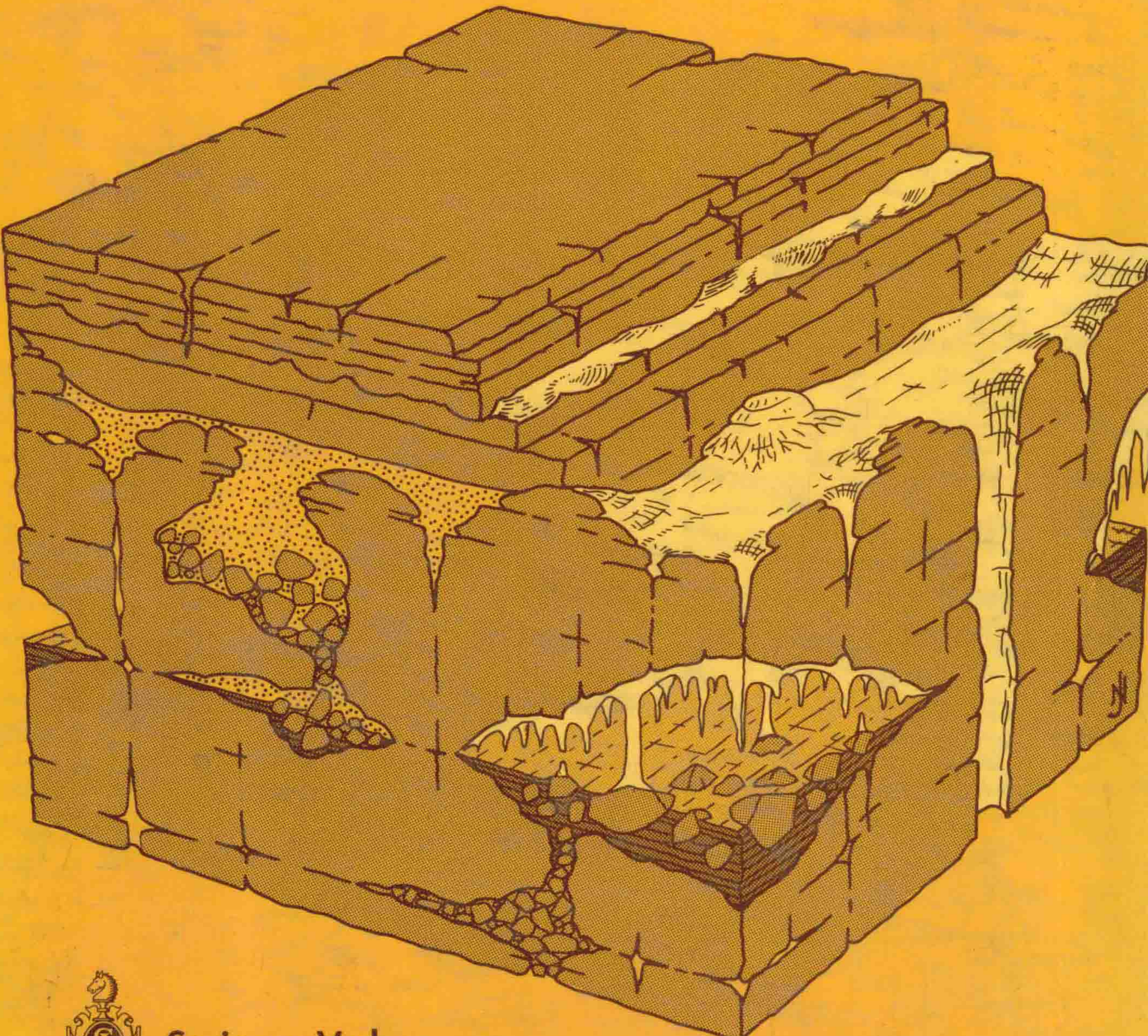
N. P. James P. W. Choquette
Editors

Paleokarst



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Paleokarst

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Paleokarst

Preface

Landscapes of the past have always held an inherent fascination for geologists because, like terrestrial sediments, they formed in *our* environment, not offshore on the sea floor and not deep in the subsurface. So, a walk across an ancient karst surface is truly a step back in time on a surface formed open to the air, long before humans populated the globe. Ancient karst, with its associated subterranean features, is also of great scientific interest because it not only records past exposure of parts of the earth's crust, but preserves information about ancient climate and the movement of waters in paleoaquifers. Because some paleokarst terranes are locally hosts for hydrocarbons and base metals in amounts large enough to be economic, buried and exhumed paleokarst is also of inordinate practical importance.

