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KARST GEOMORPHOLOGY

Edited by
M. M. Sweeting

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Series Editor's Foreword

The philosophy behind the Benchmark Papers in Geology is one of collection, sifting, and rediffusion. Scientific literature today is so vast, so dispersed, and, in the case of old papers, so inaccessible for readers not in the immediate neighborhood of major libraries that much valuable information has been ignored by default. It has become just so difficult, or so time consuming, to search out the key papers in any basic area of research that one can hardly blame a busy person for skimping on some of his or her "homework."

This series of volumes has been devised, therefore, as a practical solution to this critical problem. The geologist, perhaps even more than any other scientist, often suffers from twin difficulities—isolation from central library resources and immensely diffused sources of material. New colleges and industrial libraries simply cannot afford to purchase complete runs of all the world's earth science literature. Specialists simply cannot locate reprints or copies of all their principal reference materials. So it is that we are now making a concerted effort to gather into single volumes the critical materials needed to reconstruct the background of any and every major topic of our discipline.

We are interpreting "geology" in its broadest sense: the fundamental science of the planet Earth, its materials, its history, and its dynamics. Because of training in "earthy" materials, we also take in astrogeology, the corresponding aspect of the planetary sciences. Besides the classical core disciplines such as mineralogy, petrology, structure, geomorphology, paleontology, and stratigraphy, we embrace the newer fields of geophysics and geochemistry, applied also to oceanography, geochronology, and paleoecology. We recognize the work of the mining geologists, the petroleum geologists, the hydrologists, and the engineering and environmental goelogists. Each specialist needs a working library. We are endeavoring to make the task of compiling such a library a little easier.

Each volume in the series contains an introduction prepared by a specialist (the volume editor)—a "state of the art" opening or a summary of the object and content of the volume. The articles, usually some twenty to fifty reproduced either in their entirety or in significant extracts, are selected in an attempt to cover the field, from the key papers of the last

century to fairly recent work. Where the original works are in foreign languages, we have endeavored to locate or commission translations. Geologists, because of their global subject, are often acutely aware of the oneness of our world. The selections cannot therefore be restricted to any one country, and whenever possible an attempt is made to scan the world literature.

To each article, or group of kindred articles, some sort of "highlight commentary" is usually supplied by the volume editor. This commentary should serve to bring that article into historical perspective and to emphasize its particular role in the growth of the field. References, or citations, wherever possible, will be reproduced in their entirety—for by this means the observant reader can assess the background material available to that particular author, or, if desired, he or she too can double check the earlier sources.

A "benchmark," in surveyor's terminology, is an established point on the ground that is recorded on our maps. It is usually anything that is a vantage point, from a modest hill to a mountain peak. From the historical viewpoint, these benchmarks are the bricks of our scientific edifice.

RHODES W. FAIRBRIDGE

PREFACE

Because of the often very local character of karst geomorphology and the deveolpment of its study in southeastern Europe, the literature is scattered in isolated local journals and in many different languages. One of the aims of this volume is to bring some of this scattered literature into one place. I have tried to include as wide a range of papers as possible, subject to the constraints of the volume, and have restricted my selections to the karst geomorphology of massive limestone regions. I have not included papers on gypsum or salt karst; this is mainly due to the fact that, although gypsum and salt karsts can be very impressive, they occupy a relatively small proportion of the total world area of karst. Nor have I selected any paper on *pseudokarst*, the name normally given to solutional and other landform features, on noncalcareous rock types that resemble those of massive limestones. As P. Fénelon has said, though there are analogies between the forms of pseudokarst areas and those of karst limestones, real differences exist that "cannot be neglected." Thus I agree with him when he says that "the classical karst, that is the karst of Cvijič and de Martonne, remains exclusively associated with limestones rich in $CaCO_3$" (Commission des Phénomènes Karstiques, 4, 1964).

I have not included also any papers on paleokarst, nor have I selected from the large literature on residual and other deposits associated with karst areas. The inclusion of these topics would have given a more geological and less geomorphological flavor to the volume.

