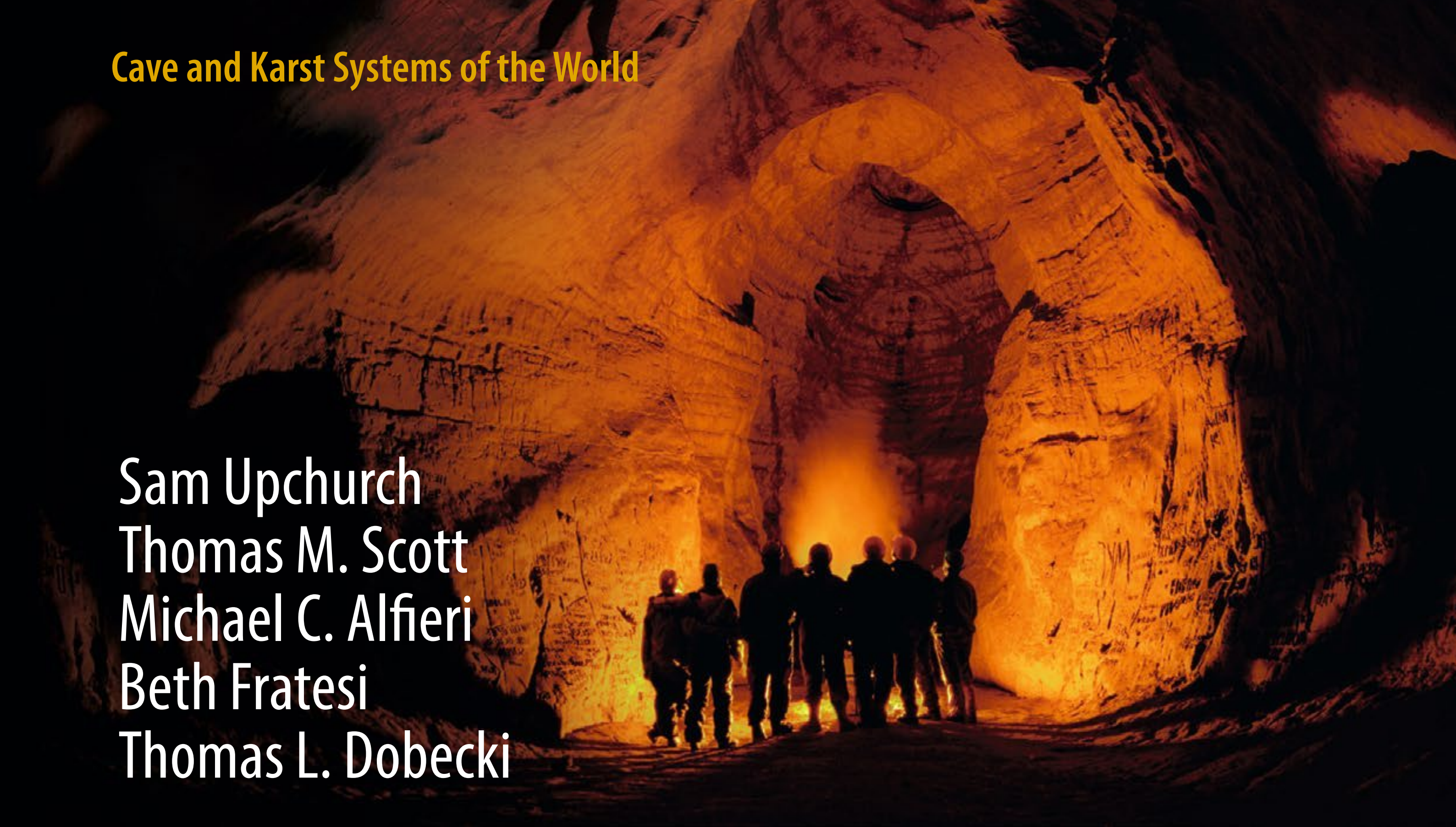

Cave and Karst Systems of the World

Sam Upchurch
Thomas M. Scott
Michael C. Alfieri
Beth Fratesi
Thomas L. Dobecki

The Karst Systems of Florida

Understanding Karst in a Geologically Young Terrain

Springer

Cave and Karst Systems of the World

Series editor

James W. LaMoreaux, Tuscaloosa, AL, USA

More information about this series at http://www.springer.com/series/11987

Sam Upchurch • Thomas M. Scott
Michael C. Alfieri • Beth Fratesi
Thomas L. Dobecki

The Karst Systems of Florida

Understanding Karst in a Geologically Young Terrain

Springer

Sam Upchurch
SDII Global Corporation
Land O' Lakes, FL, USA

Thomas M. Scott
SDII Global Corporation
Havana, FL, USA

Michael C. Alfieri
Water Resource Associates, LLC
Tampa, FL, USA

Beth Fratesi
Southwest Research Institute
San Antonio, TX, USA

Thomas L. Dobecki
Dobecki Geosciences, LLC
Mishawaka, IN, USA

ISSN 2364-4591 ISSN 2364-4605 (electronic)
Cave and Karst Systems of the World
ISBN 978-3-319-69634-8 ISBN 978-3-319-69635-5 (eBook)
https://doi.org/10.1007/978-3-319-69635-5

Library of Congress Control Number: 2018943691

Printed on acid-free paper

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

Preface

We began considering development of this book in 2010 while we were preparing a guidebook for a karst geology field trip. Our discussions resulted in realization that there are few, if any, karst areas in the world where so much research and investigation existed, especially when one considers that Florida's near-surface carbonate rocks are eogenetic. That is, they have never been deeply buried or subjected to heat and pressure or had sufficient time to substantially alter their original textures and mineral contents. The youngest karstified carbonate rocks in Florida are only about 100,000 to 150,000 years old, and the oldest, near-surface karstic rocks are about 50 million years old. We concluded that it was time for a synthesis of the extensive literature and construction of a resource to help understand Florida's karst and the processes that have created our landscape.

Sinkholes are one of the major focuses of this book because of their importance to understanding the geomorphology of the state and to the welfare and economy of Florida's residents. The media commonly report on damaging sinkholes, and there is widespread fear or concern as a result. Florida has more limestone springs than any other state, and the springs are loved by all. At present, the springs are suffering from nutrient enrichment, loss of flow, and other problems. These, and many other issues, are addressed in this book.

The highest point in Florida is located at Britton Hill in Walton County, near the community of Lakewood about 0.4 km south of the Alabama line. This hill is 105 m above sea level. With this towering hill, Florida has the lowest high point elevation of any state in the USA. Elevations in Florida are generally less than 46 m, so it is a really flat state compared to the remainder of the country. Geologists who work in Florida, however, soon become acclimated to the subtleties of topography. It is amusing to take out-of-state colleagues on a tour of the state and watch their reactions to statements such as "the hill over there" or "the bottom of that depression." When one becomes attuned to the subtle topography and lack of obvious landmarks, it is amazing to see and understand the origins of the subtle contours of the Florida landscape. The geology of Florida is quite interesting, diverse, and important. The goal of this book is to help visualize Florida's karst topography in a subtle terrain through use of digital elevation maps, geographic information systems (GIS) analysis, and light detection and ranging (LIDAR) mapping. By means of these tools, we wish to highlight the diversity, complexity, and, especially, the interesting karst features that dot the state from the Florida Keys to the Alabama and Georgia state lines.

Most of the variations of the topography are a result of three processes: (1) sea level rising and falling over the last few tens of millions of years; (2) dissolution of carbonate-rich sediments (including shell beds), limestone, and dolostone to form karst; and (3) development of surface-water and groundwater drainage systems. The excursions of sea level have resulted in deposition of sandy and clayey cover sediments on top of the older carbonate sediments and rocks. Only Plio-Pleistocene carbonate rocks in southern Florida are predominately bare. Scattered and spatially limited areas of bare karst can be found elsewhere, but cover predominates. The siliciclastic sediment cover complicates interpretation of the karst and leads to sudden and unexpected sinkholes. Our emphasis on Florida karst includes in-depth considerations of the importance and interactions between geologically young, bare, and covered karst and the cover sediments. The interplay of these three processes forms the dominant subject of this book.

Because Florida karst is a concern to the lay public and the processes of karst development in geologically young sediment and rocks are of interest to the geological and engineering communities in Florida and worldwide, we began this book with several introductory chapters that set the scene for discussing karst and interactions with cover sediments. After an introduction to the importance and uniqueness of Florida karst and to the concept of eogenetic karst in Chap. 1, we begin in Chap. 2 by presenting relevant information on the geologic materials that are common in Florida sediments and rocks. Chapter 3 presents an introduction to the most recent geomorphologic characterization of the state. Chapter 3 also discusses the geologic history of Florida and introduces the origins, names, and ages of strata that underlie the state.

Florida depends on groundwater for much of its potable water supply, and the aquifers that supply water are largely karstic in nature. Chemical processes in these aquifers result in development of karst features, and the presence of karst features makes the aquifers highly productive in terms of water supply. It is our dependence on karstic aquifers that has resulted in the abundant literature on Florida karstic, carbonate aquifers. Chapter 4 presents the hydrogeology of Florida's aquifer systems, and Chap. 5 discusses the chemistry of surface water and groundwater in terms of potential for karst development and for interactions with the clay- and sand-rich cover materials.

Chapters 6, 7 and 8 describe the karst processes operative in Florida and provide information for recognition of karst landforms, such as sinkholes and caverns. Chapter 6 describes the controls on development of karst, such as time required, and controls on locations of preferential dissolution. It emphasizes the role of dual porosity in geologically young sediment and rock as a control on development of groundwater flow and dissolution in carbonate rocks. Chapter 7 is a summary of the karst processes and landforms resulting from interaction of the host strata with groundwater. This chapter deals with formation of caves and cave decorations and sinkholes. Detailed explanations are provided to show how the different forms of sinkholes develop and their risks. Overall sinkhole risk is also addressed in Chap. 7. Chapter 8 concludes the book by discussing (1) processes and interactions with surface water, including shallow, meteoric water and streams, and (2) hypogenetic, deep-seated karst related to dissolution at saltwater transition zones and in evaporite-bound strata.

There is some overlap in content from chapter to chapter in order for the chapters to stand alone to the extent possible. This allows the publisher to offer online purchases of specific chapters. Since we hope that lay readers will enjoy this book, this repetition may also allow for better understanding and reinforcement of the provided content.

Our intent is that this book serves two audiences. Florida includes the largest expanse of well-known, eogenetic karst in the world. Therefore, by integrating knowledge of the karst, we hope to share our understanding of the eogenetic karst of Florida with our colleagues worldwide. We also hope to further inform geologists, engineers, and lay persons interested in sinkholes, springs, caves, and other karst features and hazards in Florida. We have attempted to explain karst processes in such a way that interested lay persons can understand Florida karst science.