This volume had its origins in a symposium entitled "Paleokarst Systems and Unconformities—Characteristics and Significance," which was organized and convened by us at the 1985 midyear meeting of the Society of Economic Paleontologists and Mineralogists on the campus of the Colorado School of Mines in Golden, Colorado. The symposium had its roots in our studies over the last decade, both separately and jointly, of a number of major and minor unconformities and of the diverse, and often spectacular paleokarst features associated with these unconformities. The problems of correctly interpreting such paleokarst features were brought sharply into focus while we were preparing a detailed review paper on the alteration of limestones in the meteoric diagenetic realm for Geoscience Canada (James and Choquette, 1984). What struck us most forcefully then was that while the tempo of research on karst and karst-related diagenesis had increased dramatically over the last 20 years, much of the research was following parallel but separate pathways. Hydrologists, geomorphologists, geographers, and speleologists were documenting modern karst systems; petrologists and geochemists were unraveling the complex diagenetic textures, fabrics, and water chemistries of limestones in the meteoric realm; economic geologists were modeling processes associated with base metal deposits in subsurface paleokarst—but there seemed to be little interaction between the disciplines. We felt that the time was right to assemble specialists from these diverse fields to review the status of research, to look at paleokarst together, and to present papers outlining recent studies on a variety of paleokarst terranes.

This book represents the fruits of that effort. It brings together the majority of the symposium reports, along with several other manuscripts solicited or volunteered shortly after the meeting. In an introductory article we have attempted to draw together the main threads of these contributions in a brief synthesis of our understanding of the controls, processes, and features of paleokarst. The main body of the book is devoted to presenting well-documented examples which emphasize the sedimentological and geochemical/geomorphological aspects of surface and subsurface paleokarst, together with more general discussions of the processes, features, and geological signatures associated with karst systems.

We are indebted to all of our colleagues who contributed to the symposium and to this volume, for their cooperation, good humor, and forebearance. To Judith V. James we extend special thanks for editing assistance, text manipulation, and preparation of the subject index. We especially acknowledge Derek Ford and Dexter H. Craig for their counsel during the preparation of the Introduction to this book. Richard H. De Voto and some of his associates shared their knowledge of Mississippian paleokarst in central Colorado on a field trip with many of the symposium participants. Finally, we are particularly grateful to the staff of Springer-Verlag New York Inc. for the strong interest in this project that made possible the timely publication of this book. Expenses incurred during the assembly, editing, and processing of manuscripts were defrayed in part by the Natural Sciences and Engineering Council of Canada (NPJ) and Marathon Oil Company (PWC), to whom we express our gratitude.

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Contents

Introduction

PHILIP W. CHOQUETTE and NOEL P. JAMES

Karst is as dramatic a feature of the earth's surface as it is unique and complex. The manifold and convolute landforms, the complicated and delicately adorned caves, the bizarre drainage systems and collapse structures have few analogs in other kinds of terrains. But these features are only the most obvious in an array of surface and subsurface structures which range in size down to the submicroscopic and comprise systems that are only partly understood—systems that, quite uniquely, form almost entirely by dissolution.

Aims and Emphasis of this Volume

This book is devoted to the documentation and interpretation of karst in the geologic record. Understanding paleokarst is dependent, however, upon an appreciation of modern karst systems and how they are "fossilized." The volume is therefore in two sections. Part I consists of 7 papers dealing with aspects of the development, preservation, modification, and recognition of karst terranes. Part II consists of 11 papers documenting examples of paleokarst, Proterozoic to Cretaceous in age, from a wide variety of shelf and platform settings.

State of the Art

Karst terranes, with their cave systems and distinctive landforms, have for centuries intrigued students of earth processes. Most early studies were directed toward understanding the morphology, hydrology, and development of these features, which are well documented in numerous texts (e.g., Jennings 1971 and 1985, Sweeting 1973, Jakucs 1977, Bögli 1980, Trudgill 1985) that discuss theory as well as observations.