The selection of the papers is mine alone. Because of the importance of nineteenth and early-twentieth-century European papers—and particularly those in German—five of the most important have been translated by Mary Fargher of Oxford, who has not only kept the original scientific sense of the authors but has introduced a fine sense of English style into the translations. I am also indebted to Professor Rhodes Fairbridge for his apt comments during the preparation of this volume and for his patience in waiting for it.

M. M. SWEETING

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INTRODUCTION

Karst geomorphology is the study of landforms in massive limestone regions but may also refer to similar landscape features developed on other soluble rocks. Limestones are the most commonly occurring soluble rocks on earth and occupy about 15 percent of the land surface. The landforms that result from solutional and associated processes have become known as karst landforms. These include many different types of enclosed hollows, which may replace the normal drainage channels and valleys found on other rock types; small scale solutional features found on the limestone surfaces; and the landforms caused by underground drainage, caves, and their accompanying deposits. For true karst to develop, the limestones should be impermeable but possess well-defined secondary permeability.

The study of karst developed in central and southeastern Europe in the mid-nineteenth century and was particularly influenced by the Vienna school of geology and geography under Albrecht Penck and Walter Penck. The area northeast of Trieste, now known as the "classical karst," was visited by scientists from all over the Austro-Hungarian Empire. This area is famous for its large caves, such as the Postojna (Adelsberg) Cave, and for its variety of enclosed and internally drained hollows. The word "karst" is the German form of a pre-Indo-European word "Krs" meaning barren, stony ground, which was historically a characteristic of both the classical area and that to the south—the Dinaric karst. The word "karst" appeared in geological works in about 1840, first as a regional and later as a generic term (Gams, 1973). Almost all this early work was written in German. The beginning of karst studies proper may be said to have taken place in 1893 with the publication of *Das Karstphänomen* by the Serbian geographer Jovan Cjivič, a pupil of Albrecht Penck. This work is largely concerned with a description of the landforms of the classical and Dinaric karsts but reference to other areas is made. Although it is basic-

ally descriptive, it makes the reader aware of the potentialities of both the morphometric and process approaches.

Because of the development of the subject in southeastern Europe in what is now Yugoslavia, many of the terms applied to karst landforms are of Slavic origin. These include "doline," originally meaning a little valley and used to designate an enclosed hollow of moderate dimensions (that is, a sink-hole); "polje," meaning a flat field in any terrain in Slavic languages but now applied to distinctively flat-floored depressions and often alluviated features in karst country; and "uvala," used to describe multiple dolines, often formed by collapse.

Because of the peculiarity of karst—with its disappearing streams, enclosed hollows, and underground caves—the early geomorphologists tended to consider it strange and unique, disobeying the laws of landscape development worked out for normal fluvial terrains. This tendency, evident as late as 1964 in Roglić's essay on karst valleys, was probably an inevitable stage in the development of the subject. There is no doubt that the distinctive nature of the relief with its three-dimensional character led to the development of karst as an "almost autonomous field" within geomorphology (Jennings and Mabbutt, 1967). There is, therefore, justification for treating karst in a special volume, even though there is no such thing as a unique karst process, and clearly karst areas obey the normal laws of hydrology, chemistry, and physics. The development of karst geomorphology in general has followed that of geomorphology as a whole but has been a rather muted reflection of the main trends of the subject. Thus the cyclic concept, climatic and process geomorphology, and morphometry have all made their impact on karst studies but in rather different ways and sometimes to a greater or lesser extent than in other branches of the science.

In the two decades before World War I, Europeans undertook many studies in karst areas and often produced lengthy descriptions of the main landforms. This work included many papers on the small-scale surface solution features of limestones, known as karren (in German) or lapiés (in French), that are a particular characteristic of the European Alps, (Eckert, 1902). Long papers were also produced on the conspicuous planation surfaces and poljes of the Dinaric karst. The Czech geographer Daneš wrote some of the first literature on the landforms of tropical karstlands, notably in Jamaica and Austrialia (Danes, 1914, 1916). Apart from a visit by W. M. Davis to the Dinaric karst in 1899, all this work was relatively unknown to geomorphologists in the English-speaking world.

