978; Palmer 1984). However, some permafrost karst terrains are known in Siberia, Svalbard and Canada. Nevertheless, their karstification is usually limited, and probably they were formed in climatic settings different from the present ones (Popov et al. 1972; Salvigsen and Elgersma 1985; Ford 1983a).

It was an important step in the understanding of subglacial karstification to measure the dissolution capacity of water samples collected in karst areas, which are actually glaciated. Ek (1964) was a pioneer of these studies. He collected water samples in the French Alps, and by analysing pH and carbonate content values, he concluded that the carbonate concentration is very low, and that subglacial meltwaters are not aggressive from the viewpoint of limestone dissolution capacity. Ford (1971b), who analysed the geochemistry of water samples collected in the Rocky Mountains, confirmed the statements of Ek. In the following period, further data were collected about subglacial conditions. At the beginning of the 1980s, the Castleguard Cave and the Columbia Icefield above it became a thoroughly studied sample area (Ford 1983b, c). It was revealed that subglacial secondary carbonate precipitations occur both at the rock surface and within the caves. Subglacial calcite precipitates at the rock surface were described by Hallet (1976). Below warm-based glaciers, at the stoss side of glacially polished rocks, water melts due to pressure increase and $CaCO_3$ is dissolved. At the lee side, in turn, water refreezes and calcite precipitates, this is the so-called "regelation-slip process". Maire (1976, 1990) explained similarly his field observations at the Desert de Platé in the French Alps, and at the Tsanfleuron plateau in the Bernese Alps (Switzerland). He also noted that subglacial calcite precipitates often fill karren features in the foreland of glaciers.

Cave precipitations have been studied and explained by Magaritz (1973), Dreybrodt (1982) and Atkinson (1983). In certain conditions, infiltrating subglacial waters are capable of dissolving $CaCO_3$, though only in very low concentrations. When water reaches the cave atmosphere, the temperature increases by some degrees, and water becomes supersaturated, thus speleothem growth may start (Dreybrodt 1982). However, Atkinson (1983) experienced that the above mechanism is not too effective, and the main reason for subglacial speleothem formation is the so-called *common-ion effect*. It means that if water is saturated with respect to calcite, and further dissolution of gypsum or dolomite occurs, then calcite precipitates. An important consequence of this mechanism is that speleothem growth is possible without biogenic CO_2 in glaciated karst or in other bare karsts as well, until the cave temperature is above 0 °C. These findings modified previous views, which stated that speleothem growth is possible only in warm periods, under soil-covered terrains (Ford 1976; Atkinson et al. 1978). However, this latter statement is still valid in general, though not exclusively. Smart (1983) studied the hydrological regime of glaciokarsts, and differentiated supraglacial meltwaters, which have high fluctuations (having both seasonal and daily cycles) and higher dissolution capacity, and subglacial pressure meltwaters, which have negligible dissolution capacity.

Meanwhile, due to the new explorations in Norwegian karsts, several field observations were made. First, it was presented that maze patterns are frequent features in glaciokarst caves of Scandinavia. Second, it was demonstrated that the development of some phreatic passages occurred when flow directions were opposed to the present-day topographic gradients. Based on these facts, Lauritzen (1982, 1983, 1984, 1986) outlined the theory of ice-contact speleogenesis, which takes place when ice and karstifiable rocks form a joint aquifer.

1.4 New Methodologies in Glaciokarst Research

Since the 1970s, several new techniques were introduced into earth sciences in general, and they could be used in glaciokarst studies as well. First, U-series dating methods must be mentioned, that can be applied to carbonate rocks, especially to speleothems. Cosmogenic nuclide methodology became available since the turn of the millennium. These methods provided crucial data that significantly contributed to answer the questions related to the age of speleogenesis, i.e. whether caves are formed during preglacial, interglacial, subglacial or postglacial periods. Naturally, the answer is not of global validity, instead, the age may be different depending on the actually studied cave, but the applied methods were usually similar. Besides the aforementioned techniques, other dating methods, such as luminescence or radiocarbon were also applied on glaciokarsts, but they were less significant.

The widespread use of GIS has become a quasi-standard since around the 2000s. The role of GIS in glaciokarst studies is not restricted to the acquisition of new data, but GIS is also helpful due to its good visualization and analytical capabilities. Besides dating methods and GIS, some other, less significant methodological innovations can be also listed, namely the introduction of formal stratigraphy in glaciological studies, and the application of computer simulations.