In the last 30 years, an awareness of ancient karst has developed among geologists whose primary interests lie in the stratigraphy and sedimentology of sedimentary carbonates (e.g., Roberts 1966, Roehl 1967, Bignot 1974, Quinlan 1972, Walkden 1974, Sando 1974, Meyers 1974 and 1978, Read and Grover 1977, Kobluk et al. 1977, Maslyn 1977, Wright 1982, Grover and Read 1983, Arrondeau et al. 1985). This awareness has come about because of a burgeoning of studies on meteoric-water diagenesis of carbonate sediments. Some threads of understanding between these two closely related fields have been drawn together in works by Bathurst (1971 and 1975) and more recently in major attempts at synthesis by Longman (1980), Esteban and Klappa (1983), and James and Choquette (1984). This growing appreciation of karst in the geologic record came about because of several factors: the detailed documentation of extant karst (e.g., Bögli 1980, Jennings 1985); refinement of our understanding of the hydrological and chemical processes that lead to chemical dissolution (e.g., Thrailkill 1968, Plummer et al. 1979, Hanshaw and Back 1980, Palmer 1984); substantial documentation of the diagenetic processes and features localized at the rock-soil-air interface (e.g., Esteban and Klappa 1983, and references therein); the growing recognition that paleokarst terranes, in addition to being destructive features, are also constructive sources of cations and carbonate ions for local speleothem deposition and for regional cementation (e.g., Meyers 1974 and 1978, Grover and Read 1983); and finally, a growing awareness that many puzzling fabrics and structures once thought to be meteoric in origin can be assigned to other diagenetic environments such as the sea floor and deep-burial realms (e.g., James and Choquette 1983 and 1984, Scholle and Halley 1985, Choquette and James 1987).

In spite of these encouraging trends, karst and paleokarst have received relatively little attention from carbonate sedimentologists and petrologists. Sedimentological studies have traditionally concentrated on documenting the makeup of carbonate deposits, deciphering their facies mosaics, and reconstructing their depositional and paleogeographic settings. Toward these ends, attention has focused on sedimentary structures, macroscopic features, and biotic constituents, and great effort has generally been made to record information from outcrops or drill cores. Studies of diagenesis, on the other hand, largely through thin-section petrography and geochemistry, have been directed toward unraveling the alteration history of carbonates and so have concentrated on microscopic cements and small-scale fabric-selective porosity.

The reason for this apparent neglect of larger-scale karst features may lie in the "negative," dissolutional nature of karst itself. Especially troublesome is intrastratal corrosion, which forms in the subsurface along lithologic boundaries and creates features that can be mistaken for surface karst. On a smaller scale, there is the problem of differentiating paleokarst surfaces from stylolites and other pressure-solution phenomena (Walkden 1974). It can also be quite difficult to separate local, more or less planar surfaces of a preserved paleokarst terrain from a paleokarst surface that was planed or corroded and bored during subsequent marine transgression. Finally, there is often uncertainty about when dissolution took place (Wright 1982)—did the observed features form soon after deposition of the host strata, are they the result of present-day processes, or were they fashioned at some intermediate time(s)? In short, the very *recognition* of paleokarst can be problematical.

Another reason may be that the natural laboratories of the carbonate petrologist, the mid-to-late Pleistocene carbonates of the tropics that have yielded most of our information on meteoric diagenesis, contain few accessible caves and little extant or former karst. This is because sealevel was much lower during most of the Pleistocene than it is today, so that even the most extensive Pleistocene karst systems are now drowned.

Lastly, the regional distribution and configuration of major karst unconformities have only recently become accessible with the development of high-resolution seismic profiling and reprocessing technology (recent summary and references in Fontaine et al. 1987). Until this development, attempts to reconstruct regional unconformities in any detail relied on information from large numbers of wells or outcrop sections. With the advent of sophisticated seismic technology has come the application of classical stratigraphic concepts and methods (e.g., Sloss 1963) to stratigraphic analysis using seismic-reflection profiles—the "new seismic stratigraphy" (e.g., Vail et al. 1977) in which regional and interregional unconformities are key elements (Schlee 1984).

Definitions

In this volume we use the term *karst* in the broad sense to include all of the diagenetic features—macroscopic and microscopic, surface and subterranean—that are produced during the chemical dissolution and associated modification of a carbonate sequence. By convention we also include the subsurface precipitates (speleothems) which may adorn dissolution voids, the collapse breccias and mechanically deposited "internal sediments" which may floor or fill the voids, as well as surface travertine. Evaporite karst is not considered in this volume.