The idea of a developmental sequence or cycle of landforms influenced karst geomorphology, but the first two papers, one by Beede (1911) working alone in America and the other by Grund (Paper 4) in Europe, had little impact on the growth of the subject. Grund's scheme, written in German, was overlooked in favor of more complex one of Cvijič (1918), partly because Cvijič's article was published in French and also because a part of it was translated into English by Sanders (see Paper 3). In fact, although Cvijič later changed his views, Sanders's translation of his 1918 article was all the most American and English readers knew of Cvijič's work until relatively recently. Much of what Cvijič said in 1918 was influenced by the work of W. M. Davis, and his revised views were included in his last work, *Geomorfologija*, published in Serbian in 1926. Today, the simpler scheme of Grund, which was based on both Dinaric and tropical observations, has a greater relevance to the models of the evolution of karst landforms.

From about 1918 to about 1950 there was much work done on the description and measurement of karst landforms but relatively little on the processes involved in their formation. A good deal of work was done by the successors to Cvijič in Yugoslavia, notable A. Melik in Slovenia and J. Roglič working in the Dinaric karst, both of whom were able to correct some of the mistakes caused by the influence of the Davisian cycle (Roglič, 1938; Melik, 1929). Particularly detailed work was done in France where over one-fifth of the terrain is karstic (Clozier, 1940). Very little was done in the English-speaking world with the important exception of Malott whose work in Indiana was outstanding but is still not widely known.

Because of the predominantly solutional origin of many karst landforms, their formation is much affected by climatic variables since the solution of limestone is dependent upon the availability of water and of dissolved carbon dioxide. The latter is derived partly from the atmosphere but mainly from vegetation and its concentration related to turbulence and temperature. The differentiation in karst landforms produced by climate has been noticed since the time of Cvijič, hence climatic geomorphology has been of very great importance to karst geomorphology (Cvijič, 1925). This aspect began to affect karst studies during the 1930s and is well illustrated by the work of the French in Indochina (Blondel, 1929) and the Dutch and Germans in Indonesia, particularly that by H. Lehmann in Java and later in Cuba. Many landforms in the Dinaric karst also owe their origin to the processes active during both the Tertiary and the Quaternary periods. This applies especially to the poljes and is demonstrated by the work

of K. Terzaghi, J. Roglič, and I. Gams. The various symposia of the Karst Commission of the International Geographical Union have been much occupied with the differentiation of karst landforms in the various climatic zones, after the manner of L. Peltier (Lehmann et al., 1954). Both this commission and the the International Speleological Union, set up in 1953, have paved the way for international cooperation and participation for the English-speaking world. Thus since 1950 many previously little-known areas have been studied and we now have a better idea of the main karst landform types.

The study of karst geomorphology has been greatly advanced by the development of new techniques in analytical chemistry that have enabled limestone waters to be analyzed quickly. Variations in the calcium-carbonate content of karst waters were first discussed by Corbel in 1959 (Paper 7), who contended that karst erosion was more effective in cooler than in tropical regions. This conclusion, though probably incorrect, initiated a controversy that has on the whole been beneficial to the study of karst geomorphology. A further step forward was made by Bögli (Paper 5) in his study of the superficial karren features of limestones. He suggested that one of the factors influencing karren formation is the type of chemical reaction affecting the rock. He differentiates between free karren, formed by solution of limestones by carbon dioxide in atmospheric water (rain and snow), and covered karren formed by biological carbon dioxide in a soil or peat cover.

Mainly as a result of the work by Corbel, there have been many studies of limestone solution in different climates and situations. This has not resolved the climatic controversy but has added much to our knowledge of limestone solution and karst water. The latter term was introduced in 1966 by Pitty (Paper 15), who was one of the first to realize the potential of the computer as applied to karst studies. Some of the most significant work on karst water and the different types of karst springs has been done in the United States (Shuster and White, 1977), and some of the most detailed by the University of Bristol Speleological Society in their work in the Mendips in southwest England and in County Clare, Ireland (Tratman, 1969). The study of karst hydrology, particularly in the use of isotopes, has received much stimulus from the work of D. J. Burdon and his group working in the Middle East for the Food and Agriculture Organization of UNESCO.