Largely due to the new methodologies, it is experienced that the number of glaciokarst publications abruptly increased since the 2000s. However, it may be partly caused also by the transformation of the scientific world, namely that the production of publications is increasingly enhanced in the present-day research system.

1.4.1 *Dating Methods*

1.4.1.1 U-Series Dating of Speleothems

U-series dating of speleothems began in the second half of the 1970s. The first study areas were in the Rocky Mountains, the Nahanni karst (Harmon et al. 1975, 1977; Ford 1976), the British Isles (Atkinson et al. 1978, 1987; Gascoyne et al. 1981; Gascoyne and Ford 1984), thus mostly glaciokarst terrains were investigated first by this methodology. Norwegian speleothems were dated somewhat later by Lauritzen and Gascoyne (1980) and by Lauritzen (1983, 1984), and the glaciokarsts of the Alps followed next with some delay (Audra and Quinif 1997; Spötl et al. 2002a, b; Spötl and Mangini 2007; Holzkämper et al. 2005; Audra et al. 2007; Häuselmann et al. 2008; Luetscher et al. 2011). The measurement limit of the U-series dating method was 350 ka at the beginning, but due to technical improvements, it has been doubled since that time (Dorale et al. 2004).

Given this measurement limit, U-series data can not be directly used to prove Early Pleistocene ages. However, they made it evident that there are several caves in the abovementioned glaciokarst terrains, that survived several glacial cycles, therefore they are *preglacial* in that meaning. Normally, caves are considered truly preglacial if they are older than the oldest Pleistocene glaciation. It is also noted that the above results do not mean that all caves in glaciokarst terrains are older than the last glacial.

Age determinations also made it possible to calculate erosion rates in glaciokarst terrains. In some cases, values were quite low, namely in Canada, where Ford et al. (1981) measured 0.13 mm/ka rate, while in other regions, in Norway, for instance higher values of 0.35 mm/ka were calculated (Lauritzen and Gascoyne 1980).

When speleothem ages are statistically evaluated, i.e. periods of speleothem growth are outlined, then the general approach is that hiatuses mark glacials, whereas high-intensity growth periods mean interglacials (e.g. Atkinson et al. 1978; Gascoyne et al. 1981). Nonetheless, as it was already presented, speleothem formation is possible even in glacial periods if certain conditions are satisfied (Atkinson 1983; Spötl and Mangini 2007), but the growth intensity is obviously much less. Further on, it must be taken into consideration that hiatuses can be caused by other factors as well (Häuselmann et al. 2008).

1.4.1.2 Cosmogenic Dating of Cave Depositions

The principle of cosmogenic nuclide dating is that the amount of certain cosmogenically induced radionuclides exponentially decays after the material is shielded from cosmogenic radiation. The rate of decay is dependent on the isotope. In caves, sediments frequently contain ^{10}Be and ^{26}Al in quartz grains, and they can be used for age determination. The age limit of cosmogenic nuclide method is much larger than that of the U-series technique, it is appropriate in the range of 0.1–5 Ma BP (Häuselmann and Granger 2005; Häuselmann 2007).

Careful measurements in several caves of the Alps manifested that the age of sediments is highly variegated from 0.18 to 5 Ma BP, and it is particularly important that there are several old caves, which started to develop at least in the Pliocene or even earlier (Audra et al. 2007; Häuselmann et al. 2008; Hobléa et al. 2011).

1.4.1.3 Moraine Ages Using Secondary Carbonate Cements

As for the superficial sediments, numerical dating was not possible for a long time. However, on glaciokarst terrains, where the till has some carbonate content, secondary carbonate precipitation is often found in the till, and the age of these secondary carbonates can be determined providing a minimum age for the formation of the till (moraines). U-series dating was applied to glacial deposits in the Apennines by Kotarba et al. (2001), in the Hellenides by Woodward et al. (2004), and in the Dinaric Alps by Hughes et al. (2011). These data made it possible to elaborate a precise chronology of glacial advance and retreat phases, wherever glacial till containing carbonates were preserved.

In case of glaciokarst moraines, where the proportion of carbonate material is high, scientists can use the ^{36}Cl cosmogenic isotopes as well, a technique, which was developed somewhat later, but it turned out to be very useful in carbonate glaciokarsts, and provided high precision data about terrains where previous chronology was insufficient (e.g. Sarikaya et al. 2008, 2014; Zreda et al. 2011; Çiner et al. 2015; Wilson et al. 2013b).