Paleokarst is defined here (cf. Walkden 1974, Wright 1982) as ancient karst, which is commonly buried by younger sediments or sedimentary rocks and thus includes both *relict* paleokarst (present landscapes formed in the past) and *buried* paleokarst (karst landscapes buried by sediments) as defined by Jennings (1971) and Sweeting (1973). For many who use this book, the broad definition familiar to many

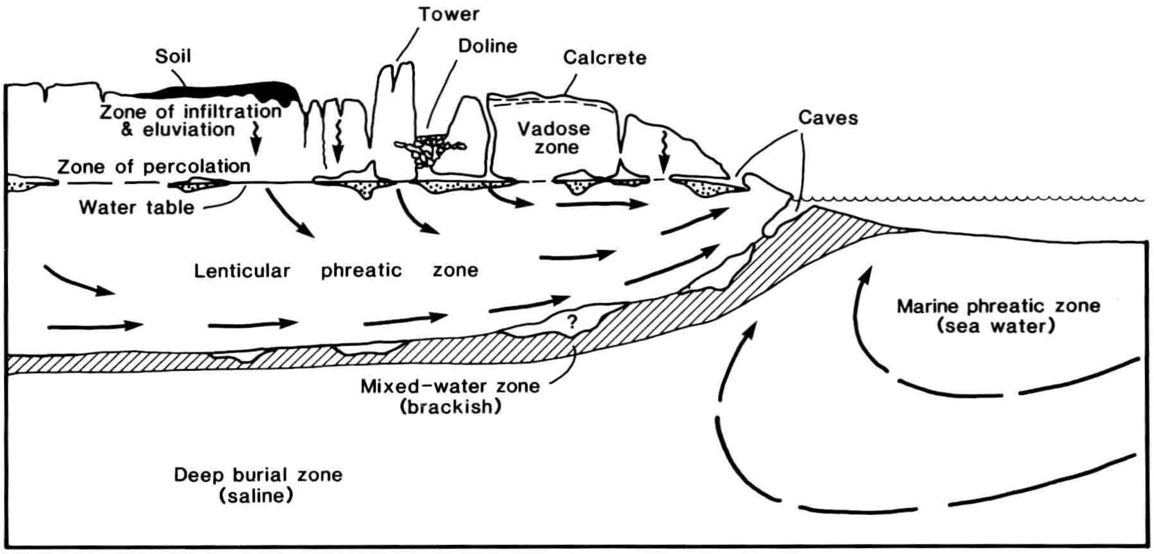

FIGURE 1. A diagram showing the general elements and hydrology of a karst terrane developed on recently deposited carbonates adjoining the sea.

carbonate petrologists and stratigraphers and expressed by Esteban and Klappa (1983, p. 11) may be helpful: "Karst is a *diagenetic facies* (our italics), an overprint in subaerially exposed carbonate bodies, produced and controlled by dissolution and migration of calcium carbonate in meteoric waters, occurring in a wide variety of climatic and tectonic settings, and generating a recognizable landscape." Karst and paleokarst are literally, in the words of Roehl (1967), *subaerial diagenetic terranes*, with an array of distinctive and generally interpretable features (Fig. 1).

For simplicity we also differentiate the types of calcite precipitated in a karst terrane into (1) *speleothems* for those precipitates deposited in spelean settings, or those cavities more than 50 cm in diameter (i.e., large enough to be explored), (2) *cements* for those precipitates which accumulate in smaller holes and are commonest in depositional, fabric-controlled (Choquette and Pray, 1970) pores, and (3) *surface travertines* for those carbonates precipitated from springs at the surface.

Controls of Karst Formation

The wide variety of karst features and the degree of karstification are the end results of interacting processes governed by intrinisic and extrinsic factors (Table 1).

Intrinsic Factors

Most important among these are the *general lithology*, the "matrix" or *stratal permeability*, and the availability of *fractures* and other potential conduits for groundwater. It is well known that, all other rock properties being equal, limestones are several orders of magnitude more soluble

TABLE 1. Factors that influence the development of karst terranes.