For those who wish to inspect karst features in the field, we have included geographic coordinates for many of the important and accessible karst features with which we are familiar. Many of the rock exposures and related karst features are either on private land or have long since been destroyed. Therefore, in some cases the karst features are best observed in historical aerial photographs, such as those provided on publicly distributed earth-imaging software. Please respect private property, and do not trespass without permission if you choose to visit these sites. Coordinates are not given for privately owned caves and properties in order to protect the caves and property owners.

We have, for many years, worked with cave divers, who routinely explore the many subaqueous caves in the state. Where possible, we have included discussions of their experiences, cave maps, and photographs of these beautiful, but dangerous, caves. Cave diving is extremely hazardous, and one should not attempt to explore underwater caverns without the proper certifications, equipment, and safety protocols. Novices and experts die each year in Florida caves, so be cautioned. The Cave Diving Section of the National Speleological Society (https://caves.org/) is an excellent source of information on cave diving and safety.

Acknowledgments

We thank the many persons who instructed, supported, and collaborated with us over the years. There are way too many to acknowledge all. Our students and colleagues at SDII Global Corporation and the Florida Geological Survey were invaluable. In addition, we acknowledge colleagues who provided us with direct support for this book. Cave divers Mark and Annette Long, Bob Schulte, Jill Heinerth, Wes Skiles, and Pete Butt taught us about underwater cave diving and the beauty of Florida's deep caves. Mark Long and Jill Heinerth graciously provided photographs for use in this book, and Bob Schulte assisted in development of our concepts about the potentially hypogenetic, deep caves on Florida's west coast. Florida Geological Survey staff, including Jon Arthur, Harley Means, Clint Kromhout, Cindy Fischler, Christopher Williams, Rick Green, Tom Greenhalgh, and Alan Baker, assisted us in developing many of the concepts presented here and provided significant GIS support. Florida Department of Environmental Protection staff, Rick Copeland, Gary Maddox, and Debra Harrington, provided data on Florida springs. Our associates at Florida's water management districts, especially Eric DeHaven at the Southwest Florida Water Management District and David Hornsby at the St. Johns River Water Management District, also provided helpful data. John Mylroie and Jim LaMoreaux encouraged us to write the book and provided helpful suggestions in its early stages of development. Lee Florea and Arthur and Margaret Palmer provided much appreciated reviews of the entire text prior to publication. Finally, we thank SDII's Bob Windschauer and WRA's Pete Hubbell and Mark Farrell for providing time and resources for Upchurch and Alfieri, and we greatly appreciate the support of Springer Nature's editors and staff, especially for their patience as we attempted to perfect the manuscript.

Land O' Lakes, FL, USA — Sam Upchurch
Havana, FL, USA — Thomas M. Scott
Tampa, FL, USA — Michael C. Alfieri
San Antonio, TX, USA — Beth Fratesi
Mishawaka, IN, USA — Thomas L. Dobecki
2018

Contents

1 Eogenetic Karst in Florida **1**
1.1 Introduction 1
1.2 Importance of Karst Processes. 1
1.2.1 Definitions of Karst and Karst Processes. 2
1.2.2 Why Study Florida Karst? 6
1.2.3 Geologic Hazards and Resources in Florida 6
1.2.4 Florida's Karstic Aquifers 7
1.3 Eogenetic and Telogenetic Karst 7
1.3.1 Primary and Secondary Porosity and Permeability 8
1.3.2 Comparison of Porosity in Geologically Ancient and Young Carbonate Sediments and Rocks 10
1.3.3 Eogenetic and Telogenetic Karst 12
1.4 Why Examine the Role of Cover Sediments in Florida?. 14
1.5 Summary 14
References. 15

2 Geological Materials: An Overview. **17**
2.1 Introduction 17
2.1.1 Definitions of Soil, Sediment, and Rock 18
2.1.2 Major Mineral Groups of Florida Carbonate Rocks and Sediments and of Cover Materials. 18
2.1.3 Definition of Cover 18
2.2 Florida Carbonate Sediments and Rocks 19
2.2.1 Carbonate Minerals in Florida Sediments and Rocks 19
2.2.2 Calcite, Dolomite, and Aragonite 19
2.2.3 Effect of Magnesium on Calcite Solubility 20
2.2.4 Aragonite Solubility. 20
2.2.5 Dolomite Solubility 21
2.3 Florida Siliciclastic Sediments. 22
2.4 Florida Evaporites 23
2.5 Physical Properties of Sediments. 24
2.5.1 Sediment Grain Size 24
2.5.2 Sorting (Gradation) of Sediments 25
2.5.3 Sediment Packing. 28
2.5.4 Consolidation and Compaction 28
2.5.5 Grain Shape 29
2.5.6 Grain Frosting 30
2.5.7 Cements and Coatings 30
2.6 Clay and Cohesive Sediments 31
2.6.1 Clay Size Definitions 32
2.6.2 Clay Minerals. 33

2.6.3 Other Minerals Likely to Occur in Clay Sizes 41
2.6.4 Clay Surface Properties: Cohesion, Permeability, and Sorption 46
2.7 Classification of Carbonate Sediments and Rocks 48
2.7.1 Dunham's Classification Scheme 48
2.7.2 Allochems, Mud, and Wave and Current Energy 49
2.8 Classification of Siliciclastic Sediments 50
2.9 Description of Sedimentary Strata 51
2.9.1 Facies and Walther's "Law" 51
2.9.2 Lithosomes 53
2.9.3 Stratigraphic Nomenclature 54
2.10 Summary 54
References 54

3 Geologic Framework of Florida 59
3.1 Introduction 59
3.2 Geologic Structure of the Florida Platform 61
3.3 Depositional Environments of the Florida Platform 62
3.4 Stratigraphy of the Florida Platform 65
3.4.1 Pre-Mesozoic Era Stratigraphy 65
3.4.2 Mesozoic Era Stratigraphy 65
3.4.3 Cenozoic Era Stratigraphy 66
3.5 General Hydrogeology of the Florida Platform 72
3.5.1 Floridan Aquifer System 73
3.5.2 Intermediate Aquifer System and Confining Unit 73
3.5.3 Surficial Aquifer System 74
3.6 Geomorphology of Florida 74
3.6.1 Introduction 74
3.6.2 Geomorphological Studies in Florida 74
3.6.3 Southern Pine Hills District 75
3.6.4 Dougherty Karst District 77
3.6.5 Apalachicola Delta District 79
3.6.6 Tifton Upland District 80
3.6.7 Okeefenokee Basin District 81
3.6.8 Ocala Karst District 81
3.6.9 Lakes District 83
3.6.10 Barrier Island District 85
3.6.11 Peace River District 85
3.6.12 Everglades District 87
3.7 Summary 89
References 89

4 Hydrogeology of Florida 93
4.1 Introduction 93
4.2 Overview of Florida Hydrogeology 94
4.2.1 Water Use in Florida 94
4.2.2 Florida's Water Budget 94
4.2.3 Precipitation and Temperatures 94
4.2.4 Evapotranspiration 95
4.2.5 Runoff and Recharge 96
4.2.6 Groundwater 100
4.2.7 The Freshwater Lens 102
4.3 Surficial Aquifer System 107
4.3.1 Aquifer Distribution 107
4.3.2 Biscayne Aquifer 108

4.3.3 Surficial Aquifer (Undifferentiated). 111
4.3.4 Karst Development in Strata of the Surficial Aquifer System 115
4.4 Intermediate Aquifer System and Intermediate Confining Unit 116
4.4.1 Aquifer Distribution. 117
4.4.2 Location and Composition. 118
4.4.3 Aquifer Recharge 119
4.4.4 Aquifer Potentials and Flow Systems 119
4.4.5 Role of the Intermediate Aquifer System in Karst Development 119
4.5 Floridan Aquifer System 120
4.5.1 Upper Floridan Aquifer 122
4.5.2 Middle Semi-confining Units of the Floridan Aquifer System 130
4.5.3 Lower Floridan Aquifer 131
4.5.4 Sub-Floridan Confining Unit 137
4.6 Summary of Florida's Karstic Groundwater Systems 137
References. 139

5 Hydrogeochemistry of Florida Karst Waters. 145
5.1 Introduction 145
5.2 Overview of Karst Geochemical Processes 145
5.2.1 Mechanisms of Carbonate Dissolution 145
5.2.2 Geochemistry of the Freshwater/Saltwater Mixing Zone 149
5.2.3 Textural Controls on Carbonate Mineral Stability. 153
5.2.4 Measurements of Relative Solubility of Modern Sediments 155
5.2.5 Karst Development as a Function of Sediment Mineralogy 155
5.3 Chemistry of Florida Precipitation. 156
5.3.1 Composition of the Atmosphere 156
5.3.2 Importance of Marine Aerosols in Florida. 158
5.4 Processes That Affect Water Quality in Florida's Aquifers 159
5.4.1 Evaporation and Transpiration. 159
5.4.2 Biotic Activity in Soils and Sediments 160
5.4.3 Reduction/Oxidation Reactions: Microbial and Chemical Transformations 162
5.4.4 Creation and Effect of Humic Substances 163
5.4.5 Chemical Reactions with Soil and Sediment Minerals 165
5.4.6 Hydrochemical Facies 167
5.4.7 Graphical Representations of Hydrochemical Properties and Facies. 169
5.4.8 Hydrochemical Facies of Florida Groundwater. 172
5.5 Surficial Aquifer System Water Quality. 175
5.5.1 Introduction 175
5.5.2 Marine Aerosol Components 175
5.5.3 Surficial Aquifer System Water Quality in Northern Florida. 177
5.5.4 Surficial Aquifer System Water Quality in Central Florida 177
5.5.5 Surficial Aquifer System Water Quality in Southern Florida. 178
5.5.6 Organic Content of Surficial Aquifer System Water 179
5.6 Intermediate Aquifer System Water Quality 180
5.6.1 Introduction 180
5.6.2 Regional Water Quality 180
5.6.3 Organics in Intermediate Aquifer System Water 180
5.7 Upper Floridan Aquifer Water Quality 180
5.7.1 Introduction 180
5.7.2 Upper Floridan Aquifer Water Quality in Northern Florida 180
5.7.3 Upper Floridan Aquifer Water Quality in Central Florida. 182
5.7.4 Upper Floridan Aquifer Water Quality in Southern Florida 182