1.4.1.4 Cosmogenic Dating of Limestone Pavements

Limestone pavements are among the most peculiar glaciokarst landforms (Waltham et al. 1997), though some researchers emphasize that they are the products of compound processes, and can not be simply considered as the "automatic consequence" of karstification on glacially eroded bare surfaces (Vincent 1995). The study of limestone pavements was completed by valuable information due to ^{36}Cl cosmogenic isotope exposure age data. Vincent et al. (2010) and Wilson (2012, 2013a) dated erratics in British limestone pavements that gives the age of post-LGM deglaciation, moreover, surface lowering rates could be calculated as well.

1.4.2 Formal Stratigraphy

Literature dealing with glaciokarst terrains has been quickly growing since the turn of the millennium. Occasionally, relatively small spatial units (mountains) are studied with larger detail than earlier. The glaciations of these mountains, especially at lower latitudes of Europe or other continents, were local phenomena, and can not be directly connected to glacial phases of the large glacierized terrains, like the Alps or the continental ice sheets. Hence, Hughes et al. (2005) suggested that in case of locally glaciated mountains, it is recommended to use a formal stratigraphy in the description of glacial (or glaciokarstic) landforms. Glacial sediments and landforms, such as moraines should have a standardized name, which reflects the different glacial phases, because it helps the interpretation and comparison of morphological data. While most of the new methodologies mentioned in the previous points were technical innovations, this latter suggestion means more a change in mind.

1.4.3 GIS, Computer Simulations

Nowadays, GIS practically replaced the former role of maps in earth sciences, moreover, it even completed the traditional map functions by a number of new capabilities. For instance, the acquisition of field data necessary to describe glaciokarst landforms became more effective and more precise with the help of GPS receivers (Hughes et al. 2011; Žebre and Stepišnik 2015a, b). The integration of geologic, topographic, hydrographic and geomorphologic data into a common coordinate system helped the analysis and statistical assessment. Digital elevation models improved the analysis of the altitudinal characteristics of glaciokarst terrains (Telbisz 2010a, b, 2011; Fig. 1.4), the identification of valley networks and larger depressions (Bočić et al. 2015), and more recently, LiDAR data make it possible to investigate relatively small scale landforms, namely the shape of dolines, stream sinks and moraines (Žebre and Stepišnik 2015a; Telbisz et al. 2016). The analysis of relatively small-scale landforms is further supported by the always better quality and availability of aerial and satellite images (Žebre and Stepišnik 2015b). The quality and the content of geomorphological maps about glaciokarst terrains are also continuously getting better due to GIS capabilities (Stepišnik et al. 2009, 2016; Aucelli et al. 2013). Thus, GIS seems to be an essential auxiliary tool in today's glaciokarst studies. Glacial or glaciokarst data are also increasingly available in different GIS formats (e.g. Ehlers et al. 2011).

Computer simulations are not strictly a part of GIS, but here we note that they are also appropriate means in the study of glaciokarst processes. They are not as widespread as GIS tools, because they need special mathematical, physical and computing skills. However, they were applied to simulate the development of maze caves, which are frequent phenomena in Norwegian glaciokarsts, and it was plausibly demonstrated that maze caves could be really formed at both the inflow and outflow sections of stripe-karsts, where the carbonate rocks are in connection with warm-based glaciers (Skoglund et al. 2010).

