Coastal Research Library 5

Michael J. Lace
John E. Mylroie *Editors*

Coastal Karst Landforms

Springer

Coastal Karst Landforms

Coastal Research Library

VOLUME 5

Series Editor:

The aim of this book series is to disseminate information to the coastal research community. The Series covers all aspects of coastal research including but not limited to relevant aspects of geological sciences, biology (incl. ecology and coastal marine ecosystems), geomorphology (physical geography), climate, littoral oceanography, coastal hydraulics, environmental (resource) management, engineering, and remote sensing. Policy, coastal law, and relevant issues such as conflict resolution and risk management would also be covered by the Series. The scope of the Series is broad and with a unique crossdisciplinary nature. The Series would tend to focus on topics that are of current interest and which carry some import as opposed to traditional titles that are esoteric and non-controversial. Monographs as well as contributed volumes are welcomed.

For further volumes:
http://www.springer.com/series/8795

Michael J. Lace • John E. Mylroie
Editors

Coastal Karst Landforms

Springer

Editors
Michael J. Lace
Coastal Cave Survey
West Branch, IA, USA

John E. Mylroie
Department of Geosciences
Mississippi State University
Starkville, MS, USA

ISSN 2211-0577 ISSN 2211-0585 (electronic)
ISBN 978-94-007-5015-9 ISBN 978-94-007-5016-6 (eBook)
DOI 10.1007/978-94-007-5016-6
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2013939786

© Springer Science+Business Media Dordrecht 2013
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Foreword

Bermuda, Bahamas, Barbados . . . . many of the places described in this book might appear to be inspired by travel brochures. But here they serve as the prime testing grounds for one of the most vibrant and far-reaching fields in geomorphology: the study of coastal karst and caves.

Seacoasts are among Earth's most dynamic places. While sedimentary deposits are constructed along some of them, erosion and dissolution tend to dominate elsewhere. These opposing processes result in a variety of unique caves, karst, and solutional pores. In water-soluble rocks, coastal caves and karst include a warren of pockets, chambers, channels, and depressions. Water seeping from the surface has decorated many of them with crystalline deposits. Where mechanical erosion dominates, sea caves can be produced in any kind of rock.

These features are significant not only for revealing geomorphic processes, but also for interpretation of past climates, sea levels, and geography. For economic geologists they provide important clues to paleoenvironments and the distribution of porosity. Biologists value them as refugia for rare plants and animals. Archeologists and paleontologists recognize their ability to shelter and protect artifacts and organic remains. Some of these coastal features have become well-known tourist sites. The majority of seacoast caves and karst, as well as the rocks that contain them, are relatively young in geologic terms – typically less than a million years old. Thus they contain records of the intense fluctuations in climate and sea level that took place during that time.

It was not until recent decades that coastal caves and karst received substantial attention from the scientific community. They had previously been the domain of scuba divers who entered them mainly for sport, as well as a few geochemists who were intrigued by the interaction of fresh water and seawater. Eventually, in their quest for new frontiers, several karst scientists were drawn from their original domains of continental karst to the attractive islands of the Caribbean and other low-latitude regions. There they found wide-open and welcoming field areas that led in many new directions of exploration and science. Since then, they have expanded their research throughout the world, and they have developed new terminology to encompass their findings. Terms such as *eogenetic karst*, *flank margin cave*, and *carbonate island karst model* are now widespread in the technical literature.

The authors of this book include many of the pioneers in the field, as well as their students and associates. Their goal is mainly geomorphic and speleogenetic, although relevant aspects of biology, archeology, and management are also included. Today many researchers utilize coastal caves for various other purposes, most notably the analysis of cave deposits for interpretation of past and present climates. Much fine science has been done in these derivative fields, but there is often a tendency for them to bypass the geomorphic fundamentals – as though building a tower with no foundation. This book provides that foundation.

Professor of Hydrogeology, Emeritus
State University of New York, Oneonta, NY
Arthur N. Palmer

Preface

Coastlines may be the most abundant landform unit on the planet earth. They come in a variety of types, shapes, origins, and function. Where the coastlines are rocky, an abundance of sea caves can develop. When those rocks are soluble, a unique set of karst features can appear, both on and within the rock. Even where the coastline is a beach, if soluble rocks are present immediately inland, coastal processes will create distinctive caves and karst not found in the interiors of continents. The literature on coastal caves, until recently, either dealt with sea (or littoral) caves, or for carbonate coasts, applied models that were developed on old limestones deep within continental platforms. The subject is further confused as dynamic coastal processes constantly modify all cave types present, obscuring cave origin. Caves have long been known as repositories of information on past ecologies, climate, hydrology, and human history. Coastlines, as the intersection point between the marine and terrestrial realms, have a wealth of information to provide if only it could be preserved. Coastal caves, especially those produced by dissolution, can create a long-term preservational environment that can enlighten us about the past. In the present, the caves harbor unique ecologies, present complex land use problems, help control fresh-water resources, and provide underground landscapes of incredible beauty and fragility.

This book is designed as a gateway to the concepts and examples of coastal karst and pseudokarst development. Part I deals with our understanding of the modern fundamental concepts that control cave development in coastal areas. Part II presents a variety of case histories from around the world, from simple islands to complicated continental coasts. The focus is on dissolutional caves, and given the paucity of evaporate rocks in coastal areas, the dissolutional caves are formed mostly in carbonate rock. The majority of carbonate coasts in the world today are in the tropics and subtropics, and consist of young carbonates that are eogenetic, that is, have not yet undergone burial and associated diagenesis. Coupled with the unique hydrology and geochemistry of these coastal environments, this youthful age creates caves and karst of a unique form and character. In areas where the rocks are older and diagenetically mature, such as the 6,000 km of carbonate coast found in Croatia, interesting parallels with younger carbonate coasts can be drawn. A chapter on the sea caves of the west coast of the USA offers an interesting comparison to carbonate coasts.

We hope that this book stimulates further interest and research in these interrelated fields of the coastal sciences. Much of the work presented in this volume is the result of extensive fieldwork conducted by numerous karst researchers, graduate students and ongoing research projects from various disciplines and organizations. We extend our thanks to the many researchers and cave explorers who have and continue to tirelessly document cave and karst resources in so many parts of the world. Our collective understanding of coastal caves and karst continues to develop as does the appreciation for the integral roles these shoreline and paleoshoreline features play in modeling coastal processes, past, present and future. We extend our thanks to the many colleagues and friends who supported and contributed to the compilation of this work with invaluable insights tempered from a range of perspectives from many fields of research.

West Branch, IA and Mississippi State, MS
Michael J. Lace
and John E. Mylroie

Contents

Part I Principles of Coastal Karst Development

Part II Selected Case Studies in Coastal Cave and Karst Development

Contributors

Robert Brinkmann Department of Geology, Environment, and Sustainability, Hofstra University, Hempstead, NY, USA

David E. Bunnell Angel's Camp, CA, USA

David A. Burney National Tropical Botanical Garden, Kalaheo, HI, USA

James G. Coke IV Kent, OH, USA

Beth Fratesi SDII Global Corporation, Tampa, FL, USA

Angel Ginés Departamento de Biologia, Universitat de les Illes Balears, Palma de Mallorca, Spain

Joaquín Ginés Departamento de Biologia, Universitat de les Illes Balears, Palma de Mallorca, Spain

Francesc Gràcia Departamento de Ciències de la Terra, Universitat de les Illes Balears, Palma de Mallorca, Spain

John J. Jenson Water and Environmental Research Institute of the Western Pacific, University of Guam, Mangilao, GU, USA

Patricia N. Kambesis Department of Geosciences, Mississippi State University, Mississippi State, MS, USA

Miklós Kázmér Department of Palaeontology, Eötvös University, Budapest, Hungary

Johanna L. Kovarik Department of Geology, University of South Florida, Tampa, FL, USA

Michael J. Lace Coastal Cave Survey, West Branch, IA, USA

Hans G. Machel Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada

Gregory J. Middleton Department of Environmental Studies, University of Tasmania, Sandy Bay, TAS, Australia

Joan R. Mylroie Department of Geosciences, Mississippi State University, Mississippi State, MS, USA

John E. Mylroie Department of Geosciences, Mississippi State University, Mississippi State, MS, USA