Our knowledge of limestones themselves lagged behind our knowledge of karst waters until the developments in carbonate sedimentology brought about by the work of many people, but

particularly R. Folk in 1959. Folk's 1959 paper is reprinted in *Sedimentary Rocks* in this Benchmark series, so it is not included here (Carozzi, 1975). His work established petrovariance as a proper factor in karst variations, which is regarded by some karst geomorphologists as of greater importance than climate. This view applies especially to the development of caves.

Inasmuch as the development of underground drainage and the formation of caves is intrinsic to the development of karst landforms, the study of caves has always been a part of karst geomorphology. Contributions to geomorphology have often been made by speleologists with little interest in landform study per se. The problem of a karst water table appears early in the literature, with differing views on the presence or absence of a unified body of ground water being taken by Grund (1903) and by Katzer and Martel (1909). Certain speleologists, such as Katzer and Martel, were strongly opposed to the normal concept of a water table existing in karst terrain, and Cvijič in his 1918 paper attempted to reconcile the two views. Nowadays it is recognized that in some favorable areas a water table in the usual geological sense does exist but that in the majority of karst areas water occurs only in fractures. American workers have applied the water-table concept more freely because the karst regions in the southeast and the midwest are in flat-lying limestones where the concept has proved useful.

In the light of this background a number of papers appeared in the 1930s, particularly in the United States, on caves and their relationship to karst relief. The most notable of these was by W. M. Davis (Paper 9) and, despite its being written at the age of 80, this is one of his best works. Davis develops the theme of a two-cycle theory of cavern formation; caves originating first in a ground water or phreatic zone and later being substantially modified by ordinary underground streams in the vadose zone. His ideas made a big step forward and he claimed that many features in both cave plans and sections enabled the two phases to be differentiated. Bretz (Paper 10) later applied these ideas to a study of several caves and discussed phreatic and vadose examples. American work on the relationship of cavern formation to karst hydrology is summarized in Thrailkill (1968). One of the most important European works on karst hydrology and its relationship to caves is that of Lehmann (1932) in "Die Hydrographie des Karstes," which is the subject of an excellent review by de. Martonne (Paper 12). In his work, Lehmann likens the relationships between big caverns and cave passages to a series of vessels connected by narrow pipes.

Since 1950 the contribution of speleology has been considerable and the proceedings of many speleological societies have much relevance to karst geomorphology especially in three main areas. First, one of the most important questions concerns the origin of caves since a vast amount of solution is necessary for their formation and they are not randomly distributed within a limestone mass. Many people, including Bögli, have attempted to tackle this problem. Second, increased knowledge of caves, improved surveys, and water tracings mean that caves are no longer isolated features in an area but can give clues to development of the hydrological network. In this connection Smith and Newsom (Paper 24) looked at caves in the Mendips (England) in fluvial terms and concluded that the spatial and temporal distribution of erosion in the caves is essentially similar to erosion by surface streams, that is, "streams with roofs on." And third, cave deposits, both calcareous and noncalcareous, have been shown to be of profound paleoclimatic significance. Oxygen isotope studies of stalactites (in combination with Ur/Th dating) have been remarkably illuminating (Hendy and Wilson, 1968).

The measurement of karst landforms dates from the time of Cvijič, but it is only in recent years that the sophisticated tools of morphometric analysis have been applied to karst geomorphology. Williams (1971) used methods that were originally applied to fluvial areas to a study of three karst areas in New Guinea, and he illustrates how new geomorphological techniques are being successfully applied to karst areas. He considered that enclosed hollows could be treated as small, separate drainage basins and that they obeyed the laws of Horton (1945); because of the development of sink holes, such drainage basins are never larger than order 3. Williams also postulates a sequence of development from a karst lightly dotted with dolines to a karst completely pitted with depressions, that is, a cellular or polygonal karst.

The differentiation of karst relief over the earth's surface is dependent on geological structure and limestone lithology; geological history; past and present climate; and present relief, vegetation, and land use. Although these factors are uniquely combined in each area, distinct karst types or styles can be recognized. These are still most frequently based on climate, karst in tropical areas usually being regarded as the most distinctive. The search for a karst model that is independent of climate is a feature of modern work as climatic geomorphology comes under attack. Climatic geomorphology is the basis for the concepts of paleokarst