Extrinsic	
Climate	Rainfall & evaporation Temperature
Base level	Elevation & relief Sealevel or local water bodies
Vegetation	
Time Duration	
Intrinsic	
Lithology	Mineralogy Bulk purity Fabric and texture Bedding thickness Stratal permeability Fractures
Structure & stratigraphy	Attitude of strata Confined or unconfined aquifers Structural conduits

than dolomites in meteoric water, and gypsum and anhydrite both are more soluble than either group of carbonates. In limestones the "maturity" or degree of stability as opposed to metastability of the $CaCO_3$ mineralogy is most important. Where carbonates with metastable forms of $CaCO_3$ are in contact with meteoric groundwaters, dissolution of aragonite will result in moldic and other forms of fabric-selective porosity, in addition to releasing Ca^{+2} and CO_3^{-2} which eventually precipitate as low-Mg calcite cement. Mineral-controlled alteration of this nature (James and Choquette 1984) may thus create new voids that form part of the karst diagenetic terrane, while concurrently occluding some original porosity (Harrison 1975).

Where poorly cemented carbonate sands or grainstones are subaerially exposed, high stratal permeability may cause groundwater flow to be diffuse, through the grain framework, bypassing or only partly using available fractures. Other processes, such as eluviation of sediment from the surface into the porous grainstone, and limited cave development above the water table, are also consequences of high permeability (Fig. 2). Low-permeability carbonates are likely to transmit groundwater chiefly by conduit flow through fractures and along bedding planes. Although most descriptions of extant karst emphasize the importance of large-scale voids and fracture-controlled dissolution, it is likely that small-scale dissolution and other alteration effects are widespread in the more permeable carbonates in karst terranes. Where dissolution cuts down deeply into the phreatically cemented "roots" of a karst terrane, stratal