Athena M. Owen Department of Geosciences, Mississippi State University, Mississippi State, MS, USA

Jason S. Polk Department of Geography and Geology, Western Kentucky University, Bowling Green, KY, USA

Kevin W. Stafford Department of Geology, Stephen F. Austin State University, Nacogdoches, TX, USA

Danko Taboroši Water and Environmental Research Institute of the Western Pacific, University of Guam, Mangilao, Guam

Island Research & Education Initiative, Palikir, Pohnpei, FM, Micronesia

Abbreviations

AAR	amino acid racemization
ASL	above sea level
$CaCO_3$	Calcium Carbonate
CIKM	carbonate island karst model
DEM	digital elevation model
DOC	dissolved organic carbon
ENSO	El Nino Southern Oscillation
ka	thousands of years ago
LIDAR	light detection and ranging
Ma	million years ago
MIS	marine isotope state
MLLW	tidal datum referring to the "mean lower level water" height of sea level observed
MPA	marine protected area
MSL	mean sea level
NGO	non-governmental organization
RYBP	radiocarbon years before present
U/Th	Uranium Thorium disequilibrium dating
XRD	x-ray diffraction

Part I

Principles of Coastal Karst Development

Pseudokarst Caves in the Littoral Environment

1

John E. Mylroie and Joan R. Mylroie

Abstract

Rocky coastal regions can host caves produced by karst (dissolutional) processes, and caves produced by pseudokarst (non-dissolutional) processes. On limestone coasts, which are common world wide, both processes can be active and a complex interplay can result. Lava tubes, calcaerous tufa deposition, and reef growth all produce constructional caves, voids formed as the rock itself is formed. Only reef growth is an obligatory result of the marine coastal environment. Tafoni result from subaerial weathering of a variety of lithologies exposed on a cliff or steep slope, and can mimic other types of pseudokarst caves and karst caves. Talus and fissure caves result from failure of steep slopes and cliffs, themselves a result of coastal erosion which can quickly remove these pseudokarst cave types. Sea arches and sea caves are abundant on rocky coasts, as the interaction of wave dynamics and rock properties create a variety of erosional voids. Sea cave processes can overprint other cave types to produce a hybrid cave. Sea caves are likely the most common cave type in the world, but on limestone coasts, dissolutional mixing zone caves also form in great numbers, and are commonly overprinted to make abundant hybrid caves.

1.1 Introduction

Caves that are found in coastal cliffs and rocky shorelines today (Fig. 1.1) can have a variety of origins. These can be classified as two major categories, karst caves and pseudokarst caves. Karst consists of the landforms developing on, and the water flow system forming within, soluble rock material; pseudokarst is defined as karst-like features that form by processes other than dissolution (modified from Palmer 2007). Common karst-forming rocks are the carbonate rocks limestone, dolomite, and marble (Fig. 1.2). Less common, especially in coastal areas, are evaporite rocks such as gypsum and halite (Fig. 1.2), although they can be found in very arid coastlines. Evaporite rocks are highly soluble, and readily dissolve when in contact with seawater. These rocks are also mechanically weak,

J.E. Mylroie (✉) • J.R. Mylroie
Department of Geosciences, Mississippi State University,
Mississippi State, MS 39762, USA
e-mail: mylroie@geoscience.msstate.edu

M.J. Lace and J.E. Mylroie (eds.), *Coastal Karst Landforms*, Coastal Research Library 5,
DOI 10.1007/978-94-007-5016-6_1,

Fig. 1.1 Breached cave chamber, in a coastal location, north shore Curaçao. The cave is developed in late Pleistocene limestone, a large chamber that is laterally open to the sea and waves surge out on to the limestone bench. The cave origin is thought to be dissolutional, with later marine invasion and modification to make it a hybrid cave

and do not endure the mechanical pounding that occurs in wave-swept coastal areas. Carbonate rocks, on the other hand, are both mechanically stronger, and chemically less soluble than evaporite rocks, and can structurally persist for long periods of time in the energy-rich coastal environment. Other rock types, such as quartzites, granites and sandstones, have been known to produce true karst under certain conditions, but karst caves developed by dissolution in these rocks in coastal zones are not yet recognized. Soluble rocks of sufficient mechanical strength can also form caves in coastal settings by non-dissolutional, or pseudokarst, processes.

Pseudokarst processes operating in coastal environments are an amalgamation of geological processes that characteristically operate in continental interiors, and processes unique to coastal settings. Because coastal landforms are the interface between the marine and terrestrial realm, there is a focus of these pseudokarst processes at that interface. Pseudokarst caves can form from a wide variety of weathering mechanisms. In coastal areas, these can be expressed as tafoni, talus caves, fissure caves, sea (littoral) caves, or caves shaped by a combination of these processes.

1.2 Constructional Caves

Other pseudokarst cave types, such as lava tubes (Fig. 1.3), can also occur in the coastal realm, but these caves are a product of rock deposition, as opposed to rock weathering. The presence of lava tubes in a coastal environment is a geologic accident, independent of coastal processes. However, since many islands around the world are volcanic in origin, lava tubes reaching the coast are not uncommon. Lava tubes are a pseudokarst cave type, but also fall into the category called *constructional caves*, in that they form as an outcome of the deposition of the rock that hosts them. Lave tubes are made as lava flows are forming, moving, and solidifying. The Lanzarote anchialine lava tube system in the Canary Islands is a classic example of a lava tube overprinted by marine processes (Wilkens et al. 2009).

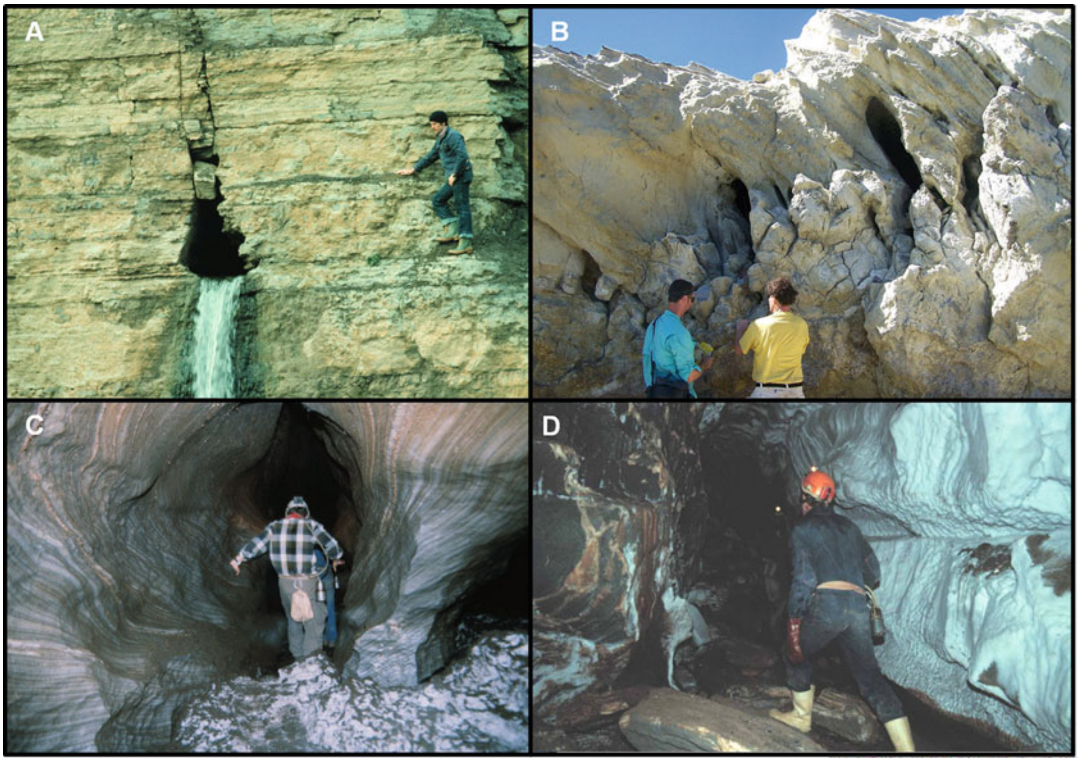

Fig. 1.2 Cave development by dissolution in a variety of soluble rocks. (**a**) Devonian limestone cave exposed in a quarry in New York State. (**b**) Small caves in Miocene dolomitized chalk exposed in a sea cliff, Barbados. (**c**) Cave passage in marble in Glomdalen, northern Norway (note remnant winter snow on floor). (**d**) Cave passage in rock salt (halite), northeastern Spain