5.7.5 Organic Content of Upper Floridan Aquifer Water 182
5.7.6 Trends in Upper Floridan Aquifer Water Quality 184
5.8 Lower Floridan Aquifer Water Quality 184
5.9 Connate Water, Residual Water, and Brine 184
5.10 Regional Studies of Saturation States of Floridan Aquifer Water 185
5.11 Age Dating of Upper Floridan Aquifer Water 189
5.12 Dolomitization in Florida. 189
5.12.1 Dolomitization Chemistry 189
5.12.2 Dolomite in Recent Florida Sediments 190
5.12.3 Ancient, Syndepositional Dolomitization Processes 191
5.12.4 Diagenetic Dolomite in the Floridan Aquifer System 193
5.12.5 Relationship of Dolostone and Dolosilt to Karst Processes. 194
5.13 Other Karst-Related, Water-Quality Issues 195
5.13.1 Aquifer Storage and Recovery and the Arsenic Issue 196
5.13.2 Sulfide and Sulfate Issues 196
5.13.3 Nitrate Issues 196
5.13.4 Ion Exchange Reactions. 200
5.14 Summary 200
References. 201

6 Controls on Karst Landforms in Florida 207
6.1 Purpose of This and Subsequent Chapters. 207
6.2 Introduction 208
6.3 Factors that Affect the Distribution of Florida Karst 208
6.3.1 Porosity and Permeability 208
6.3.2 Residence Time and Contact Surface Area 221
6.4 Fractures and Photolineaments 227
6.4.1 Definitions and Properties 227
6.4.2 Importance of Fracture Trace Identification 230
6.4.3 Importance of "Ground Truthing" Photolineaments 231
6.4.4 Causes of Fractures 233
6.4.5 Regional Photolineament Analyses 233
6.5 Development of Epigenetic and Hypogenetic Karst Systems 234
6.5.1 Eogenetic Versus Hypogenetic Karst Systems. 234
6.5.2 Epigenetic Karst Processes 236
6.5.3 Development of Hypogenetic Karst. 241
6.5.4 Speleogenesis and Cave Morphology 244
6.6 Limestone Dissolution and Denudation Estimates 251
6.6.1 Denudation Rate Estimates for the Limestones of the Floridan Aquifer. 251
6.6.2 Denudation Rates in the Biscayne Aquifer 252
6.6.3 Overview of the Rate of Carbonate Rock Dissolution. 254
6.7 Timing of Karst Development 254
6.7.1 Unconformities and Paleosols 255
6.7.2 Fossils 256
6.7.3 Relationship of Karst Landforms to Sea-Level Fluctuations. 256
6.7.4 The Mio-Pliocene Unconformity: Florida's most Intense Episode of Karstification 257
6.8 Caves and Void Spaces. 258
6.8.1 Introduction 258
6.8.2 Pore Versus Void Space 258
6.8.3 Distribution of Void Space. 258
6.9 Summary and Conclusions 259
References. 261

7 Caves and Sinkholes in Florida 267
7.1 Purpose 267
7.2 Cave Development 268
7.2.1 Phreatic Caves 269
7.2.2 Vadose Caves 271
7.2.3 Lengths and Depths of Florida Caves 273
7.2.4 Relationship of Cave Elevations to Ancient Water-Table Elevations . . 274
7.2.5 Relationships of Caves to Modern Stream Systems 274
7.2.6 Cave Decorations 276
7.3 Subsidence Features 283
7.3.1 Karst and Pseudokarst Depressions in Florida 283
7.3.2 Sinkholes (Dolines) 283
7.3.3 Pseudokarst Depressions 311
7.3.4 Coalescent Sinkholes 315
7.4 Mechanisms of Cover Failure 319
7.4.1 Fundamentals 320
7.4.2 Raveling and Suffosion 320
7.4.3 Piping 326
7.4.4 Disaggregation or Movement of Cohesive Sediment 328
7.4.5 Settlement of Poorly Supported Strata 330
7.4.6 Consolidation, Relaxation and Flow 332
7.4.7 Stress-Strain Relationships and Pressure Arches 333
7.5 Sinkhole Risk in Florida 336
7.5.1 Wright's Sinkhole Map of Florida 336
7.5.2 Sinclair and Stewart's Sinkhole Type Map 336
7.5.3 Quantifying Sinkhole Risk 336
7.5.4 Loss of Relict Sinkhole Information 341
7.5.5 Comparisons of Modern and Relict Sinkhole Occurrences 341
7.5.6 Beck and Sayed's Sinkhole Evaluation of Pinellas County 343
7.5.7 Wilson and Beck's Investigation of Sinkhole Risk in the Orlando Area 344
7.5.8 Wilson's Northern Peninsular Florida Sinkhole Risk Assessment 345
7.5.9 West-Central Florida Sinkhole Risk Study by Scheidt et al. 346
7.5.10 Florida Geological Sinkhole Favorability Study 346
7.5.11 Summary: Evaluating Sinkhole Risk 347
7.6 What Are the Costs of Sinkhole Development? 347
7.6.1 Injuries and Loss of Life 347
7.6.2 Flooding and Drainage Wells 349
7.6.3 Groundwater Pollution 349
7.6.4 Property Damage 350
7.7 Summary 351
7.7.1 Sinkholes 351
7.7.2 Caves 354
References 355

8 Epigene and Hypogene Karst 359
8.1 Introduction 359
8.2 Major Landforms 359
8.2.1 Conical Hills and "Star-Shaped" Valleys 359
8.2.2 Arches and Natural Bridges 361
8.2.3 Sandhill Lakes 367

8.3 Fluviokarst: Karst Features and the Action of Surface Water 368
8.3.1 Swallets 369
8.3.2 Siphons. 372
8.3.3 Blind Valleys 372
8.3.4 Resurgences 374
8.3.5 Traces 374
8.3.6 Examples of Fluviokarst Systems 376
8.4 Karst Escarpments 393
8.4.1 Introduction 393
8.4.2 The Cody Scarp 393
8.4.3 Other Hydrologic or Topographic Karst Escarpments. 400
8.4.4 Hard-Rock Phosphate Deposits: Evidence of Karst
Escarpment Evolution 401
8.5 Springs 404
8.5.1 Spring Locations 404
8.5.2 Importance of Florida Springs 405
8.5.3 Spring and Springshed Definitions 405
8.5.4 Spring Magnitude. 405
8.5.5 Spring Plumbing and Flow Pathways 408
8.5.6 Springs Are Changing!. 409
8.6 Karst Features Related to In Situ Rock-Surface Erosion. 410
8.6.1 Epikarst 410
8.6.2 Karren 414
8.6.3 Duricrusts. 420
8.6.4 Caprock 421
8.6.5 Rubble Zones 423
8.6.6 Caliche and Vadose Concretions 423
8.6.7 Phytokarst 424
8.6.8 Microkarst 426
8.6.9 Collapse Breccias: Recognizing Sinkhole Fill and Cave Collapse 426
8.7 Hypogene Karst in Florida. 427
8.7.1 Introduction 427
8.7.2 Speleogenesis by Groundwater Mixing 428
8.7.3 Speleogenesis by Sulfuric Acid Solutions 430
8.8 Coastal Anchialine Caves. 433
8.9 Summary and Conclusions 434
References. 436

Index 443

1 Eogenetic Karst in Florida

Abstract

Florida's karst constitutes some of Earth's largest expanses of geologically young carbonate sedimentary deposits (shelly sediments, limestone and dolostone) with bare and covered karst. Because of the large population of Florida and the dependence of that population on carbonate aquifers, the karst of Florida is has been extensively investigated. This book synthesizes our knowledge about Florida karst, beginning with why Florida karst differs from older, telogenetic karst elsewhere in North America and the world.

Florida's highly productive aquifers are part of an exemplary karst landscape, an extensive, mantled, geologically young carbonate terrain with dozens of first magnitude springs. Florida's karst has provided water resources to an exploding population and fueled tourism, while creating or exacerbating problems such as sinkhole formation and saltwater intrusion.

The Florida Platform is low and flat and its geology has been dominated by sea-level fluctuations that have left behind a variety of carbonate strata and karst landforms ranging in age from Eocene to Recent. The eogenetic carbonates that comprise these aquifers were never deeply buried and, therefore, they have extensive primary porosity and well developed permeability, distinguishing them from older, telogenetic karst with little remaining primary porosity and very low matrix permeability. Florida's karst is polygenetic, resulting in a complex array of karst features. The overlying siliciclastic sediments create an environment ripe for damaging sinkholes and other hazards.

Keywords

Florida karst · Floridan Aquifer System · Biscayne Aquifer · Eogenetic karst · Carbonate aquifer

1.1 Introduction

Florida's carbonate aquifers and springs are world famous for the quality of their waters. Florida is also world famous for sinkholes and other artifacts of karst development. These conditions represent eogenetic karst. Florida includes the largest expanse of eogenetic karst in North America and one of the largest in the world. Because Florida is low-lying, it has been inundated and exposed many times by sea-level fluctuations. These sea-level excursions have alternately exposed carbonate rocks to karst-development processes and covered the karstic limestones and dolostones with sand and clay cover materials. The properties of Florida's eogenetic karst and importance of understanding the interactions of karstic sediments and rocks with cover materials are explained in this chapter.

1.2 Importance of Karst Processes

- By 1900, groundwater from Florida's limestone and dolostone aquifers was becoming the dominant source of potable water for its inhabitants. The water was touted worldwide for its purity and abundance. Tourist attractions had developed at many springs.
- In 1927, the U.S. Geological Survey's noted hydrogeologist O.E. Meinzer declared that Florida's Silver Springs was the largest spring in a carbonate aquifer in the United States, and that Florida had more first magnitude springs[1] than any other state in the U.S.
- In 1968, the Florida legislature authorized property insurance companies in Florida to offer *optional* insurance against damage caused by sinkhole development. This was the first attempt at legislating sinkhole insurance in

[1] First magnitude springs are springs that discharge at least 2.8 m^3/s on average.

S. Upchurch et al., *The Karst Systems of Florida*, Cave and Karst Systems of the World,
https://doi.org/10.1007/978-3-319-69635-5_1

the U.S. There was little public interest in this insurance coverage.