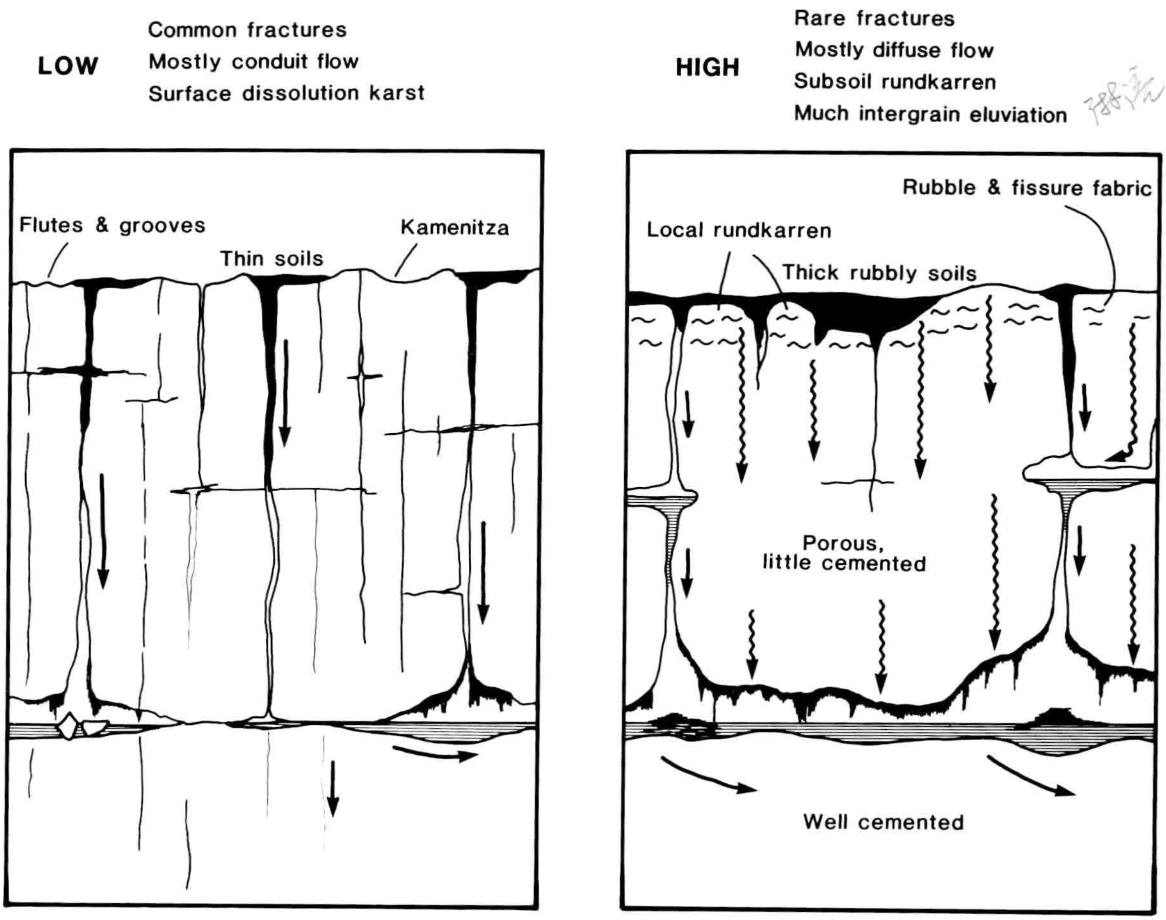

FIGURE 2. A sketch illustrating effects of contrasting stratal permeability on styles of surface and subsurface karst. Low-permeability carbonate might be a partly-lithified to well-lithified lime mudstone or tightly cemented grainstone. High-permeability limestone might be a little-cemented and/or leached, well-sorted lime sand or grainstone. A warm, temperate or humid climate is assumed.

permeability effects will be lessened and fractures will play a more important role in flow patterns.

In order to form intricate surface karst features such as grooves, flutes, and other karren, rainwater must run off rather than percolate into the rock. For this to happen low permeability is required, through either extensive cementation, high lime mud content, or a surface veneer of impermeable calcrete (Fig. 2).

Fractures are particularly important as water conduits in the development of caves. The role of fracturing is commonly "iterative," as small-fracture networks formed by dissolution-collapse become new conduits. Dissolution-enlarged fracture systems act as agents of mass transfer, transmitting soil and sediment downward from the surface and feeding vadose seepage waters that precipitate speleothems in caves.

Extrinsic Factors

Perhaps the most crucial extrinsic factor is *climate*, although *vegetation*, the relationship between initial subaerial relief and *diagenetic base level*, and, of course, the *time duration* of exposure are all important.

In areas of high rainfall and warm temperatures, alteration proceeds quickly, resulting in well-developed soil and terra rossa, abundant sinkholes (dolines), and subsurface dissolution-collapse breccias (Fig. 3). In some regions spectacular landforms evolve and may include pinnacles, jagged ridges, towers, and canyons with interspersed closed depressions that can be virtually impenetrable. In temperate or Mediterranean-type climates, karst and calcrete are common but their development is often seasonal or guided by longer-term cycles. On Caribbean islands built of Cenozoic calcarenite, it is common to find shallow sinkholes and other dissolution cavities veneered by calcrete (James 1972), or conversely, calcrete crusts that have been breached by dissolution. Deserts generally have little karst other than local surface karren, and in warm semiarid climates calcrete is common because of intense evaporation after occasional rains. In cold climates, karst is common even though reaction rates are slow; surface karst is well developed and subsurface karst forms at depth up to the continuous permafrost boundary. Calcrete is not present but calcite does precipitate onto clasts in the soil (D. Ford pers. comm. 1987).

The recognition that caliche and karst require somewhat different combinations of rainfall, evaporation, and to lesser extent temperature to form has led to the proposal that there are "karst facies" and "caliche facies" (Es-

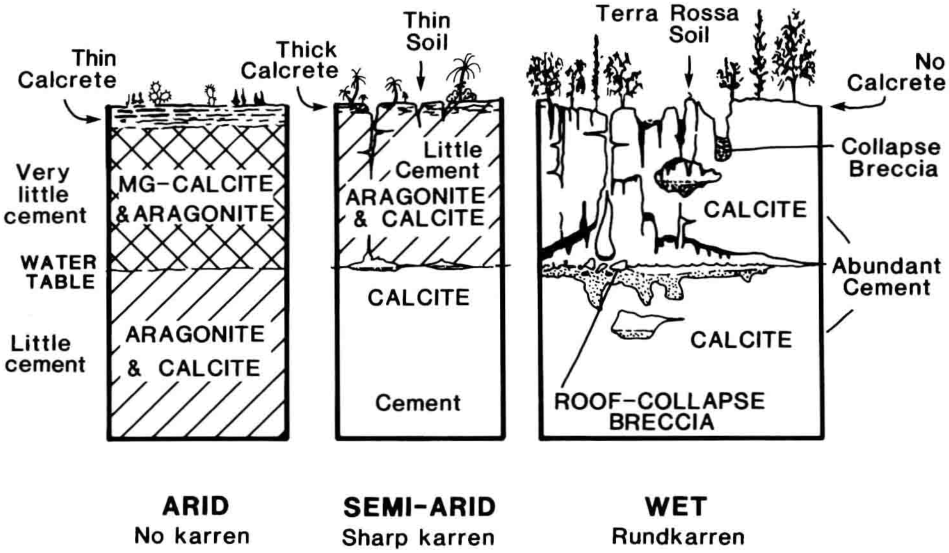

FIGURE 3. A diagram showing common karst features associated with different climatic conditions. Modified from James and Choquette (1984).