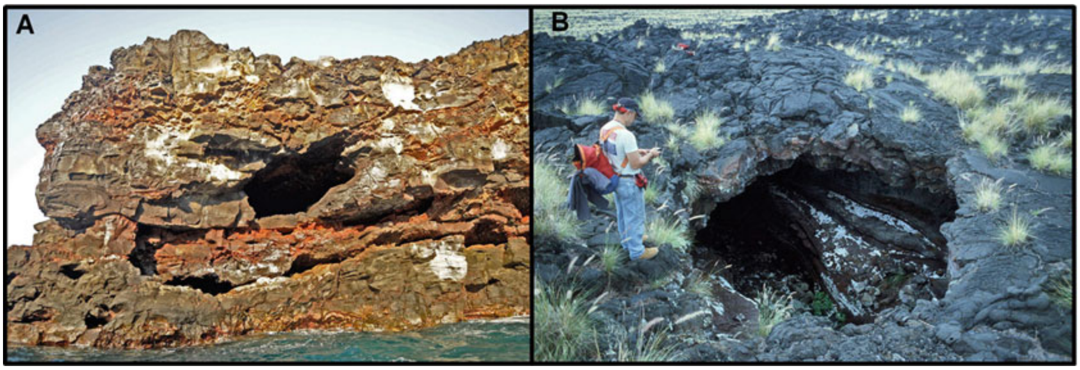

Fig. 1.3 Lava tubes in coastal settings in Hawaii. (**a**) Lava tube intersected by coastal retreat. (**b**) Lava tube in a coastal setting, entered by roof collapse (Photos by D. Bunnell)

Other examples of constructional caves exist; one example are large primary voids in reef limestones, created as the coral reef grows, branches, and is buried in its earlier stages. In ancient rocks that have been buried and undergone diagenetic maturation, such voids are usually infilled and closed, at least at the macroscopic scale. However, in very young limestones that have not undergone burial, such as uplifted Pleistocene coral reefs or submerged modern reefs, such large voids may allow human entry into actual caves.

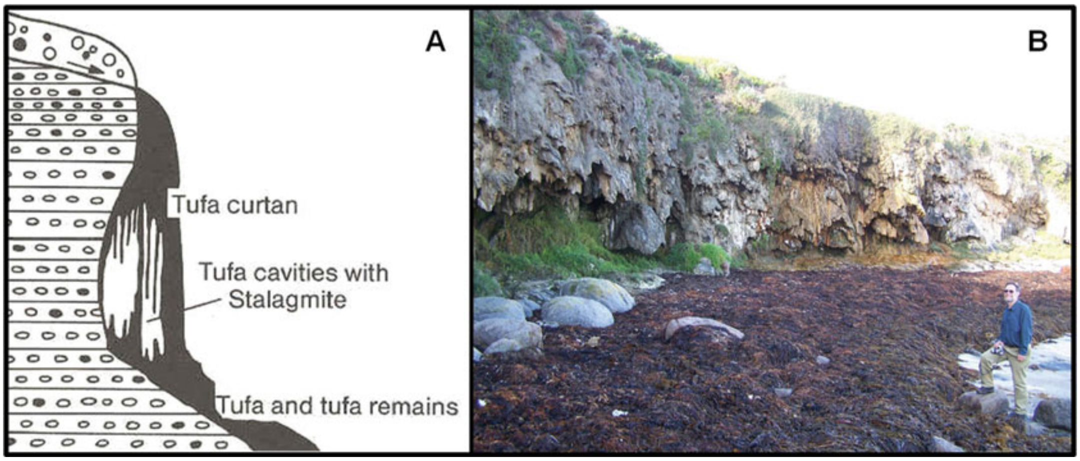

Fig. 1.4 Constructional caves formed by carbonate tufa deposition. (**a**) Cartoon of how tufa cascades can enclose a void to make a cave (Adapted from Bögli 1980). (**b**) Tufa cascades forming tufa caves on a small sea cliff, Margaret River, Western Australia

Another example is where surface waters have excessive loads of dissolved $CaCO_3$; degassing of CO_2 may result in massive deposition of $CaCO_3$ to form calcareous tufa and travertine. These deposits, especially on steep slopes and cliffs (Fig. 1.4), may grow outward and then downward, so as to enclose open spaces to form tufa caves (Bögli 1980). The reef and tufa examples may be somewhat counter-intuitive, as the process of enclosing the void is done by manipulation of the chemistry of $CaCO_3$. But the process in these two cases is $CaCO_3$ deposition, not dissolution; the $CaCO_3$ entered the water as dissolved species at some location distant in time and space from the final depositional site. The caves were made by construction, at the depositional site, and not by *in situ* dissolution.

1.3 Hybrid Caves

Caves that are formed by karst processes, or by depositional processes such as lava tubes or tufa caves, may eventually end up in the coastal environment. In that case, the caves may be overprinted by coastal processes to form a cave type called a *hybrid cave* (Machel et al. 2012). A hybrid cave is a cave structure produced by one geologic process that has been overprinted by a second geologic process. The overprinting of a lava tube, or a karst cave, by wave action along a rocky coast is the most common example of cave hybridization. Figure 1.1 presents a possible hybrid cave; Fig. 1.4 shows tufa caves undergoing wave attack.

1.4 Sea Level

As noted earlier, the coast is the interface between the marine and terrestrial realms. This interface is not static over geologic time. The migration of this interface is called sea-level change. There are two main ways in which sea level changes. *Eustatic sea-level change* is a change that occurs essentially simultaneously, and by similar (but not necessarily exact) amount and rate, at all coasts of the world (Kelletat 1995). The major ways to cause a eustatic change is to change the amount of ocean water, change the volume of the ocean basin holding the water, or change the physical properties of the ocean water.

An example of changing the amount of water would be glaciation-deglaciation cycles, called *glacioeustasy*, where ice is stored on continents, resulting in sea level fall; when the earth warms, the ice melts and water returns to the sea, raising sea level (Fig. 1.5a). An example of changing

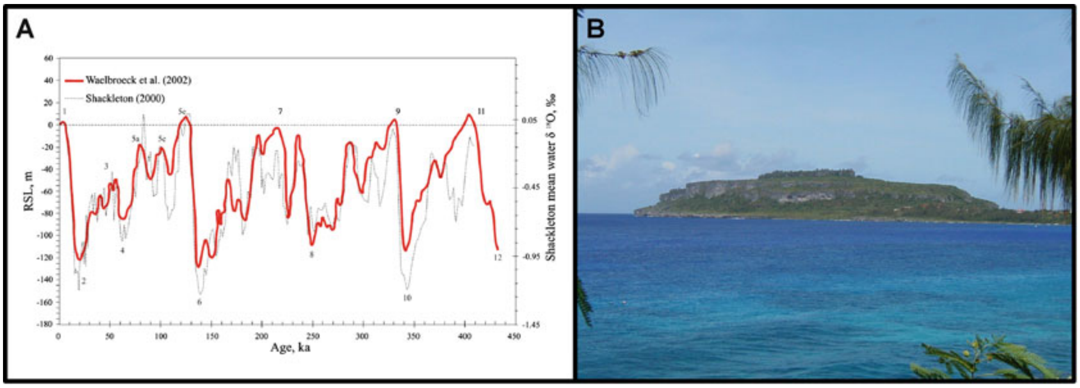

Fig. 1.5 Examples of sea level change. (**a**) The glacioeustatic sea-level curve for the last 450 ka, a summary of curves by Shackleton (2000) and Waelbroeck et al. (2002), amalgamated by Lascu (2005). Note how fast sea level change occurs, and how little time sea level has been spent at or near modern levels. (**b**) Tectonic uplift of Rota Island, Mariana Archipelago; the flat limestone terraces and steep cliffs represent periods of tectonic quiescence and uplift, respectively

the volume of the ocean basin would be sea-floor spreading rates, where rapid spreading leads to large, thermally inflated mid-oceanic ridges. This situation results in oceanic crust taking up more space on the ocean floor, and sea level rises. Slow sea-floor spreading results in colder, denser oceanic crust near the ridge axes, and a deeper and higher volume ocean basin, such that sea level falls. An example of changing the physical properties of seawater would be to change its temperature. For each degree Celsius rise in ocean temperature, sea level globally would rise a meter or two as a result of thermal expansion of the water.