- In 1981, a massive sinkhole opened in the urban area of Winter Park, Florida. This sinkhole "swallowed" several Porsches, half of an Olympic-sized swimming pool, and other structures. The press around the world spread the word about Florida's sinkholes. Public interest was aroused.
- In 1981, the Florida legislature passed a law requiring property insurers in the state to provide *mandatory* insurance coverage for damage caused by sinkhole development. After 1981, all insured property in Florida was "protected" from sinkhole damage by insurance.
- In 1994, a sinkhole developed within a waste-gypsum disposal area, draining slightly acidic and radioactive water into the underlying Floridan aquifer. There was widespread public concern about pollution potential, but little evidence as to where the water went.
- In the late 1990s, concerns began to be expressed about springs, a major water and tourism resource, experiencing reductions in discharge and increases in algae and other indicators of eutrophication. In 1999, the Florida Department of Environmental Protection created the Florida Springs Task Force, a multi-agency group of experts on springs.
- In 2000, the Florida Springs Task Force concluded that Florida's springs are threatened by eutrophication caused by nitrate in their water. The Task Force recommended strategies for mitigation of flow and nitrate issues.
- In 2003, M.A. Bonn and F.W. Bell reported that Florida's springs constitute major sources of economic benefit to Florida with individual public springs generating as much as $23 million annually.
- In 2010, a deep freeze resulted in heavy pumping of the Floridan Aquifer. As a result, potentials in the aquifer plummeted and over 200 sinkholes developed near Plant City (Hillsborough County).
- By 2011, Florida's property insurance carriers were reporting large financial losses as a result of sinkhole claims and litigation.
- In 2012, heavy rainfall from Tropical Storm Debby caused hundreds of sinkholes in west-central and northern Florida.
- In 2013, a man was killed when a sinkhole beneath his house caused the collapse of his bedroom floor slab. He was in bed when the sinkhole developed. His body was never recovered.
- In 2016, another sinkhole developed in a waste gypsum disposal facility near the 1994 sinkhole. Public outcry was loud.
- By 2016, all of Florida's water management districts had issued "water use caution areas" in order to control permitting for consumptive groundwater use. They were developing water conservation measures, including development of alternative sources, water reuse, and water trading.
- In 2017 a large (80 m) diameter sinkhole developed in Land O'Lakes (Pasco County) destroying two homes and causing five others to be condemned. News of this sinkhole spread throughout the U.S. and Europe.

These, and many other events, have made Florida's 67 counties (Fig. 1.1) famous for sinkholes, springs and other issues related to karst. In order to understand the processes, hazards, and resources related to karst in Florida, one should have an understanding of karst and its origins in Florida. So what is karst and what are karst processes?

1.2.1 Definitions of Karst and Karst Processes

The term "karst" is derived from the Serbo-Croatian word "Kras" meaning barren, stony ground, which is a characteristic of some of the classical karst terrains in middle Europe (Cvijic 1893; Sweeting 1981). The term has come to mean land features that have been developed by dissolution of sediments and rocks that are soluble in water. In Florida, these materials are carbonate sediments and shell beds and carbonate rock, specifically limestone and dolostone. Karst most commonly forms in areas where limestone**,** a sedimentary rock composed of calcite (calcium carbonate, $CaCO_3$) or dolostone**,** a sedimentary rock composed of the mineral dolomite (calcium, magnesium carbonate, $CaMg(CO_3)_2$) are near the land surface or in contact with waters capable of causing mineral dissolution. These rock types are collectively known as carbonate rocks. In Florida, karst development is not restricted to just carbonate rocks. Shell beds and other unconsolidated or poorly consolidated, carbonate-rich sediments are also developing karst-like landforms.

Karst is found in many areas of the world, and it gives a distinctive appearance to landscapes wherever it exists. Karst processes include (1) the dissolution of sediments and rocks in natural ground or surface water and related movement of any sediments or rocks that overlie the voids created by dissolution and (2) precipitation of minerals from water in caves and on the land surface.

Karst landforms dominate many areas of the United States, especially Florida, Kentucky, Tennessee, Missouri, Texas, and many other states in the eastern and mid-continent U.S. (Fig. 1.2; Veni et al. 2001; Weary and Doctor 2014). Karst landscapes, or karst terrains, are areas characterized by a series of landforms that have been created by the chemical and physical actions of water on soluble rocks, such as limestone or dolostone. Chemical action generally relates to dissolution or chemical precipitation of soluble sediments and rocks of a karst terrain by surface water or groundwater. The

Fig. 1.1 Locations of Florida's 67 counties

process of dissolution is the dominant cause of development of karst landforms, but precipitation of minerals and rocks in caves and springs is also part of the karst process. In addition, the movement of water that is transporting sediment can also contribute to destruction of sediments and rocks in karst terrains.

Physical landforms are natural, physical features of the landscape, such as hills and valleys, which make up the surface and shallow subsurface details of an area. Examples of landforms that form in karst terrains include sinkholes, caves, springs, sinking streams, towers and pinnacles, and arches.

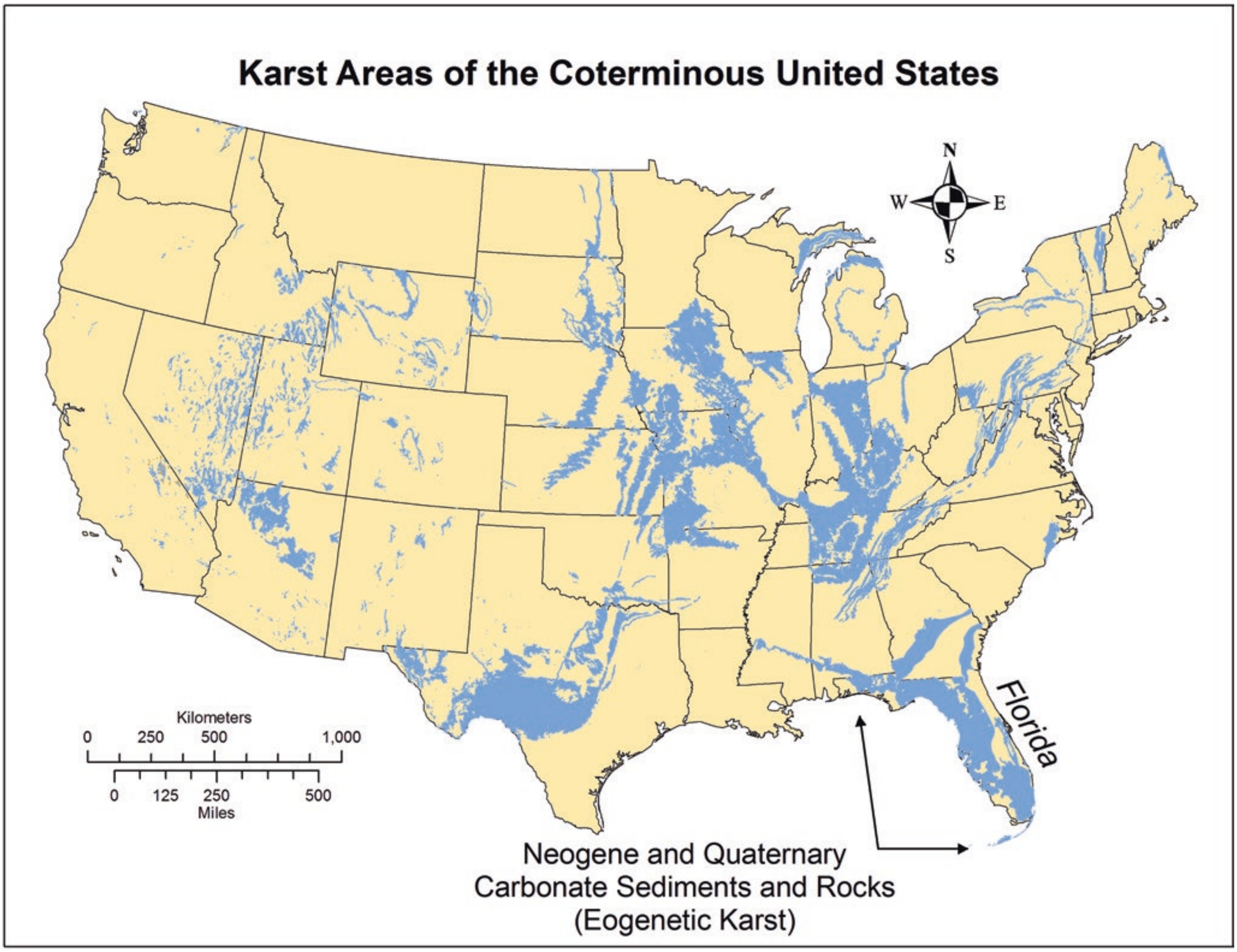

Fig. 1.2 Karst distribution in the United States. Note the exposed or shallow karst in the Coastal Plain of Florida and adjacent states. (Modified from Weary and Doctor (2014))

This text is about the about how the karst features in Florida form and how to recognize them. However, the subject has significant, broader implications that should be of interest to karst scientists worldwide and to those interested in the social and political implications of karst as a geologic hazard or resource. Here's why.

- Florida and limited portions of Georgia and South Carolina (Fig. 1.2) contain the most extensive expanse of geologically young (Paleogene to Quaternary age), eogenetic karst (see Sect. 1.3) in North America, and it is one of the largest areas in the world where geologically young carbonate sediments and rocks have developed karst landforms. Eogenetic karst consists of landforms whose host rocks are geologically young and have never been deeply buried. As a result, the host rocks have not been subjected to pressure and heat that alter the fabric of the rocks and change their ability to transmit water.
- The sediments affected by karst processes in Florida include a complete range of carbonate strata from unconsolidated or poorly consolidated, carbonate-rich sediment, such as shell beds, to well-lithified rock. Mineral content ranges from aragonite and high-magnesium calcite, which are chemically unstable, to low-magnesium calcite and dolomite, which are chemically relatively stable.
- Karst landforms range from minor, newly formed and poorly understood small-scale features to large-scale landforms reminiscent of the well-known karst regions with ancient rocks that have been altered by deep burial, heat, and pressure, such as the carbonate rocks shown elsewhere in the continental United States (Fig. 1.2).
- The karstic carbonates of Florida include two of the most productive aquifers in the world, the Floridan Aquifer System and the Biscayne Aquifer. These aquifers are among the most studied in the world because of their extensive use for water supply.