teban and Klappa 1983). At the same time, observations on relatively large islands at low latitudes, with marked orographic effects, have shown that both facies can develop not only in sequence, but synchronously, adjacent to one another, during the same season.

Climate also plays an important role in vadose and phreatic cementation beneath exposure surfaces. Recognition that cementation proceeds slowly in arid and semiarid regions such as the Persian Gulf, and that Jurassic carbonate reservoirs in the region commonly had very little cement, for example, led Illing et al. (1967) to suggest a climatic effect. It appears that different styles and abundances of meteoric cements are associated with paleokarst in arid as opposed to humid climates—and as such can be sensitive indicators of climate. Arid-climate diagenetic terranes tend to have little vadose cement other than needle-fiber crystals and sparse low-iron, blocky phreatic cement. Humid terranes, in contrast, tend to have extensive vadose and phreatic cements. Other factors, in particular, relief above water table and as a consequence hydraulic head, will come into play as well, since they too influence the throughput and vigor of groundwater.

The important concept of a base level for diagenesis in the meteoric zone, generally coincident with local drainages and/or the sea, appears in the landmark writings of Davis (1930) and Bretz (1942). Now that the effects of sea-level variations, the anatomy of broad, low-relief carbonate platforms standing only slightly above sealevel, and the contrasts between vadose and phreatic diagenetic alteration (e.g., Steinen and Matthews 1973, Longman 1980, James and Choquette 1984) are better understood, it is timely to reexamine this concept. The role of the water table per se in guiding the development of cave systems now seems strongly dependent on the nature of the conduit (pore) system offered by the host carbonates. In relatively "new" and/or little-cemented strata with high matrix or stratal porosity and permeability, the water table will be a general locus near which many caves first develop (Fig. 1). Cave systems also form in the vadose zone, where their prevailing elongation roughly normal to the water table betrays their origins, but these seem to make up only a small percentage of known caves (Bretz 1942). In more "mature" and/or extensively cemented carbonates that have little or no stratal permeability, any conduits available will be fractures, faults, and bedding surfaces, and in these rocks the development of caves will determine where the water table will be, rather than vice versa (D. Ford pers. comm. 1987). Caves will thus develop to depths dictated by these larger conduits and topographic relief, and in the process will themselves create vadose and phreatic zones and intervening water tables. In general, whether stratal permeability is high or low, as cave systems develop groundwater will be diverted along them, bypassing deeper zones which then will become relatively stagnant. Karst landscapes erode down to a base level approximating the elevation of local water bodies, and the zone of maximum cave development encompasses the water table.

Cave systems also develop in sublenticular mixing zones along the coasts of some exposed carbonate platforms (e.g., Hanshaw and Back 1980, Back et al. 1984 and 1986), and may also form in inland brackish zones of extensive aquifers, such as the "boulder zone" in the Biscayne aquifer of south Florida (Vernon 1969). The importance of cave formation in the lower reaches of inland aquifers to depths of hundreds of meters below any extant water table has been demonstrated (e.g., Ford, this volume).

In general, the maximum relief possible on a karst landscape or paleolandscape will depend on initial elevation above local water bodies or the sea at the start of subaerial exposure (Fig. 4). This base level will control the depth of surface-karst erosion, but cave systems will generally develop to varying, often substantial depths (hundreds of meters) below it. On widespread carbonate platforms adjacent to the sea, relief will be limited by the elevation of the platform, which may be tens to hundreds of meters but is commonly a very few meters for very low-lying islands and coastal parts of such platforms. Subaerial exposure surfaces in the Pleistocene of Florida and the Bahamas (e.g., Perkins 1977, Beach 1982) now have relatively low relief (order of 10^0–10^1 m) but probably represent drowned paleokarst terranes of higher relief. In strongly uplifted regions such