The second sea-level change category is *local sea-level change*, a rise or fall of sea level restricted to a local area of coast. Such change is the result of the properties of the specific coastal area, as opposed to being an effect observed on coasts world wide. Tectonics is one of the more common means of local sea-level change, where the coast can be uplifted, or down warped, to give the appearance of a sea-level change (Fig. 1.5b). What has actually happened is sea level has remained constant and the land has moved vertically with respect to that constant datum. Coastal subsidence as the result of sediment compaction (as in the Mississippi River delta) is another way to produce local sea-level change on tectonically quiescent coasts. Isostasy, the vertical adjustment of the lithosphere to the addition or subtraction of a load, can also move tectonically quiescent coasts. Subsidence of the lithosphere due to ice loading, and lithosphere rebound following deglaciation, are significant factors in changing local sea level. For ice loading and removal, "local" can occur along thousands of kilometers of coast. Asthensosphere adjustment effects in the mantle can extend far away from the site of ice loading, called "far field effects", one of the reasons glacioeustasy effects are not exactly similar on all coasts world-wide. Persistent winds (*seiche*) or currents can also move sea level tens of centimeters, but usually for limited time periods of a few days. Even tide rise and fall represents a local sea-level change with a possible magnitude of meters and a duration of hours.

The causes of local and eustatic sea-level change are more varied and complex than the simple discussion presented here. The major sea-level changes that concern coastal caves are primarily glacioeustasy, acting globally, and tectonics and isostasy, acting locally. A couple of key points in this discussion: first, because of glacioeustasy, eustatic sea level has only been at its present position for about 3,000 years; second (Fig. 1.5a), ignoring seiche and tides, only tectonics at the local level consistently works faster than glacioeustasy (isostatic rebound from deglaciation is slower than glacioeustasy but still significant to coastal cave preservation by uplifting coastal caves away from wave attack; see Chap. 14). As a result, the many other mechanisms of sea-level change are mostly irrelevant to understanding coastal cave-forming processes today.

An additional point must also be emphasized: the coastlines we see today are the result of a short 3,000 year time window, in places modified by tectonics and isostasy. As illustrated in the following chapters, coastal caves and karst features evolve in conjunction with dynamic coastline evolution. Most contemporary coastlines are not static landforms; shore platforms, such as wave cut benches, are still advancing inland on rocky coasts, barrier islands are still migrating and modifying on depositional coasts (Pilkey 2003). Caves found in rocky coastal settings today have either been produced in the last 3,000 years by coastal processes, have persisted from an earlier sea-level position similar to modern, or are inherited from a previous non-coastal cave forming mechanism.

The migration of coastlines inland as sea level rises, and their migration seaward during sea-level's subsequent fall at a later time, mean that caves formed by past coastal processes may be found in inland settings today (i.e. paleoshorelines). Isostatic rebound following deglaciation has been especially efficient at removing caves formed at sea level to elevations above that datum. The understanding of cave-forming processes helps make caves an important indicator of past sea-level position. Lava tubes are poor indicators of past sea levels, whereas sea caves can serve as excellent indicators, as discussed in greater detail in the next chapter.

1.5 Minor Pseudokarst Cave Types

Tafoni are simple chambers and openings in the rock surface produced by weathering that causes rock grains to separate and fall away. They can form in almost any rock lithology (Fig. 1.6), and a wide variety of weathering mechanisms have been proposed for their development. They can develop on any steeply inclined or vertical rock surface in a variety of settings and a variety of weathering environments. Coastal locations seem to neither favor nor discourage tafoni development, except that coastal processes help create the cliffs and steep slopes deemed essential to tafoni development. A case history of tafoni in Quaternary eolianites, with a review of the subject, is presented in Chap. 8.

Talus caves are voids created when cliff failure produces a collection of blocks sufficiently large that people can enter and move around within the block interstices. They are very common in actively uplifting mountain areas, and glaciated areas, both environments where over-steepening of slopes and cliffs leads to rock failure and the collection of massive, large block material as a talus. Coastal areas are another place where over-steepening and basal erosion routinely cause cliff failure and the deposition of large blocks of rock (Fig. 1.7). In many cases, the wave energy that caused the cliff failure quickly acts to reduce and remove the collapsed block material, but in some areas the blocks can persist sufficiently long enough to create cave systems that can be mapped. But such caves are commonly transitory.

Fissure caves, sometimes called tectonic caves where internal earth forces are thought to have cracked the rock, are also common on over-steepened hillsides and cliffs. Coastal areas, as with talus caves, commonly have over-steepened slopes and cliffs which can begin to fail, opening fissures that may become partially or totally roofed with collapse material, creating linear cave systems which at times are complex and extensive (Fig. 1.8). Fissure caves are common in tectonic areas of continental interiors (Fig. 1.8d). Because the processes that create the fissures are on-going in coastal areas, cliff collapse is also on-going and fissure caves are constantly being destroyed and replaced by new fissure caves as the cliff retreats under the coastal erosion onslaught (e.g. Fig. 1.8b).

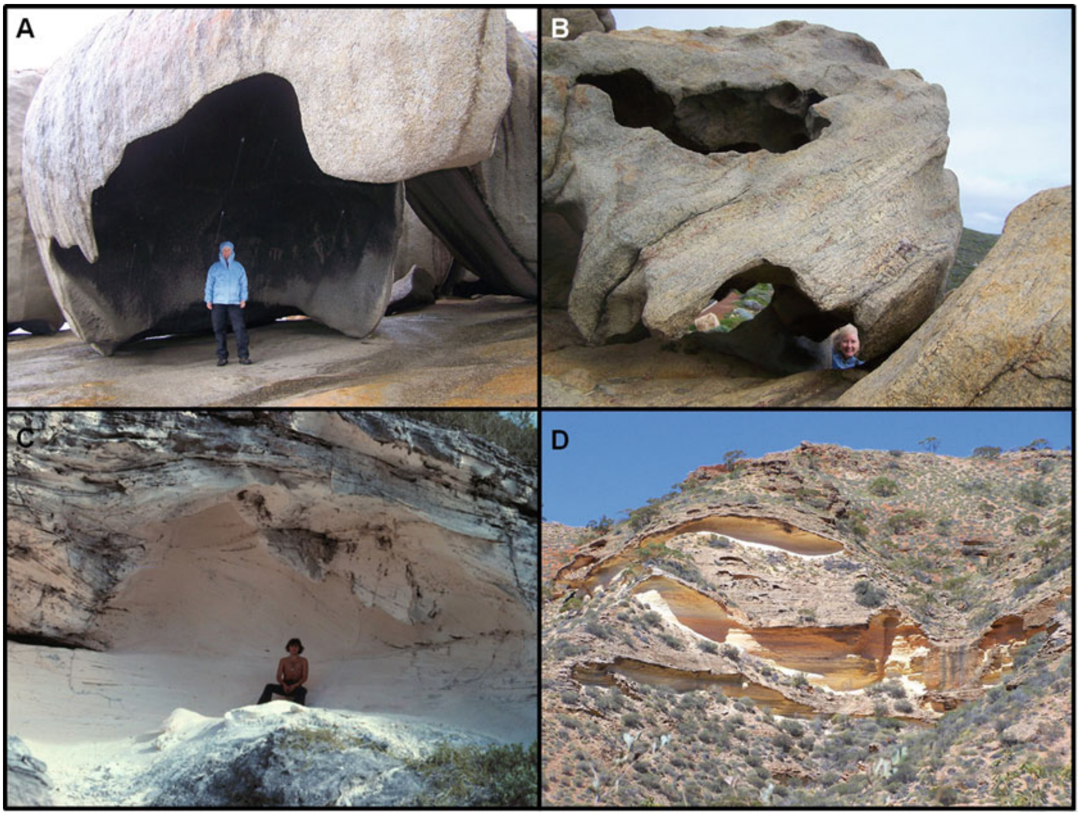

Fig. 1.6 Examples of tafoni in coastal settings. (**a**) In granite, Kangaroo Island, Australia (see Chap. 18). (**b**) In gneiss, Margaret River, Australia. (**c**) In Quaternary eolian calcarenites, San Salvador Island, Bahamas. (**d**) In Miocene limestones, Exmouth Gulf, Australia. Examples (**c**) and (**d**) are instructive as pseudokarst caves in a soluble rock type