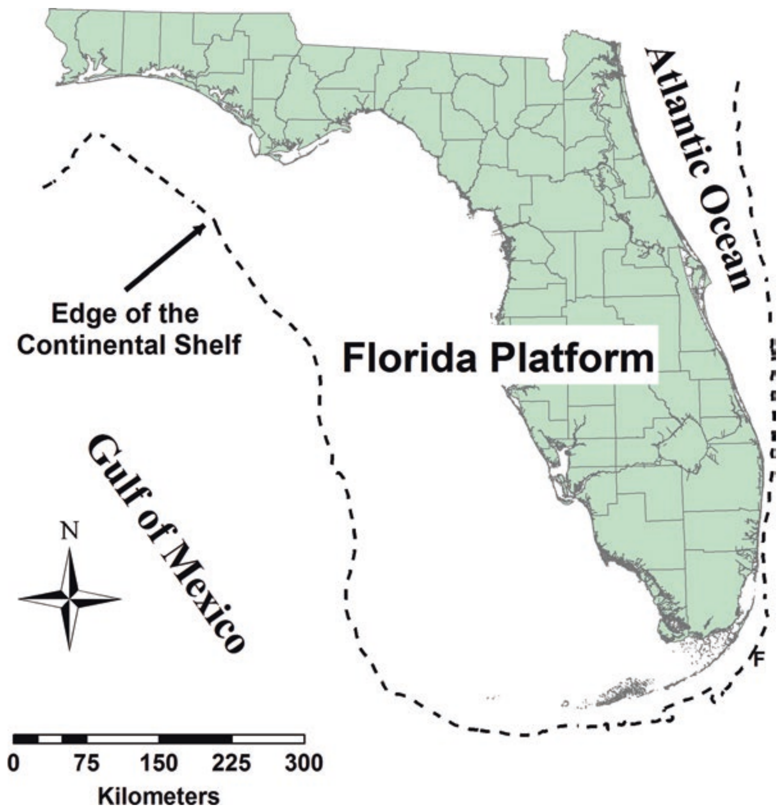

Fig. 1.3 The extent of the Florida Platform, which includes both mainland Florida and the continental shelf

- Because of Florida's large, and growing, population, the effects of water extraction from the aquifers provides an excellent laboratory for studying rock and soil mechanics, hydraulics, hydrogeology, and hydrogeochemistry of karstic limestone and dolostone aquifers under stress.
- The highest point in Florida is only 105 m above sea level, and about half of the Florida Platform (Fig. 1.3), the area of modern land and continental shelf, is currently submerged with an approximate average water depth of about 75 m. Karst features are known to exist on the continental shelf and even in deeper water on the continental slope.
- Since the Florida Platform is topographically low and flat, Florida has been dramatically affected by the sea-level changes resulting from glaciers forming and melting over the past five million years or so.[2] High, interglacial sea stands resulted in deposition of sand, clay, and carbonate sediment over carbonate rock in many areas. Low sea stands during glacial episodes resulted in development of near-surface alteration of the sediment and rock, including development of karst features. Circulation of groundwater in Florida's aquifers during low sea stands also resulted in deeply buried karst features in the limestones and dolostones. As a result, Florida karst features and the processes that formed them are complex and multi-dimensional in both time and space.
- With its long coastline, saline-water intrusion into the freshwater aquifers is a regional problem in Florida, especially where the karstic aquifers are highly confined, and recharge from rainfall is limited. Much of the seminal research on saltwater intrusion was done in Florida.
- Florida's springs are world famous. It has been said that Florida contains more first-magnitude springs than any other state or nation. This statement is certainly true for springs in carbonate rocks (Meinzer 1927). These springs have been extensively studied for a variety of reasons, including concerns about water supply, maintenance of ecological and recreational values, and eutrophication and deterioration of environmental values.
- Unlike many areas of eogenetic karst elsewhere, most of Florida's karst is covered by mixtures of varying percentages of sand and clay that mask and exacerbate geological hazards normally present in karst terrains. These hazards include sinkholes, soil creep and slope movement, and the expansion and shrinkage of certain clays.
- Carbonate sediments are being formed at the present time in Florida. Older carbonate sediments have been converted into rock, which remains at shallow depths. Because of these circumstances, an extensive literature exists concerning carbonate sediment deposition and

[2]Glaciers during this timeframe extended as far south as southern Ohio in North America. The rise and fall of sea level due to the repeated melting and formation of the glaciers had a direct effect on depositional and erosional processes in Florida.

post-depositional alteration (diagenesis); hydrogeology; saltwater intrusion; soil and rock mechanics and development of sinkholes; springs and surface water/groundwater interactions; and other issues of concern in Florida.
- Florida was the first state to develop laws providing for property insurance coverage[3] as a result of sinkhole damage. In the context of this book, insurance claim investigations have resulted in thousands of subsurface test borings and/or soundings in search of evidence of sinkhole development. No other location has produced such a wealth of geological and geotechnical information.
- Finally, most texts on karst science focus on the landforms and processes that directly affect development of karst landforms. They do not deal in detail with the mechanics of failure and movement of sediments that overlie and interact with the karstic features of the carbonate. Because of the widespread sand and clay deposits that overlie carbonate sediments and rocks in much of Florida and because these cover sediments, in some instances, have the potential to collapse suddenly into voids in the underlying carbonate rocks and cause damage, the geotechnical and geological properties of the cover materials are addressed in this text.

Because of these factors, Florida has gained an international reputation for its water-filled caverns, springs, sinkholes, and other landforms associated with karst. Few have attempted to integrate and synthesize data from numerous different, but related, disciplines in order to present the story of Florida karst development and encourage understanding of eogenetic karst in a carbonate- and sand or clay- sediment-rich terrain that has been affected by interplay with changing sea levels. In their discussion of the evolution of the concept of carbonate aquifers with multiple forms of permeability, Vacher and Florea (2015) synthesized the development concepts of the evolution of permeability in Florida karst. Others have synthesized portions of the story of Florida karst, such as sinkhole-development processes. It is the goal of this text to synthesize this rich and diverse literature in order to understand eogenetic karst, the landforms and sediment or rock properties that have developed in Florida and provide an explanation as to how these features formed. The authors have added our insights and ideas where gaps in the literature exist.

[3]It is not the intent of this text to discuss sinkhole insurance and the sociopolitical issues that have resulted from the insurance coverage. These topics will be addressed in a later publication.

1.2.2 Why Study Florida Karst?

Florida includes the largest geographic area of geologically young carbonate sediments and rocks with well-developed karst features in North America, and it is one of the world's largest eogenetic karst areas. The extensive Yucatan Peninsula in Mexico has a similar karst landscape, but substantially less is known about the details and origins of its karst. As such, the thoroughly studied karst of Florida provides an excellent laboratory for understanding how karst landforms evolve within a few thousand to millions of years after deposition. With the exception of a few carbonate islands, such as the Bahamas and Bermuda, there are few areas where karst processes have been so intensely studied in areas where the rocks have not been deeply buried and primary porosity and permeability not destroyed.

A societal reason that the karst of Florida is of interest is that millions of dollars in damage occur each year as a result of sinkhole development. Understanding the risks and causes of sinkholes should be a priority for all Floridians.

This book synthesizes what we know and understand about (1) how Florida's geologically young karst has formed, and (2) how it has affected the Florida landscape. These landforms include sinkholes, caves, springs, and many other artifacts of dissolution and/or precipitation of soluble materials.

1.2.3 Geologic Hazards and Resources in Florida

In addition to a need to develop its karstic aquifers as water resources and protect the many scenic and environmental benefits of the carbonate terrain, karst development is a well-known geologic hazard in Florida. Inadequate foundation support, sinkholes, groundwater contaminant migration and other issues frequently confront Floridians. Construction continually has to deal with designing for the karst in the subsurface (Fig. 1.4); property is damaged by sinkholes and subsidence (Fig. 1.5); and groundwater contaminants travel in unpredicted pathways through caverns and fractures in the carbonate strata.

Karst features are also highly prized resources. Florida's springs (Fig. 1.6) are major tourist attractions and local recreational sites, sites for the development of bottled water plants, plant and animal refuges (Fig. 1.7), and sources of many streams. Sinkhole lakes are prime real estate with scenic water-front lots and swimming, boating, and wildlife observation and conservation opportunities.

Finally, most of Florida's potable water comes from its karstic aquifers. These resources are, without doubt, our most valuable karst resources of all.

Fig. 1.4 Collapse failure of a landfill over a sinkhole at the Southeast Hillsborough Landfill near Wimauma, Hillsborough County in 2010. Site, which has been remediated, was located at 27.776°N, 82.188°W. People provide scale

1.2.4 Florida's Karstic Aquifers

The state's two major, karstic, carbonate aquifers are the Floridan Aquifer System (FAS) and the Biscayne Aquifer (Fig. 1.8; Table 1.1). Because of their high permeabilities, these aquifers are considered to be among the most productive in the world. Each is capable of providing millions of cubic meters of water to wells each day. In addition, there is a number of sub-regional limestone, dolostone, or shell aquifers that are also, to some degree, karstic (Fig. 1.8).

The Sand and Gravel Aquifer in the extreme western part of the Florida panhandle (Fig. 1.8) is the only Florida aquifer without a significant carbonate sediment component and that has not been affected by karst processes. It produces 401,000 m^3/d of freshwater (Marella 2009; Table 1.1). The Sand and Gravel Aquifer only produced about 1.5% of the fresh water utilized by Florida in 2005, however (Marella 2009). As indicated in Table 1.1, about 60% of all freshwater consumed in Florida is derived from the karstic aquifers.

The FAS (Fig. 1.8) is the primary karstic, limestone and dolostone aquifer in Florida. Well over half of the state's population depends on the FAS for potable water. In southern Florida, the FAS is brackish to salty, so communities utilize shallower aquifers. In southeastern Florida, the Biscayne Aquifer, which is part of the Surficial Aquifer System (SAS), predominantly consists of limestone that is about 1 million to 125,000 years old. The Biscayne Aquifer, which is one of the most productive aquifers in the world, is the primary source of potable water for the Miami-Dade area and Florida Keys.

Because of the dependence of the population of Florida on groundwater derived from its karstic limestone and/or dolostone aquifers (Table 1.1), state and Federal agencies, local governments, industry, and academic institutions have sponsored numerous water-resource related studies of the karstic aquifers.

1.3 Eogenetic and Telogenetic Karst

In Sect. 1.1, the term eogenetic karst was freely utilized. In this section, the term is explained. It is because Florida's carbonate strata have not been subject to deep burial and the effects of heat and pressure that we can call the karst eogenetic, and it is because the karst is eogenetic that Florida has so many sinkholes, such productive aquifers, and so many large, limestone springs.

Fig. 1.5 The 1981 Winter Park sinkhole (28.594°N, 81.362°W), located in Winter Park, Orange County, Florida. The largest sinkhole recorded in modern times in Florida captured the attention of the population and governments of Florida. (Photo courtesy of the Florida Geological Survey)

1.3.1 Primary and Secondary Porosity and Permeability

When carbonate sediments are originally deposited, they contain abundant void space within the sediment mass. Over time, this sediment may undergo diagenesis (physical and chemical changes that lead to conversion of sediment to rock) that result in development of additional porosity as solutions modify the sediment particles. When particles dissolve away, the resulting molds and other dissolution-related openings begin to touch each other, further enhancing porosity and permeability (Lucia 1995; Vacher and Mylroie 2002). The distinction between diagenesis and karst-related dissolution is often unclear, but the result is the same: a geologically young, carbonate-sediment deposit with enhanced porosity and permeability.