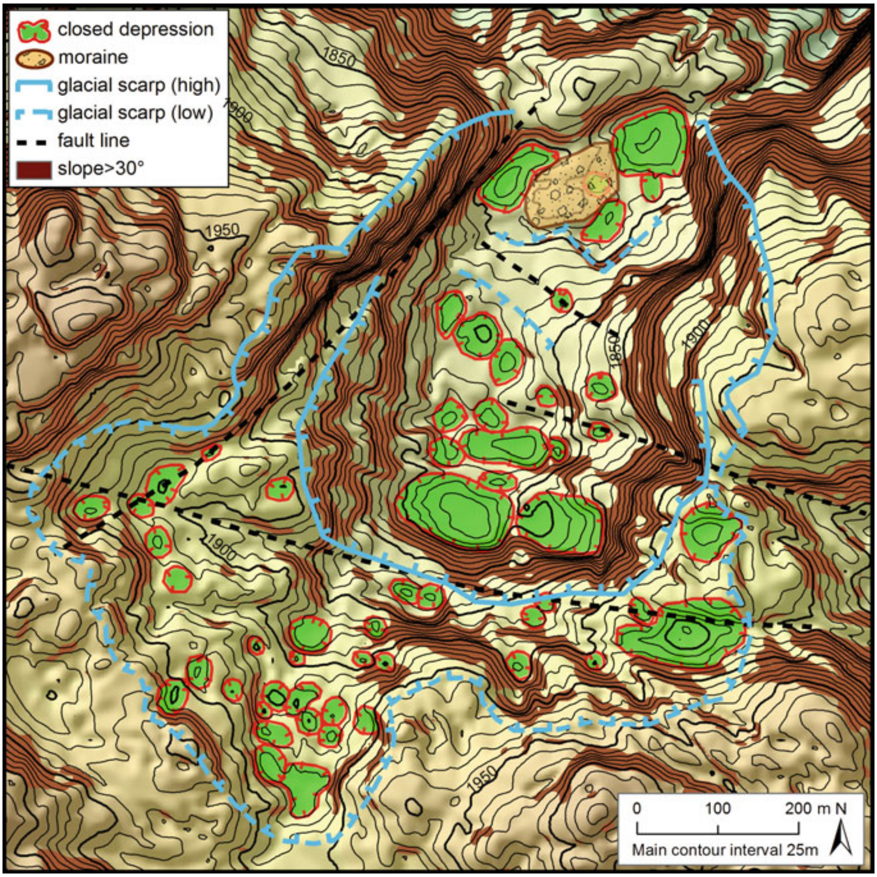

Fig. 1.4 GIS-based geomorphological map of a sample area in Canin Mountains (after Telbisz et al. 2011)

1.5 Age of Synthesis

As a result of more than 150 years of research, the bulk of data about glaciations has grown to extremely large sizes. Hence, it became possible and at the same time necessary to create synthesizing works, which try to briefly and uniformly present the actual knowledge about the spatial distribution of glacial landforms and the chronology of glacial phases. Here, only some of them are highlighted, namely the work of Svendsen et al. (2004) about Europe, of Dyke (2004) about North America, and the global overview of Ehlers and Gibbard (2008), which contain many further citations. Essentially, these glacial syntheses provide input data to glaciokarst research, but occasionally, glaciokarst studies themselves may offer valuable information to glaciology, as speleothems or other glaciokarstic sediments like well-preserved moraines, are suitable for gaining data about climate history. Or simply, if carbonate rocks are predominant in the geological composition of a region, then the glacial synthesis may be largely based on glaciokarsts like in the Mediterranean region (Hughes et al. 2017). Moreover, there are syntheses, which are mostly about glaciokarst features of certain regions, such as the works of Maire (1990) and Audra et al. (2007) about the Alps, or Delmas (2009) and Jiménez-Sánchez et al. (2013) about the Pyrenees.

Beside regional reviews, thematic syntheses are sparse. Notably, the chapters "Alpine Karst" and "Glacierized and Glaciated Karst" of Smart (2004) in the Encyclopedia of Caves and Karst Science, or the book of Veress (2010) about karren features of high mountain, or the review paper of Veress (2017) about glaciokarst depressions can be mentioned. And the present book…

1.6 Anthropogenic Effects and Climate Change on Glaciokarsts

Anthropogenic impacts on glaciokarsts were first studied in the British Isles. Drew (1983) and Moles and Moles (2002) stated that humans contributed to the destruction of vegetation and to the erosion of soils already in the prehistoric times. Nonetheless, later in history, mining exerted a more direct effect on glaciokarsts demolishing occasionally certain landforms (Viles 2003).

Today, the fact of global warming is acknowledged by most researchers (though not everybody), even if the reasons and consequences are not yet fully understood. Viles (2003) examined how much the protected glaciokarst terrains of the British Isles can be affected by the ongoing climate change. He concluded that it is not likely that significant geomorphological changes would occur because of the warming itself. However, he warns that mining and pollution may have significant local effects on glaciokarsts.

Larson and Mylroie (2013) investigated karst terrains from the viewpoint of the global CO_2 budget. In fact, their study focused not primarily on the present climate change, instead, they compared the present climate to the Last Glacial Maximum (LGM) conditions. They calculated that during glacial periods, several million km^2 of continental karst areas were out of the carbon cycle due to the ice sheets and mountain glaciers. On the other hand, similarly large tropical carbonate platforms became subaerial due to the lowering of the sea level, therefore these areas were involved in the carbon cycle during glacial periods.

The hydrological and geochemical properties of water originating from glaciers found on karst terrains were studied by Gremaud et al. (2009) in the Alps, and by Zeng et al. (2012, 2015) in Yunnan (SW China). They tried to quantify how the water budget and the functioning of glaciokarst aquifers are changed due to global warming.

At present, research directions presented in the last section are not among the most significant topics in the study of glaciokarsts, however, it is likely that the examination of anthropogenic effects will grow in the future.

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