1.6 Sea Caves

The most common cave found in coastal environments is the sea cave, or littoral cave. Fingal's Cave in Scotland, the Blue Grotto of Capri in the Mediterranean, Sea Lion Cave on the coast of Oregon, and Arcadia Cave on the coast of Maine are well-known examples of sea caves visited by tourists on a regular basis. Many organisms use sea caves as a refuge, particularly seals, sea lions and other marine mammals, as well as birds, which roost in the ceiling ledges above the reach of waves. From the viewpoint of cave exploration, sea caves are not a major category, primarily because they are short in length. In areas where other types of caves are rare, such as in southern California, sea caves offer the best cave exploration option (see Chap. 14). Occasionally, sea caves can have spacious chambers and over 400 m of passages. Exploration of sea caves can be very dangerous for people who are inexperienced with the littoral environment of strong waves, tides, and/or currents. Sea arches are a type of natural bridge formed by wave action on rocky coasts, and from overprinting of other cave types, both karst and pseudokarst, that occur in coastal environments.

Sea caves are pseudokarst caves. Sea caves can vary from arches (Fig. 1.9) and small voids only a few meters across to very large chambers up to 100 m deep and wide (Fig. 1.10). These caves, formed by wave action on rocky coastlines, can be found in almost any rock lithology on coastlines around the world, and in inland freshwater bodies as well. They may be the most

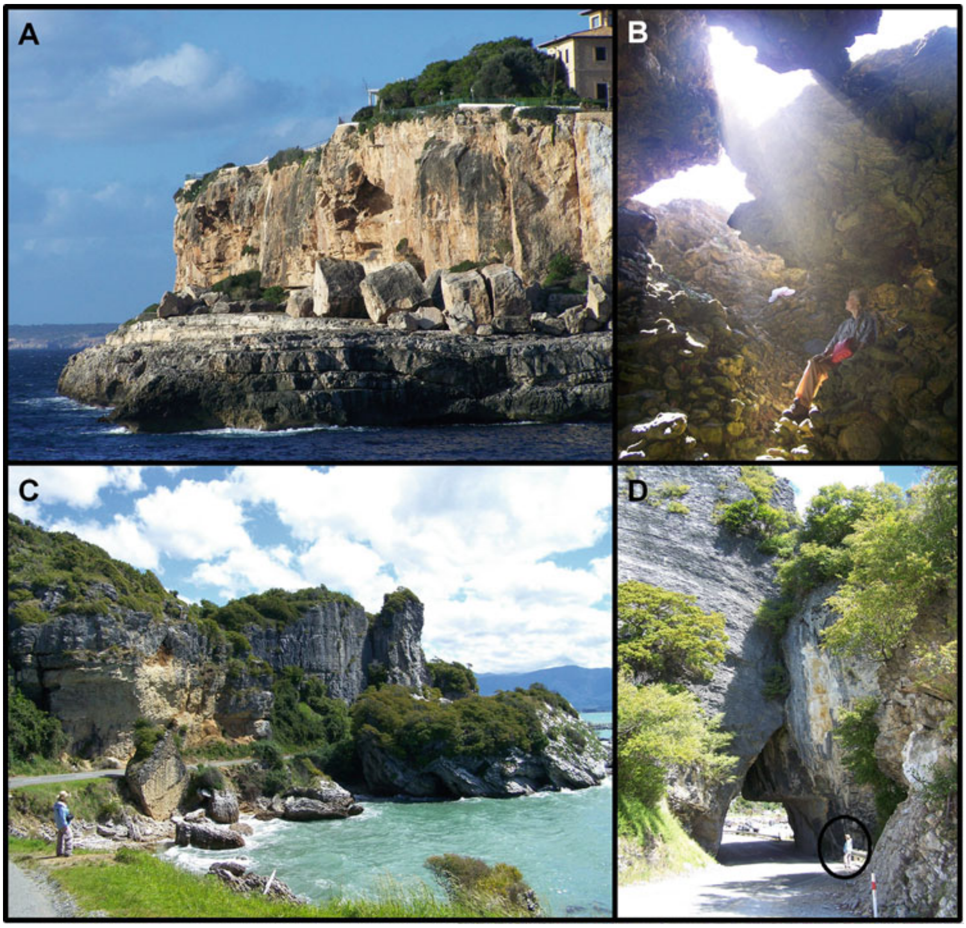

Fig. 1.7 Talus caves in coastal settings. (**a**) Talus blocks collecting on a wave-cut bench, Cala Figuera, Mallorca Island, Spain. (**b**) Talus cave within talus, north coast of Barbados. (**c**) North shore of South Island, Pohara, New Zealand. One of the blocks here has a fragment of a dissolution cave within it, from when the block was still in the cliff to the left of the image, an example of a hybrid cave. (**d**) Road seen in (**c**) going under a natural bridge formed by talus blocks (person in *black circle* for scale). All these pseuodkarst talus caves are in soluble limestone

common coastal cave type in the world. Moore (1954, p. 71) presented an outline of the critical requirements for sea cave genesis: *"The prerequisite conditions of [sea] cave formation are: 1) the presence of a sea cliff which is in direct contact with the erosive forces of waves and currents; 2) the exposed face of the cliff must contain certain geologic structures, or textures, which will allow the establishment of differential erosion; 3) the rock of which the cliff is composed must be of sufficiently resistant nature so as to prevent rapid formation of a protective beach at its base."* Unstated, but assumed is that the rock material has sufficient mechanical strength to support a void carved into it by wave action. Bunnell (1988), for Santa Cruz Island, California, demonstrated the importance of heterogeneity in the rock, such as joints and faults that allowed wave energy to exploit those pre-existing weaknesses to produce sea caves of a linear nature. Chapter 14 presents case histories involving sea caves of the west coast of the United States. The east coast south of New York City, and the Gulf Coast lack the rocky coastlines necessary for sea cave development, and few sea caves are found over those many thousands of kilometers of shoreline.

Waterstrat et al. (2010) examined sea caves formed in Quaternary eolianites of the Bahamas. These rocks are very uniform and isotropic, and being young and never buried, lack faults or