In Florida, the near-surface carbonate sediments are geologically young (less than about 40 million years old), have never been deeply buried (the shallow karstic carbonate strata in Florida have not been buried more than 100 m), and abundant pore space often remains between particles within the body of the carbonate mass. The early-stage pore space consists of the open spaces within and between fossils, sediment particles, and structures within the sediment. This original pore space is termed primary porosity. Unless the sediment is muddy, water can freely circulate between and within the sediment grains and porosity/permeability are enhanced by dissolution of sediment particles. Thus, Lucia's "touching vug" type of pore space, a form of secondary porosity (Vacher and Mylroie 2002) slowly emerged.

Because of the abundant pore space in Florida carbonate sediments and rocks, water movement is normally not restricted to fractures and other secondary openings. The result is a different pattern of pore and void space development in young carbonate strata as opposed to much older carbonate rocks. Geologically young rocks also develop fractures and poorly-developed bedding planes (Fig. 1.9b), so typically both primary and secondary porosity are present in rocks such as occur in Florida. This double set of open pore spaces and high permeability results in the high productivity of the aquifers, geologically rapid sediment and rock dissolution, and karst formation.

Much of the world literature on karst landforms and how they develop deals with areas where the carbonate strata were deeply buried in the geologic past where they underwent significant alteration as a result of the time, heat, and pressures that accompanied burial. As a result, this older, highly modified carbonate rock normally has little of the

Fig. 1.6 Ichetucknee Head Spring, located in Ichetucknee State Park (29.984°N, 82.762°W), near Ft. White, Florida, is a popular swimming and tubing site. It is estimated that Ichetucknee Springs State Park alone brings $23 million to the economy of north Florida (Bonn and Bell 2003)

Fig. 1.7 Biologist counting manatee seeking refuge during cold weather in the Blue Spring run, Blue Springs State Park (28.943°N, 81.341°W), near Orange City, Volusia County, Florida. There were 300 manatees in the spring and its run when the photo was taken

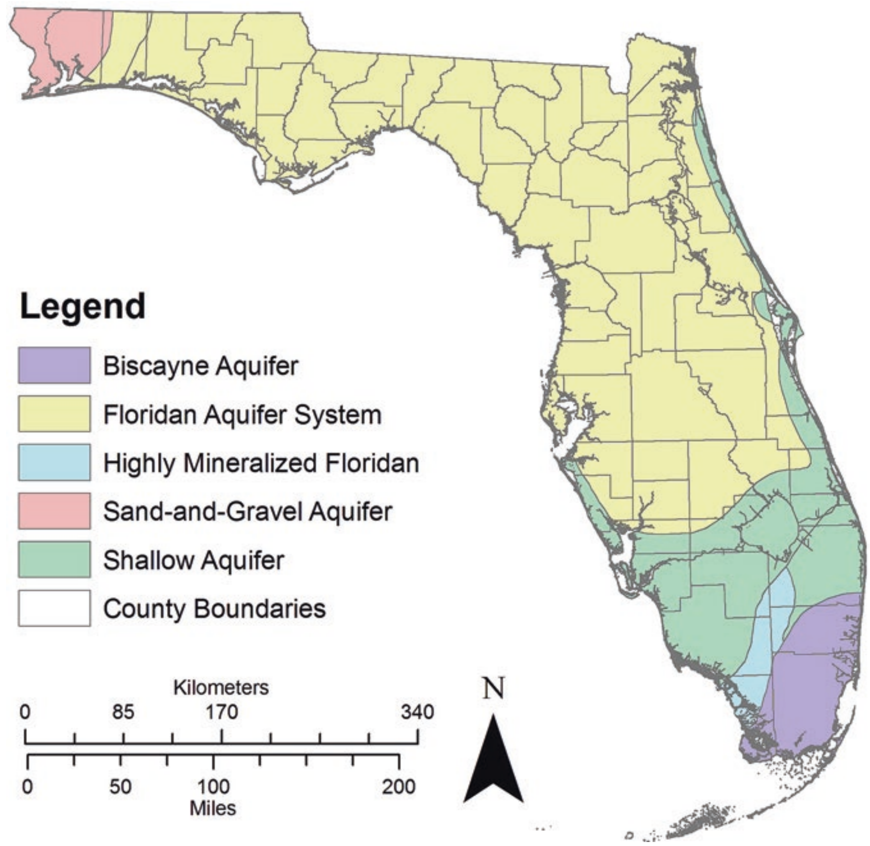

Fig. 1.8 Florida's principal aquifers. The only aquifer without karst features is the Sand and Gravel aquifer of extreme west Florida

original pore space (porosity) remaining between the carbonate particles that originally accumulated and formed carbonate sediment and then carbonate. Permeability in these old carbonate deposits is typically developed along cracks and openings between sediment layers (Fig. 1.9a). There is little or no pore space within the matrix of the carbonate rock, so primary porosity in these carbonates is typically near zero.

After deep burial (hundreds to thousands of meters below the land surface) and for tens to hundreds of millions of years, the limestone (or other water-soluble rock) may be uplifted and exposed to near-surface conditions. With uplift, the old, low porosity carbonate rock is likely to be fractured and bedding planes (contacts between beds of sedimentary rocks that originally formed during deposition) may open. With the release of confining pressure and the onset of groundwater circulation, bedding planes become accentuated through dissolution. Groundwater and surface water seek these fractures and bedding planes because they are more permeable than the rock matrix. As the water flows through the fractures and bedding planes, they become enlarged due to the dissolution of the rock adjacent to these openings. As a result, much of the existing void space in these geologically old carbonate rocks is secondary porosity, or porosity that formed after deposition and burial of the carbonate.

Table 1.1 Water use from surface water and all Florida aquifers in 2005

	Daily water use ($\times 10^6$ m^3)	Percent of total
Saline water	43.5	63
Fresh water	26.0	37
Total water use	69.5	100
Fresh groundwater	16.1	62
Fresh surface water	9.9	38
Total water use	26.0	100
Saline groundwater	0.042	0.01
Saline surface water	43.4	99.9
Total water use	43.5	100

Data from Marella (2009)

1.3.2 Comparison of Porosity in Geologically Ancient and Young Carbonate Sediments and Rocks

The most common forms of large openings along which water can flow in carbonate sediments and rocks are bedding planes, fractures, and, possibly, faults. In ancient, once deeply buried carbonate rocks, these structures dominate water movement. In young carbonate sediments and rocks that have never been deeply buried, intact and modified primary porosity is likely to remain and serve as a second set of

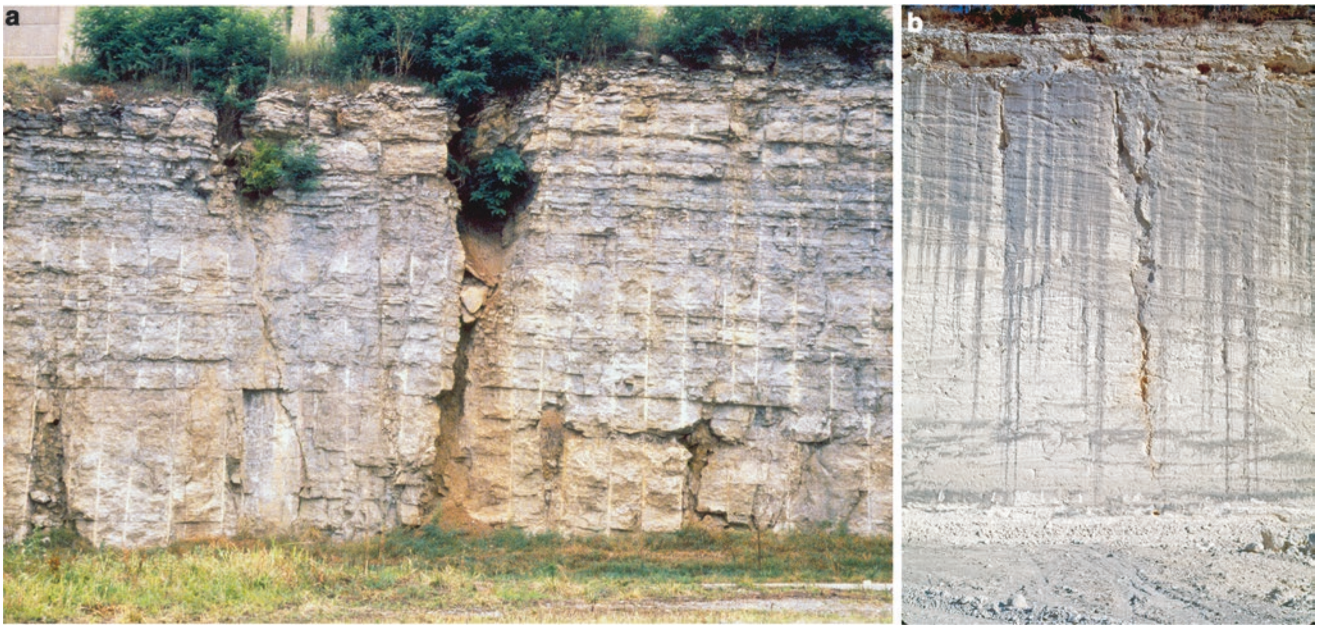

Fig. 1.9 (**a**) Secondary porosity – solution-enlarged vertical fracture and horizontal bedding planes in an Ordovician[4] limestone near Nashville, Tennessee. Outcrop is about 6 m high. (**b**) The effects of primary and secondary porosity on the structure of the fractured Eocene Ocala Limestone in a quarry near Lowell, Marion County, Florida. Note the absence of well-developed bedding planes and rudimentary enlargement of the fracture. Quarry face is 15 m high and located near 29.322°N, 82.179°W

pathways for water movement (permeability) through the smaller, interstitial pore openings and touching vugs.

In ancient carbonates that have once been deeply buried and subjected to the effects of heat and pressure over millions of years, evidence can often be found in the body of the rock of the original, deposition-related composition, structure, and geologic history of the rock, but in the absence of small-scale, interstitial porosity and permeability related to these features, they do not normally substantially affect karst development. Permeability of the carbonate rock matrix is too low.

In many ways, the long and complex history of once deeply buried limestone or dolostone serves as a hydrogeologic simplifying process. The original properties of the carbonate rock matrix, which developed during deposition, early diagenesis (the physical and chemical changes in the sediment that result in transformation of the sediment into rock), and early karstification, are lost or obscured, resulting in carbonate strata with bulk properties that reflect burial rather than pre-burial diagenesis or karstification. Evidence of pre-burial diagenesis and/or karstification may be evident, but burial normally obliterates or significantly reduces primary and pre-burial secondary porosity and permeability, such as touching vug spaces.