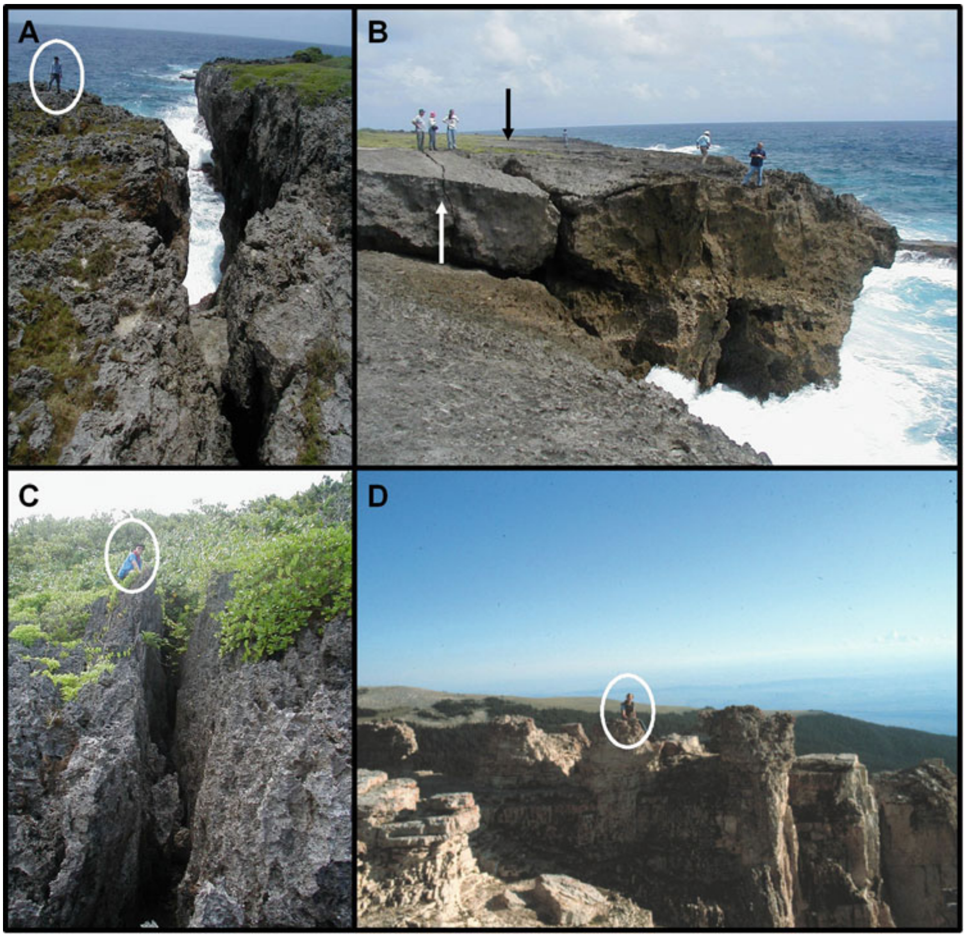

Fig. 1.8 Fissure caves (*white circles* around persons for scale). (**a**) Large open coastal fissure from cliff failure, Tinian Island, Mariana Archipelago. (**b**) Sequence of fissure development, Rota Island, Mariana Archipelago. *Black arrow* points to a widening fissure as the block to the right creeps seaward. *White arrow* points to an incipient fissure. (**c**) Fissure on Tinian Island, Mariana Archipelago, note blocks collecting in the fissure to roof it over. The young age of the limestone makes it susceptible to recrystallization when fluid first flowed down the incipient fissure. As the fissure widened, the more resistant fissure walls stand out in positive relief. (**d**) Gravity sliding of dolomite over weaker shales in the Bighorn Mountains of Wyoming creates a series of fissure caves. These pseudokarst fissure caves are all in a soluble rock

joints. Sea cave development in this case appears controlled by wave energy differences produced by wave interference, lagoon and reef physiography, tides, and wind direction and magnitude. Bioerosion may also play a part in these diagenetically immature carbonate rocks. So while differences in rock strength and character are important to sea cave formation, such differences are not the sole arbiter of sea cave placement or size.

Historic photographs of sea caves and arches show that they can undergo development and destruction at a fairly rapid pace. Given that sea level has only been at current elevations for ~3,000 years, it is clear that sea cave development can be relatively fast. Sea caves are commonly found on the inland side of wave-cut benches 50 m or more across (Fig. 1.11). As this bench must be only 3,000 years old or less, the age of the current sea-level highstand, one must assume that a series of sea caves has been created and destroyed as the sea cliff retreated through the late Holocene. At high latitudes, isostatic rebound following deglaciation has uplifted former wave-cut benches and associated sea caves

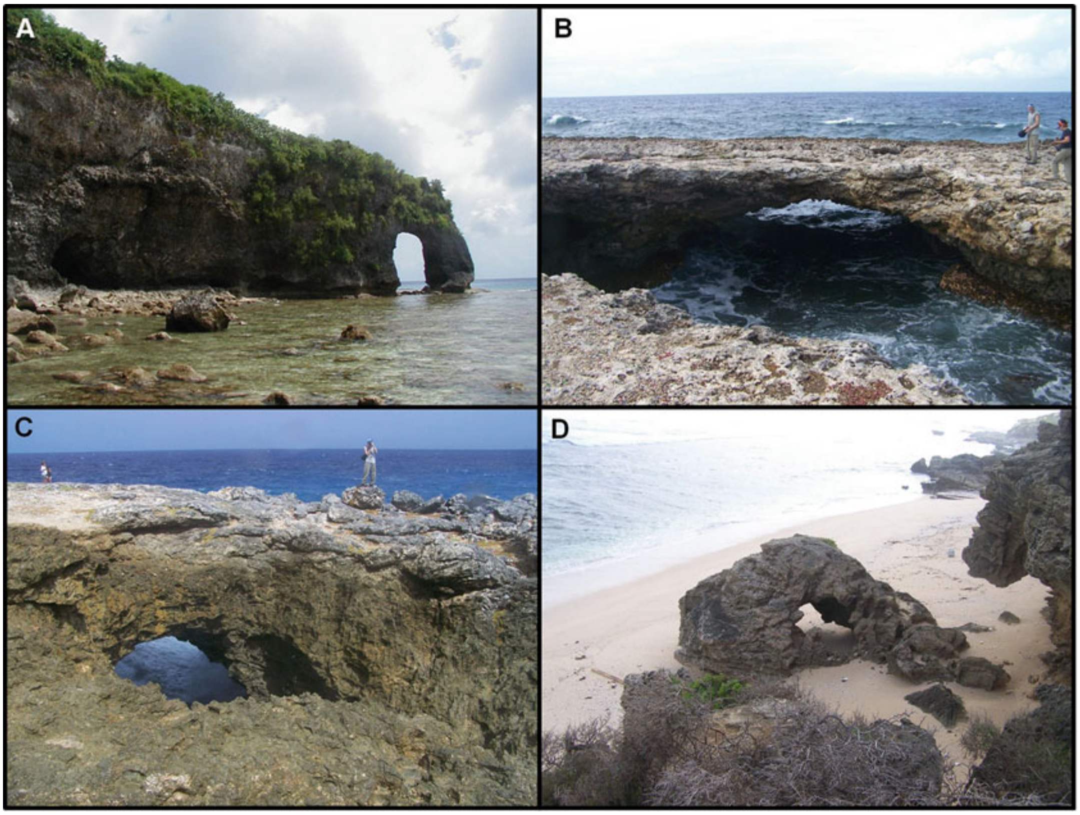

Fig. 1.9 Sea arches. (**a**) High sea arch, Tinian Island, Mariana Archipelago. (**b**) Broad sea arch, Curaçao. (**c**) Sea arch, Barbados. (**d**) Isolated sea arch, Rottnest Island, Australia. The arches are all in limestone

many meters above present datum (see Chap. 14 examples). The time window for development of these sea caves was necessarily restricted to much less than the 3,000 years of the current sea-level highstand. Despite the rapidity of sea cave formation and subsequent destruction, they can persist in their formational environment for a greater duration compared to talus caves and fissure caves, unless tectonic or isostatic uplift moves the various cave types from the destructive coastal regime.

1.7 Conclusions

In some cases, as noted earlier, caves formed by weathering processes other than wave action are coincidentally located in the intertidal coastal zone. These caves are rapidly overprinted to become hybrid caves. With sufficient overprinting, their origin may become obscured and they may be interpreted to have formed solely by wave processes. Of particular note on carbonate coasts are karst caves that develop in the freshwater lens, just inland from the coast, called *flank margin caves*. Their origin is tied to sea level (see Chap. 4), and their near-coastal location makes them vulnerable to exposure and overprinting by wave processes. Overprinted flank margin caves are the most common hybrid cave found in coastal areas.

Talus caves and fissure caves require cliff failure to develop. They exist in an active and ephemeral environment, and are short-lived. Tafoni require only an exposed cliff, which may be relatively stable. Tafoni are not tied to any specific sea-level position, and can develop at many elevations on a sea cliff simultaneously. Tafoni

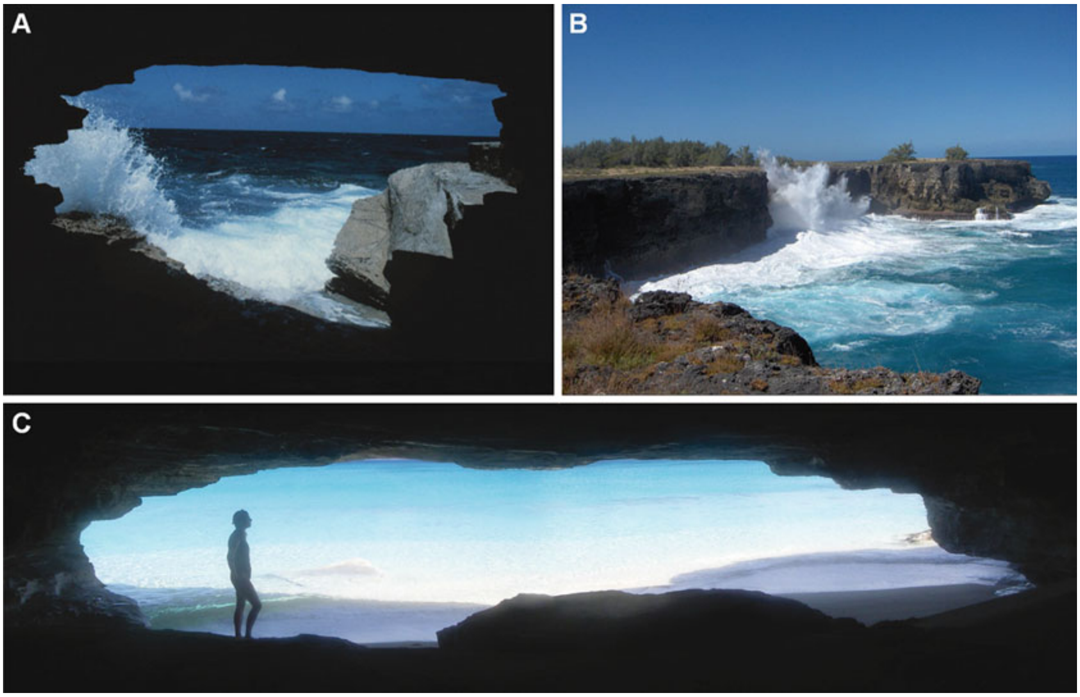

Fig. 1.10 Sea caves. (**a**) Wave energy making a sea cave in Holocene eolian calcarenites, San Salvador, Bahamas. (**b**) Demonstration of wave energy on a limestone cliff 25 m high, Barbados. (**c**) Sea cave in Pleistocene subtidal deposits, San Salvador Island, Bahamas, with a fronting beach, contrary to Moore (1954). As has been consistently noted in earlier figures, these pseudokarst cave examples are all in soluble rock

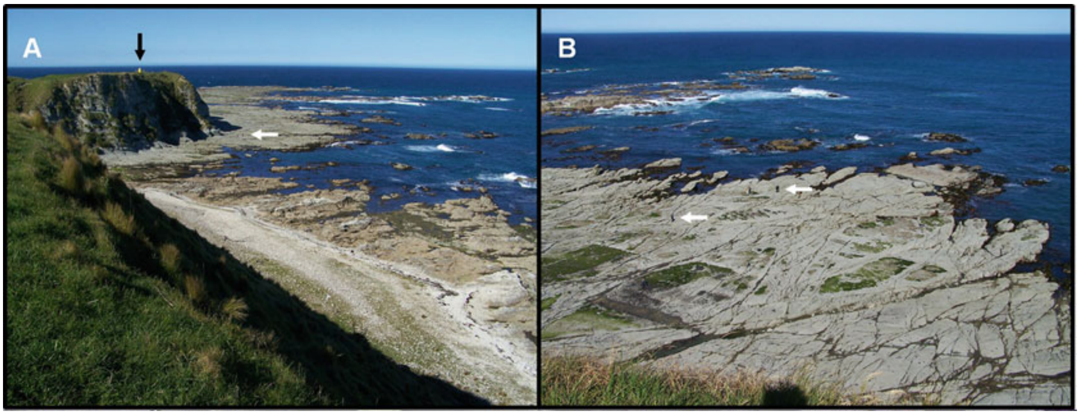

Fig. 1.11 Implications of coastal wave-cut benches. (**a**) Wave cut bench at the Kaikoura Peninsula, South Island, New Zealand. People at *white arrow* too small to be seen, structure under the *black arrow* is 3 m high. (**b**) Expanded image of the scene in a; *white arrows* point to people barely visible. The entire bench must have been carved since sea level stabilized 3,000 years ago, therefore sea caves must have been repeatedly created and destroyed as the sea cliffs migrated landward

can appear by casual observation to be incorrectly identified as uplifted sea caves, or overprinted flank margin caves, and can create a false sense of past sea-level position (Walker et al. 2008).

Pseudokarst caves formed by coastal processes are necessarily ephemeral. The wave action that creates them immediately begins their subsequent removal. Tafoni, lava tubes, and tufa caves are accidental, and their presence in the coastal environment is somewhat decoupled from coastal processes, although one can argue that tafoni are tied to coastal cliff development. Some karst caves in coastal settings are also accidental, remnant fragments of earlier flow systems now decayed and abandoned. But other karst caves are directly tied to the coastal environment by the base level that sea level creates. Chap. 4 will investigate the unique karst processes that make dissolution caves in coastal environments.

References

Bögli A (1980) Karst hydrology and physical speleology. Springer, New York, 284 p

Bunnell D (1988) Sea caves of Santa Cruz island. McNally and Loftin, Santa Barbara, 123 p

Kelletat DH (1995) Atlas of coastal geomorphology and zonality, CERF special issue 13. Coastal Education & Research Foundation, Charlottesville, 286 p

Lascu I (2005) Speleogenesis of large flank margin caves of the Bahamas. M.Sc. Thesis, Department of Geosciences, Mississippi State University, 218 p. http://library.msstate.edu/etd/show.asp?etd=etd-05102005-132949

Machel HG, Kambesis PN, Lace MJ, Mylroie JR, Mylroie JE, Sumrall JB (2012) Overview of cave development on Barbados. In: Kindler P, Gamble DW (eds) Proceedings of the 15th symposium on the geology of the Bahamas and other carbonate regions, Gerace Research Centre, San Salvador, Bahamas, pp 96–106

Moore DG (1954) Origin and development of sea caves. Natl Speleological Soc Bull 16:71–76

Palmer AN (2007) Cave geology. Cave Books, Dayton, 454 p

Pilkey OH (2003) A celebration of the world's barrier islands. Columbia University Press, New York, 309 p

Shackleton NJ (2000) The 100,000-year ice-age cycle identified and found to lag temperature, carbon dioxide, and orbital eccentricity. Science 289:1897–1902

Waelbroeck C, Labeyrie L, Michel E, Duplessy JC, McManus JF, Lambeck K, Balbon E, Labracherie M (2002) Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quaternary Sci Rev 21:295–305

Walker LN, Mylroie JE, Walker AD, Mylroie JR (2008) The caves of Abaco Island Bahamas: keys to geologic timelines. J Cave Karst Stud 70(2):108–119

Waterstrat WJ, Mylroie JE, Owen AM, Mylroie JR (2010) Coastal caves in Bahamian eolian calcarenites: differentiating between sea caves and flank margin caves using quantitative morphology. J Cave Karst Stud 72:61–74

Wilkens H, Iliffe TM, Oromí P, Martínez A, Tysall TN, Konemann S (2009) The Corona lava tube, Lanzarote: geology, habitat diversity and biogeography. Mar Biodivers 39:155–167

Erosional and Depositional Textures and Structures in Coastal Karst Landscapes

2

Danko Taboroši and Miklós Kázmér

Abstract

Exposed surfaces of limestones on marine coastlines are characterized by a tremendous range of rock textures and structures. Many of them are features limited to coastal areas and are morphologically and genetically distinct from inland analogs. This distinction is due to idiosyncrasies of both coastal environments and coastal limestones. Processes operating in coastal settings are not limited to dissolution by fresh water and involve profound chemical and physical action of sea water and marine biota. In addition, these processes act upon rocks that are frequently younger and diagenetically less mature than inland limestones that have undergone deep burial and accompanying changes. The outcomes are distinct types of karren sculpturing, bioerosional markings, deposited and precipitated fabrics, bioconstructions, and compound structures that are unique to coastal karst. Many are limited to particular microenvironmental settings and certain elevations with respect to the sea level and can, therefore, be used as powerful paleoenvironmental and past sea level indicators.