The karst of Florida differs from the majority of the karst in the United States in that Florida's carbonate strata are significantly younger (all of the near-surface carbonate in Florida is less than 40 million years old, and near-surface limestone in southeastern Florida is 1 million to 125,000 years old) and has never been buried more than a hundred meters below the land surface. As a result, the original depositional features and primary porosity of the carbonate sediment or rock are often well-preserved and post-depositional alterations to the carbonate sediment or carbonate rock caused by early diagenesis are evident. In many areas of Florida, carbonate sediments have not even undergone sufficient diagenesis to result in well-lithified rock. In this setting, karstification and diagenesis may be synonymous, or at least they are complimentary and contemporaneous processes. Note that there are more deeply buried, karstic strata in Florida, but they are not involved in development of epikarst, the karst features that occur on or near the upper surface of the limestone or dolostone.

Compare the two exposures of limestone shown in Fig. 1.9. The limestone shown in Fig. 1.9a is over 400 million years old, has been deeply buried, subjected to burial diagenesis, and then uplifted to near the land surface. This section of Ordovician[4] limestone has been exposed to karst development for at least six million years (Middle Tennessee State University 2016). The limestone has a vertical fracture (joint) that has been enlarged by dissolution as groundwater passed through the rock. In addition, the bedding planes are well developed and many have also been enlarged by dissolution. The only significant pathways for groundwater circulation are through the secondary porosity of the fracture and

[4]The Ordovician Period extended from 485.4 to 443.8 million years ago (Mya).

along bedding planes. The matrix of the limestone is well-lithified (solidified into rock). As a result, the rock is hard and difficult to break or dig out of the rock face without a hammer or excavator.

Figure 1.9b is an exposure of the Ocala Limestone, which was deposited sometime between about 37 and 34 million years ago (Mya), has never been buried more than 100 m, and has not been subjected to geologically significant loading (application of weight from later sediments deposited on top of the limestone) or thermal stresses. This limestone exposure also has a fracture that has been enlarged by dissolution. The exposure is a quarry face, so weathering has not significantly accentuated the bedding planes. The limestone itself is often soft and easily excavated with a pick or shovel. In fact, in some areas of the exposure, one can dig the limestone out of the quarry face with bare hands. In this loose, poorly lithified limestone, pore spaces between the original particles of calcium carbonate (microscopic fossils, pellets, and other remains) are well preserved as primary porosity.

The differences in age, degree of burial diagenesis, and porosity and permeability in the two different limestones affect their appearance, how karst develops, and their engineering and hydrologic properties.

1.3.3 Eogenetic and Telogenetic Karst

In 2002, Vacher and Mylroie introduced the term eogenetic karst to describe karst features developed in geologically young, relatively unmodified carbonate sediments and rocks. Their use of the term eogenetic was derived from the classification of porosity development with time and depth of burial by Choquette and Pray (1970; Fig. 1.10).

According to the classification scheme developed by Choquette and Pray (1970), porosity in carbonate rocks develops in three "zones" – the eogenetic, mesogenetic, and telogenetic zones. The eogenetic zone reflects porosity development in a post-depositional regime before burial and deep-seated, heat- and pressure-related changes to the carbonate rock occur. The mesogenetic zone (Fig. 1.9) includes the environment of deep burial, where elevated temperature and pressure conditions exist. Burial and uplift of strata within the mesogenetic zone requires millions of years, so time is an important factor as compared to eogenetic processes. The telogenetic zone reflects porosity development after uplift and exposure to erosion at or near the land surface. Time, measured in tens to hundreds of millions of years, is required for a rock body to transition from eogenetic to mesogenetic and then to telogenetic zones.

Vacher and Mylroie (2002; Fig. 1.11) took this simple, rock-cycle-based porosity-development sequence and applied it to karst, suggesting that karst that develops shortly after deposition and early diagenetic alterations but before significant burial should be termed eogenetic karst. Telogenetic karst, in contrast, is karst developed on carbonate rocks that have been deeply buried, subjected to burial and tectonic pressures and heat over millions of years, and then uplifted to the land surface where they are exposed to subaerial and shallow subsurface erosion and dissolution processes. The mesogenetic zone is not subject to karstification because of depth of burial and high confining pressures. Note in Fig. 1.11 that the initial, primary porosity is typically lost during burial and that secondary porosity increases upon uplift and exposure to near-surface weathering, fracturing, and unloading.

As an example of the differences in the eogenetic karst of Florida and typical telogenetic karst, consider Table 1.2. This table compares some of the general properties of eogenetic and telogenetic karst based on Florida and the karst of mid-continent United States (Fig. 1.2). Note that there are substantial differences in the suite of host sediments and rocks

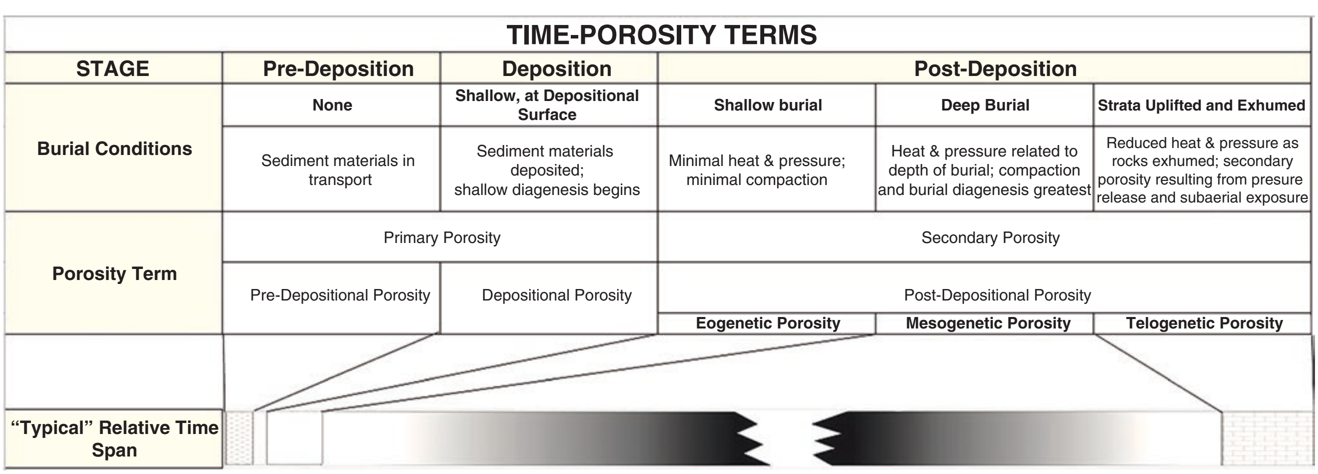

Fig. 1.10 Time- and burial-related porosity terminology as suggested by Choquette and Pray (1970)

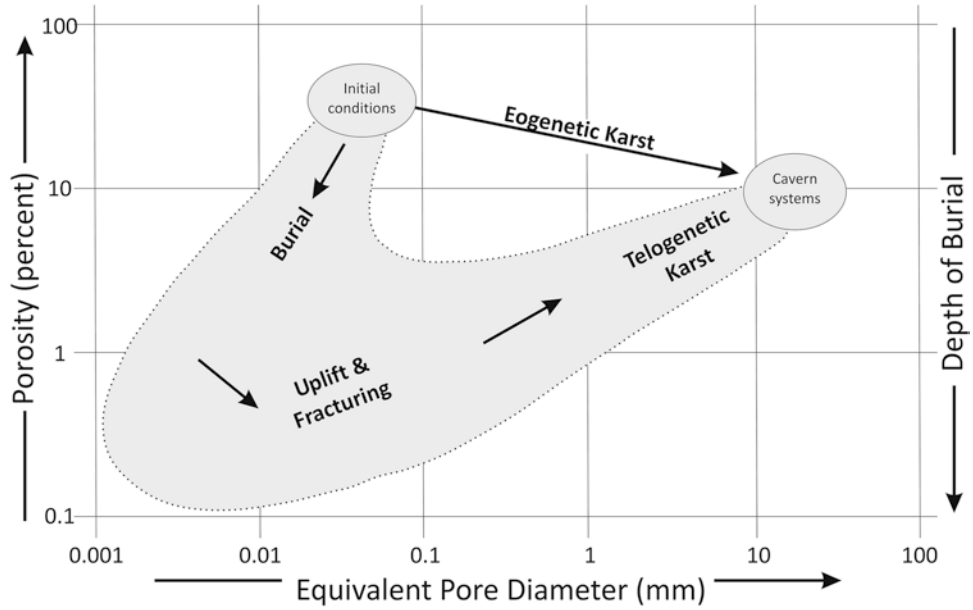

Fig. 1.11 Evolution of porosity in eogenetic and telogenetic karst as a function of burial and time. (Modified from Vacher and Mylroie (2002))

and processes that affect karst development, including mineralogy, depth of burial, porosity distribution, relationship to sea level, and sediment/rock surface area available for chemical reactions with water.

We know from work in Florida and elsewhere around the world that near-surface, eogenetic karstification begins to develop upon exposure to subaerial and relatively shallow groundwater environments, so the eogenetic zone is not simply an environment of development of primary porosity as a result of deposition. Diagenesis and later karst processes related to dissolution in meteoric and groundwater systems can also result in secondary porosity, ranging from microscopic to very large pore spaces.

The depth of development of eogenetic and telogenetic karst is limited to those areas where groundwater can circulate. If karst features develop as a result of dissolution at or near the land surface, where groundwater is actively recharging and circulating through the shallow aquifer, the karst that develops is termed epigenetic, or karst that develops near the top of the soluble rock. Karst features that develop at depth as a result of acidic fluids migrating up from below or of mixing of saline and fresh ground water are termed hypogenetic.

Groundwater circulation is somewhat compartmentalized vertically. Within the upper part of the FAS, Biscayne Aquifer, and other shallow carbonate strata, karst is mostly epigenetic and groundwater circulation is limited to relatively shallow depths. Deeper circulation is limited by beds that prevent mixing with the shallower aquifers. This circulation may occur in strata to depths of at least 600 m in the FAS (Puri and Winston 1974; Smith and Griffin 1977). Any karst in these deeper strata either formed before the rocks were buried or is hypogenetic. For the most part, epigenetic karst in Florida is more-or-less restricted to the upper 100 m.

In Florida, the zone where eogenetic karst has formed has the following general physical and temporal constraints:

1. Both unconsolidated carbonate and carbonate-rich sediments and variably lithified carbonate rocks can be involved in karstification;
2. Host sediments and rocks are late Paleogene to Quaternary in age (sediments and rocks deposited between 40 Mya and about 10,000 years ago);
3. Karstification has been controlled by development of a groundwater flow system that responds to variations in sea level;
4. Eogenetic karst in Florida is likely multicyclic and polygenetic owing to changes in sea level of as much as 98 m (−90 to +8 m) over the last 120 thousand years and probably even more over the last 40 million years;
5. Landform development by epigenetic karst processes (development of sinkholes, caves and springs, etc.) is limited to approximately the upper 100 m, in sediments that have not been deeply buried or subjected to pressures equivalent to burial depths greater than 100 m;
6. Artifacts of deep karst (100 to over 600 m) consist of possible dissolution features developed as a result of groundwater mixing along the salt-water/fresh-water transition zone, prior to burial, or during extreme low sea stands; and
7. Owing to the youth and lack of burial to great depths, carbonate sediments and rocks within the upper 100 m in Florida retain texture, fabric, mineralogy, and structure related to their environments of deposition and early diagenesis.