2.1 Introduction

Limestones exposed along marine coastlines display a prodigious array of rock textures and structures. These include both erosional and depositional features, many of which are characteristic of coastal areas and distinct from analogs found in other karst environments. They are generally limited to the narrow coastal belt (from the always-submerged subtidal zone, through the intertidal zone, to the supratidal zone of wave splash and sea spray) and are shaped by a variety of marine weathering processes that occur in the

D. Taboroši (✉)
Water and Environmental Research Institute of the Western Pacific, University of Guam,
Mangilao 96923, Guam

Island Research and Education Initiative, Palikir,
Pohnpei, FM 96941, Micronesia
e-mail: taborosi@gmail.com

M. Kázmér (✉)
Department of Paleontology, Eötvös University, Pázmány sétány 1/c, H-1117 Budapest, Hungary
e-mail: mkazmer@gmail.com

M.J. Lace and J.E. Mylroie (eds.), *Coastal Karst Landforms*, Coastal Research Library 5,
DOI 10.1007/978-94-007-5016-6_2, © Springer Science+Business Media Dordrecht 2013

presence of sea water (Paskoff 2005) and marine biota (Spencer 1988).

Erosion of limestones and geomorphic evolution of exokarst (exposed karst surface) is usually equated with the process of solution of calcium carbonate. This is appropriate in inland areas, where the main agent that shapes rock surfaces is fresh water. However, most sea water at normal pressure is saturated with respect to calcium carbonate and is not expected to produce dissolutional features. Even so, limestone dissolution does occur in the coastal zone under a variety of conditions, many of which are insufficiently understood and involve input of fresh water or biologic agents. In addition to chemical and biologically-mediated dissolution (jointly known as corrosion, Guilcher 1953), coastal limestones are subject to a number of physical processes peculiar to the coastal zone: mechanical breakdown by the action of surf, salt weathering (haloclastism), wetting and drying, abrasion by wave-suspended sediment, and other forces that are absent or less intense in inland karst.

Also of great importance is the widespread and potent geomorphic action of marine biota, whose dwelling and feeding lifestyles involve effective reshaping of rock and account for a truly fundamental difference between the fates of karst rocks exposed in coastal and inland settings. Inundated or wetted by water, coastal rocks are superficially but in effect "alive" – coated with pervasive, persistent, and complex communities of organisms that engage in erosion, but also other, often opposing processes. In addition to powerful destructive effects of bioeroding organisms, some coastal biota protect the rock from erosion, baffle water currents and garner sediment, or precipitate their own calcium carbonate. This offsets and locally reverses the effects of erosion, resulting in a complex miniature landscape where the net result of removal and deposition of calcium carbonate may be different in any given spot. This is controlled by presence or absence of specific organisms and their own controlling factors: tidal and wave regime, coastal exposure and water energy fluctuations, shading and illumination patterns, and biologic interactions such as competition for space and predator-prey relationships. Therefore, unlike inland exokarst, where broad areas see comparable denudation rates and spatially consistent geomorphic reduction of the landscape, coastal exokarst surface can be imagined as a "battlefield" between destruction and construction (erosion and deposition), which, controlled by physicochemical and biologic microenvironmental variations, act in discrete locations, in various ways, at varying intensities, and at different scales; shift both spatially and temporally; and create a dynamic and multiplex overall pattern of rock textures and structures.

Furthermore, some baseline lithologic differences between coastal limestones and limestones that dominate inland karst settings should be considered. Many limestone coasts, especially those in the tropics and subtropics, are in young, diagenetically immature limestones that have never undergone deep burial and accompanying changes. Such rocks, described as eogenetic, tend to be coarse grained and retain much depositional heterogeneity that has not been smoothed and averaged by deep burial diagenesis. For the same reason, they also preserve high primary porosity. Extremely young units can include the calcium carbonate polymorph aragonite, which is more soluble than the traditional calcite found in older limestones. The combination of high textural variability, relatively high porosity, and differential solubility substantially adds to the complexity of exokarst forms that develop in coastal environments.

In addition to intrinsic scientific interest in such complex features and the sheer beauty of coastal karst landscapes, understanding their textures and small-scale (mm to cm) and medium-scale (dm to m) elements may have several important applications. They are increasingly utilized for their high potential in paleoenvironmental interpretation (e.g. Vescogni et al. 2008), tracking climate change (e.g. Silenzi et al. 2004), recognition of past catastrophic events (e.g. Benac et al. 2004), analysis of sea level fluctuations (e.g. Laborel and Laborel-Deguen 1994, 1995), studies of biologic community interactions (e.g. Jones 1989), and even research in planetary geology (Bourke and Viles 1997). The purpose of this chapter is to provide an overview of small-scale and medium-scale exokarst features produced in carbonate rock surfaces by various inorganic and biologic erosional and depositional processes that operate along marine coastlines. We will explore erosional and bioerosional textures and depositional and bioconstructional features; and consider how the compounding and overprinting of such basic forms on small- and medium-scales creates larger structures and engenders typical coastal karst landscapes.

2.2 General Characteristics

Small- and medium-scale erosional sculpturing of karst rocks has been of interest to geomorphologists for over a century. A collective term "lapiéz" was applied to various rills, flutes, channels, and cracks in limestone rocks already in the nineteenth century (Chaix 1895) and the first comprehensive studies and classifications ensued (Martel 1921 and Cvijić 1924). Most of this early research took place in mountainous regions of the Alps and classical karst of southern Europe and is well summarized by Ginés (2009). With the studies by Bögli (1951, 1960), and subsequent work by Trimmel (1965), Monroe (1970), Jennings (1971), and Sweeting (1972), the term "karren" came to stand for all dissolutional sculpturing in soluble rocks. Karren research became a vital element of geomorphologic, hydrologic, and paleoenvironmental studies in karst terrains and remains a dynamic field today (e.g. Ginés 2009; Veress 2010). Some of the first detailed descriptions of rock sculpturing as observed specifically in marine coastal settings were produced by Macfadyen (1930), Wentworth (1939, 1944), Emery (1946), Corbel (1952), Guilcher (1958) and others; and were paralleled with studies of biological zonation on rocky coasts (Stephenson and Stephenson 1949; Doty 1957; Southward 1958). Attempts to link the observed morphologies with specific processes (e.g. Guilcher 1953; Dalongeville 1977; Ley 1979) increasingly led to awareness that rock-shaping processes operating in coastal karst settings are unique and distinct from what is happening in other karstlands. An appreciation of idiosyncrasies in the forms observed, as well as processes operating along carbonate coasts had led to an understanding that small- and medium-scale rock sculpturing of coastal carbonates form unique "coastal karren" (or "marine karren" – Ley 1977 and "littoral karren" – Malis and Ford 1995) assemblages that are discrete from those of other karst settings ("normal" rainfall-solution karren, subsoil karren, cave karren, etc.). Just to what extent can the processes and morphologies that exist on karst coasts differ from those of inland karst settings was elucidated by the landmark paper of Folk et al. (1973). They described the extremely jagged and chaotic karren of Cayman Island coast and contrasted its highly irregular morphology with the orderly and linear classical karren features studied thus far. They named these features "phytokarst" to emphasize the role of cyanobacteria in their evolution. By that time, the studies of biological erosion were blossoming (e.g. Neumann 1966; Schneider 1976; Bromley 1978) and converged with research on coastal karst, as several influential studies calculated erosion rates of coastal karst surfaces and found that much of it was biological in nature (Hodgkin 1964; Trudgill 1976, 1987; Viles and Trudgill 1984; Spencer 1985a; Kelletat 1988). These advances were paralleled by increasing research on carbonate deposition along karst coastlines. Many geomorphic features constructed by living organisms were described for the first time (e.g. Bosence 1973; Focke 1978) and in due course became recognized as integral elements of coastal karst landscapes. Compound effects of entire biologic communities on erosional sculpturing and production of sediment along carbonate coasts were considered by Schneider and Torunski (1983) and biological construction of carbonate deposits was understood as concurrent and inseparable from biological destruction (Kelletat 1985). Ultimately, the concept of coastal "biokarst" (Viles 1984) solidified to recognize that carbonates along marine coasts are shaped by invertebrate action in addition to inorganic and microbially-mediated processes and that this includes both erosion and deposition. The term "halokarst" was also offered as an umbrella