Given this variable range of constraints, the eogenetic karst of Florida is complex. There are areas of Florida where

Table 1.2 Comparison of some properties of eogenetic karst in Florida and in the telogenetic karst of the mid-continent United States

Property	Eogenetic karst of Florida	Telogenetic karst of the mid-continent U.S.
Host materials	Carbonate-rich sediments, limestone, dolostone	Limestone, dolostone, calcitic and dolomitic marble
Age of host sediments and rocks	Tertiary and Quaternary	Primarily Paleozoic
Age of karst development	On-going, Eocene and younger	On-going, age variable
Influence by sea-level fluctuations	On-going karst development controlled by sea-level position and timing of deposition and subaerial exposure	No direct control; effects of sea level fluctuations absent for millions of years
Maximum depth of burial	Less than 100 m for subaerial and shallow karst	Thousands of meters
Karst development on the salt-water/fresh water transition zone	On-going	Effects of sea-water/fresh-water interaction absent; interaction with basin-derived brine possible
Sediment and rock mineral content	Aragonite, calcite, dolomite	Calcite, dolomite
Sediment and rock matrix primary porosity and permeability	Generally present	Generally absent
Sediment and rock secondary porosity and permeability	Poorly to well developed	Well developed
Relative surface area of sediment and rock in contact with groundwater	Very high	Low

karstification and diagenesis are just beginning in geologically young sediments and there are areas where the eogenetic karst features strongly resemble features commonly associated with old, telogenetic karst (Table 1.2). For example, sinkholes develop in both eogenetic and telogenetic karst. As a result, the eogenetic karst of Florida stands as an excellent laboratory for documenting and synthesizing the range of eogenetic karst processes, a subject of concern to karst scientists, and for comparison to karst processes in older, telogenetic systems.

Florea (2012) summarized the explosion of investigations of eogenetic karst worldwide in a paper given at the 2012 Annual Meeting of the Geological Society of America. He concluded his abstract by saying

> In the decade following 2002, a wealth of research has highlighted the importance of eogenetic karst worldwide, and … stimulated revisions to the origin and morphology of paleokarst. …. [W]e may ultimately come to view eogenetic karst with equal importance to classical karst in older, diagenetically mature carbonates.

Synthesis of Florida karst science can contribute to this rise in importance of eogenetic karst, especially in areas where sand and clay have been deposited over the limestone or dolostone and sea level has risen and fallen multiple times.

1.4 Why Examine the Role of Cover Sediments in Florida?

One of the ways that this text differs from most traditional karst texts is emphasis on the materials and behavior of cover, the sediment that overlies the carbonate sediments or rocks. Throughout most of the state, the carbonate strata are covered by a wide range of sand and clay-rich sediments. It is this cover material that migrates into the void space within the carbonate sediment or rock and has the potential to cause unexpected damage through sinkhole development.

This text includes an extensive discussion of the role of the sediments that cover Florida limestone and dolostone because these cover sediments control karst development and, when sinkholes develop, the movement of cover materials that support structures usually causes the damage.

1.5 Summary

There is a prodigious amount of data available for piecing together the story of Florida karst. All totaled, we probably know more about Florida karst than any region of the United States. Unfortunately, most of these data have not been synthesized into a single story describing the formation of such a large and important expanse of eogenetic karst.

It is this wealth of data developed over many years by our friends and colleagues that we draw upon for this text. It is the authors' intent to characterize the eogenetic karst of Florida and assist those interested in the "sinkhole problem" in Florida to understand karst. Most important, the authors have attempted to synthesize and integrate these data into a "big picture" of eogenetic karst.

Notable conclusions from this chapter include:

- Shallow Florida karst can be considered eogenetic;
- Karst is developed in unconsolidated shell and other carbonate sediments and in well-lithified limestone and dolostone;

- Near-surface, eogenetic, karstic sediments and rocks have never been buried more than about 100 m, so they have not been subjected to significant burial pressures or temperatures;
- Near-surface karstic sediments and rocks, which range in age from Eocene to late Pleistocene, represent a variety of epigenetic karst landforms and aquifer characteristics;
- Deeper karst includes hypogenetic karst formed on saltwater/freshwater transition zones and in other environments;
- Because of the presence of primary and secondary porosity in the carbonate aquifers, they tend to be highly productive in terms of water supply; and
- Because of Pliocene to late Pleistocene sea-level fluctuations, many of the carbonate sediments and rocks have been covered by siliciclastic cover and subject to multiple cycles of karstification.

References

Bonn MA and Bell FW (2003) Economic impact of selected Florida springs on surrounding local areas. Report prepared by Florida State University for the Florida Department of Environmental Protection. Tallahassee, Florida

Choquette PW and Pray LC (1970) Geologic nomenclature and classification of porosity in sedimentary carbonates. Bulletin, Amer. Assoc. Petrol. Geologists, 54:207–250

Cvijič J (1893) Das Karstphänomen. Geographische Abhandlungen, 5(3):215–319

Florea LJ (2012) Eogenetic karst aquifers after a decade of investigation. Geol. Soc. Amer. Abstracts with Programs, 44(7):205

Florida Springs Task Force (2000) Florida's springs: strategies for protection & restoration. Tallahassee, Florida Department of Environmental Protection. Available at http://www.dep.state.fl.us/springs/reports/files/SpringsTaskForceReport.pdf. Accessed 22 July 2014

Lucia FJ (1995) Rock fabric/petrophysical classification of carbonate pore space for reservoir characterization. Bulletin, Amer. Assoc. Petrol. Geologists, 79(9):1275–1300.

Marella RL (2009) Water withdrawals, use, and trends in Florida, 2005. USGS Sci. Inv. Report 2009-5125

Meinzer OE (1927) Large springs in the United States. USGS Water Supply Paper 557.

Middle Tennessee State University (2016) The history of the glades of the Central Tennessee Basin. Available at http://w1.mtsu.edu/gladecenter/gladehistory.php. Accessed December 15 2016

Puri HS and Winston GO (1974) Geologic framework of the high transmissivity zones in south Florida. Fla Bur Geology Sp. Pub. No. 20

Smith DL and Griffin GM (eds.) (1977) The geothermal nature of the Floridan Plateau. Fla Bur Geol. Sp. Pub. No. 21

Sweeting MM (1981) Karst geomorphology. Hutchinson Ross Pub. Co., Stroudsburg, Pennsylvania, Benchmark Papers in Geology, Vol. 59

Vacher HL and Florea LJ (2015) Quantitative hermeneutics: Counting forestructures on a path from W.M. Davis to the concept of multiple permeability karst aquifers. International Journal of Speleology, 44(3):207–230.

Vacher HL and Mylroie JE (2002) Eogenetic karst from the perspective of an equivalent porous medium. Carbonates and Evaporites, 17:182–196.

Veni G, DuChene H, Crawford NC, Groves, CG, Huppert GH, Kastning EH, Olson R, and Wheeler BJ (2001) Living with karst: A fragile foundation. Environmental Awareness Series, American Geological Institute

Weary DJ and Doctor DH (2014) Karst in the United States: A digital map compilation and database. USGS Open-File Report 2014-1156

2 Geological Materials: An Overview

Abstract

In Florida's mantled, eogenetic karst, the sedimentology and mineralogy of siliciclastic and carbonate geological materials greatly impact karst development. Florida's cover materials are integral parts of the karst development story, and they can present hazards themselves. Cover materials are mostly allochthonous quartz, feldspars, clay minerals, while carbonate rocks consist of calcite with some aragonite and dolomite. Magnesium content of calcite affects diagenetic and karst processes very little; but aragonite dissolves preferentially, and dolostone deposits can be resistant to dissolution. Therefore, it is important to understand the mineralogy of geologically young, carbonate sediments and rocks.

Marine sediments in Florida are predominantly well-sorted, fine-to-medium sands, sourced from areas with limited grain sizes and deposited by waves, currents, and wind. Eolian sands are poorly consolidated with frosted grain surfaces. Grain shapes range from angular shells through variable sands to rounded pebbles and cobbles.

Under-consolidated clay beds in the Miocene Hawthorn Group (Chap. 3) act as confining layers despite high porosities, and the fine-grained sediments have the potential to flow if sinkholes develop. Smectites are common expansive clays in the Hawthorn Group. The Hawthorn clays were significantly altered during two periods of intense weathering in the Late Miocene-Early Pliocene and Late Pliocene-early Pleistocene. The first weathering event formed a prominent paleosol throughout central and northern Florida.

Florida's carbonate rocks were deposited in broad, shallow seas, creating flat, laterally extensive layers. The overlying siliciclastics, in contrast, represent complex environments resulting in sediment facies with great lateral and vertical variations. This chapter describes the origins and properties of these sediments.

Keywords

Carbonate sediments · Limestone · Dolostone · Paleosols · Depositional environments · Sand · Clay

2.1 Introduction

This chapter introduces the classification and chemical/mineralogical properties of geological materials involved with karst in Florida. This chapter is included for those readers who are unfamiliar with the basics of sediment classification and mineralogy or the terminology used to characterize such materials. In eogenetic karst systems, the mineralogy of geological materials strongly impacts karst development because of the presence of thermodynamically unstable minerals, mineral deposits that add to our knowledge of Florida karst, and evidence that minerals provide with respect to weathering, transport and deposition, and age.

Carbonate minerals and rocks are discussed first, because of their importance to formation of karst features. The properties of cover sediments that overlie carbonate rocks are discussed toward the end of this chapter. Note that geologic formation names are used in this chapter in order to optimize the utility of the chapter. Refer to Chap. 3 for a discussion regarding formation names and lithologies.

It is important to understand the materials that comprise Florida's eogenetic carbonate sediments and rocks and the materials that cover the carbonates. It is the intent of this chapter to introduce sediment and rock terminology, mineralogy, textures, and classification schemes utilized in this text. After discussing these issues, the concepts of facies, lithosomes, and depositional control on sediment textures and compositions are introduced. By understanding the nature of Florida carbonate sediments and rocks and siliciclastic sediments that commonly overlie the carbonates, the

S. Upchurch et al., *The Karst Systems of Florida*, Cave and Karst Systems of the World,
https://doi.org/10.1007/978-3-319-69635-5_2